Effect of Intermittent Generation on Conventional Generators in Power Systems

Thesis presented for the degree of

Doctor of Philosophy

at the University of Strathclyde

by

Peiran Shi

B.Sc. (Hons.)

Supervisor: Professor K. L. Lo

Power Systems Research Group

Department of Electronics and Electrical Engineering

University of Strathclyde

Glasgow, United Kingdom

June 2010

Effect of Intermittent Generation on Conventional Generators in Power Systems

By

Peiran Shi

In the fulfillment of the requirement
of the degree of Doctor of Philosophy

Institute for Energy and Environment
Department of Electronic and Electrical Engineering
University of Strathclyde
June 2010

Declaration of Author's Right

Dedication:

To my beloved parents

and

my grandmother

who did not live long enough to witness this achievement

Contents

CHAPTER 3 OVERVIEW OF POWER SYSTEM SECURITY AND EFFECT OF WIND GENERATION ON THE SYSTEM STABILITY 56

CHAPTER 4 A METHOD TO CALCULATE HEATING PROBLEM OF CONVENTIONAL GENERATOR CAUSED BY WIND POWER GENERATION (I): A THERMAL MODEL FOR GENERATOR 98

List of Figures

List of Tables

Acknowledgement

I would like to express my sincere gratitude to my supervisor, Professor K. L. Lo, Head of the Power Systems Research Group (PSRG), for his supervision and valuable guidance throughout the period of my research work. His encouragement and help contributed greatly in my current achievements.

I also wish to extend my gratitude to all the colleges at PSRG for their kindness and readiness to help. In particular I would like to thank Dr. Zhong Xiaotao and Mrs. Zhang Mingming for the valuable academic discussions and the help that they provided me during the days in Glasgow.

A special thanks to Mr. Zeng Xuexing in Centre for excellence in Signal and Image Processing (CeSIP), EEE Department, University of Strathclyde, for his help, advice and support in Matlab programming and other technical discussion in various stages or in other perspective issues.

Last but not least, I deeply appreciate my mother and my father for all their encouragement, inspiration and unlimited love throughout my life and financial support, understanding and patience during the period of my PhD study.

Abstract

In recent years, as a result of increasing environmental concern, there is a widespread growth in the exploitation of renewable energy and its technology. The level of penetration of wind generation has increased rapidly in many countries. The development of wind power is also one of the national energy strategies with the aim to reduce carbon dioxide emissions. Many countries have set targets for replacing a certain percentage of their conventional generator capacity by renewable energy. Comparing with conventional ones, generation from renewable sources have nearly no harmful emissions and no investment cost in fuel resources but it will affect systems in operation and behaviour. Generating from wind energy is one of the most popular ways of using renewable energy.

In wind power generation the energy source is wind and wind speed has stochastic and probabilistic characteristics. As a result, the output of wind generation is variable especially during the high wind velocity periods. When wind power penetration level in a system is low, the whole behaviour of the power system is still determined by conventional generators. When the wind power penetration level in a system is high, the fluctuation of wind farm output becomes an important problem for creating potential difficulties for both steady state and transient state and it will impact the operation of other generators in the system. The mismatch of wind farm output will also lead to output fluctuation of other generators. These small changes of output will not immediately break the heating limitations of generator machine but it may cause heating problem in the long run. When the system is large, all the generators can share this influence. But in a weak system, there are just several generators or only one to match the fluctuating output.

Past research in this area has been focused on transient stability of the system that reflects the dynamic performances of the wind farm and the power system after a fault, but these are usually relied on an average wind speed wind turbine model and the study time period is in the range of normally less than several seconds. In this thesis, the aim is to investigate the effects of the wind farm on heating problem of conventional generator

on the steady state performance of the system under continuous wind speed changing condition. And a thermal model based on flux density will be developed to calculate the heating effect. Furthermore, existing cooling systems in generating machines should take away the extra heat generated inside the machines and the effect of cooling system on the heating problem will be modeled.

In this thesis, simulation study will cover a 24 hours period under different penetration levels of wind generation condition ranging from 5%, 15% to 30% of total generation capacity and also under different probability distribution of wind speed data situation. Moreover, the different types of cooling system in different types of conventional generator are also considered. In this thesis, the test systems also include IEEE-14-Bus system and IEEE-39-Bus system.

CHAPTER 1

INTRODUCTION

Electric power system is a fundamental infrastructure in societies and probably is the most complex and largest man-made system in the world. Generally, the power system contains three main parts, generation, transmission and distribution: [1]

- For generation of electricity, prime moves convert the primary sources of energy to mechanical energy and then the mechanical energy is converted to electrical energy mainly relied on synchronous generators.
- Transmission system is used to transmit electric power over significant distances over a wide area and is required to comprising of subsystems operating at different voltage levels.
- And distribution system represents the final stage in the transfer of electric power from the high voltage transmission lines to industrial and individual customers.

With the development of electricity demand the power systems have become very huge and complex systems which also include thousands of nodes and ten of thousands of MW generating capacity especially in big countries such as the U.S.A, China; and transmission lines, transformers and other facilities also require more capacity. For economy and operational reasons, interconnection of neighbouring systems and the high voltage dc (HVDC) transmission systems become more common. In addition, more and more information and communication technology (ICT) is used in power system, so the systems is becoming more intelligent and control and protection need to be more efficient and reliable [2]. Furthermore, the trend towards deregulation has forced power systems to operate closer to security boundaries. After electricity market existed, all the companies in power system take much more attentions to economy than before so they usually make the systems running at the edge of security in order to get more profit. The value of security is the key point of the balance between economy and system security and the level of security will be decided. [3]

1.1 Conventional Generation

There are many primary sources of fuel, so there are many kinds of generation. Each kind of plant has its own operating characteristics and influences to systems and the surrounding environment. It means different plants are suitable for different characteristics of load and reserve margins, the latter usually use fast start-up plants. However, power plants that are based on synchronous generators are very important ones and are the main electric sources. The basic features of power systems are mainly relied on the characteristics of synchronous generators. Characteristics of synchronous generators are also represented on the buses which they are connected to. It can influence the ability of power transfer and the reliability in a system. Maximum use of generators with characteristics should be maintained to supply the maximum power to the load before reaching the boundary of a system limit which can be a low voltage boundary, a voltage collapse boundary or a thermal limit boundary. [4]

A synchronous machine has two essential parts which are the field and the armature. In general, the field is on the rotor and the armature is on the stator. When the direct current excites the rotating magnetic field and a turbine which is connected to prime mover drives the rotor, alternating voltages in the three-phase armature windings of the stator are induced. Both the frequency of the induced alternating voltages and the frequency of currents in the stator windings depend on the speed of the rotor when a load is connected. The frequency of the stator electrical quantities is synchronized with the rotor mechanical speed. When two or more synchronous machines are interconnected, the stator voltages and currents and the rotor mechanical speed of all the machines must have the same frequency. Therefore, the rotors of all interconnected synchronous machines must be in synchronism. In a generator, changing the mechanical torque input by the prime mover is the only way to change electrical torque output of the generator. Increasing or reducing of the mechanical torque or power input will advance or retard the rotor to a new position relative to the revolving magnetic field of the stator. As a result, the responses of currents and magnetic field in the machine are the index of operation condition. [5]

When a machine is in a fluctuating field and stator current operation condition, the generator is easily under thermal pressure and may cause temperature rise in the short-term or long-term. The temperature rise of a machine or device has a direct bearing on the power rating and impacts its useful service life directly. So it is necessary to keep the synchronous machine under stable field current and stator current operation condition. [6]

1.2 Intermittent Generation and Its Influences on Power Systems

1.2.1 Intermittent Generation

Because of the pressure of climate change and global warming and the security of energy which is more important in some countries to rely on overseas energy, some green and clean new energy such as the solar, wind, waves, tidal and biomass need to be used to reduce pollution and dependence on fossil fuels. As renewable energy produces very little carbon or other greenhouse gases, it plays a very important role in tackling climate change. In recent years, there is a widespread growth in the exploitation of renewable energy and its technology. The penetration level of renewable energy has increased rapidly in many countries. The development of renewable energy is also one of the national energy strategies with the aim to reduce carbon dioxide emissions for some countries. For example, in the 2003 Energy White Paper, UK government set a long-term aim of reducing CO_2 emissions by 60% by 2050; increase electricity supply from renewable energy to 10% by 2010 and to 20% by 2020 and with an acceptable price. The UK is a country which is naturally endowed with plenty of resources of renewable energy, especially onshore and offshore wind. [7]

At present, generating from wind energy is the most popular and also the most explored way of using new renewable energy in some countries. Renewable energy especially the wind energy has stochastic and probabilistic characteristics. As a result, the output of generation based on renewable energy is variable in a certain time period. For example, wind power generation usually has variable output especially during the high wind fluctuating periods. For this feature, the generation which has stochastic and probabilistic characteristics is also called intermittent generation and most of intermittent generation in present power systems is wind power generation. When intermittent generation penetration level in a system is low, the whole behaviour of the power system is still determined by conventional generators. When the intermittent generation increasingly integrated into power systems, the impact of wind power generation on the operation and behaviours of power system is more and more significant. The mismatch of intermittent generation output will also lead output fluctuation of other generators which can become an important problem for creating potential difficulties for both steady state and transient state. [8]

1.2.2 Previously Done Researches

Increasing wind power generation leads to the problem of their impacts on power system. Wind turbine generators are subjected to both electrical disturbances which affect the generator during electrical transients and mechanical disturbances which affect the turbine when there are sudden wind speed changes. Wind turbine generator may impact on the rotor angle stability, voltage stability and frequency stability of the power system. [9] In the past, there have been several researches in this area which focused on stability especially transient stability of the system reflecting the dynamic performances of the wind farm and the power system after a fault. [10, 11] Some achievements are list in below:

- For the small-signal rotor angle stability, constant speed wind turbines have the better feature of increasing the damping of power system oscillations than variable speed type and variable speed wind turbines have the better characteristics of increasing the frequency of power system oscillations than constant speed type. [9, 10] Furthermore, wind turbine generation does not induce new oscillation mode. [10, 11] Following the increasing of wind power penetration level, the effect of wind turbine generation on system oscillations also increases. [9] For the transient rotor angle stability, the impact from wind turbine generators is influenced by the location of wind turbine generators. All of these influences will be explained in details in chapters that are to follow.

- For the voltage stability [12, 13], the lack of reactive power support is the key issue of wind farm that causes voltage instability to power system and the effect could be more severe when the inject power from wind generation is large. The reactive power requirements of wind farm are reactive compensation equipments such as SVCs and synchronous condensers to support the voltage stability. [14]

- For frequency stability, the increasing penetration of wind power generation in electricity grid which displaces a number of connected conventional synchronous generators will result in a reduction of the system inertia. The frequency of a power system with lower inertia will have larger and faster deviations after occurrence of abrupt variations in generation and load. In this case, additional frequency response ancillary services must be provided to ensure frequency limits are not exceeded. [15]

For conventional generator, the increasing of wind power generation has directly influence on the output of conventional generators and their operation condition. The conventional generators which are usually required to balance the wind power generator output will also result in the fluctuating of their outputs. The fluctuating response can lead to the internal responses which include variation of rotor and stator currents. As a result, the machine can experience under long term thermal over stress as well as under currents variation condition. [6]

In order to maintain the machine within the permissible temperature, there have been lots of researches [16, 17] and tests [18, 19] on the limits of maximum permissible rotor and stator currents to establish a capability limit curve for operation of generator. However, the vibration of rotor and stator currents caused by wind power generation is usually within the boundaries of the curve; however, it may lead to heating problem in the long run.

In the former study of heating problem within an electrical machine, there are some methods and thermal models have already been proposed and are used in the design of electric machine to estimate thermal behaviour and calculate temperatures of rotor and stator region in a generator machine. A lumped parameter thermal model proposed by Mellor and Turner [20, 21] has been widely used for the researchers working on electrical machine thermal problems. Moreover, there are also many researches on simplifying this model for better calculation efficiency [22, 23] and developing the models of electrical elements in the machine [24, 25, 26].

In this thesis the aim is to look at the heating of conventional generator during operating especially during the intermittent output of wind generator. The conventional generator will need to follow, and to hunt, the output of the wind generation. This means the rotor angle of the conventional generator may suffer small oscillation. This can lead to extra heating effect generated inside the conventional generator and it is not a design characteristic of conventional generator. Some of the previous described which on calculation of short term heating effects [22, 23, 24, 25, 26] will be modified as extended in this thesis.

1.3 Objectives of the Thesis

The following objectives have been chosen for the research work performed in this thesis:

- To review the understanding of stochastic and probabilistic characteristics of wind speed distribution and the understanding of definition and classification of power system security.

- To establish a method to produce wind speed data according to Weibull distribution from original wind speed data and to develop a simulation model to simulate wind generation output according to wind speed data.

- To explore the influences caused by wind power generation on conventional generators and the power system under both steady and transient states.

- To investigate the heating problem and thermal performances inside generator machines which are caused by fluctuating output of wind turbine generators.

- To establish a method to calculate the thermal and heating effects of conventional generator which includes the model for the calculation of temperature rise inside the machine; and the method of calculating on the cooling effect from the cooling system in generator machine under wind power generation output fluctuating condition.

- To test the method of calculating the thermal and heating effects of conventional generator under different operation situations and conditions to obtain more practical simulation results

1.4 Original Contributions of the Thesis

Based on the above objectives, this research has achieved the following main original contributions:

- A useful method for simulating wind speed which represents stochastic and probabilistic characteristics with different parameters of probability distribution for different situations is proposed based on the understanding of the characteristics of the wind resources. Through this method, any certain number of wind speed data can be obtained according to this probability distribution from the original wind speed data from different research conditions.

- A summary of explanation and analysis of the impact from wind turbine generation on different types of system stability: rotor angle stability, voltage stability and frequency stability under both steady state and transient state is provided which bases on the understanding of definition and classification of power system security and how the different types of security problems are interrelated. This could help engineers and system operators to more clearly understand the benefits and challenges from the wind power generation.

- A new method, which follows heat transfer theories, for calculating the thermal performances and heating effects of conventional generator which is caused by fluctuating of wind turbine generator output is established. This method contains a modified model of calculation about temperature rise inside the machine based on currents and magnetic fields of the stator and rotor with wind power generation under fluctuating output condition.

- A new method for calculating cooling effect from cooling system in conventional synchronous generator machine under wind power generation output fluctuating condition is proposed. This method is based on the heat exchange theories, the 3D steady state temperature field with boundary conditions and the some liquid heat exchange convection coefficients.

- Using the proposed methods, simulation and analysis of the heating problem about conventional generator in a power system with wind turbine generators is performance under different conditions which include extremely unfavourable wind speed condition, different wind power generation penetration levels condition, different types of generator condition and more complicated power systems condition including the IEEE-14-Bus system and IEEE-39-Bus system. These can be used as basis and data for power system engineers or operators to re-schedule duty cycle of generators which are the remediation about temperature rise in the winding of conventional generators lead by intermittent output of wind power resources.

1.5 Outline of the Thesis

This thesis is made up of seven chapters. They are organised as follows:

Chapter 1 presents an introduction of conventional generators in power systems, intermittent generation and previously researches of influences from intermittent generation to power systems. Then, objective and scope of this thesis and main original contributions of the thesis are presented.

Chapter 2 first discusses the stochastic and probabilistic characteristics of wind speed and introduces Weibull distribution as the probability distribution function of wind speed data which can be used in the method of developing wind speed data. Then it explores the characteristics and performances of wind turbine generators which are about the relationship of wind speed and power output and comparing the different types of wind turbine generators. Chapter 2 especially discusses operation of doubly-fed induction generator (DFIG), control systems of wind turbine generator, both of active and reactive power output features and reactive power support from voltage source converters. In addition, there are results in simulations of wind speed and wind generation output in this Chapter.

Chapter 3 provides an overview of definition and concept of power system security and the states of system operating condition. Moreover, the discussion continues with the power system planning problem and the basic concepts and categories of power system stability which mainly rely on dynamic performances of the power system. Then it explains and analyses the impact of wind turbine generators on operation of other conventional generators and the different types of system stability: rotor angle stability, voltage stability and frequency stability. Lastly, two study cases represent the wind power generation affect of the output of conventional generators and the transient characteristics of the power system are included.

In chapter 4 and chapter 5, a method to calculate heating problem of conventional generator caused by wind power generation is proposed in two parts which are thermal calculation model and cooling system effects. Chapter 4 first discusses the IEEE standards classification of insulation system of generator machines. Continually, chapter 4 explains and analyses the relationship between currents and magnetic fields and control of the excitation current and stator current. A simulation of fluctuation of rotor current, stator current and power angle in a conventional generator following fluctuation of output is included. Then chapter 4 develops a thermal model based on magnetic field and currents to be suitable for a power system with wind farms. Moreover, it also analyses the thermal energy transfer processes and lists the temperature rise calculation processes.

Chapter 5 first introduces the three main types of cooling system for different types of generators which includes air-cooled, hydrogen-cooled and water-cooled system. It continues to introduce the 3-Dimensions steady state temperature field and different boundary conditions. Then, it discusses and describes the temperature distribution of coolant in the cooling system and the calculation processes to determine the coolant convection coefficient. Finally, chapter 5 lists the calculation processes of the coolant convection coefficient and cooling water way-out temperature rise. And there is simulation example to calculate the thermal performance of the synchronous generator.

Chapter 6 uses the heating performance calculation method to simulate and analyse the heating problem of conventional generator in a power system with wind power generation under different conditions through four simulation examples. The first simulation analyses the influences from fluctuating wind speed condition to the power system. Second one analyses the impact from different penetration level of wind energy to the power system. The third one explores the heating performance of other types of conventional generator. The final simulation researches the heating problem calculation in IEEE-14-Bus system and IEEE-39-Bus system.

Finally, chapter 7 presents the conclusion of the research work in this thesis and possible future research works.

1.6 Publications

- Peiran Shi and K. L. Lo, "Effect of Wind Farm on the Steady State Stability of a Weak Grid," IEEE 3rd International Conference on electric Utility Deregulation, Restructuring and Power Technologies (DRPT2008), Nanjing, China, 6-9 April 2008, pp. 840-845.

- Perian Shi and K. L. Lo, "Thermal Effect of Intermittent Generation on Conventional Generator," The 44th International Universities' Power Engineering Conference (UPEC2009), Glasgow, UK, 1-4 September 2009.

- Perian Shi and K. L. Lo, "Re-schedule Duty Cycle of Conventional Generators to Balance the Influence from Wind Power Generation Based on Heating Problem Research," Under preparation for journal submission.

1.7 References

[1] B. M. Weedy, B. J. Cory, *Electric Power Systems*, Forth Edition, UK: John Wiley & Sons, Ltd, 1998.

[2] J. D. Glover, M. S. Sarma, *Power System analysis and design*, Forth Edition, Toronto, Oratorio: Thomson Learning, 2007..

[3] D. S. Kirschen and G. Strbac, *Fundamentals of Power System Economics*, UK: John Wiley & Sons, Ltd, 2004.

[4] A. J. Wood, B. F. Wollenberg, *Power Generation, Operation and Control*, Second Edition, New York: John Wiley & Sons, Ltd, 1996.

[5] T. Wildi, *Electrical machines, drives, and power systems*, 6th International Edition, New Jersey: Pearson Education, 2006.

[6] S. J. Chapman, *Electric Machinery and Power System Fundamentals*, New York: McGraw-Hill, 2002.

[7] Secretary of State of Trade and Industry of UK, "The Energy Challenge Energy Review Report 2006", Department of Trade and Industry.

[8] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, *Wind Energy Handbook*, UK: John Wiley & Sons, Ltd, 2001.

[9] E. Muljadi, C. P. Butterfield, B. Parsons and A. Ellis, "Effect of Variable Speed Wind Turbine Generator on Stability of a Weak Grid," *IEEE Transactions on Energy Conversion*, Vol. 22, No.1 March 2007.

[10] J. G. Slootweg and W. L. Kling, "The Impact of Large Scale Wind Power Generation on Power System Oscillations," *Electric Power System Research*, Vol. 67, pp. 9-20, 2003.

[11] A. Tabesh and R. Iravani, "Small-Signal Model and Dynamic Analysis of Variable Speed Induction Machine Wind Farms," *IET Renewable Power Generation*, Vol. 2, No. 4, pp. 215-227, February 2008.

[12] Y. Chi, Y. Liu, W. Wang and H. Dai, "Voltage Stability Analysis of Wind Farm Integration into Transmission Network," *International Conference on Power System Technology, PowerCon 2006*, pp. 1-7, 22-26 October 2006.

[13] N. R. Ullah and T. Thiringer, "Variable Speed Wind Turbines for Power System Stability Enhancement," *IEEE Transactions on Energy Conversion*, Vol.22, No.1, pp. 52-60, March 2007.

[14] E. Camm and C. Edwards, "Reactive Compensation Systems for Large Wind Farms," *IEEE/PES Transmission and Distribution Conference and Exposition*, pp. 1-5, 21-24 April 2008.

[15] J. Ekanayake and N. Jenkins, "Comparison of the Response of Doubly Fed and Fixed-Speed Induction Generator Wind Turbines to Changes in Network Frequency," *IEEE Transactions on Energy Conversion*, Vol. 19, No. 4, pp. 800-802, December 2004.

[16] W. Nakayama, K. Fuzioka and S. Watanabe, "Flow and Heat Transfer in the Water-Cooled Rotor Winding of a Turbine Generator," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-97, no. 1, pp. 225-231, January/February 1978.

[17] W. B. Gish, W. E. Feero and G. D. Rockefeller, "Rotor Heating Effects from Geomagnetic Induced Currents," *IEEE Transactions on Power Delivery*, Vol. 9, No.2, pp. 712-719, April 1994.

[18] S. J. Salon, M. R. Shah and L. W. Montgomery, “Analysis and Testing of Negative Sequence Heating of Turbine Generator Rotors,” *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, No.8, pp. 3940-3949, August 1981.

[19] J. H. Dymond, R. Ong and N. Stranges, “Instrumentation, Testing, and Analysis of Electric Machine Rotor Steady-State Heating,” *IEEE Transactions on Industry Applications*, Vol. 38, No. 6, pp. 1661-1667, November/December 2002.

[20] P. Mellor, D. Roberts, and D. Turner, “Lumped parameter thermal model for electrical machines of TEFC design,” *IEE Proceedings-B*, Vol. 138, No. 5, pp. 205-218, September 1991.

[21] P. Mellor and D. Turner, “Real time prediction of temperature in an induction motor using microprocessor,” *Electric Machines and Power Systems*, Vol. 13, pp. 333–352, 1988.

[22] A. Boglietti, A. Cavagnino, M. Lazzari, and M. Pastorelli, “A Simplified Thermal Model for Variable-Speed Self-Cooled Industrial Induction Motor,” *IEEE Transactions on Industry Applications*, Vol. 39, No. 4, pp. 945-952, July/August 2003.

[23] M. J. Duran and J. Fernandez, “Lumped-Parameter Thermal Model for Induction Machines,” *IEEE Transactions on Energy Conversion*, Vol. 19, No.4, pp. 791-792, December 2004.

[24] S. S. Choi and X. M. Jia, “Under Excitation Limiter and Its Role in Preventhing Excessive Synchronous Generator Stator End-Core Heating,” *IEEE Transactions on Power Systems*, Vol. 15, No. 1, pp. 95-101, February 2000.

[25] H. H. J. M. Janssen, E. J. W. ter Maten and D. van Houwelingen, “Simulation of Coupled Electromagnetic and Heat Dissipation Problems,” *IEEE Transactions on Magnetics*, Vol. 30, No. 5, pp. 3331-3334, September 1994.

[26] A. F. Armor, “Transient, Three-Dimensional, Finite-Element Analysis of Heat Flow in Turbine-Generator Rotors,” *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-99, No. 3, pp. 934-946, May/June 1980.

CHAPTER 2

THE WIND SPEED CHARACTERISTICS AND WIND TURBINE GENERATOR PERFORMANCE

2.1 Introduction

The level of penetration of wind generation has increased rapidly in recent years in many countries. The development of wind power is also one of the items of national energy strategies with the aim to reduce carbon dioxide emissions. The UK government has set targets for 10% electricity energy is from renewable sources by 2010 and 20% is from renewable sources by 2020. [1]

The energy that can be extracted in the wind is as the cube of the wind speed, so an understanding of the characteristics of the wind resource is critical to all aspects of wind energy exploitation and using from identification of suitable location of wind farm and analysis of the commercial value of wind energy to the design of wind turbines and research the influence on power network and demand side. The most remarkable features of wind are stochastic and probabilistic characteristics. The wind resource is both highly geographically and temporally variable so this variability is in quite a wide range of scales in both of space and time. As a result, wind speed can be described through probability distribution form and relationship among mean value and standard deviation also can be found. A wind speed mode based on this distribution is performed features of wind speed and also can be used in wind energy study. Furthermore, different parameters of probability distribution can be used depending on different situations. Lastly, any certain number of wind speed data will be getting according to this probability distribution from original wind speed data from different research conditions.

A wind turbine with generator is a device for extracting and transferring wind energy to electrical energy. Only the kinetic energy of the air which passes through the rotor of wind turbine will be extracted and follows the aerodynamics and fluid dynamics. A modern wind generation usually includes a three-bladed stall-regulated rotor, induction or synchronous generator and a high tower, which is shown in Fig. 2.1. The pattern and the size of wind turbine and generator are according to wind characteristics. Depending on different design of rotor and generator, the wind generation can be divided into several types for different conditions. The wind generation is not only active power resource but also reactive power resource so it can influence both of power flow in the system and system voltage. There are also control systems in wind turbine and generator to adjust both of active and reactive power or voltage which are evidences for research of impact to power grid from wind generation.

This chapter aims to discuss the characteristics of wind and wind turbine with generators which influence the performances of wind generation and power grid. And it will also introduce the methods that are used to get wind speed and wind generation output data for further research. First, this chapter will introduce Weibull probability distribution and the way to develop wind speed data. Next, it will discuss performances of wind turbine and induction generator especially doubly-fed induction generator and simulate the output of wind generator.

Fig. 2.1 A wind turbine with generator in a wind farm.

2.2 Wind Probability Distribution

In order to research the wind generation, a model of wind speed is essential. Because of the variability of wind speed, the behaviour of wind speed was studied based on its characteristics and historical data based on daily, monthly, season and yearly data collection. Wind speed variations during a certain period can be well characterized in terms of a probability distribution function through historical statistical data, this probability function is called Weibull probability distribution. [2, 3]

2.2.1 Weibull Probability Distribution Function

The Weibull distribution is employed to represent probability distribution of wind speed variation, while mean wind speed (MWS) value, standard deviation of wind speed and scale and shape parameters of Weibull distribution are also derived. [2, 4]

The probability density function (pdf) of a Weibull random variable wind speed v (m/s) is:

$$f(v;k,\lambda)=\begin{cases}\frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1}e^{-(v/\lambda)^k}, v\geq 0\\ 0, v<0\end{cases}$$

Equation 2.1

where v is the wind speed, $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution. The Weibull distribution function is:

$$F(v)=\int_0^v f(v;k,\lambda)dv=e^{-(v/\lambda)^k}$$

Equation 2.2

Both the shape parameter k and scale parameter λ describe the variability deviated from mean wind speed (MWS) value. A Weibull pdf is shown in Fig. 2.2. The MWS and the standard deviation can be derived respectively:

Mean wind speed value:

$$\bar{v}_{MWS} = \int_0^\infty v f(v) dv = \int_0^\infty \frac{kv}{\lambda}\left(\left(\frac{v}{\lambda}\right)^{k-1}\right) e^{-\left(\frac{v}{\lambda}\right)^k} dv$$

Let $x = \left(\frac{v}{\lambda}\right)^k$, $x^{\frac{1}{k}} = \frac{v}{\lambda}$ and $dx = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} dv$,

MWS can be simplified as:

$$\bar{v}_{MWS} = \int_0^\infty \lambda x^{\frac{1}{k}} e^{-x} dx$$

By substituting a gamma function Γ, which is $\Gamma(z) = \int_0^\infty t^{Z-1} e^{-t} dt$, let $t = x$ and $z = 1 + \frac{1}{k}$, at last:

$$\bar{v}_{MWS} = \lambda \Gamma\left(1 + \frac{1}{k}\right) \qquad \text{Equation 2.3}$$

Standard deviation:

$$\sigma = \sqrt{\int_0^\infty (v - \bar{v}_{MWS})^2 f(v) dv}$$

$$= \sqrt{\int_0^\infty \left(v^2 - 2v\bar{v}_{MWS} + \bar{v}_{MWS}{}^2\right) f(v) dv}$$

$$= \sqrt{\int_0^\infty v^2 f(v) dv - 2\bar{v}_{MWS} \int_0^\infty v f(v) dv + \bar{v}_{MWS}{}^2 \int_0^\infty f(v) dv}$$

$$= \sqrt{\int_0^\infty v^2 f(v) dv - 2\bar{v}_{MWS}{}^2 + \bar{v}_{MWS}{}^2} = \sqrt{\int_0^\infty v^2 f(v) dv - \bar{v}_{MWS}{}^2}$$

Use the simplification and substitution mentioned above:

$$\int_0^\infty v^2 f(v)dv = \int_0^\infty v^2 \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} e^{-\left(\frac{v}{\lambda}\right)^k} dv$$

$$= \int_0^\infty v^2 e^{-\left(\frac{v}{\lambda}\right)^k} d\frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} = \lambda^2 \int_0^\infty x^{\frac{2}{k}} e^{-x} dx$$

$$= \lambda^2 \Gamma\left(1+\frac{2}{k}\right)$$

So,

$$\sigma = \lambda\sqrt{\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)} \qquad \text{Equation 2.4}$$

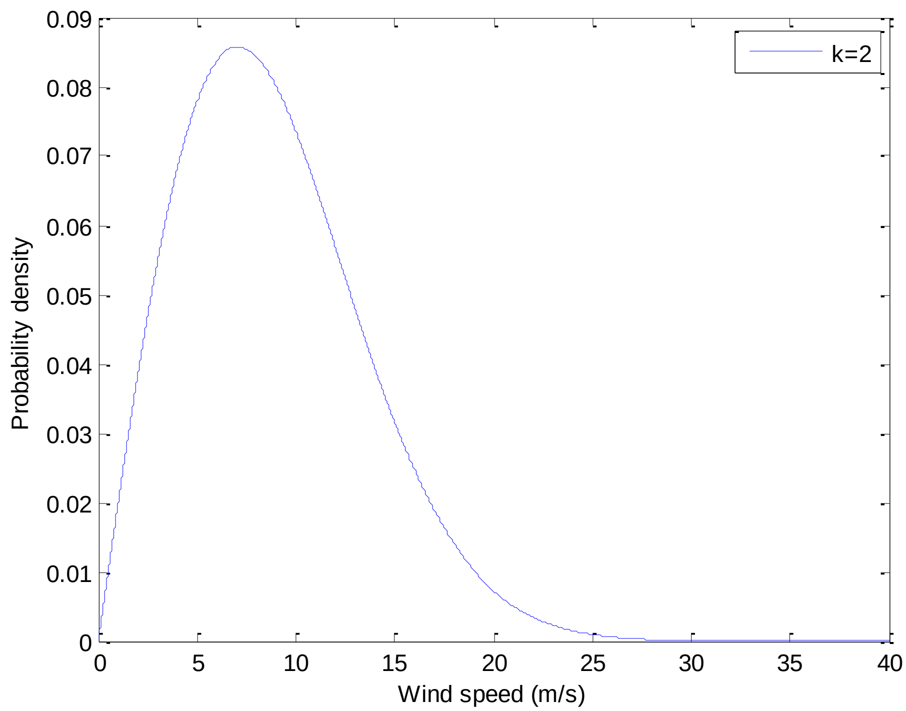

Fig. 2.2 Weibull distribution density under a constant value of k=2 and λ=10.

2.2.2 Distribution for Different Shape and Scale Parameters

In Weibull probability density function, $k > 0$ is the shape parameter. The value of shape parameter will influence the slope of the probability plot and also take effects on the behavior of the distribution. Fig. 2.3 shows a Weibull pdf with constant value of λ and values of k=1, k=2, k=3.

These are shown on Fig 2.3, when k=1, the pdf of the three-parameter Weibull reduces to that of the two-parameter exponential distribution, the wind speed is low in most of data collection period; when k=2, it becomes equivalent to the Rayleigh distribution [5] which more wind speed date is lower than mean speed in data collection period; when k=3, it appears similar to the normal distribution, the distribution curve is more like bell shape or Gaussian distribution [5] and which more wind speed data is around mean speed in a certain period.

A higher value of k, such as 2.5 and 3, indicated that the mean value of any small time period deviated from the whole period mean value is small. On the other hand, a lower value of k, such as 1.2 or 1.5, indicates a greater deviation away from mean value. Fig 2.4 shows the changes of shape parameter k.

And $\lambda > 0$ is the scale parameter of the Weibull distribution. A change in the scale parameter λ has the same effect on the distribution as a change of the abscissa (Y-axis, wind speed) scale. Changing the value of λ when k keeps constant will take effect of stretch or compress the pdf curve and the peak value of the pdf curve will also change with the increase or decrease of λ, as indicated in Fig. 2.5. [2, 5]

Under constant k condition, when λ increases, the distribution curve gets stretched out to the right and its peak value decreases, while maintaining its shape and location. When λ decreases, the distribution gets pushed in towards the left, and its peak value increases.

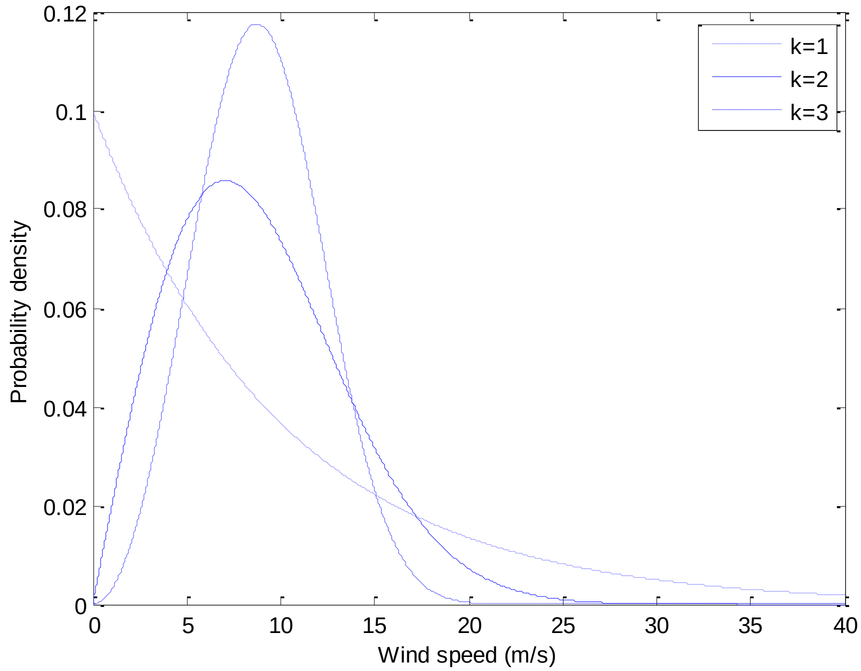

Fig.2.3 Weibull distribution density of different wind speed under a constant value of λ=10 and different values of k=1, 2, 3.

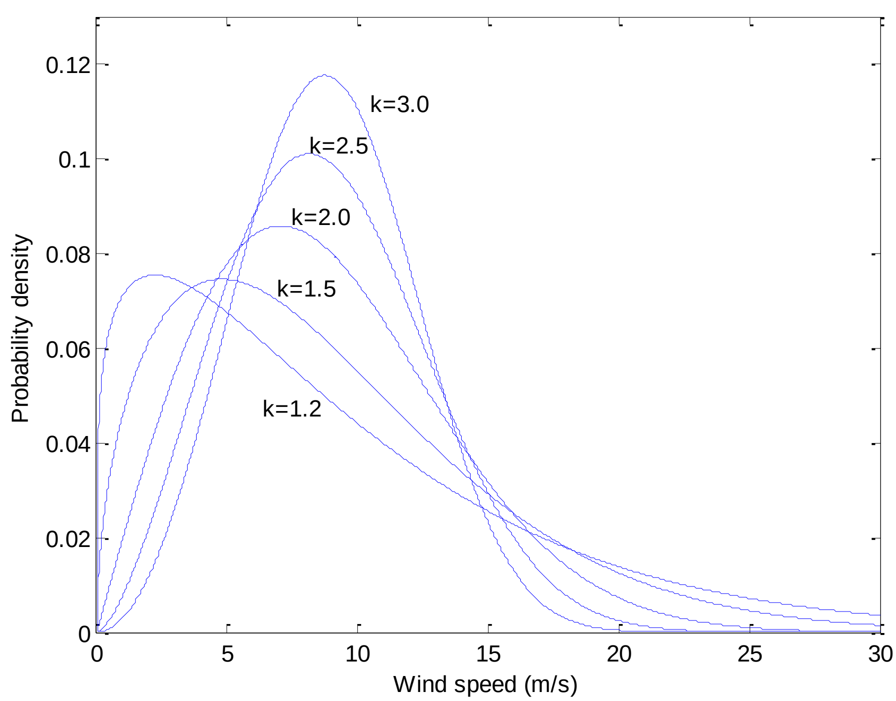

Fig.2.4 Weibull distribution density of different wind speed under a constant value of λ=10 and different values of k=1.2, 1.5, 2, 2.5, 3.

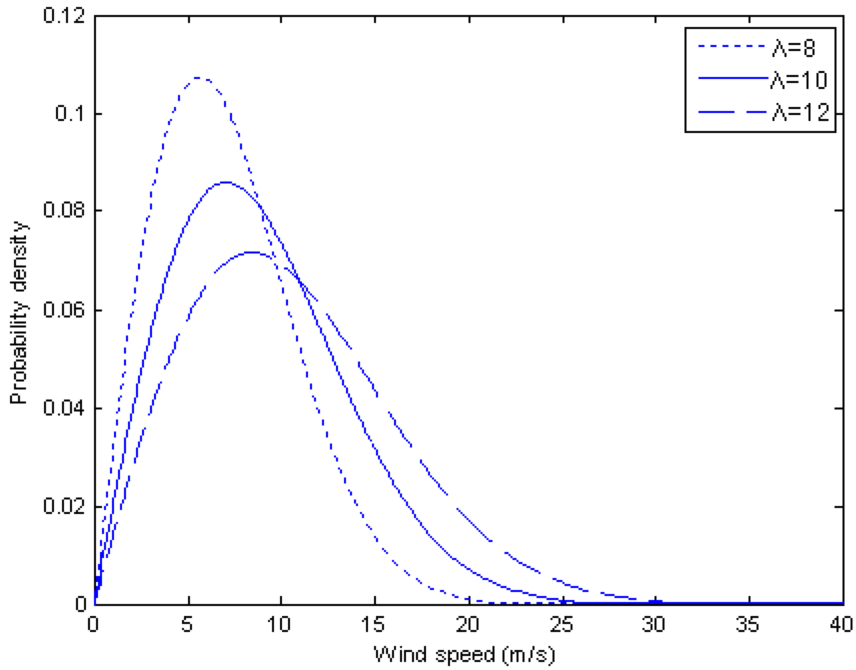

Fig.2.5 Weibull distribution density of different wind speed under a constant value of k=2 and different values of λ =8, 10, 12.

2.2.3 The Relationship between Mean Value and Scale Parameters

From the Equation 2.3, the relationship of λ and mean wind speed can be derived:

$$\lambda / \bar{v}_{MWS} = \frac{1}{\Gamma\left(1+\frac{1}{k}\right)} \qquad \text{Equation 2.5}$$

By considering the value of $\lambda/\bar{v}_{MWS}$ as a function of k, the curve is shown on Fig.2.6. From the curve, it is shown that if the shape parameter k is less than 1, the ratio $\lambda/\bar{v}_{MWS}$ may decrease rapidly; when k is greater than 1.5 and less than 3, the value of $\lambda/\bar{v}_{MWS}$ is essentially a constant of 1.12. So λ approximate to $1.12\bar{v}_{MWS}$ when $1.5 \le k \le 3.0$ and λ is directly proportional to the MWS for this range of k and the MWS is affected mainly by λ.

Most of good farms have k in this range ($1.5 \le k \le 3.0$) and good estimate for parameter λ in $\lambda \approx 1.12\bar{v}_{MWS}$. Further more mean value of wind speed is mainly depended on λ in Weibull distribution. [2, 6]

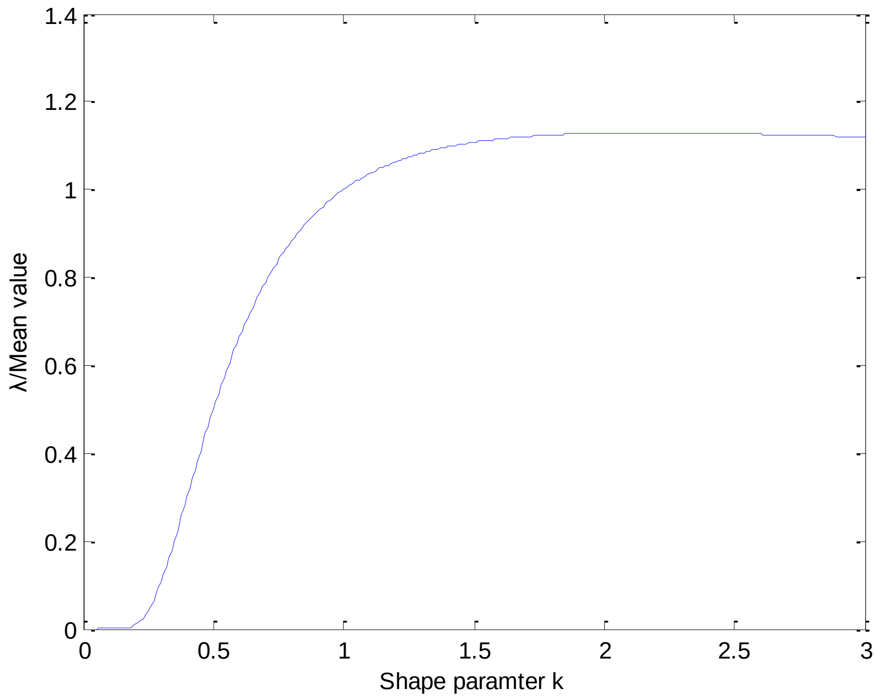

Fig.2.6 Characteristic curve of λ/Mean versus shape parameter k.

2.2.4 Specific Wind Speed Pattern

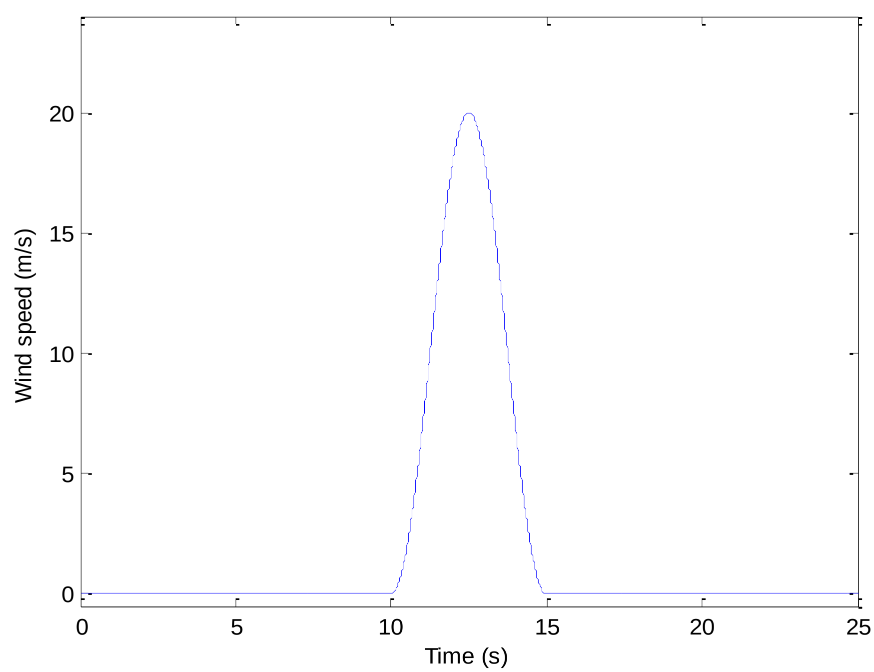

Fig. 2.7 Wind speed curve of gust wind pattern.

In transient stability study, operation of the wind farm is usually under several wind speed patterns: gust wind, ramp wind and noise (or turbulent) wind in order to simulate the disturbances.

When the wind disturbance is gust wind pattern, the wind speed curve is shown on Fig. 2.7. Gust wind is used to describe the wind speed sudden increase and decrease. Wind speed increases to peak value from lowest speed rapidly and decreases to lowest speed in the same way. And the characteristics of transient stability after a large wind disturbance are usually under gust wind pattern in system simulation.

When the wind pattern is ramp wind, the wind speed curve is shown on Fig. 2.8. Ramp wind is used to describe the wind speed change in a certain time period. Wind speed increases from lowest speed to peak value gradually and keeps in that value.

Noise (or turbulent) wind pattern is used to describe the wind speed with many small wind disturbances and the wind speed curve is shown on Fig. 2.9. It is also used to research the influence of small disturbances to power systems. [1, 7, 8]

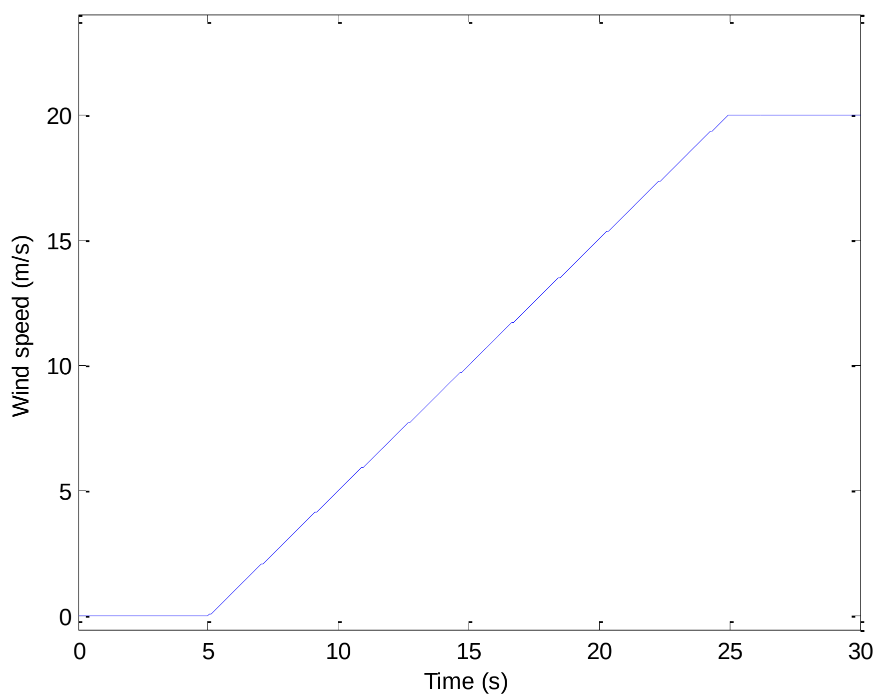

Fig. 2.8 Wind speed curve of ramp wind pattern.

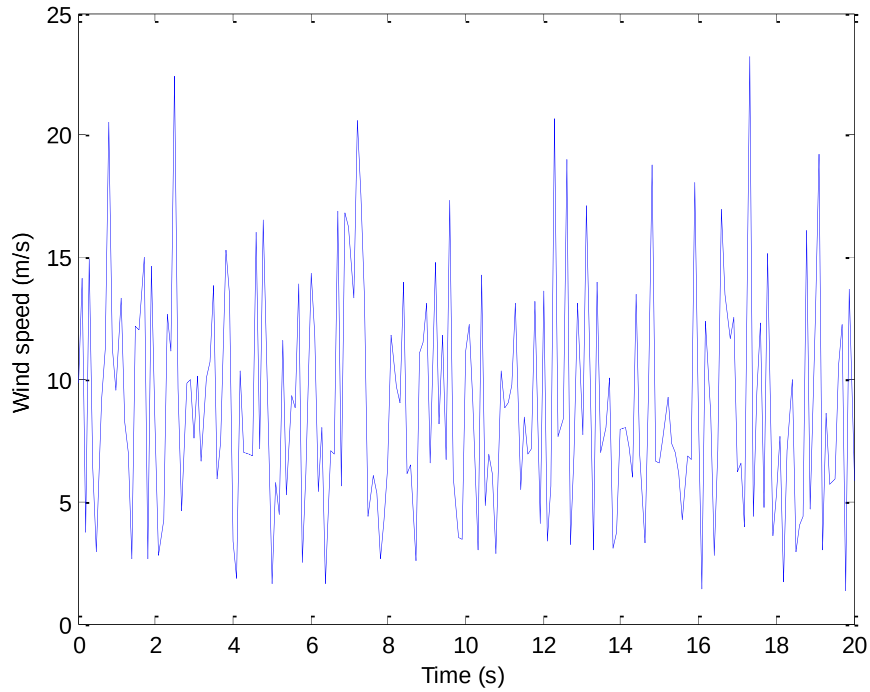

Fig. 2.9 Wind speed curve of noise wind pattern.

Fig 2.9 represents a short term wind pattern in terms of minutes and seconds. This means that the noise level of the wind pattern is also included and is reflected in the sudden change of wind speed within a very short time span. This type of pattern is best to illustrate wind turbulence which can cause the most fluctuation in power output. Another model for wind pattern is the longer term pattern in terms of hours, months and years, the output wind pattern is smoother and has much fewer sudden changes of wind speeds. Wind prediction model is still extensively investigated [1].

2.3 Wind Speed Random Data Production Process

The flowchart in Fig.2.10 describes the processes to get the random data:

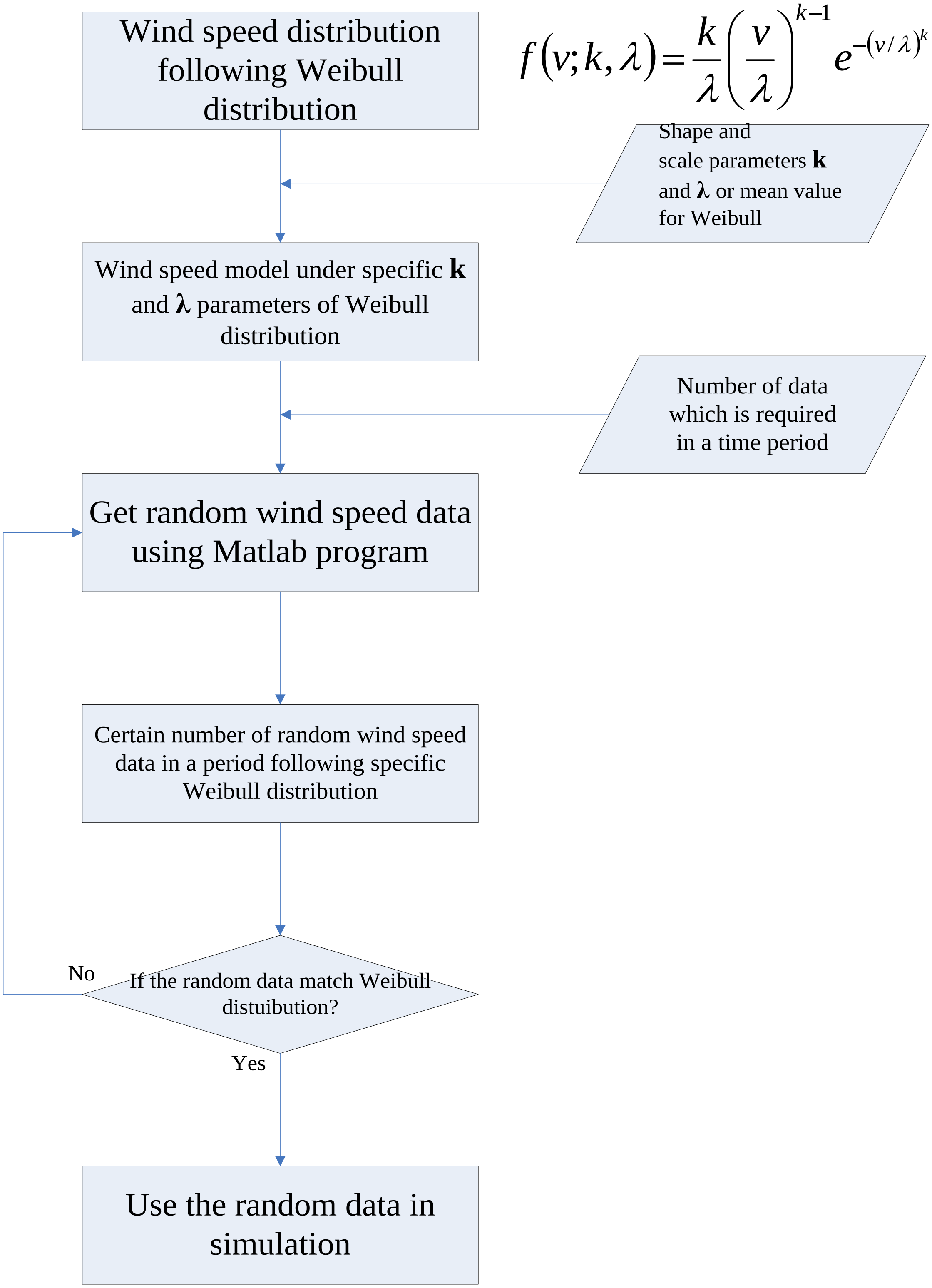

Fig.2.10 Flowchart of production of wind speed random data.

The time period of wind speed data is usually about 10 minutes or even longer. As a result, it needs to be developed into shorter time period data for some wind generation simulation. Because of stochastic and probabilistic characteristics of wind speed, random wind speed data which are developed under specific Weibull distribution can be used in wind generation simulation as real time wind speed.

In this thesis, the production of random uses Matlab program to random data under Wribull probability distribution, so the parameters k and λ are key factor of the random program. For different wind conditions, shape parameter k and scale parameter λ are in variable value and if it in good condition k is in 1.5~3.0 and λ equal to 1.12mean value. Depending on require for different time periods of data, Matlab program can produce different number of random data. After the process, if the random data match the Weibull distribution which is used in Matlab program to produce them, the random data can be considered as wind speed data and can used in simulation. On the contrast, if it does not match, the random data can not be used until it matches. [9]

2.4 Example for Wind Speed Data Production

As an example, a real measure wind speed data is developed to use in wind speed simulation using the method mentioned before. Under a specific Weibull distribution, a wind speed in a certain time period is used as a mean wind speed value for production of random speed data in this time period. Every random speed data is the wind speed for a smaller time period and scale parameter and is depended on the mean speed value.

The production program as follows:

- First, original wind speed data is introduced.
- Second, shape parameter is determined and scale parameter is calculated through mean wind speed value.
- Then, the random speed data is produced under confirmed Weibull distribution by program using Matlab.
- Finally, the probability distribution of random results data is compared with the Weibull distribution which is used to produce them.

2.4.1 Case Study

In this case, the aim is to get 24 hours wind speed data of a wind farm. The original wind speed data is for every 10 minutes and every 10-mins data will be developed to 60 data for every 10 seconds. Moreover, because the amount of data is large, the results data of wind speed will be divided into every one hour time period to analyse and to compare with confirmed Weibull distribution.

2.4.1.1 Wind Speed

The original wind speed data is a 24 hours data for every 10 minutes of a wind farm in an ordinary summer day. And this data is from RERL-Resource Data-Wind Data, Renewable Energy Research Laboratory (RERL). [10] Wind speed curve is shown on Fig. 2.11 and the detail speed data is shown on Table 2.1.

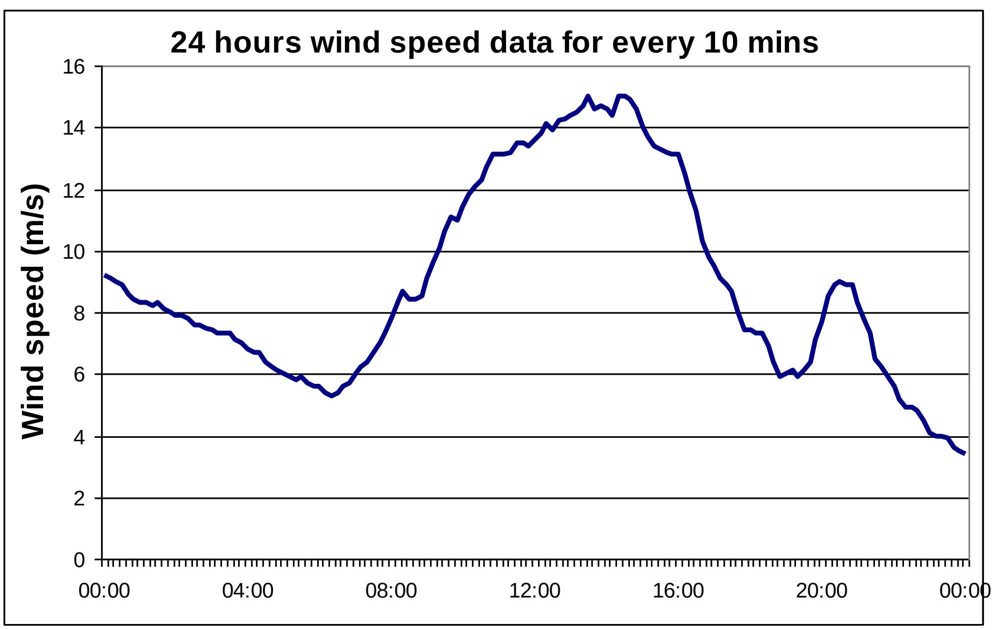

Fig. 2.11 Original 24 hours wind speed for every 10 minutes in a wind farm.

Table 2.1 Wind speed data for 24 hours in every 10 minutes from RERL Wind Data

Time	Wind speed (m/s)	Time	Wind speed (m/s)	Time	Wind speed (m/s)	Time	Wind speed (m/s)
00:00	9.2	**07:20**	6.4	**14:40**	14.9	**22:00**	5.6
00:10	9.1	**07:30**	6.7	**14:50**	14.6	**22:10**	5.2
00:20	9	**07:40**	7	**15:00**	14	**22:20**	4.9
00:30	8.9	**07:50**	7.3	**15:10**	13.7	**22:30**	4.9
00:40	8.6	**08:00**	7.8	**15:20**	13.4	**22:40**	4.8
00:50	8.4	**08:10**	8.3	**15:30**	13.3	**22:50**	4.5
01:00	8.3	**08:20**	8.7	**15:40**	13.2	**23:00**	4.1
01:10	8.3	**08:30**	8.4	**15:50**	13.1	**23:10**	4
01:20	8.2	**08:40**	8.4	**16:00**	13.1	**23:20**	4
01:30	8.3	**08:50**	8.5	**16:10**	12.5	**23:30**	3.9
01:40	8.1	**09:00**	9.1	**16:20**	11.9	**23:40**	3.6
01:50	8	**09:10**	9.6	**16:30**	11.3	**23:50**	3.5
02:00	7.9	**09:20**	10.1	**16:40**	10.3	**00:00**	3.4
02:10	7.9	**09:30**	10.6	**16:50**	9.8		
02:20	7.8	**09:40**	11.1	**17:00**	9.5		
02:30	7.6	**09:50**	11	**17:10**	9.1		
02:40	7.6	**10:00**	11.4	**17:20**	8.9		
02:50	7.5	**10:10**	11.8	**17:30**	8.7		
03:00	7.4	**10:20**	12.1	**17:40**	8		
03:10	7.3	**10:30**	12.3	**17:50**	7.4		
03:20	7.3	**10:40**	12.7	**18:00**	7.4		
03:30	7.3	**10:50**	13.1	**18:10**	7.3		
03:40	7.1	**11:00**	13.1	**18:20**	7.3		
03:50	7	**11:10**	13.1	**18:30**	6.9		
04:00	6.8	**11:20**	13.2	**18:40**	6.4		
04:10	6.7	**11:30**	13.5	**18:50**	5.9		
04:20	6.7	**11:40**	13.5	**19:00**	6		
04:30	6.4	**11:50**	13.4	**19:10**	6.1		
04:40	6.2	**12:00**	13.6	**19:20**	5.9		
04:50	6.1	**12:10**	13.8	**19:30**	6.1		
05:00	6	**12:20**	14.1	**19:40**	6.4		
05:10	5.9	**12:30**	13.9	**19:50**	7.1		
05:20	5.8	**12:40**	14.2	**20:00**	7.7		
05:30	5.9	**12:50**	14.3	**20:10**	8.5		
05:40	5.7	**13:00**	14.4	**20:20**	8.9		
05:50	5.6	**13:10**	14.5	**20:30**	9		
06:00	5.6	**13:20**	14.7	**20:40**	8.9		
06:10	5.4	**13:30**	15	**20:50**	8.9		
06:20	5.3	**13:40**	14.6	**21:00**	8.3		
06:30	5.4	**13:50**	14.7	**21:10**	7.8		
06:40	5.6	**14:00**	14.6	**21:20**	7.3		
06:50	5.7	**14:10**	14.4	**21:30**	6.5		
07:00	6	**14:20**	15	**21:40**	6.2		
07:10	6.2	**14:30**	15	**21:50**	5.9		

2.4.1.2 Shape Parameter and Scale Parameter

Table 2.2 Scale parameter of wind speed data for 24 hours in every 10 minutes

Time	λ scale parameter	Time	λ scale parameter	Time	λ scale parameter	Time	λ scale parameter
00:00	10.304	**07:20**	7.168	**14:40**	16.688	**22:00**	6.272
00:10	10.192	**07:30**	7.504	**14:50**	16.352	**22:10**	5.824
00:20	10.08	**07:40**	7.84	**15:00**	15.68	**22:20**	5.488
00:30	9.968	**07:50**	8.176	**15:10**	15.344	**22:30**	5.488
00:40	9.632	**08:00**	8.736	**15:20**	15.008	**22:40**	5.376
00:50	9.408	**08:10**	9.296	**15:30**	14.896	**22:50**	5.04
01:00	9.296	**08:20**	9.744	**15:40**	14.784	**23:00**	4.592
01:10	9.296	**08:30**	9.408	**15:50**	14.672	**23:10**	4.48
01:20	9.184	**08:40**	9.408	**16:00**	14.672	**23:20**	4.48
01:30	9.296	**08:50**	9.52	**16:10**	14	**23:30**	4.368
01:40	9.072	**09:00**	10.192	**16:20**	13.328	**23:40**	4.032
01:50	8.96	**09:10**	10.752	**16:30**	12.656	**23:50**	3.92
02:00	8.848	**09:20**	11.312	**16:40**	11.536	**00:00**	3.808
02:10	8.848	**09:30**	11.872	**16:50**	10.976		
02:20	8.736	**09:40**	12.432	**17:00**	10.64		
02:30	8.512	**09:50**	12.32	**17:10**	10.192		
02:40	8.512	**10:00**	12.768	**17:20**	9.968		
02:50	8.4	**10:10**	13.216	**17:30**	9.744		
03:00	8.288	**10:20**	13.552	**17:40**	8.96		
03:10	8.176	**10:30**	13.776	**17:50**	8.288		
03:20	8.176	**10:40**	14.224	**18:00**	8.288		
03:30	8.176	**10:50**	14.672	**18:10**	8.176		
03:40	7.952	**11:00**	14.672	**18:20**	8.176		
03:50	7.84	**11:10**	14.672	**18:30**	7.728		
04:00	7.616	**11:20**	14.784	**18:40**	7.168		
04:10	7.504	**11:30**	15.12	**18:50**	6.608		
04:20	7.504	**11:40**	15.12	**19:00**	6.72		
04:30	7.168	**11:50**	15.008	**19:10**	6.832		
04:40	6.944	**12:00**	15.232	**19:20**	6.608		
04:50	6.832	**12:10**	15.456	**19:30**	6.832		
05:00	6.72	**12:20**	15.792	**19:40**	7.168		
05:10	6.608	**12:30**	15.568	**19:50**	7.952		
05:20	6.496	**12:40**	15.904	**20:00**	8.624		
05:30	6.608	**12:50**	16.016	**20:10**	9.52		
05:40	6.384	**13:00**	16.128	**20:20**	9.968		
05:50	6.272	**13:10**	16.24	**20:30**	10.08		
06:00	6.272	**13:20**	16.464	**20:40**	9.968		
06:10	6.048	**13:30**	16.8	**20:50**	9.968		
06:20	5.936	**13:40**	16.352	**21:00**	9.296		
06:30	6.048	**13:50**	16.464	**21:10**	8.736		
06:40	6.272	**14:00**	16.352	**21:20**	8.176		
06:50	6.384	**14:10**	16.128	**21:30**	7.28		
07:00	6.72	**14:20**	16.8	**21:40**	6.944		
07:10	6.944	**14:30**	16.8	**21:50**	6.608		

For most wind farms [1], shape parameter k is 2 and the scale parameter λ is $1.12\,\bar{v}_{MWS}$. The scale parameter for every 10 minutes can be calculated from the 24 hours wind speed data for every 10 minutes mentioned above. And from these scale parameter results, the different Weibull distribution of wind speed data for different time period can be confirmed which can be used for analysis in the researches in this thesis. Weibull distribution scale parameter λ is shown on Table 2.2.

2.4.2 Simulation Results

2.4.2.1 Random Data Results Comparing

After the production of random data, the identity of probability distribution of results data to the Weibull distribution will be checked for every one hour.

The Fig.2.12 (a) shows the results random wind speed data for the period of 00:00-01:00. And from Fig.2.12 (b), the distribution of random data is nearly equal to the original data. The mean value of probability distribution of 00:00-01:00 is the average value of 6 mean values of 10-mintue data.

In the same way, all of wind speed data for 24 hours will be developed and compared. For instance, the Fig.2.12 (c) and Fig.2.12 (e) show the random wind speed data for the periods of 14:00-15:00 and 22:00-23:00. Fig.2.12 (d) and Fig.2.12 (f) show the distribution of random data is nearly equal to the original data.

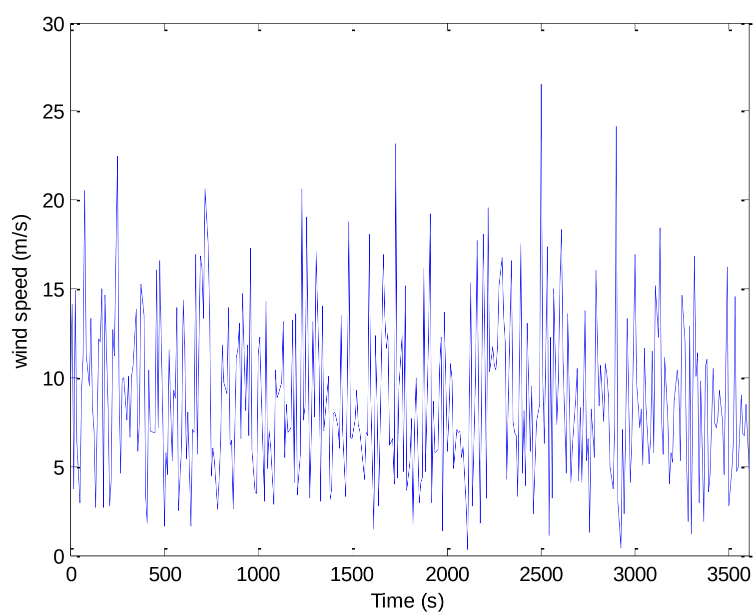

Fig.2.12 (a) Developed wind speed data in one hour for every 10 seconds from 00:00-01:00.

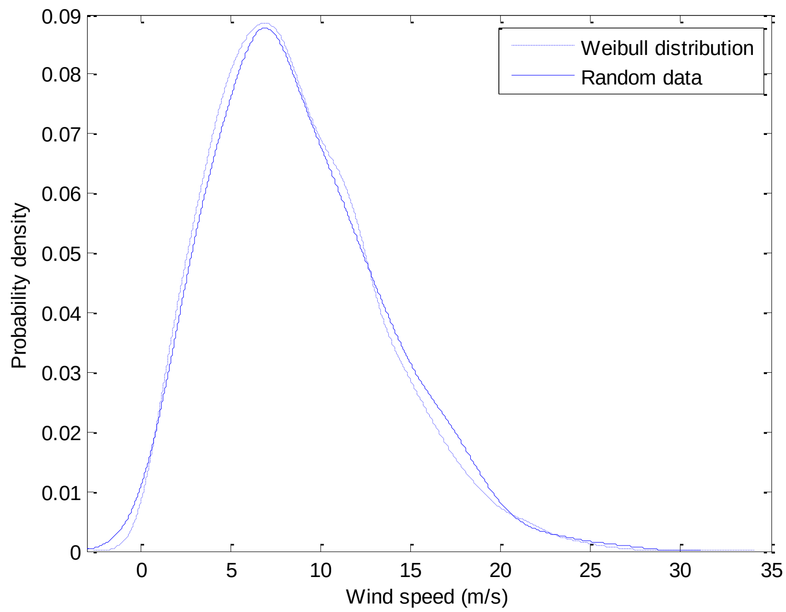

Fig.2.12 (b) Weibull probability distribution of wind speed at 00:00-01:00 and probability distribution of random data for 00:00-01:00.

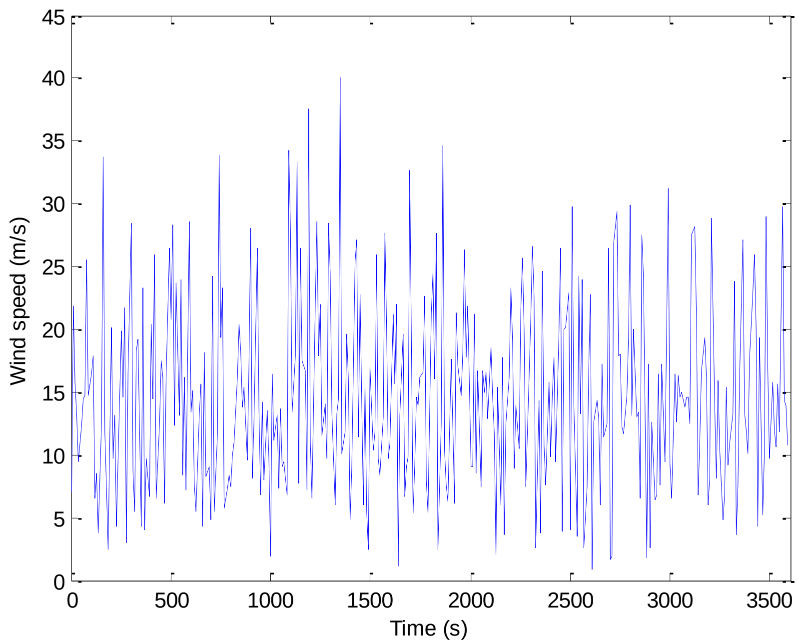

Fig.2.12 (c) Developed wind speed data in one hour for every 10 seconds from 14:00-15:00.

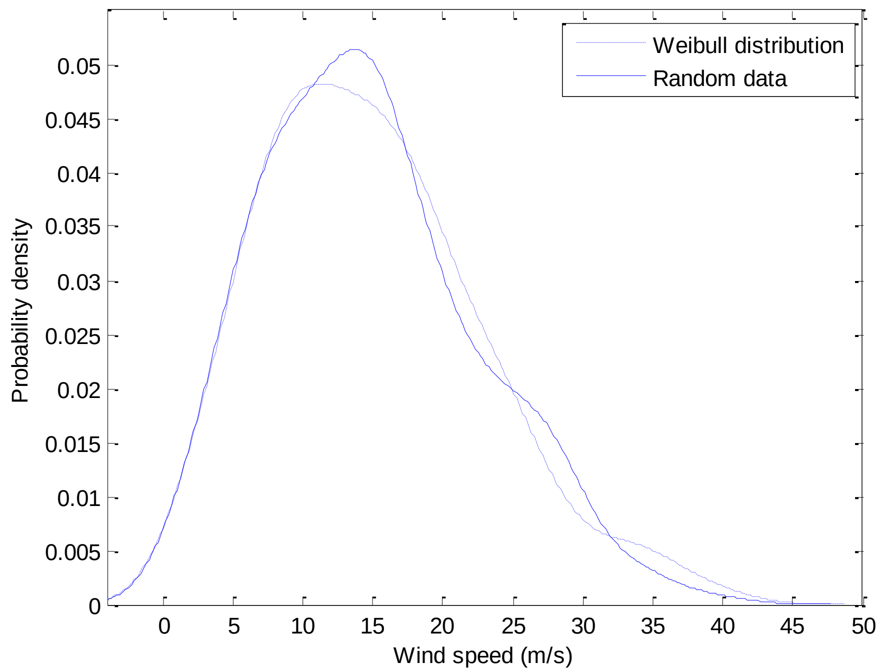

Fig.2.12 (d) Weibull probability distribution of wind speed at 14:00-15:00 and probability distribution of random data for 14:00-15:00

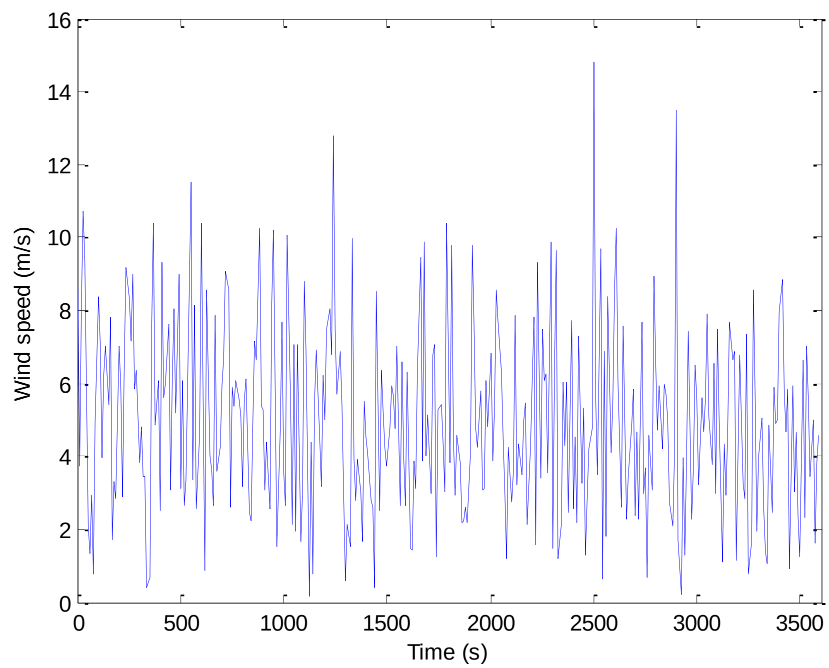

Fig.2.12 (e) Developed wind speed data in one hour for every 10 seconds from 22:00-23:00.

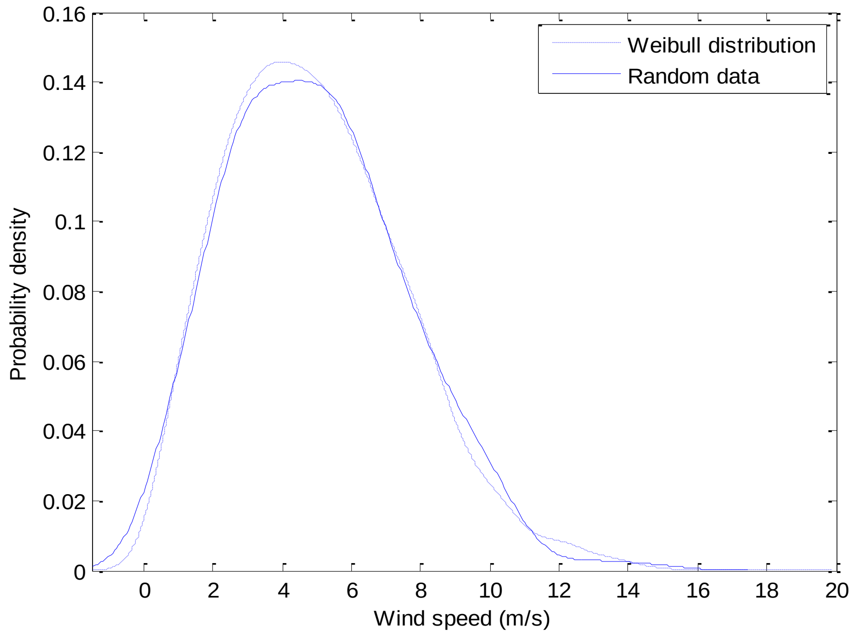

Fig.2.12 (f) Weibull probability distribution of wind speed at 22:00-23:00 and probability distribution of random data for 22:00-23:00

2.4.2.2 Final Example Results of Wind Speed Data

At last, the final wind speed data are confirmed and these are shown on Fig.2.13 (a) and Fig2.13 (b)

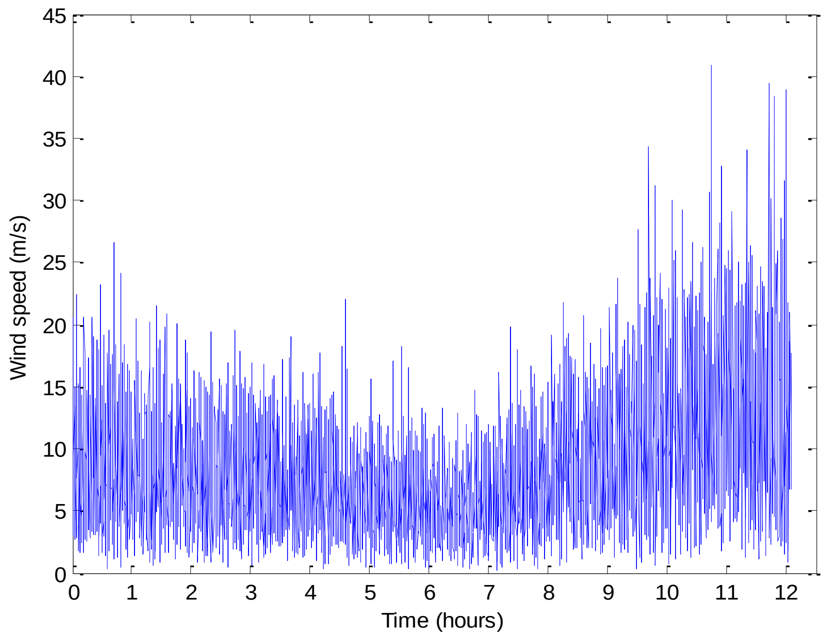

Fig.2.13 (a) First half of 24 hours developed wind speed data for every 10 second from 00:00-12:00.

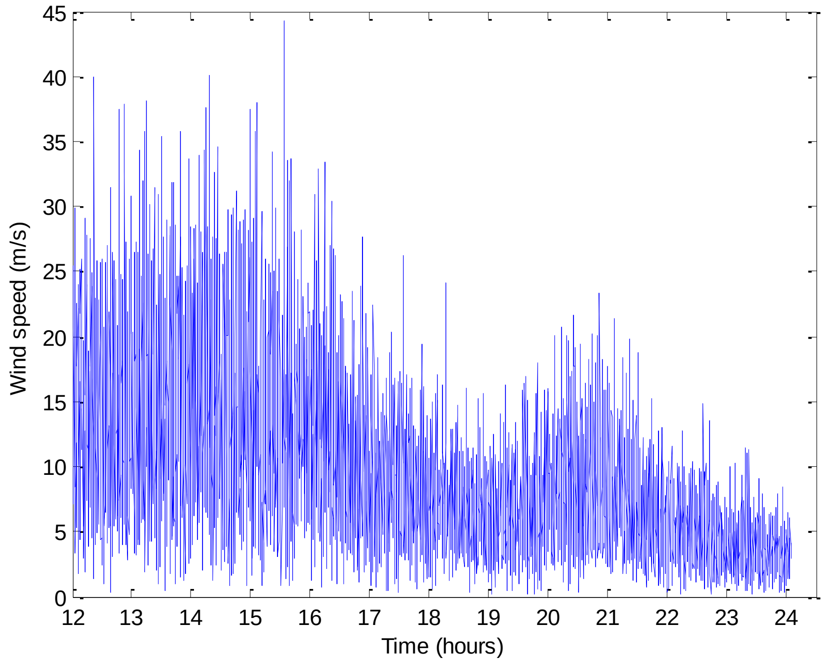

Fig.2.13 (b) Second half of 24 hours developed wind speed data for every 10 second from 12:00-24:00.

2.5 Wind Turbine Operation Characteristics

A wind turbine is a device for extracting kinetic energy from the wind and for transforming to electrical energy. The power output from a wind turbine is given by the expression below [1, 11]:

$$P_W = \frac{1}{2} C_P(\lambda_W, \beta) \rho_{air} \pi R_t^2 v^3 \quad \text{Equation 2.6}$$

where P_W is the power output from the wind, C_P is the power coefficient which is a function of both tip speed ratio λ and blade pitch angle β, ρ_{air} is the air density, R_t is the wind turbine radius and v is the wind speed.

The density of air is 800 times less than that of water so this leads directly to the large size of a wind turbine. For example, a 1.5 MW wind turbine may have a rotor that is more than 60m in diameter. A doubling of wind turbine radius leads to a four-time increase in power output.

Major increases in the output power can only be achieved by increasing the swept area of the rotor or by locating the wind turbines on sites with higher wind speeds. The influence of the wind speed is more pronounced with a doubling of wind speed leading to an eight-time increase in power. There have been considerable efforts to ensure that wind farms are developed in areas of the highest wind speeds and the turbines optimally located with wind farms. In certain countries very high towers are being used with more than 60-80 m in height to take advantage of the increase of wind speed with height.

The value of C_p needs to be determined to calculate the power output from wind and the C_P equation shown in below from [12, 13],

$$C_P = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}}$$

$$\lambda_i = \left(\frac{1}{\lambda_W + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right)^{-1} \qquad \text{Equation 2.7}$$

And the tip speed ratio λ_W is defined as the tip speed of the turbine blades divided by wind speed, as

$$\lambda_W = \frac{\omega_t R_t}{v} \qquad \text{Equation 2.8}$$

where ω_t is the rotational speed of the turbine. For small turbines, the turbine blades are fixed at a constant pitch angle and for large ones, the pitch angle can be changes in a certain range in order to get the maximum wind power output. The C_p-λ_W relationship curve under different pitch-angle β is shown in Fig. 2.14.

At both low and high tip speed ratios, the power coefficient is low so it will be ideal if a turbine can be operated at all wind speeds at a tip speed ratio λ_W in which area gives the maximum power coefficient.

The purpose of wind turbines is to extract as much energy from the wind as possible so each component of the turbine has to be designed optimally for that goal. Optimal design is influenced by the modes of operation of the turbine, which are, constant (or fixed) rotational speed and variable rotational speed mode. If the rotational speed of a turbine is maintained at constant level and tip speed ratio λ_W changes continuously, the turbine is under constant (or fixed) speed mode. In the contrary, a turbine operating at variable speed mode can maintain the constant tip speed ratio required for the maximum power coefficient and also can rotate at the optimal rotational speed for each wind speed. To develop the maximum possible power coefficient requires a suitable design for the whole turbine.

Nowadays, most of the wind turbines used is variable speed turbines. Variable speed operation mode improves the dynamic behavior of the turbine and the power production from variable speed turbines is higher than for fixed-speed turbines. [14]

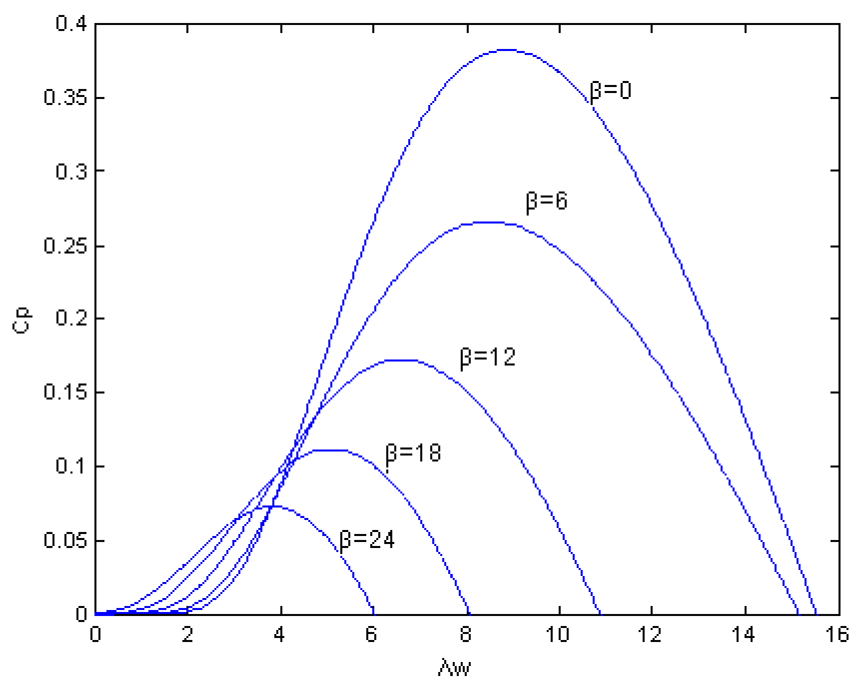

Fig. 2.14 Power coefficient-Tip speed ratio performance curve for different pitch angles.

2.6 Wind Turbine Induction Generator Performance

2.6.1 Type of Wind Turbine Generator

After rotor of a turbine extracts kinetic energy from the wind and converts it into a rotating movement, wind generator converted energy into electricity. There are three different wind turbine generator concepts which are currently mainly applied in wind farm. [14, 15] The Fig. 2.15 shows these three concepts of wind generation.

2.6.1.1 Constant Speed Wind Turbine with Squirrel Cage Induction Generator (SCIG)

The first type is a constant speed wind turbine with squirrel cage induction generator (SCIG). The wind turbine rotor is connected to the generator through a gearbox. In this type of wind generation, the power extracted from the wind is limited which means that the rotor is designed in such a way that its aerodynamic efficiency decreases in high wind speeds, in order to preventing the mechanical power extracted from the wind becoming too large. In this concept, no any active control systems are necessary. But pitch control system needs to be installed on constant speed wind turbines.

For this type, it is necessary to maintain the excitation current from the stator terminal of SCIG and SCIG always needs reactive power from the grid, so it is impossible to support grid voltage control.

The main advantages of constant speed wind turbine with squirrel cage induction generator are this type wind generator is robust, easy to install and lower cost. In addition, generator operates at constant speed mode provides a stable frequency control. The main disadvantages of this type are generator operation speed is not controllable and the range of the speed is very narrow and wind speed fluctuations are directly translated into electromechanical torque variations.

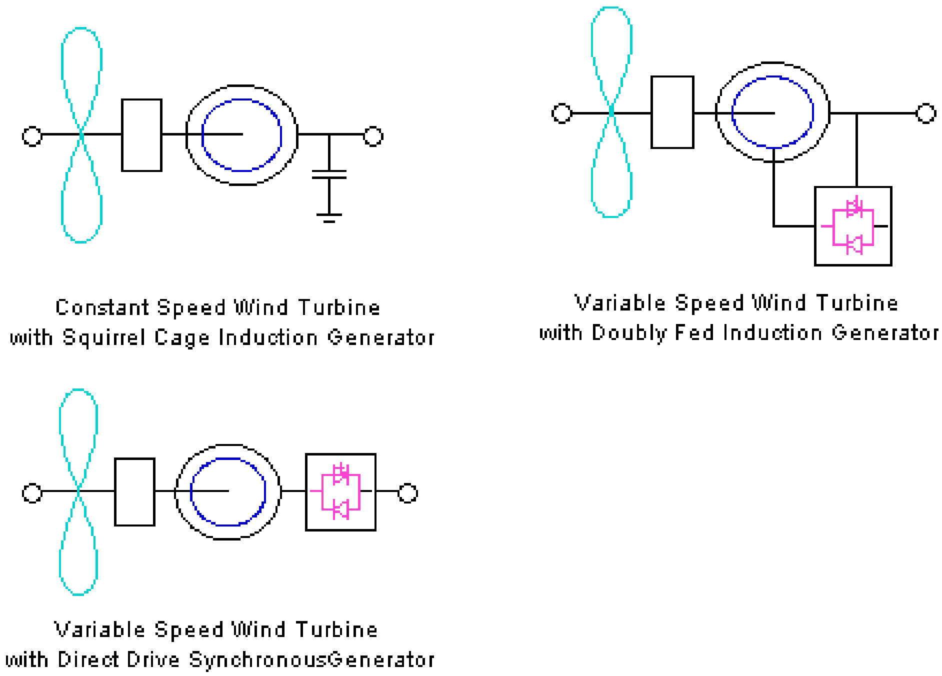

Fig. 2.15 The three different wind turbine generation concepts.

2.6.1.2 Variable Speed Wind Turbine with Doubly Fed Induction Generator (DFIG)

The second type is a variable speed wind turbine with doubly fed induction generator (DFIG). The rotor winding is fed using a back-to-back voltage source converter. The wind turbine rotor is also connected to the generator through a gearbox. In high wind speeds, the power extracted from the wind is limited by pitching the rotor blades.

This type of wind generator is one of the preferred technologies in wind generation applications as it supports a wide range operation of wind speed. The typical variable speed range is 30% more of the synchronous speed.

And it provides the effective control of active power and reactive power of the wind generator because of using back-to-back converters. Furthermore, the power converter system can perform as reactive power compensation and voltage support for the grid. The DFIG type also has advantages at reducing mechanical stress and optimizing power capture. But during grid fault period, power converter system needs to be protected.

2.6.1.3 Variable Speed Wind Turbine with Synchronous Direct Drive

The third is variable speed wind turbine with direct drive synchronous generator. The synchronous generator can have a wound rotor or be excited using permanent magnets. It is connected to power grid through a back-to-back voltage source converter or a diode rectifier and voltage source converter. And the gearbox is not needed in this concept. Like in the DIFG type, the power extracted from the wind is limited by pitching the rotor blades in high wind speeds.

Because the generator connects to the wind turbine rotor directly without a gearbox, it is necessary to make lower speed to produce a higher torque when a certain power is delivered. As a result, the synchronous generator is a low speed multi-pole generator. Moreover, a higher torque means a larger size of the generator.

The main advantages of direct-drive type are higher overall efficiency, reliability and availability. The size of direct drive wind generators is usually large so this type is more suitable for offshore wind farm.

Comparing with the annual energy, generator cost, system cost of three types of wind generation and size, weight, radius of different wind turbines, variable speed wind turbine with DFIG is the most suitable choice for many wind power system so the wind generator model in this thesis bases on the DFIG model.

2.6.2 Operation of Wind Turbine Doubly-Fed Induction Generator (DFIG)

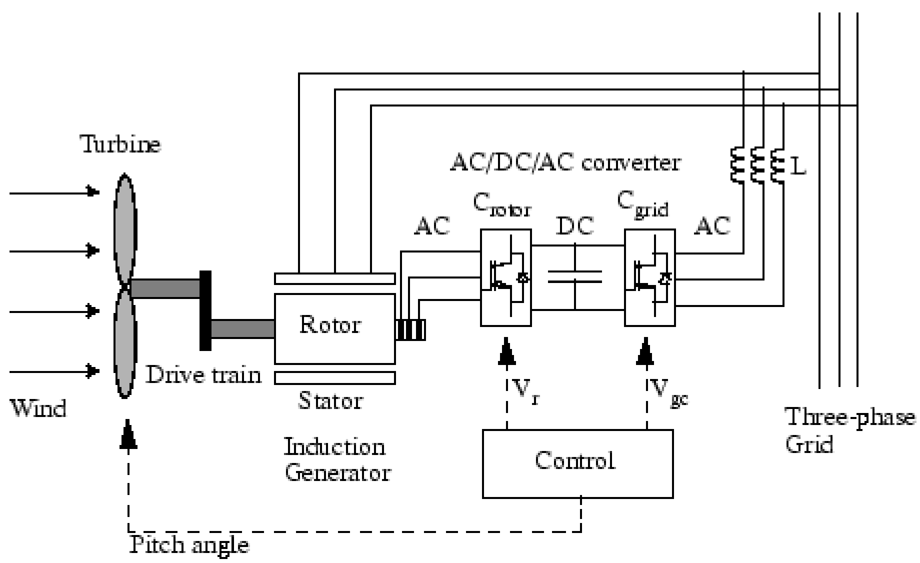

Fig. 2.16 Wind turbine and the Doubly-Fed Induction Generator System.

A variable wind turbine with the doubly-fed induction generator (DFIG) is shown in the Fig. 2.16. The back-to-back converter is an AC/DC/AC converter which is divided into the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). Voltage-Sourced Converters C_{rotor} and C_{grid} which contain power electronic devices IGBTs are used to transform an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source and a coupling inductor L is used to connect C_{grid} to the grid. The three-phase rotor winding is connected to C_{rotor} and the three-phase stator winding is directly connected to the grid. The power extracts from wind is converter into electrical power and transferred to the grid by the windings of stator and the rotor.

Operating principle of the wind turbine doubly-fed induction generator is described through the power flow in wind turbine with DFIG which is shown on Fig. 2.17. [16]

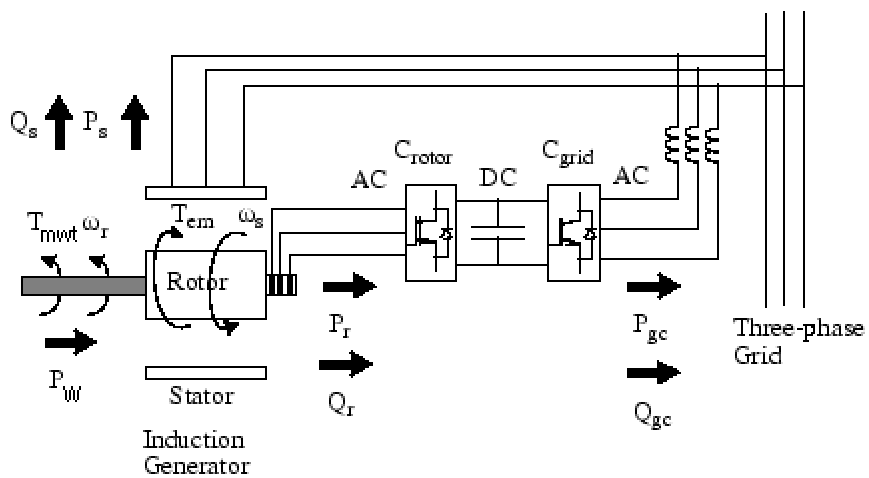

Fig. 2.17 Power flow in a wind turbine with Doubly-Fed Induction Generator.

The equations of the mechanical power, the stator active power and the rotor active power are: [17]

$$P_w = T_{mwt}\omega_r \ , \quad P_S = T_{em}\omega_S$$

and $P_w = P_S + P_r$ Equation 2.9

where P_w is mechanical power of wind turbine from wind, P_s is stator active power output and P_r is rotor active power output which supports the running of AC/DC/AC converter and control systems of wind turbine with DFIG; T_{mwt} is mechanical torque applied to rotor from wind turbine and T_{em} is electromagnetic torque applied to rotor; ω_r is rotational speed of rotor and ω_s is synchronous speed of generator.

The unbalance of mechanical and electromagnetic torques can lead the acceleration or deceleration of rotor speed, which is described as:

$$J_w \frac{d\omega_r}{dt} = T_{mwt} - T_{em} \qquad \text{Equation 2.10}$$

where J_w is combined rotor and wind turbine inertia coefficient.

And when the wind speed is fixed, two torques are in balance and the wind turbine generator is also in steady state which means T_m=T_{em} at fixed speed for a loss-less generator. So,

$$P_r = P_w - P_S = T_{mtw}\omega_r - T_{em}\omega_S = -T_{em}\left(\frac{\omega_S - \omega_r}{\omega_S}\right)\omega_S ,$$

where s is the slip of generator and $s = \frac{\omega_S - \omega_r}{\omega_S}$. As a result,

$$P_r = -sP_S \text{ and } P_r = \frac{s}{s-1}P_w \qquad \text{Equation 2.11}$$

Generally the absolute value of slip s is much smaller than 1, so P_r is a fraction of P_S. P_r is positive for negative slip s and it is negative for positive slip.

Moreover, the parameters which are also in Fig.17 include Q_s stator reactive power output, Q_r rotor reactive power output, P_{gc} C_{grid} active power output and Q_{gc} C_{grid} reactive power output. In steady state for a loss-less AC/DC/AC converter P_{gc}=P_r.

2.6.3 Control Systems of Wind Turbine Generator

As the DFIG contains an AC-DC-AC converter, it allows the control of both active and reactive power and has two separate control loops which are rotor-side control system and grid-side control system. [18, 19]

The rotor-side (C_{rotor}) converter system is used to control the wind generator power output and the voltage or reactive power at the grid terminals of the wind generator. The power output is measured at the terminals of wind generator. The control command signal for power output is voltage V_{qr} (q-axis V_r which generated by C_{rotor} which is shown on Fig.16) and it controls current I_{qr} (q-axis I_r which generated by C_{rotor} on Fig. 2.16) which creates electromagnetic torque T_{em}. For voltage or reactive control, it is controlled by the I_{dr} (d-axis I_r) and is injected into the rotor by converter C_{rotor} and the control command signal is voltage V_{dr} (d-axis V_r).

The grid-side (C_{grid}) converter system is used to control the capacitor dc voltage through the real power transfer between the grid and the dc link. Furthermore, it also can be used on generating or absorbing reactive power. The voltage V_{gc} generated by C_{grid} which is shown on Fig.16 is the control command signal which regulates current I_{gc} which is also generated by C_{grid} to control voltage of dc.

There is also pitch angle control system, which depends on wind speed and rotor speed, to change the pitch angle for extracting maximum power from wind. [20]

2.6.4 Wind Turbine Generator Active Power Output Characteristics

Wind speed distributes in a quite wide range and the operational speed range will be between the cut-in speed and the cut-out speed. The cut-in speed is the wind speed at which the turbine begins to generate power. And the cut-in speed value is determined by the transmission losses during the electrical power transfer from wind farms to the power system which requires the output of wind farms to be greater than the transmission losses to realize the power supply to power systems. The cut-in speed is usually chosen to be somewhat higher than the zero power speed, about 5m/s. The cut-out speed is chosen to protect the turbine from high wind, usually about 25m/s. Through the variable speed wind turbine with DFIG simulation model in Matlab Simulink, a simple active power output of wind turbine generator is shown on Fig. 2.18.

According to these data, MATLAB gives the approximate express equation:

$$P = \begin{cases} 0\,(\text{p.u.}), \quad 0 \le V_{\text{wind}} \le 4.8\,(\text{m/s}); \\ -7.8239\times10^{-6}x^5 + 0.00032159x^4 - 0.0045x^3 \\ +0.030886x^2 - 0.063074x - 0.062359\,(\text{p.u.}), \\ \quad 4.8\,(\text{m/s}) < V_{\text{wind}} < 14.6\,(\text{m/s}); \\ 1\,(\text{p.u.}), 14.6 \le V_{\text{wind}} \le 25\,(\text{m/s}); \\ 0\,(\text{p.u.}), \quad 25\,(\text{m/s}) < V_{\text{wind}} \end{cases} \qquad \text{Equation 2.12}$$

At each line of Equation 2.12 the first value in per unit (p.u.) indicates the electric power output of the wind turbine under the condition given in the second part of the corresponding line. For example in the first line when the wind speed is between ‘0’ to 4.8 m/s the output electrical power is 0 p.u. In line 2 and 3 ‘x’ represents the wind speed in m/s and the output electrical power is also in p.u. Using this equation, for every wind speed data will find a corresponding wind turbine generator output.

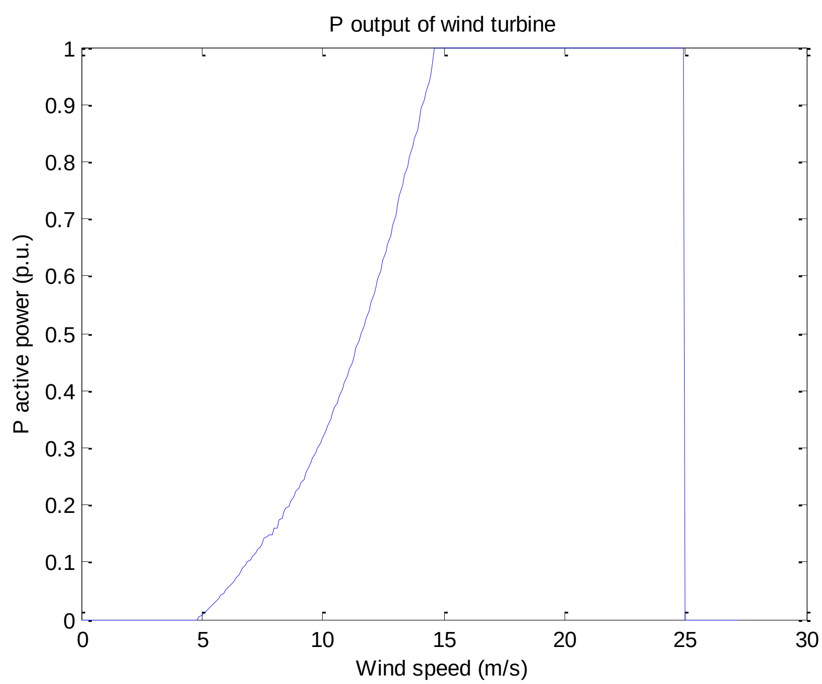

Fig. 2.18 Wind turbine active power output characteristics for different wind speed.

2.6.5 Reactive Power Support from Voltage Source Converters (VCS and GCS) of Wind Turbine Generator

As mentioned before, variable speed wind turbines are equipped with voltage source converters. As a result, C_{rotor} and C_{grid} have the capability of generating or absorbing reactive power and could be used as the reactive power sources to control the voltage at the grid terminals.

Fig. 2.19 shows a typical reactive power capability curve (P-Q characteristic) of doubly-fed induction generators with variable speed wind turbine. [21] The reactive power capability of a DFIG depends on the grid-side converter (GSC) and rotor-side converter (RSC) capability which means the maximum reactive and active power of the converter are limited by the maximum absolute current and the magnetizing current of the induction generator. From the P-Q characteristics, there are two special features: firstly, wind generator can absorb more reactive power in an under excited mode than in an overexcited operation. Secondly, wind generator can support reactive power even if no active power is generated. So in low wind speed periods, when the wind turbine is still not running, the reactive power capability is available if the converter can be switched solely to the grid. [22]

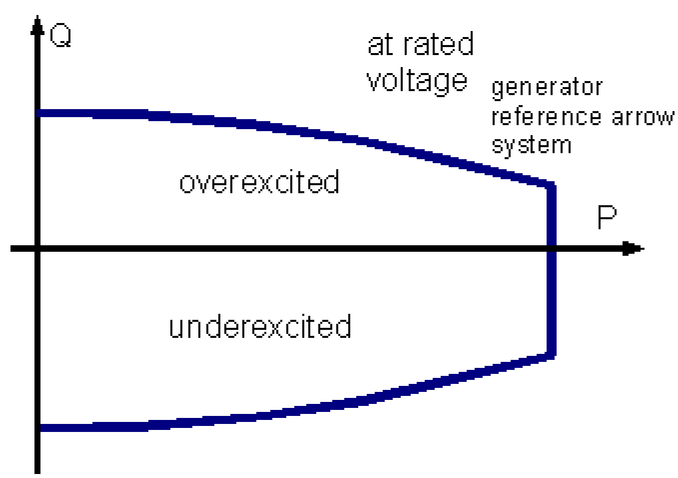

Fig. 2.19 P-Q-characteristic of a wind turbine with DFIG

Although the DFIG wind generation has a certain reactive capacity, it still requires some reactive power support to maintain the voltage at the point of common coupling with the power supply systems when the output of the wind power generation fluctuates.

To meet requirements of the interconnecting to grid for large wind farms, it is often necessary to install reactive power compensation equipment such as FACTS devices like thyristor controlled reactors (TCR), static VAr compensator (SVC) and static synchronous compensator (STATCOM).

2.7 Example for Wind Turbine Generator Output

Using the wind generation output equation mentioned above, wind turbine generator output can be calculated from any wind speed data. Developed wind speed data results in section 2.4 are the wind speed input in this simulation and the wind turbine generator output in certain time periods are the results.

2.7.1 Case Study

In this case, the aim is to get 24 hours wind turbine generator output data. Based on the developed new wind speed data, the output of wind turbine generators is calculated according to Equation 2.12. The same is with the developed wind speed data, wind generator output is a 24 hours data for every 10 minutes.

2.7.2 Simulation Results

Finally the final wind turbine generator output data are calculated and these are shown in Fig.2.20 (a) to Fig.2.20 (f). Because of the fluctuation of wind speed data, there are also fluctuations on the outputs of wind turbine generators which are shown in these figures.

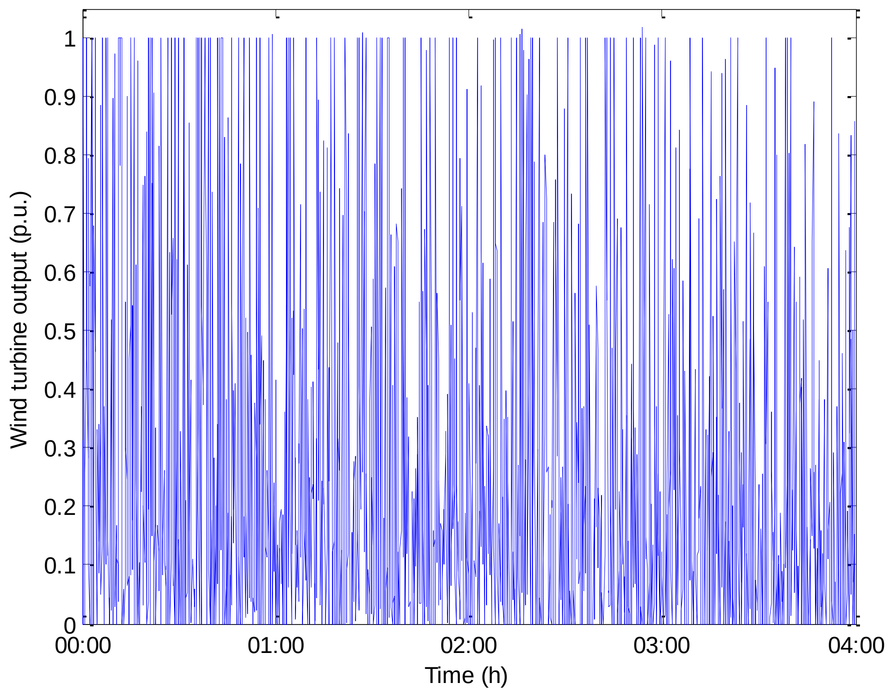

Fig. 2.20 (a) Wind turbine output in four hours for every 10 seconds from 00:00-04:00.

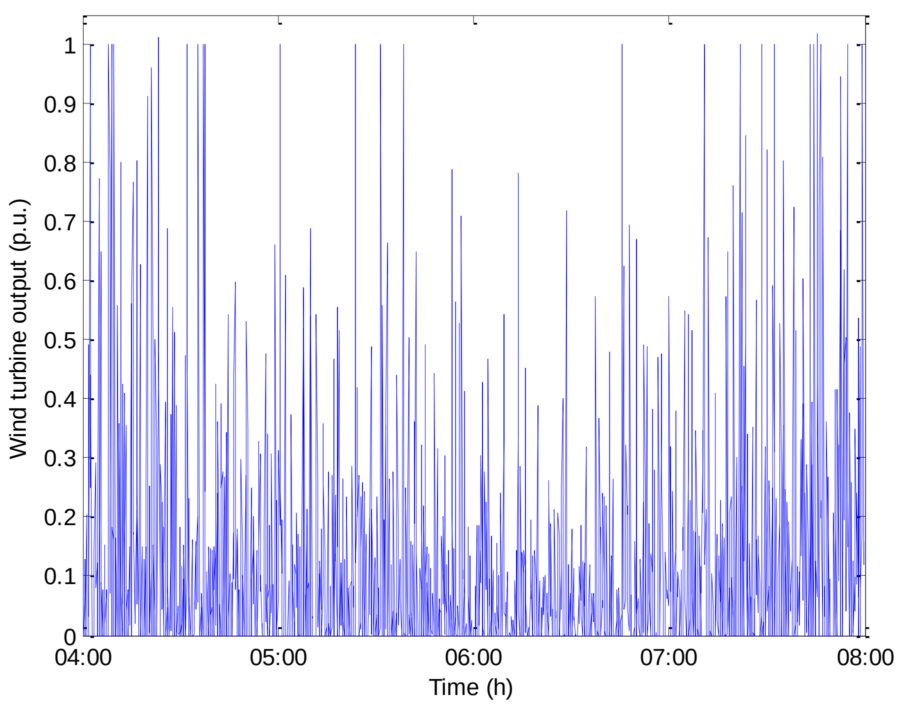

Fig. 2.20 (b) Wind turbine output in four hours for every 10 seconds from 04:00-08:00.

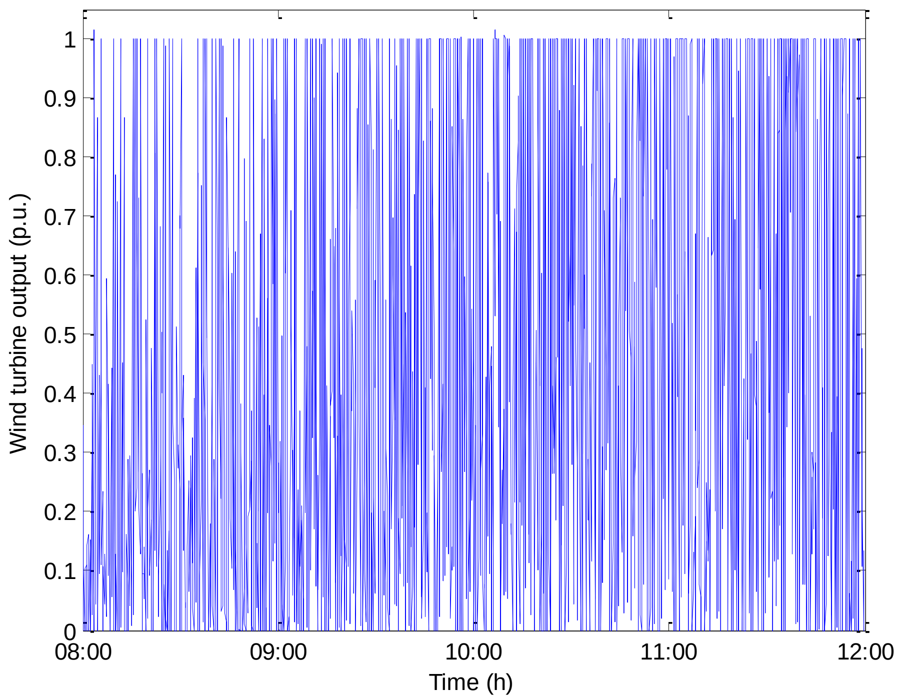

Fig. 2.20 (c) Wind turbine output in four hours for every 10 seconds from 08:00-12:00.

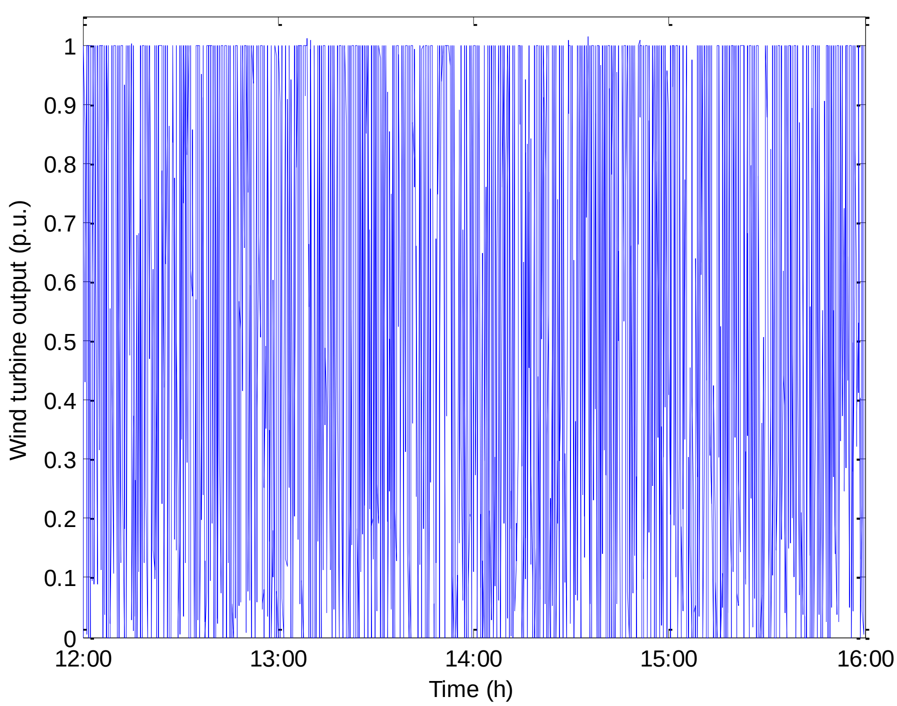

Fig. 2.20 (d) Wind turbine output in four hours for every 10 seconds from 12:00-16:00.

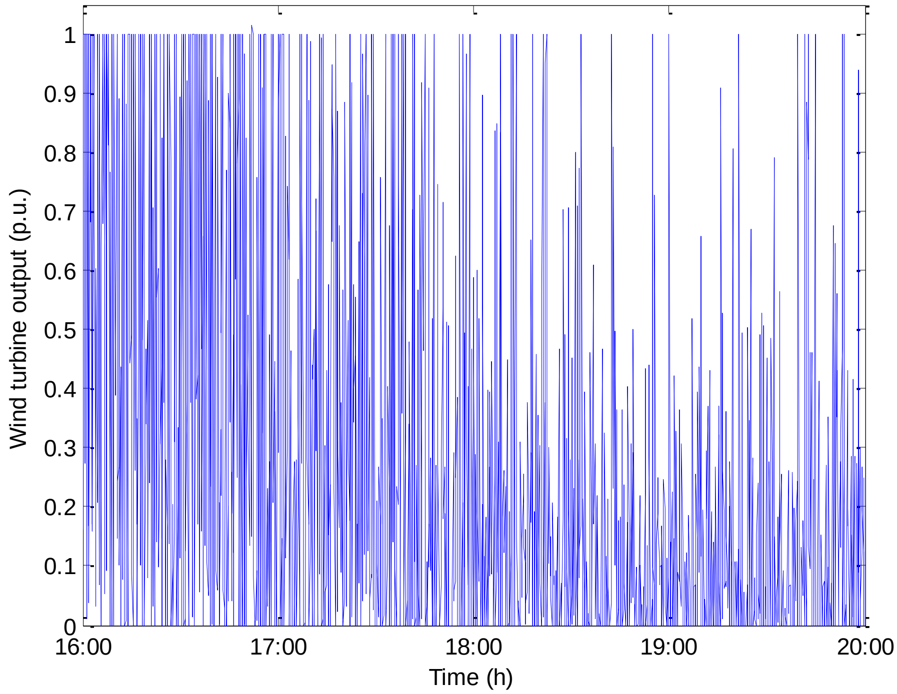

Fig. 2.20 (e) Wind turbine output in four hours for every 10 seconds from 16:00-20:00.

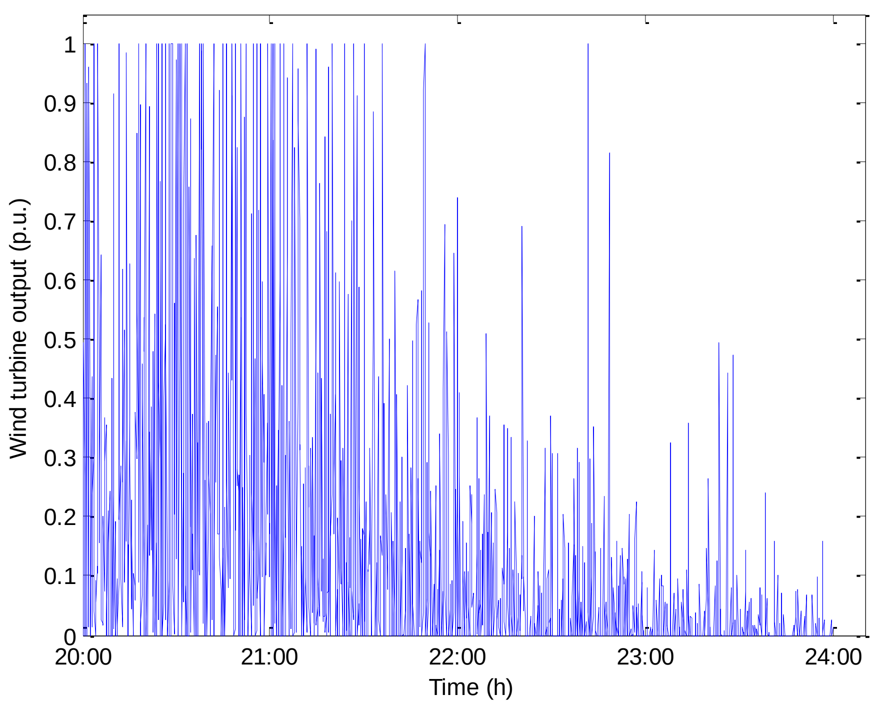

Fig. 2.20 (f) Wind turbine output in four hours for every 10 seconds from 20:00-24:00.

2.8 Summary

This chapter discussed some characteristics of wind and wind turbine generator which can decide wind generation performance and also introduced processes for producing wind speed data and wind turbine generator output data in simulation.

The first part of this chapter defined Weibull distribution as the probability distribution function of wind speed data and identify the influences of the shape and scale parameters in Weibull distribution to probability curve. The discussion continues with the three specific wind speed pattern: gust wind, ramp wind and noise (or turbulent) wind. Then, it introduce the method of developing wind speed data and do the simulation of produce wind speed data as an example.

The second part of this chapter discusses wind turbine characteristic which is about the relationship of wind speed and power output and compares the different types of wind turbine generator: constant speed wind turbine with SCIG, variable speed wind turbine with DFIG and variable speed wind turbine with synchronous direct drive. Because variable speed wind turbine with DFIG is the most popular wind turbine generator in current power system, the further discussing focuses on the features of this kind of wind generation. As a result, this chapter also discusses operation of DFIG, control systems of wind turbine generator, both of active and reactive power output features and reactive power support from voltage source converters. Lastly, the example is a simulation of producing wind generation output using the developed wind speed data obtained before.

In conclusion, this chapter provides useful methods for simulating wind speed and wind generation output based on characteristics of wind speed and wind turbine generator. They can be used as wind and wind generation models in any further research about wind generation in power system to represent wind and wind turbine generator parts. According to different situations, the simulation can be adjusted for different number of results and different distribution.

2.9 References

[1] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, *Wind Energy Handbook*, UK: John Wiley & Sons, Ltd, 2001.

[2] T. H. Yeh and L. Wang, " A Study on Generator Capacity for Wind Turbines Under Various Tower Heights and Rated Wind speeds Using Weibull Distribution," *IEEE Transactions on Energy Conversion*, Vol. 23, No.2, pp. 592-602, June 2008.

[3] J. Wang, M. Shahidehpour and Z. Li, "Security-Constrained Unit Commitment with Volatile Wind Power Generation," *IEEE Transactions on Power Systems*, Vol. 23, No. 3, pp. 1319-1327, August 2008.

[4] M. R. Haghifam and M. Omidvar, "Wind Farm Modeling in Reliability Assessment of Power System," *9th International Conference on Probabilistic Methods Applied to Power Systems KTH*, Stockholm, Sweden - June 11-15, 2006.

[5] A. E. Feijoo, J. Cidras and J. L. G. Dornelas, "Wind Speed Simulation in Wind Farms for Steady-State Security Assessment of Electrical Power Systems," *IEEE Transactions on Energy Conversion*, Vol. 14, No. 4, pp. 1582-1588, December 1999.

[6] F. Vallée, J. Lobry, and O. Deblecker, "System Reliability Assessment Method for Wind Power Integration," *IEEE Transactions on Power Systems*, Vol. 23, No. 3, pp. 1288-1297, August 2008.

[7] M. **A.** B. Amora, U. H. Bezerra, "Assessment of the Effects of Wind Farms Connected in a Power System," *Proc. IEEE Porto Power Tech*, 10-13 Sept. 2001.

[8] Y. A. Kazachkov, J. W. Feltes, R. Zavadil, "Modeling Wind Farms for Power System Stability Studies," Power Engineering Society General Meeting, 2003, IEEE Volume 3, 13-17 July 2003.

[9] R. Karki, P. Hu and R. Billinton, "A Simplified Wind Power Generation Model for Reliability Evaluation," *IEEE Transactions of Energy Conversion*, Vol. 21, No. 2, pp. 533-540, June 2006.

[10] RERL-Resource Data-Wind Data, RERL (Renewable Energy Research Laboratory), Center for Energy Efficiency & Renewable Energy, University of Massachusetts Amherst, MA, USA, http://www.ceere.org/rerl/publications/resource_data/index.html.

[11] P. M. Anderson and A. Bose, "Stability Simulation of Wind Turbine Systems," *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-102, No. 12, pp. 3791-3795, December 1983.

[12] S. M. Muyeen, M. H. Ali, R. Takahashi, T. Murata, J. Tamura, Y. Tomaki, A. Sakahara and E. Sasano, "Comparative Study on Transient Stability Analysis of Wind Turbine Generator System Using Different Drive Train Models," *IET Renewable Power Generation*, Vol. 1, No.2, pp. 131-141, June 2007.

[13] S. Heier, *Grid Integration of Wind Energy Conversion Systems*, UK: John Wiley & Sons, Ltd, 1998.

[14] H. Li and Z. Chen, "Overview of Different Wind Generator Systems and Their Comparisons," *IET Renewable Power Generation*, Vol. 2, No.2, pp. 123-138, June 2008.

[15] J. G. Slootweg and W. L. Kling, "The Impact of Large Scale Wind Power Generation on Power System Oscillations," *Electric Power System Research*, Vol. 67, pp. 9-20, 2003.

[16] S. Muller, M. Deicke, R. W. de Doncker, "Doubly Fed Induction Generator Systems for Wind Turbines," *IEEE Industry Applications Magazine*, Vol. 8, No.3 pp. 26-33, May/June 2002.

[17] R. Pena, J. C. Clare and G. M. Asher, "A Doubly Fed Induction Generator Using Back-to-back PWM Converters Supplying an Isolated Load from a Variable Speed Wind Turbine," *IET Electric Power Applications*, Vol. 143, No.5, pp. 380-387, September 1996.

[18] J. B. Ekanayake, L. Holdsworth and N. Jenkins, "Control of doubly fed induction generator (DFIG) wind turbines," *IEE Power Engineer*, Vol. 3, No. 1, 2003, pp. 28–32, 2003.

[19] M. E. Moursi, G. Joos and C. Abbey, "High-performance voltage control scheme for wind park integration," *IET Renewable Power Generation*, Vol. 1, No.3, pp. 151-159, September 2007.

[20] D. Santos-Martin, J. L. Rodriguez-Amenedo and S. Arnalte, "Dynamic Programming Power Control for Doubly Fed Induction Generators," *IEEE Transactions on Power Electronics*, Vol. 23, No. 5, September 2008.

[21] N. R. Ullah and T. Thiringer, "Variable Speed Wind Turbines for Power System Stability Enhancement," *IEEE Transactions on Energy Conversion*, Vol.22, No.1, pp. 52-60, March 2007.

[22] V. S. Pappala, S. N. Singh, M. Wilch, I. Erlich, "Reactive Power Management in Offshore Wind Farms by Adaptive PSO," *International Conference on intelligent Systems Applications to Power Systems (ISAP)*, pp. 1-8, 5-8 November, 2007.

CHAPTER 3

OVERVIEW OF POWER SYSTEM SECURITY AND EFFECT OF WIND POWER GENERATION ON THE SYSTEM STABILITY

3.1 Introduction

Power system security has been recognized as an important problem for operation of power system in a long time. System security includes static security and dynamic security. Static security is the ability of power systems to operate at steady-state conditions which mainly refer to the planning of the power system. Dynamic security is the ability of power system to return to an acceptable state after disturbances which is usually described as power system stability. Historically, rotor angle instability has been the most serious problem on most systems and much effect has been focused on this area. As the interconnections of systems grow continually and more new technologies and controls are used in power systems, different forms of system security problems have emerged. For instance, voltage stability and frequency stability and inter-area oscillations have become greater concerns than in the past. [1] Moreover, the planning and design of power systems also need to satisfy the security requirement in this situation. Especially after deregulation of the electric power industry which has forced modern systems to operate closer to security boundaries, the power systems work under highly stressed conditions and have higher probability for encountering unforeseen contingencies. [2] As a result, it is essential for the satisfactory design and operation of power systems that a clear understanding of definition and classification of power system security and how the different types of security problem are interrelated.

As a result of increasing world-wide concern about the environment, there is a requirement for development of renewable generation which have the advantages of the absence of harmful emissions. Nowadays, most popular method of generating electricity from renewable sources is using wind turbine and installed wind power generation capacity is continuously and quickly increasing in many power systems around the world. [3] When wind power generation is connected to systems, there are also some changes in the form of system security which are introduced to power systems. Both control systems and power electronic based equipments in wind turbine generators and operation characteristics of wind farms are the main resources of influencing the system security. As wind energy is increasingly integrated into power systems, the impact of wind power generation on the operation and behaviours of power system is more and more significant. For planning and design issue, the power systems which include wind farms should be planned or reinforced to suit wind power generation running and satisfy the security standards. At the same time, the performances of wind turbine generators can also affect characteristics of rotor angle stability, voltage stability and frequency stability of the power systems. [4]

This chapter aims to make clear and define the understanding of the power system security problem which is an important issue for operation of power system and discuss the impact of wind power generation on the power system stability. And it will also use the power flow calculation program to get the output data of other conventional generators in the system with wind farms for further research. Then, there is another simulation example of transient stability study in a power system with a wind farm.

3.2 Power System Security

The trend toward deregulation has forced power systems to operate closer to security boundaries in order to get more profit. After electricity market existed, all the companies in power system take much more attentions to economy and concern with minimizing the cost of operation. But the most important factor in operation of a power system is maintaining the security of system. The value of security is the key point of the balance between economy and system security to decide the level of security.

3.2.1 Definitions of System Security

Power system security is a very complex problem which has been a quite difficult challenge for power system engineers. Power system security refers to the system's ability to maintain the flow of electricity energy from the generators to loads without interruption of the service for customers, especially under unforeseen disturbances (contingencies) which could compromise the correct system operation such as unexpected modifications to the power system structure or a sudden change of the operational conditions. [1] For example, a transmission line may be damaged by a storm and taken out by automatic relaying and a generating unit may be switched out of service because of auxiliary equipment failure.

System security can be divided into static security and dynamic security:

Static security is the ability of power systems to operate at steady-state conditions before or after disturbances (contingencies) without violating equipments ratings and system constraints, which include limits on bus voltages and the thermal bounds of the line. The steady state solution of the power system state equations is required for static security assessment in order to identify the powers flow (real and reactive power) and the voltages in all the network nodes and the current flows in each transmission line. [1, 2] The power flow at a bus is:

$$P_k = \sum_{m \neq k} V_k V_m (G_{km} \cos\theta_{km} + B_{km} \sin\theta_{km})$$

$$Q_k = \sum_{m \neq k} V_k V_m (G_{km} \sin\theta_{km} - B_{km} \cos\theta_{km})$$

where $\theta_{km} = \theta_k - \theta_m$ Equation 3.1

P_k and Q_k are the real and reactive power injections in bus k; V_k is the voltage in bus k, V_m is the voltage in other buses; Θ_k is the voltage angle in bus k, Θ_m is the voltage angle in other buses; $\mathbf{Y}_{km}=G_{km}-jB_{km}$ where $\mathbf{Y}_{km}$ is an element of the admittance matrix, G is conductance and B is susceptance. [5] Through these equations the power flows and voltage levels throughout the transmission system can be determined.

Dynamic security is the ability of power system to return to an acceptable state after disturbances (contingencies), which focus on the transient behaviour of power system. The main parts of dynamic security are power system stability and operation security which will be discussed in the following sections. It is different to static security that the only way to make an unstable case stable is the preventive control, and any action after the fault is not available. [1, 2] Since power system equipments are designed to be operated within certain limits, most of equipments are protected by automatic devices which may cause equipments to be taken off-line if these limits are violated. When an event leaves a system operating with violated limits, the event may be followed by a series of further actions that switch other equipments out of service. If this process of failures continues, the more parts of system may collapse in a cascading action it is usually refers to a system blackout.

For purposes of analyzing power system security and designing appropriate control systems, the system-operating conditions are classified into five states [6] which is shown on Fig. 3.1: normal, alert, emergency, in extremis, and restorative and the transitions can take place from one state to another.

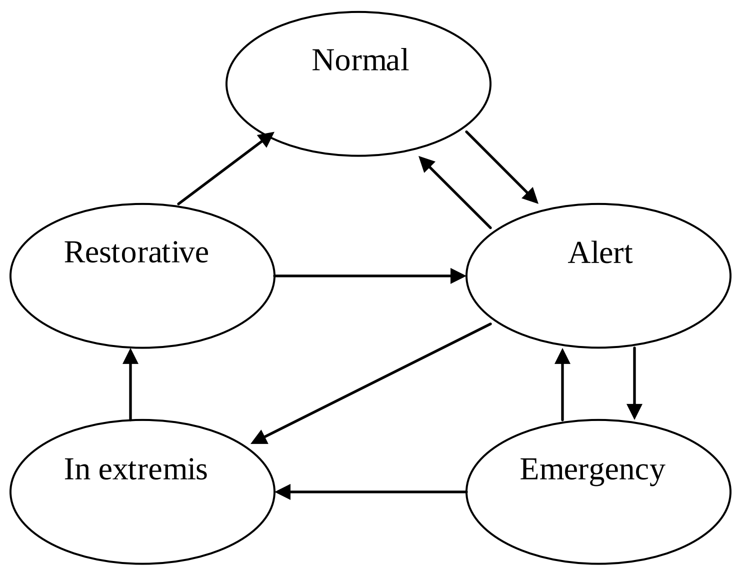

Fig. 3.1 Power system operating states.

Normal state: The system operates in a secure condition and has ability to withstand a contingency without violating any of the constraints.

Alert state: All system variables are still within the acceptable range and all constraints are satisfied but the system has been weakened to a level where a contingency may cause an overloading of equipment.

Emergency state: Voltages at many buses are low and equipments may be overload and exceed operating limit. The system may be restored to the alert state by the emergency control actions such as fault clearing, excitation control and generation off-line and in-line.

In extremis: A series of outages will happen and a major portion of the system will shut-down. The aim of control actions such as load shedding and controlled system separation is saving as much of the system as possible from a widespread blackout.

Restorative state: Control action is being taken to reconnect all the facilities and to restore system load. The system transits from this state to the alert state or the normal state, depending on the system conditions.

3.2.2 Power System Planning

For reliable service, a power system must be strong enough to maintain the supply and have ability to withstand a wide variety of disturbances. Therefore, it is necessary that systems be designed and operated so that more contingencies can be sustained without loss of load and most contingencies do not result in uncontrolled, widespread and cascading power interruptions. As a result, power systems planning are very important.

It is a very complex problem to ensure stable operation at minimum cost for the design of a large interconnected system. And the system planning is getting more complicated due to the liberalization of electricity industry and the increasing concern for environmental impact of electricity generation. The power system which operates in a constantly changing environment is a highly nonlinear system whose dynamic performance is influenced by a wide array of facilities in different response rates and characteristics. The system planning mainly contains generation planning, transmission planning and demand side management which will be explained below.

3.2.2.1 Generation Planning

Several resources such as coal, gas, oil, hydro, nuclear and renewable energy includes solar, wind bio-fuels etc. can be used as the fuel, so there are many types of generation system. Fig. 3.2 is shown an example for different generation in a power system. [7]

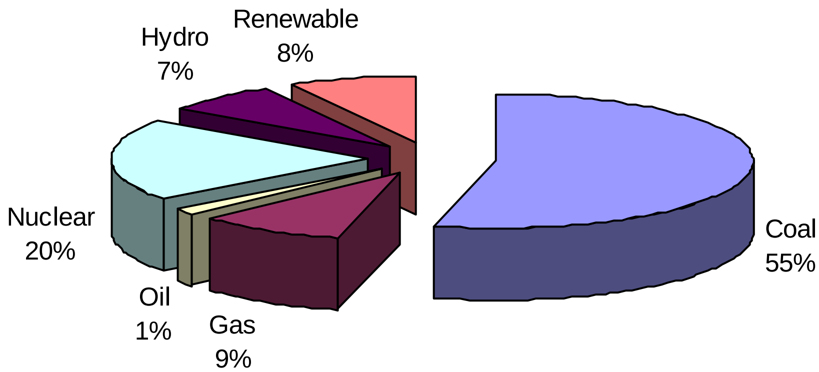

Fig. 3.2 Percentage of different types of electric energy generation in US, 2000.

Each kind of plant has its own operating characteristics and influences to systems and the surrounding environment. Generally, the thermal power generation, which includes coal, gas, oil plant, has critical operating constraint for minimum load at which a plant can operate is that the generator cannot operate below 30% of design capability. And for 800MW-1200MW large capacity thermal power generation unit, the minimum load limit is higher and at about 40% of design capability. The hydro electric plants are usually coupled both electrically and hydraulically and their characteristics are affected greatly by the hydraulic configuration. And hydro power plants have more smooth characteristics for changing output. [8] As a result, different plants are suitable for different power system condition and it is a crucial issue in generation planning.

To maintain reliability and security of supply on power systems, reserves of real and reactive power, which are located around the network strategically, are required. The reserves generation is usually planned about 20% over the annual peak demand. These reserves include spinning reserve, standing reserve, replacement reserve, reactive power reserve and 'black-start' reserve and are listed on Table 3.1. [5]

Table 3.1 Different types of reserves

Reserves	Generation Type	Situations
Spinning Reserve	Part-loaded synchronized generators	Sudden frequency change due to loss of unbalance
Standing Reserve	Fast start-up plant(hydro, gas turbine)	Demand sudden increases or capacities are out of service
Replacement Reserve	Hot-standby plant/Deferred-start plant	The event of a shortfall in standing reserve
Reactive Power Reserve	Generation operate at an instructed power factor/Synchronous compensators and wind turbine generator	Have a prescribed excitation response on change of voltage
'Black-start' capability Reserve	Batteries/Diesel generators/Gas turbines	In emergency, generators can start one or more units without external electrical supply within a given period

Spinning reserves: fast-response capability held on part-loaded synchronized generators to check any sudden frequency change due to loss of balance between generation and demand. Generator capability requires monitoring and periodic assessment to ensure contracted response is available. Response is classified into primary, which is available within 10s, and secondary, which is available within 30s.

Standing reserve: fast start-up plants such as hydro and gas turbine which is available within 5 min or less belongs to this kind of reserve. Demand reduction by operator instruction can also be used in this category.

Replacement reserve: plant that can be brought into service with longer notice in the event of a shortfall in standing reserve. This may be hot-standby plant or deferred-start plant, designated by the system operator.

Reactive power reserve (voltage control): to have a prescribed excitation response on change of system voltage, the generator is required to operate at an instructed power factor within registered capabilities. Moreover, synchronous condensers and wind turbine generator are also effective reserves for voltage control.

'Black-start' capability reserve: In the event of serious emergency such as a system shun-down, a system needs several generators that can start one or more units without external electrical supply within a given period a self-start which is called 'black-start' capability. This kind of reserve usually includes batteries, diesel generators and gas turbines.

And there is also another issue in generation planning, which is generator scheduling. Firstly, the generators should be scheduled to satisfy the peak and valley demand in order to maintain the service. Secondly, the operating schedules are for an optimum operating policy which provides the minimum operating cost, according to economic characteristics of every power plant. And finally, the schedules also deal with the maintenance and forced outage of generation. Nuclear plants usually have the highest rate of scheduled maintenance requirement and on the contrary, gas turbines have the lowest rate for maintenance. [8, 9]

3.2.2.2 Transmission Planning

It is a difficult question that how much transmission capacity should be built in transmission planning. The decision of transmission capacity in planning depends on the location and characteristics of both of generating units and of demand as well as the maximum acceptable risk of failing to meet demand in the systems. The objectives of the planning not only satisfy the current service but also provide sufficient transmission capacity against a future with uncertain development of demand and generation. [10] For interconnection capacity between two regions, the minimum secure capability of the system is about maximum exchange of power between two regions when all demand is satisfied and is the main basis of determining the required interconnection capacity. [11]

In addition, the plan of transmission system is also required to satisfy the (N-1) criterion which is frequently used and a widely applied method to assess power system security. (N-1) criterion is that when a transmission line is damaged by a failure such as a storm and taken out of service, the remaining transmission lines can take the increased loading and still remain within limits. So (N-1) criterion requires the systems should be planed and expanded in such a way that after any single component is out of service the systems can still operate adequately, otherwise any single failure of line may leave other components overloaded and cascading failures of the transmission system. Similarly, in some transmission lines which is connected to important loads areas, (N-D) ('D' represents a double circuit outage) or (N-2) (two separate single circuit outages) secure is required. [5]

Both transmission capacity and (N-1) criterion planning need the calculation of power flow to identify the power transfer in transmission lines and determine if the lines and equipments are overload after one unit is out of service. Furthermore, transmission losses problem is also involved in planning which bases on calculation of power flow too and the losses on the transmission line are proportional to the square of the power flow. The power loss in the network increases the total generation demand and the generation schedule may have to adjust to obtain the optimal power flow in order to reduce the total transmission losses in the system. [7]

3.2.2.3 Demand Management

The major consumption grouping of loads is industrial, residential and commercial. Industrial loads occupy around 40% of the total in many industrialized countries and an essential item is the induction motor. The amount of electricity of industrial output depends on the development of economic so the industrial demands increase very fast in some developing countries such as China and India. In addition, the increase of using electricity energy in industry is also influenced by the growth of energy-intensive industries such as chemicals, steel manufacturing and aluminium.

Residential loads are largely household electric appliances such as space heater, freezer, cookers, lighting, and air-conditioning. This part of loads is really significant for daily life of people so the energy supply for this part need quite high reliability and quality to satisfy the demand of the public. And many loads are constant power loads whose impedance has an inverse ratio with square of system voltage.

Commercial loads usually comprise the central air conditioning, heating and fluorescent lighting load in offices, shops, schools etc. Its growth rate also depends on the development of economic of the country and the commercial consumption focus on the same time period in a day with industrial consumption. [7]

Because the load pattern characteristic can hardly be controlled relatively, analyze the representation of loads at a system is very important for the safety and reliability of the electricity supply and is the foundation of plan or design systems. As a result, load forecasting is an efficient method to recognise the load characteristic. And it is based on historic data especially loading of previous year and is updated by factors which include economic factor, time factor such as season and public holiday, weather factor and random factor. For the planning of power systems, the period of load forecasting is usually from several months to one year even to ten years. And for the operating of the power systems, it is usually from several minutes to 168 hours (a week). [5]

3.2.3 Power System Stability

Power system stability has been recognized as an important problem for system operation for quite a long time. Stability of power systems mainly focus on continuance of intact operation following disturbances or contingencies. These disturbances and contingencies, which have a significant probability of occurrence in power systems, include: permanent three-phase faults on any generators, transmission circuits, transformers or bus sections with normal fault clearing; permanent phase-to-ground faults on any transmission circuits, transformers, bus sections or circuit breakers; loss of any element without a fault; and permanent loss of both poles of a dc bipolar facility. And there are also extreme contingencies, which have low probabilities of occurrence, such as loss of capability of generation; loss of all lines connects generation and substation; and sudden dropping of a large load or a major load centre.

As power systems have growth in interconnections, use of new technologies and controls and increased stressed conditions, system stability has become of greater concerns than in the past.

3.2.3.1 Basic Concepts and Definitions

Power system stability is defined as that the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. [1]

Depending on the system configuration and operation mode, instability in a power system can have many different ways. Most of generators used in power systems are synchronous machines so maintaining system operation in synchronous mode are required. This aspect of stability is influenced by the dynamics of generator rotor angles and power-angle relationships. Instability may be collapse of system voltage without loss of synchronism and the concern is reactive power and control of voltage. This form of instability can also occur in loads covering an extensive area, where generator feeding an induction motor load, supplied by a large system. Additional, instability may also be system frequency swings and this aspect of stability depends on balance between generation and load. As a result, the power system stability is divided into rotor angle stability, voltage stability and frequency stability.

The understanding of stability problems can be much easier by the classification of stability into various categories. Categories and subcategories of the power system stability problem are shown on Fig. 3.3. [1] And these will be explained in details at following sections.

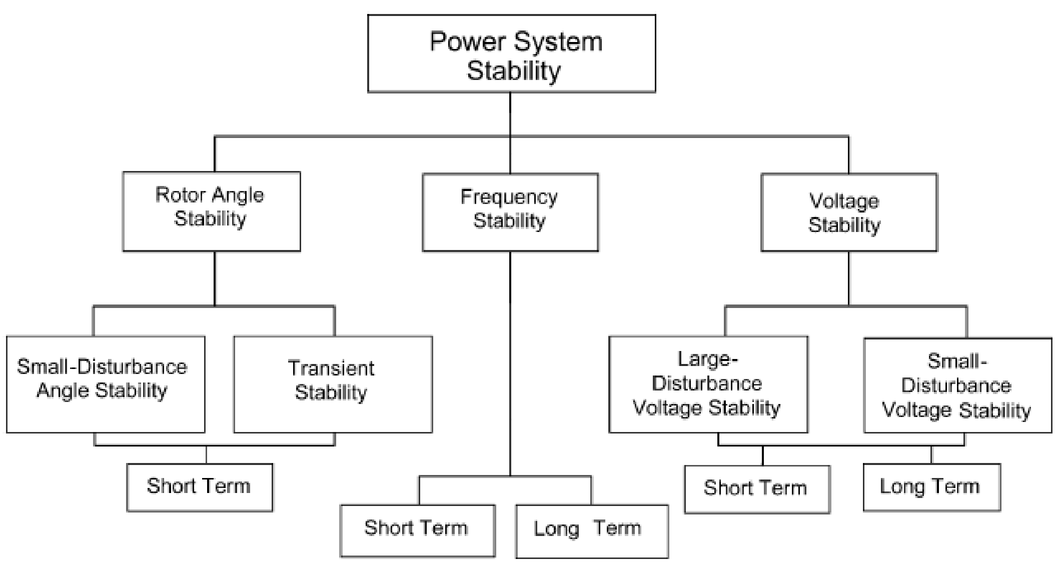

Fig. 3.3 Classification of power system stability.

3.2.3.2 Rotor Angle Stability

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. Instability, which occurs in the form of increasing angular swings, may lead to some generators loss of synchronism with other generators.

The rotor angle stability mainly concerns generators in the power systems. When the rotor is driven by a turbine (prime mover), the rotating magnetic field of the field winding, which is excited by direct current, induces alternating voltages in the three-phase armature windings of the stator. When a load is connected, the frequency of the induced alternating voltages and the frequency of resulting currents that flow in the stator windings depend on the speed of the rotor. And if the frequency of the stator electrical quantities is synchronized with the rotor mechanical speed, the generating machine is synchronous. It is very significant for rotor angle stability to maintain synchronous of each synchronous machine in the system. [12] When two or more synchronous machines are interconnected, the stator voltages and currents and the rotor mechanical speed of all the machines must have the same rotation speed. Therefore, the rotors of all interconnected synchronous machines must be in synchronism.

Under steady-state conditions, rotational speed of rotor of a generator machine is equal to rest of generators in a power system. If the system is perturbed by any disturbances, it will result in acceleration or deceleration of the rotational speed of rotor. And the changes in rotor speed will create the angular position difference between this rotor and with other ones, which can influence the output of a generator. After a disturbance, if angular position difference decreases until the machine reaches the synchronous speed again, the system possesses rotor angle stability. And if the angular position difference increases continually, the machine will lose synchronism with the rest of the system and it will also result in large fluctuations in the machine power output, current and voltage. Finally, the protection system will act to isolate the unstable machine from the system. [6]

It is usual to characterize the rotor angle stability phenomena in terms of the two categories: small-signal stability and transient stability. Small-signal stability (or small-disturbance stability) is the ability of the power system to maintain synchronism under small disturbances. The character of system response to small disturbances depends on a number of factors including the initial operating point, the transmission system strength, and type of generator excitation controls used. Transient stability (or large-disturbance rotor angle stability) is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. Stability depends on both the initial operating state of the system and the severity of the disturbance.

3.2.3.3 Voltage Stability

Voltage stability is the ability of a power system to maintain steady acceptable voltage at all buses in the system under normal operating conditions and after being subjected to a disturbance. It is voltage instability when a disturbance, in load demand or change in system condition causes a progressive and uncontrollable drop in voltage. Voltage instability is basically a local phenomenon but its consequences may have a widespread impact which may result in a sequence of events accompanying voltage instability leading to voltage collapse of the entire power system.

The main reason of causing instability is the inability of the power system to meet the demand for reactive power. A major factor contributing to this problem is the voltage drop that occurs when active power and reactive power flow through inductive reactance associated with the transmission network and this limits the capability of the transmission network for power transfer and voltage support. The power transfer and voltage support are further limited when some of the generators hit their field or armature current time-overload capability limits. Voltage stability is threatened when a disturbance increases the reactive power demand beyond the sustainable capacity of the available reactive power resources. [13]

It is useful to classify voltage stability into following categories: large-disturbance voltage stability and small-disturbance voltage stability. Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation or circuit contingencies. This ability is determined by the system and load characteristics and the interactions of both continuous and discrete controls and protections. Small-disturbance voltage stability refers to the ability of system to return to and maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This ability is influenced by the characteristics of loads, continuous controls and discrete controls at a given instant of time.

The time of interest for voltage stability problems vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short-term or a long-term phenomenon as identified in Figure3.3. Short-term voltage stability refers to dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. The study period of interest extend to several seconds and analysis requires solution of appropriate system differential equations. Dynamic modelling of loads is often essential. Long-term voltage stability refers to slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of interest extend to several or many minutes and long-term simulations are required for analysis of system dynamic performance. [1, 13]

3.2.3.4 Frequency Stability

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. Instability, which occurs in the form of sustained frequency swings, may lead to tripping of generating units or loads. The stability depends on the ability to maintain and restore equilibrium between system generation and load with minimum unintentional loss of load. [1]

Serious system upsets generally result in large fluctuation of frequency such as power flows, voltage and other system variables. Generally, frequency stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve. In large interconnected power systems, extreme system situation is most commonly associated with conditions following splitting of system into islands. For this case, stability is a question of whether or not each island will reach a state of operating equilibrium with minimal unintentional loss of load. In isolated island systems, frequency stability concern for any disturbance causing a relatively significant loss of load or generation.

As show in Figure3.3 frequency stability may be a short-term or a long-term phenomenon. During frequency fluctuation, the processes characteristic times of devices and equipments will range from several seconds such as under-frequency load shedding and generator controls and protections, to several minutes such as prime mover energy supply systems and load voltage. [1, 6]

3.3 Effect of Wind Generation on the System Stability

When the capacity or penetration level of wind power generation increases, more conventional generation capacity will be displaced and the influences from wind generation to the power system become more and more significant. Wind turbine generator may impact the rotor angle stability, voltage stability and frequency stability of the power system. [14] Wind turbine generators are subjected to both electrical disturbances which applied at the generator during electrical transients and mechanical disturbances which applied at the turbine when there are sudden wind speed changes. In power systems with wind turbine generators, all the possible electrical disturbances are the same with systems with only conventional turbine generators and mechanical disturbances of them are peculiar to turbine and generator structure. [15]

In the past, there have been several researches in this area which focused on transient stability of the system reflection the dynamic performances of the wind farm and the power system after a fault. And these are relied on both fixed speed wind turbine model and variable speed wind turbine model. Moreover, the study and simulation time period is in the range of normally less than several seconds and wind speed is usually assumed to be constant during the simulation. [14, 16, 17]

3.3.1 Impact of Wind Power on Generation of the Power System

In a power system with wind farm, the operation and behaviour of wind turbine generator influence the power flow in the system and the power output of other conventional generators and it may also impact the rotor angle stability of the system which may result in conventional generators loss synchronism with the whole system.

3.3.1.1 Influence on the Operation of Conventional Generation

The rotational speed of generator depends on mechanical torque and electromagnetic torque which affects the rotor. Mechanical torque is decided by the prime mover of power plant and electromagnetic torque relies on operating state of the power system which connects to the generator. When a synchronous machine operates under steady load conditions with fixed load angle δ, mechanical torque and electromagnetic torque are in balance:

$$T_m - T_e = 0 \qquad \text{Equation 3.1}$$

where Te is electromagnetic torque in N·m and Tm is mechanical torque in N·m.

If a generator is connected to a system with wind farm, T_e will be changed a ΔT_e following the change of wind farm output and T_m is unable to match this instantaneously. As a result, the balance between T_m and T_e will create an imbalance torque and will accelerate or decelerate rotor speed [18]:

$$J_G \frac{d\omega_{rm}}{dt} = T_a = T_m - T_e \qquad \text{Equation 3.2}$$

where T_a is accelerating or decelerating torque in N·m; J_G is the combined moment of inertia of generator and turbine in kg·m^2 ; ω_{rm} is mechanical angular velocity of the rotor in rad/s. And,

$$2H_G \frac{d\overline{\omega}_r}{dt} = \overline{T}_m - \overline{T}_e$$

and $\overline{\omega}_r = \omega_r / \omega_0$, $\overline{T}_m = T_m / T_0$ and $\overline{T}_e = T_e / T_0$ Equation 3.3

where H_G is inertia constant in per unit, ω_r is electrical angular velocity of the rotor in rad/s, ω_0 is rated value of angular velocity and T_0 is rated value of torque.

The inertia of a generator plays a significant role in maintaining the power system stable during the condition of supply and demand or torques imbalance. For wind turbine generators, the kinetic energy of a wind turbine is from the rotating blades, the gearbox and the electrical generator. And the wind turbine generators have lower inertia than conventional generators because of its size. The increasing of wind turbines may result in a reduction of conventional power plants and it also will lead to reduction of inertia in the system. [19] The smaller the system inertia, the greater changes in rotor speed when system experiences imbalance condition. The rotor speed no longer equals to synchronous speed so load angle δ will also change: [12, 18]

$$\frac{2H_G}{\omega_0}\frac{d^2\delta_G}{dt^2} = \overline{T}_m - \overline{T}_e$$

and $\frac{d\delta_G}{dt} = \omega_r - \omega_0$, $\frac{d^2\delta_G}{dt^2} = \frac{d(\omega_r - \omega_0)}{dt} = \omega_0 \frac{d\overline{\omega}_r}{dt}$ Equation 3.4

Additional torque results in a load angle change and a change in the kinetic power of the rotor in needed to balance extra power demand. To operate at the next balance state, there is a process of torques, load angle and rotor speed to reach new value and damping oscillation is always in the process [12].

3.3.1.2 Influence of the Rotor Angle Stability

For the small-signal stability (or small-disturbance stability), any small disturbances may lead the power system to instability which results in power system oscillations and wind power generation will take effects on system oscillations. The three main types of power system oscillations are: [6]

- Local oscillations: oscillations of one generator or a group or generators against a strong system.
- Intra-area oscillations: oscillations of generators in a certain area of the system against each other but hardly affecting the rest of the generators in the power system.

- Inter-area oscillations: oscillations of generators in a certain area of the system against generators in another area of the system also hardly affecting the rest of the generators in the power system.

The effect of wind power on power system oscillations depends on the wind turbine concepts (constant or variable speed). Constant speed wind turbines increase the damping of power system oscillations but their impact on the variation of oscillation frequency depending on the type of oscillation. And variable speed wind turbines increase the frequency of power system oscillations and their impact on the damping is rather limited in all types of oscillation. Wind power tends to improve the damping of oscillations and constant speed wind turbines have better effects than variable speed type which caused by the damping effect of the squirrel cage induction generator used in constant speed type. Furthermore, wind turbine generation dose not induce new oscillation mode. [20, 21]

Following the increasing of wind power penetration level, the effect of wind turbine generation on system oscillations also increases. [14] And the types of oscillations are also influenced by the location of wind turbine generators. From [20], wind power generation mainly affects on local oscillation and inter-area oscillation.

For transient stability (or large-disturbance rotor angle stability), wind power generation will also impact the transient stability of the system. After a fault, there is a limit of maximum possible critical fault times for synchronous machine in the power system. Beyond this limit, the synchronous machine speed will increase rapidly due to loss of synchronism and this is usually used to define the stability margin. [22]

When a fault happens near a conventional synchronous generator, the output of wind power generation is maintained to be stable because the rotor speed control of the wind turbine generator. During the fault, it improves the balance the generators and loads in the system and contributes to reduction of synchronous generator acceleration. After the fault, the values of wind turbine generator go to the previous value before the fault by actions of the control system. The wind turbine generator represents a benefit to increase the transient stability margin of the conventional synchronous generator. As a result, it has a good effect on transient stability of the other generators. [23] Like the effect on small-signal stability mentioned above, wind turbine generator also provides a good damping performance for transient stability of the system. [13, 24]

When the fault happens near the wind farm, both the output and the electromagnetic torque of wind turbine generator will be reduced because of the short circuit current which results in a voltage drop at the wind generator terminal. And the mechanical torque is still applied to the wind turbine so the balance of torques will be broken. For this situation, the wind turbine generator hardly has contribution on transient stability. [14, 23, 24]

3.3.2 Impact of Wind Power on Reactive Power and Voltage of the Power System

When a power system connects with a wind farm, the voltage stability is one of the most important factors that affect both the wind farm and operation of the system. The impact of wind power generation on power system voltage stability also depends on different types of wind turbine generator and penetration level of wind energy.

For the long-term voltage stability and small-disturbances stability, when the active power output of wind farm is low, the voltage of interconnection point is not affected significantly. However, when wind power injects into the transmission system increase largely, the voltage decreased becomes more simply during any small disturbances which may cause voltage collapse at last. Variable-speed wind turbine with DFIG can supply nearly double active power to the power system than fixed-speed type within voltage stability limit because DFIG based wind turbines can provide the reactive power to maintain the voltage of interconnection point. Additionally, control systems of wind turbine with DFIG also have benefit for system voltage stability. [25, 26]

The lack of reactive power support is the key issue of wind farm that causes voltage instability to power system and the effect could be more severe when the inject power from wind generation is large. The reactive power requirements of wind farm are reactive compensation equipments such as SVCs and synchronous condensers to support the voltage stability. [27]

For the short-term voltage stability and large-disturbance voltage stability, it is a basic topic that the voltage recovery issue of wind farm interconnecting point after the clearance of a fault. If the terminal voltage of wind farm, which is connected to the network, can be restored, the wind turbine generator can still be connected into the grid and keep in service and balance of torques and rotor speed may also restore. On the contrary, if the voltage is not able to be recovered back to around the normal value, the wind turbine generators require an increase of reactive power consumption. Then the voltage may decrease further to lead to voltage instability of the whole system and it may also accompany rotor angle instability. Untimely, the wind power generation need to be out of service to protect the local grid voltage through the voltage protection devices. [4] The DFIG based wind turbine has a better voltage recovery performance than the fixed-speed type due to the control systems of reactive power capability and voltage. [25]

3.3.3 Impact of Wind Power on Frequency of the Power System

The increasing penetration of wind power generation in electricity grid which displaces a number of connected conventional synchronous generators will result in a reduction of the system inertia. The frequency of a power system with lower inertia will has larger and faster deviations after occurrence of abrupt variations in generation and load. In this case, additional frequency response ancillary services must be provided to ensure frequency limits are not exceeded. [28]

When the fixed-speed wind turbines replace conventional synchronous generation, there is no significant change in minimum frequency reached following a loss of generation or load because the fixed-speed turbine generator can still supply plenty of inertia. However, when variable-speed wind turbines with DFIG displace conventional power plants, the lowest frequency following a loss of generation or load reduces due to the negligible inertial response provided by DFIG wind turbines. As the DFIG wind turbines become more and more popular, the problem of lacking of inertia becomes more significant. [29]

According to [19, 30], adding a supplementary control loop into the DFIG wind turbines can provide a better inertial response to support the power system frequency. This is a possible solution for this problem.

3.4 Example for Conventional Generation Operation in a System with a Wind Farm

The output of conventional generators and the energy transferred in transmission can be calculated by power flow programs. For the power systems with a wind farm, using the simulated wind turbine generator output data which is calculated in Section 2.7, wind farm output values for 24 hours in every 10 seconds are obtained. Based on these data, output of other conventional generators can be obtained thought power flow calculation program.

In this simulation, the power flow calculation program is PowerWorld™ Simulator program.

3.4.1 Case Study

In this case study, the aim is to get 24 hours conventional generators output data. Because of the form of wind turbine generator output data, the simulation results data are also in 24 hours for every 10 seconds.

The goal of this simulation is to investigate the impact of wind farm to other conventional generators in a power system. So in the case, the model system is shown on Fig. 3.4. In this system, a single 1000MVA synchronous generator supplies energy to a 1000MW load centre through a pair of 500km long distance backbone 500kV high-voltage transmission lines. The nominal voltage of the generator is 13.8kV and connects to 500km long double-line of 500kV transmission system with a 13.8kV/500kV transformer. And the capacity of wind turbine generator is 150MW which is 15% of conventional generator capacity and the wind farm connects to the load area in 35kV distribution system with a 0.69kV/35kV transformer. Then the information and data of this model power system is listed in the Table 3.2.

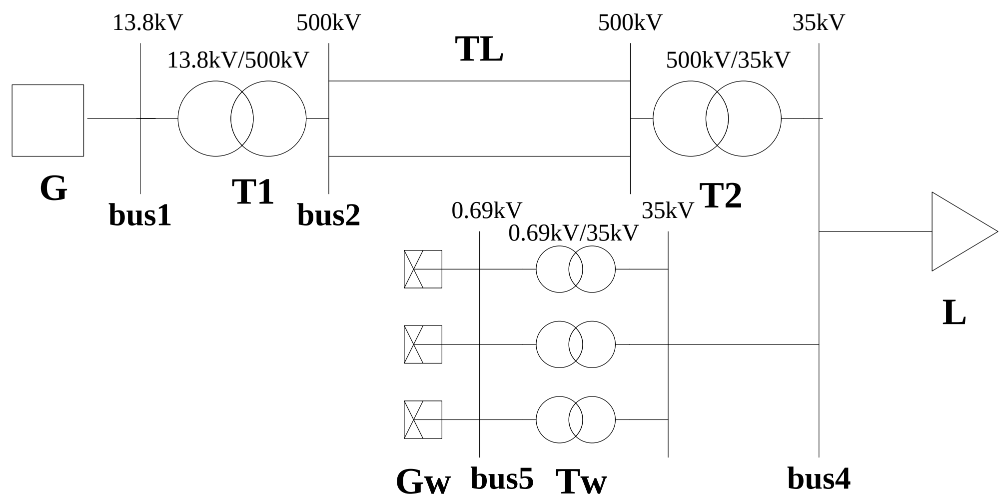

Fig. 3.4 The model system of the 3.4.1 case study.

Table 3.2 The information and data of model power system in Case study 3.4.1

Symbol	Information	Data (System frequency is 50Hz)
G	A conventional generator connected to transmission system	**Capacity:** 1000MVA; **Voltage level:** 13.8kV
Gw	A large wind farm contains 100 wind turbines integrated connected to distribution system	**Capacity:** 100*1.5MW; **Voltage level:** 0.69kV
TL	A double-line long distance backbone 500kV high-voltage transmission system	**Length:** 500km; **Voltage level:** 500kV; **Resistance R:** 1.755×10^{-2} Ω/km; **Inductance L:** 8.737×10^{-2} H/km; **Capacitance C:** 1.339×10^{-8} F/km
L	A load centre with a stable constant load	**Total demand:** 1000MW; **Voltage level:** 35kV
T1	Transformer connects conventional generator and transmission system	**Ratio:** 13.8kV/500kV; **Capacity:** 1000MVA
T2	Transformer connects transmission system and load in distribution system	**Ratio:** 500kV/35kV; **Capacity:** 1000MVA
Tw	Transformer connects wind farm and distribution system	**Ratio:** 0.69kV/35kV; **Capacity:** 200MVA

The simulated wind turbine generator output data which is calculated in Section 2.7 is considered as continual wind farm output in 24 hours for every 10 seconds in this simulation in order to express the fluctuation of wind power generation output. From the power flow calculation program, the simulation will get a series of results of conventional generator output and the power flows in transmission system and these results can also considered as continual data for 24 hours. As a result, the fluctuation effect of output of wind farm on conventional generator output is expressed through the simulated results of power flow calculation. The fluctuation effect of conventional generator will also influence the inside operation of the machine such as heating problem of the rotor and stator. In the following chapters, the research will focus on the thermal (or heating) problem of conventional generator, which is caused by fluctuation of output, based on this simulation results.

3.4.2 Simulation Results

Finally, the results of conventional generator output can be obtained by the simulation. For example, in Fig. 3.5 (a), the output of the conventional generator from 00:00 to 04:00 for every 10 seconds is shown. In order to find out the characteristics of these output data, the concept of probability density function (pdf) can be introduced to investigate the data. The pdf describes the density of probability at each point in the sample space which can represent probability is high or low for any point in the sample space.

Using Matlab^{TM}, the probability density function program computes a probability density estimate of the sample, which includes of 100 points covering the range of the data, in the vector of conventional generator output data. Then, based on the computation results, the figure of probability density against conventional generator output can be drawn and shown on Fig. 3.6 (a).

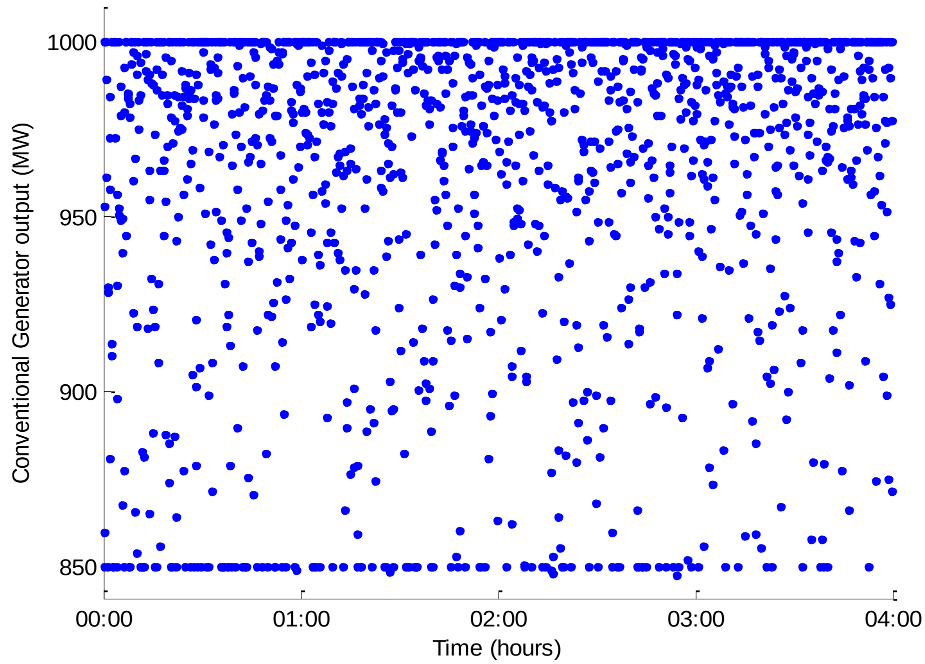

Fig. 3.5 (a) Conventional generator output in four hours for every 10 seconds from 00:00-04:00.

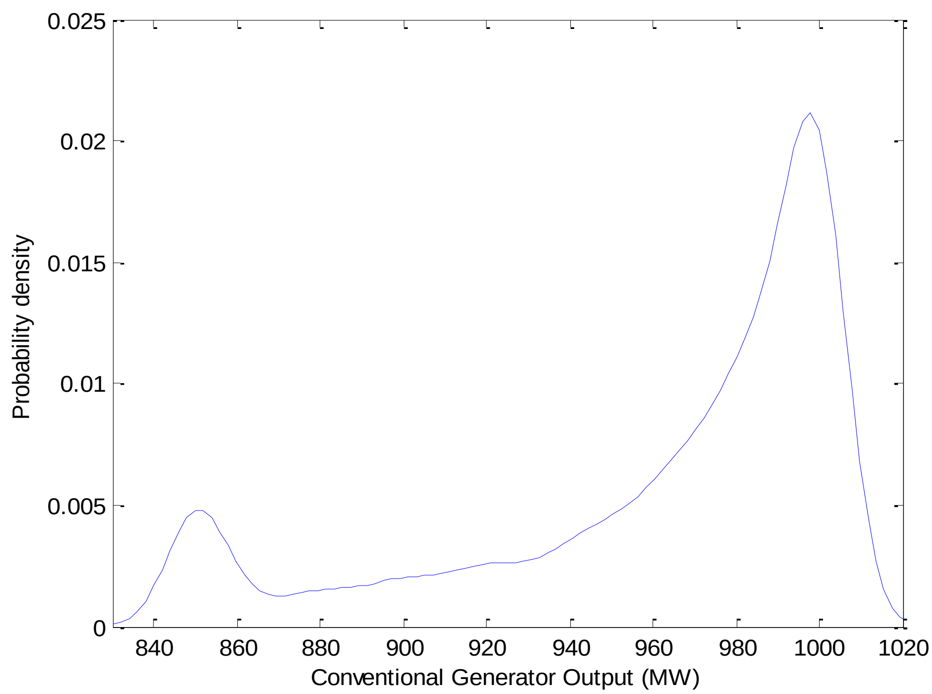

Fig. 3.6 (a) Probability distribution of conventional generator output at 00:00-04:00.

From this figure, it is shown that the output of conventional generator mainly focuses on the area around 990MW which is close to the full output 1000MW. It represents that the percentage of wind turbine generator output of the total wind generation capacity is low for most of the time in the 00:00-04:00 period so output of conventional generator is around the full output. Moreover, because of cut-in and cut-out speed in wind turbine generator active power output characteristics, which is discussed in Section 2.6.4, data around full output and zero output of wind generation usually have higher probabilities than other output data. As a result, there is also an area around 850MW which represents the full output of wind generation and it has higher probability density than the area between 870MW and 940MW.

If there is no wind power generation or the output of wind generation is stable in the sample system, the output of conventional generator would be a constant value. However, practical wind turbine generator operational characteristics results in a variety of probability distribution of conventional generator output.

In the same situation, the rest of output data results and their probability distribution are shown on Fig. 3.5 (b) to Fig. 3.5 (f) and Fig. 3.6(b) to Fig. 3.6(f).

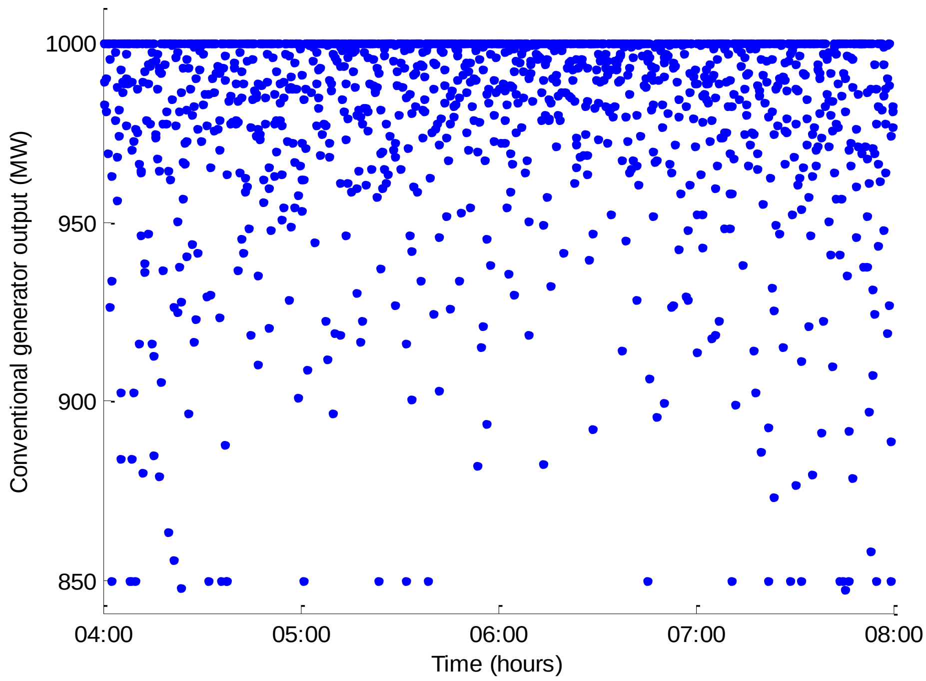

Fig. 3.5 (b) Conventional generator output in four hours for every 10 seconds from 04:00-08:00.

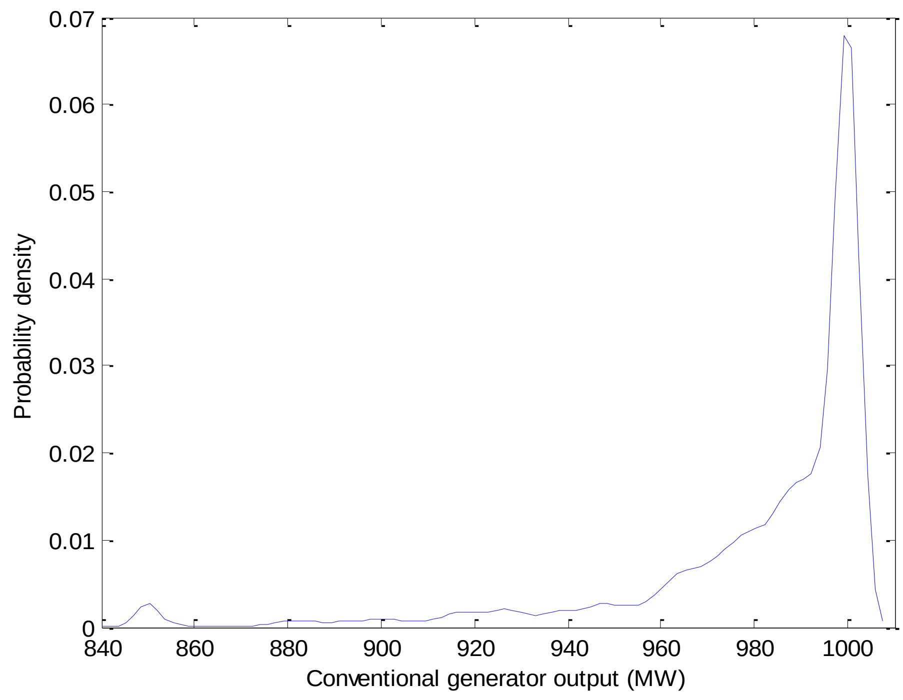

Fig. 3.6 (b) Probability distribution of conventional generator output at 04:00-08:00.

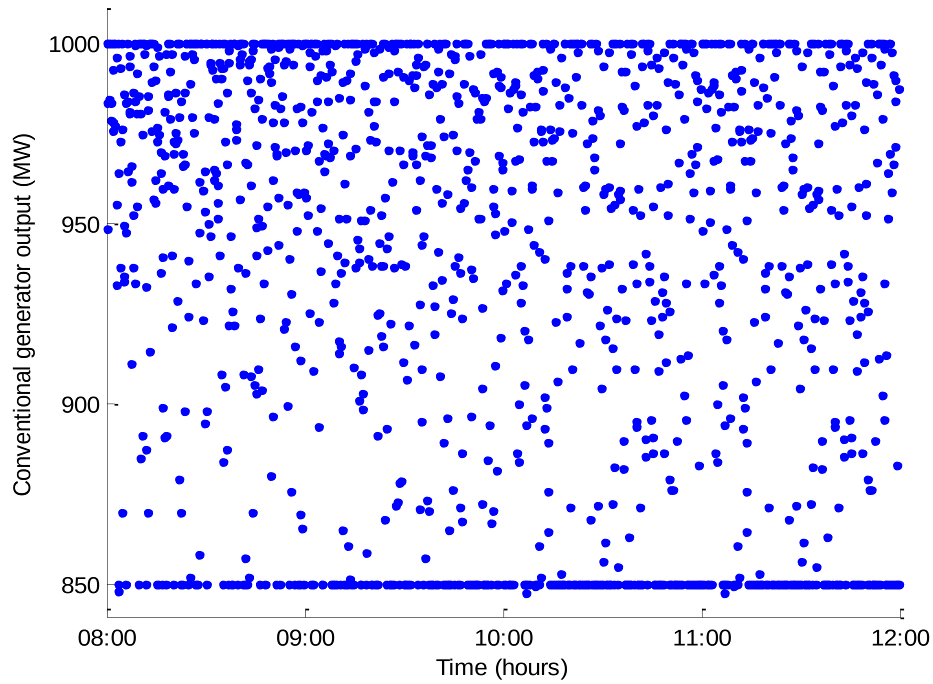

Fig. 3.5 (c) Conventional generator output in four hours for every 10 seconds from 08:00-12:00.

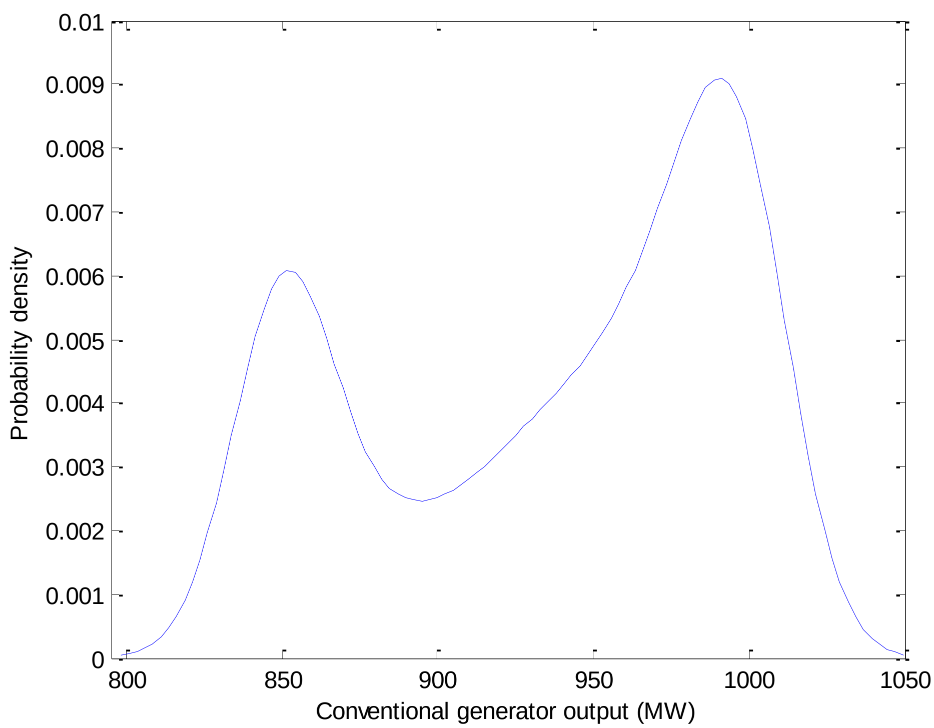

Fig. 3.6 (c) Probability distribution of conventional generator output at 08:00-12:00.

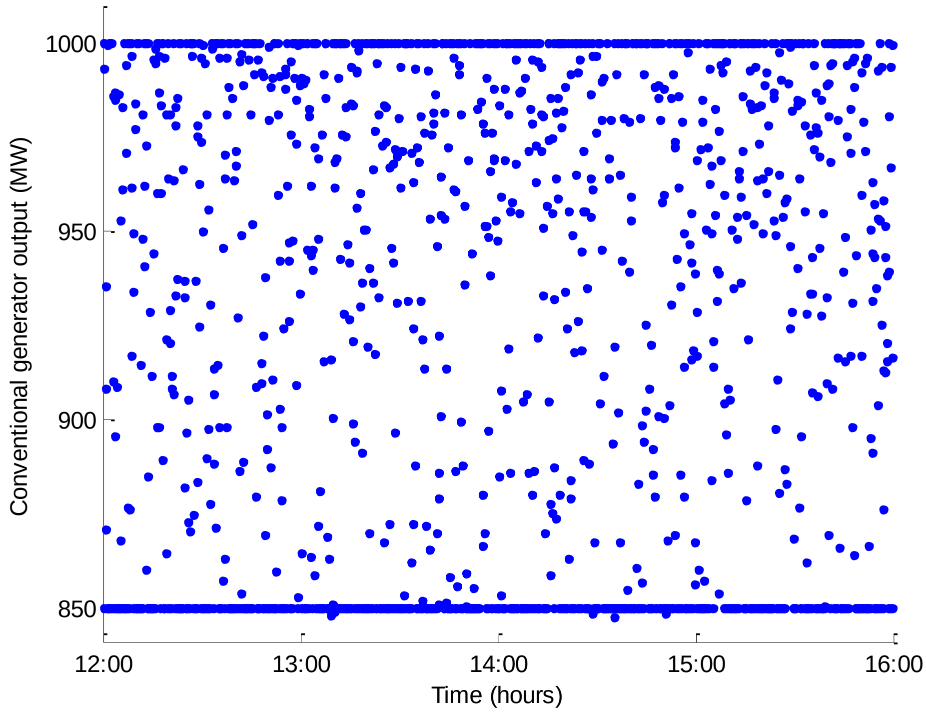

Fig. 3.5 (d) Conventional generator output in four hours for every 10 seconds from 12:00-16:00.

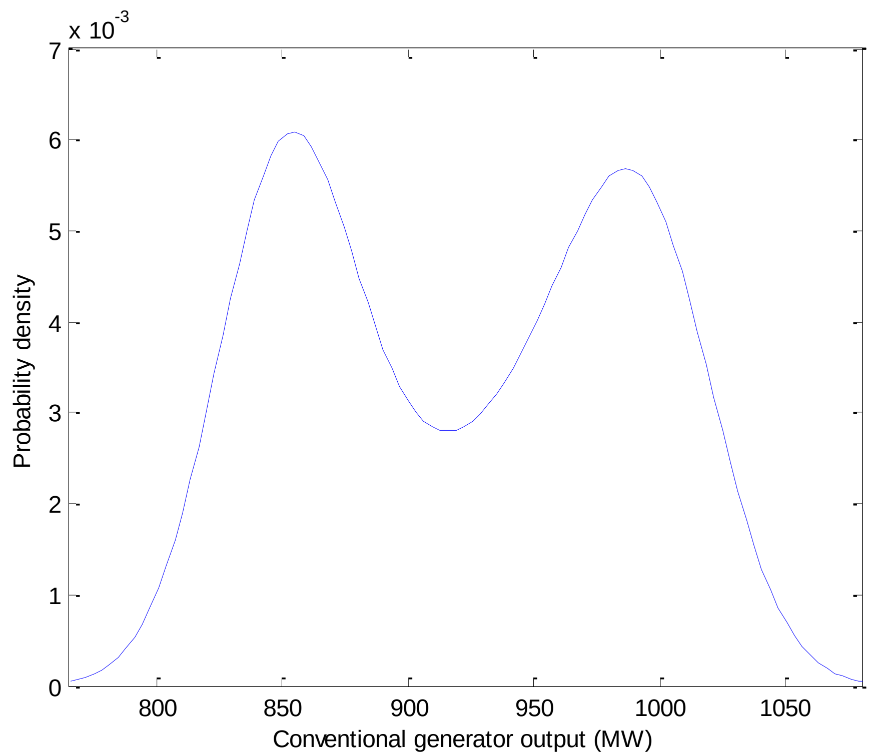

Fig. 3.6 (d) Probability distribution of conventional generator output at 12:00-16:00.

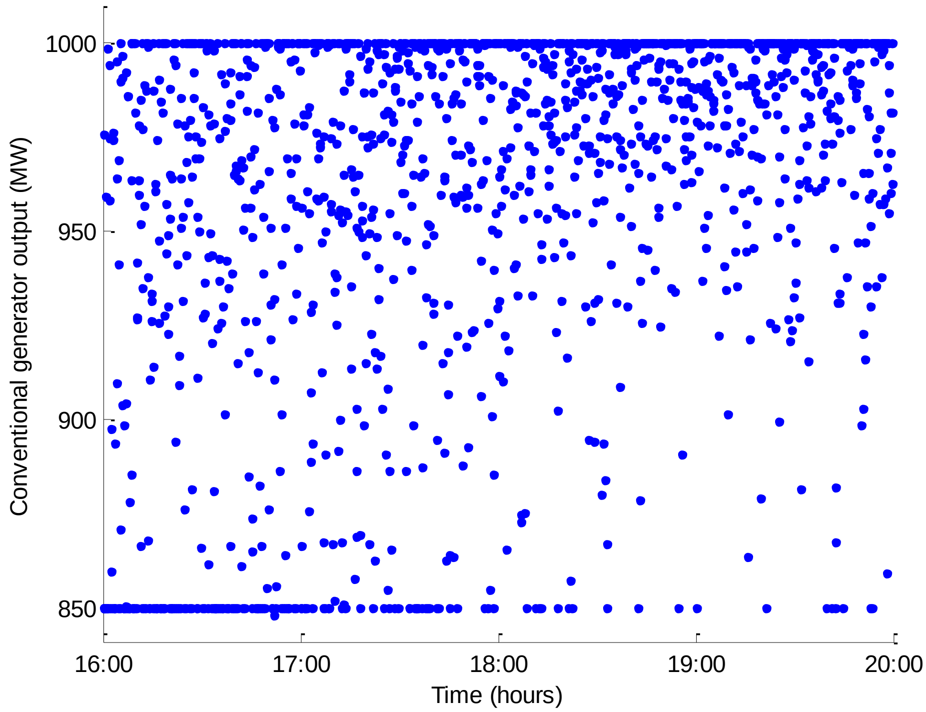

Fig. 3.5 (e) Conventional generator output in four hours for every 10 seconds from 16:00-20:00.

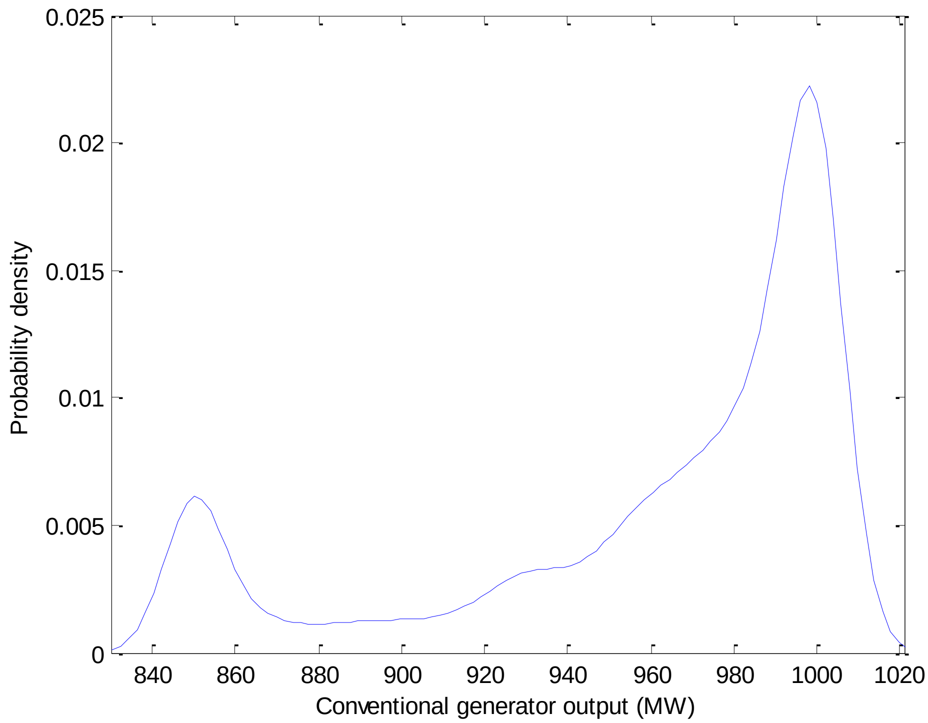

Fig. 3.6 (e) Probability distribution of conventional generator output at 16:00-20:00.

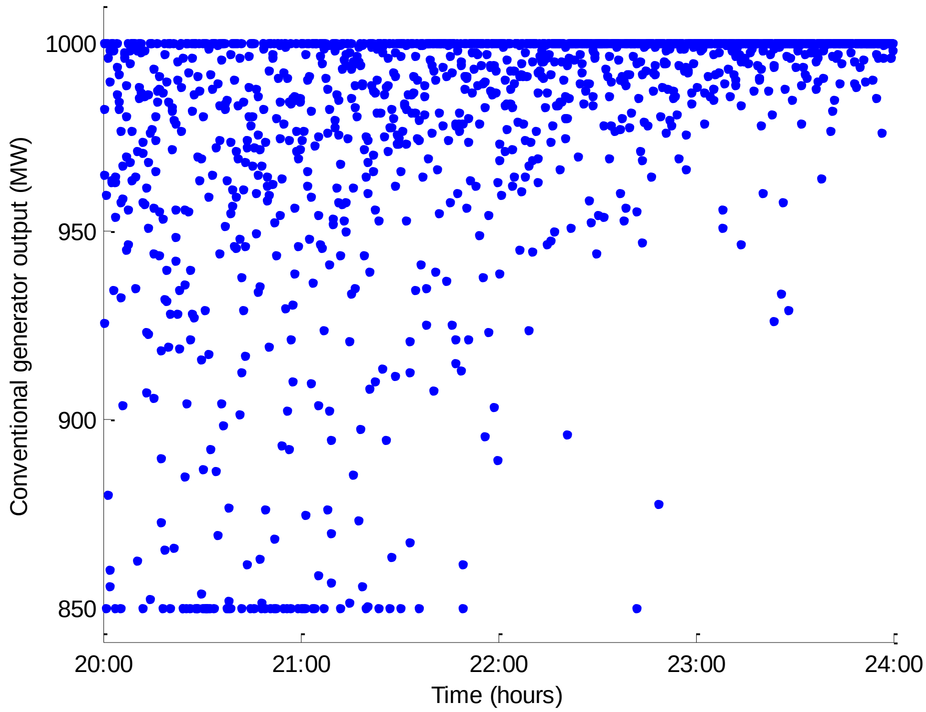

Fig. 3.5 (f) Conventional generator output in four hours for every 10 seconds from 20:00-24:00.

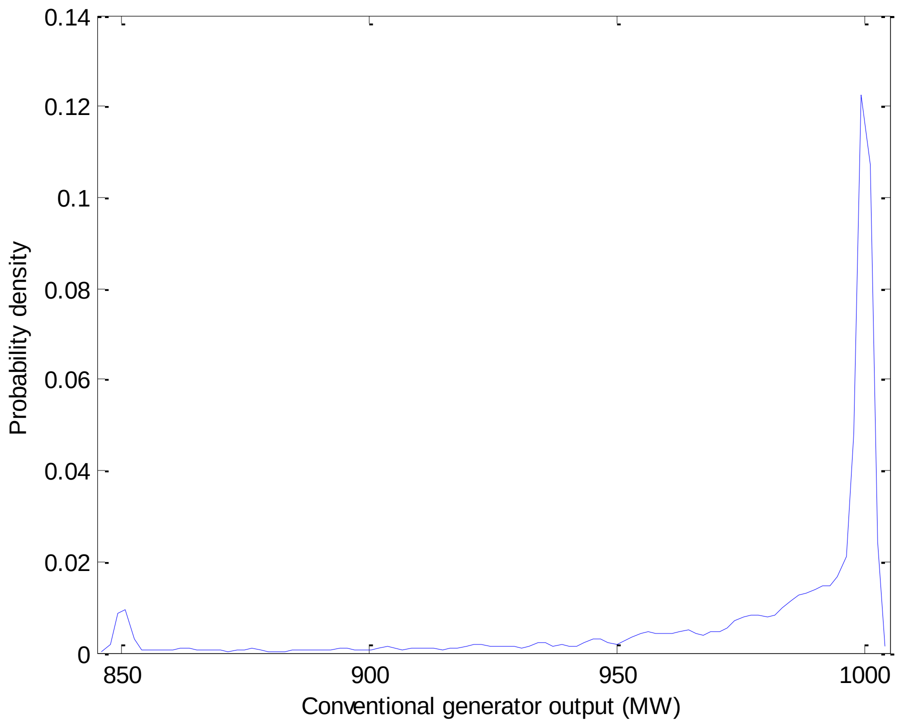

Fig. 3.6 (f) Probability distribution of conventional generator output at 20:00-24:00.

3.5 Simulation of Transient Stability of Power System with a Wind Farm

In order to analyse the transient stability issue in a power system which includes wind power generation, the simulation should contain the processes of a fault in the system and also need to focus on the system behaviour after the fault such as oscillations of the system voltage and rotor angle.

Based on two examples in Matlab Simulink SimPowerSystems™ which are Single-line Diagram of the Wind Farm Connected to a Distribution System and Description of the Transmission System, a system of a wind farm connected to a transmission system can be developed to simulate the impact of wind power generation on transient stability.

3.5.1 Case Study

In this case, the aim is to simulate the transient stability issue of a power system which is connected a wind farm after a fault. Because the research mainly focuses on transient operational behaviour, the time period of this simulation is 10 seconds.

Based on the two examples in Matlab mentioned above, the model system of this case study is shown on Fig. 3.7. In this system, a single 1000MW conventional power plant provides energy to a load centre through a 700km long distance backbone 500kV high-voltage transmission line. The nominal voltage of the generator is 13.8kV and is connected to a 700km long single-line 500kV transmission system with a 13.8kV/500kV transformer. And the load centre contains a 1000MW resistive load in a 35kV distribution system. The wind farm consists of 60 wind turbines whose total capacity is 90MW and it is connected to the load area in the 35kV distribution system through a 0.69kV/35kV transformer.

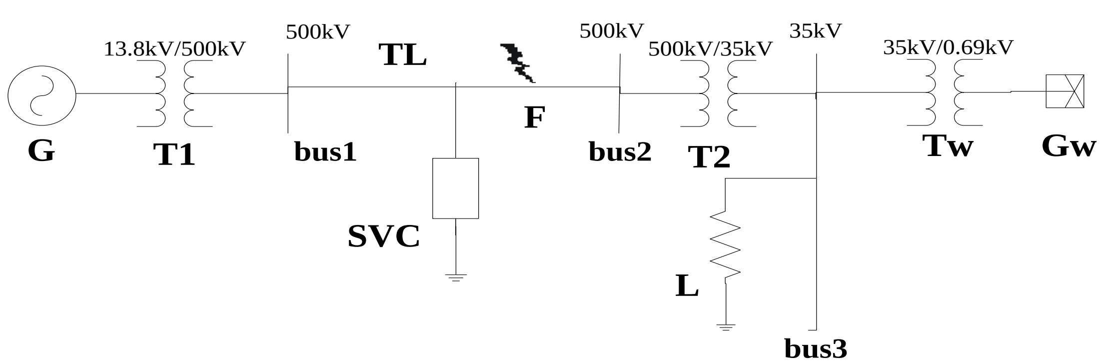

Fig. 3.7 The model system of the 3.5.1 case study.

In this system, the wind turbines use doubly-fed induction generator (DFIG) and include protection systems to monitoring voltage, current and machine speed. Because the time period of simulation is really short, the wind speed is considered to be constant and wind turbine generators are at maximum output during the simulation. To maintain system stability after faults, the transmission line is shunt compensated at its centre by a 200MVAr static var compensator (SVC). And there is a single phase ground fault happens at the transmission line and it is cleared within two second. Then the information and data of this model power system is listed in the Table 3.3.

Table 3.3 The information and data of model power system in Case study 3.5.1

Symbol	Information	Data (System frequency is 50Hz)
G	A conventional generator connected to transmission system	**Capacity:** 1000MVA; **Voltage level:** 13.8kV; **Reactances Xd:** 1.305 p.u. **Xd':** 0.296p.u. **Xq:** 0.474p.u. **Xq'':** 0.18p.u.; **Stator resistance Rs:** 2.544×10^{-3}p.u.
Gw	A large wind farm contains 60 wind turbines integrated connected to distribution system	**Capacity:** 60*1.5MW; **Voltage level:** 0.69kV; **Stator reactances Rs:** 7.06×10^{-3}p.u.; **Rotor reactances Rr:** 5.0×10^{-3}p.u.
TL	A single-line long distance backbone 500kV high-voltage transmission system	**Length:** 700km; **Voltage level:** 500kV; **Resistance R:** 1.755×10^{-2} Ω/km; **Inductance L:** 8.737×10^{-2} H/km; **Capacitance C:** 1.339×10^{-8} F/km
L	A load centre with a stable constant load	**Total demand:** 1000MW; **Voltage level:** 35kV
T1	Transformer connects conventional generator and transmission system	**Ratio:** 13.8kV/500kV; **Capacity:** 1000MVA
T2	Transformer connects transmission system and load in distribution system	**Ratio:** 500kV/35kV; **Capacity:** 1000MVA
Tw	Transformer connects wind farm and distribution system	**Ratio:** 0.69kV/35kV; **Capacity:** 200MVA
SVC	A Mvar static var compensator (SVC) shunt compensate the transmission line to maintain system stability after faults	**Reactive power limits:** 200Mvar to -200Mvar; **Voltage level:** 500kV
F	A single-phase ground fault occurs on transmission line	**Fault resistance Ron:** 1.0×10^{-3}Ω; **Ground resistence Rg:** 1.0×10^{-3}Ω; **Fault applied** at t=2.0s and **cleared** at t=2.1s

The simulation can obtain the transient effects from wind power generation on the power system such as the oscillation of rotor angle, variation of field current of the conventional generator and variation of system voltage. In order to investigate the transient responses of this sample system, it is necessary to compare the transient behaviors between a power system with wind turbine generators and one without them. As a result, this case study also needs to involve a simulation of the transient stability issue of a power system without wind farms after a fault. The model system without wind farms is shown on Fig. 3.8 and the information and data of this system is the same with which are listed in Table 3.3.

After the simulation, the comparison of the transient behaviors of these two model systems can be present and the effects from wind power generation on power systems are explained.

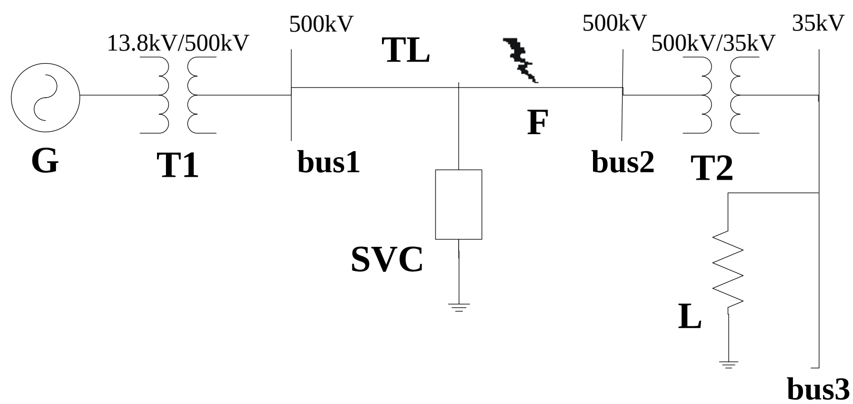

Fig. 3.8 The model system without wind farms of the 3.5.1 case study.

3.5.2 Simulation Results

After the simulation, the transient system responses of both model power systems which include the oscillation of rotor angle, variation of field current of the conventional generator and variation of system voltage after a single phase ground fault are obtained and are shown from Fig. 3.9 to Fig. 3.11.

The Fig. 3.9 (a) and Fig. 3.9 (b) represent swings and oscillations of the rotor angle in the model systems with and without a wind farm respectively. From these two figures, they show that the rotor angle variation of the model power system without wind farms has larger amplitude value of rotor angle variations and lower oscillation frequency than in the power system with a wind farm. It means that the wind power generation improves the damping effect on the rotor angle variation and increases the frequency of oscillation of the conventional generators in the power system which has been discussed in Section 3.3.1.2. The wind turbine generators make some contribution to rotor angle stability in the power system.

In the same way, Fig. 3.10 (a) to Fig. 3.10 (b) display field current variations of the two model systems in this case study respectively. These two figures prove that the wind farm also provides a good damping effect on reducing the amplitude value and increase the frequency of oscillation of field current variation in the conventional generator when compared with the field current variation in the system without wind farms.

For Fig. 3.11 (a) to Fig. 3.11 (b) express the voltage variation of the transmission system at bus 3 which is nearest to the wind power generation. The amplitude value of the voltage variations are nearly the same in these two model systems, however, the power system without wind farms has a better restoring ability. After the fault, the voltage of the transmission system in the system with a wind farm doesn't return to the original voltage value. Although the voltage decreases at the new stable point the voltage at bus3 is near its lower limit in this simulation, the decrease may be more serious when the larger capacity of wind power generation is connected to the power system. And it shows that the wind power generation usually reduces the voltage recover ability of the system which has been discussed in Section 3.3.2.

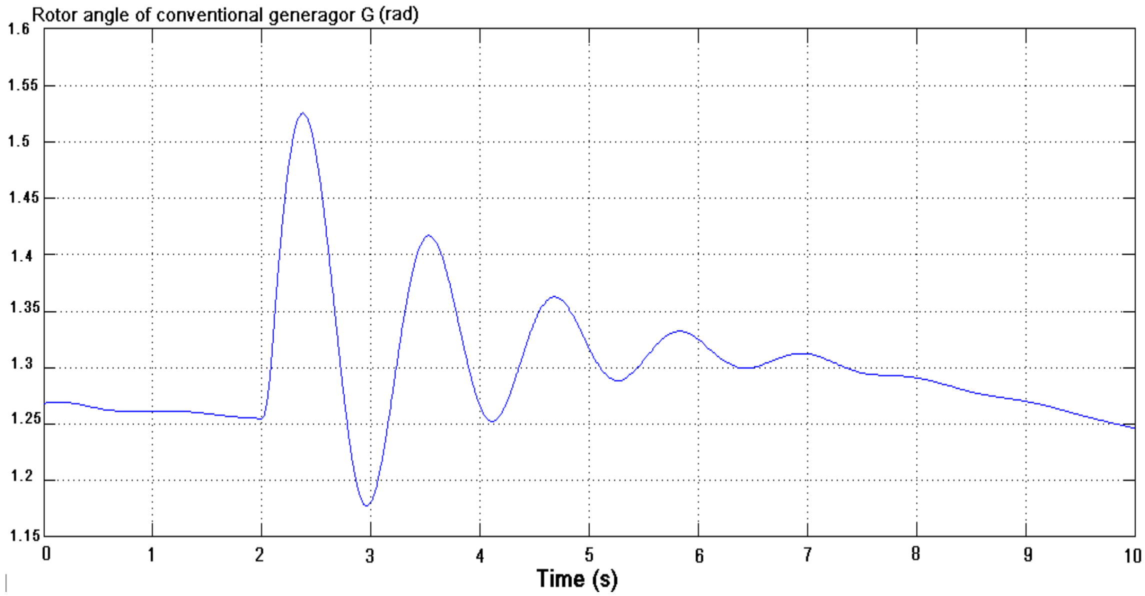

Fig. 3.9 (a) Rotor angle variation of the model power system with a wind farm after the fault.

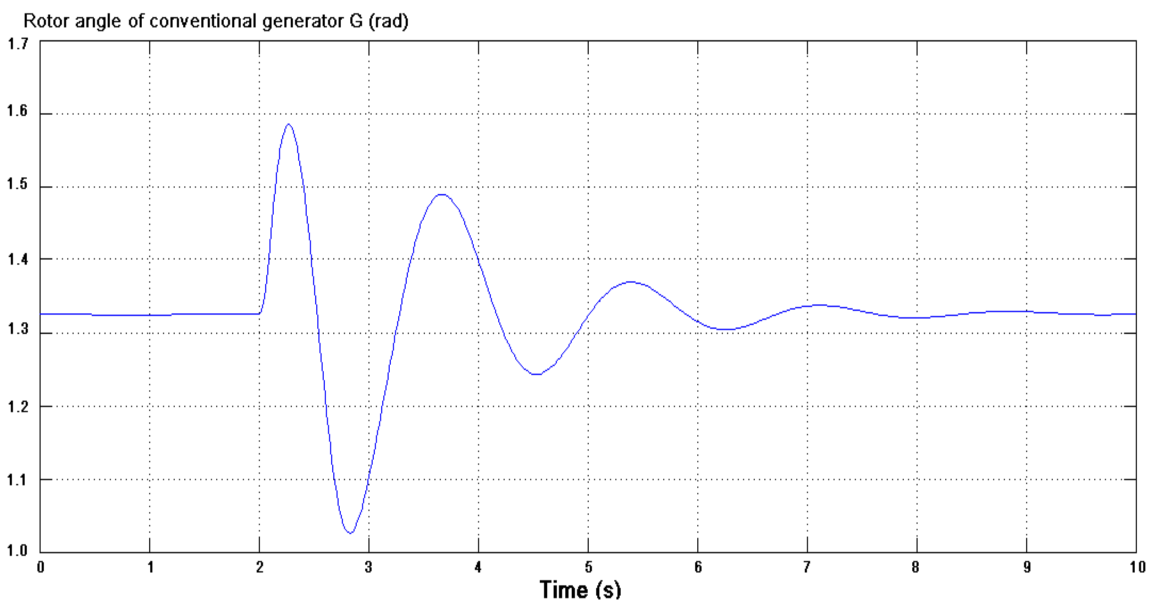

Fig. 3.9 (b) Rotor angle variation of the model power system without wind farms after the fault.

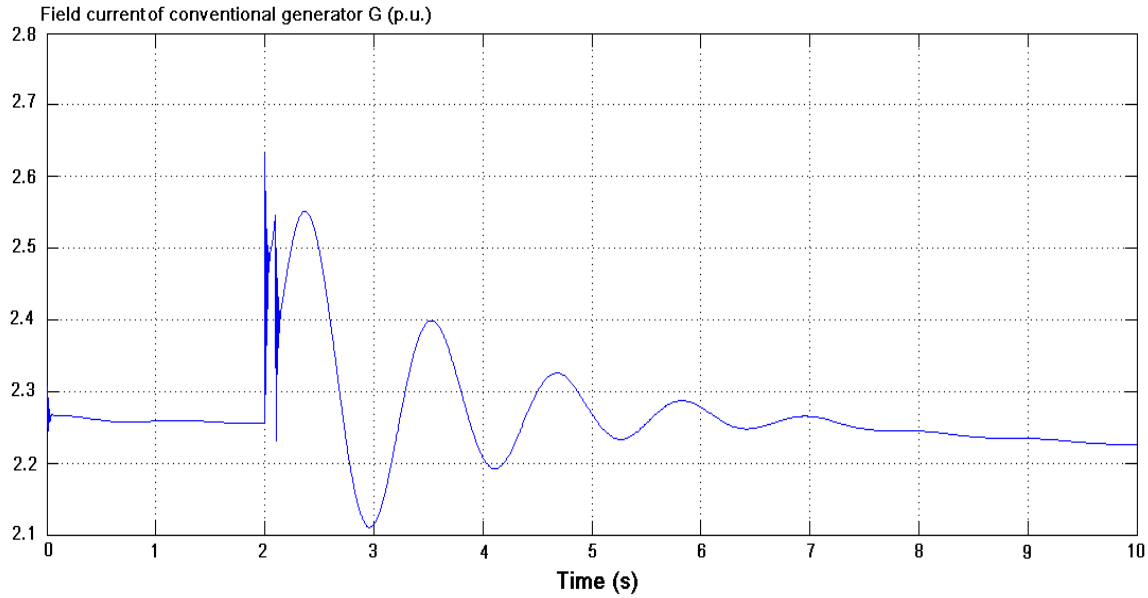

Fig. 3.10 (a) The conventional generator field current variation of the model system with a wind farm after the fault.

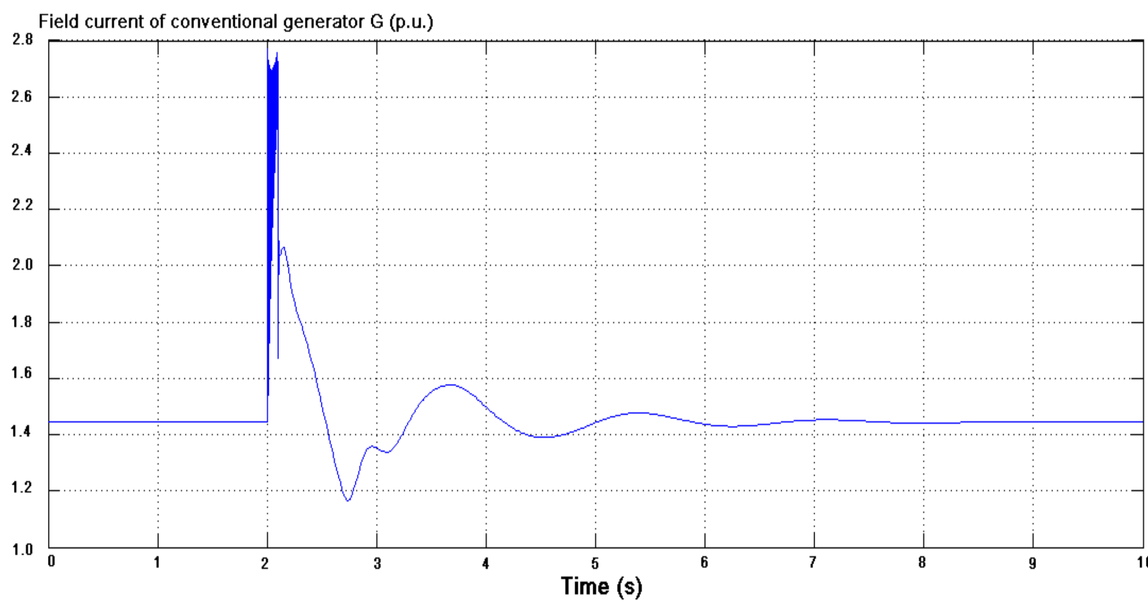

Fig. 3.10 (b) The conventional generator field current variation of the model system without wind farms after the fault.

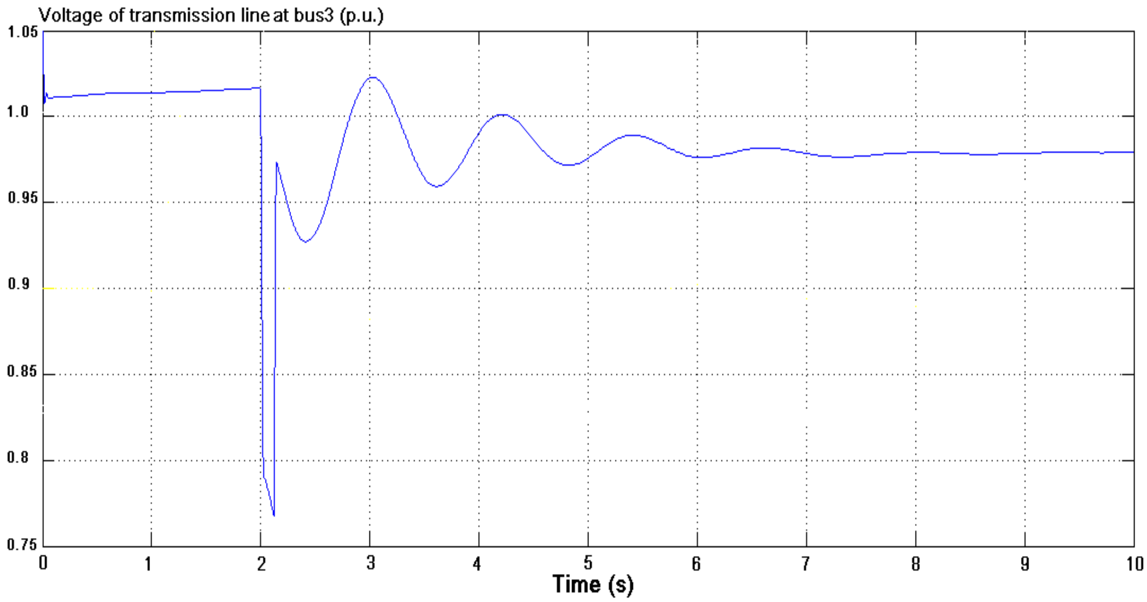

Fig. 3.11 (a) Voltage variation of the transmission system at bus 3 in the model system with a wind farm after the fault.

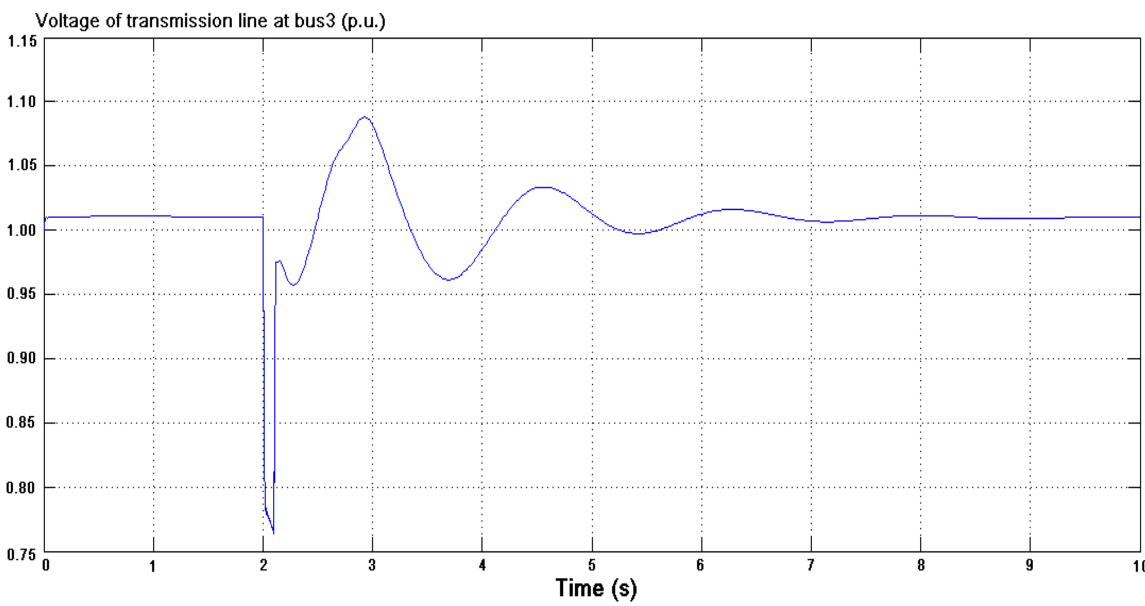

Fig. 3.11 (b) Voltage variation of the transmission system at bus 3 in the model system without wind farms after the fault.

3.6 Summary

This chapter overviewed the power system security issue which is considered as the boundaries of power system operation, introduced the effects of wind power system on power system security and also analysed the reaction of the system with wind farms through simulations.

The first part of this chapter explained the definition and concept of power system security and the states of system operating condition. Next, the discussion continued with the power system planning problem divided into generation planning, transmission planning and demand management which confirmed that the power system would be designed to have enough security margins. Then, it introduced the basic concepts and categories of power system stability which mainly relied on dynamic performances of the power system and described and compared the different categories of stability: rotor angle stability, voltage stability and frequency stability in details separately.

The second part of this chapter explained and analysed the impact of wind turbine generation on operation of other conventional generators and the different types of system stability: rotor angle stability, voltage stability and frequency stability. It shows that the wind turbine generators may contribute to rotor angle stability or reduce the stability margin of voltage and frequency stability which depends on the types and the connect location of wind turbine generators, the system ancillary services and the reactive power support. The widely-used variable speed wind turbine with DFIG has several disadvantages on power system stability, so the system supports are required in the power system with this type of wind farms to maintain the stability level. Lastly, the two study cases represent that how the wind power generation affects on the output of conventional generators and the transient characteristics of the power system.

In conclusion, this chapter provides a clear understanding of definition and classification of power system security as a foundation for further researches. And it also summaries and sorts out the influences on system stability from wind power generation. The simulation results data of conventional generators output can be used on conventional generation stability research in chapters that are followed.

3.7 References

[1] P. Kundur, J. Paserba, V. Aijarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. V. Cutsem, V. Vittal, "Definition and Classification of Power System Stability," *IEEE Transactions On Power Systems*, Vol.19, No.2, pp.1387-1401, May 2004.

[2] M. D. Santo, A. Vaccaro, D. Villacci, E. Zimeo, "A Distributed Architecture for Online Power System Security Analysis," *IEEE Transactions On Industrial Electronics*, Vol.51, No.6, pp.1238-1248, December 2004.

[3] K. Bell, G. Ault and J. McDonald, "All Eyes on Wind," *IET Power Engineer*, pp. 30-33, June/July 2006.

[4] Z. Chen, Y. Hu and F. Blaabjerg, "Stability Improvement of Induction Generator-Based Wind Turbine Systems," *IET Renewable Power Generation*, Vol. 1, No. 1, pp. 81-93, March 2007.

[5] B. M. Weedy, B. J. Cory, *Electric Power Systems*, Forth Edition, UK: John Wiley & Sons, Ltd, 1998.

[6] P. Kundur, *Power System Stability and Control*, New York: McGraw-Hill, 1994.

[7] J. D. Glover, M. S. Sarma, *Power System analysis and design*, Forth Edition, Toronto, Oratorio: Thomson Learning, 2007.

[8] A. J. Wood, B. F. Wollenberg, *Power Generation, Operation and Control*, Second Edition, New York: John Wiley & Sons, Ltd, 1996.

[9] R.Wang, R.H.Lasseter, "Re-Dispatching Generation to Increase Power System Security Margin and Support Low Voltage Bus," *IEEE Transactions on Power Systems*, Vol. 15, No. 2, pp. 496-501, May 2000.

[10] T. D. Torre, J. W. Feltes, T. G. S. Roman and H. M. Merrill, "Deregulation, Privatization and Competition: Transmission Planning under Uncertainty," *IEEE Transactions on Power Systems*, Vol. 14, No. 2, pp. 460-465, May 1999.

[11] Q. Zhou, J. W. Bialek, "Approximate Model of European Interconnected System as a Benchmark System to Study Effects of Cross-Border Trades," *IEEE Transactions on Power Systems*, Vol. 20, No. 2, pp. 782-788, May 2005.

[12] G. McPherson and R. D. Laramore, *An Introduction to Electrical Machines and Transformers*, 2nd Edition, New York: John Wiley & Sons, 1990.

[13] C. W. Taylor, *Power system Voltage Stability*, New York: McGraw-Hill, 1994.

[14] E. Muljadi, C. P. Butterfield, B. Parsons and A. Ellis, "Effect of Variable Speed Wind Turbine Generator on Stability of a Weak Grid," *IEEE Transactions on Energy Conversion*, Vol. 22, No.1 March 2007.

[15] E. N. Hinrichsen and P. J. Nolan, "Dynamics and Stability of Wind Turbine Generators," *IEEE Transactions on Power Apparatus and System*, Vol. PAS-101, No. 8, pp. 2640-2648, August 1982.

[16] D. J. Trudnowski, A. Gentile, J. M. Khan and E. M. Petritz, "Fixed-Speed Wind-Generator and Wind-Park Modeling for Transient Stability Studies," *IEEE Transactions on Power Systems*, Vol. 19, No.4, November 2004.

[17] M. V. A. Nunes, J. A. P. Lopes, H. H. Zurn, U. H. Bezerra and R. G. Almeida, "Influence of the Variable-Speed Wind Generators in Transient Stability Margin of the Conventional Generators Integrated in Electrical Grids," *IEEE Transactions on Energy Conversion*, Vol. 19, No. 4, pp. 692-701, December 2004.

[18] C. B. Gray, *Electrical Machines and Drive Systems*, London: Longman Scientific & Technical and New York: John Wiley & Sons, 1989.

[19] J. Morren, J. Pierik and S. W.H. de Haan, "Inertial Response of Variable Speed Wind Turbines," *Electric Power Systems Research*, Vol. 76, pp. 980-987, 2006.

[20] J. G. Slootweg and W. L. Kling, "The Impact of Large Scale Wind Power Generation on Power System Oscillations," *Electric Power System Research*, Vol. 67, pp. 9-20, 2003.

[21] A. Tabesh and R. Iravani, "Small-Signal Model and Dynamic Analysis of Variable Speed Induction Machine Wind Farms," *IET Renewable Power Generation*, Vol. 2, No. 4, pp. 215-227, February 2008.

[22] C. D. Vournas, E. G. Potamianakis, C. Moors and T. V. Cutsem, "An Educational Simulation Tool for Power System Control and Stability," *IEEE Transactions on Power Systems*, Vol. 19, No.1, pp. 48-55, February 2004.

[23] M. V. A. Nunes, J. A. P. Lopes, H. H. Zurn, U. H. Bezerra and R. G. Almeida, "Influence of the Variable-Speed Wind Generators in Transient Stability Margin of the Conventional Generators Integrated in Electrical Grids," *IEEE Transactions on Energy Conversion*, Vol. 19, No. 4, pp. 692-701, December 2004.

[24] D. J. Trudnowski, A. Gentile, J. M. Khan and E. M. Petritz, "Fixed-Speed Wind-Generator and Wind-Park Modeling for Transient Stability Studies," *IEEE Transactions on Power Systems*, Vol. 19, No.4, November 2004.

[25] Y. Chi, Y. Liu, W. Wang and H. Dai, "Voltage Stability Analysis of Wind Farm Integration into Transmission Network," *International Conference on Power System Technology, PowerCon 2006*, pp. 1-7, 22-26 October 2006.

[26] N. R. Ullah and T. Thiringer, "Variable Speed Wind Turbines for Power System Stability Enhancement," *IEEE Transactions on Energy Conversion*, Vol.22, No.1, pp. 52-60, March 2007.

[27] E. Camm and C. Edwards, "Reactive Compensation Systems for Large Wind Farms," *IEEE/PES Transmission and Distribution Conference and Exposition*, pp. 1-5, 21-24 April 2008.

[28] J. Ekanayake and N. Jenkins, "Comparison of the Response of Doubly Fed and Fixed-Speed Induction Generator Wind Turbines to Changes in Network Frequency," *IEEE Transactions on Energy Conversion*, Vol. 19, No. 4, pp. 800-802, December 2004.

[29] G. Lalor, A. Mullane and M. O'Malley, "Frequency Control and Wind Turbine Technologies," *IEEE Transactions on Power Systems*, Vol.20, No.4, pp. 1905-1913, November 2005.

[30] G. Ramtharan and J.B. Ekanayake and N. Jenkins, "Frequency Support from Doubly Fed Induction Generator Wind Turbines," *IET Renewable Power Generation*, Vol. 1, No. 2, pp.3-9, June 2007.

CHAPTER 4

A METHOD TO CALCULATE HEATING PROBLEM OF CONVENTIONAL GENERATOR CAUSED BY WIND POWER GENERATION (I): A THERMAL MODEL FOR GENERATOR

4.1 Introduction

In a power system, synchronous generators, which are used to convert mechanical energy into electric power, are very important elements and are the primary sources. The basic features of power systems are mainly relied on the characteristics of synchronous generators and keeping them stable is the foundation of power system stability. After the research of influence on power systems operation from wind power generation in the last chapter, it shows that the working performances of conventional synchronous generator could be impacted by the wind farms. It is necessary to explore the inside responses of synchronous generators which are against wind power generation effects in detail. In a synchronous generator, a dc current is applied to the rotor winding which produces a rotor magnetic field. And the rotor of the generator is then turned by a prime mover which produces a rotating magnetic field within the machine. This rotating magnetic field induces a three-phase voltage within the stator windings of the generator. As a result, the responses of currents and magnetic field in the machine are the index of operation condition.

When a machine is in an unstable operation condition, the generator machine is easily under thermal pressure and causes temperature rise. The temperature rise of a machine or device has a direct bearing on the power rating. For heating problem, the insulation system is the weakest element in the machine and if it is damaged that the machine or device can not run regularly. As a result, the temperature rise also impacts its useful service life through the insulation system directly. For all the reasons above, it requires a method to calculate temperature rise inside the machine which is caused by fluctuation of the wind turbine generators. Furthermore, the synchronous generator always installed cooling system inside the machine. This chapter and the next chapter will solve the generator machine heating problem by two steps which are thermal calculation model and cooling system model.

This chapter aims to introduce a thermal and heating effect calculation model, which bases on currents and magnetic fields of the rotor and stator inside the machine, to calculate the heating effect of the conventional synchronous generator machine and also improve this model into a more effective one for a power system with wind power generation under output fluctuation condition. It will also introduce the heat transfer theories, the insulation system installed in the machine and discuss the characteristics of the currents and magnetic fields. And there is also a simulation example of currents operation performance inside the machine in a power system with a wind farm.

4.2 Heating Problem

Heat is a form of energy and when heat is applied to a body of an object, it receives thermal energy. For a given amount of heat, the temperature rise, which is the difference between the temperature of its warmest accessible part and the ambient temperature, depends upon the mass of the body and the material of the body. The relationship between these quantities is given by the equation: [1]

$$Q_a = m_b c_m T_{rise} \qquad \text{Equation 4.1}$$

where Q_a is the quantity of heat added to (or removed from) a body, in [J]; m_b is the mass of the body, in [kg]; c_m is the specific heat capacity of the material making up the body, in [J/(kg ·℃)]; T_{rise} is the temperature rise, in [℃]. The temperature rise has a direct bearing on the power rating of a machine or device and it also has a direct bearing on its useful service life. Consequently, temperature rise is a very important quantity.

For the heat transfer, there are three methods to transfer heat and energy which are conduction, radiation and convention. [1] The first method is the heat transfer through the thermal conductor and the rate of transfer depends upon the thermal conductivity of the material. The calculation of the thermal power transmitted through a body is by the equation:

$$P_{heat} = \frac{k_m A_S (t_1 - t_2)}{d_t} \qquad \text{Equation 4.2}$$

where P_{heat} is heat energy transmitted, in [W]; k_m is the thermal conductivity of the body, in [W/(m ·℃)]; A_S is the surface area of the body, in [m^2]; (t_1-t_2) is the difference of temperature between opposite faces of the body, in [℃]; d_t is the thickness of the body, in [m]. The second method is radiation of heat energy to surroundings. In fact, all bodies radiate heat to surrounding area and also absorb radiant energy from surrounding and the amount of energy which is given off or absorbed depends on the temperature of the body and the environment. When the temperature of the body is the same as that of its environment, the body radiates as much energy as it receives. On the other hand, if a body is hotter than its environment, the heat that a body loses by radiation is given by the equation:

$$P_{rad} = k_r A_S \left((T_b + 273)^4 - (T_{akb} + 273)^4 \right) \qquad \text{Equation 4.3}$$

where P_{rad} is the heat energy radiated, in [W]; T_b is the temperature of the body, in [℃]; T_{akb} is the temperature of the surrounding object, in [℃]; k_r is a constant which depends on the nature of the body surface, in [W/(m^2 ·K^4)]. The third method is the heat transfer through the convection of different materials such as solid surface and the fluid. And this method will be explained in the next chapter through the operating principle of cooling system.

4.3 Insulation System in Generator Machines

For synchronous generator machine, there are insulation systems in both rotor and stator windings. The insulation system consists of the conductor or wire insulation which usually is natural or synthetic varnish, the coil insulation often is some kind of tape or several layers of tape and the slot liner. The function of insulation system is to prevent short circuits between turns of winding coil and insulating the windings from the core iron and it must protect the machine against every kind of damages likely to be encountered under all circumstances. [2]

The design of the insulation system in windings is one of the most critical parts of a generator machine design because the machine shorts out if the insulation of a generator breaks down. Moreover, from a thermal point of view, the insulation is the weakest part of the machine. The life expectancy of electrical apparatus is limited by the temperature of its insulation and the higher the temperature, the more effects on deterioration of insulation system. There are tests made on many insulating materials which have shown that the service life of insulation system diminishes by half every time the temperature increases by 10 ℃. [1, 3] As a result, it is necessary to limit the temperature of the windings insulation to prevent the insulation system from overheating which may lead to break down of the machine.

According several committees and organizations, IEEE sets some standards, which have grouped insulators into five classes, depending upon their ability to withstand heat and these standards are shown on Table 4.1:

Table 4.1 Classes of insulation system in IEEE standards [1]

Classes of insulation systems	Maximum temperature	Maximum permissible hot-spot temperature rise	Ambient temperature T_{akb}
Class A	105 ℃	65 ℃	40 ℃
Class B	130 ℃	90 ℃	
Class F	155 ℃	115 ℃	
Class H	180 ℃	140 ℃	

Class R	220 ℃	180 ℃	

From the Table 4.1, it is shown that each insulation system class specifies the maximum temperature permissible for that class of insulation and from class A to class R, each class represents a higher permissible temperature than the one before. The IEEE standards have also established a maximum ambient temperature T_{akb}, which is usually 40 ℃, in order to enable electrical manufactures to foresee the worst ambient temperature conditions that their machines are likely to encounter and also standardize the size of machines. The temperature of a machine varies from point to point and there are places where the temperature is hotter than other parts, so they are called the hot-spot temperature which also must not exceed the maximum allowable temperature of the particular class of insulation used. The maximum permissible temperature rise for each insulation class is the temperature difference between maximum ambient temperature and temperature limit for each class which are also listed on the Table 4.1. [1, 3]

The ability of the insulation to withstand high temperatures sets the currents limit for windings of rotor and stator sections. Furthermore, the maximum currents in rotor and stator limit the maximum power that can be supplied continuously by the generator machine which will be discussed in the next section.

4.4 Excitation Current I_f and Stator Current I_S of the Generator

In a synchronous generator, windings on the rotor of a machine are field windings and the windings on stator are armature windings. A dc current which is from a dc generator is applied to the rotor winding and this current is called exciting current or field current I_f and rotor current. And the exciting current is the source of the magnetic field of a rotor which is called rotor magnetic field B_R. This magnetic field in a machine forms the energy link between the electrical and mechanical systems. The rotor of the generator is then turned by a prime mover, producing a rotating magnetic field within the machine. This rotating rotor magnetic field B_R produces an induced three-phase set of voltages within the stator windings of the generator. The stator winding is the source of voltage and electrical power when the machine is operating as a generator. Moreover, the induced voltage produces stator current when there are load connected to machine. The current flowing in the stator windings also produces a magnetic field of its own which is called stator magnetic field B_S. In this condition, the total magnetic field B_{net} from all windings is the sum of the rotor and stator magnetic field: [1, 2]

$$\dot{B}_{net} = \dot{B}_R + \dot{B}_S \qquad \text{Equation 4.4}$$

4.4.1 Circuit Model and the Capability Curve of a Synchronous Machine

In stator, stator magnetic field B_S is divided into three-phase magnetic fields B_a, B_b and B_c which has the relationship of:

$$\dot{B}_S = \dot{B}_a + \dot{B}_b + \dot{B}_c \qquad \text{Equation 4.5}$$

As a result, a balanced set of three-phase voltages consists of three equal voltages of the same frequency that are mutually 120° out of phase. To generate balanced three-phase, the stator winding of a three-phase machine must have three sets of coils and each set having the same number of turns of windings N_s. The voltages induced in the three phase windings, E_a, E_b and E_c must be 120° apart in time. X_{ad} is the armature reactance which related to the armature flux, X_L is leakage reactance which represents armature leakage flux effects, R_s is the armature resistance and $X_d = X_{ad} + X_L$ is defined as the synchronous reactance. The one phase equivalent circuit of a three-phase synchronous generator is shown on Fig. 4.1:

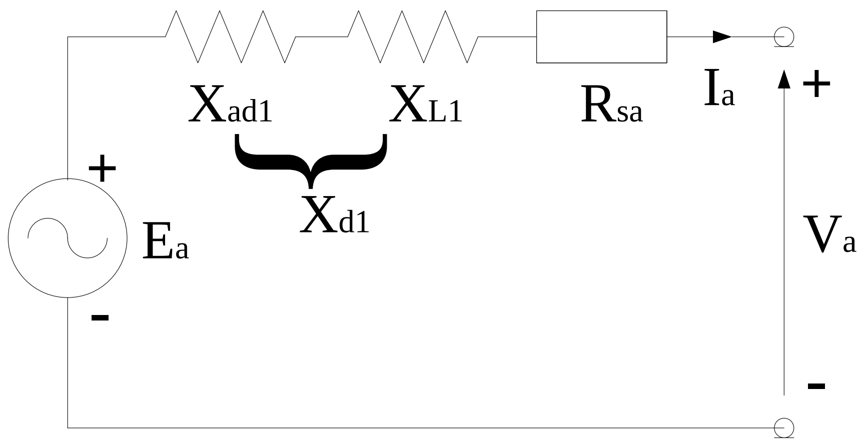

Fig. 4.1 equivalent circuit of one phase in a three-phase synchronous generator.

The same stator winding design of other two phases produces the same one-phase equivalent circuit of E_b and E_c. In the equivalent circuit, X_{ad1}, X_{L1} and X_{d1} are reactance per phase X_{d1}, R_{sa} is the armature resistance per phase, V_a is terminal voltage and I_a is armature current in one phase. [4] According to this equivalent circuit, the Kirchhoff's voltage law equation used to describe the voltage is:

$$E_a = V_a + \dot{I}_a R_{sa} + j\dot{I}_a X_{d1} \qquad \text{Equation 4.6}$$

The phasor vector relationship of voltage and current is also shown on Fig. 4.2 and θ_f is the power factor of the synchronous generator. [3]

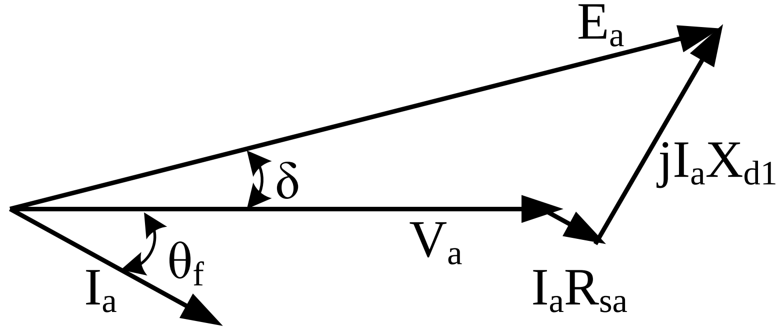

Fig. 4.2 Phasor vector diagram for one phase of a synchronous machine.

In order to maintain the windings within the permissible temperature rise of the windings and the stability of the machine, there are limits placed on the electrical active and reactive power. The stator and rotor heat limits, together with any external limits on a synchronous generator, can be expressed in graphical form by a generator capability diagram in Fig. 4.3.

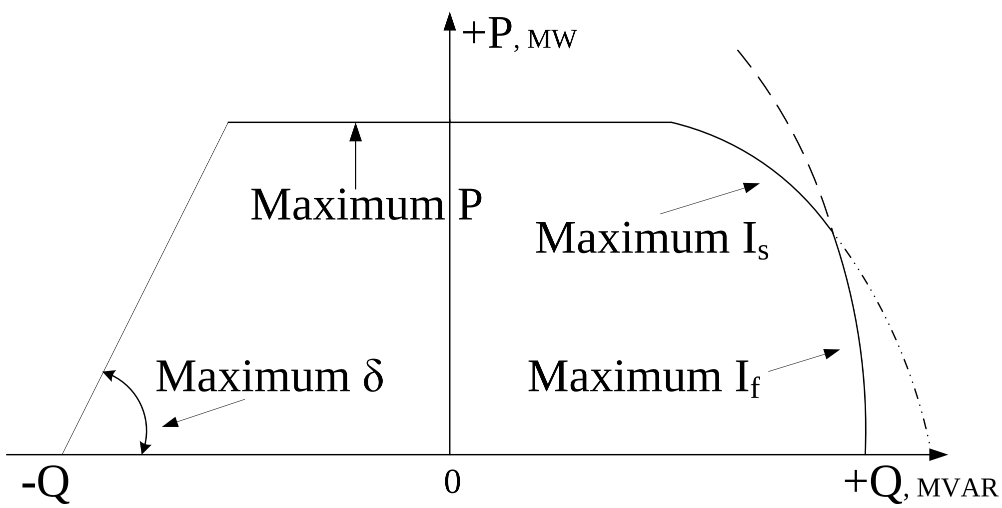

Fig. 4.3 Synchronous generator capability curve.

The capability curve of a synchronous machine shows the power limit is determined by the prime mover rating which is fairly definite, rotor heating which means maximum permissible I_f and stator heating which means maximum permissible I_s. In this typical capability curve for a generator, it means that operation within the boundaries of the curve is safe from the standpoints of heating and stability. [2, 5, 6]

4.4.2 Control of I_f and Dynamic Response of I_f and I_s in a Synchronous Generator

In synchronous generator, the speed of rotor is controlled by the governor. However, there is no control over the armature current and power factor. As a result, the only method to influence them is that the control of field current.

When load changes the voltage will swing wildly because the synchronous reactance X_d of the generator is quite large, so it is necessary to use an automatic voltage regulator to control the I_f. And the field current is also adjusted to maintain the terminal voltage of the machine matched the system bus voltage. Moreover, the generator needs to change the power factor which is determined by the field current in order to adjust the machine to over-excitation or under-excitation which is required to supply or consume reactive VARs in the system. Therefore, it is often important to know how much field current I_f must be supplied to the rotor winding in order to obtain the above requirements. The range of field currents required by a given machine is required to determine the rating of the exciter generator. The excitation current is limited by the winding resistance R_f because the electrical power $I_f^2R_f$, which is supplied by field current, to the rotor is all converted to heat. The excitation heating power $I_f^2R_f$ is a major heating source in a synchronous machine, I_f must be known to calculate the efficiency under given load conditions. [2, 7, 8]

Another issue for the field current of a generator is that calculating the field current to determine how much increase in terminal voltage would occur if the machine were suffered to a disturbance. A serious disturbance on the system may produce a sudden voltage drop across the terminals of the alternator. The exciter must then react very quickly to keep the ac voltage from falling. The field current must ensure not only a stable ac terminal voltage, but must also respond to sudden load changes in order to maintain system stability.

Under normal conditions, the rotor speed turns at synchronous speed so the current through the windings maintain in stable situation. However, when the load or the output of wind turbine generators change suddenly which has been discussed on Section 3.3.1.1, the rotor speed begins to fluctuate which produce momentary speed variations above and below synchronous speed, the balance between mechanical and electromagnetic torques is broken and the rotor angle also begins to fluctuate. Moreover, the changing condition would lead the changing of stator current I_s and voltage induced in one phase windings E_a can not change immediately. According the Equation 4.4, terminal voltage V_a will follow the stator current changes and it will influence the connection of synchronous generator to power system. As a result, the excitation current must adjust to maintain the connection of synchronous generator and the currents in windings will fluctuate following the changing condition. [3]

4.5 Simulation of Fluctuation of I_f, I_s and δ in a Conventional Generator

With the aim to analyse the responses of currents on power system operation changes, this simulation simulates and collects the rotor current, stator current and power angle data of the conventional synchronous generator in a power system with wind power generation under wind turbine output fluctuating condition. And the simulation system should also contain a highly detailed synchronous generator machine model to record the currents data of the machine.

In this simulation, the simulation power system and data collection tools are the models in Matlab Simulink SimPowerSystems™. Moreover, in order to represent the output fluctuation of conventional generation, the simulated synchronous generator power flow data which is calculated in Section 3.4 simulation are used as generation input data.

4.5.1 Case Study

In this case study, the simulation uses the 24 hours conventional generators output data which is obtained from Section 3.4.1 case study as the input data. So, the simulated results data of rotor current, stator current and power angle results data have the same form with the input data which contains 24 hours data for every 10 seconds. In this case, the model power system is the same with the one the Section 3.4.1 case study in last chapter which includes single synchronous generator supplies energy to a load centre through a pair of long distance backbone high-voltage transmission lines and wind turbine generator connects to the load area in distribution system and this model is shown on Fig. 4.4.

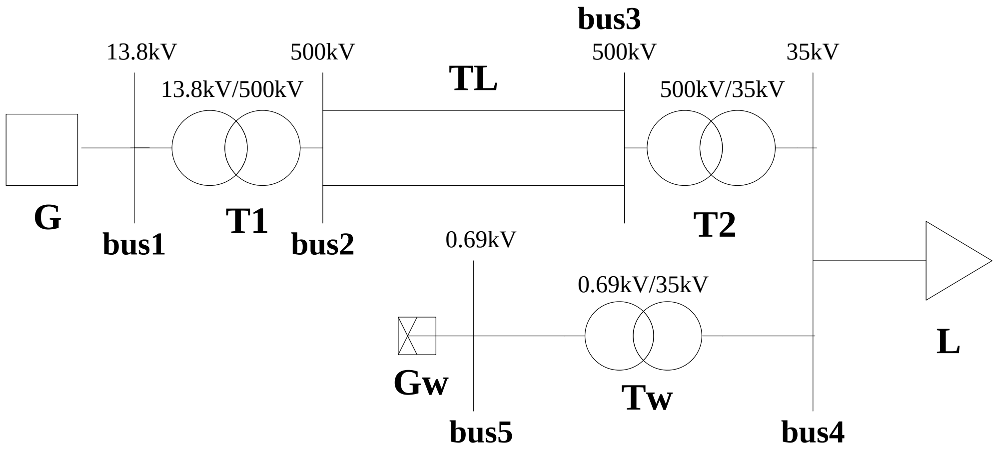

Fig. 4.4 The model system of the 4.5.1 case study.

Furthermore, the synchronous generator model with data collection tool and waveform scope tool is shown on Fig. 4.5. At first, setting the synchronous generator power flow data as the output data of generator machine in this case, the model system operates under these power flow situation and the data collection and waveform scope tools collect and record the data and waveform of rotor current, stator current of one phase and power angle. Then, the model system also operates under steady state which has constant output of conventional generator and output of wind turbine generators in order to collect and record the steady value of rotor current, stator current of one phase and power angle through the data collection and waveform scope tools. The information and data of this model power system is listed in the Table 4.2.

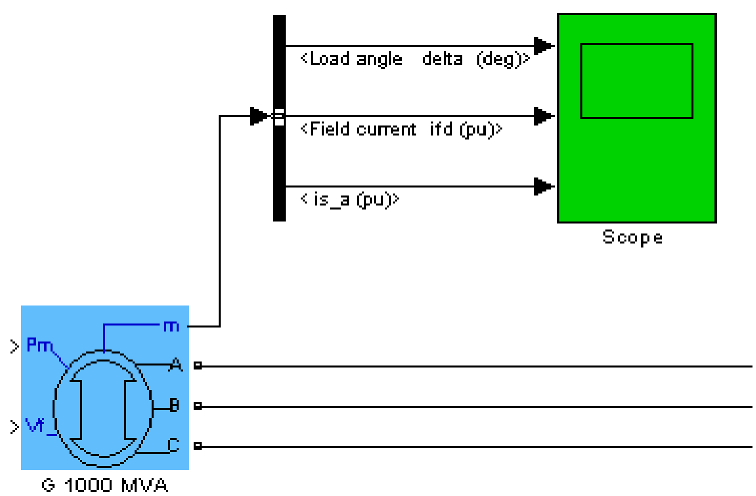

Fig. 4.5 The synchronous generator model with data collection and waveform scope tools.

Table 4.2 The information and data of model power system in Case study 4.5.1

Symbol	Information	Data (System frequency is 50Hz)
G	A conventional generator connected to transmission system	**Capacity:** 1000MVA; **Voltage level:** 13.8kV; **Reactances Xd:** 1.305 p.u. **Xd':** 0.296p.u. **Xq:** 0.474p.u. **Xq'':** 0.18p.u.; **Stator resistance Rs:** 2.544×10^{-3}p.u.
Gw	A large wind farm contains 100 wind turbines integrated connected to distribution system	**Capacity:** 100*1.5MW; **Voltage level:** 0.69kV
TL	A double-line long distance backbone 500kV high-voltage transmission system	**Length:** 500km; **Voltage level:** 500kV; **Resistance R:** 1.755×10^{-2} Ω/km; **Inductance L:** 8.737×10^{-2} H/km; **Capacitance C:** 1.339×10^{-8} F/km
L	A load centre with a stable constant load	**Total demand:** 1000MW; **Voltage level:** 35kV
T1	Transformer connects conventional generator and transmission system	**Ratio:** 13.8kV/500kV; **Capacity:** 1000MVA
T2	Transformer connects transmission system and load in distribution system	**Ratio:** 500kV/35kV; **Capacity:** 1000MVA
Tw	Transformer connects wind farm and distribution system	**Ratio:** 0.69kV/35kV; **Capacity:** 200MVA

4.5.2 Simulation Results

After the simulation, the results data of rotor current, stator current of one phase and power angle under conventional generator output fluctuation condition for 24 hours in every 10 seconds can be obtained and are shown on Fig. 4.6, Fig. 4.7 and Fig. 4.8 respectively.

And steady results data of rotor current, stator current of one phase and power angle also can be obtained and are shown on Fig. 4.9.

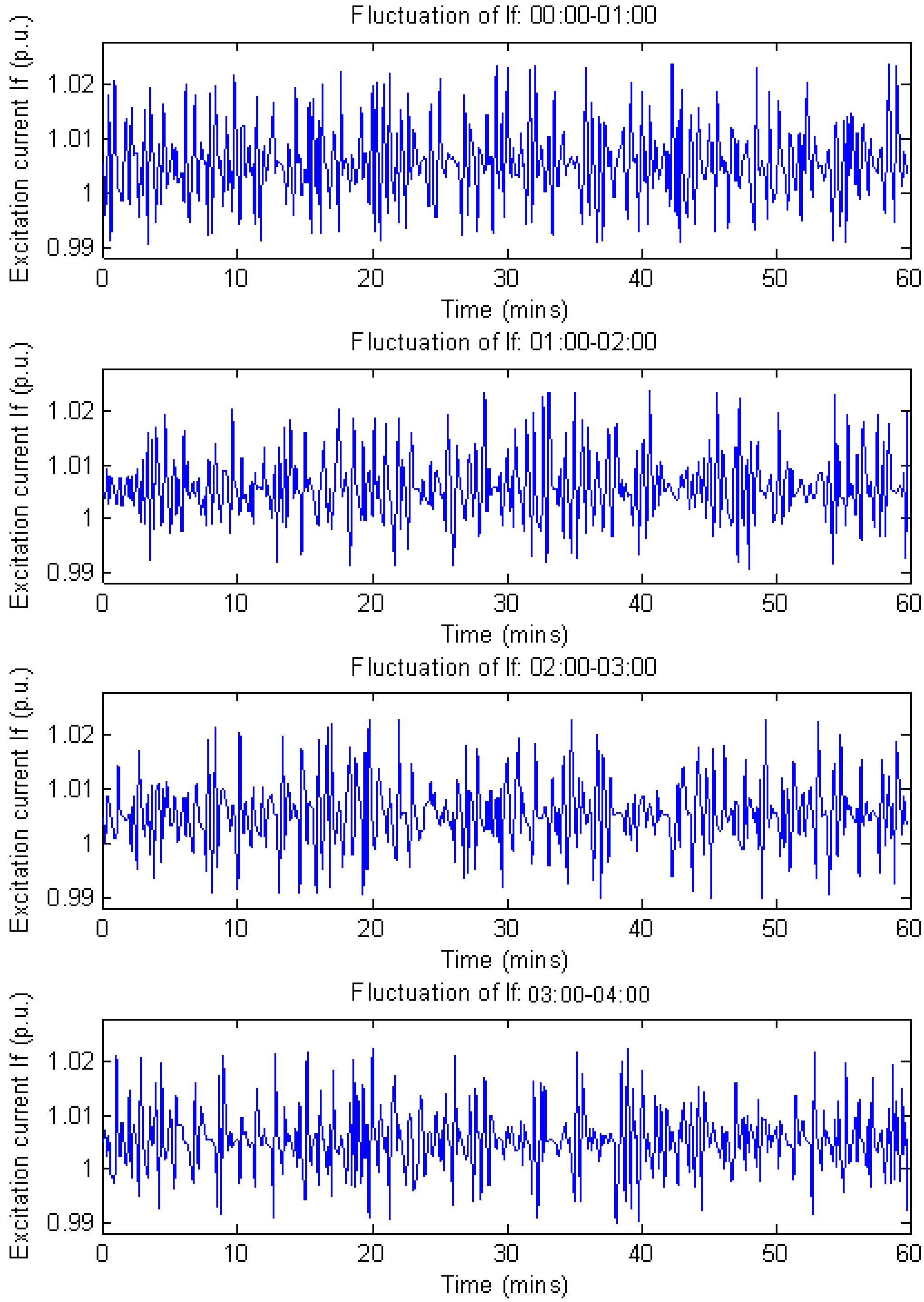

Fig. 4.6 (a) Excitation current I_f of synchronous generator in the simulation system for every 10 seconds from 00:00-04:00.

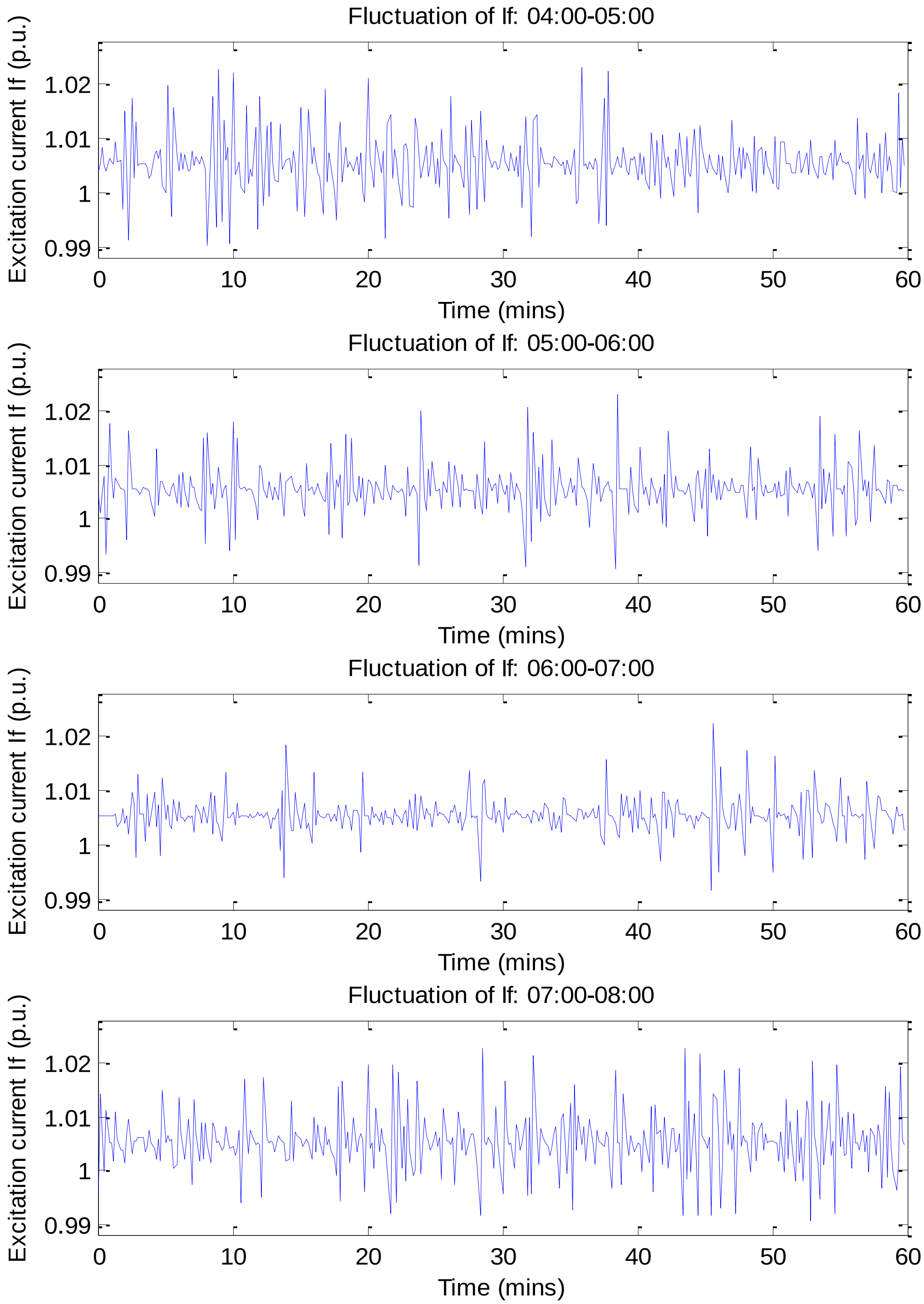

Fig. 4.6 (b) Excitation current I_f of synchronous generator in the simulation system for every 10 seconds from 04:00-08:00.

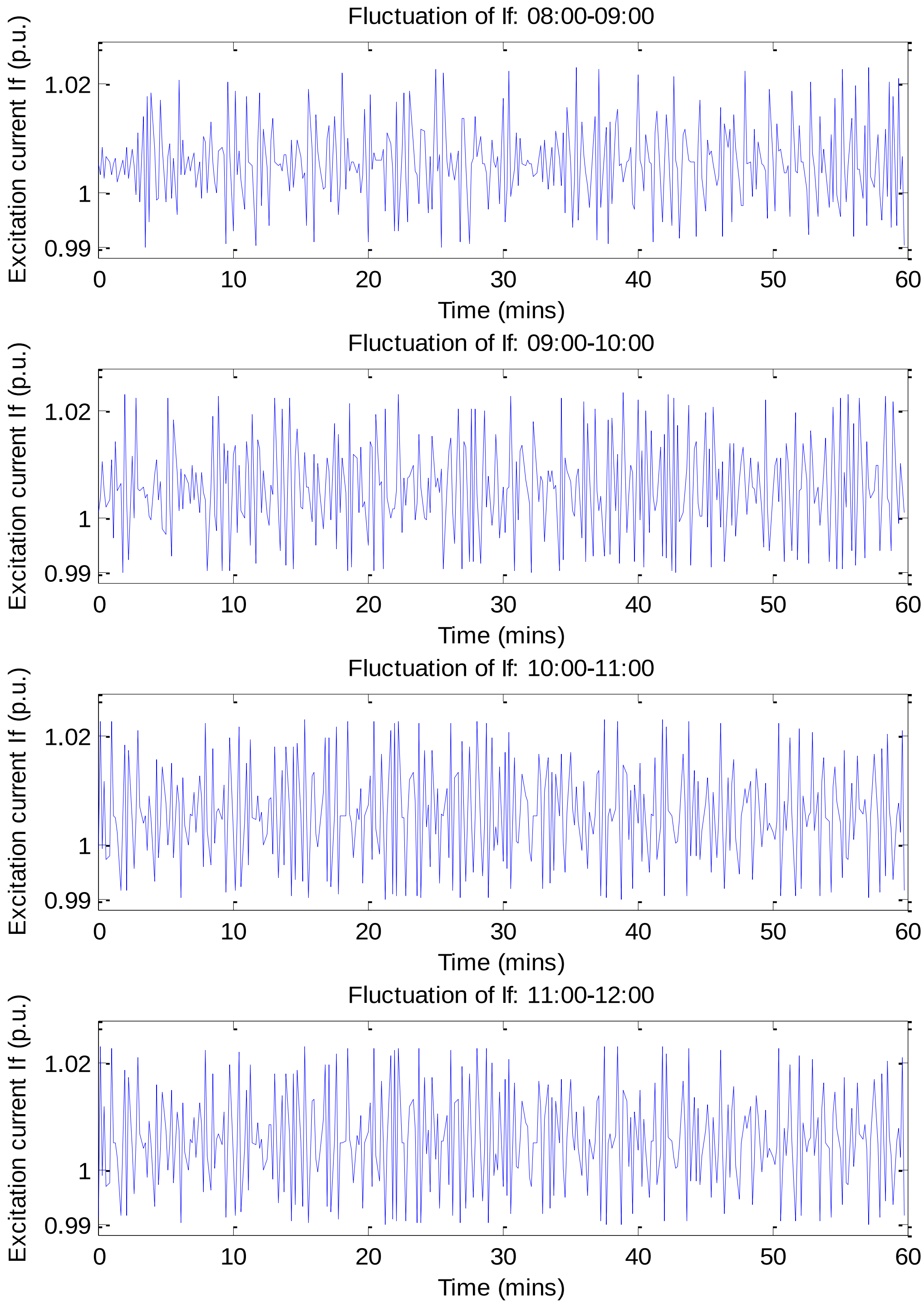

Fig. 4.6 (c) Excitation current I_f of synchronous generator in the simulation system for every 10 seconds from 08:00-12:00.

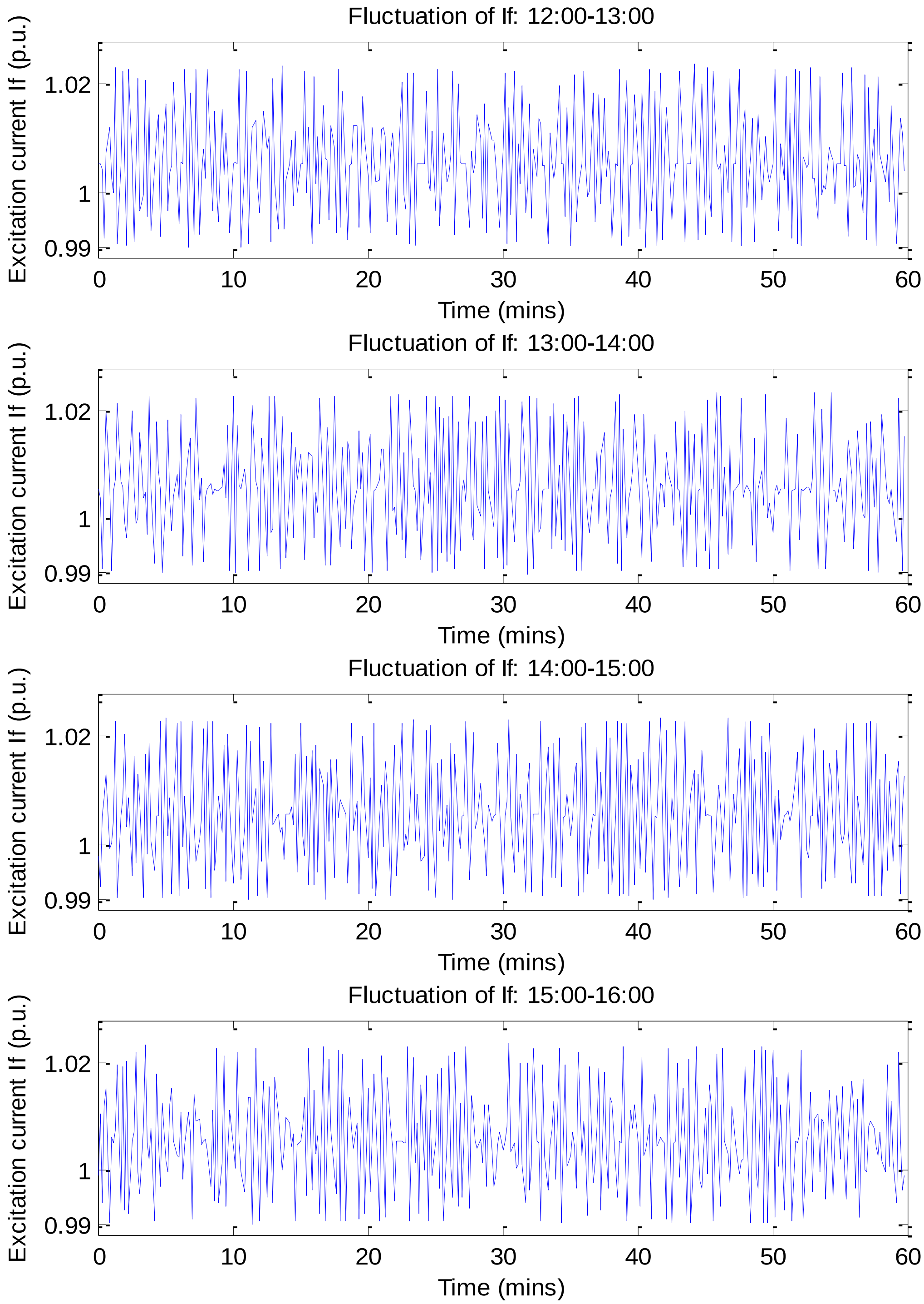

Fig. 4.6 (d) Excitation current I_f of synchronous generator in the simulation system for every 10 seconds from 12:00-16:00.

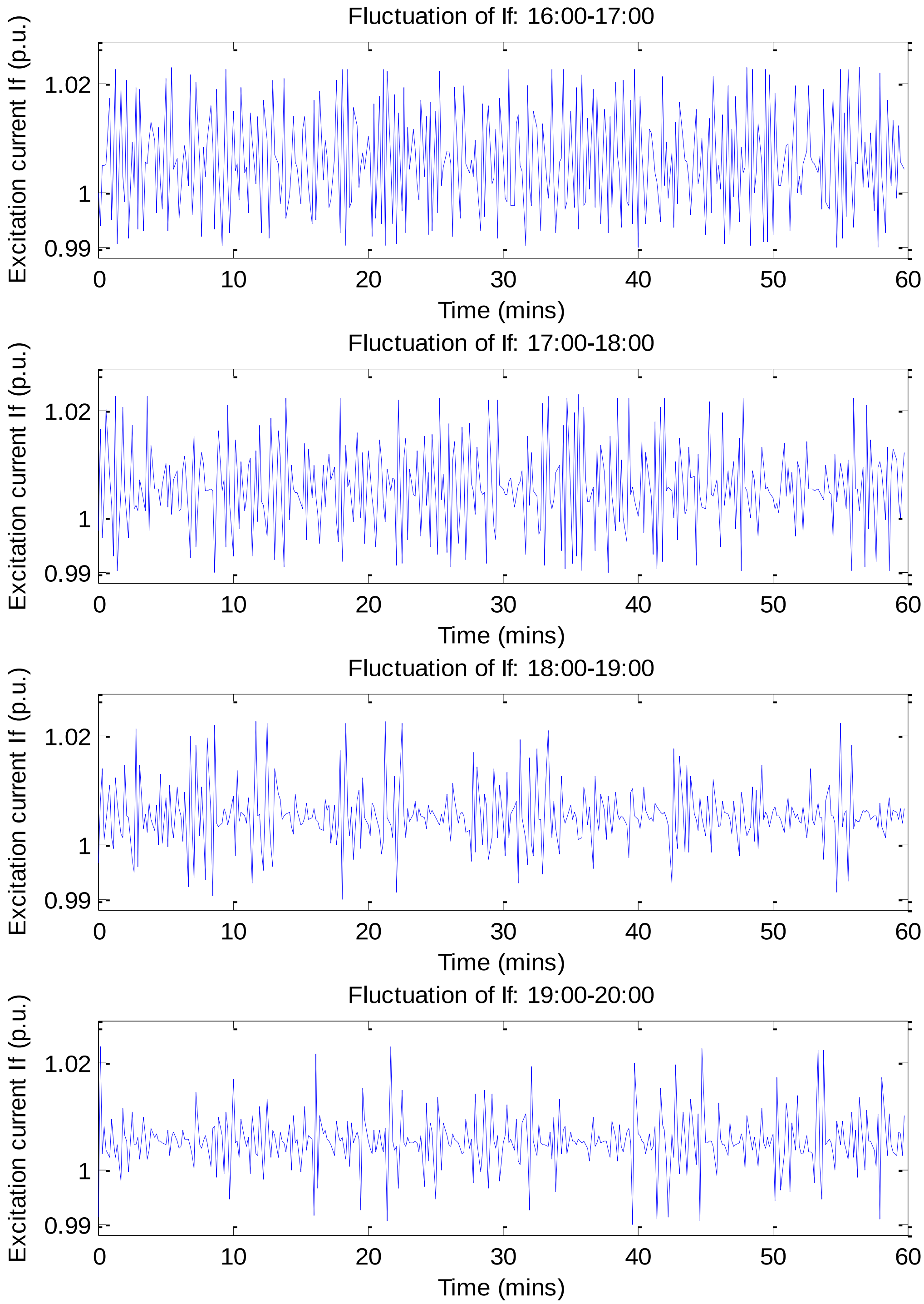

Fig. 4.6 (e) Excitation current I_f of synchronous generator in the simulation system for every 10 seconds from 16:00-20:00.

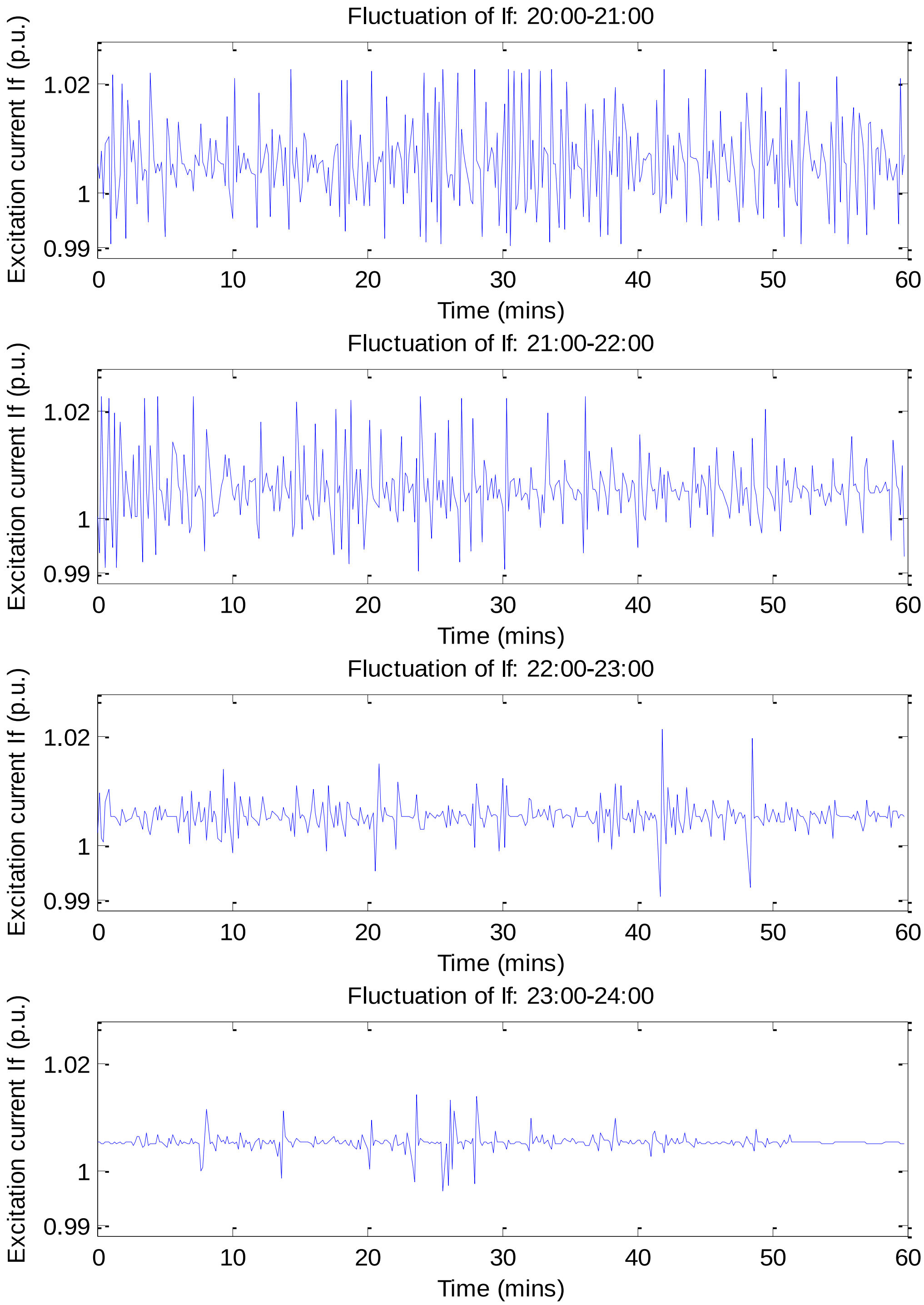

Fig. 4.6 (f) Excitation current I_f of synchronous generator in the simulation system for every 10 seconds from 20:00-24:00.

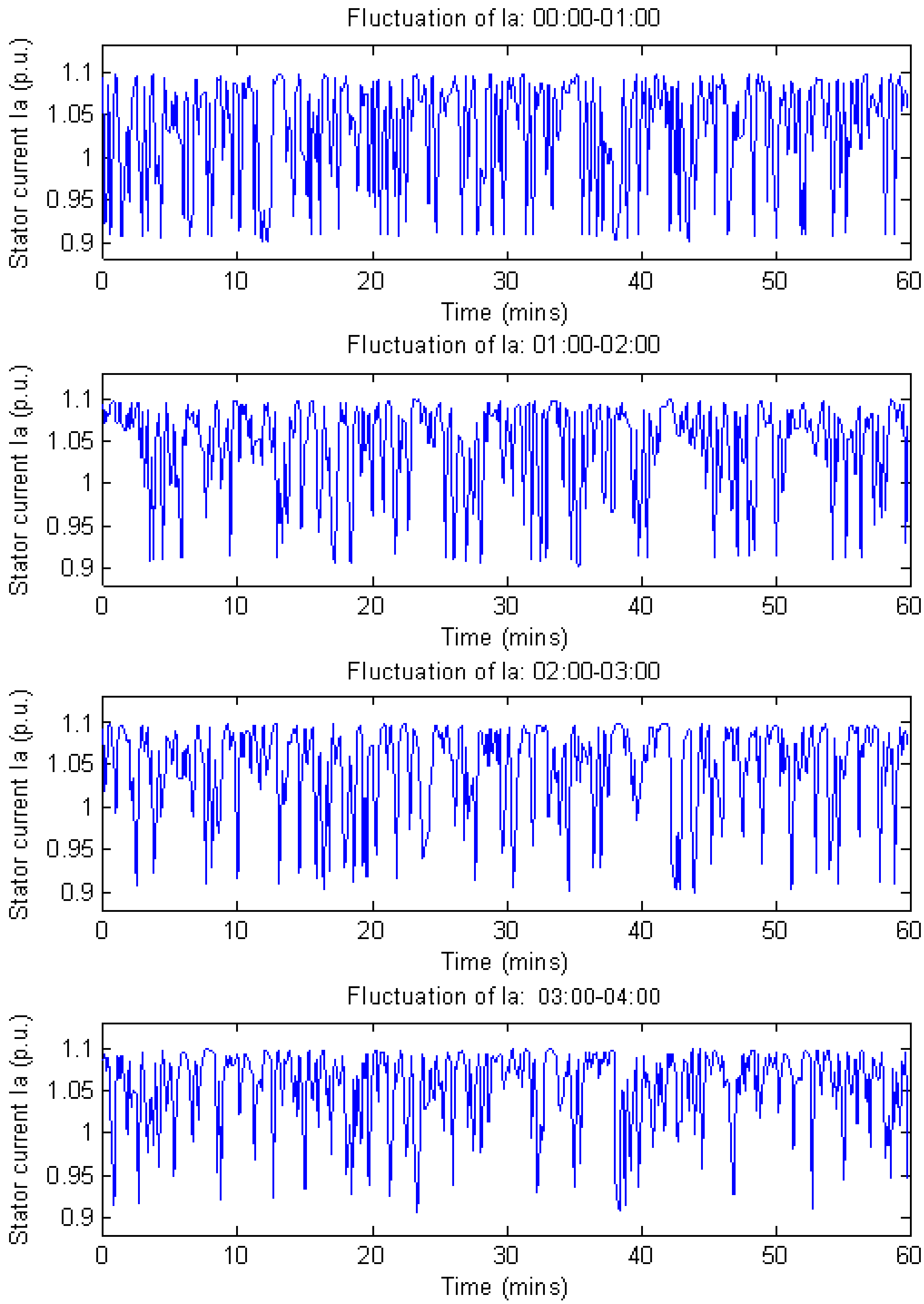

Fig. 4.7 (a) Stator current I_a of synchronous generator in the simulation system for every 10 seconds from 00:00-04:00.

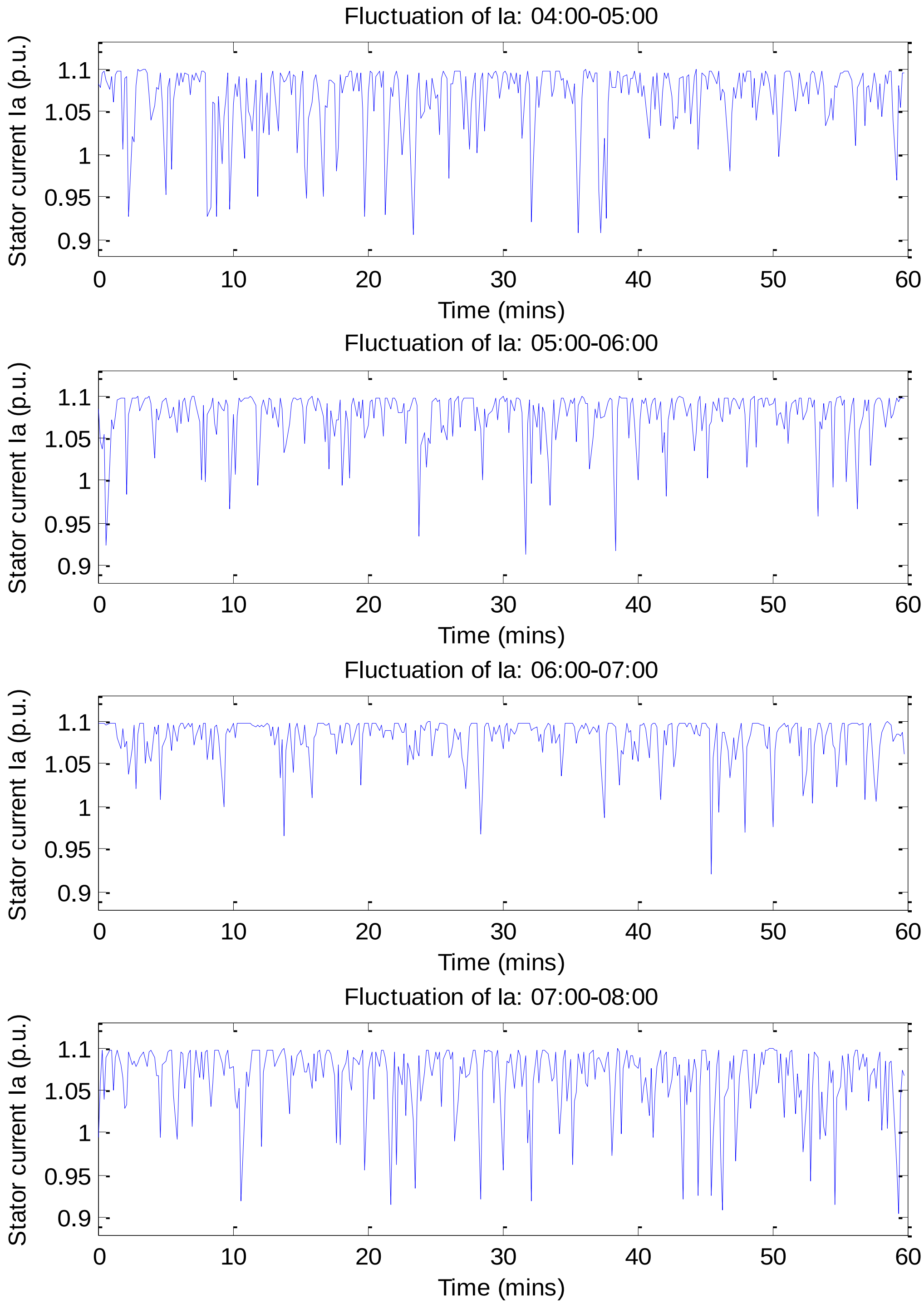

Fig. 4.7 (b) Stator current I_a of synchronous generator in the simulation system for every 10 seconds from 04:00-08:00.

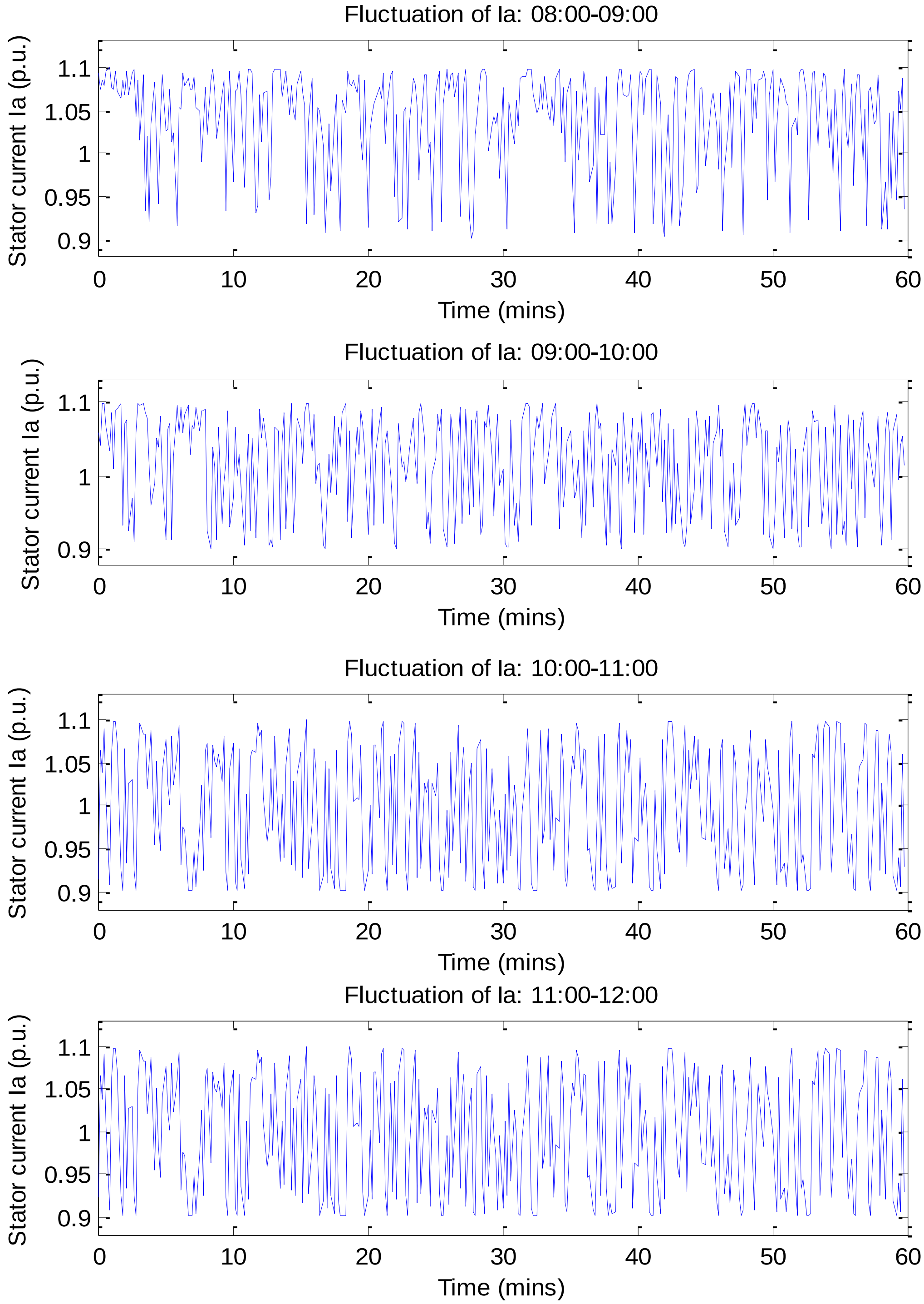

Fig. 4.7 (c) Stator current I_a of synchronous generator in the simulation system for every 10 seconds from 08:00-12:00.

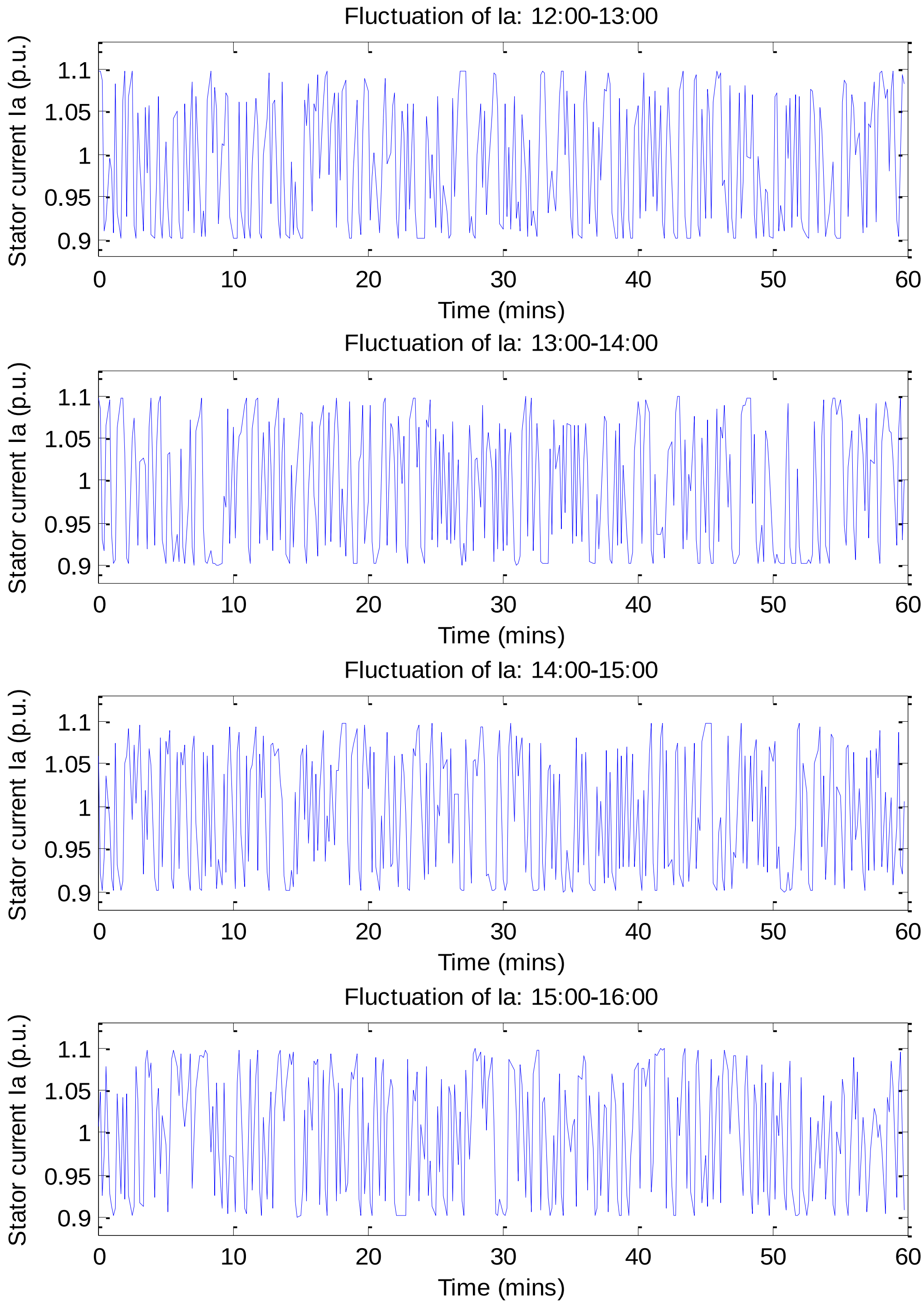

Fig. 4.7 (d) Stator current I_a of synchronous generator in the simulation system for every 10 seconds from 12:00-16:00.

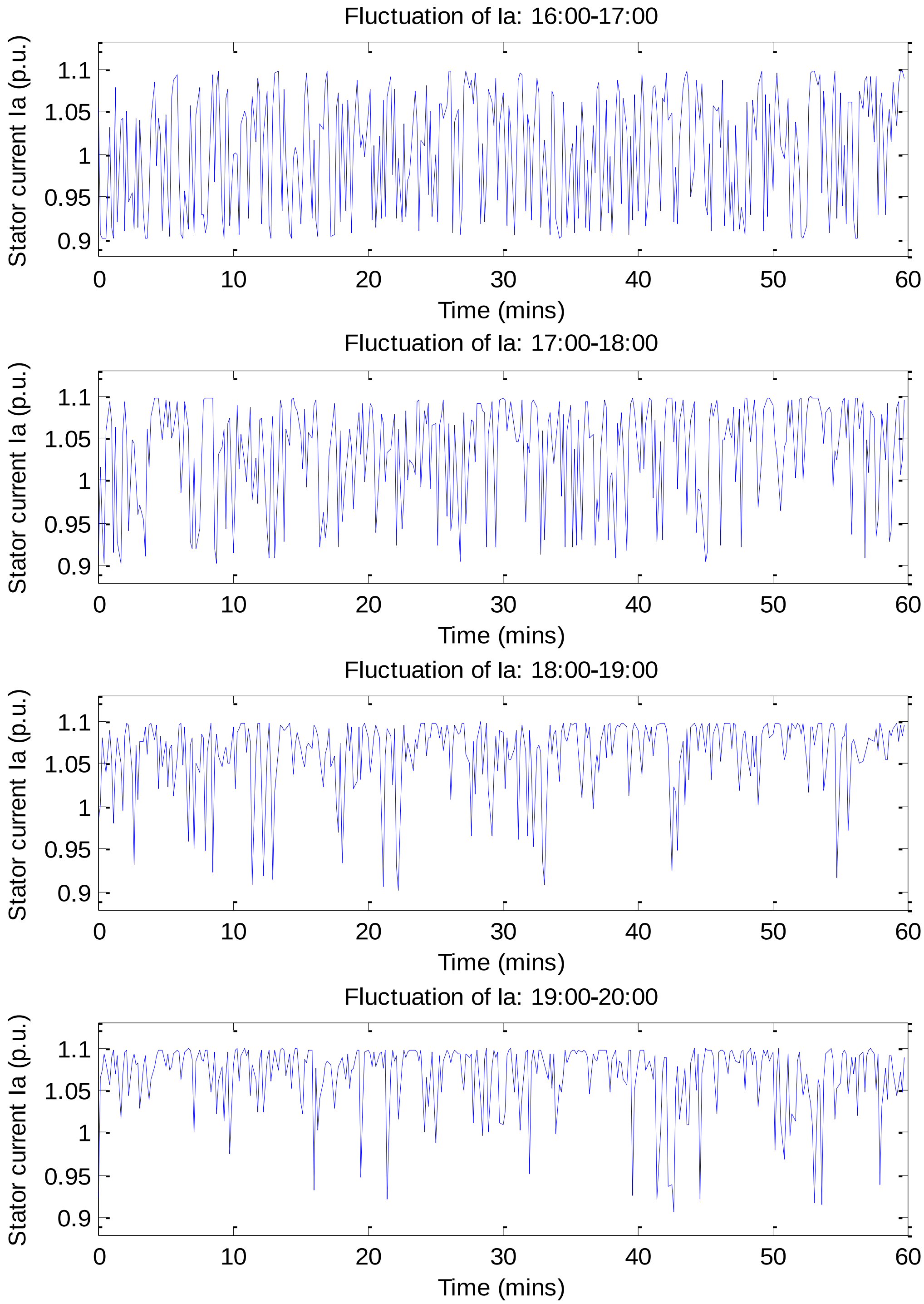

Fig. 4.7 (e) Stator current I_a of synchronous generator in the simulation system for every 10 seconds from 16:00-20:00.

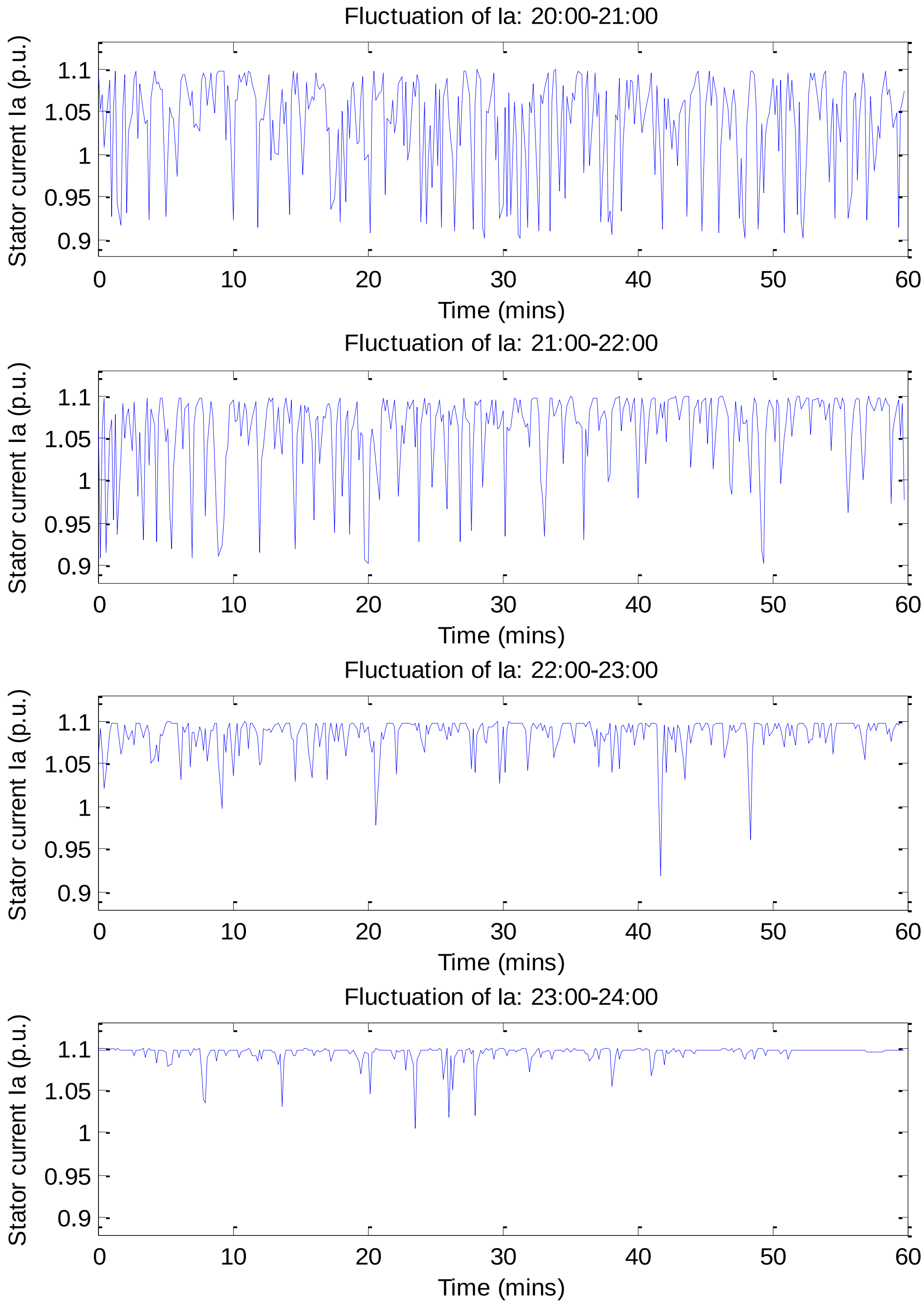

Fig. 4.7 (f) Stator current I_a of synchronous generator in the simulation system for every 10 seconds from 20:00-24:00.

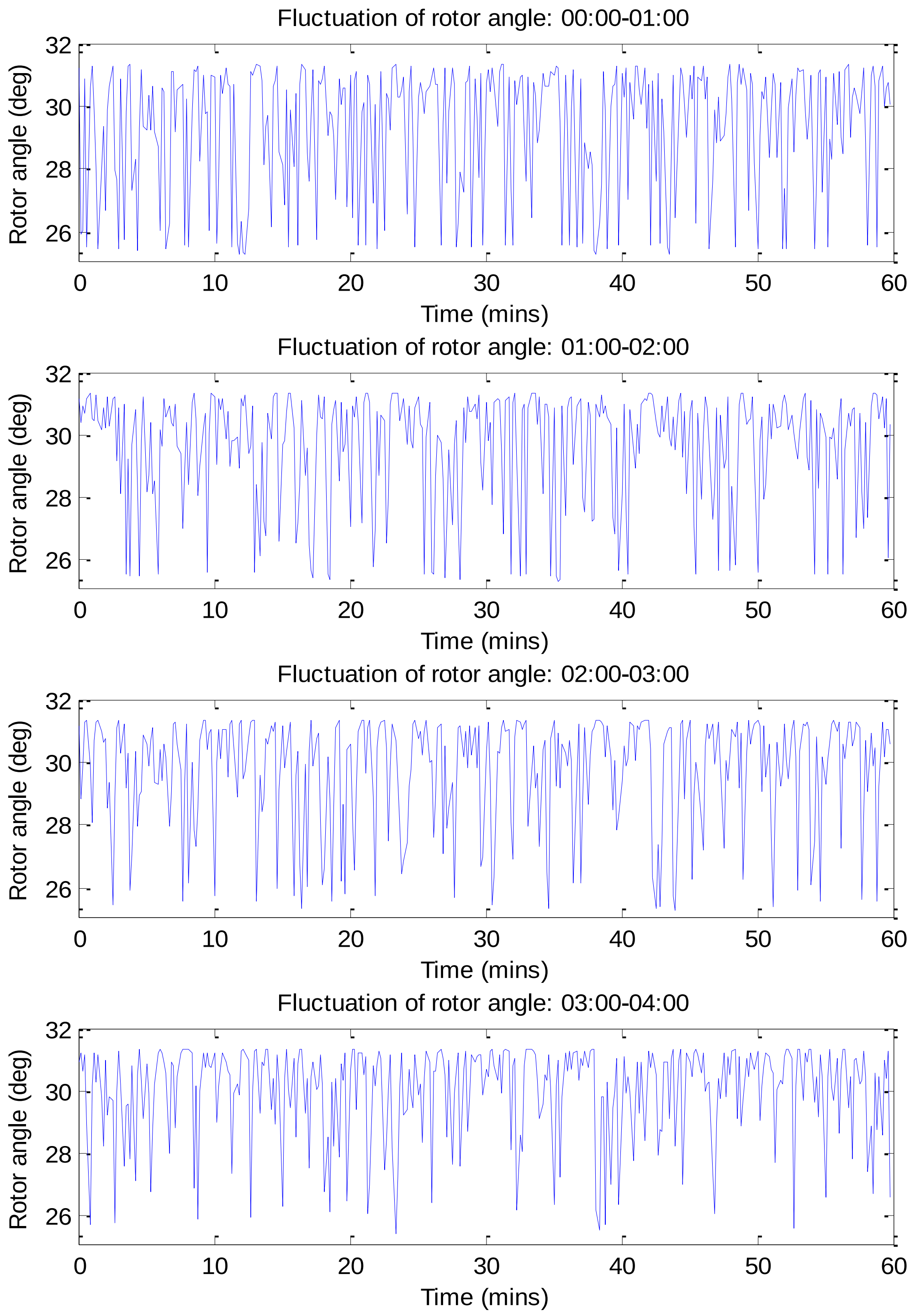

Fig. 4.8 (a) Rotor angle δ of synchronous generator in the simulation system for every 10 seconds from 00:00-04:00.

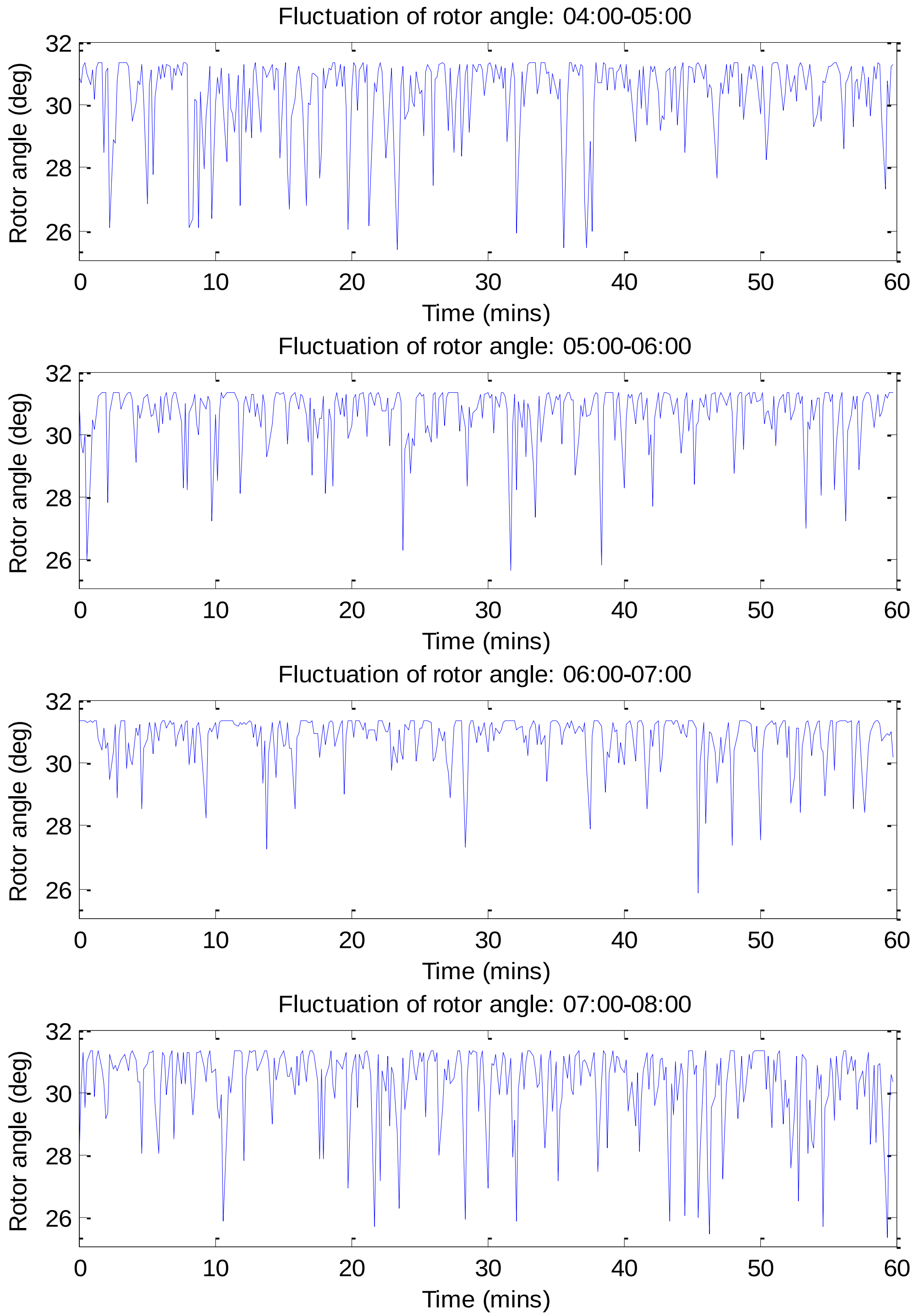

Fig. 4.8 (b) Rotor angle δ of synchronous generator in the simulation system for every 10 seconds from 04:00-08:00.

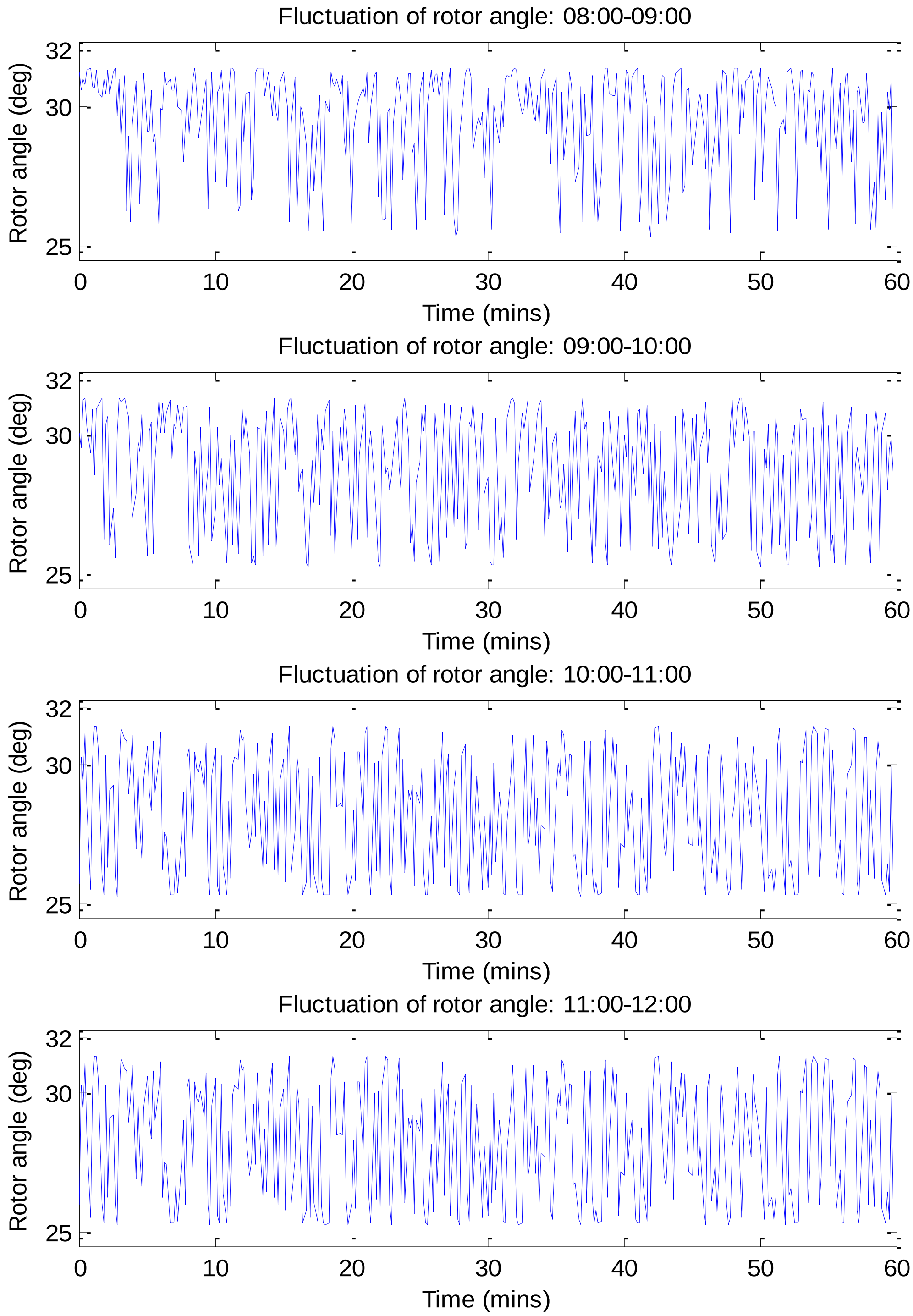

Fig. 4.8 (c) Rotor angle δ of synchronous generator in the simulation system for every 10 seconds from 08:00-12:00.

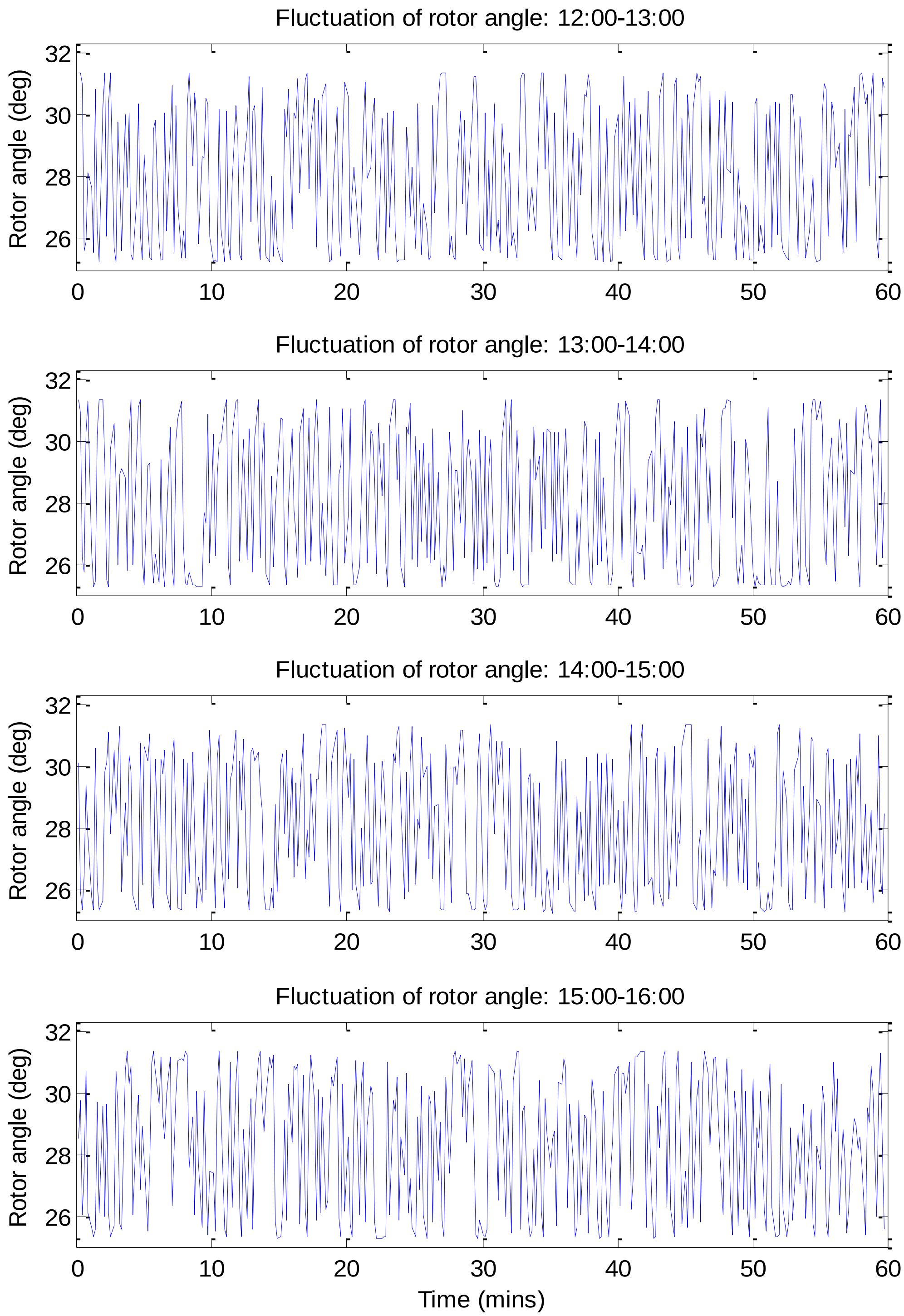

Fig. 4.8 (d) Rotor angle δ of synchronous generator in the simulation system for every 10 seconds from 12:00-16:00.

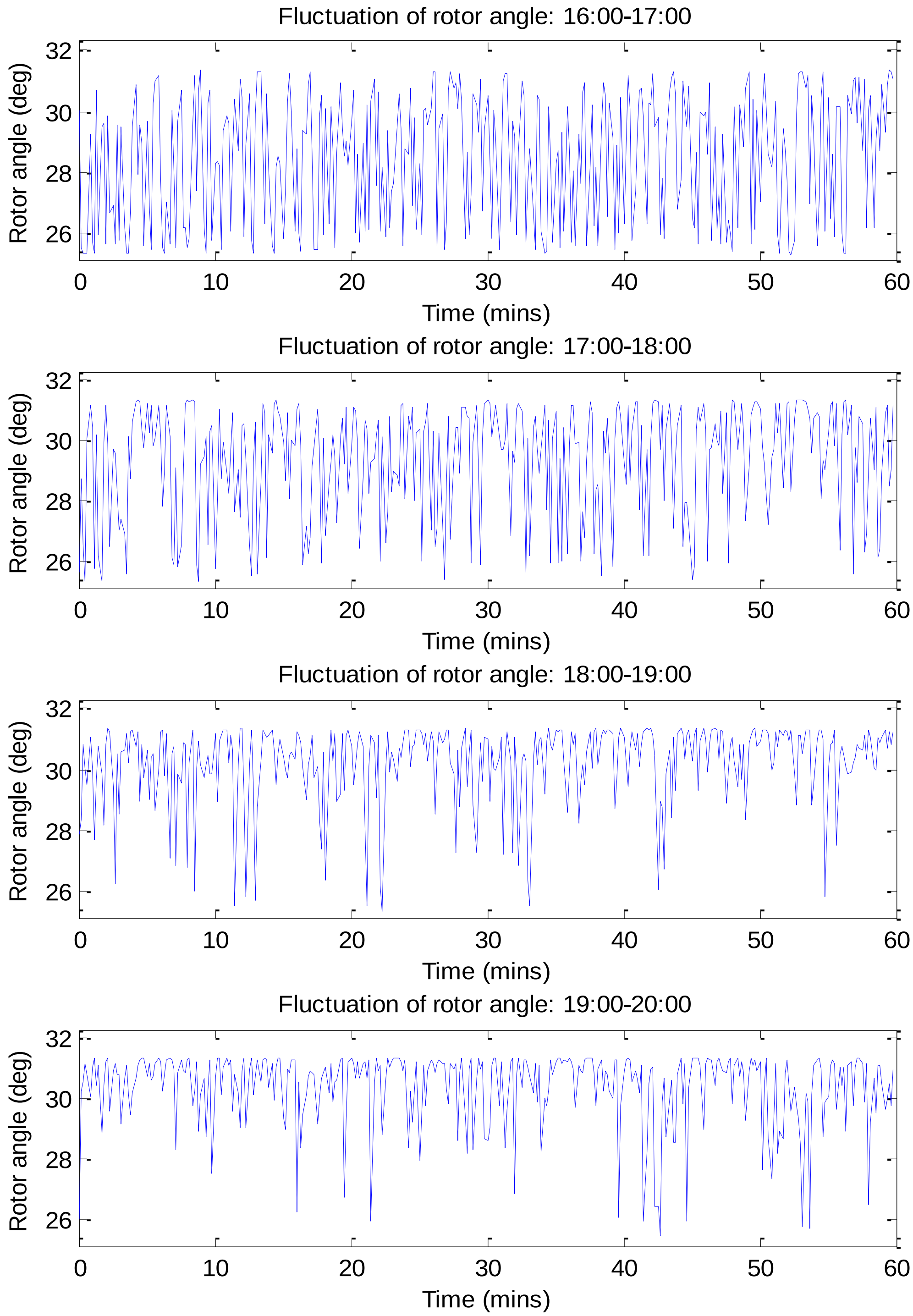

Fig. 4.8 (e) Rotor angle δ of synchronous generator in the simulation system for every 10 seconds from 16:00-20:00.

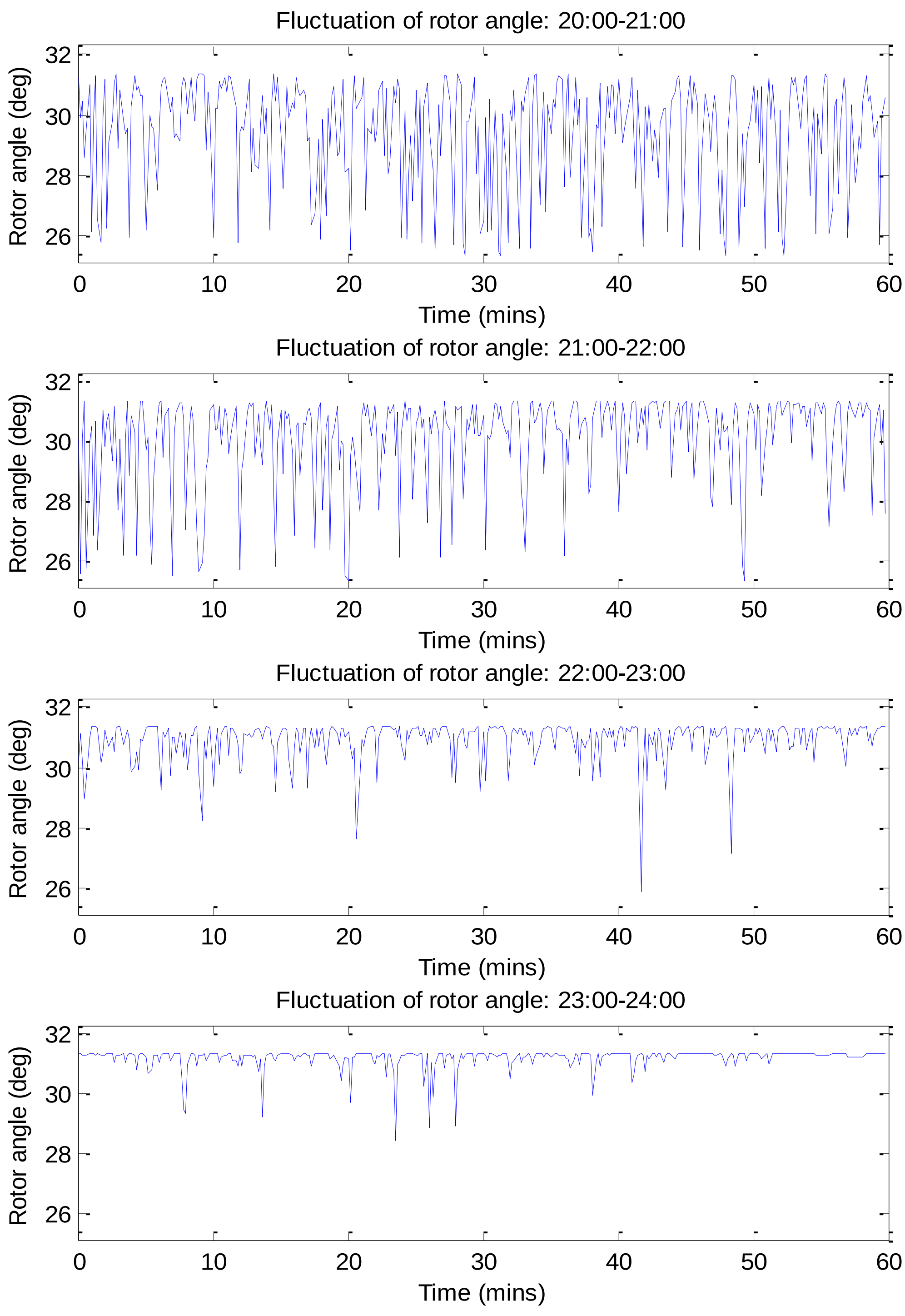

Fig. 4.8 (f) Rotor angle δ of synchronous generator in the simulation system for every 10 seconds from 20:00-24:00.

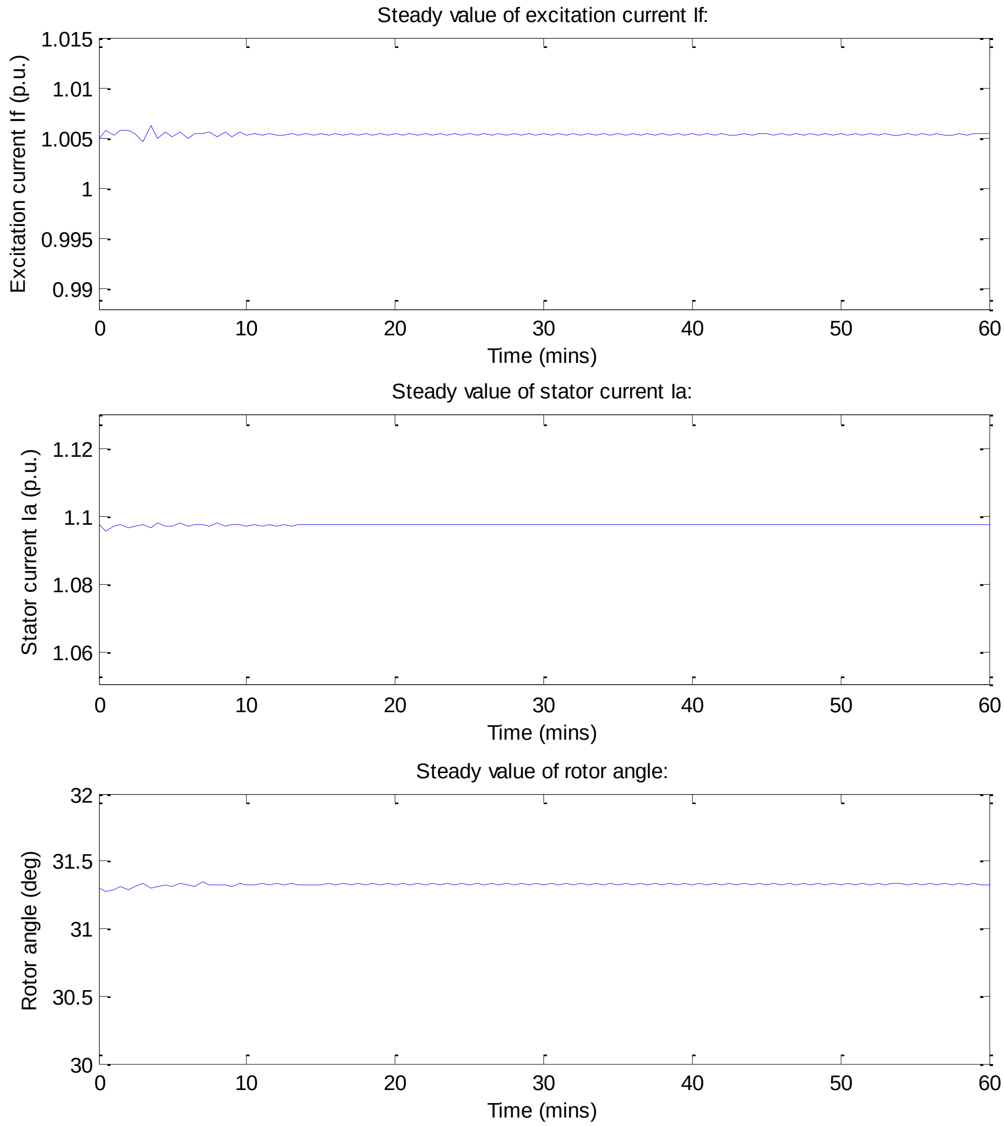

Fig. 4.9 Steady value of excitation current I_f, stator current I_a and rotor angle δ in the simulation system.

From Fig. 4.6 (a) to Fig. 4.6 (f), these are shown the result curve of field current (or rotor current) of the synchronous generator machine when the wind fluctuates. And comparing with steady state values of the excitation current, calculated under constant full output of wind farm, which is shown on Fig. 4.9, there are many random fluctuations of field current which are as many as the synchronous generator active power output in a power system with wind farms. And the fluctuate frequency changes of field current follow the frequency changes in generator output, so the wind speed variation level also influence the field current performance indirectly. And the amplitude value of field current variation of the generator machine is also impacted by the synchronous generator output variation amplitude. Furthermore, comparing with simulation results of Section 3.5 simulation in dynamic response of I_f during transient state after a fault, the changes of I_f in a conventional generator under steady state in a power system with wind turbine generation is relatively much smaller in this simulation.

In the same way, the result data of stator current in one phase, which are shown on Fig. 4.7 (a) to Fig. 4.7 (f), and the result data of power angle, which are shown on Fig. 4.8 (a) to Fig. 4.8 (f), also have the same characteristics with the field current. And these results data can be used to calculate the heating effect on the following section.

4.6 A Developed Thermal Model Based on Flux Density

From the simulation in Section 3.5 last chapter, simulation results shows the variation of I_f and δ of a conventional generator after a fault simulation. On the contrary, simulation in Section 4.5 obtains the results of I_f, I_s and δ fluctuation of a conventional generator in a power system with wind farm under steady state. Comparing the results from these two simulation, it shows that the changes of I_f and I_s in a conventional generator under steady state in a power system with wind turbine generation is relatively small comparing with dynamic response of I_f during transient state. As a result, fluctuation of rotor and stator current in Section 4.5 simulation do not break the heating limit and also do not cause the thermal problem immediately but it is necessary to do the simulation to ascertain if the fluctuation could to lead heating problem of the machine in a long run.

In studying heating problem within an electrical machine, there are some methods and thermal models have already been proposed and used in the design of electric machine to estimate thermal behaviour and calculate temperatures of rotor and stator region in a generator machine. A lumped parameter thermal model proposed by Mellor and Turner [9, 10] has been widely used reference model for the researchers working on electrical machine thermal problems. The lumped parameter model is based on a subdivision of the electrical machine in several parts that are assumed to have the same thermal behaviour and it is sufficiently complex to identify the temperatures at most locations in the machine such as the peak temperatures in the windings and the surface temperatures of the rotor and stator. The Mellor and Turner thermal model is very accurate and able to analyze in detail the heat transfers inside the machine because it takes into account both axial and radial heat fluxes and a complex convective heat transfer involving the air inside the machine.

However, because the structure of generator machine is much more complicated and the heating transfer processes are variable it is difficult to compute all the lumped parameter model parameters and it also wastes plenty of calculation time. Moreover, in the situation as Section 4.5 simulation, this thermal model can not describe the currents fluctuation effectively. As a result, even if many paths are allowed for heat transfer from the machine to the ambient, the most amount of heat flows through only a number of electrical machine elements. The thermal analysis problem of generator machines can use a simpler model with a reduced number of parameters. These parameters can be computed by simple equations or they can be evaluated from tests. [11, 12] Based on the relationship with production of heat, currents of generator machine and magnetic field (or flux density), a thermal model can be developed to calculate the heating effect. So in this thermal model, the flux density are calculated using the stator terminal voltage V_a, stator current I_a, power factor of synchronous generator θ_f, exciting current I_f and the power angle δ which can be collected from the simulation temperature rises of synchronous generator and then actual temperature rises of synchronous generator is obtained. And the heat dissipation processes are also involved in this thermal model. [13, 14]

As mentioned above, both the armature and field current will increase flux densities and the flux densities produced by rotor and stator are described by the following equations: [14]

$$\left.\begin{aligned}\dot{B}_R &= N_r j\dot{E}_0 \\ \dot{B}_S &= N_s \dot{I}_s X_d\end{aligned}\right\} \text{ and } E_0 = X_{ad} I_f \qquad \text{Equation 4.7}$$

N_r and N_s are number of turns of the windings; E_0 is the no-load voltage and is proportional to the field current according to the short-circuit ratio. From Equation 4.4, the phasor diagram of rotor flux density, stator flux density and the sum of the rotor and stator magnetic field total magnetic field B_{net} are shown in Fig. 4.10.

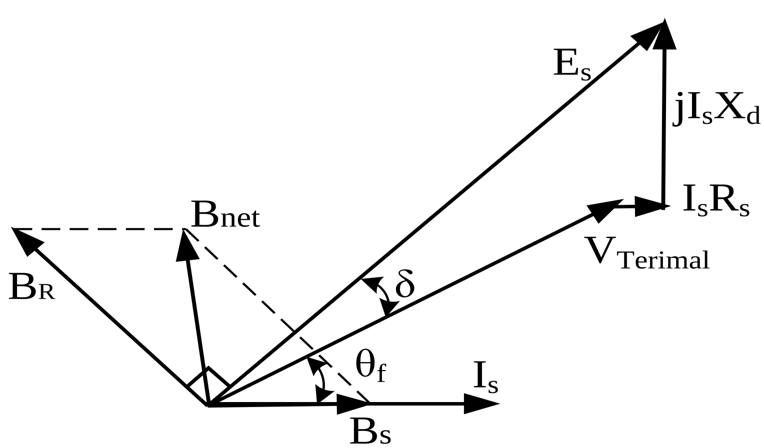

Fig. 4.10 Phasor diagram of rotor and stator flux density B_R and B_S

Therefore, the amplitude of total magnetic fields B_{net} is

$$B_{net} = \sqrt{B_R^2 + B_S^2 - 2B_R B_S \cos\left(\frac{\pi}{2} - \delta - \theta_f\right)} \quad \text{or}$$

$$B_{net}^2 = B_R^2 + B_S^2 - 2B_R B_S \cos\left(\frac{\pi}{2} - \delta - \theta_f\right). \qquad \text{Equation 4.8}$$

According to [11, 12, 13, 14], this thermal model is used for calculating the heating effect of induction machine. However, even though the synchronous generator machine has a different structure, Equation 4.7 and 4.8 and the phasor diagram described in Fig. 4.10 are still applicable for the calculation of magnetic field in synchronous generator machine because of the same electromagnetic induction theory. [1]

For the production of heat, thermal energy W_T is proportional to the square of rotor and stator current I_f and I_s respectively. And from Equation 4.7, the currents are proportional to flux densities B_S and B_R. As a result, W_T is also proportional to the square of flux density B_S and B_R and is described in the following equation:

$$W_T = K_T {B_{net}}^2 = K_T N_r^2 {E_0}^2 + K_T N_s^2 {I_S}^2 X_d^2$$
$$- 2K_T N_s N_r E_0 I_S X_d \cos\left(\frac{\pi}{2} - \delta - \theta_f\right) \qquad \text{Equation 4.9}$$

K_T is the constant proportionality coefficient between W_T and B^2_{net}. Then, the equation can be expressed as:

$$W_T = [b] \times [A]^T \text{, as } [A] = [a_1\ a_2\ a_3],\ [b] = [b_1\ b_2\ b_3] \qquad \text{Equation 4.10}$$

where $a_1 = K_T N_r^2$, $a_2 = K_T N_s^2$, $a_3 = K_T N_s N_r$ and $b_1 = {E_0}^2$, $b_2 = {I_s}^2 X_d^2$, $b_3 = -2E_0 I_s X_d \cos\left(\frac{\pi}{2} - \delta - \theta_f\right)$.

The production of heat result in T, which represents temperature inside the machine, increases especially at the area where both rotor and stator flux density can take effects. The temperature rise is $T-T_{akb}$ where T_{akb} is maximum ambient temperature 40 ℃ which have keen mentioned above. As a result, the differential in the machine and the surrounding temperature will cause the heat dissipation from an area to other parts in the machine. And the heat dissipation is proportional to $T-T_{akb}$ so it can be described as $\alpha_w (T-T_{akb})$, where α_w is a proportionality constant. Through the thermal model, the heat energy dissipation at every state or temperature level can be evaluated. [15, 16]

Under steady state, before and after a transient state,

$$T(0)=\frac{W_T(0)}{\alpha_W}+T_{akb} \text{ and } T(\infty)=\frac{W_T(\infty)}{\alpha_W}+T_{akb} \qquad \text{Equation 4.11}$$

During a changing process, the heat produced may exceed the heat dissipated which is $W_T > \alpha_w (T-T_{akb})$. The excess heat will make the temperature keep on increasing. The excess energy gradually increases the rotor temperature until a new steady state temperature is reached. This process is described in the Equation 4.12:

$$H_{Thermal}\frac{dT}{dt}=W_T(t)-\alpha_W(T_{rise}(t)-T_{akb}) \text{ and } T(t)=\frac{W_T(t)}{\alpha_W}+T_{akb}$$

also as $$T_{rise}(t)=(T(t)-T_{akb})-(T(t)-T_0)e^{-(\alpha_W/H_{Thermal})t} \qquad \text{Equation 4.12}$$

where $T_{rise}(t)$ is the temperature rise of the machine after a certain time period t; T_0 is the initial temperature of the machine; $H_{Thermal}$ is thermal inertia constant. After this process, when $W_T=\alpha_W (T-T_{akb})$, the temperature will reach the final value. However, process time t usually depends on the change of machine heat state, in other words process time t relies on number of currents data collection. Finally, the sum of all $T_{rise}(t)$ can obtain the total temperature rise T_{rise}. Based on these equations, the calculation processes is obtained and shown in the next section. [15, 16, 17]

4.7 Temperature Rise Calculation Process

The flowchart in Fig.4.11 describes the calculation program of temperature rise:

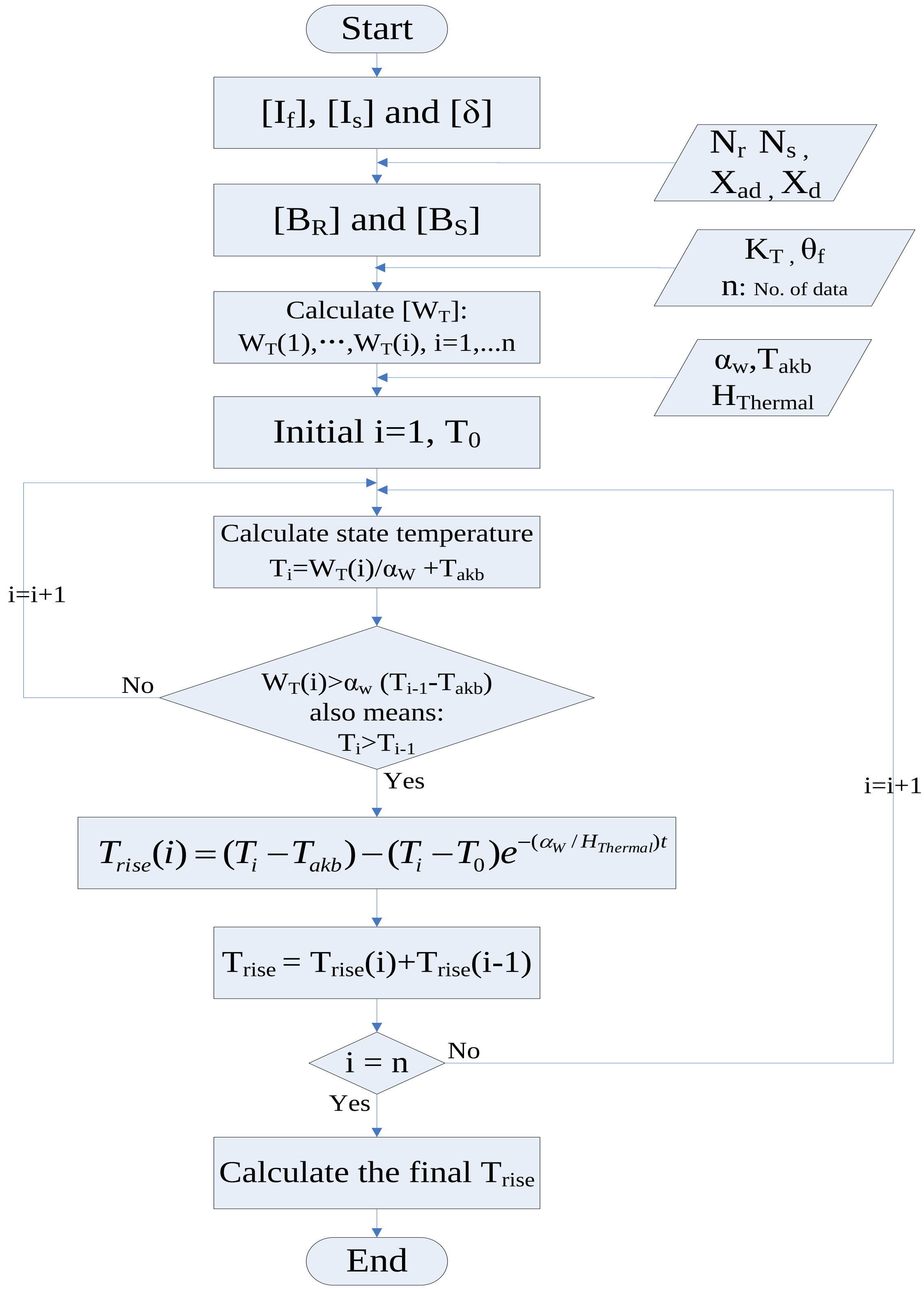

Fig. 4.11 Flowchart of the temperature rise calculation program for generator machine.

In this thesis, the calculations are based on Matlab program. Firstly, after input the machine and thermal parameters, heat energy for every state is calculated through the thermal model which uses rotor current, stator current and power angle data. Then, equations for charging process which is mentioned above are used to calculate the heating dissipation effects and temperature rise. If a heating energy at a state is larger than the last one, there will be a heating dissipation so the temperature rise of the machine after a certain time period $T_{rise}(t)$ needed to be calculated. If not, the program will get the next state information and compare again. Finally, after the whole calculating processes are competed, the final temperature rise which is sum of all the $T_{rise}(t)$ for the whole data collection period can be obtained. [15]

The simulation of this part will be processed at the next chapter after the cooling system effects are taken into account.

4.8 Summary

This chapter outlined a method to calculate heating problem which is the thermal model of conventional generator cased by wind power generation.

Firstly, this chapter overviewed the heat transfer theories which include heat transfer methods and their equations. Continually, it discussed the insulation system of the generator machine about IEEE standards classification of insulations and the limitation of maximum ambient temperature and hot-spot temperature rise of the machine. Next, it explained and analysed equivalent circuit of synchronous generator, the relationship between currents and magnetic fields and control the excitation current and stator current within maximum current limits. Then, it represented the current operation performance inside the machine through a simulation example in a power system with a wind farm.

Secondly, this chapter discussed previous heating calculation model and developed a thermal model based on flux density to be suitable for a power system with wind farm. Then, it analysed the thermal energy transfer process and also described heating energy state and heating transfer in equations. Finally, it listed the temperature rise calculation processes which are used for producing the calculation program of Matlab in the flowchart.

The next chapter will research the cooling system effect which is the second step of this method and the joining of these two steps together will complete the method. The simulation results data of rotor current, stator current and power angle of the generator machine can be used after the method is completed.

4.9 References

[1] T. Wildi, *Electrical machines, drives, and power systems,* 6th International Edition, New Jersey: Pearson Education, 2006.

[2] G. McPherson and R. D. Laramore, *An Introduction to Electrical Machines and Transformers*, 2nd Edition, New York: John Wiley & Sons, 1990.

[3] S. J. Chapman, *Electric Machinery and Power System Fundamentals*, New York: McGraw-Hill, 2002.

[4] C. B. Gray, *Electrical Machines and Drive Systems,* London: Longman Scientific & Technical and New York: John Wiley & Sons, 1989.

[5] W. Nakayama, K. Fuzioka and S. Watanabe, "Flow and Heat Transfer in the Water-Cooled Rotor Winding of a Turbine Generator," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-97, no. 1, pp. 225-231, January/February 1978.

[6] W. B. Gish, W. E. Feero and G. D. Rockefeller, "Rotor Heating Effects from Geomagnetic Induced Currents," *IEEE Transactions on Power Delivery*, Vol. 9, No.2, pp. 712-719, April 1994.

[7] S. J. Salon, M. R. Shah and L. W. Montgomery, "Analysis and Testing of Negative Sequence Heating of Turbine Generator Rotors," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, No.8, pp. 3940-3949, August 1981.

[8] J. H. Dymond, R. Ong and N. Stranges, "Instrumentation, Testing, and Analysis of Electric Machine Rotor Steady-State Heating," *IEEE Transactions on Industry Applications*, Vol. 38, No. 6, pp. 1661-1667, November/December 2002.

[9] P. Mellor, D. Roberts, and D. Turner, "Lumped parameter thermal model for electrical machines of TEFC design," *IEE Proceedings-B*, Vol. 138, No. 5, pp. 205-218, September 1991.

[10] P. Mellor and D. Turner, "Real time prediction of temperature in an induction motor using microprocessor," *Electric Machines and Power Systems*, Vol. 13, pp. 333–352, 1988.

[11] A. Boglietti, A. Cavagnino, M. Lazzari, and M. Pastorelli, "A Simplified Thermal Model for Variable-Speed Self-Cooled Industrial Induction Motor," *IEEE Transactions on Industry Applications*, Vol. 39, No. 4, pp. 945-952, July/August 2003.

[12] M. J. Duran and J. Fernandez, "Lumped-Parameter Thermal Model for Induction Machines," *IEEE Transactions on Energy Conversion*, Vol. 19, No.4, pp. 791-792, December 2004.

[13] J. Trigeol, Y. Bertin and P. Lagonotte, "Thermal Modeling of an Induction Machine Through the Association of Two Numerical Approaches," *IEEE Transactions on Energy Conversion*, Vol. 21, No. 2, pp. 314-323, June 2006.

[14] S. S. Choi and X. M. Jia, "Under Excitation Limiter and Its Role in Preventhing Excessive Synchronous Generator Stator End-Core Heating," *IEEE Transactions on Power Systems*, Vol. 15, No. 1, pp. 95-101, February 2000.

[15] H. H. J. M. Janssen, E. J. W. ter Maten and D. van Houwelingen, "Simulation of Coupled Electromagnetic and Heat Dissipation Problems," *IEEE Transactions on Magnetics*, Vol. 30, No. 5, pp. 3331-3334, September 1994.

[16] A. F. Armor, "Transient, Three-Dimensional, Finite-Element Analysis of Heat Flow in Turbine-Generator Rotors," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-99, No. 3, pp. 934-946, May/June 1980.

[17] W. R. Lachs and D. Sutanto, "A Voltage Stability Indicator Based on Rotor Heating," *IEE 2nd International Conference on Advances in Power System Control, Operation and Management, Hong Kong*, December 1993.

CHAPTER 5

A METHOD TO CALCULATE HEATING PROBLEM OF CONVENTIONAL GENERATOR CAUSED BY WIND POWER GENERATION (II): EFFECT OF COOLING SYSTEM ON HEATING PROBLEM

5.1 Introduction

In power systems, the cooling system is a highly significant element for a generator and is installed in nearly all kinds of generating machines. The cooling system is used to absorb the heat produced by any part of the generator machine, which is based on convection theory of heating energy transfer, and maintain its temperature especially the rotor and stator parts in order to protect the insulation system. Taking away the heat and maintaining the machine under the heating limits are the necessary conditions for the proper operation of generators. In this way, a generator has the larger total capacity, the higher efficiency it has required. The mechanical structure of cooling system influences the windings distribution in rotor and stator, the mechanical design of generator and even power plant construction. And the operating characteristics and working condition of cooling system can also impact the operation performances and output range of generators. Even more, if there are any chemical defects or mechanical faults in the cooling system, the electrical energy supply may be forced to reduce or even interrupt until it returns to normal condition. [1, 2] As a result, cooling systems play a very important role in maintaining the electric power supply and even the power system stability.

After introducing a thermal model for generator and the calculation processes for temperature rise of the machine as the first step of calculating heating problem, the calculation of generator machine temperature rise can be obtained. If the temperature rise does not exceed the thermal capacity of cooling system, the cooling system can still absorb the extra heat energy and maintain the temperature of rotor and stator surface. And if the thermal capacity can not deal with the temperature rise, the generator machine will under suffer over-heating threat. For this situation, the index for judging the thermal capacity of cooling system is exceeded or not is the temperature of the coolant in the cooling system such as the cooling water of the water-cooled system. [1, 3] As a result, the temperature of coolant is the final calculating results in this chapter.

This chapter aims to introduce the second step of the method to calculate thermal performance of machine which bases on the first step of the calculated method and principles of heat transfer and thermodynamics. And it also improves the calculated method into a more suitable one for within mechanical structure and operating characteristics of cooling system to calculate its cooling effect on conventional synchronous generator machine. It will also introduce the heat exchange theories, the 3D steady state temperature field with boundary conditions and discuss the some liquid heat exchange convection coefficients which are usually used. And there is also a simulation example of the thermal performance of the synchronous generator machine in a power system with a wind farm.

5.2 Types of Cooling System in Generator Machine

In order to remove the heat in the stator and rotor, it is necessary to install cooling system in generators which can include air-cooled, hydrogen-cooled or water-cooled system. On small machines, which have output around 50-200 MW, usually use air cooling in open cycle or closed cycle. As both the capacity and size of generator increases to 200-500 MW such as some combined cycle gas turbine generators (CCGTs), hydrogen gas cooling is used, hydrogen gas has a very high coefficient of heat capacity and low density to get higher efficiency cooling effect. And for generators with larger capacity than 500MW, they usually use water cooled system, which has better cooling capabilities than the other two cooling methods, because of the requirement of reliability. [2]

5.2.1 Air-cooled System

Air-cooled systems are an ideal choice for small capacity generators and power system applications which demand simplicity and flexibility of operation. Air-cooled generators are cooled by forced air provided by fans installed on rotor shaft.

And this cooling system can operate under either open-loop or closed-loop condition. Under the open-loop system, the generator draws air from the atmosphere to cool its active components and then it exhausts the air back into the atmosphere. In another way, under the closed-loop system, cooling air is circulated continuously through the generator while hot generator exhaust air is cooled by flowing through water-to-air heat exchangers before returning to generator inlet so this is also called water-to-air cooled (TEWAC) system.

Because of the absence of a pressurised atmosphere for air-cooled system within the generator, the structure of components of air-cooled generator is simple and easy to handle and the routine maintenance is convenient. As a result, this characteristic supports these small capacity generators to suit peaking duty of electrical energy supply which requires generators can be load cycled freely during operation.

Furthermore, the potential for severe corona discharge damage is a challenge to the design of air-cooled system so it requires good condition insulating systems and voltage-grading materials to ensure generators avoid from damaging corona activity. [3]

5.2.2 Hydrogen-cooled System

As a coolant, hydrogen has three outstanding properties, low density, high specific heat and thermal conductivity which make it a superior coolant and a compact, highly efficient and reliable design for rotating electrical machines.

In this cooling system, hydrogen gas is circulated in a closed loop within the generator to remove heat from its actives parts, and then it is cooled by water-to-gas heat exchangers which are part of the stator mechanical structure. For safety reasons, the mechanical structure needs to be tightly sealed to prevent gas leakage so oil seals are installed on the shaft at each end of the stator to prevent leakage as a part of stator mechanical structure. So the interior of the hydrogen-cooled generator is completely sealed from the atmosphere and dust, humidity, salt or chemicals have no effect on the machine.

As a result, the high-voltage insulation system of generator will not be damaged by corona activity in the stator windings of generator for the absence of oxygen in its cooling hydrogen gas. This is a significant factor in the reliability of machine. [2]

5.2.3 Water-cooled System

Water-cooled systems, which have larger cooling capability than air-cooled or hydrogen-cooled system, are exceptionally suited to large capacity generators and applications such as central power stations. Water as the coolant has a lot of advantages because its specific heat is large and the viscosity of water is small which means the flowing character is very good.

The water-cooled system is that the continual high level of pure water flow passes through the waterway in stator and rotor to take away heat inside the generator. The cooling water is clean chemical dechloridation water which is from chemical workshop and supplement water will be processed in ion exchanger and water filter before it is filled to water tank. The cooling water in tank will be forced into generator by pump.

After cooling the generator, heated cooling water out of generator is cooled by cooling apparatus and goes back to water tank again. [4, 5] And the basic component of water cooled system and cooling water flow are shown on Fig. 5.1: [2, 4]

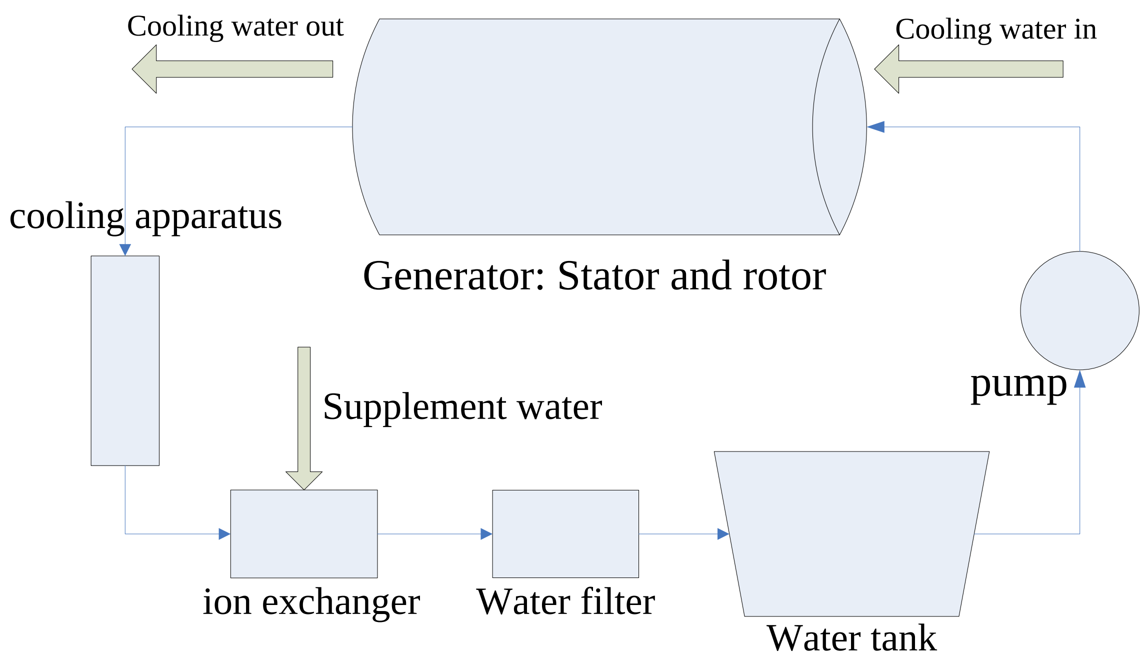

Fig. 5.1 Basic component of water cooling system and cooling water flow.

Because high-output generators are very important to the overall stability of the grid, reliability is a primary requirement of water cooled system. The cooling water is always under the high pressure and is provided by pumps so water leakage problem could become very serious in water cooled system. Optimising of cooling system design is required to maintain its reliability and improve its performance. Moreover, the oxygenic ion and impurity in the cooling water also leads the corrosion of pipes of cooling system and oxidation of machine material. As a result, the cooling water must be processed by chemical dechloridation before being infused into the circulating loop and also need a set of complicated water purifying system. [4, 5]

The last chapter had discussed that the insulation systems of windings on rotor and stator are the weakest part of the machine from a thermal point of view. As a result, cooling the insulation systems of windings is the most significant function of cooling system to protect the insulation system.

For water-cooled system, the cooling water is divided into plenty of small pipes as waterways which distributed in the windings of rotor and stator equally. A waterway pipe is usually grouped with several windings to absorb the heat from them and the surface of rotor and stator. [2, 6, 7]

5.3 The 3D Steady State Temperature Field

In this thesis, the researches mainly focus on high-output water-cooled generators so the thermal model and calculation processes of cooling system is depending on the water-cooled system to be analysed. According to waterway structure which had mentioned above, it requires a three-dimensional model to describe the processes of heating energy dissipation and absorption between machine and water-cooled system.

The 3D steady state temperature field in x, y and z three directions can be used to describe the heat transfer in a certain space. And in this thesis, it is used to describe the heat transfer between the machine and cooling system. [8, 9, 10]

$\nabla \bullet (\lambda \nabla T) = -p_h$ also as

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) + p_h = 0$$

where λ_x, λ_y and λ_z are the thermal conductive coefficient in x, y and z directions respectively, $\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)$ is used to describe the heating transfer process in the x direction , T is temperature of material and P_h is the density of heat. As a result, the 3D thermal model describes the processes for different directions.

And this 3D thermal model requires determining the solution region and boundary conditions to definition the range of heating transfer space and calculating conditions. And these are determined as follows:

1. First boundary conditions:

$$T|_{S1} = T_{S1}$$

It means that S_1 is the first boundary of a thermal insulating surface which keeps constant temperature and T_{S1} is the known temperature of boundary S_1. This region and boundary condition is used to describe the surrounding environment around the machine. In this thesis, the first boundary is the one between rotor, stator of the machine and the insulation system. Assumed the temperature of this boundary follows the temperature of rotor and stator, so machine and the insulation system have the same temperature.

2. Second boundary conditions:

$$\lambda_n \frac{\partial T}{\partial n}|_{S2} = -\alpha_{CCW}(T - T_W)$$

It means that the heat flow transfer from inside to S_2 the second boundary of a thermal insulating surfaces equal to the heat flow transfer to medium around; and λ_n is the thermal conductive coefficient in a certain direction; α_{ccw} is the convection heat transfer coefficient of water and its range are within 500-10,000 $W/m^2 \cdot ℃$; T_w is the water temperature. This region and boundary condition is used to describe the heat transfer from the heat source to cooling system coolant. [10] In this thesis, the second boundary is the surfaces of pipe of cooling system and the insulation system on machine. In this boundary, the thermal energy transfers across this boundary and it also leads the temperature changing of coolant in cooling system.

3. Third boundary conditions:

$$\lambda_n \frac{\partial T}{\partial n}|_{S3} = 0$$

It means that S_3 is the third boundary of a thermal insulating surface with no heat transfer. This region and boundary condition is used to describe the thermal insulation condition. In this thesis, the third boundary is the one between insulation system and the surrounding environment. Assumed there is no heating transfer between these two areas so the only way to transfer the thermal energy is relied on the cooling system.

As a result, the equation of 3D steady state temperature field together with boundary conditions can be described as:

$$\begin{cases} \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) = -p_h \\ T\big|_{S1} = T_{S1} \\ \lambda_n \frac{\partial T}{\partial n}\big|_{S2} = -\alpha_{CCW}\left(T - T_W\right) \\ \lambda_n \frac{\partial T}{\partial n}\big|_{S3} = 0 \end{cases} \qquad \text{Equation 5.1}$$

This equation with three boundary conditions is the basic theoretical principle which describes the heating source and its surrounding of the machine.

5.4 The Calculation of Temperature Rise of Coolant in Cooling System

Under well-working condition, the temperatures of stator and rotor are maintained stably by the cooling system. The heat is taken away from machine and absorbed into coolant of cooling system. As a result, the temperature rise of cooling water is considered as an important index of heating condition of generator machine. There is also a limitation about temperature rise of cooling water to quantify the thermal effects.

To calculate the temperature rise of cooling water, there are some fundamental hypothesises which accord to 3D steady state temperature model: [10]

1. The transfers of heat energy to every direction of surrounding are equal.

2. There is the thermal insulation boundary outside the water-cooled system so the only path to transfer the heat energy is from stator and rotor to cooling system.

3. All the heat energy which is produced inside the machine is taken away by cooling water.

4. The temperature of environment around the machine is constant.

5.4.1 Temperature Distribution of Coolant in Cooling System

According to second boundary condition in 3D steady state temperature model, heat transfer between machine and cooling coolant is studied in more detail below.

Firstly, cooling water goes through the waterway, which the whole length is L_C, so the heat transfers from rotor and stator to cooling water Q_1 when cooling water flow passes a certain length dx can be obtained: [11, 12]

$$dQ_1 = \alpha_{CCW} S_l \left(T_{GM} - T_W\right) dx$$

where T_{GM} is the temperature inside the machine and S_l is the perimeter of transversal section of waterway.

Secondly, the heat absorbed by cooling water Q_2 when the water flow passes a certain length dx can be obtained:

$$dQ_2 = W_{mr} c_W dT_W$$

W_{mr} is the cooling water mass flow rate, c_w is the specific heat of cooling water at constant pressure and dT_W is the temperature rise of water temperature after cooling water flow passes a certain length dx.

Then, when the heat transfer is at the steady state, there is

$$\alpha_{CCW} S_l (T_{GM} - T_W) dx = W_{mr} c_W dT_W$$

$$\frac{dT_W}{T_{GM} - T_W} = \frac{\alpha_{CCW} S_l}{W_{mr} c_W} dx \text{, if } \frac{\alpha_{CCW} S_l L_C}{W_{mr} c_W} = NTU \text{,}$$

$$\frac{dT_W}{T_{GM} - T_W} = \frac{NTU}{L_C} dx \qquad \text{Equation 5.2}$$

L_C is the length of waterway and NTU is the number of heat transfer units. The NTU is a dimensionless parameter which is as a measure of the heat transfer size of the exchanger used widely in the analysis of heat exchangers. [7, 11, 13]

At last, both sides of Equation 5.2 can be integrated over T_W and x to yield the cooling water temperature distribution: [11, 12]

$$\int \frac{dT_W}{T_{GM} - T_W} = \int \frac{NTU}{L_C} dx$$

$$\int \frac{dT_W}{T_{GM} - T_W} = \int_{T_{in}}^{T_W} \frac{dT_W}{T_{GM} - T_W}$$
$$= \int_{T_{GM} - T_{in}}^{T_{GM} - T_W} \frac{-dy}{y}, (y = T_{GM} - T_W; dy = -dT_W) = -\ln \frac{T_{GM} - T_W}{T_{GM} - T_{in}}$$

$$\int \frac{NTU}{L_C} dx = \int_0^x \frac{NTU}{L_C} dx = \frac{NTU}{L_C} x$$

so $$-\ln\frac{T_{GM}-T_W}{T_{GM}-T_{in}}=\frac{NTU}{L_C}x,\ \frac{T_{GM}-T_W}{T_{GM}-T_{in}}=e^{-\frac{NTU}{L_C}x},$$

$$T_W=T_{GM}-\left(T_{GM}-T_{in}\right)e^{-\frac{NTU}{L_C}x} \qquad \text{Equation 5.3}$$

T_{in} is the inlet temperature of cooling water T_{out} is the outlet temperature of cooling water which has already passed the machine.

Finally, when $x=L_C$, $T_W=T_{out}$ the final equation of cooling water can be obtained:

$$T_{out}=T_{GM}-\left(T_{GM}-T_{in}\right)e^{-NTU} \qquad \text{Equation 5.4}$$

The Equation 5.4 can be used to calculate the temperature changes of cooling water in the cooling system. As an example, in the Fig. 5.2, it shows a pipe model of the waterway of cooling water and also marks the water flow direction. And according to Equation 5.4, the temperature distribution curve of cooling water inside the pipe of waterway under different NTU values can be obtained and shows on Fig. 5.3. [14, 15]

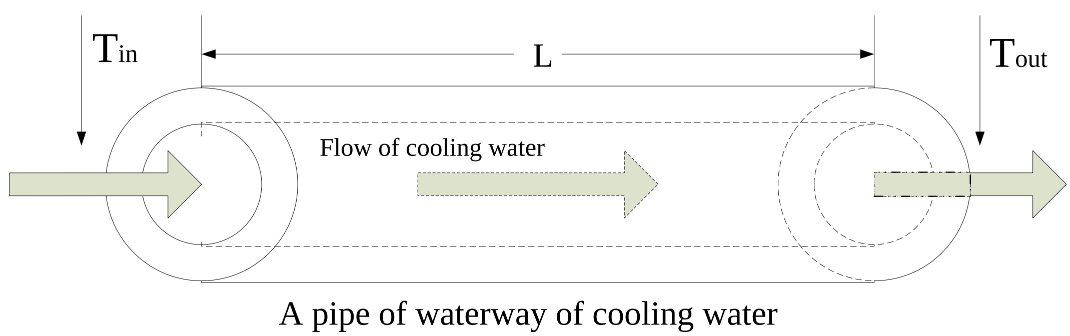

Fig. 5.2 Pipe model of the waterway of cooling water.

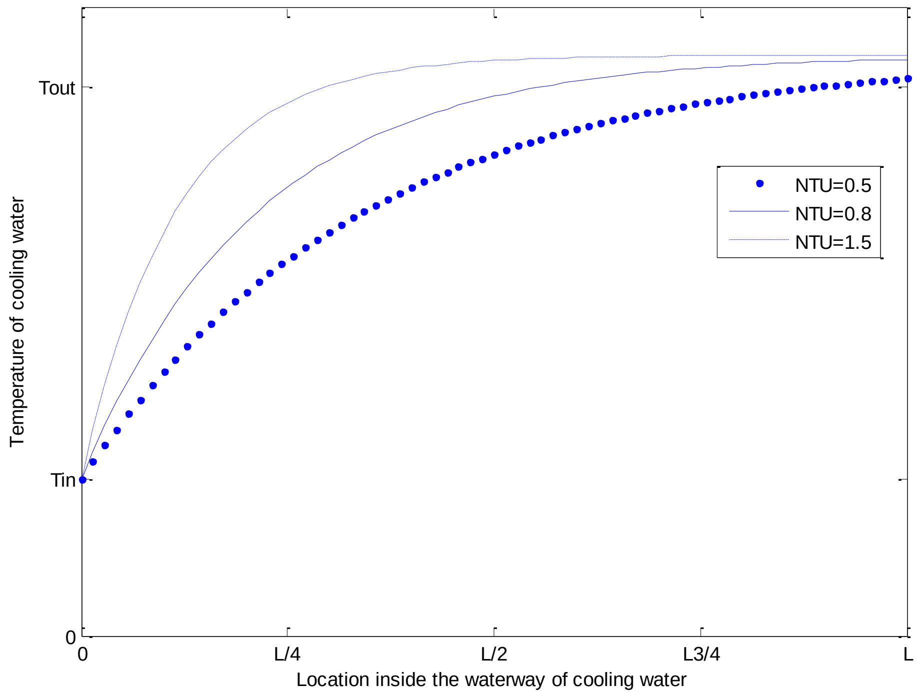

Fig. 5.3 The temperature distribution of cooling water inside the waterway under different NTUs .[15]

From the curves, these express that the temperature of cooling water keeps increasing when the cooling water flows under a certain speed and go through the pipe in the cooling system. Before cooling water enter the pipe, the temperature of the water is T_{in} and after the heat exchange process, the temperature is increased to T_{out}. Moreover, these curves also indicate the NTU value has certain influence on the shape of temperature distribution curve. For smaller NTU value, the curve is trends to be more linear. On the contrary, larger NTU value makes the curve is more saturate. According to the heat transfer theories [7, 10], the larger the value of NTU, the closer the heat exchanger approaches its thermodynamic limit and a well-designed cooling system should avoid reaching this limit.

To protect the cooling water under good condition, there are limits of T_{in} and T_{out} to maintain the cooling effects. If the temperature of cooling water exceeds these limits especially T_{out} limitation, the heat exchange capability may reach its saturation which could cause the cooling system loss its cooling ability for generator machine. When the limits are broken, the overheating protection installed in cooling system will operate to reduce the load on generator to decrease the temperature of generator machine. In the calculation of cooling system, the T_{in} is usually considered as being kept constant unless there are any disturbances in the circulation of cooling water. [2, 11]

5.4.2 The Determination of Coolant Convection Coefficient

From Equation 5.4, it shows that calculating the number of heat transfer units NTU is essential for evaluation of cooling water condition. Moreover, determination of the convection heat transfer coefficient of water α_{ccw} is the key issue for the calculation of the NTU.

For water-cooled system, the heat transfer is internal forced convection and occurs between the inside surface of the pipe of cooling system and the coolant. As a result, α_{ccw} can be obtained according to the equations of several important parameters in heat transfer theory: [10, 13]

1. Reynold number Re:

$$\mathrm{Re} = \frac{W_{mr} D_H}{\mu_W A_{CS}} \qquad \text{Equation 5.5}$$

W_{mr} is the cooling water mass flow rate, Re number is one of many dimensionless parameters used in fluid mechanics and heat transfer and it can describe the behaviour of the fluid within the boundary layer such as flow over a flat surface. D_H is the equivalent hydraulic diameter of waterway, μ_W is the viscosity of cooling water which is a measure of resistance to flow of a fluid and A_{CS} is the cross-sectional area of water flow.

Physically, Re number is the ratio of the inertia force to the viscous force in the boundary layer. A large Reynold number indicates that inertia forces are dominant, whereas a small Reynold number indicates that viscous forces are dominant. For flow in a pipe, laminar flow occurs when $\mathrm{Re} < 2300$ and turbulent flow occurs when $\mathrm{Re} > 4000$. In the interval between 2300 and 4000, laminar and turbulent flows are depending on other factors, such as pipe roughness and flow uniformity.

2. Nusselt number Nu:

$$Nu = \frac{\alpha_{CCW} D_H}{K_W} \qquad \text{Equation 5.6}$$

Nu number is interpreted as a dimensionless parameter of temperature gradient at the surface and it provides a measure of the convective heat transfer at the surface. K_W is thermal conductivity of water.

Normally the Nusselt number for water flow is typically under 100 with laminar flow and in the 100-1000 range with turbulent flow; for gas or air the Nusselt number is around 1. A large Nusselt number indicates a large temperature gradient at the surface and high heat transfer by convection.

3. Prandtl Number Pr:

$$\Pr = \frac{c_W \mu_W}{K_W} \qquad \text{Equation 5.7}$$

Pr number is interpreted physically as the ratio of the rate of velocity effect and the rate of convection effect at layer surface and c_w is the specific heat of cooling water at constant pressure. The size of the Prandtl number is an indication of the relative rates of growth of the velocity and convection effect at the layer surface. For most liquid, Pr number is normally greater than 1. The typical range of Prandtl number for gas or air is from 0.7 to 0.8 and is around 7 for water.

And according to one of the most widely used relationship of these important parameters, the equation also can be written as: [7]

$$Nu = 0.023 \mathrm{Re}^{0.8} \Pr^{0.4} \qquad \text{Equation 5.8}$$

As a result, the convection heat transfer coefficient of water can be described as:

$$\alpha_{CCW} = \frac{K_W}{D_H} Nu$$

$$\alpha_{CCW} = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \frac{K_W}{D_H} \qquad \text{Equation 5.9}$$

And the number of heat transfer units NTU can be described as:

$$NTU = \frac{0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \frac{K_W}{D_H} S_l L_C}{W_{mr} c_W}$$

$$= \frac{0.023 \left(\frac{W_{mr} D_H}{\mu_W A_{CS}} \right)^{0.8} \left(\frac{c_W \mu_W}{K_W} \right)^{0.4} \frac{K_W}{D_H} S_l L_C}{W_{mr} c_W} \qquad \text{Equation 5.10}$$

S_l is the perimeter of transversal section of waterway and L_C is the length of waterway. Through this method and based on parameters of cooling water and cooling system mechanical structure data, the convection coefficient of water α_{ccw} and the number of heat transfer units NTU can be calculated.

As previously mentioned, there are many small pipes as waterways which distributed in the windings of rotor and stator equally in water-cooled system to absorb heat. According to heat exchange theories [7, 10], NTU must be replaced by NTU/n under this kind of mechanical structure, where n is the number of waterways which are parallel in one heat exchange unit. Based on Equation 5.5 to Equation 5.10, the calculation process of coolant convection coefficient is obtained and is shown in the next section. At last, the Equation 5.4, which is calculating equation of cooling water way-out temperature T_{out}, is completed by adding the convection coefficient of cooling water and the calculation processes are also shown in the next section.

5.5 Cooling System Effect Calculation Process

The flowcharts which describe the calculation program of coolant convection coefficient and the calculation processes of cooling water way-out temperature T_{out} are shown in Fig. 5.4 and Fig. 5.5 respectively:

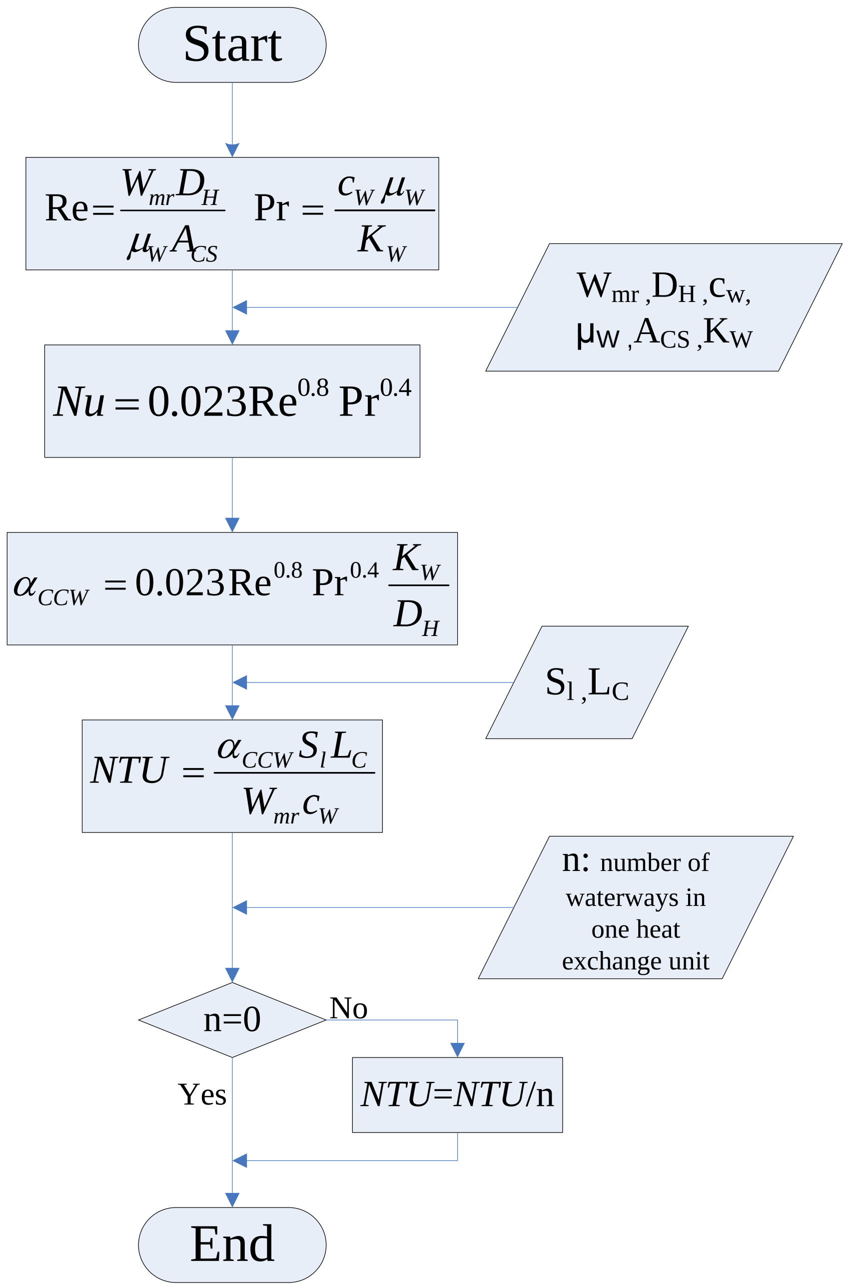

Fig. 5.4 Flowchart of the number of heat transfer units NTU calculation program.

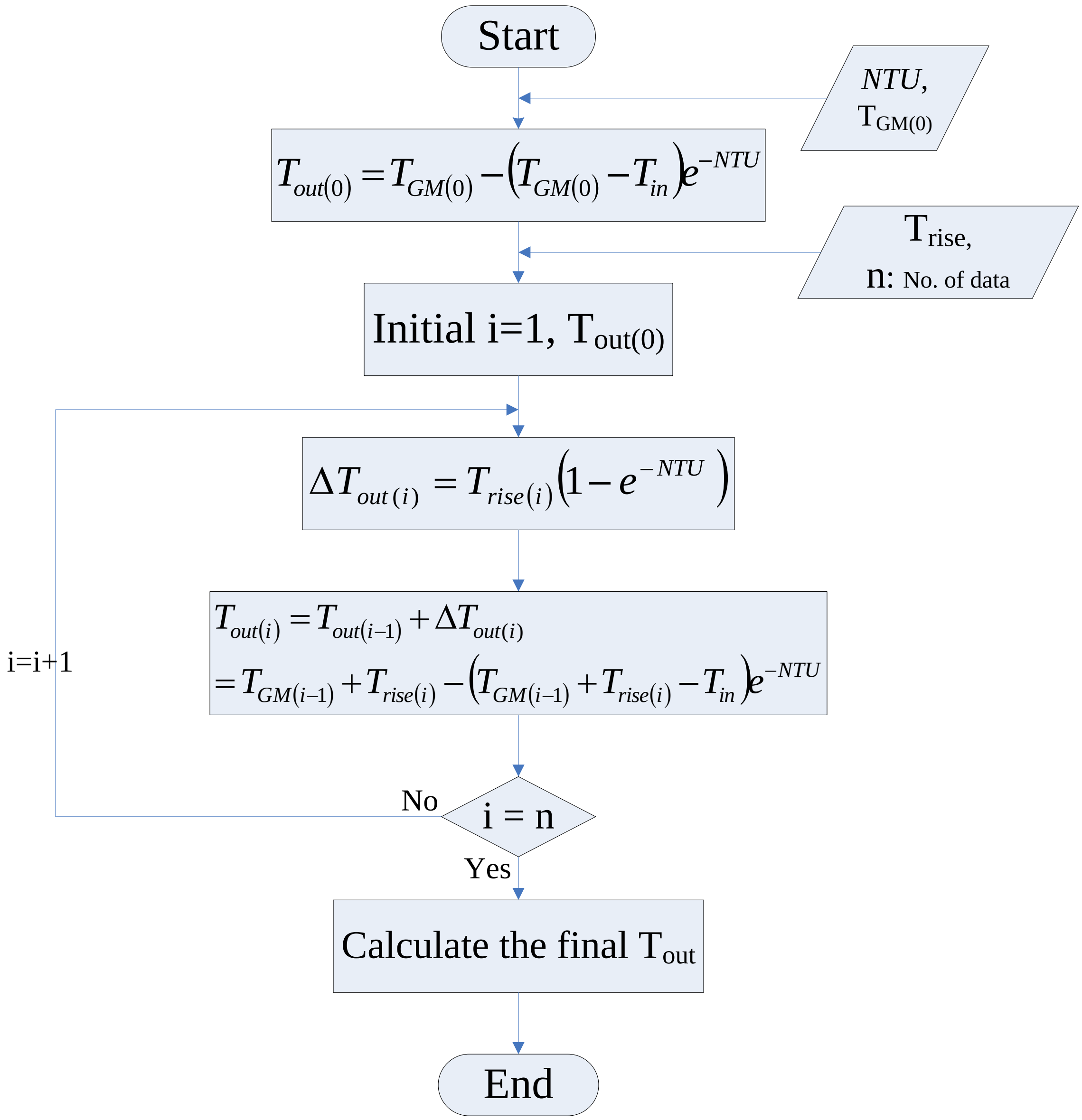

Fig. 5.5 Flowchart of the cooling water way-out temperature Tout calculation processes.

After analysing cooling system effects, the method to calculate heating problem of conventional generator caused by wind power generation is completed. The whole calculation method of thermal performance can be divided into three parts which are calculations of machine effects, coolant convection coefficient and cooling system effects. At first, the temperature rise results of rotor and stator of a synchronous generator T_{rise} are based on the calculation processes and program introduced at Section 4.7 of Chapter 4.

And then, the calculation of the number of heat transfer units NTU follows the processes which are listed in Fig. 5.4. The collections of mechanical structure data of cooling system and thermodynamic information of coolant are very essential for this part of calculation.

At last, as list in Fig. 5.5, the calculation of cooling system effects is also relied on Matlab program. Firstly, using the calculating results of NTU and steady state temperature of rotor and stator $T_{GM(0)}$, steady state way-out temperature of cooling water $T_{out(0)}$ is calculated. Then, the calculated temperature rise results of machine T_{rise} are collected. And based on these input data, every corresponding results of way-out temperature $T_{out(i)}$ and way-out temperature rise $\Delta T_{out(i)}$ can be calculated through the program. Finally, after the whole calculating processes are competed, the final way-out temperature T_{out} and way-out temperature rise of cooling water ΔT_{out} for the whole data collection period can be obtained.

At the next section, there is a simulation example which uses this method to analyse the thermal performance of a conventional synchronous generator in a power system with wind power generation which has fluctuating output.

5.6 Example of Calculation of Temperature Rise and Cooling System Effects in Synchronous Generator

After the calculation processes of cooling system effects are introduced, the analyses about the influences from wind power generation to conventional generators can be completed finally. This example will follow the processes described above and use the calculation method introduced in the last and this chapter.

In this example, the calculating programs are programmed and operated in Matlab. And the input data are rotor current, stator current and power angle data for 24 hours of a synchronous generator of Section 4.5 of Chapter 4. Moreover, in order to represent the calculating results more distinctly and comparable, the time periods of calculation focus on every hour and the results are also represented for every hourly.

5.6.1 Calculation of Temperature Rise in Rotor and Stator of a Synchronous Generator

Because the input data of rotor current, stator current and power angle are simulated at Section 4.5, the synchronous generator machine model introduced in the last chapter is still used in this example. And the information and data for temperature rise calculation are listed in Table 5.1: [16, 17]

Table 5.1 The information and data of synchronous generator and heating transfer indexes for temperature rise calculation of generator machine in Section 5.6

Symbol	Information	Data
$K_TN_r^2$	a_1 of [a_1 a_2 a_3]	3.03×10^{-2}
$K_TN_s^2$	a_2 of [a_1 a_2 a_3]	0.11
$K_TN_rN_s$	a_3 of [a_1 a_2 a_3]	5.8×10^{-2}
X_d	the reactance of generator machine	1.305 p.u.
X_{ad}	the armature reactance of generator machine	≈ Xd
θ_f	the power factor	0.95
T_{akb}	the maximum ambient temperature	40 ℃
α_w	the proportionality constant between heat energy and temperature	3.33×10^{-3} MW/ ℃ (1/300 MW/ ℃)
$H_{Thermal}$	the thermal inertia constant	2 MW s/ ℃

Based on these data and the calculation processes, the results can be obtained and are shown from Fig. 5.6 to 5.8:

Fig. 5.6 shows that the stable temperature of the 1000MW conventional generator at constant output of 850MW with a 150MW constant output wind turbine generation in the power system is 72 ℃.

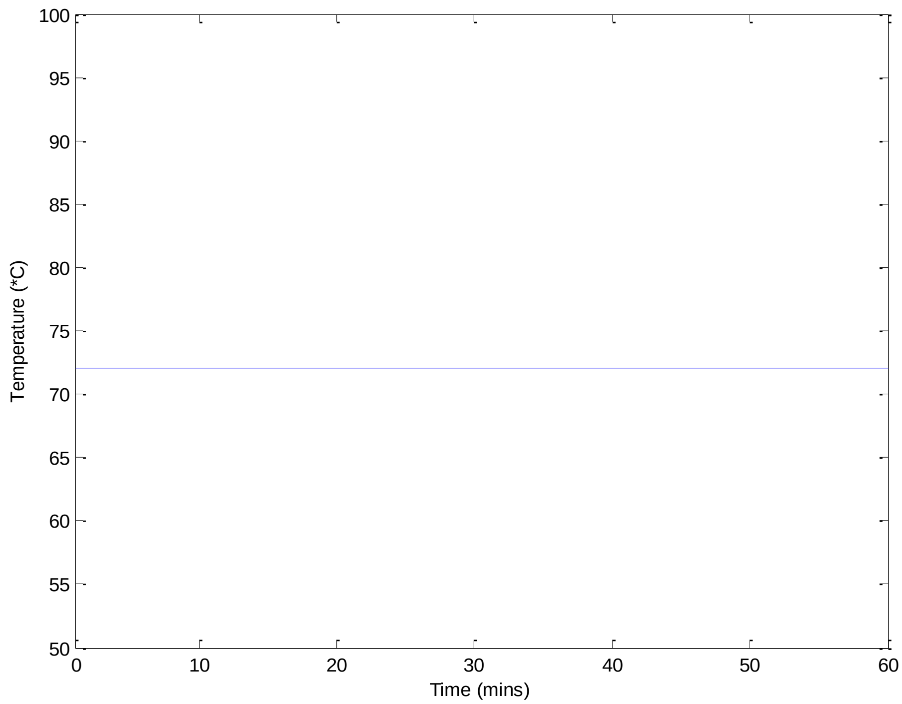

Fig. 5.6 The stable temperature of 1000MW conventional generator at constant output 850MW.

In fact, the temperature rise is continuative effect to the machine so the calculated results for this example are continual in 24 hours. However, the simulation and calculating processes are very complicated and the quantity of data are also very huge so the simulation is divide into every one hour to calculate the heating effect. In addition, for more clear about the representing and comparing of simulation results and also highlighting the results in different time periods, the temperature rise calculating results are shown in every hour for 24 hours. Fig. 5.7(a) to Fig. 5.7(f) show changing processes of calculated temperature rise of the machine in every one hour for 24 hours. And Fig. 5.8(a) and Fig. 5.8(b) represent and compare the final temperature rise results for every hour in a day respectively.

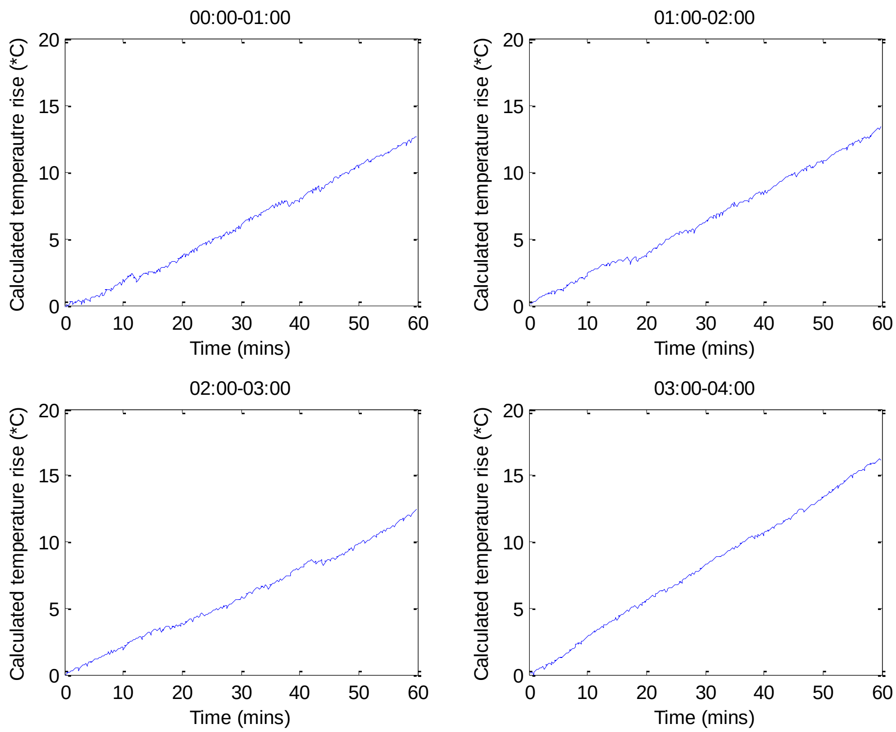

Fig. 5.7(a) Calculated temperature rise of machine for one hour of 00:00-04:00.

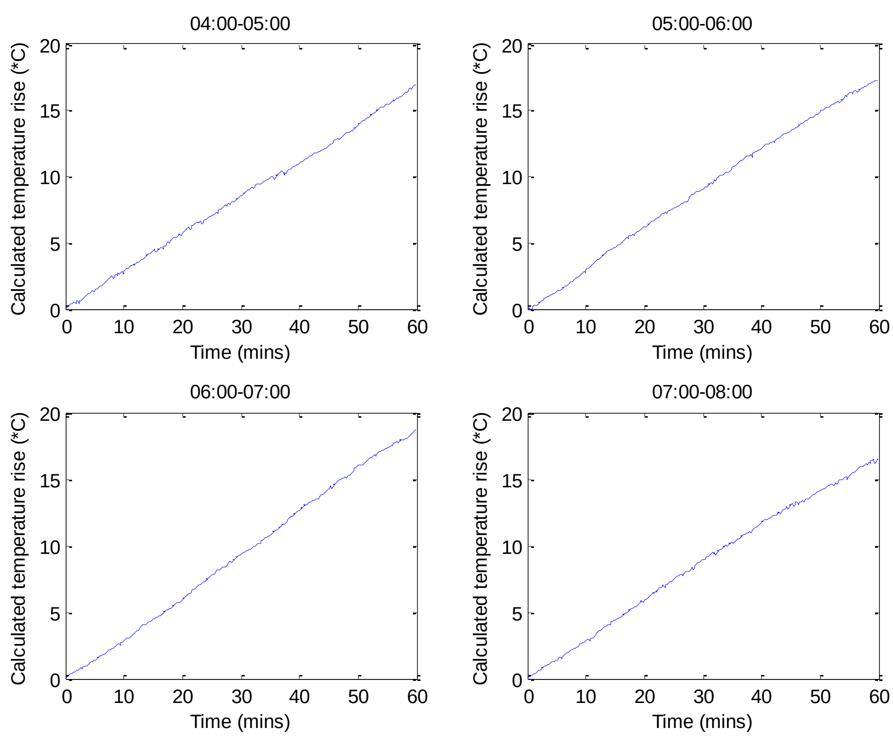

Fig. 5.7(b) Calculated temperature rise of machine for one hour of 04:00-08:00.

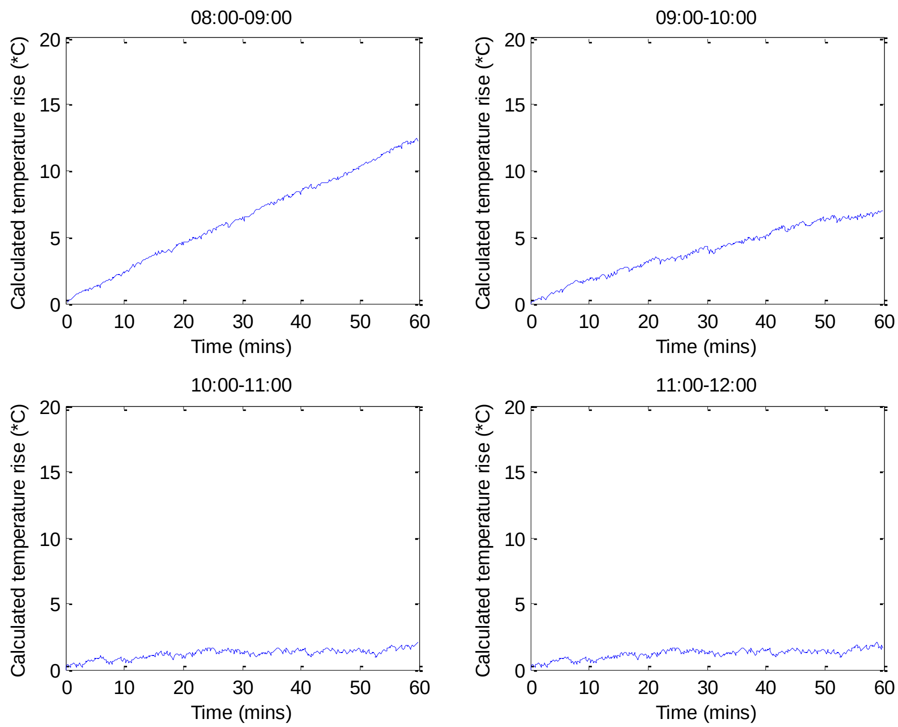

Fig. 5.7(c) Calculated temperature rise of machine for one hour of 08:00-12:00.

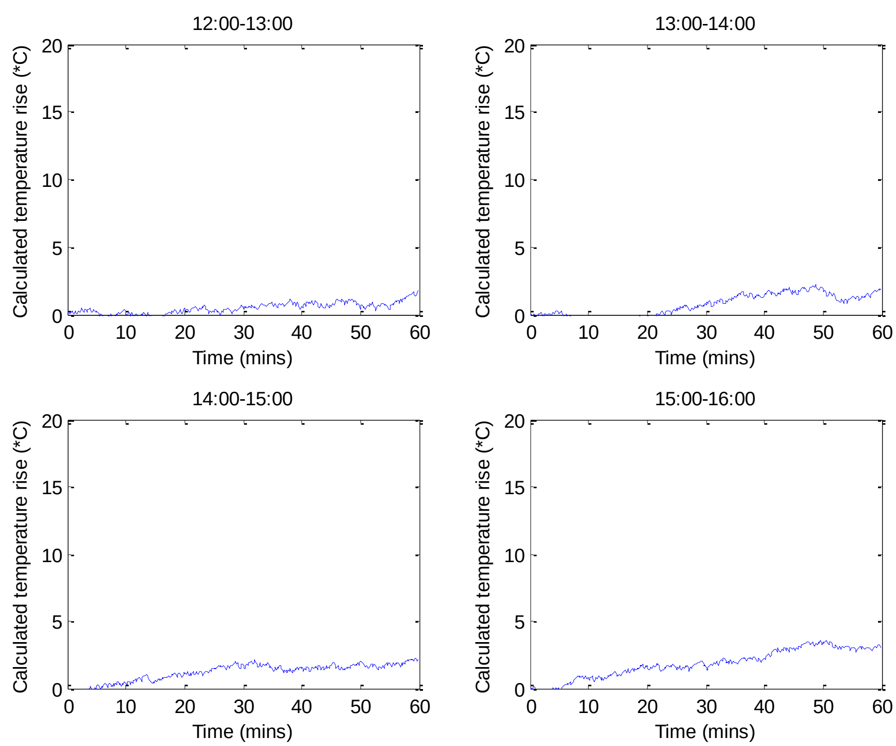

Fig. 5.7(d) Calculated temperature rise of machine for one hour of 12:00-16:00.

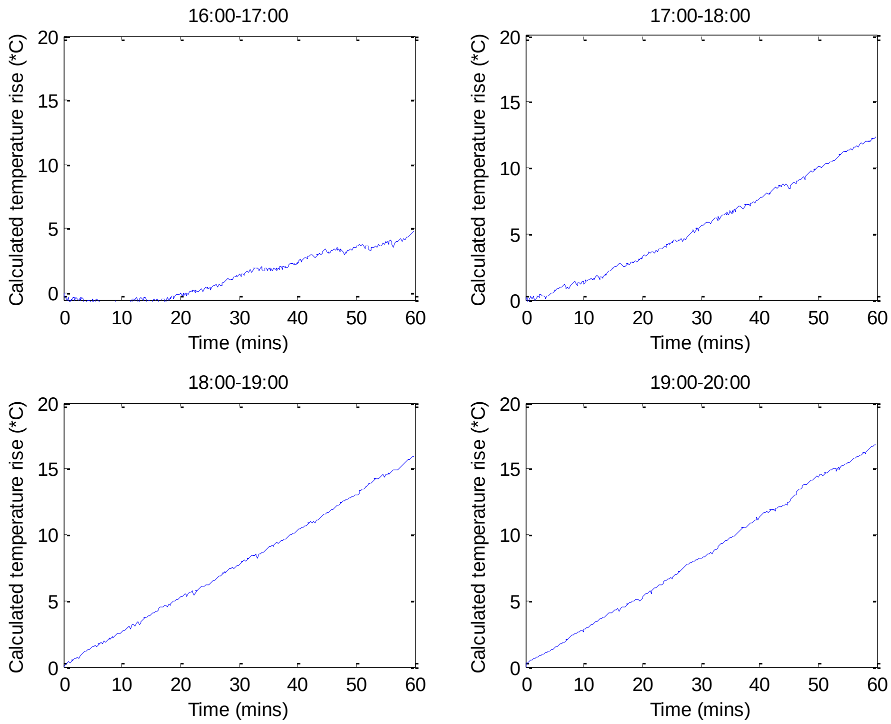

Fig. 5.7(e) Calculated temperature rise of machine for one hour of 16:00-20:00.

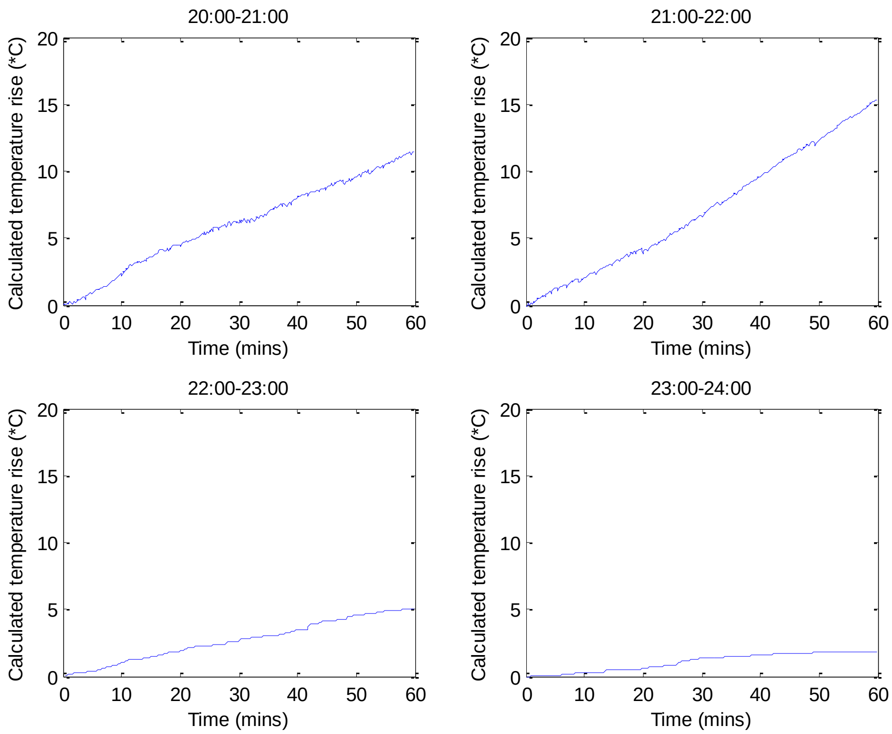

Fig. 5.7(f) Calculated temperature rise of machine for one hour of 20:00-24:00.

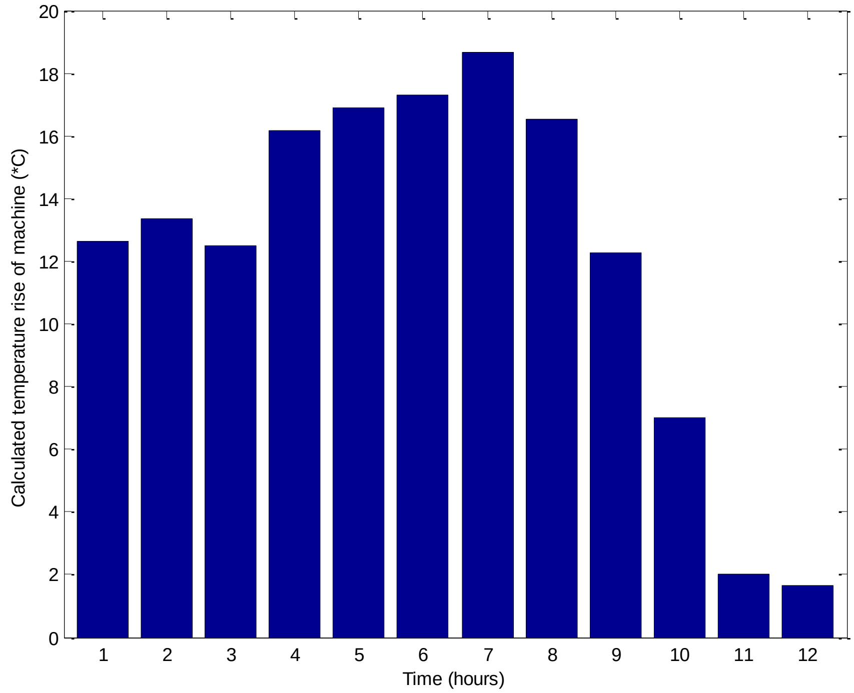

Fig. 5.8(a) Calculated temperature rise of machine in every one hour at 00:00-12:00.

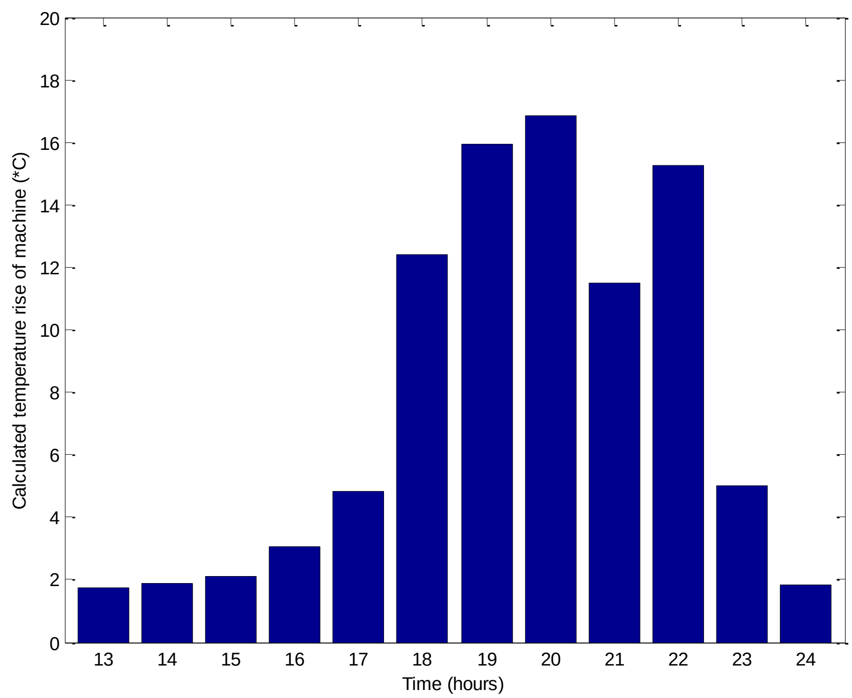

Fig. 5.8(b) Calculated temperature rise of machine in every one hour at 12:00-24:00.

5.6.2 Calculation of Coolant Convection Coefficient and Cooling System Effects

According to [2, 7, 13, 18], Table 5.2 lists the information and data for calculation of cooling system.

Table 5.2 The information and data of water-cooled system and cooling water for calculation of heat exchange index in Section 5.6

Symbol	Information	Data
W_{mr}	the cooling water mass flow rate	0.0255 m^3/s (or 0.0255 kg/s, 90 t/h)
S_l	the perimeter of transversal section of waterway	3.142×10^{-2} m
L_C	the length of waterway	18 m
D_H	the equivalent hydraulic diameter of waterway	1.0×10^{-2} m (10 mm)
A_{CS}	the cross-sectional area of water flow	7.854×10^{-5} m^2
limit of T_{in}	the maximum allow temperature of cooling water which get into the machine before	45 ℃
limit of T_{out}	the maximum allow temperature of cooling water which has passed the machine	73 ℃
n	the number of waterways which are parallel in one heat exchange unit	84
c_w	the specific heat of cooling water at constant pressure	4.2×10^3 J/kg ·℃
μ_W	the viscosity of cooling water	8.0×10^{-4} kg/m s
K_W	the thermal conductivity of water	0.6 W/m•ºC

Based on these data, coolant convection coefficients can be calculated and are listed in Table 5.3.

Table 5.3 The calculated results of water-cooled system heat exchange indexes in Section 5.6

Symbol	Information	Calculated results
Re	Reynold number	4058
Nu	Nusselt number	35.29
Pr	Prandtl number	5.6
α_{ccw}	the convection heat transfer coefficient of water	5163
NTU	the number of heat transfer units	0.325

Based on the calculated results of temperature rise and NTU above and following the calculation processes, the final results can be obtain and are shown in Fig. 5.9 to 5.11:

Fig. 5.9 shows the stable temperature of cooling water way-out temperature is 52.5 ℃ in a 1000MW conventional generator at constant output of 850MW with a 150MW constant output wind turbine generation in the power system. And the limits of inlet and outlet temperature 45 ℃ and 73 ℃ are also shown in the figure.

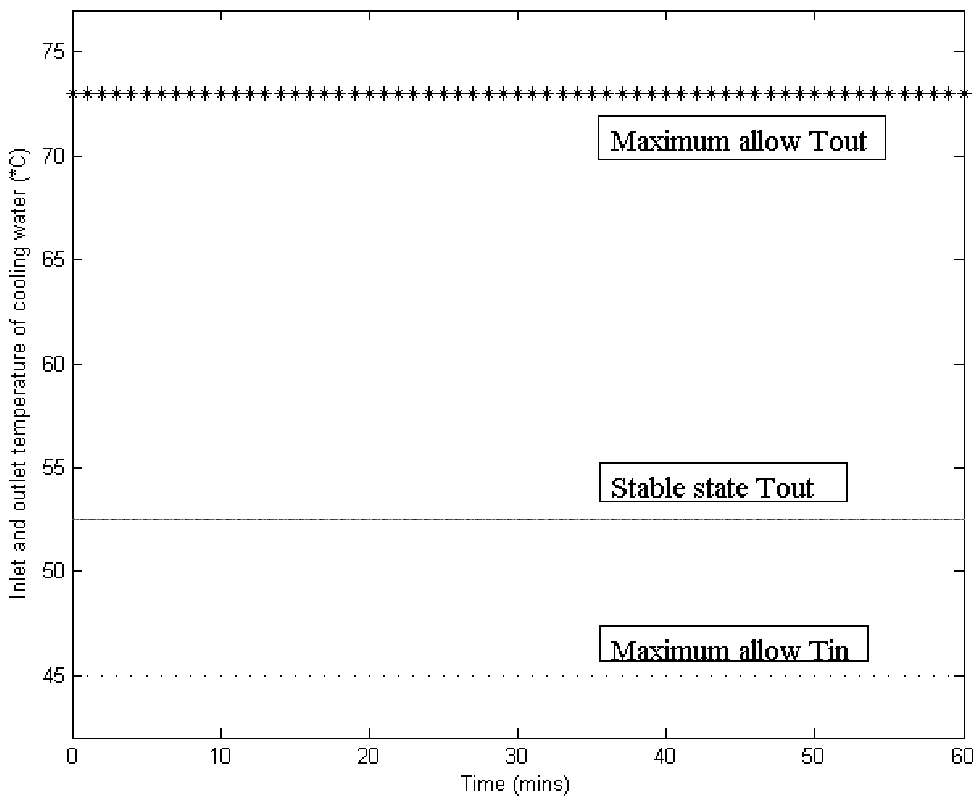

Fig. 5.9 Cooling water inlet and outlet temperature limits and the stable outlet temperature in a 1000MW conventional generator at constant output 850.

Similarly with the calculating results of temperature rise of machine in last example, the 24 hours continuative cooling water outlet temperature rise simulation results of this example are calculated and also shown in every hour. Fig. 5.10(a) to Fig. 5.10(f) show changing processes of calculated way-out temperature rise of cooling water in every one hour for 24 hours. Fig. 5.11(a) and Fig. 5.11(b) represent and compare the final way-out temperature rise of cooling water for every hour in a day.

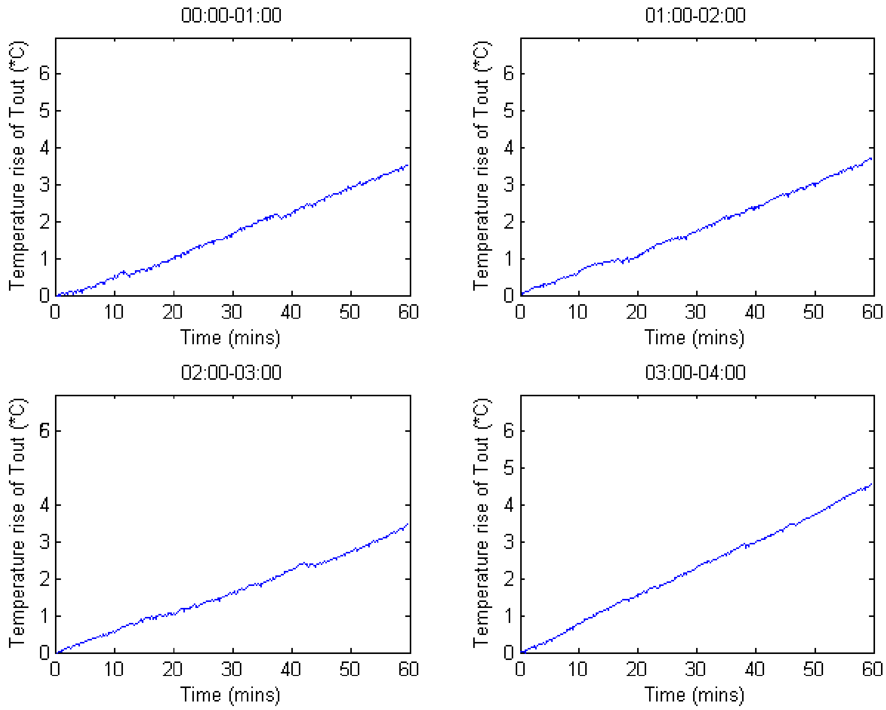

Fig. 5.10(a) Calculated way-out temperature rise of cooling water for one hour of 00:00-04:00.

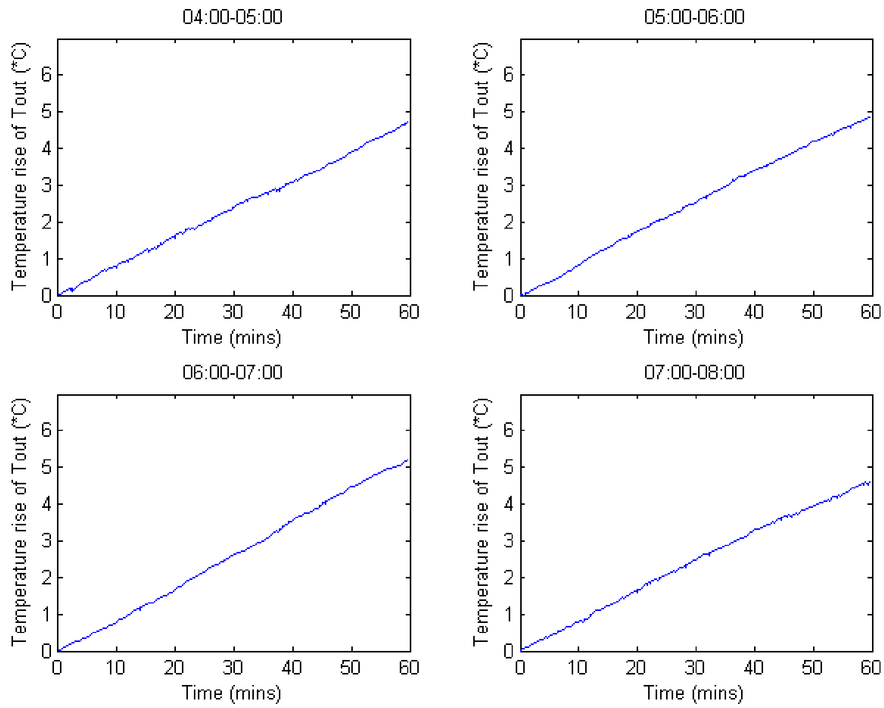

Fig. 5.10(b) Calculated way-out temperature rise of cooling water for one hour of 04:00-08:00.

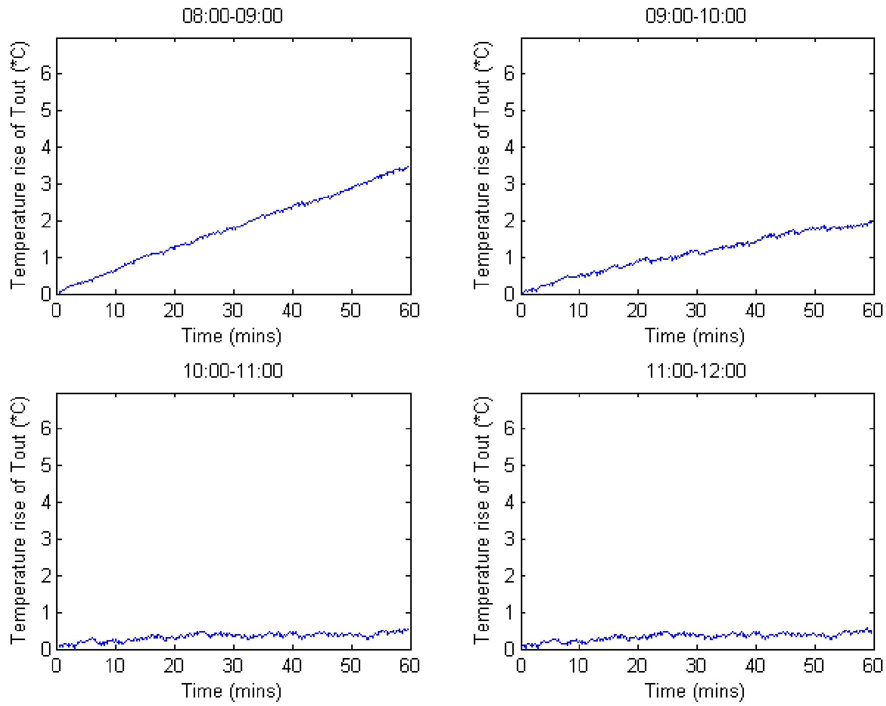

Fig. 5.10(c) Calculated way-out temperature rise of cooling water for one hour of 08:00-12:00.

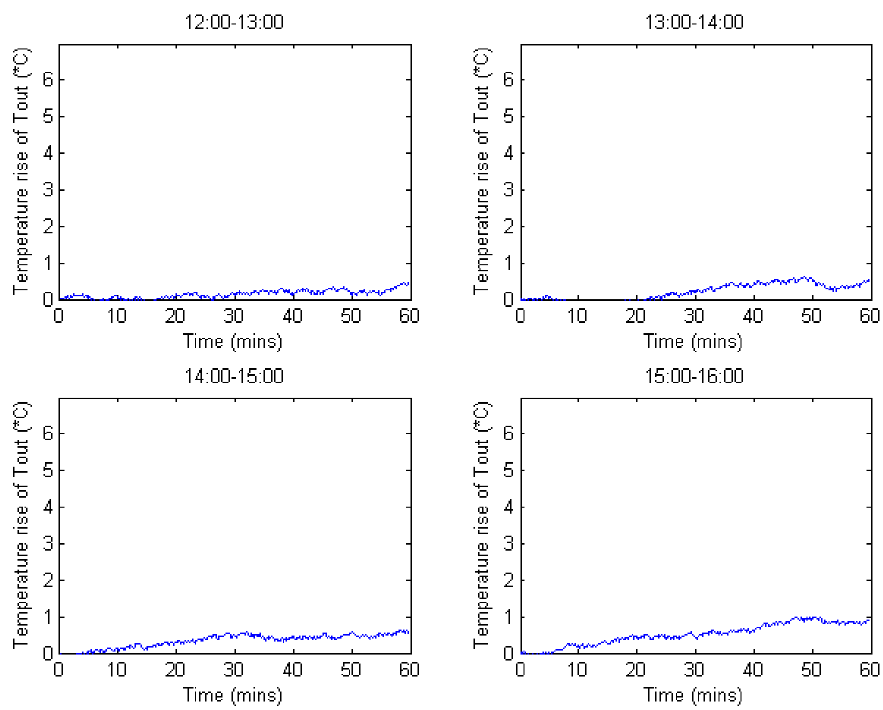

Fig. 5.10(d) Calculated way-out temperature rise of cooling water for one hour of 12:00-16:00.

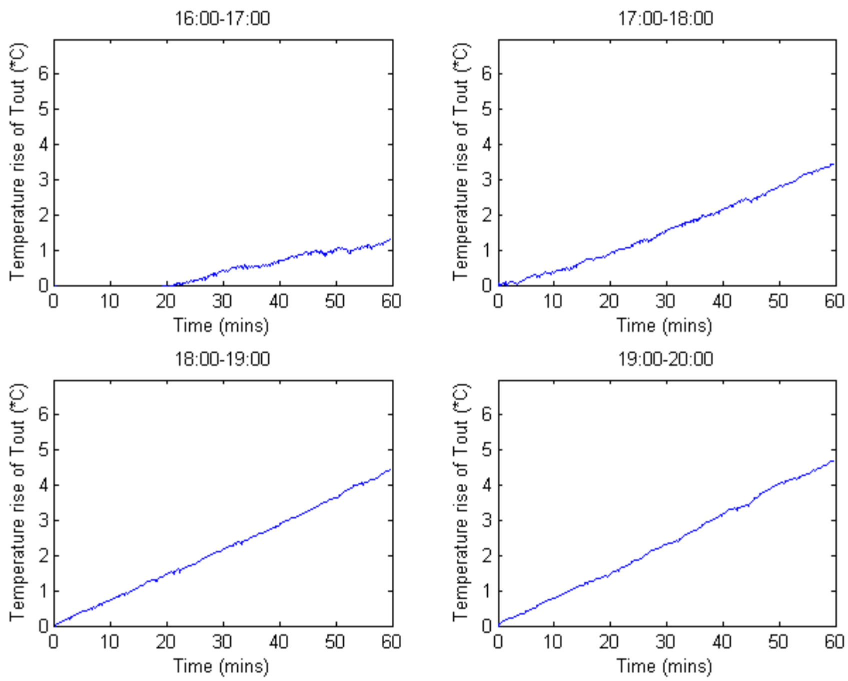

Fig. 5.10(e) Calculated way-out temperature rise of cooling water for one hour of 16:00-20:00.

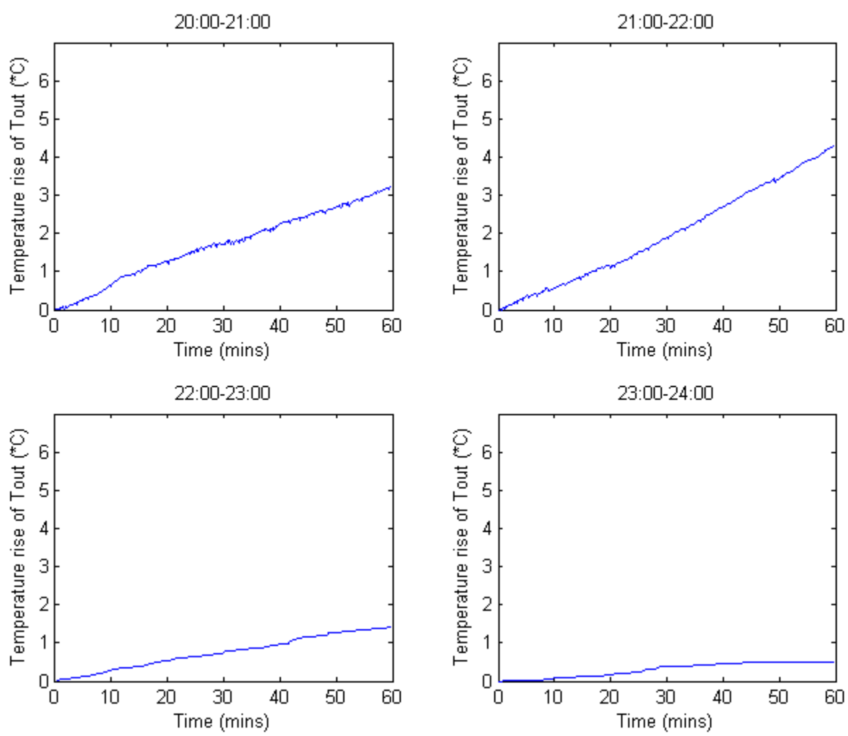

Fig. 5.10(f) Calculated way-out temperature rise of cooling water for one hour of 20:00-24:00.

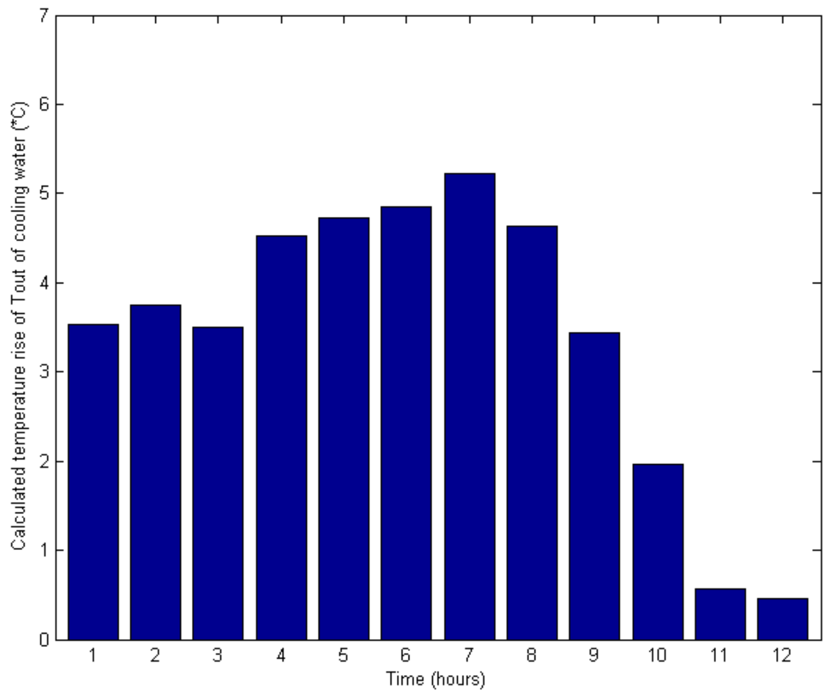

Fig. 5.11(a) Calculated way-out temperature rise of cooling water in every one hour at 00:00-12:00.

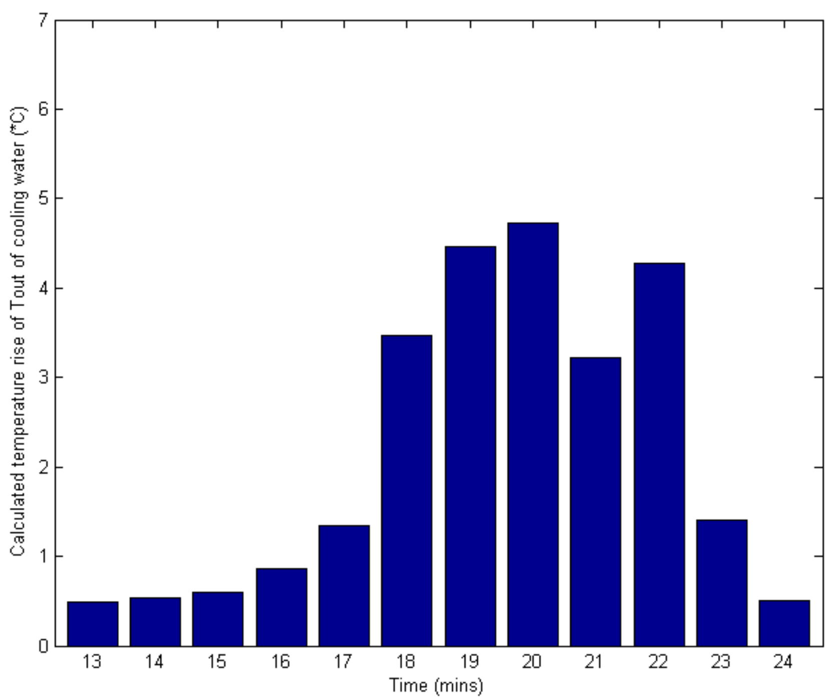

Fig. 5.11(b) Calculated way-out temperature rise of cooling water in every one hour at 12:00-24:00.

5.6.3 Calculation Results Analysis

The final calculated results of way-out temperature rise of cooling water are shown in Fig. 5.11(a) and Fig. 5.11(b) respectively. These results are used as the index for thermal performance of generator machine to determine if the machine operates in an allowed thermal range and under good thermal condition. The results give an estimate of temperature per hour and it is not a cumulative temperature rise of several hours but it is a cumulative temperature rise over ONE hour.

From the calculation, the stable temperature of T_{out} is 52.5 ℃ under steady state condition and the maximum allowed T_{out} is 73 ℃. From Fig. 5.11(a) and Fig. 5.11(b), it can be found that the generator could break the temperature limit of T_{out} during 05:00-06:00 if the conventional generator operates under the situation which is described in this example. And the over-heating protection in the machine could act to reduce the load of the generator. As a result, it can be summarized that the wind turbine generators could cause the thermal problem on other conventional generators and impact their operation in this simulation system.

Moreover, from Fig. 5.11(a) and Fig. 5.11(b), it can be also realised that the values of T_{out} temperature rise are relatively larger during the period of 04:00-08:00 and the values are quite small during the period of 11:00-15:00. Comparing and analysing the wind speed, wind turbine generator output and conventional generator output data of these two time periods, the reason of thermal problem can be concluded. During the time period of 11:00-15:00, the mean wind speed values are around 12-16 m/s and the wind speed also mainly distributes around this range. According to wind turbine generator active power output characteristics mentioned in Section 2.6.4, the wind speed around this range can provide wind turbine generators have more opportunities to operate at their full output and also have more opportunities to maintain stable output to the power system. And the conventional generator output is also more stable in this time period. As a result, the thermal problem is not serious at this time period. On the contrary, during the time period of 04:00-08:00, the mean wind speed values are around 5-7 m/s and the wind speed also mainly distributes around this range. The wind speed around this range can provide wind turbine generators output is more variable. And it could lead to more fluctuation output in both of wind turbine generators and conventional generator. As a result, the thermal problem is more serious at this time period.

5.7 Summary

This chapter outlined the second step of the method to calculate thermal performance of machine which is the calculation model and processes of cooling system effects to the heating problem.

Firstly, this chapter introduced the three main types of cooling system for different types of generators which includes air-cooled, hydrogen-cooled and water-cooled system. Continually, it also introduced the 3-Dimensions steady state temperature field and different boundary conditions which are used to describe the processes of heating energy dissipation and absorption between machine and water-cooled system.

Secondly, this chapter discussed and described the temperature distribution of coolant in cooling system based on 3D steady state temperature field and different boundary conditions. Next, it discussed the calculation processes to determine the coolant convection coefficient according to principles of heat transfer and exchange. Then, it listed the calculation processes of the coolant convection coefficient and cooling water way-out temperature rise which are programmed and executed in Matlab. Finally, it used a simulation example to calculate the thermal performance of the synchronous generator and analyse this heating problem caused by wind turbine generators.

The next chapter will deeply explore and analyse the thermal problem of conventional generators caused by wind power generation through several simulation examples under different operating situations in power systems.

5.8 References

[1] A. G. Brown, "The Growth of Turbogenerators," *Philosophical Transactions of Royal Society of London A. Mathematical and Physical Sciences*, Vol. 275, pp. 51-67, August 1973.

[2] L. F. Drbal, P. G. Boston, K. L. Westra and R. B. Erickson, *Power Plant Engineering*, New York: Chapman & Hall, 1996.

[3] C. Concordia, "Future Developments of Large Electric Generators," *Philosophical Transactions of Royal Society of London A. Mathematical and Physical Sciences*, Vol. 275, pp. 39-49, August 1973.

[4] L. Ruan, G. Gu, X. Tian and J. Yuan, "The Comparison of Cooling Effect between Evaporative Cooling Method and Inner Water Cooling Method for the Large Hydro Generator," *Proceeding of International Conference on Electrical Machines and Systems, Seoul, Korea*, October 8-11, 2007.

[5] J. Tseng, L. Fan and C. Hwang, "Optimal Control of Cooling Water Discharge from a Power Plant," *IEEE Transactions on System, Man and Cybernetics*, Vol. SMC-4, No. 6, pp. 523-531, November 1974.

[6] W. S. Janna, *Engineering Heat Transfer*, Second Edition, USA: CRC Press LLC, 2000.

[7] K. D. Hagen, *Heat Transfer with Applications*, USA: Prentice-Hall, 1999.

[8] K. H. Huebner, E. A. Thorton, and T. G. Byrom, *The Finite Element Method for Engineers*, 3rd Edition: John Wiley & Sons, 1995.

[9] L. J. Segerlind, *Applied Finite Element Analysis*, 2nd Edition: JohnWiley & Sons, 1984.

[10] F. Kreith and M. S. Bohn, *Principles of Heat Transfer*, Sixth Edition, USA: Thomson Learning, 2001.

[11] C. C. Silverstein, *Design and Technology of heat pipes for cooling and heat exchange*, Washington: Taylor & Francis, 1992.

[12] W. D. Morris, *Heat Transfer and Fluid Flow in Rotating Coolant Channels*, England: Research Studies Press, John Wiley & Sons Ltd.

[13] W. M. Rohsenow, J. P. Hartnett and Y. I. Cho, *Handbook of Heat Transfer*, Third Edition, USA: McGraw-Hill, 1998.

[14] X. Xu, M. He and H. Zheng, "Neuron Based Control of Main Engine Cooling Water Temperature," *IEEE International Conference on Control and Automation, Guangzhou, China*, May 30-June 1, 2007.

[15] C. Hwang, S. S. Wu and Y. H. Jiang, "Novel Approach to the Solution of Temperature Distribution in the Stator of an Induction Motor," *IEEE Transactions on Energy Conversion*, Vol. 15, No. 4, pp. 401-406, December 2000.

[16] M. Rioual, "A Thermohydraulic Modelling For the Stator Bars of Large Turbogenerators: Development, Validation by Laboratory and on Site Tests," *IEEE Transactions on Energy Conversion*, Vol. 12, No.1, pp. 1-9, March 1997.

[17] S. S. Choi and X. M. Jia, "Under Excitation Limiter and Its Role in Preventhing Excessive Synchronous Generator Stator End-Core Heating," *IEEE Transactions on Power Systems*, Vol. 15, No. 1, pp. 95-101, February 2000.

[18] L. Meysenc, M. Jylhakallio and P. Barbosa, "Power Electronics Cooling Effectiveness Versus Thermal Inertia," *IEEE Transactions on Power Electronics*, Vol. 20, No. 3, pp. 687-993, May 2005.

CHAPTER 6

CALCULATING HEATING PROBLEM OF CONVENTIONAL GENERATOR CAUSED BY WIND POWER GENERATION UNDER DIFFERENT SITUATIONS: SIMULATIONS AND RESULTS

6.1 Introduction

Practical power systems are complicated and their operation conditions can be very variable. Power system characteristics are influenced by many factors such as generation distribution and transmission system structure. When wind energy is introduced, because of the differences of wind resources distribution and development level in different areas, it introduces future complexities into power systems operation.

As explained in Chapter 5, the intermittent output of wind power resources could lead to temperature rise in the winding of conventional generators. Power system engineers would need to seek remediation. One possible way is to reinforce insulation/cooling system of generators but this is not practiced economically. Another way is to re-scheduled duty cycle of generators. [1]

However, it is necessary to simulate and calculate the heating effects on conventional generators under different conditions in order to research and analyse the heating problem in more details and practical operation conditions. In this chapter, there are four simulations for different wind speed data, different penetration level of wind energy, different types of conventional generators and different model systems include IEEE-14-Bus system and IEEE-39-Bus system.

6.2 Simulation of Heating Problem Calculation for Extremely Unfavourable Wind Speed Period

From Chapter 2, it has explained that the active power output of wind turbine generator and its characteristics are deeply influenced by wind speed. And the wind turbine generator extracts and transfers wind energy to electrical energy only when the wind speed is in the range between cut-in and cut-out speed. According to this characteristic, the active power output of wind turbine generator will switch between full output and zero output if wind speed increase or decrease across the cut-out speed. As a result, the wind speed could be extremely unfavourable when it distributes and fluctuates around cut-out speed and heating performances of conventional generators under this wind speed condition. [2]

In this simulation, the simulations are based on the methods and programs that were already introduced in previously chapters.

6.2.1 Case Study

In this case study, the simulation model system is shown in Fig. 6.1 and it includes a single synchronous generator supplies energy to a load centre through a pair of long distance backbone high-voltage transmission lines and wind turbine generator is connected to the load area in distribution system. This system is similar to the one used previously. Furthermore, the data of power system, generators and cooling system do not change.

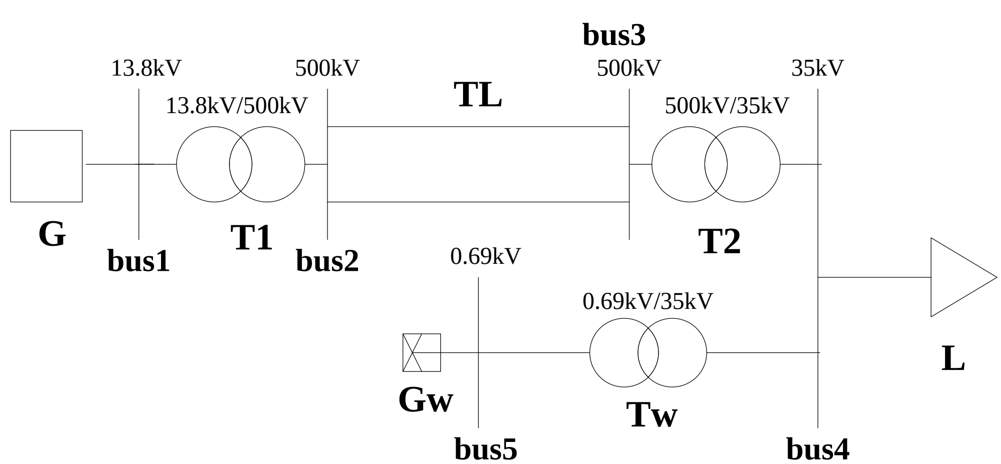

Fig. 6.1 The model system of the 6.2.1 case study.

However, the wind turbine generators operate under new extremely unfavourable wind speed data. According to Weibull distribution and wind speed random data production process which have been discussed in the Chapter 2, a two-hour wind speed data for every 10 seconds, which fluctuates around cut-out speed (25 m/s), can be obtained through Matlab program. The wind speed data and its probability distribution curve are shown on Fig. 6.2(a), Fig. 6.2(c) and Fig. 6.2(b), Fig. 6.2(d) respectively:

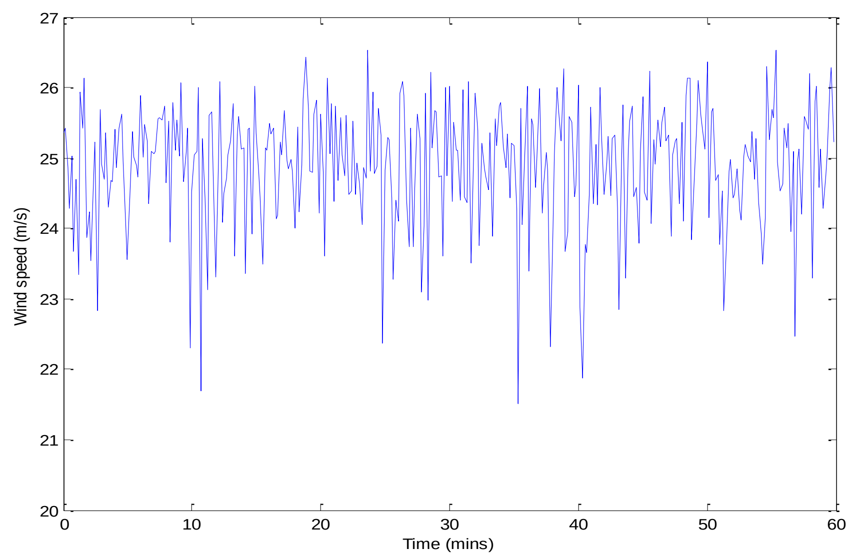

Fig.6.2(a) Developed wind speed data in every 10 seconds for the first hour.

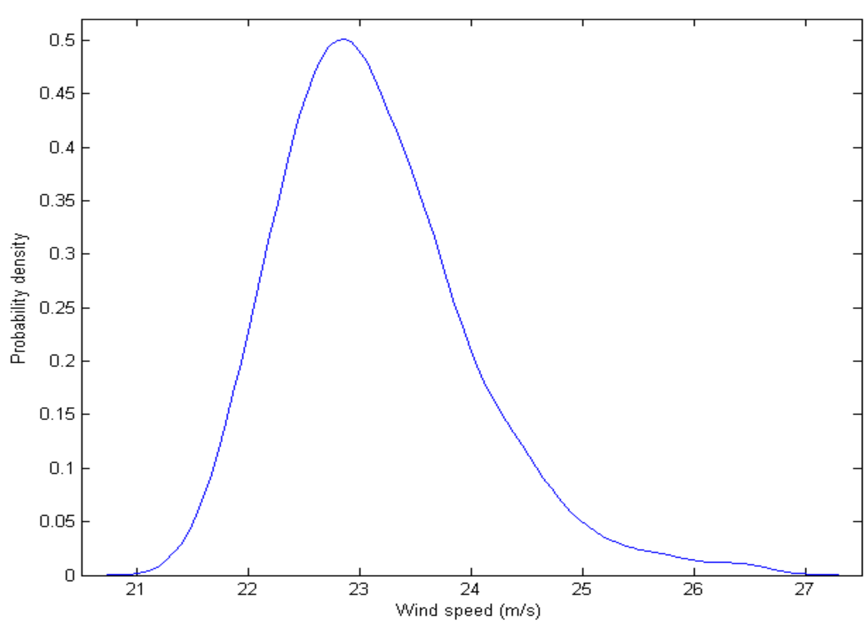

Fig. 6.2(b) The probability distribution of random data for the first hour.

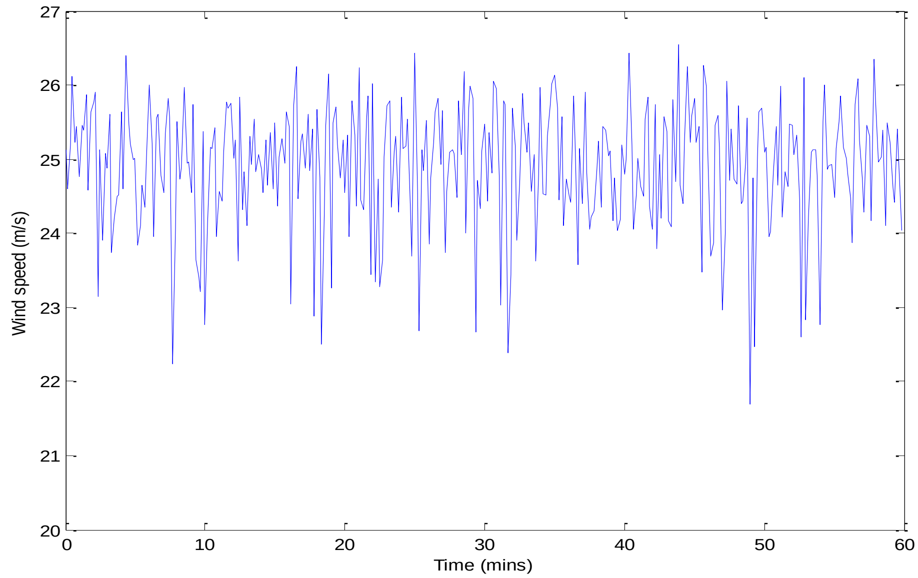

Fig.6.2(c) Developed wind speed data in every 10 seconds for the second hour.

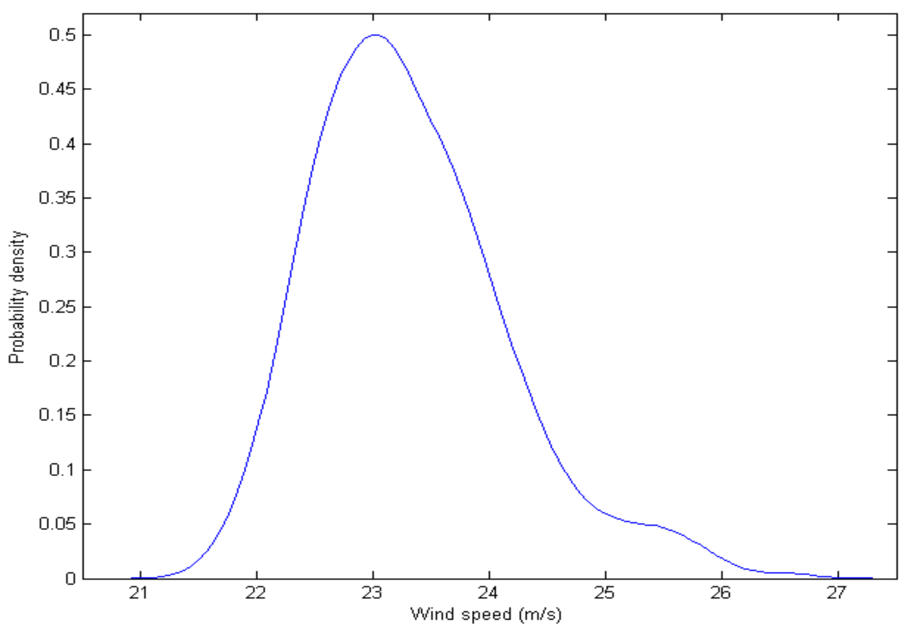

Fig. 6.2(d) The probability distribution of random data for the second hour.

6.2.2 Simulation Results

Based on these new wind speed data, wind turbine generator output can be calculated through the wind generation output equation which has also been mentioned in the Chapter 2 and is shown on Fig. 6.3(a) and Fig. 6.3(b) respectively:

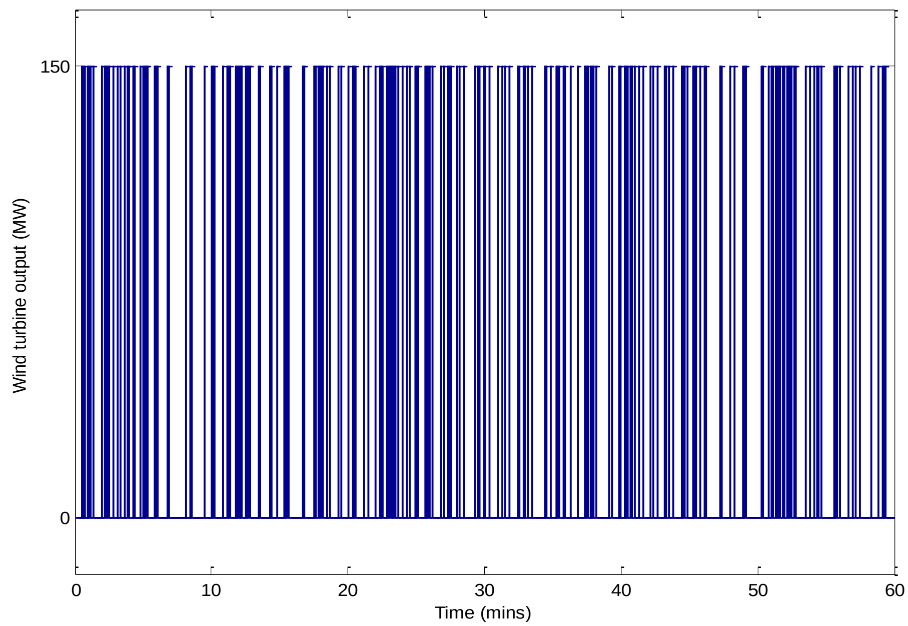

Fig. 6.3(a) Wind turbine output in every 10 seconds for the first hour.

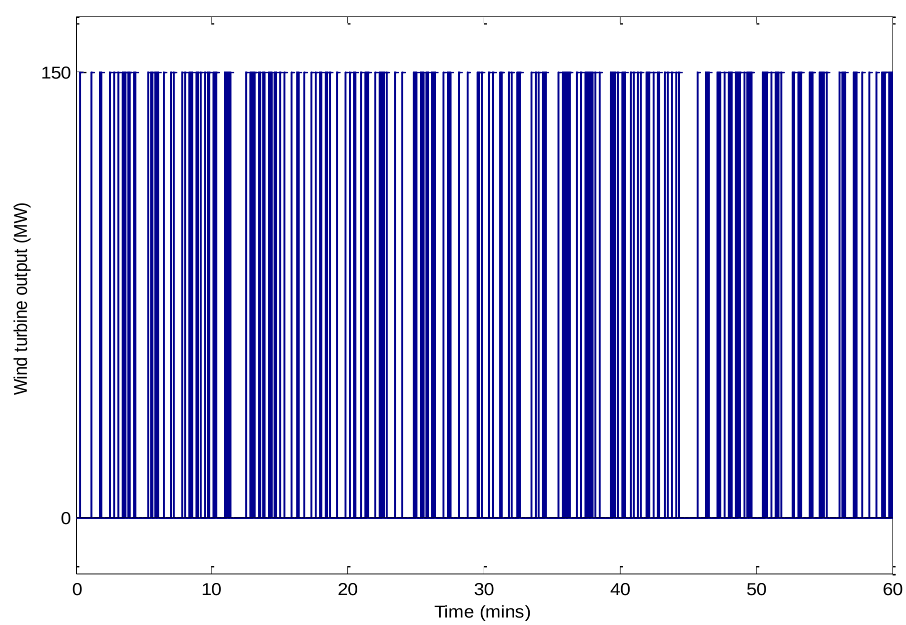

Fig. 6.3(b) Wind turbine output in every 10 seconds for the second hour.

Next, relying on the power flow calculation program, the output of conventional generator can be obtained and the conventional generator output data and the percentage distributions of these data are shown in Fig. 6.4(a), Fig. 6.4(c) and Fig. 6.4(b), Fig. 6.4(d) respectively:

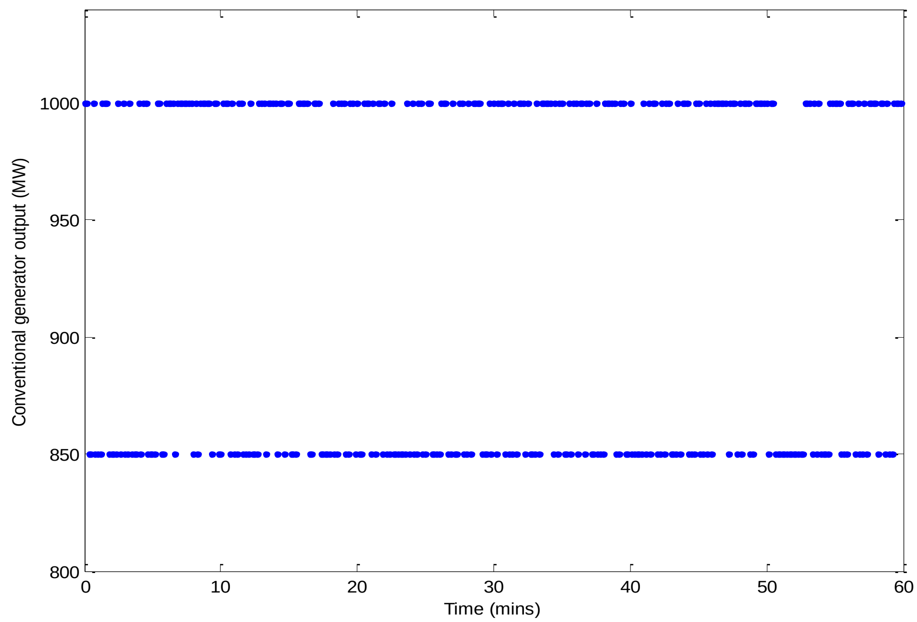

Fig. 6.4(a) Conventional generator output in every 10 seconds for the first hour.

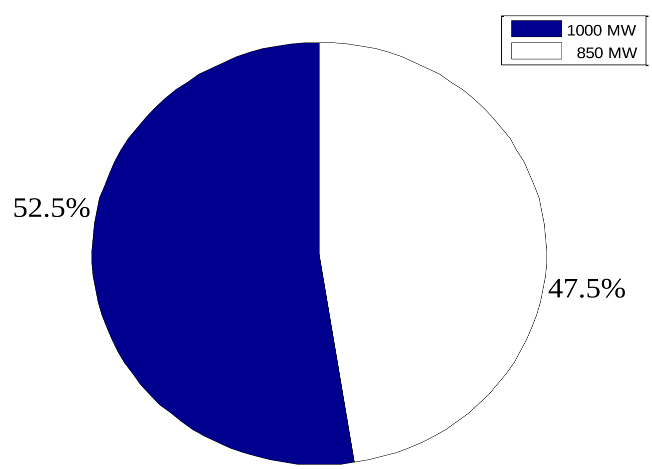

Fig. 6.4(b) Percentage distribution of conventional generator output at the first hour.

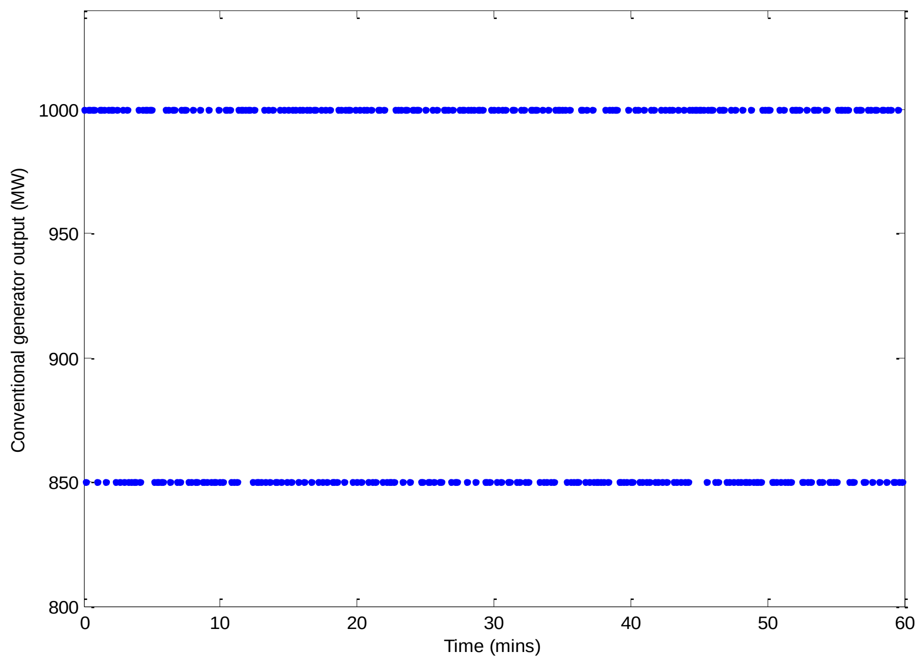

Fig. 6.4(c) Conventional generator output in every 10 seconds for the second hour.

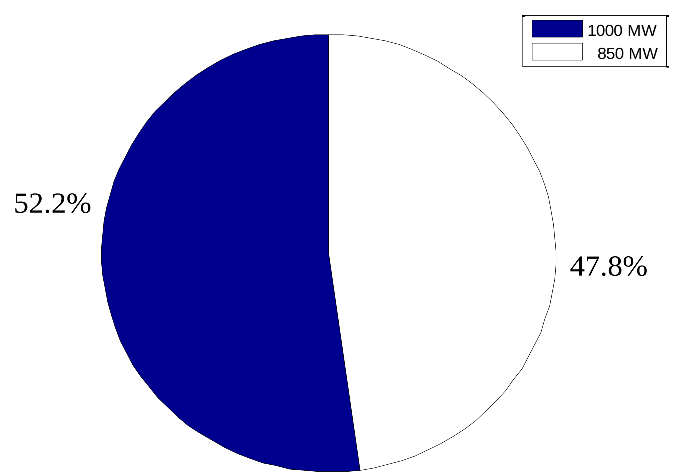

Fig. 6.4(d) Percentage distribution of conventional generator output at the second hour.

Then, using Matlab Simulink SimPowerSystems™, the results data of rotor current, stator current of one phase and power angle under conventional generator output fluctuation condition for 2 hours in every 10 seconds can be obtained and are shown in Fig. 6.5(a), Fig. 6.5(b) and Fig. 6.5(c) respectively.

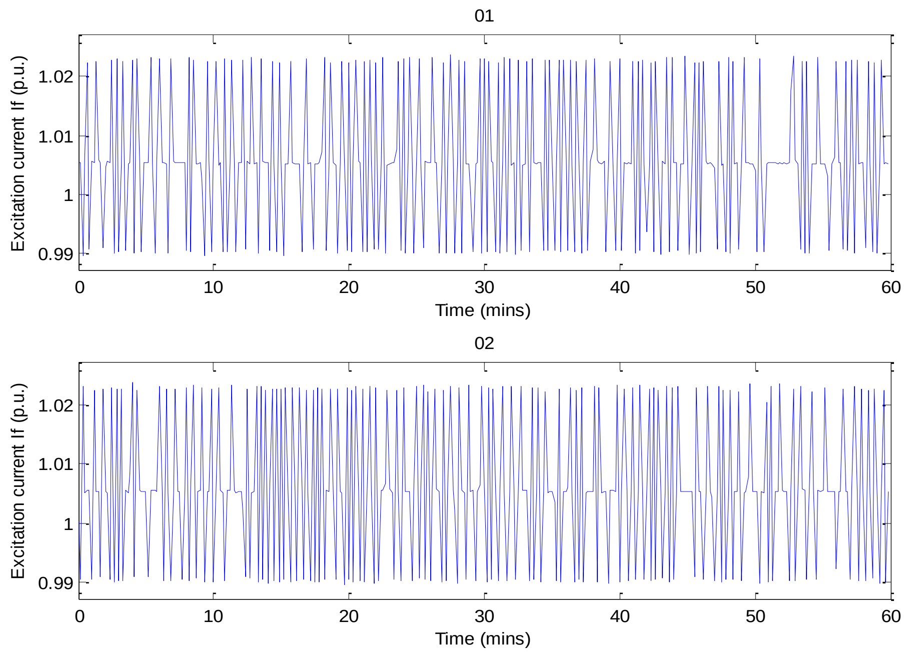

Fig. 6.5(a) Rotor current I_f of synchronous generator in every 10 seconds for two hours.

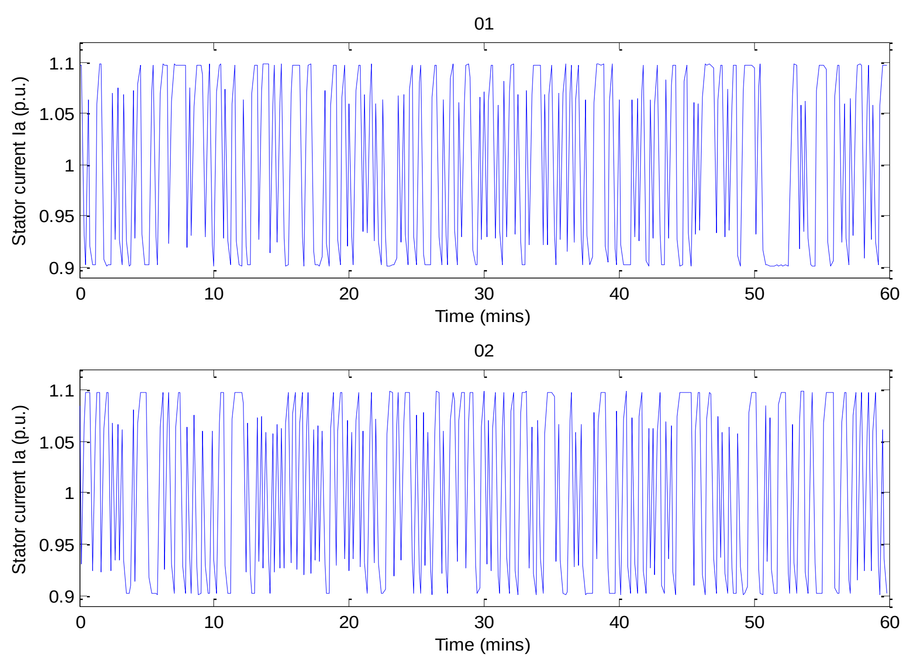

Fig. 6.5(b) Stator current I_a of synchronous generator in every 10 seconds for two hours.

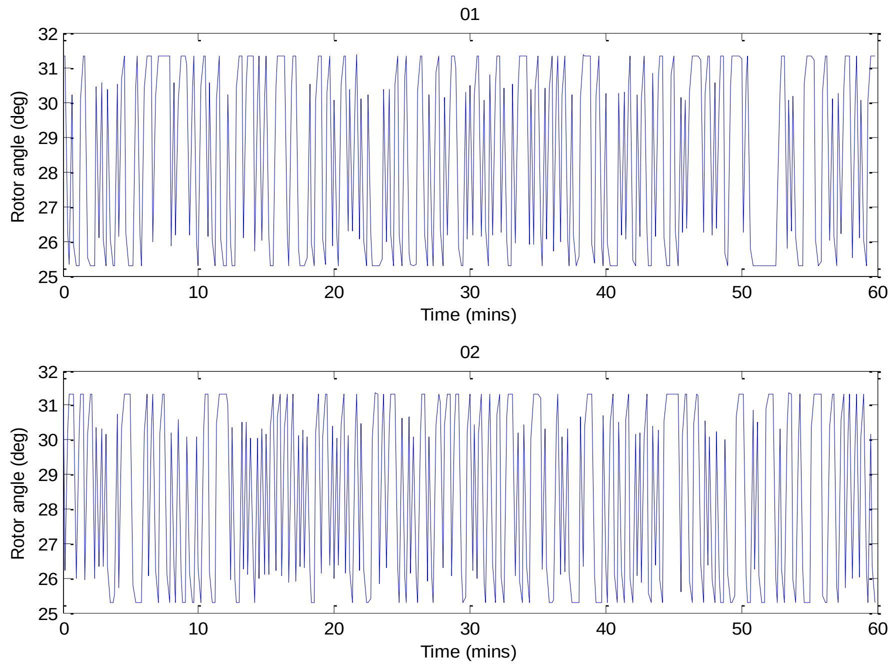

Fig. 6.5(c) Rotor angle δ of synchronous generator in every 10 seconds for two hours.

Finally, based on these data and the method to calculate heating problem of conventional generator which has been introduced in Chapter 5, changing processes of calculated temperature rise of the machine and changing processes of calculated way-out temperature rise of cooling water for these two hours can be obtained and are shown in Fig. 6.6(a) and Fig. 6.6(b) respectively. Then, the final temperature rise results and the final way-out temperature rise of cooling water for these two hours are represented on Fig. 6.7.

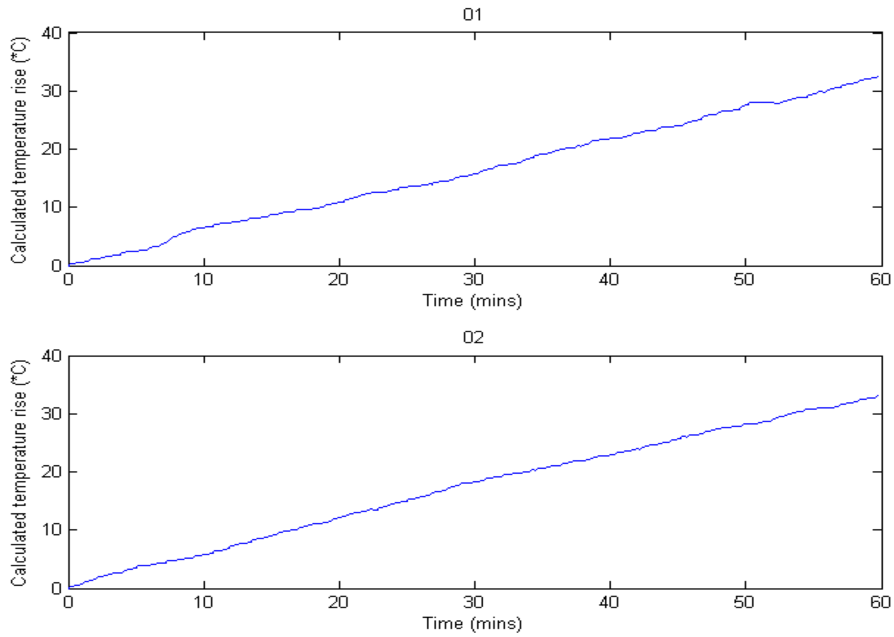

Fig. 6.6(a) Calculated temperature rise of machine for two hours.

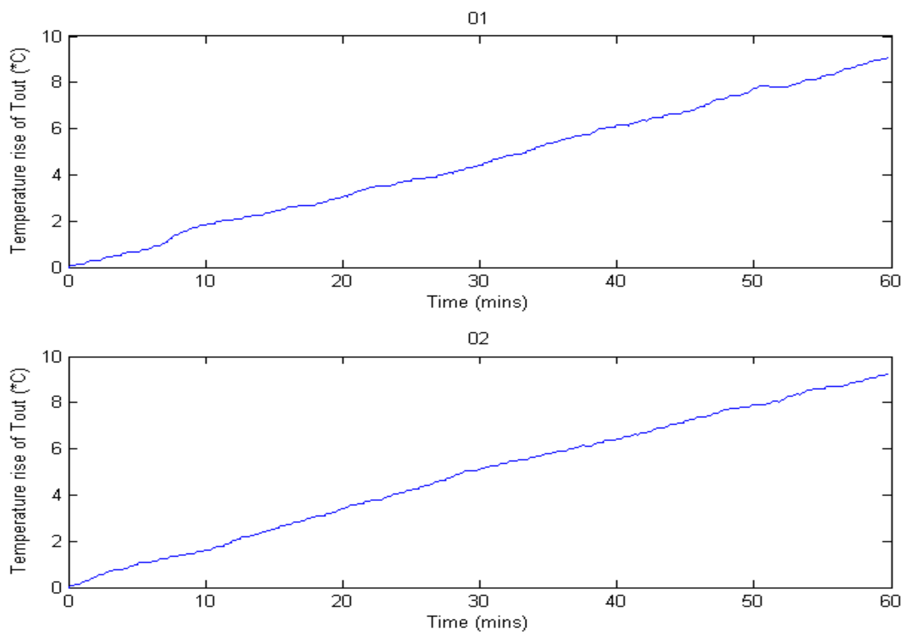

Fig. 6.6(b) Calculated way-out temperature rise of cooling water for two hours.

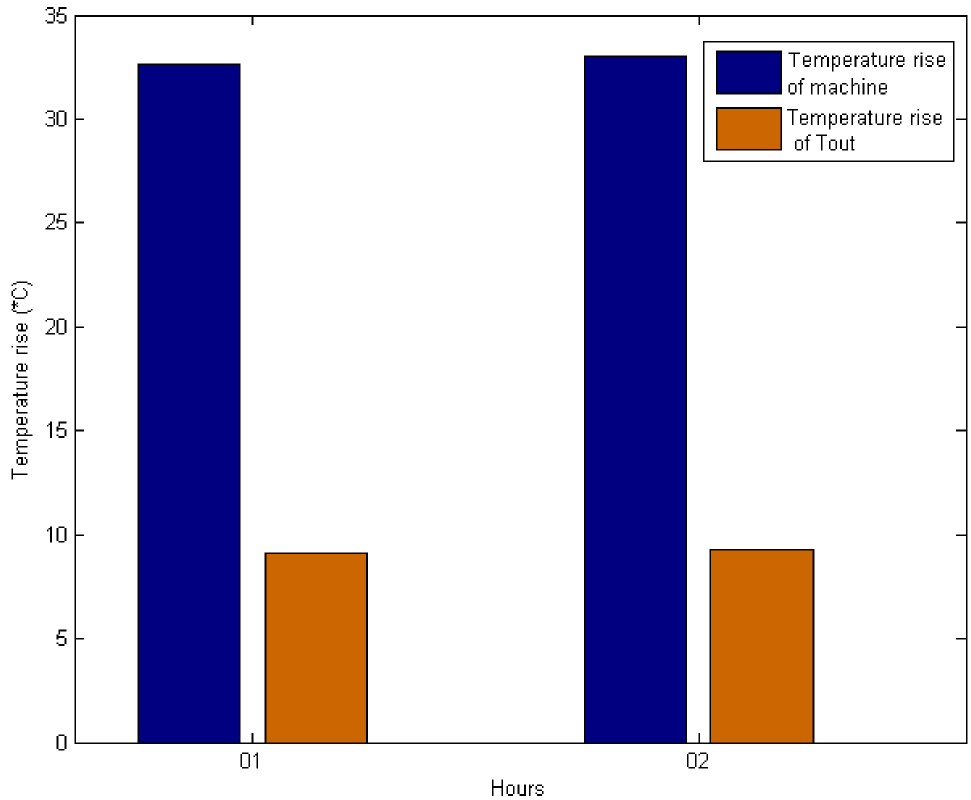

Fig. 6.7 Calculated temperature rise of machine and way-out temperature rise of cooling water for two hours.

From the example in Section 5.6 last chapter, it shows that the steady state way-out temperature of cooling water is 52.5 ℃ and the maximum allowed way-out temperature is 73 ℃. According to Fig. 6.6 and Fig. 6.7, the calculated results of cooling water way-out temperature are 9.13 ℃ and 9.24 ℃ respectively which means the cooling system of generator works very near to its thermal limits after two hours time. As a result, when the power system operates under this extremely unfavourable wind speed pattern, the conventional generator reaches its heating limits more quickly than other normal wind speed data which has been simulated previously.

In conclusion, if a wind speed characteristic is similar with this extremely unfavourable wind speed pattern of a wind farm location or during a certain period, the power system and power plant operators is necessary to pay a lot of attention on the heating performances of conventional generators which are used to match the wind farm output fluctuation.

6.3 Simulation of Heating Problem Calculation for Wind Power Generation for Different Penetration Levels

In different areas, wind energy resources distribution and the level of wind generation technology development are different so the wind energy penetration levels are also a variable in different power systems. The differences of wind energy penetration levels will bring about different effects to the power systems.

The examples and simulations in Chapter 3, 4 and 5 all relied on 150MW active power capacity wind turbine generators model which means 15% of total generation capacity is replaced by wind power generation. In the simulation here, the power system will operate under two more wind power generation penetration levels to analyse the heating performances of conventional generators which are 5% and 30% of total generation capacity.

6.3.1 Case Study

In this case study, the simulation is on the same system which operated under 15% wind energy penetration level to analyse the impacts from wind power generation in Section 4.5 and Section 5.6 (also is shown on Fig. 6.1) respectively. And the capacity of wind turbine generators is set to 50MW and 300MW separately which stands for 5% and 30% penetration level of wind energy. In this simulation, it still uses the same 24 hours wind speed data which is developed in the Chapter 2.

Following the same simulation processes and heating problem calculation method described in the previous chapters, the heating performances of conventional generators in the power systems with 5% and 30% penetration level of wind energy can be calculated.

6.3.2 Simulation Results for 5% of Total Generation Capacity is Replaced by Wind Power Generation

Firstly, the simulation gets the results for wind energy at 5% penetration level. The calculating results of temperature rises in machine and cooling water are continual in 24 hours. However, for more clear about the representing and comparing of simulation results and also highlighting the results in different time periods, calculating results are shown in every hour for 24 hours. Fig. 6.8(a) to Fig. 6.8(f) show changing processes of calculated temperature rise of the machine in every one hour for 24 hours. And Fig. 6.9(a) and Fig. 6.9(b) respectively represent and compare the final temperature rise results for every hour in a day.

And Fig. 6.10(a) to Fig. 6.10(f) show changing processes of calculated way-out temperature rise of cooling water in every one hour for 24 hours. And Fig. 6.11(a) and Fig. 6.11(b) represent and compare the final way-out temperature rise of cooling water for every hour in a day.

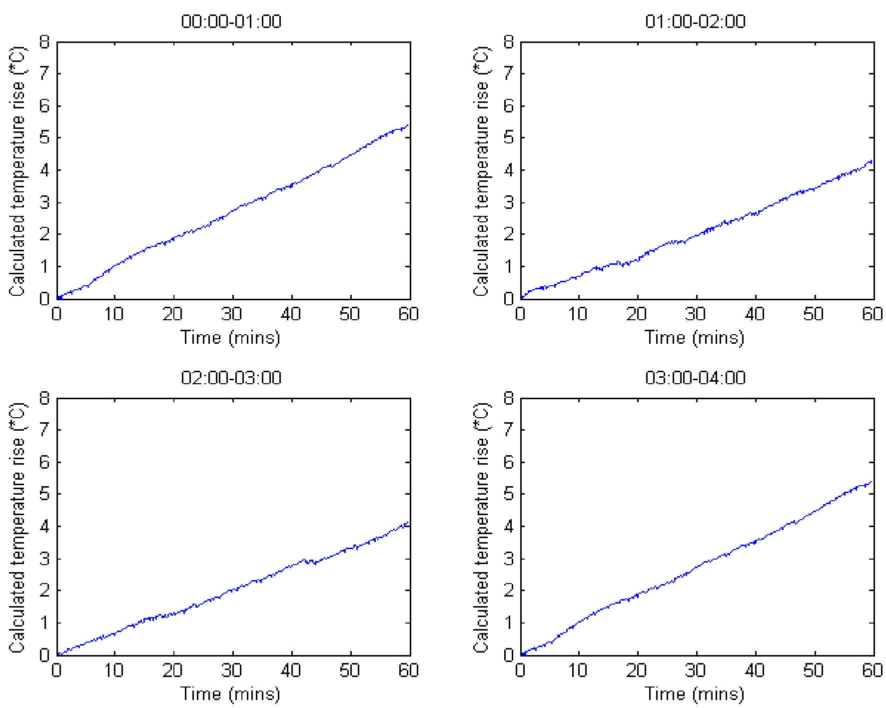

Fig. 6.8(a) Calculated temperature rise of machine of 00:00-04:00 for 5% penetration level.

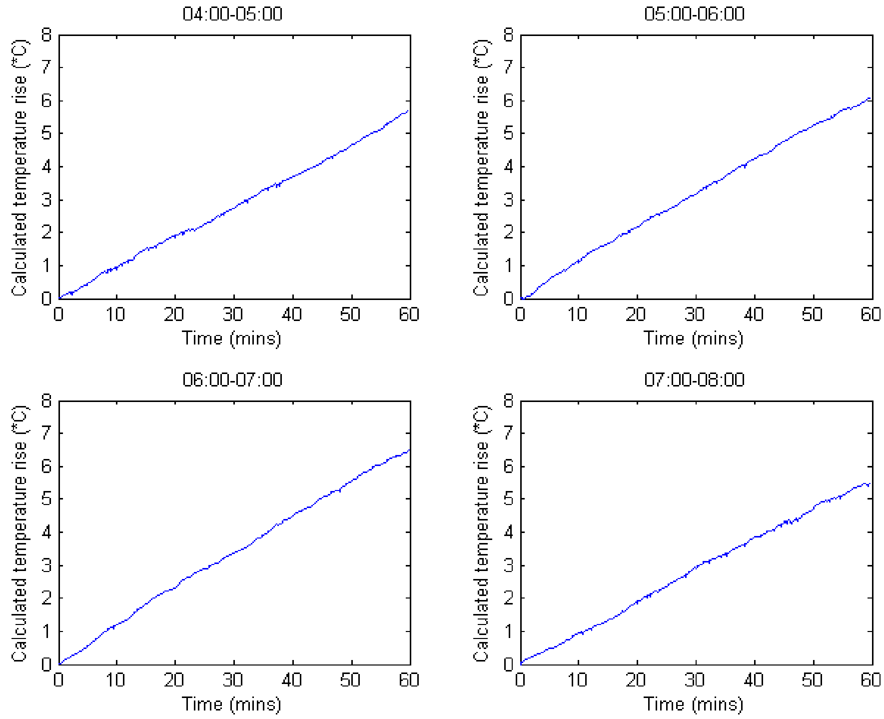

Fig. 6.8(b) Calculated temperature rise of machine of 04:00-08:00 for 5% penetration level.

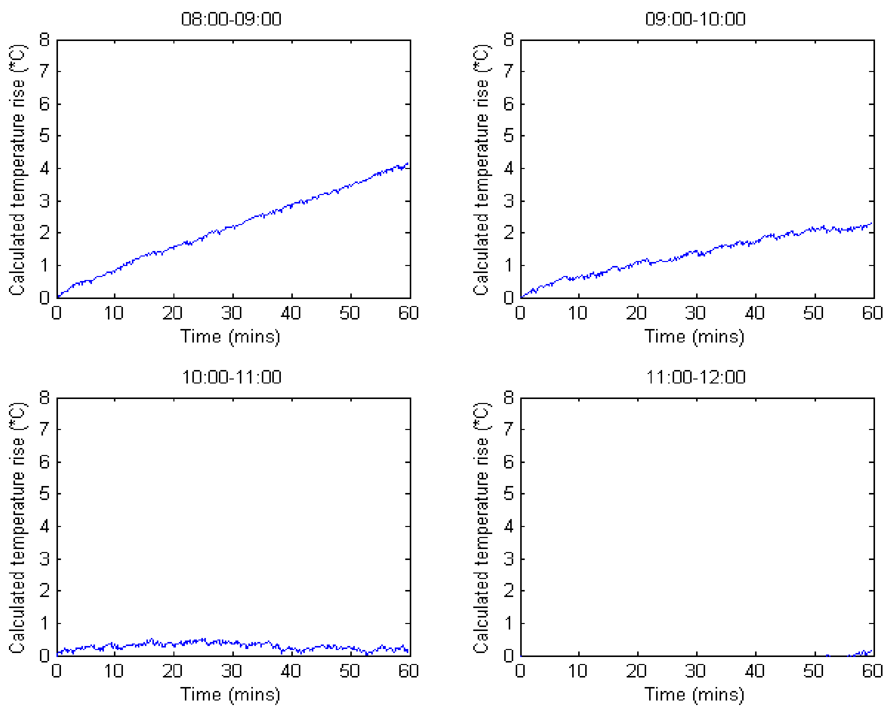

Fig. 6.8(c) Calculated temperature rise of machine of 08:00-12:00 for 5% penetration level.

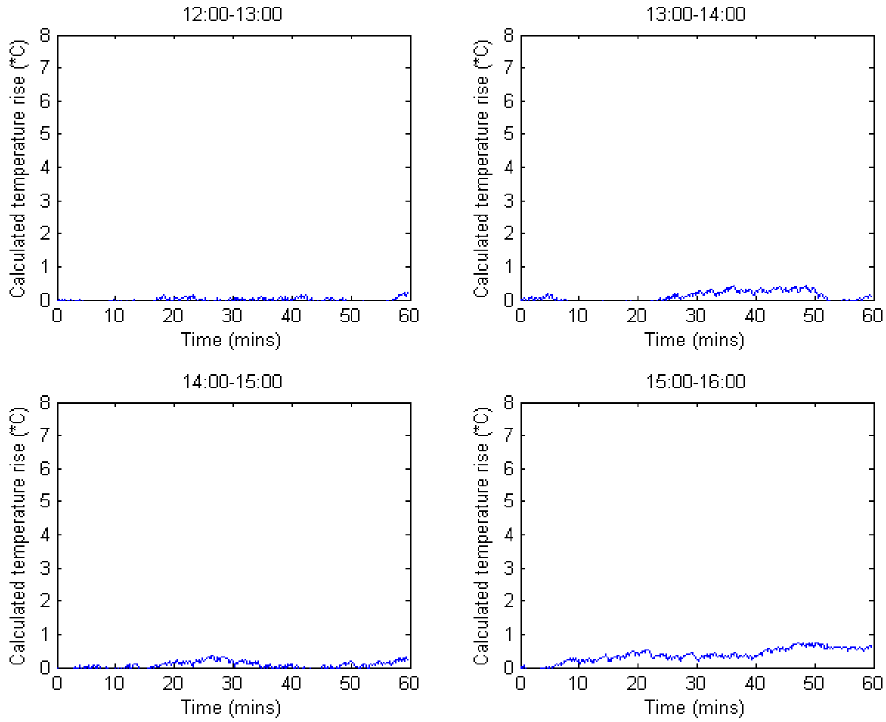

Fig. 6.8(d) Calculated temperature rise of machine of 12:00-16:00 for 5% penetration level.

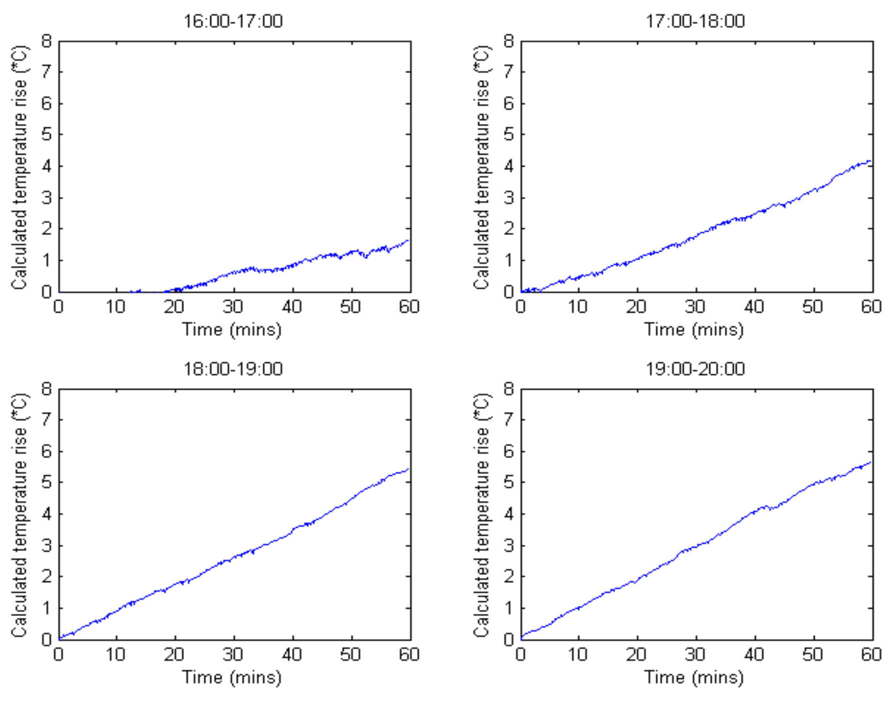

Fig. 6.8(e) Calculated temperature rise of machine of 16:00-20:00 for 5% penetration level.

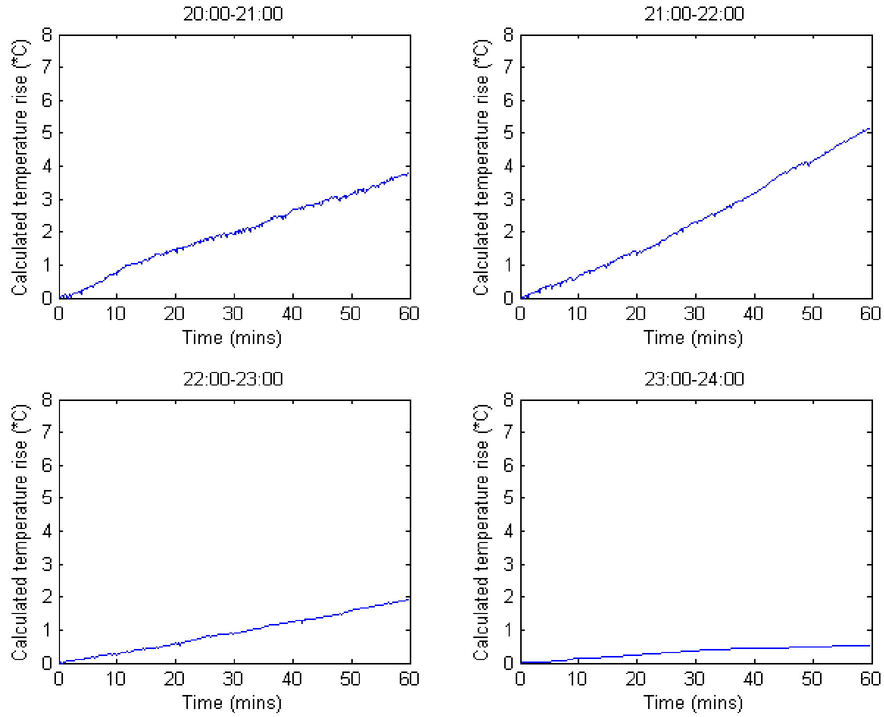

Fig. 6.8(f) Calculated temperature rise of machine of 20:00-24:00 for 5% penetration level.

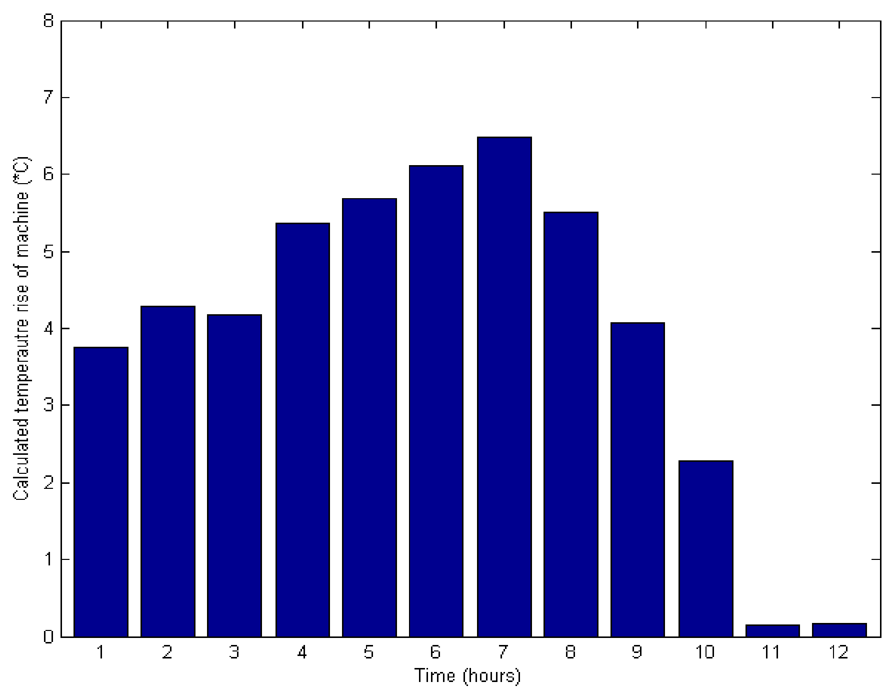

Fig. 6.9(a) Calculated temperature rise of machine in every one hour at 00:00-12:00 for 5% penetration level.

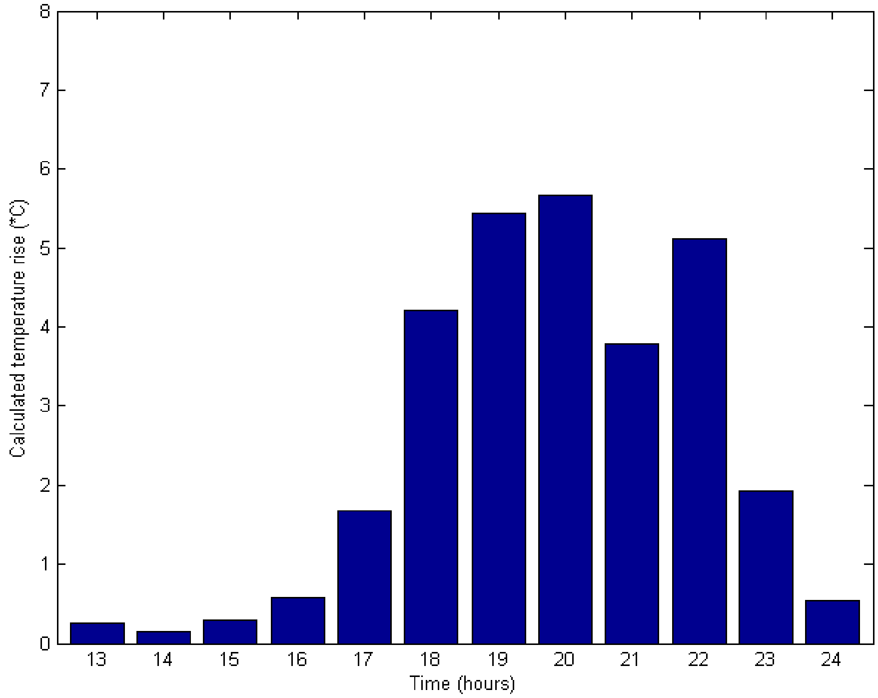

Fig. 6.9(b) Calculated temperature rise of machine in every one hour at 12:00-24:00 for 5% penetration level.

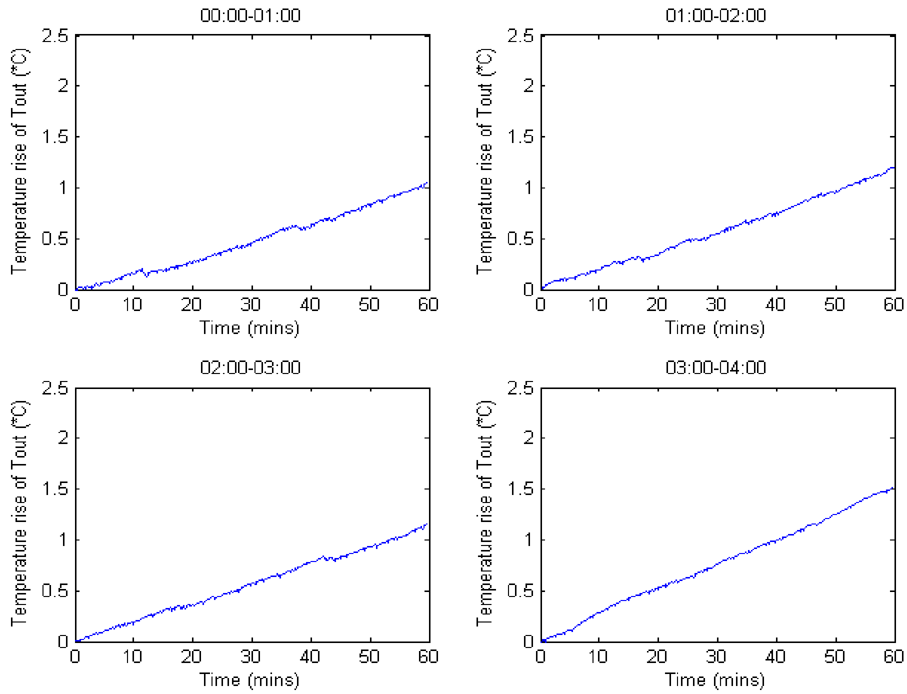

Fig. 6.10(a) Calculated way-out temperature rise of cooling water of 00:00-04:00 for 5% penetration level.

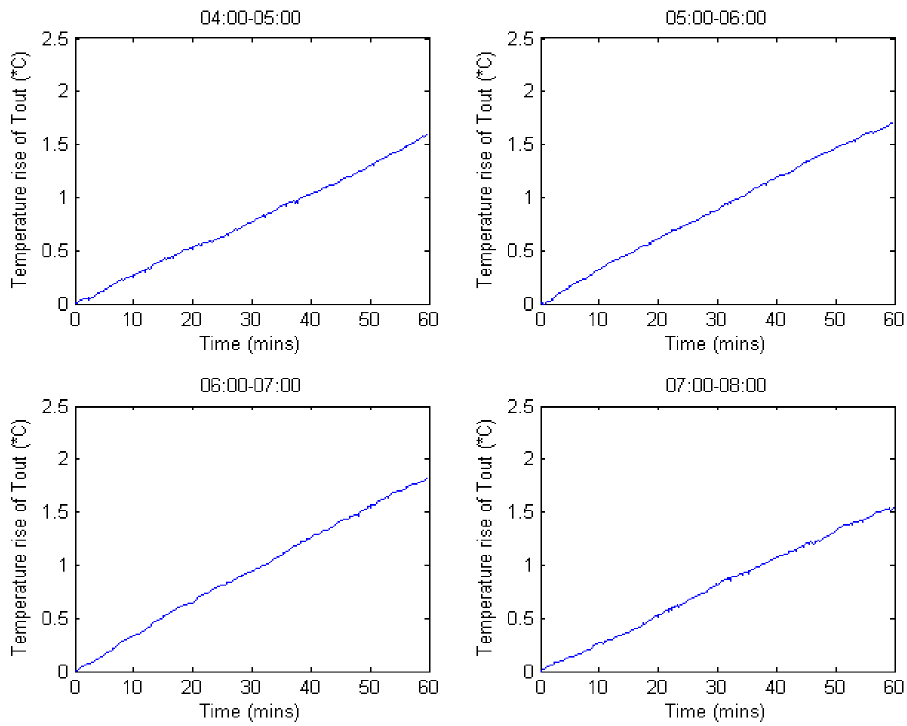

Fig. 6.10(b) Calculated way-out temperature rise of cooling water of 04:00-08:00 for 5% penetration level.

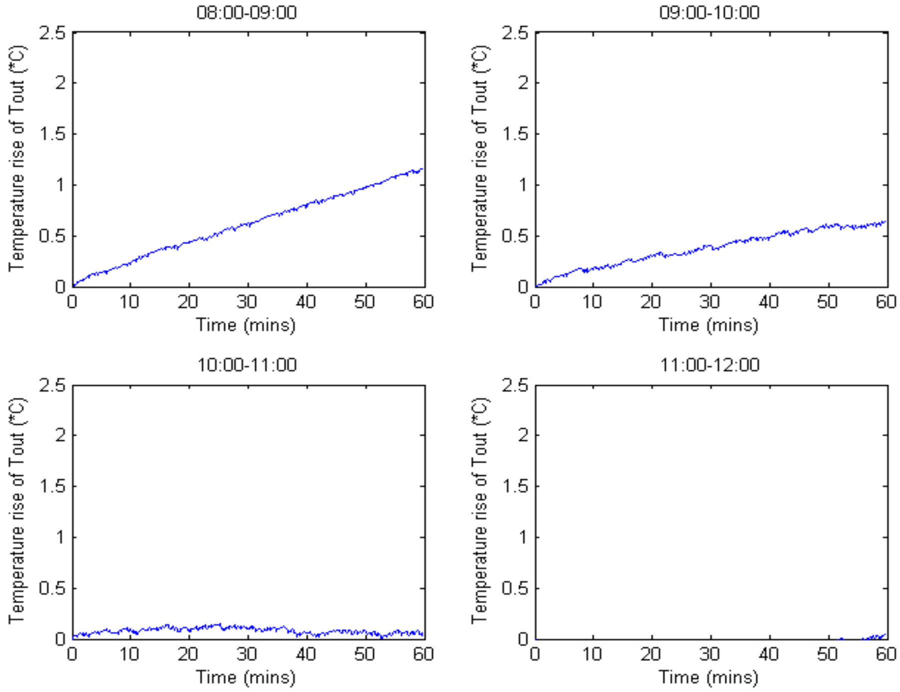

Fig. 6.10(c) Calculated way-out temperature rise of cooling water of 08:00-12:00 for 5% penetration level.

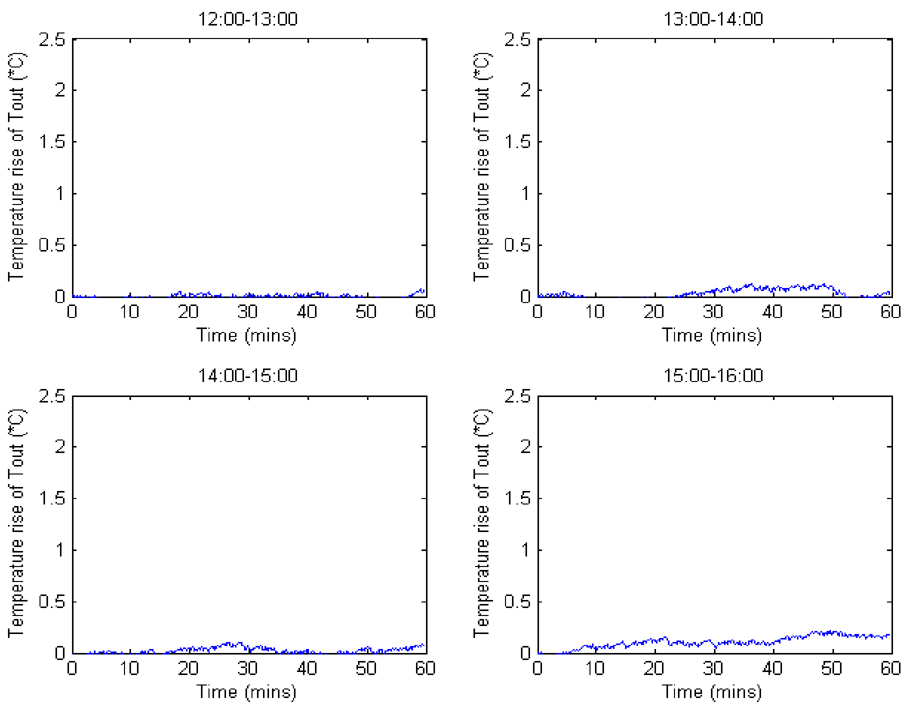

Fig. 6.10(d) Calculated way-out temperature rise of cooling water of 12:00-16:00 for 5% penetration level.

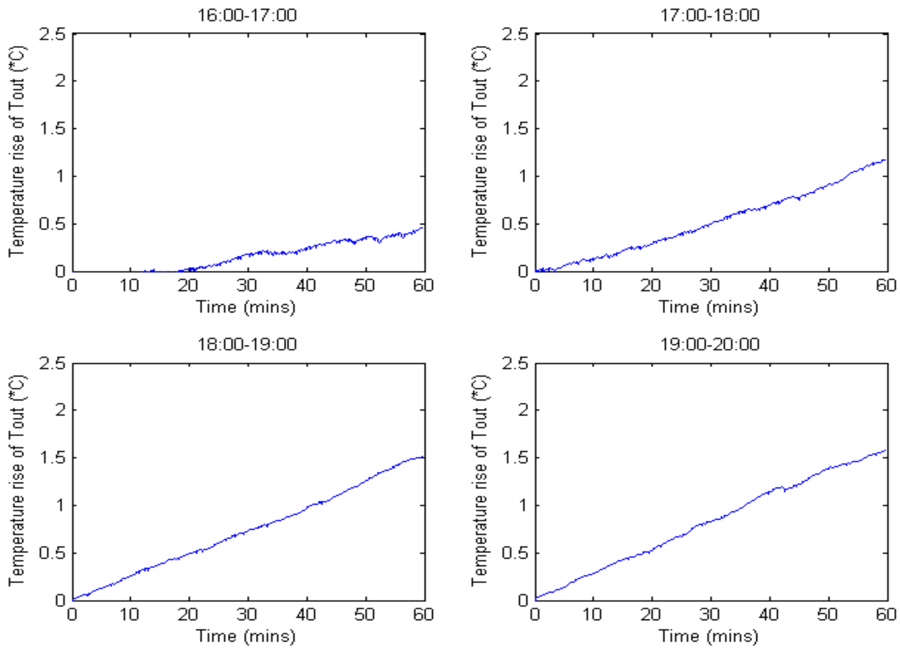

Fig. 6.10(e) Calculated way-out temperature rise of cooling water of 16:00-20:00 for 5% penetration level.

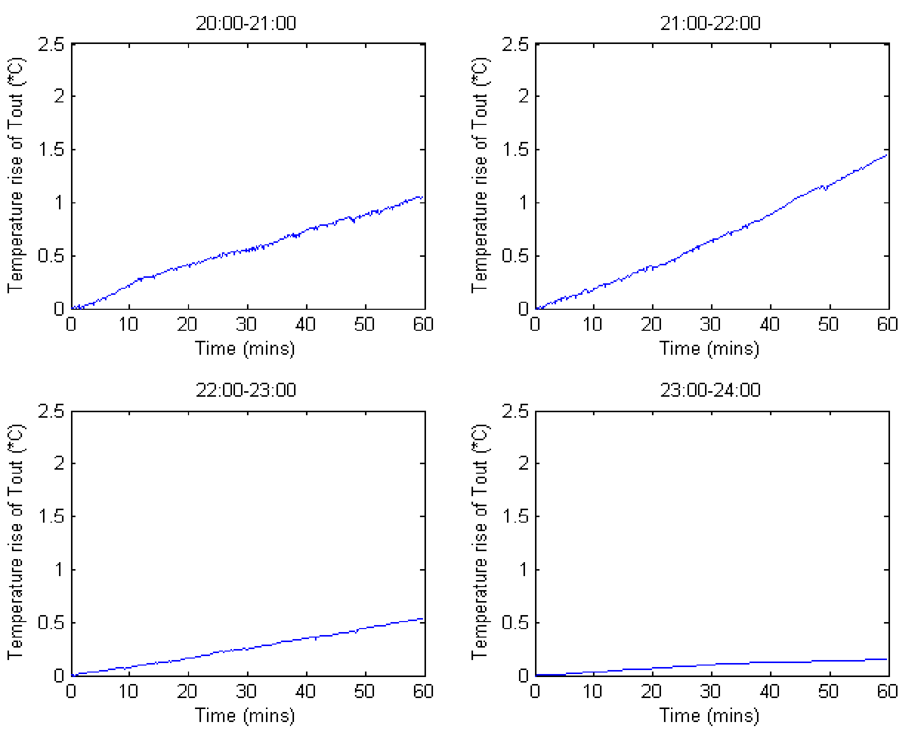

Fig. 6.10(f) Calculated way-out temperature rise of cooling water of 20:00-24:00 for 5% penetration level.

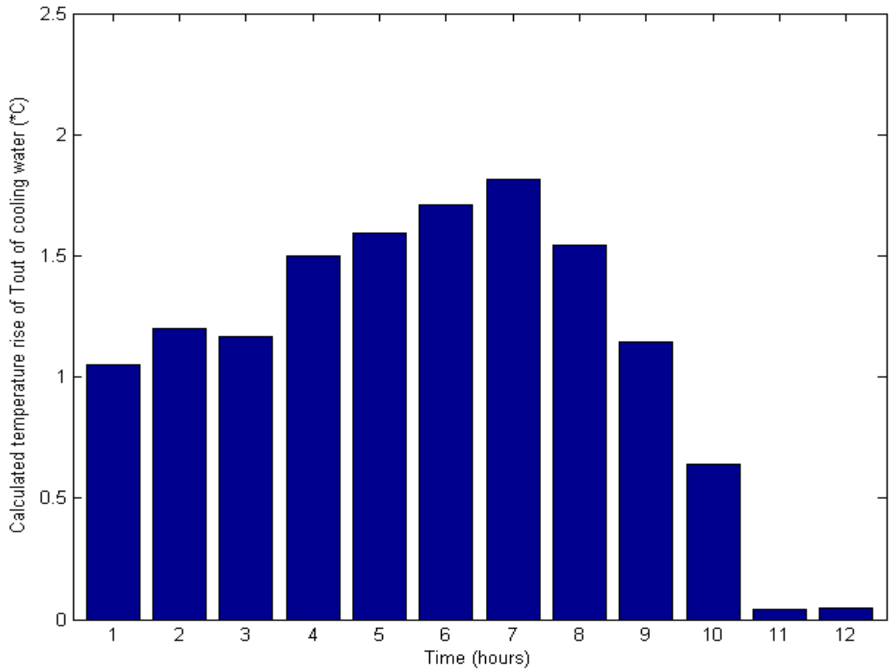

Fig. 6.11(a) Calculated way-out temperature rise of cooling water at 00:00-12:00 for 5% penetration level.

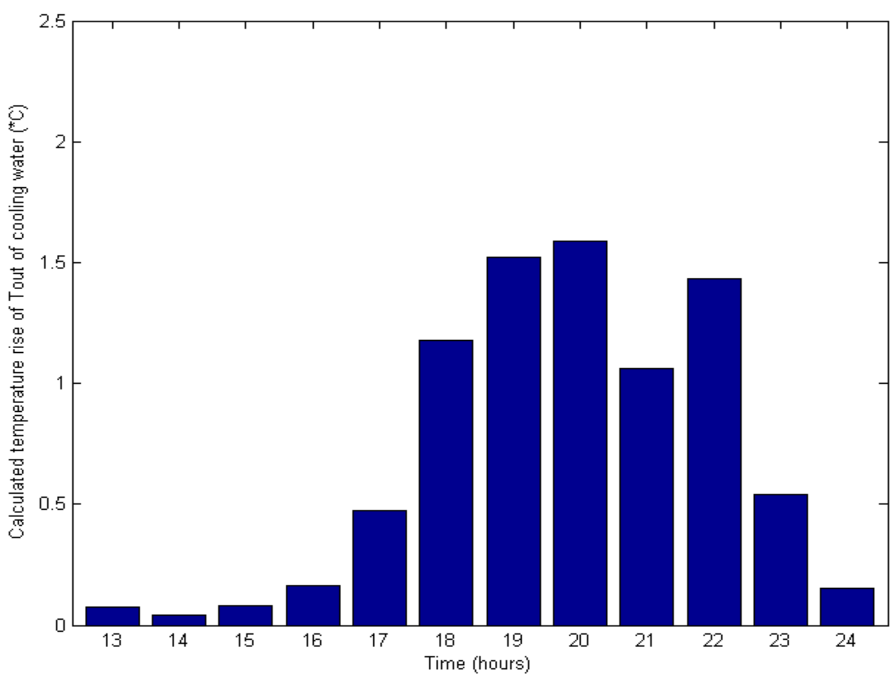

Fig. 6.11(b) Calculated way-out temperature rise of cooling water at 12:00-24:00 for 5% penetration level.

6.3.3 Simulation Results for 30% of Total Generation Capacity is Replaced by Wind Power Generation

Then, following the same process, the simulation gets the results for wind energy at 30% penetration level. The calculating results of temperature rises in machine and cooling water are also continual in 24 hours and calculating results are also shown in every hour for 24 hours. Fig. 6.12(a) to Fig. 6.12(f) show changing processes of calculated temperature rise of the machine in every one hour for 24 hours. And Fig. 6.13(a) and Fig. 6.13(b) respectively represent and compare the final temperature rise results for every hour in a day.

And Fig. 6.14(a) to Fig. 6.14(f) show changing processes of calculated way-out temperature rise of cooling water in every one hour for 24 hours. And Fig. 6.15(a) and Fig. 6.15(b) represent and compare the final way-out temperature rise of cooling water for every hour in a day.

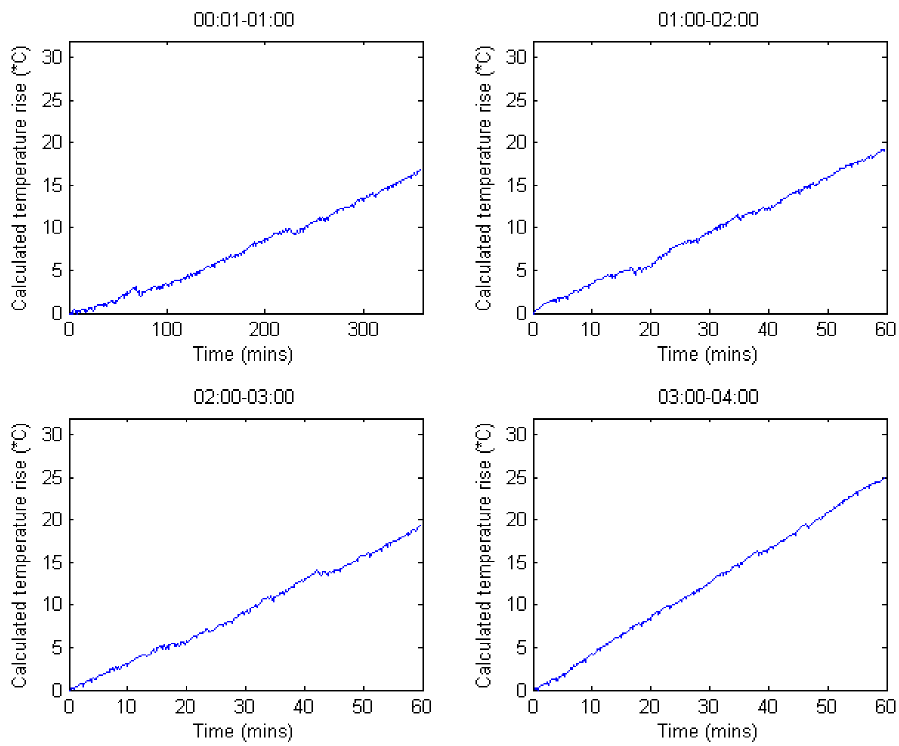

Fig. 6.12(a) Calculated temperature rise of machine of 00:00-04:00 for 30% penetration level.

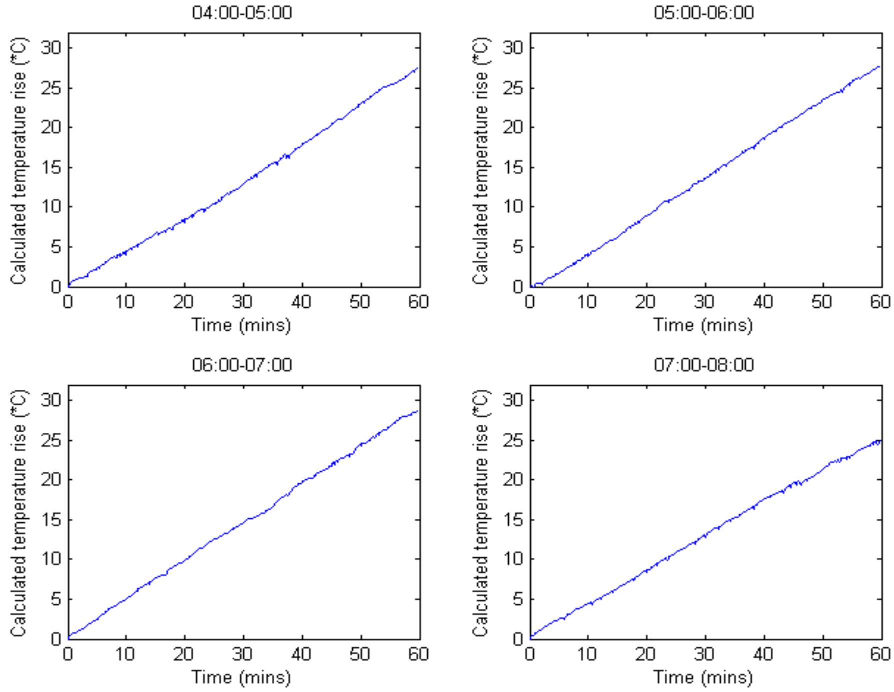

Fig. 6.12(b) Calculated temperature rise of machine of 04:00-08:00 for 30% penetration level.

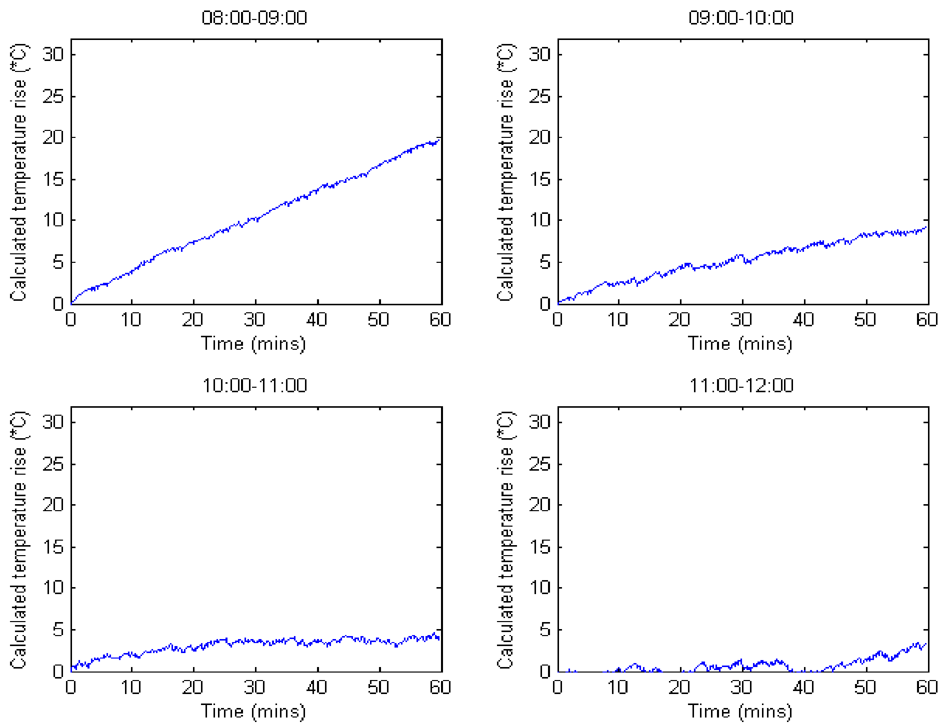

Fig. 6.12(c) Calculated temperature rise of machine of 08:00-12:00 for 30% penetration level.

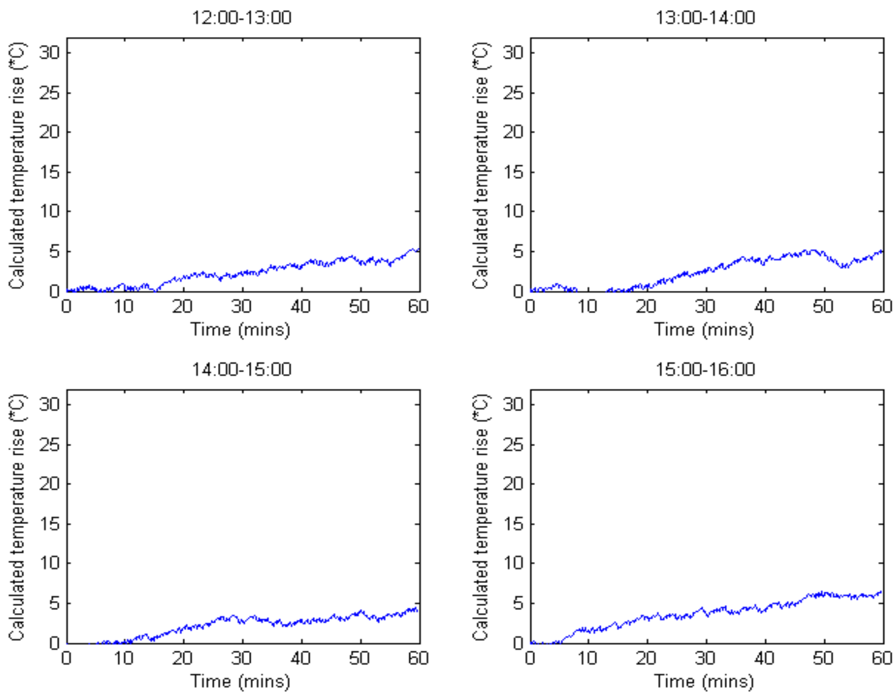

Fig. 6.12(d) Calculated temperature rise of machine of 12:00-16:00 for 30% penetration level.

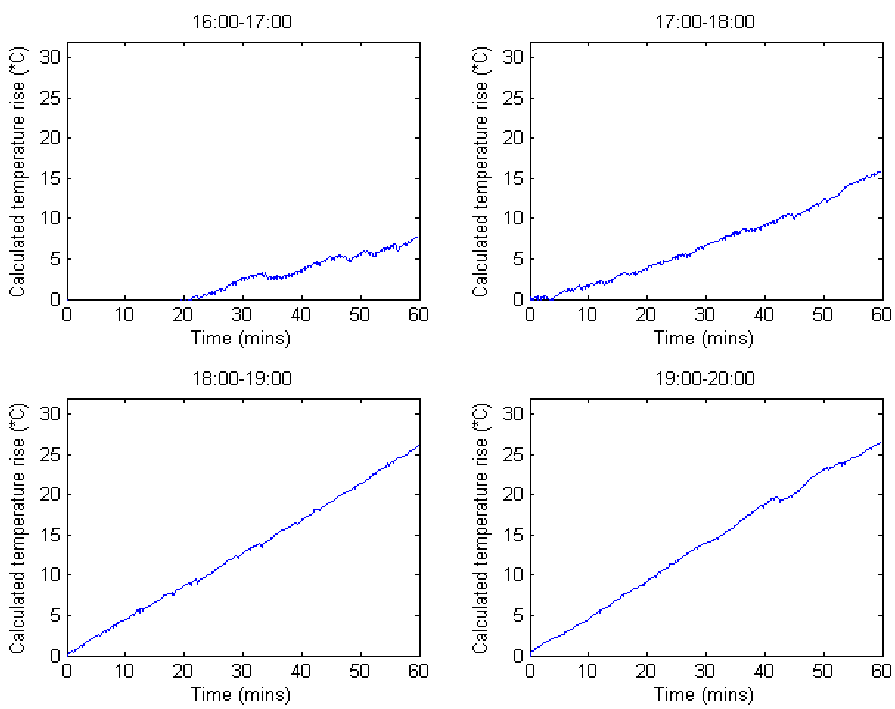

Fig. 6.12(e) Calculated temperature rise of machine of 16:00-20:00 for 30% penetration level.

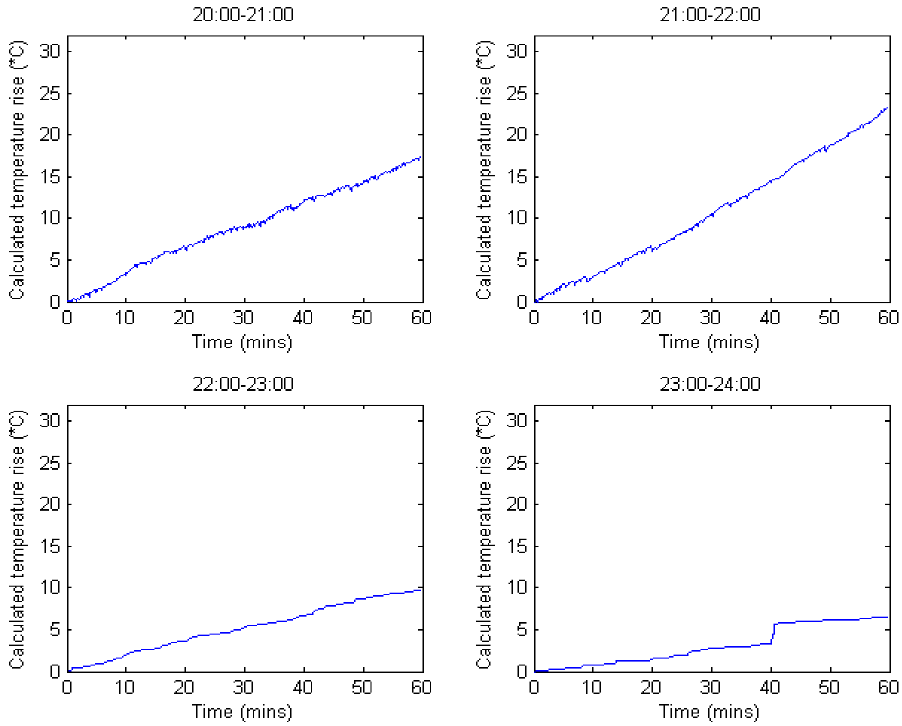

Fig. 6.12(f) Calculated temperature rise of machine of 20:00-24:00 for 30% penetration level.

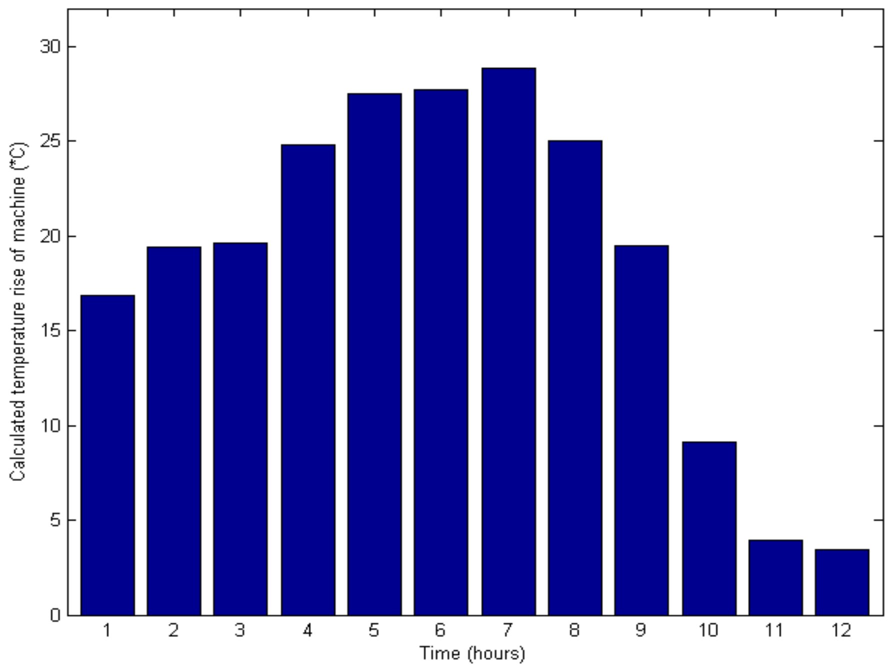

Fig. 6.13(a) Calculated temperature rise of machine at 00:00-12:00 for 30% penetration level.

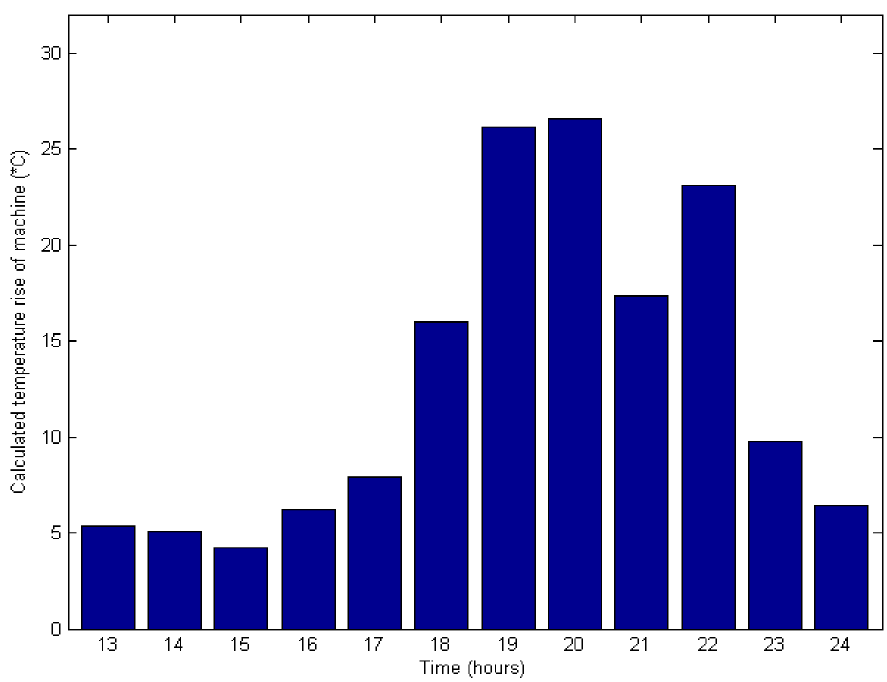

Fig. 6.13(b) Calculated temperature rise of machine at 12:00-24:00 for 30% penetration level.

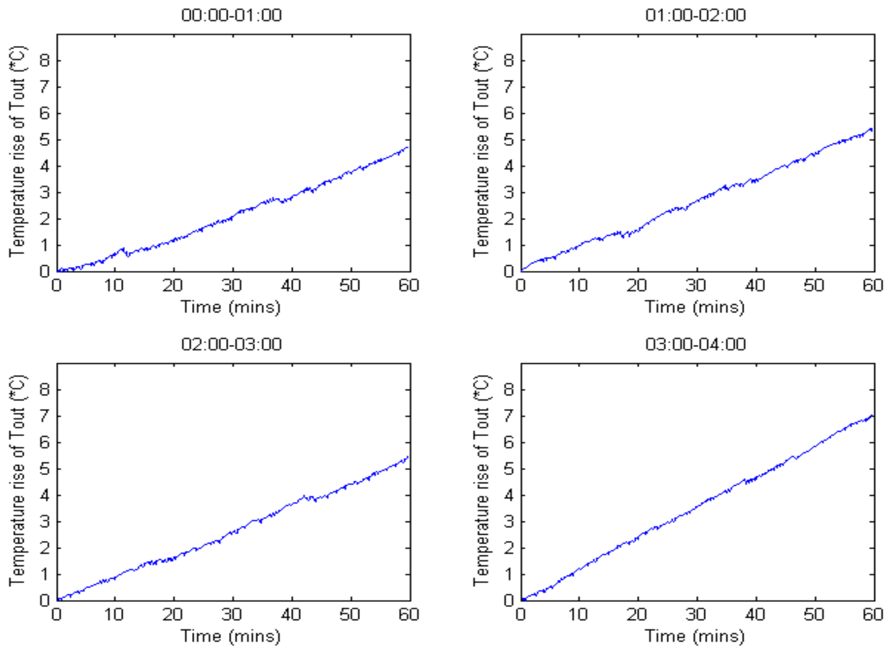

Fig. 6.14(a) Calculated way-out temperature rise of cooling water of 00:00-04:00 for 30% penetration level.

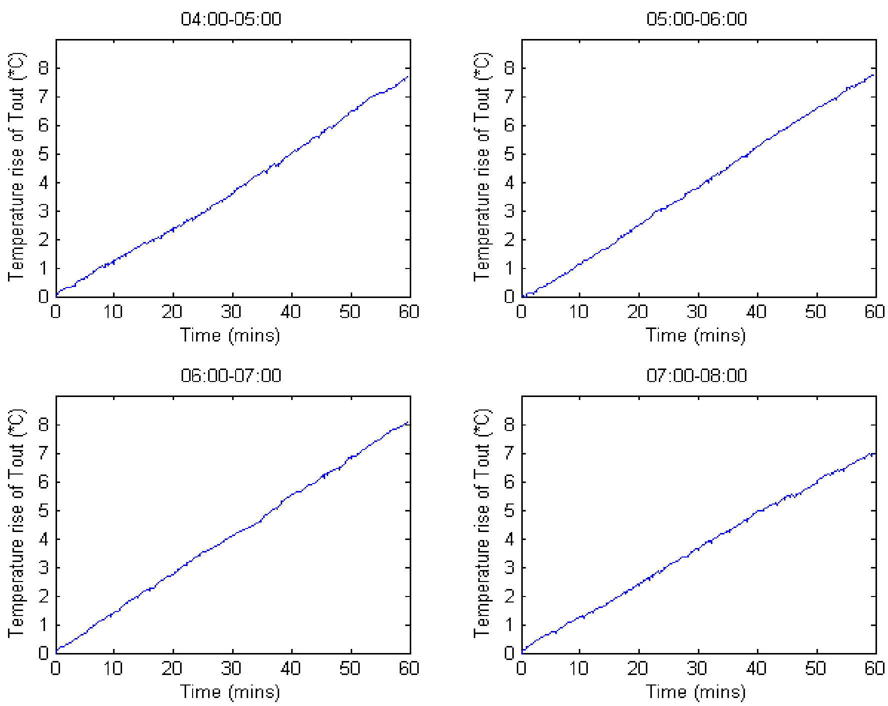

Fig. 6.14(b) Calculated way-out temperature rise of cooling water of 04:00-08:00 for 30% penetration level.

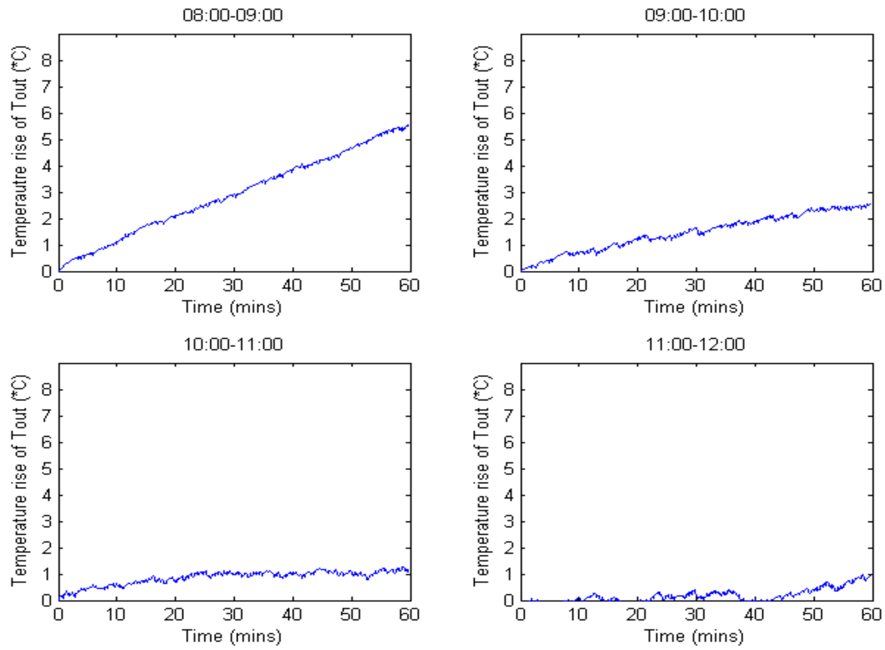

Fig. 6.14(c) Calculated way-out temperature rise of cooling water of 08:00-12:00 for 30% penetration level.

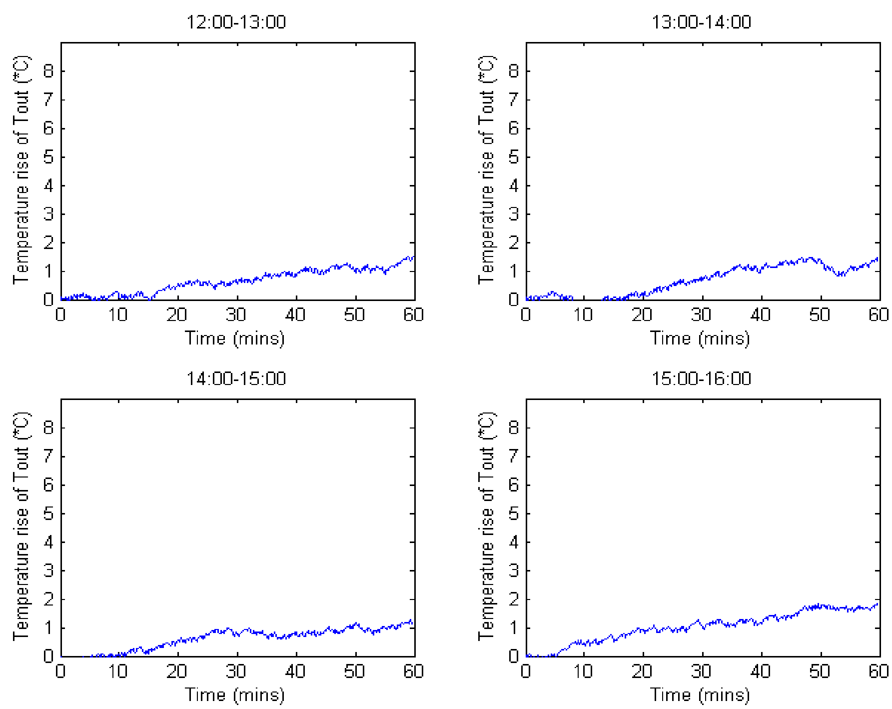

Fig. 6.14(d) Calculated way-out temperature rise of cooling water of 12:00-16:00 for 30% penetration level.

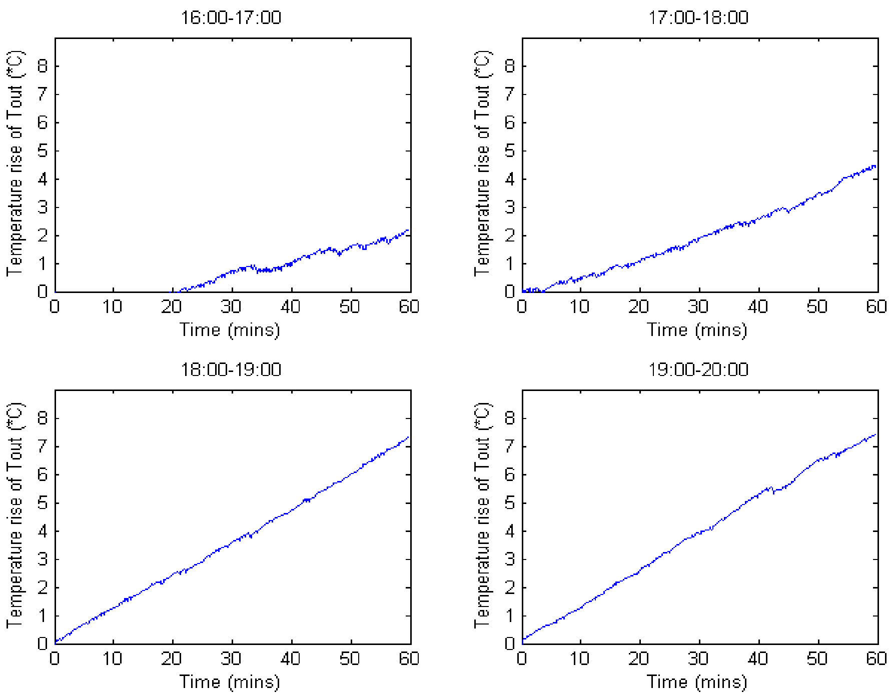

Fig. 6.14(e) Calculated way-out temperature rise of cooling water of 16:00-20:00 for 30% penetration level.

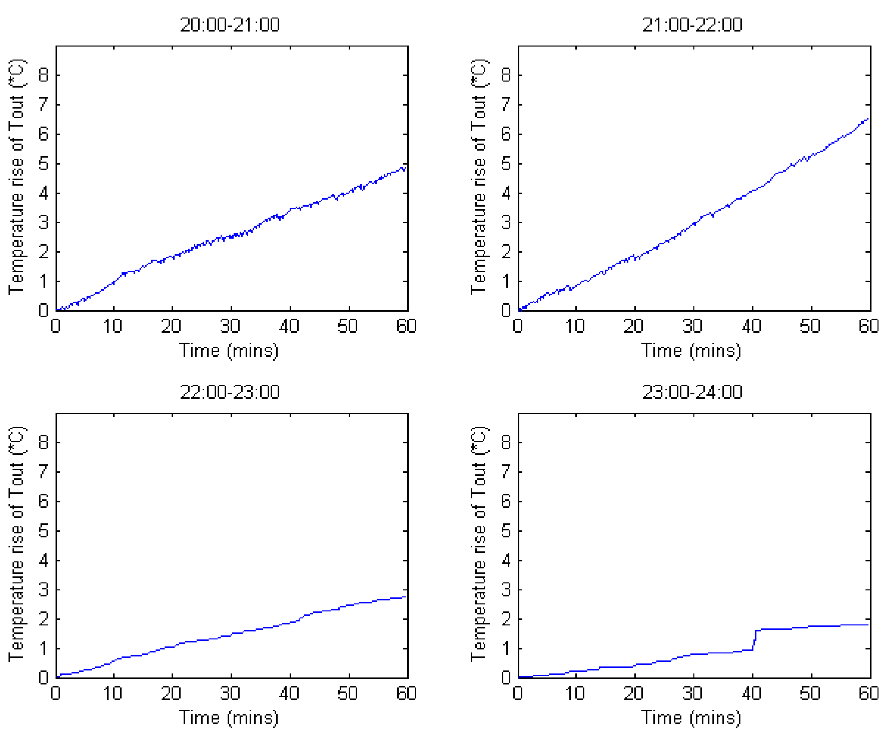

Fig. 6.14(f) Calculated way-out temperature rise of cooling water of 20:00-24:00 for 30% penetration level.

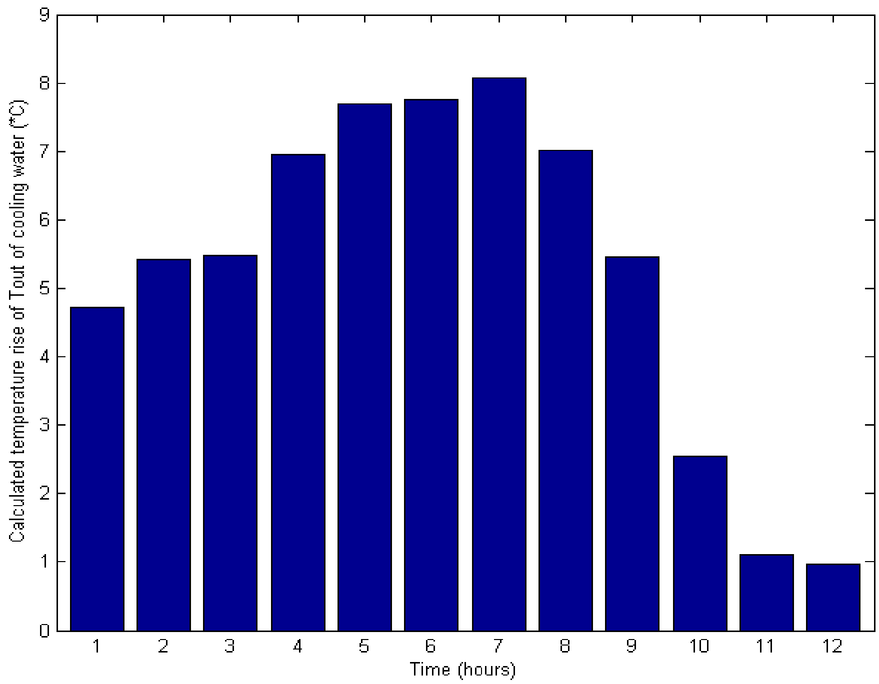

Fig. 6.15(a) Calculated way-out temperature rise of cooling water at 00:00-12:00 for 30% penetration level.

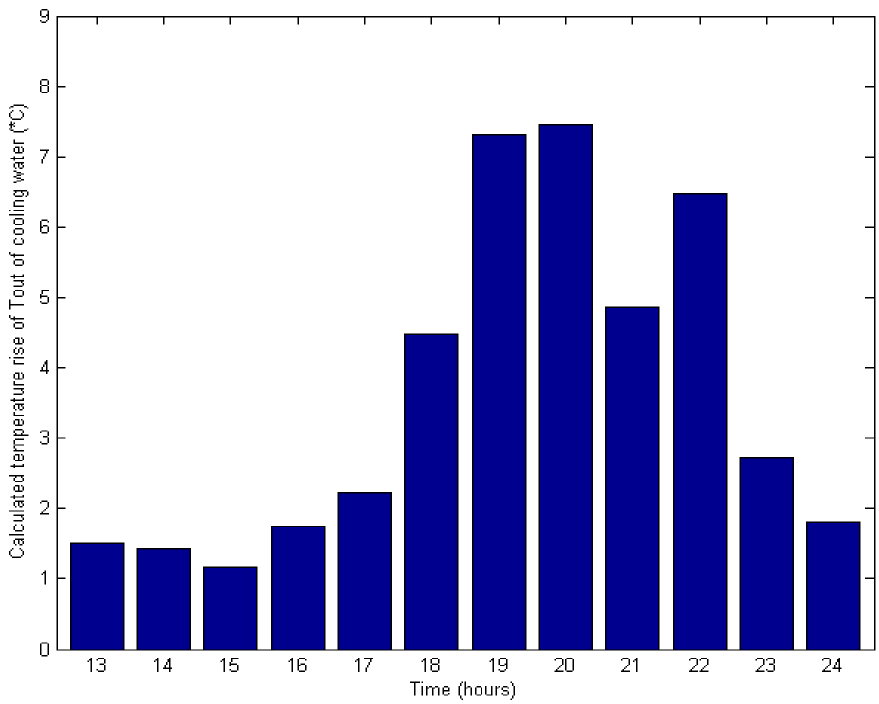

Fig. 6.15(b) Calculated way-out temperature rise of cooling water at 12:00-24:00 for 30% penetration level.

6.3.4 Comparison and Analyse the Simulation Results of 5%, 15% and 30% Penetration Levels

After the simulation, the results of cooling water way-out temperature rise of conventional generator under wind power generation 5% and 30% penetration levels can be calculated. Together with the cooling water way-out temperature rise results under wind power generation 15% penetration level which has calculated in the last chapter, the results of three different situations can be represented and compared.

So, the results for wind energy 5%, 15% and 30% penetration level at same time are list at every hour on Fig. 6.16(a) to Fig. 6.16(d):

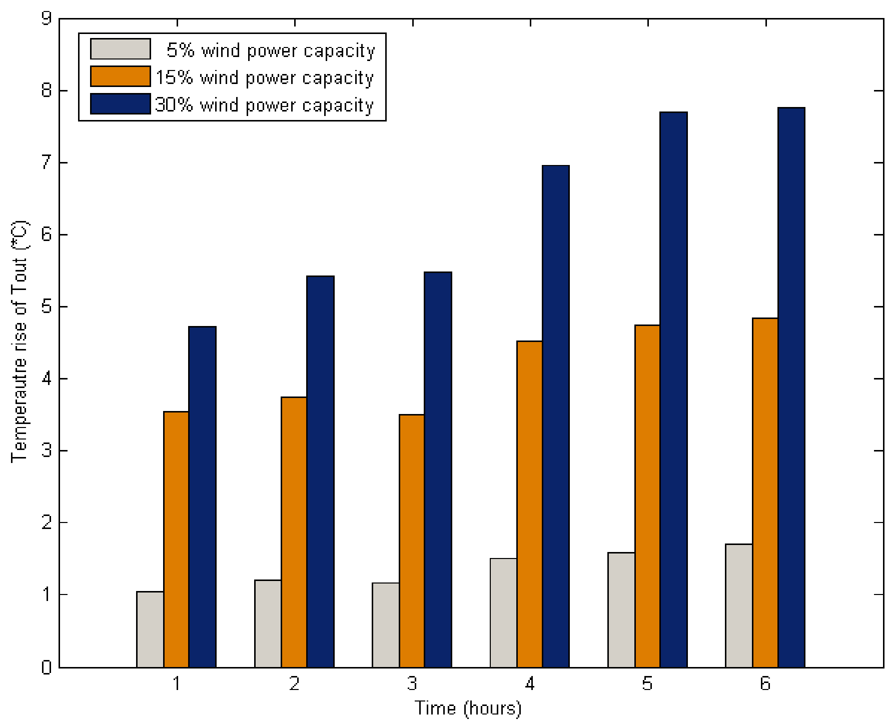

Fig. 6.16(a) Calculated way-out temperature rise of cooling water in every one hour for 5%, 15% and 30% wind energy penetration level at 00:00-06:00.

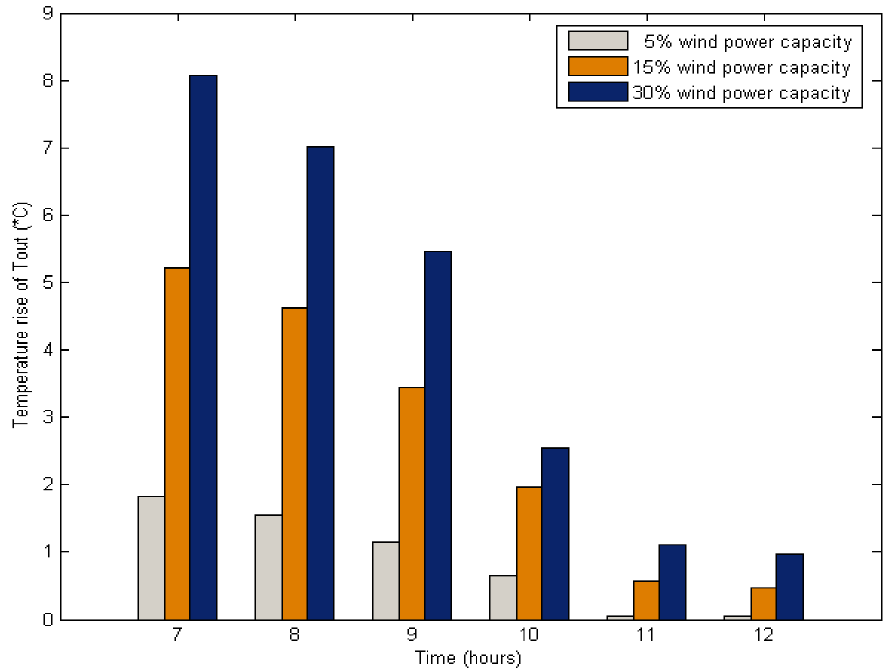

Fig. 6.16(b) Calculated way-out temperature rise of cooling water in every one hour for 5%, 15% and 30% wind energy penetration level at 06:00-12:00.

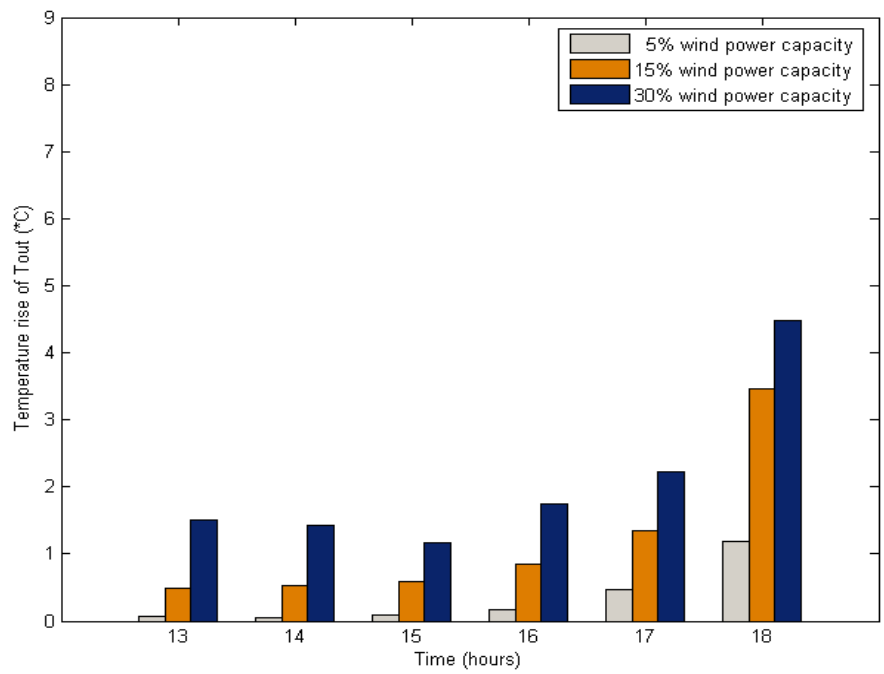

Fig. 6.16(c) Calculated way-out temperature rise of cooling water in every one hour for 5%, 15% and 30% wind energy penetration level at 12:00-18:00.

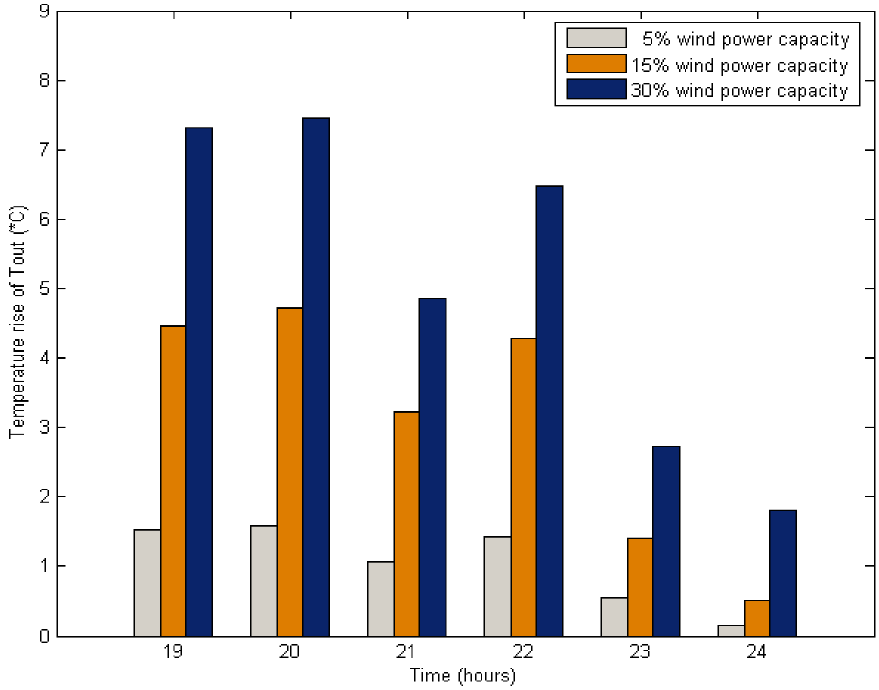

Fig. 6.16(d) Calculated way-out temperature rise of cooling water in every one hour for 5%, 15% and 30% wind energy penetration level at 18:00-24:00.

From these figures, it can be found that along with the increasing of wind energy penetration level in a power system the cooling water way-out temperature rise is also increased. For the simulation results at every hour, the temperature rise of T_{out} at wind energy 30% penetration level is larger than the results at 15% and similarly the temperature rise of T_{out} at wind energy 5% penetration level is smaller than the results at 15%. According to this characteristic of simulation results, it can be summarised that when the more percentage of total generation capacity is replaced by wind power generation, the power system will suffer more influences from wind power generation and these impacts will also lead to conventional generators are greater under thermal pressure and have higher risk to break the heating limits of generator machines. When the capacity of wind power generation in the total capacity reaches to around 30%, the heating problem of conventional generators in the power system will become certainly serious.

Moreover, it also can be realised that the way-out temperature rise of cooling system under three different penetration levels have the similar changing trend. For all three situations, temperature rise during the period of 04:00-08:00 are larger than those in other time periods and the values during the period of 11:00-15:00 are smaller than others. It means that the wind turbine generators output, which also can be considered as wind speed value, is another important aspect to influence the heating performance of conventional generators.

6.4 Simulation of Heating Problem Calculation for Different Types of Generator

In a practical power system, if there are enough operating capacities or stand-by capacities, they will be used to deal with the fluctuation of load and system frequency. Generally, the hydro power plants and small capacity steam power plants such as gas turbine generators are usually used to maintain stable energy supply. [3]

When the wind farms are connected to a power system, it may also produce some fluctuation of power flow in the system. From the power system point of view, it also can be looked as the fluctuation of load in the system. As a result, the hydro power plants and small capacity steam power plants may still be used to match the fluctuation of wind turbine generators output.

In this simulation, the aim is to research, analyse and compare the heating performances of different types of generators when the wind farms are connected to the power system. The first example is hydro generator and the second one is gas turbine generator.

6.4.1 Simulation of Water-cooled Hydro Generator

Hydroelectric units have similar input-output characteristics to steam turbine units. The input is volume of water per unit time and the output is electrical power. The hydroelectric plants and their characteristics are affected greatly by the hydraulic configuration includes the installing location of plant and the requirements for water flows. Hydroelectric plants are usually coupled both electrically and hydraulically so they are more flexible to match the peak load, balance the fluctuation and can be as stand-by capacity. And the water-cooled systems are also installed in hydro generators generally. Furthermore, because of the natural differences in the watersheds, the differences in the man-made storage and release elements used to control the water flows, and different types of natural and man-made constraints imposed on the operation of hydroelectric systems, hence no two hydroelectric systems are totally same. [1, 4]

In this simulation, the conventional generator model used is the hydroelectric type to research the heating performances of hydro generator.

6.4.1.1 Case Study

In this case, the model system based on the previously one but the 1000MW normal conventional generator model is replaced by a 1000MW hydro generator model and the model system is shown in Fig. 6. 17. The hydro generator model is a synchronous machine associated with the hydraulic turbine, governor and excitation system blocks which are from Matlab Simulink SimPowerSystems™. And the mechanical information of water-cooled system in hydro generator is also list in Table 6.1. [5]

The other data of power system and wind speed do not change for this simulation and the capacity of wind turbine generators remain at 150MW.

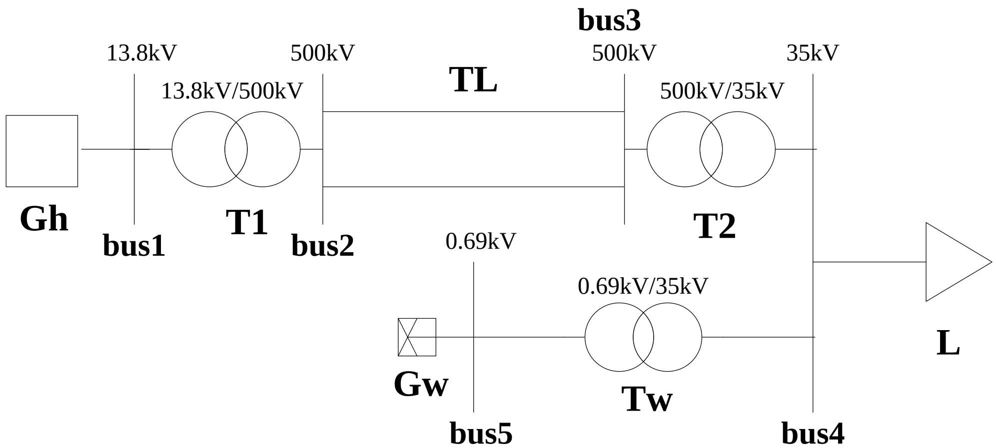

Fig. 6.17 The model system of the 6.4.1.1 case study.

Table 6.1 The information and data of water-cooled system in hydro generator

Symbol	Information	Data
θ_f	the power factor	0.9
T_{akb}	the maximum ambient temperature	20 ℃
S_l	the perimeter of transversal section of waterway	3.927×10^{-2} m
L_C	the length of waterway	27 m
D_H	the equivalent hydraulic diameter of waterway	1.25×10^{-2} m (12.5 mm)
A_{CS}	the cross-sectional area of water flow	1.227×10^{-4} m^2
limit of T_{in}	the maximum allow temperature of cooling water which get into the machine before	25 ℃
limit of T_{out}	the maximum allow temperature of cooling water which has passed the machine	55 ℃
n	the number of waterways which are parallel in one heat exchange unit	180

6.4.1.2 Simulation Results

After the simulation, the results of temperature rise of machine can be obtained and are shown on Fig. 6.18(a) and Fig. 6.18(b) respectively. The stable temperature of 1000MW hydro generator machine at constant output 850MW with a 150MW constant output wind turbine generation in the power system is 72.5 ℃.

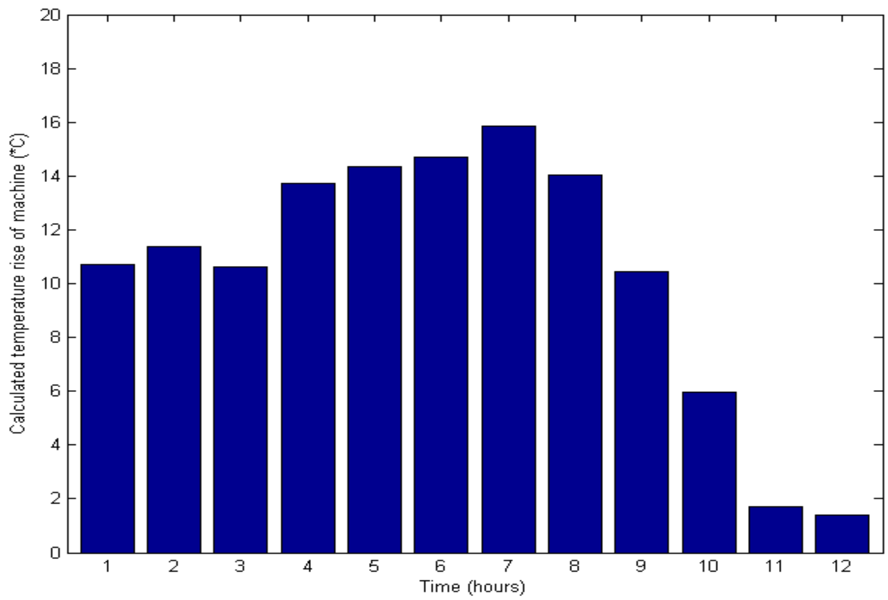

Fig. 6.18(a) Calculated temperature rise of hydro generator machine at 00:00-12:00.

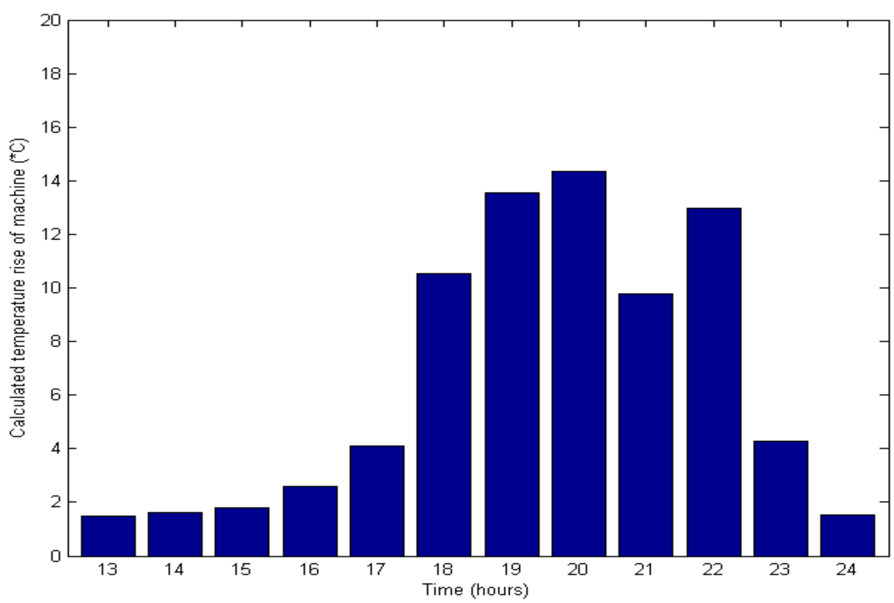

Fig. 6.18(b) Calculated temperature rise of hydro generator machine at 12:00-24:00.

Then, relied mechanical information of water-cooled system in hydro generator, coolant convection coefficients can be calculated and lists in Table 6.2.

Table 6.2 The calculated results of hydro generator water-cooled system heat exchange indexes

Symbol	Information	Calculated results
Re	Reynold number	3247
Nu	Nusselt number	83.42
Pr	Prandtl number	5.6
α_{ccw}	the convection heat transfer coefficient of water	4004
NTU	the number of heat transfer units	0.22

At last, based on the results of temperature rise of hydro generator and NTU, the results of cooling water way-out temperature rise can be obtained and through the calculation processes and are shown in Fig. 6.19(a) and Fig. 6.19(b) respectively. The stable cooling water way-out temperature is 34.5 ℃ when hydro generator machine has a constant output 850MW with a 150MW constant output of wind turbine generation in the power system. From Table 6.1, it can be noticed that both the maximum limits of T_{in} and T_{out} (25 ℃ and 55 ℃) are about 20 ℃ lower than the ones of water-cooled system in steam generator (45 ℃ and 73 ℃)which has been simulated in the last chapter. The reason of this difference is that the cooling water of hydro generator machine is from the surrounding water sources directly and the way-in temperature of cooling water depends on the environment.

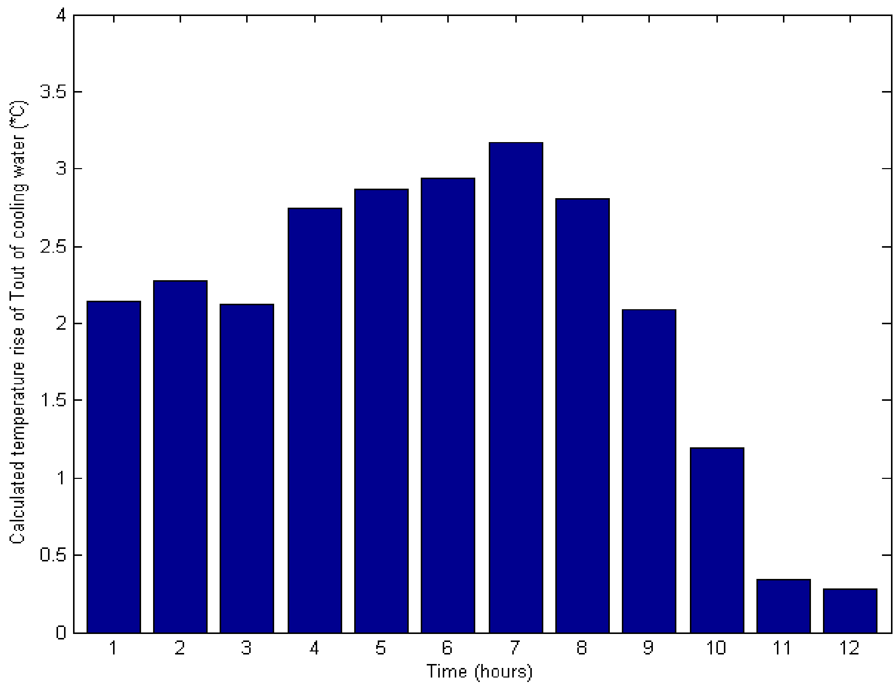

Fig. 6.19(a) Calculated way-out temperature rise of cooling water in hydro generator machine at 00:00-12:00.

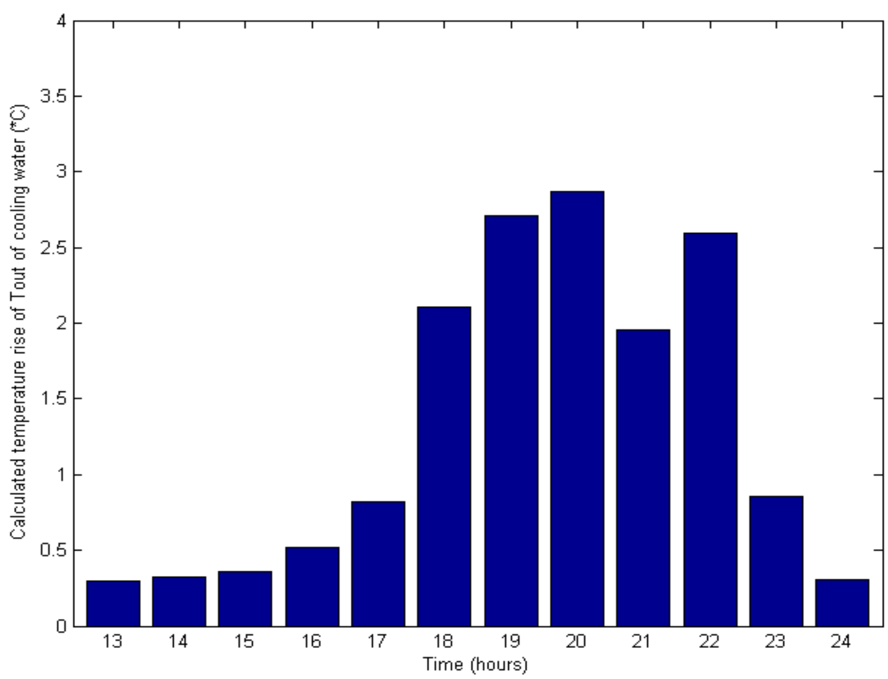

Fig. 6.19(b) Calculated way-out temperature rise of cooling water in hydro generator machine at 24:00-24:00.

In order to compare the results of two types of generator, both simulation results of water-cooled steam generator and water-cooled hydro generator are represented in the Fig. 6.20(a) and Fig. 6.20(b) respectively.

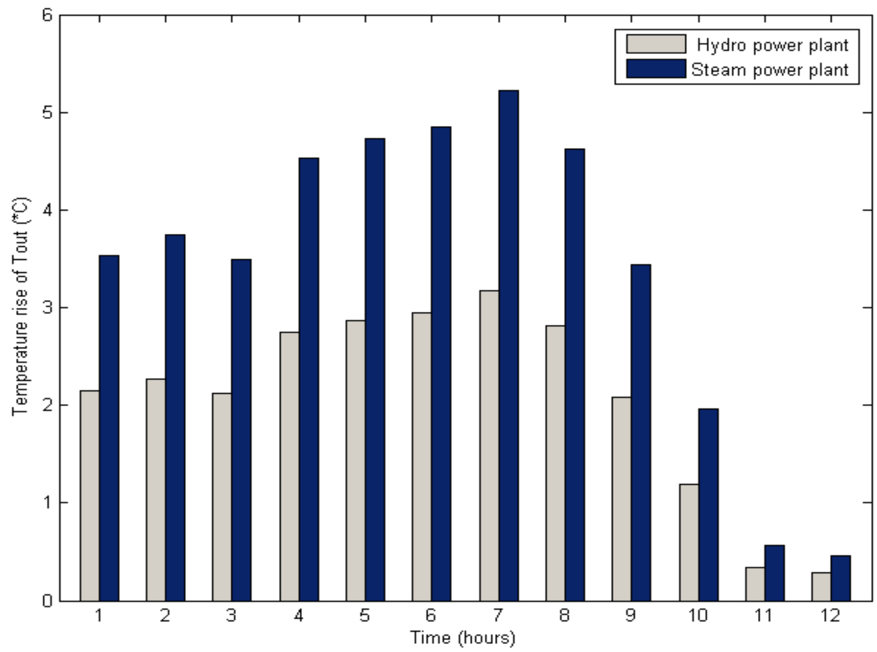

Fig. 6.20(a) Simulation results for hydro generator and steam generator at 00:00-12:00.

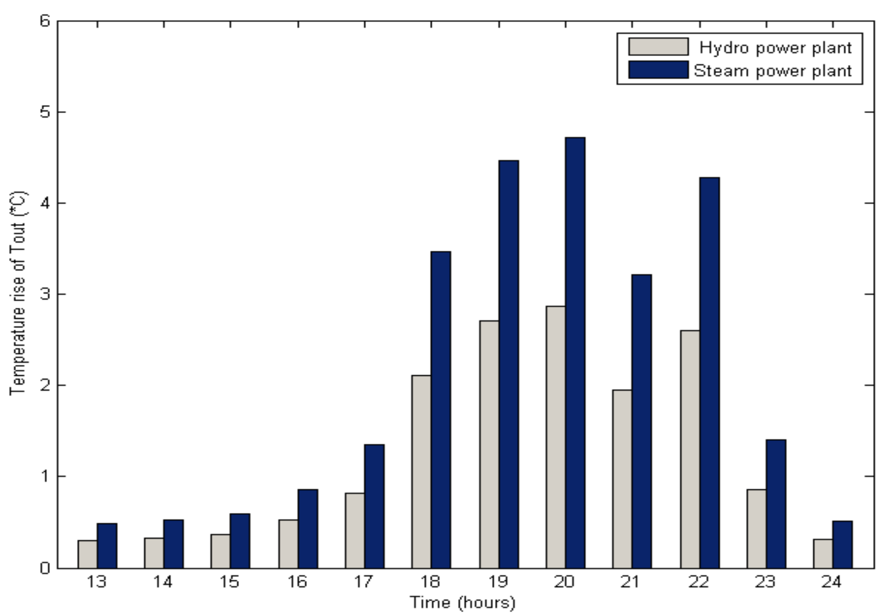

Fig. 6.20(b) Simulation results for hydro generator and steam generator at 12:00-24:00.

From the comparision of results, it shows that the cooling water way-out temperature rise in hydro generator is smaller than in steam generator for every hour in a day under the same wind energy penetration level and wind power generaion output fluctuation condition in a power system. Generally, the prime mover of hydro generator can control the rate of water flow easily. This is due to the design and construction of hydro generation system and in particular the operation characteristics of water turbines which enable rapid response control.. Furthermore, for cooler enivornment and larger inside space, the water cooling system in hydro generator is more efficiency. [1] It can be summaried that the hydro generator has the better heating performances than steam generator when it is used to deal with the wind power generation output fluctuation under the same situation. As a result, if a power system requires some capacity to balance the wind power generation influences, the hydro generator capacity should be considered first.

6.4.2 Simulation of Hydrogen-cooled Gas Turbine Generator

Gas turbine generator is also a common generator capacity type in the practical power system. And this kind of generators usually is middle size or small size capacity so the cooling systems in gas turbine generators are usually hydrogen-cooled system. In this simulation, the aim is to simulate and analyse the heating performances of gas turbine generator in the power system with wind turbine generators.

6.4.2.1 Case Study

In this case, the simulation model system shown on Fig. 6.21 includes one large capacity 1000MW steam synchronous generator supplies energy to a load centre through a pair of long distance backbone high-voltage transmission lines, one small capacity 200MW gas turbine generator supplies energy to a load centre through a single long distance high-voltage transmission lines, and wind turbine generators with 150MW connected to the load area in the distribution system. In this model system, the output of the large capacity generators keep constant to maintain the stable of the generator and the 200MW gas turbine generator is used to match the fluctuation of wind power generation.

And the information and data of this power system model and hydrogen cooling system in gas turbine generator are listed in the Table 6.3 and Table 6.4 respectively. [6]

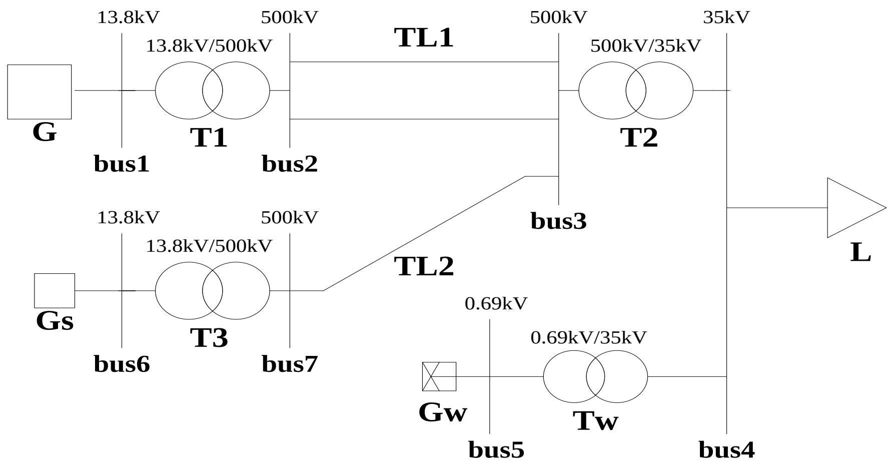

Fig. 6.21 The model system of the 6.4.2.1 case study.

Table 6.3 The information and data of model power system in Case study 6.4.2.1

Symbol	Information	Data (System frequency is 50Hz)
G	A conventional generator connected to transmission system	**Capacity:** 1100MVA; **Voltage level:** 13.8kV **Reactances Xd:** 1.305 p.u., **Xd':** 0.296p.u., **Xq:** 0.474p.u., **Xq'':** 0.18p.u.; **Stator resistance Rs:** 2.544×10-3p.u.
Gs	A hydrogen-cooled gas turbine generator connected to transmission system	**Capacity:** 250MVA; **Voltage level:** 13.8kV **Reactances Xd:** 0.5917 p.u., **Xd':** 0.0785p.u., **Xq:** 0.257p.u., **Xq'':** 0.094p.u.; **Stator resistance Rs:** 1.29×10-3p.u.
Gw	A large wind farm contains 100 wind turbines integrated connected to distribution system	**Capacity:** 100*1.5MW; **Voltage level:** 0.69kV
TL1	A double-line long distance backbone 500kV high-voltage transmission system	**Length:** 500km; **Voltage level:** 500kV; **Resistance R:** 1.755×10^{-2} Ω/km; **Inductance L:** 8.737×10^{-2} H/km; **Capacitance C:** 1.339×10^{-8} F/km
TL2	A single-line long distance backbone 500kV high-voltage transmission system	**Length:** 200km; **Voltage level:** 500kV; **Resistance R:** 1.755×10^{-2} Ω/km; **Inductance L:** 8.737×10^{-2} H/km; **Capacitance C:** 1.339×10^{-8} F/km
L	A load centre with a stable constant load	**Total demand:** 1000MW; **Voltage level:** 35kV
T1	Transformer connects conventional generator and transmission system	**Ratio:** 13.8kV/500kV; **Capacity:** 1100MVA
T2	Transformer connects transmission system and load in distribution system	**Ratio:** 500kV/35kV; **Capacity:** 1100MVA
T3	Transformer connects gas turbine generator and transmission system	**Ratio:** 13.8kV/500kV; **Capacity:** 250MVA
Tw	Transformer connects wind farm and distribution system	**Ratio:** 0.69kV/35kV; **Capacity:** 200MVA

Table 6.4 The information of hydrogen-cooled system in gas turbine generator

Symbol	Information	Data
θ_f	the power factor	0.85
T_{akb}	the maximum ambient temperature	45 ℃
S_l	the perimeter of transversal section of hydrogen gas passageway	2.073 m
L_C	the length of hydrogen gas passageway	6 m
D_H	the equivalent hydraulic diameter of hydrogen gas passageway	0.66m
A_{CS}	the cross-sectional area of hydrogen	0.902 m^2
limit of T_{in}	the maximum allow temperature of hydrogen gas which get into the machine before	45 ℃
limit of T_{out}	the maximum allow temperature of hydrogen gas which has passed the machine	80 ℃
W_{mr}	the hydrogen gas mass flow rate	0.0139 m^3/s (or 1.123×10^{-3} kg/s, 50 m^3/h)
c_H	the specific heat of hydrogen gas at constant pressure	14.3×10^3 J/kg ·℃
μ_H	the viscosity of hydrogen gas	8.9×10^{-6} kg/m s
K_H	the thermal conductivity of hydrogen gas	0.168 W/m•°C
n	the number of passageways which are parallel in one heat exchange unit	1

6.4.2.2 Simulation Results

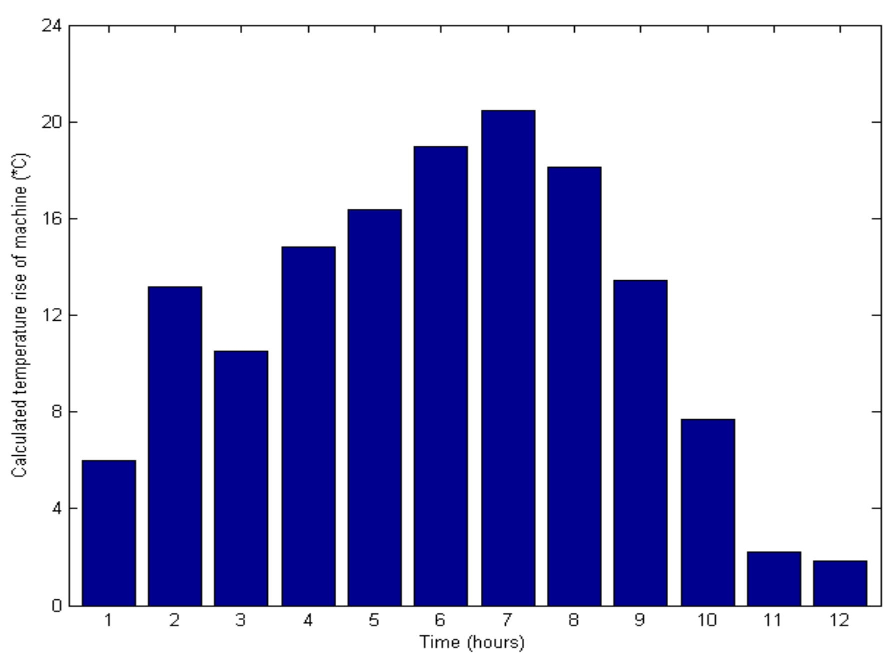

Fig. 6.22(a) Calculated temperature rise of gas turbine generator at 00:00-12:00.

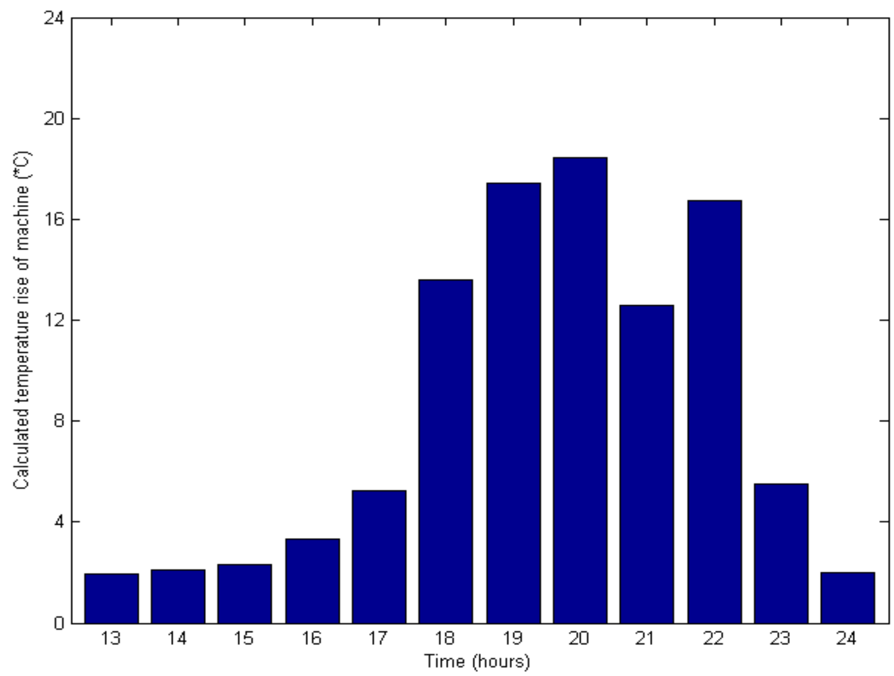

Fig. 6.22(b) Calculated temperature rise of gas turbine generator at 12:00-24:00.

After the simulation, the continuative results of temperature rise of the gas turbine machine can be obtained firstly and are shown in Fig. 6.22(a) and Fig. 6.22(b) respectively. And the stable temperature of the 200MW gas turbine machine at a constant output of 150MW is 65 ℃.

Then, related mechanical information of hydrogen-cooled system in gas turbine generator, coolant convection coefficients can be calculated and are listed in Table 6.5.

Table 6.5 The calculated results of gas turbine generator hydrogen-cooled system heat exchange indexes

Symbol	Information	Calculated results
Re	Reynold number	92.24
Nu	Nusselt number	0.768
Pr	Prandtl number	0.758
α_{ccH}	the convection heat transfer coefficient of hydrogen gas	0.196
NTU	the number of heat transfer units	0.152

At last, based on the results of temperature rise of gas turbine generator and NTU, the continuative results of hydrogen gas way-out temperature rise can be obtained and through the calculation processes and are shown in Fig. 6.23(a) and Fig. 6.23(b) respectively. The stable hydrogen gas way-out temperature is 49 ℃ when gas turbine generator machine has a constant output 150MW. And the simulation results shows that the gas turbine generator with hydrogen-cooled have the similar heating performances with hydro generator.

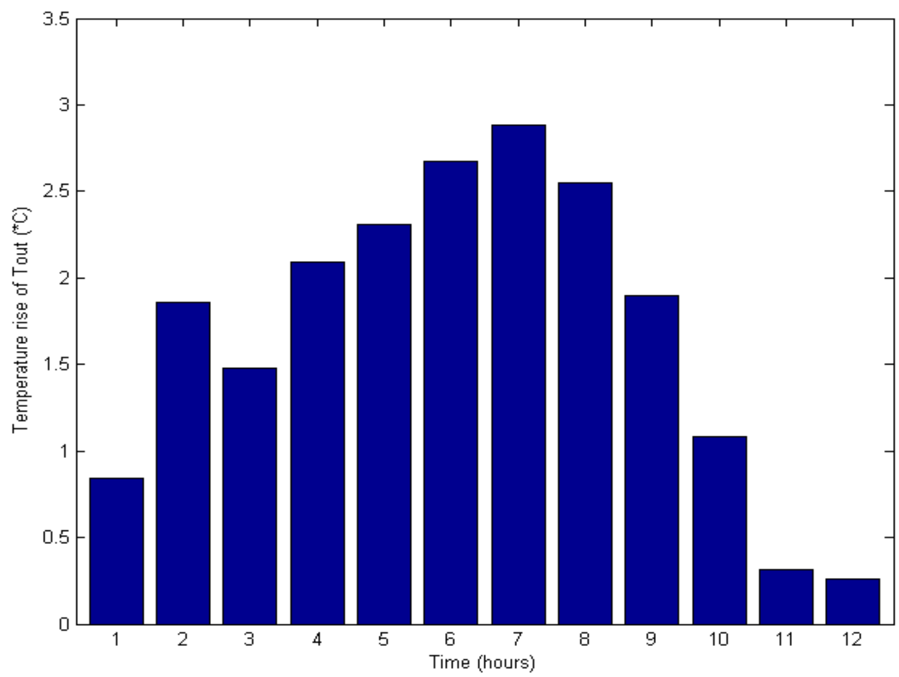

Fig. 6.23(a) Calculated way-out temperature rise of hydrogen gas in gas turbine generator machine at 00:00-12:00.

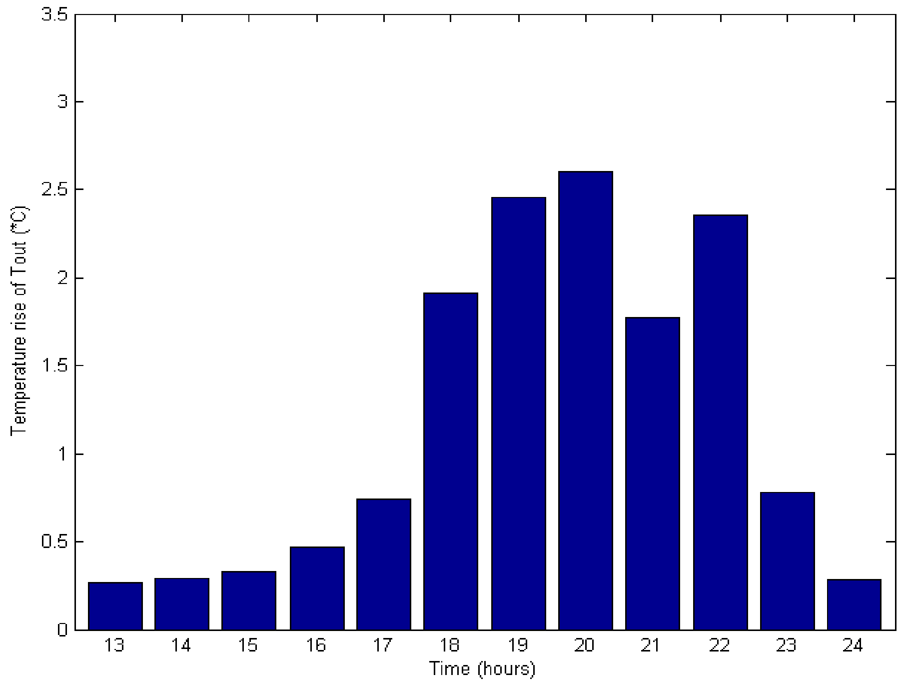

Fig. 6.23(b) Calculated way-out temperature rise of hydrogen gas in gas turbine generator machine at 12:00-24:00.

6.5 Simulation of Heating Problem Calculation in IEEE-14-Bus System and IEEE-39-Bus System

After simulating the heating problems under many different situations in a single power system, it is also necessary to research this problem in some more complex and practical power systems. Larger systems usually have more complicated scenarios for operating.

In this simulation, the research is based on IEEE-14-Bus system and IEEE-39-Bus system with certain capacity of wind turbine generator connected to these systems.

6.5.1 Simulation of IEEE-14-Bus System

The one-line diagram of IEEE-14-Bus system is shown in Fig. 6.24 and the detailed data of the system is shown in Appendix A. [7]

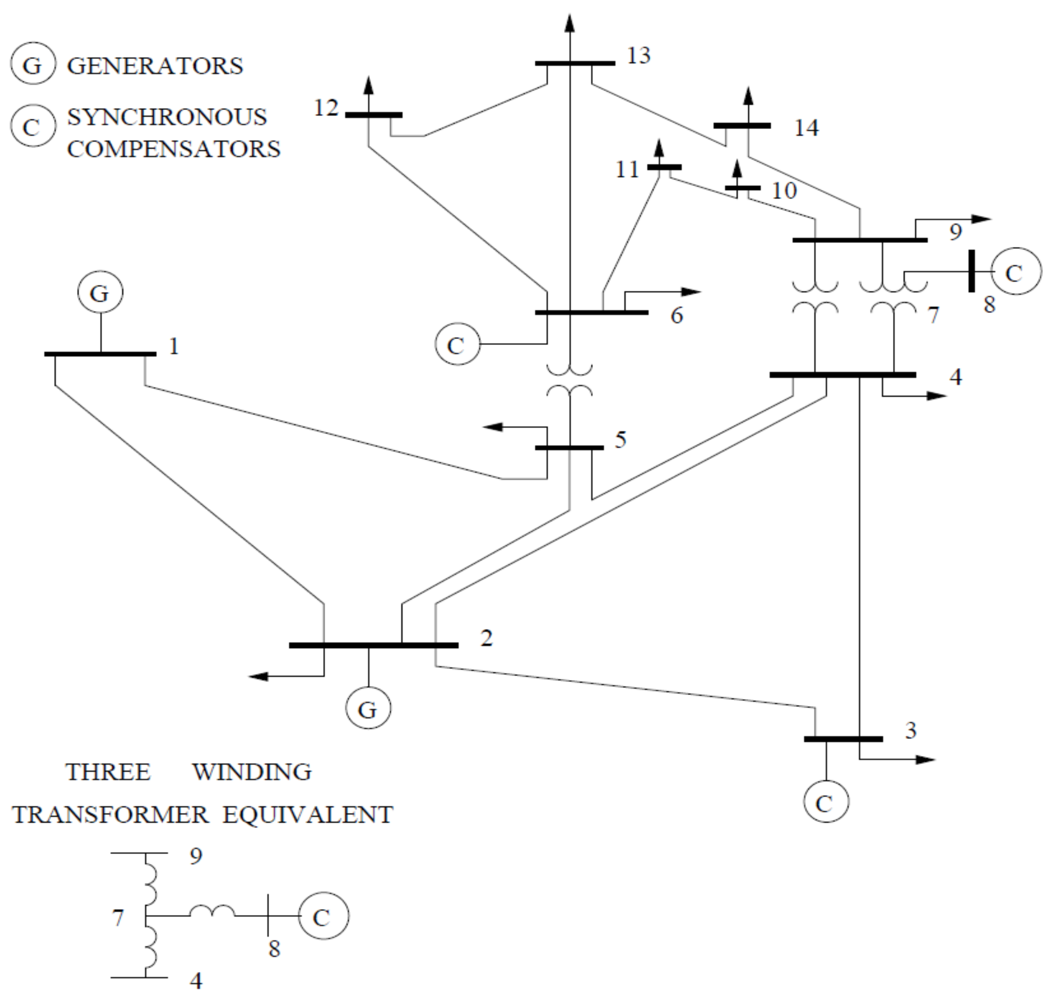

Fig. 6.24 The one-line diagram of IEEE-14-Bus system.

Simulation scenario:

A wind farm which has 100MW installed capacity is connected to the load area of this power system at bus 6.

The generator at bus 1 which has 615MVA capacity is used to balance the influences from wind power generation. And the cooling system used in this generator is set to water-cooled system with the same data of the water-cooled system in steam turbine generator which has introduced in the Chapter 5.

The power flow calculation is processed under both without and with wind farm. For the system with wind farm, the simulation time is 60mins and the wind speed of the wind turbine generators is 00:00-01:00 wind speed data which is developed in the Chapter 2.

Simulation results:

The output of generator at bus 1 under two different conditions is shown in the Fig. 6.25:

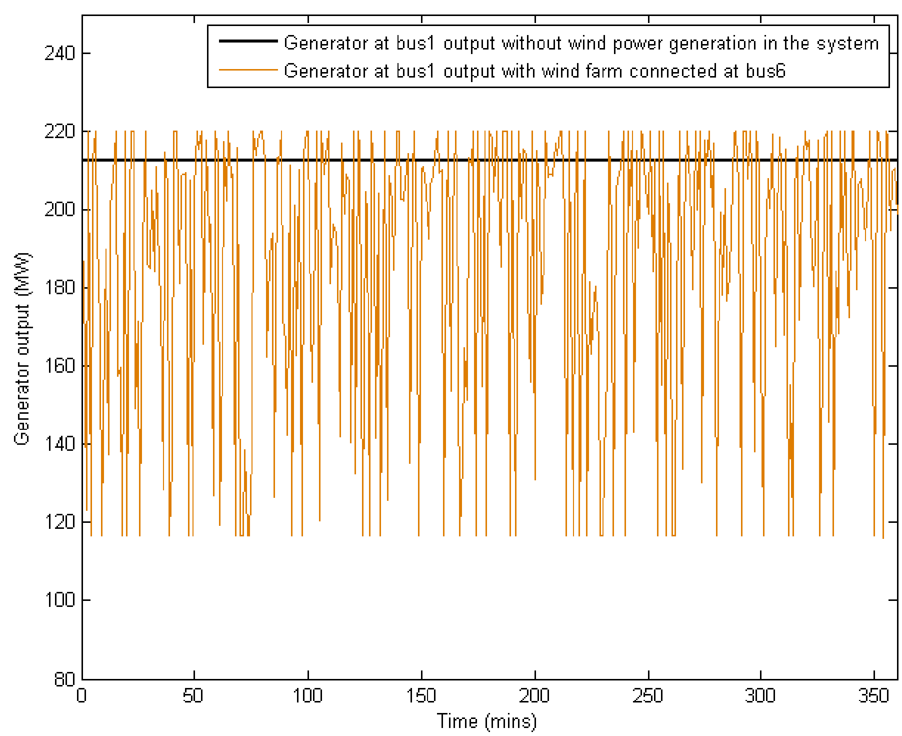

Fig. 6.25 The output of generator at bus 1 under two different conditions.

According to these power flow results and the heating problem calculation method, the heating performance of the generator at bus 1 can be obtained and list in the Table 6.6:

Table 6.6 Simulation results of heating performances for generator at bus 1

	Stable Temperature of Generator	**Stable Temperature of T_{out} in Cooling Water**
Power System without Wind Power Generation	65 ℃	50.6 ℃
	Calculated Temperature Rise of Generator	**Temperature rise of T_{out} in Cooling Water**
Power System connected with Wind Farm	6.06 ℃	1.69 ℃

In the same way, this calculation method can be used for other scenarios such as different wind farm connection points, different wind speed data and different conventional generators to match the fluctuation of wind farm output. The next simulation is based on IEEE-39-Bus system will consider more operation conditions of the power system.

6.5.2 Simulation of IEEE-39-Bus System

The one-line diagram of IEEE-39-Bus system is shown in Fig. 6.26 and the detailed data of the system is shown in Appendix B. [8]

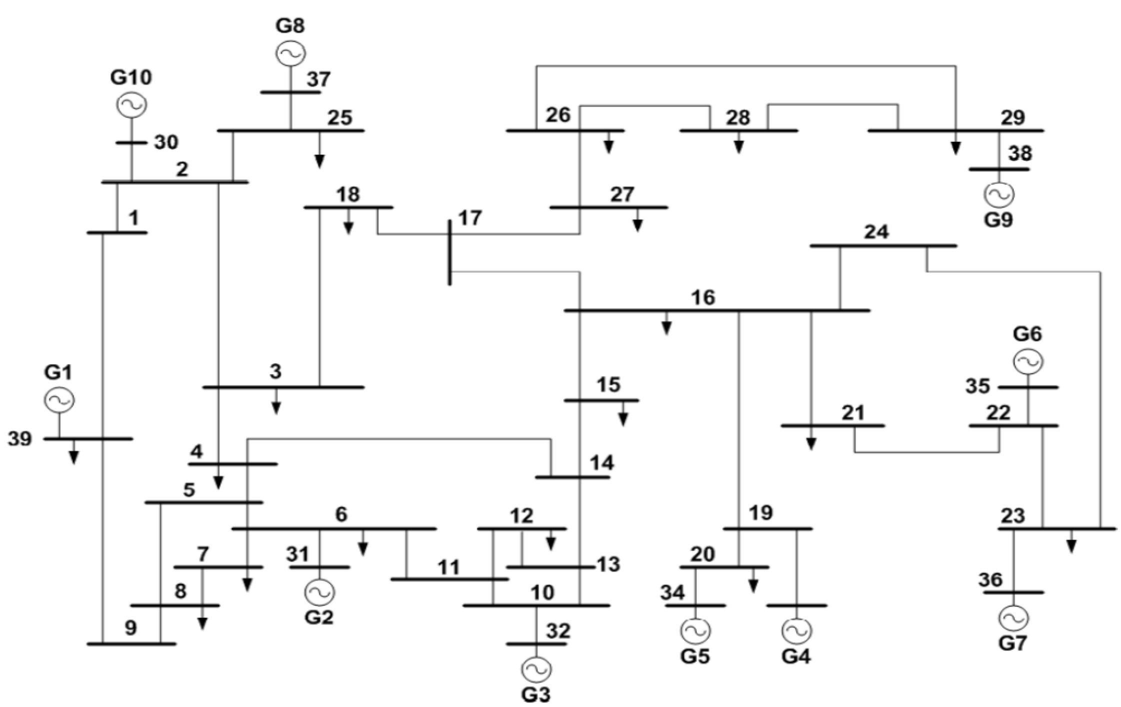

Fig. 6.26 The one-line diagram of IEEE-39-Bus system.

Simulation scenario:

There are two wind farms and each has 300MW capacity are connected to the power system. First wind farm is connected to a load area of this power system at bus 9. The second one is connected to another load area of this power system at bus 19. However, the two wind farms use the different wind speed data at the same simulation period. The wind speed of the wind farm at bus 9 is 05:00-06:00 wind speed data and the wind speed of the wind farm at bus 17 is 00:00-01:00 wind speed data which are developed in Chapter 2.

In this simulation, all the 10 conventional generators are used to match the fluctuation of wind turbine generators output. As the result, the optimal power flow (OPF) program is used to calculate the output fluctuation of every conventional generator in the IEEE-39-Bus system. And the cooling systems used in these conventional generators are also set to water-cooled system with the same data of the water-cooled system in steam turbine generator which was introduced in Chapter 5.

The optimal power flow (OPF) calculation is processed under both without and with wind farms. For the system with wind farm, the simulation time is 60mins.

Simulation results:

The output of generators in the optimal power flow results of the original IEEE-39-Bus system without wind power generation is shown in Fig. 6.27. The results of generators output in the IEEE-39-Bus system connected with two wind farms are also shown in Fig. 6.28(a) to Fig.6.28(c).

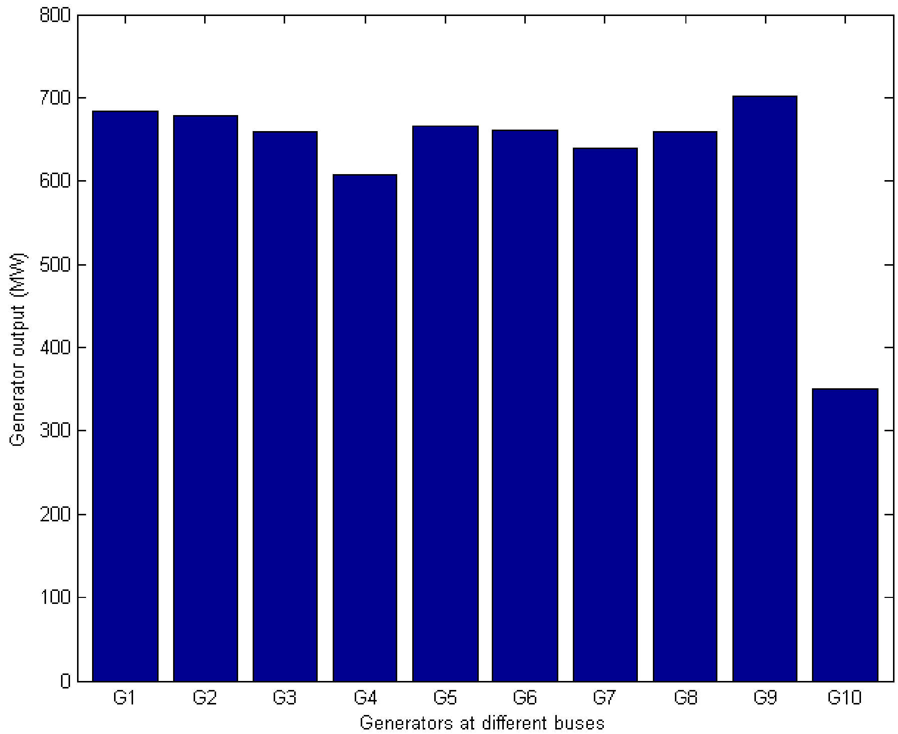

Fig. 6.27 The output of generators in the IEEE-39-Bus system.

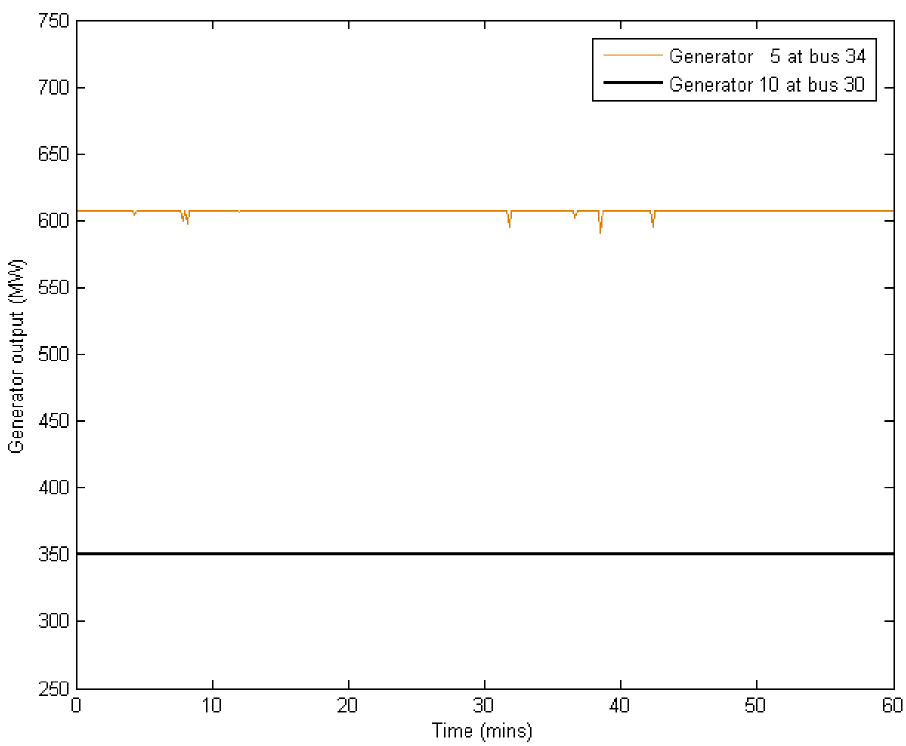

Fig. 6.28(a) Generators output of Generator 5 and Generator 10.

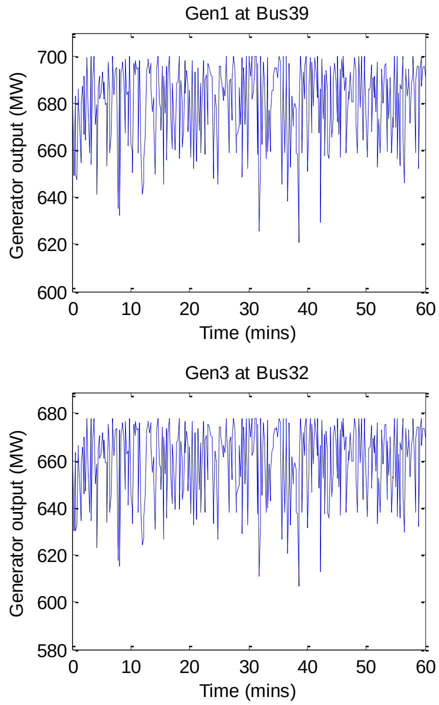

Fig. 6.28(b) Generators output of Generator 1 to Generator 4.

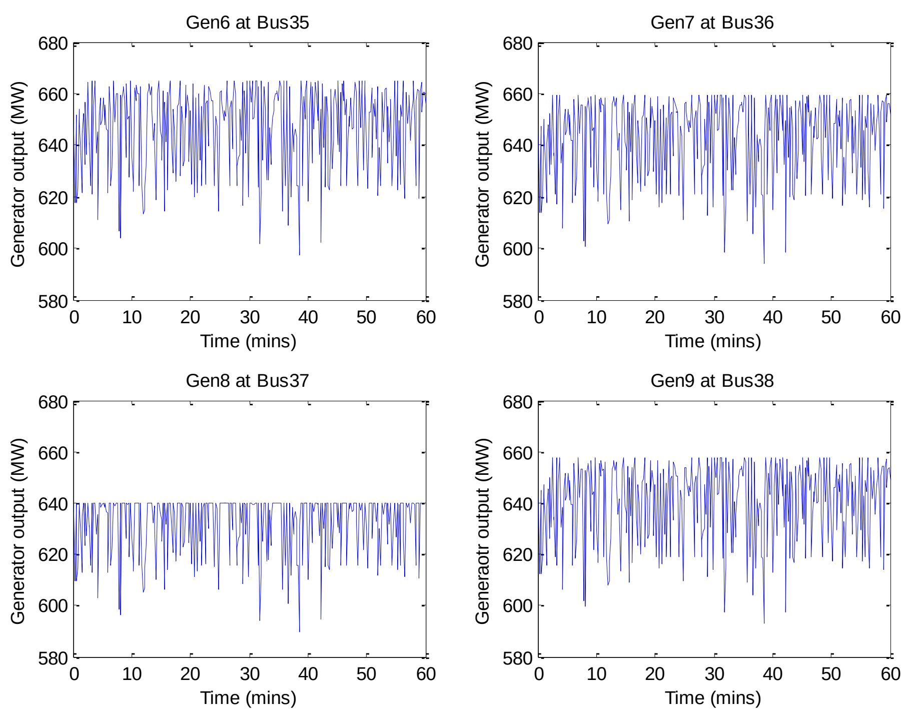

Fig. 6.28(c) Generators output of Generator 6 to Generator 9.

From the figures, the outputs of generator 5 at bus 34 and generator 10 at bus 30 are nearly constant so they are not influenced by the wind farms. However, the outputs of the other eight generators fluctuate during the simulation period. According to the results and the heating problem calculating method, the heating performance of these generators can be obtained and are listed in Table 6.7. It shows that nearly all the conventional generators are influenced by the wind farms and are all under the different thermal pressure.

Table 6.7 Simulation results of heating performances for generators

Gen No.: / Temperature:	Gen1 Bus39	Gen2 Bus31	Gen3 Bus32	Gen4 Bus33	Gen6 Bus35	Gen7 Bus36	Gen8 Bus37	Gen9 Bus38
Stable Temperature of Generator Machine	67.70 ℃	65.90 ℃	74.95 ℃	70.85 ℃	75.05 ℃	78.71 ℃	74.90 ℃	64.29 ℃
Stable Temperature of Tout in Cooling Water	51.36 ℃	50.85 ℃	53.39 ℃	52.24 ℃	53.41 ℃	54.44 ℃	53.37 ℃	50.40 ℃
Calculated Temperature Rise of Generator	5.09 ℃	4.96 ℃	5.71 ℃	5.40 ℃	4.86 ℃	3.37 ℃	4.85 ℃	4.17 ℃
Temperature rise of T_{out} in Cooling Water	1.43 ℃	1.39 ℃	1.60 ℃	1.51 ℃	1.36 ℃	0.94 ℃	1.36 ℃	1.17 ℃

6.6 Summary

This chapter used the heating performance calculation method to simulate and analyse the heating problem of conventional generator in a power system with wind turbine generators under different conditions which include extremely unfavourable wind speed condition, different wind power generation penetration levels condition, different types of generator condition and more complicated power systems condition. Because of the complicated simulation and calculating processes and huge quantity of data, the simulation is also divided into every hour. For more clearance for representing and comparing, the simulation results are also shown in one hour.

For analysing the influences from more fluctuating wind speed condition to the power system, it can be obtained that for extremely unfavourable wind speed period the conventional generator reaches its heating limits more quickly than other normal wind speed condition and it is necessary to pay a lot of attention on the heating performances of conventional generators which are used to match the wind farm output fluctuation.

For analysing the impact from different penetration level of wind energy it can be summarised that when the more percentage of total generation capacity is replaced by wind power generation, conventional generators are greater under thermal pressure and have higher risk to break the heating limits of generator machines. When the capacity of wind power generation in the total capacity reaches to around 30%, the heating problem of conventional generators in the power system will become certainly serious.

For exploring the heating performances of other types of conventional generator, it can be summaried that the hydro generator has the better heating performances than steam generator when it is used to deal with the wind power generation output fluctuation under the same situation and gas turbine generator with hydrogen-cooled have the similar heating performances with hydro generator.

For the simulation in IEEE-14-Bus system and IEEE-39-Bus system, heating problem is researched in some more complex and practical power systems which usually have more complicated scenarios for operating.

6.7 References

[1] A. J. Wood, B. F. Wollenberg, *Power Generation, Operation and Control*, Second Edition, New York: John Wiley & Sons, Ltd, 1996.

[2] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, *Wind Energy Handbook*, UK: John Wiley & Sons, Ltd, 2001.

[3] B. M. Weedy, B. J. Cory, *Electric Power Systems*, Forth Edition, UK: John Wiley & Sons, Ltd, 1998.

[4] P. Kundur, *Power System Stability and Control*, New York: McGraw-Hill, 1994.

[5] IEEE Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, "Hydraulic Turbine and Turbine Control Models for Dynamic Studies," *IEEE Transactions on Power Systems*, Vol.7, No.1, February, 1992, pp. 167-179.

[6] L. F. Drbal, P. G. Boston, K. L. Westra and R. B. Erickson, *Power Plant Engineering*, New York: Chapman & Hall, 1996.

[7] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*, IEEE Press, 1994.

[8] P.W. Sauer and M.A. Pai, *Power System Dynamics and Stability*, Prentice Hall, Upper Saddle River, NJ, 1998.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

This thesis introduces a method for simulating wind speed with different parameters of probability distribution for different situations is proposed based on understanding of the stochastic and probabilistic characteristics of wind resources. Through this method, any number of wind speed data can be produced according to this probability distribution from original wind speed data from different research conditions. A simulation model is developed to simulate wind generation output according to wind speed data.

Next, this thesis provides an overview of definition and classification of power system security with how the different types of security problem are interrelated and the states of system operating condition. And it also makes a summary of explanation and analysis of the impact from wind turbine generation on different types of system stability: rotor angle stability, voltage stability and frequency stability under both steady state and transient state. It is provided to help engineers and system operators to more clearly understand the benefits and challenges from the wind power generation.

This thesis then modifies a model of calculation about temperature rise inside the machine based on currents and magnetic fields of the rotor and stator which is improved into a more effective one for a power system with wind power generation under output fluctuation condition. And it also establishes a method for calculating the thermal performances and heating effects of conventional generator which is caused by fluctuation output of wind turbine generators based on heat transfer theories.

Following, this thesis makes a summary of the different types of cooling system, the 3D steady state temperature field with boundary conditions and the some liquid heat exchange convection coefficients as the basis. And then it proposes a method for calculating cooling effect from cooling system in conventional synchronous generator machine under wind power generation output fluctuating condition.

At last, this thesis provides simulation and analysis of the heating problem about conventional generator based on the proposed methods in a power system with wind turbine generators is processed under different conditions which include extremely unfavourable wind speed condition, different wind power generation penetration levels condition, different types of generator condition and more extensive power systems including the IEEE-14-Bus system and IEEE-39-Bus system. These can be used as basis and data for power system engineers or operators to simulate to learn how to re-schedule duty cycle of generators to alleviate temperature rise in the winding of conventional generators caused by intermittent output of wind power resources.

7.2 Future Work

Due to the time constraint, many issues were not addressed in this research. There are several expansions and improvements that can be suggested for the methods and concepts proposed in this thesis. These include:

- For the method of wind speed simulation, one of the obvious possible extensions is to collect more practical wind resources data, wind patterns model and probability distribution model to develop and complete the method. Moreover, more wind speed data can be used to test the simulations in this thesis.

- The model of wind turbine generator active power output can be extended to include reactive power output.

- For the method of calculating the thermal performances and heating effects, one of the expansions can focus on improving the method to include more detail of mechanical and electrical structures. Calculations efficiency could be improved when the transfer theories are simplified.

- One of the works that could be built on the method of calculating cooling effect from cooling system in this thesis is to collect more information about the different types of cooling systems both mechanical and chemical to make the method more practical.

- Even though the proposed method of calculating heating problem of conventional generator caused by wind power generation in this thesis have been tested and simulated extensively, testing more real practical system is still very beneficial to deal with any possible practical problems. In addition, the calculations efficiency could be improved when schedule duty of generators is available.

- The focus of this thesis was mainly on the influences from intermittent generator to the conventional generation. For the remedial, there are several improvements can be researched continually. One is optimise the availability of conventional capacity through re-scheduling of conventional generators. Some energy storage technologies such as pumped storage, battery and electric vehicles which become more and more popular can also be considered. In fact, the management of energy storage equipments is can also be seen as a generation re-scheduling availability.

Appendix A: IEEE 14-Bus Test System

Table A.1: Generator data

Generator Bus No.	P generated (MW)	Q Generator (Mvar)	P Maximum (MW)	P minimum (MW)	Q Maximum (Mvar)	Q Minimum (Mvar)
1	232	-16.9	615	0	100	-100
2	40	42.4	60	0	50	-40
3	0	23.4	60	0	40	0
6	0	12.2	25	0	24	-6
8	0	17.4	25	0	24	-6

Table A.2: Bus data

Bus No.	P generated (MW)	Q Generated (Mvar)	P Load (MW)	Q Load (Mvar)	Bus Type
1	232	-16.9	0	0	2
2	40	42.4	21.7	12.7	1
3	0	23.4	94.2	19	2
4	0	0	47.8	0	3
5	0	0	7.6	1.6	3
6	0	12.2	11.2	7.5	2
7	0	0	0	0	3
8	0	17.4	0	0	2
9	0	0	29.5	16.6	3
10	0	0	9	5.8	3
11	0	0	3.5	1.8	3
12	0	0	6.1	1.6	3
13	0	0	13.5	5.8	3
14	0	0	14.9	5	3

Bus Type: 1. swing bus; 2. PV bus (generator bus) and 3. PQ bus (load bus)

Table A.3: Line data

From Bus	To Bus	Resistance X (p.u.)	Reactance L (p.u.)	Line charging B (p.u.)
1	**2**	0.01938	0.05917	0.0528
1	**5**	0.05403	0.22304	0.0492
2	**3**	0.04699	0.19797	0.0438
2	**4**	0.05811	0.17632	0.0374
2	**5**	0.05695	0.17388	0.034
3	**4**	0.06701	0.17103	0.0346
4	**5**	0.01335	0.04211	0.0128
4	**7**	0	0.20912	0
4	**9**	0	0.55618	0
5	**6**	0	0.25202	0
6	**11**	0.09498	0.1989	0
6	**12**	0.12291	0.25581	0
6	**13**	0.06615	0.13027	0
7	**8**	0	0.17615	0
7	**9**	0	0.11001	0
9	**10**	0.03181	0.0845	0
9	**14**	0.12711	0.27038	0
10	**11**	0.08205	0.19207	0
12	**13**	0.22092	0.19988	0
13	**14**	0.17093	0.34802	0

Appendix B: IEEE 39-Bus Test System

Table B.1: Generator data

Generator Bus No.	P generated (MW)	Q Generator (Mvar)	P Maximum (MW)	P minimum (MW)	Q Maximum (Mvar)	Q Minimum (Mvar)
30	250	136.21	350	0	400	-140
31	572.93	170.36	1145.55	0	300	-100
32	650	175.9	750	0	300	-150
33	632	103.35	732	0	250	0
34	508	164.4	608	0	167	0
35	650	204.84	750	0	300	-100
36	560	96.88	660	0	240	0
37	540	-4.44	640	0	250	0
38	830	19.39	930	0	300	-150
39	1000	68.46	1100	0	300	-100

Table B.2: Bus data

Bus No.	P generated (MW)	Q Generated (Mvar)	P Load (MW)	Q Load (Mvar)	Bus Type
1	0	0	0	0	3
2	0	0	0	0	3
3	0	0	322	2.4	3
4	0	0	500	184	3
5	0	0	0	0	3
6	0	0	0	0	3
7	0	0	233.8	84	3
8	0	0	522	176	3
9	0	0	0	0	3
10	0	0	0	0	3
11	0	0	0	0	3
12	0	0	8.5	88	3
13	0	0	0	0	3
14	0	0	0	0	3
15	0	0	320	153	3
16	0	0	329	32.3	3
17	0	0	0	0	3
18	0	0	158	30	3
19	0	0	0	0	3
20	0	0	680	103	3
21	0	0	274	115	3
22	0	0	0	0	3
23	0	0	247	84.6	3
24	0	0	308	-92.2	3
25	0	0	224	47.2	3
26	0	0	139	17	3
27	0	0	281	75.5	3
28	0	0	206	27.6	3
29	0	0	283.5	126.9	3
30	250	136.21	0	0	2
31	572.93	170.36	9.2	4.6	1
32	650	175.9	0	0	2
33	632	103.35	0	0	2
34	508	164.4	0	0	2
35	650	204.84	0	0	2
36	560	96.88	0	0	2
37	540	-4.44	0	0	2
38	830	19.39	0	0	2
39	1000	68.46	1104	250	2

Bus Type: 1. swing bus; 2. PV bus (generator bus) and 3. PQ bus (load bus)

Table B.3: Line data

From Bus	To Bus	Resistance X (p.u.)	Reactance L (p.u.)	Line charging B (p.u.)
1	**2**	0.0035	0.0411	0.6987
1	**39**	0.001	0.025	0.75
2	**3**	0.0013	0.0151	0.2572
2	**25**	0.007	0.0086	0.146
3	**4**	0.0013	0.0213	0.2214
3	**18**	0.0011	0.0133	0.2138
4	**5**	0.0008	0.0128	0.1342
4	**14**	0.0008	0.0129	0.1382
5	**6**	0.0002	0.0026	0.0434
5	**8**	0.0008	0.0112	0.1476
6	**7**	0.0006	0.0092	0.113
6	**11**	0.0007	0.0082	0.1389
7	**8**	0.0004	0.0046	0.078
8	**9**	0.0023	0.0363	0.3804
9	**39**	0.001	0.025	1.2
10	**11**	0.0004	0.0043	0.0729
10	**13**	0.0004	0.0043	0.0729
13	**14**	0.0009	0.0101	0.1723
14	**15**	0.0018	0.0217	0.366
15	**16**	0.0009	0.0094	0.171
16	**17**	0.0007	0.0089	0.1342
16	**19**	0.0016	0.0195	0.304
16	**21**	0.0008	0.0135	0.2548
16	**24**	0.0003	0.0059	0.068
17	**18**	0.0007	0.0082	0.1319
17	**27**	0.0013	0.0173	0.3216
21	**22**	0.0008	0.014	0.2565
22	**23**	0.0006	0.0096	0.1846
23	**24**	0.0022	0.035	0.361
25	**26**	0.0032	0.0323	0.513
26	**27**	0.0014	0.0147	0.2396
26	**28**	0.0043	0.0474	0.7802
26	**29**	0.0057	0.0625	1.029
28	**29**	0.0014	0.0151	0.249