Reduction of Wind Power Curtailment in Power System Operation

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by

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Declaration of Author’s Right

This thesis is the result of the author’s original research. It has been completed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

Clean, affordable energy is essential for continued growth of the economy in a country. Almost every country's laws and policies put in place in the last decade encourage energy suppliers to incorporate large amounts of renewable generation (wind and solar). This has changed the traditional mix of "fuels" used for energy generation. Integrating these resources into a reliable and affordable power system will require an unprecedented level of cooperative action within the electric industry, related utilities and the state. Power grid has existing flexibility in the system to cost-effectively integrate wind resources but, as operated today, more can be done. Integration involves managing the variability (the range of expected electricity generation output) and uncertainty (when and how much that generation will change during the day) of energy resources.

Wind is one kind of free energy and this "must-take" wind power generation is integrated into the system operation. In this thesis, the impacts on the combined conventional generators, the transmission lines and the operation costs will be examined under different system operation conditions (constrained and unconstrained) with increasing wind power penetration.

The firm scheduled bilateral contract from the conventional generation can cause transmission congestion and free wind power cannot be integrated into the power system operation sufficiently. This thesis proposes a combined pool/bilateral trade model to cooperate with wind power output fluctuations to increase the utilisation of wind farm which are currently constrained by the transmission networks. The one-step optimal power flow model dispatches the pool in combination with the curtailed part of fixed bilateral contracts from conventional generators. The aim is integrating maximum wind energy into the power system while minimizing costs.

A dynamic wind turbine model is used to identify the impacts of integrating wind power into system operation; the *Weibull Distribution Function* is used to analyze the problem of wind distribution; and the *Monte Carlo Simulation (MCS)* method is used to simulate the output of wind power generation. The proposed combined pool/bilateral trade model is applied to the modified *IEEE-9* bus system for verification and validation.

Following this, the analysis on *IEEE-30* bus system is the comparison studies with the proposed one-step combined pool/bilateral trade model under different bidding prices. Two case studies with different market strategies through the proposed method are introduced, with different volume values of the firm bilateral contracts and the different payments for the curtailment bids. The simulation results show the relative level of pool versus bilateral trading and these influences on the performance in terms of individual power generation levels and costs.

The well-proven software tools *MATLAB* and *MATPOWER* support the study.

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Nomenclature

WDF	Weibull Distribution Function
α	Weibull scale parameter
β	Weibull shape parameter
MCS	Monte Carlo Simulation (MCS)
IEA	International Energy Agency
ISO	Independent System Operator
DA	Day-ahead
RT	Real-time
BPA	Bonneville Power Administration
SPP	Southwest Power Pool
MISO	Midcontinent Independent System Operator (MISO)
ERCOT	Electric Reliability Council of Texas
EIM	Energy imbalance market
PIRP	Participating Intermittent Resource Program
LSEs	Load serving entities
NWP	Numerical weather prediction
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
W_s	Wind speed (m/s)
V_{ci}	Cut-in speed of wind turbine (m/s)

V_r	Rated speed of wind turbine (m/s)
V_{co}	Cut-out speed of wind turbine (m/s)
P_{wr}	Rating power output of wind turbine (MW)
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MTBF	Mean Time between Failures
FOR	Forced Outage Rate
λ	Failure rate
μ	Repair rate
LOLP	Loss of Load Probability
LOLE	Loss of Load Expectation
LOEE	Loss of Energy Expectation
LOLF	Loss of Load Frequency
LOLD	Loss of Load Duration
CIC	Customer Interruption Cost
CDF	Customer Damage Function
SIC	Standard Industrial Classification
ISO	Independent System Operator
BETTA	British Electricity Trading and Transmission Arrangement
PJM	Pennsylvania, New Jersey, Maryland
NY	New York
OPF	Optimal Power Flow

LMP	Locational Marginal Price
ED	Economic Dispatch
$C_{gen,k}(P_{gen,k})$	Energy bid function of bus *k*
λ_k	Lagrange multiplier for the marginal value of the active power balance constraint at bus *k* (i.e. LMP active power at bus *k*)
π_k^{max}	Lagrange multiplier of upper limit of active power at bus *k*
π_k^{min}	Lagrange multiplier of lower limit of active power at bus *k*
π_l	Marginal (shadow) cost of transmission constraint at line *l*
$P_{gen,k}^{max}$	Upper limit of active power injection at bus *k*
$P_{gen,k}^{min}$	Lower limit of active power injection at bus *k*
λ_0	Marginal cost of energy
λ_k^{loss}	Marginal cost of loss component at bus *k*
$\frac{\partial P_{loss}}{\partial P_k}$	Real power loss sensitivity factor at bus *k*, denotes as L_k
$T_{l,k}$	Sensitivity factor of the network at bus *k* due to network constraint on line *l*
KKT	Karush-Kuhn-Tucker
C_{G_i}	Bid price of generator i in £/MWh
P_{G_i}	Power produced by generator i
$P_{G_i}^{max}$	Maximum generation capacity of generator i
N_G	Number of generators
N_D	Number of loads
$PTDF_{kl,i}$	DC-Power Transfer Distribution Factor

C	Cost of wind generation in £/kWh
Q	Capital investment in £/kW
r	Annual capital recovery rate
n	Wind turbine’s operating time in years
F	Power generation factor of the wind turbine,
P_{wa}	Wind turbine’s annual mean output
P_{wr}	Wind turbine’s rated power output
UCED	Unit Commitment and Economic Dispatch
MPEC	Mathematical program with equilibrium constraints
FIT	Feed-in-tariff
AESO	Alberta Electric System Operator
APS	Allegheny Power Systems
CAISO	California
HECO	Hawaiian Electric Companies
ISO-NE	ISO New England
BCs	Bilateral forward contracts
f_{kl,T_i}	Contribution of transaction T_i, between generator at bus m and load at bus n to the power flow in line *k*-*l*
P_{T_i}	Contractual energy of bilateral transaction T_i
CP_{T_j}	Compensative price of transaction j
T_j	Transaction between generator at node m and load at node n
$\Delta P_{G_i}^{+}$	MW increment variables of generator *i*

$\Delta P_{G_i}^{-}$	MW decrement variables of generator *i*
$C_{G_i}^{+}$	Cost of MW increment of generator *i*
$C_{G_i}^{-}$	Cost of MW decrement of generator *i*
$\sum_{all\ G_i} \Delta P_{G_i}^{+}$	Total MW increment of generators
$\sum_{all\ G_i} \Delta P_{G_i}^{-}$	Total MW decrement of generators
$\Delta P_{G_i}^{offer}$	Submitted energy offers from generator on bus *i* to ISO
$\Delta P_{G_i}^{bid}$	Submitted energy bids from generator on bus *i* to ISO
LP	Linear Programming
π_i^b	Price of the bilateral contract.
$C(\mathrm{P}_{\mathrm{G}_i}^{b})$	Generation cost when the selected conventional generator' output is $\mathrm{P}_{\mathrm{G}_i}^{b}$,
$\mathrm{P}_{\mathrm{G}_i}^{b}$	Be delivered at one period for the bilateral contract.
π_i^c	Price for the generators who asked for the curtailment.

Chapter 1

Introduction

1.1 Motivation

The worldwide demand for energy is growing steadily. At the same time, this trend is being accompanied by rising greenhouse gas emissions. At an event in February 2014 in Indonesia, the US Secretary of State John Kerry said “climate change ranks among the world’s most serious problems”, such as disease outbreaks, poverty, terrorism and the proliferation of weapons of mass destruction and called on all nations to respond to “the greatest challenge of our generation”. Two weeks later in March 2014 the Chinese Premier at the annual opening session of the country’s Parliament said, “We will resolutely declare war against pollution as we declared war against poverty”. [2] From the published calculations of [2] by 2035, renewables will be generating more than 25% of the world’s electricity, with a quarter of this coming from wind, being the second largest renewable energy source after hydro power according to the International Energy Agency (IEA). This will lead to a substantial reduction in CO_2 emissions and create jobs for hundreds of thousands of people.

Global trend to increase the penetration of wind energy in power system is still growing, it has proved that wind energy is environmentally and economically valuable in long-term planning. However, this kind of energy are still has great potential for expansion and needs to be supported and operated economically.

1.1.1 Characteristics of Wind Power Generation and Reasons for lower Wind Penetration

Wind is clean, inexhaustible but intermittent. It is difficult to forecast the variable output of wind generation, the distribution of this energy source is depending on climate, season and many other elements. With the high uncertainty, the output of wind power generation is very difficult for short-term and long-term forecast. Due to its inherent variable nature, integrating wind power plants into current electric systems pose several challenges to both producers as well as system operators. It is very important to have means to maintain system security. A sudden change in wind speed will significantly change a wind farm's power output. Even such variation lasts for a very short time interval; the fluctuating output will still be able to affect the power flow, system balance, generating system reliability. As well as its uncertainty in its production, a wind power producer may withhold its capacity from the power market. This in turn could result in lower wind penetration. [2]

1.1.2 The Concerns from the System Operation

Transmission constraints have been the most common reason for wind curtailments. [3] With the construction of new transmission lines and the adoption of new transmission operating procedures to increase the transfer capacity on existing transmission system, most curtailment occurs when the construction of necessary transmission line lags behind the pace of wind power integration development. [3] The result is insufficient infrastructure and delays the amount of wind generation to be integrated.

Some wind power generation curtailment has been attributed to challenges in balancing the system with higher penetrations of wind energy due to oversupply of wind generation, typically at low load periods.[3] Some utilities or system operators have curtailed generation from wind plants when minimum generation levels on conventional plants are reached.[3] This is because the cost of stopping and restarting fossil units within a few hours is significantly more expensive than payment for a few hours of wind curtailment. This type of situation will always occur at night when substantial amounts of wind power output is available but loads are at a very low level, and this phenomena will be exacerbated in some small regional areas. [3]

There are also some other reasons for wind power curtailment, such as addressing voltage issues, interconnection issues, and maintain frequency and stability requirements.[3]

1.1.3 The Concerns from the Power Market

Current electricity markets consist of primarily two modes of operation - bilateral trading and competitive electricity pools [25, 26, 27]. In the former mode, generators and loads negotiate a bilateral contract to transfer certain amount of electricity at a given future date. In competitive electricity pools, all of the buyers and sellers participate in one single market and the bilateral trading is cleared by a third party called the Independent System Operator (ISO). These markets typically consist of a day-ahead (DA) forward market as well as a real-time (RT) market. In a DA market, each producer submits a bid to the ISO to supply electricity for the next day, and each buyer submits an offer to the ISO to purchase electricity. The ISO then uses this data to compute the optimal aggregate supply and demand function and determine the market clearing price. All producers that submitted bids below the market clearing price will be scheduled and hence obligated to dispatch their power during the following day [1].

With the current established market structure, a wind power generation is scheduled and required to dispatch power when asked by the ISO. But the ability of wind generation depends on the current wind strength, the inherent uncertainty makes it harder for the ISO to rely on the wind power. If the available wind power output is less than what it was scheduled for, the wind power generation will incur an imbalance penalty. This penalty is derived because the wind power generation is required to purchase the shortfall from the RT market, which typically has higher prices. Thus, with the uncertainty in its production, a wind power producer may withhold its capacity from the DA market. [1]

In this thesis a proposed method is focusing on how to deal with the imbalance on a mixed thermal and wind power system, it will involve power market strategies in pool and bilateral contracts.

1.1.4 Current Strategies to Mitigate Curtailment

Higher levels of variable generation require improved integration approaches, including new operational and market tools as well as flexible demand- and supply-side resources. Drawing from existing studies and experience to date. From the related publication and reports, strategies and integration actions are described in the following paragraphs.

In order to incentivize construction of utility-scale wind farms, many countries offer extra-market support in the form of construction subsidies, tax-relief, and feed-in-tariffs with guaranteed grid access. The latter amounts to an operating paradigm where the independent system operator (ISO) is obliged to accept all wind power production subject to certain contractual constraints. [8] For example, the United States has many balancing areas, each of which may have its own curtailment practices. The areas with the greatest amount of curtailment of wind power to date include the Bonneville Power Administration (BPA) balancing area, the Southwest Power Pool (SPP), and Hawaii, which has struggled primarily with excess wind at low-load periods and minimum generation requirements. Both the Midcontinent Independent System Operator (MISO) and the Electric Reliability Council of Texas (ERCOT) have recently implemented market-based solutions and have seen reductions in curtailment levels. [14] In the United Kingdom, large wind farm must now participate in conventional two-settlement electricity markets and are subject to ex-post financial penalties for deviations from their contracted positions [18].

From [6, 10, 11, 12] an energy imbalance market (EIM) is a centralized market mechanism is the Western U.S. to: re-dispatch generation every five minutes, maintain load and resource balance, addressing generator schedule deviations and load forecast errors and provide congestion management service by re-dispatching generation to relieve grid constraint, and increase the efficiency and flexibility of system operations integrating higher levels of wind resources. It is a real-time energy-only market that recognizes existing bilateral transmission delivery rights while automating intra-hour economic dispatch. In the EIM, energy imbalance is defined as the difference between scheduled and actual energy, at both generation and load settlement locations. It would optimize the dispatch of imbalance energy by incorporating real-time information on generation capabilities and transmission constraints using nodal locational pricing. Generators and loads pay or receive payment based on the difference between scheduled and actual energy delivered. [6]

Power system reserves are quantities of generation or demand side that are available as needed to maintain electric service reliability. A higher penetration of wind resources increases the variability and uncertainty of generation in the system, increasing the need for balancing reserves. [21, 13] Within the realm of demand-side management, demand response is distinct from conservation or energy efficiency. [29] Demand response has traditionally referred to short-term reductions in demand in response to temporary shortages of energy. Yet the value of demand response in reliably and cost effectively integrating variable renewable energy resources dramatically transcends its traditional role. [6] An example is the Participating Intermittent Resource Program (PIRP) in California [23]. As wind power output is inherently variable, the accepted wind power is treated as a negative load and additional reserves are procured to compensate for the increased variability in net load. These reserve costs are allocated amongst the load serving entities (LSEs) and ultimately passed on to consumers. At high levels of wind energy penetration, the increased levels of reserves and the attendant socialization of reserve costs will become unacceptable.

In [16, 4, 22] dynamic transfer refers to electrically transferring generation from the balancing authority area in which it physically resides to another balancing authority area in real-time. It involves software, communications and agreements and requires the appropriate amount of firm, available transmission capacity between locations. Such transfers allow generation to be located and controlled in a geographic location that is outside of the receiving balancing authority area. Using dynamic transfers, the within-hour variability and uncertainty of wind can be managed by the balancing authority where the energy is being used. It can result in greater geographic diversity of wind facilities and reduced integration costs and imbalance charges. From [8] the dynamic transfer method used for a specific operating arrangement may depend on the service to be provided, the capabilities of the system models and energy management system used by the balancing authorities, and who has responsibility for providing information on unit commitment and maintenance.

From [15] if high wind penetrations are desired, there is a strong case for implementing energy storage in the power system to aid supply/demand matching and absorb surplus wind electricity [24,19]. If water electrolysis plant is implemented at or near wind farms (in combination with compression and hydrogen storage systems), wind power curtailment could be reduced or eliminated by using the electrolysis as controllable loads for absorbing the otherwise curtailed wind power output. Although the generated hydrogen may then be reconverted to electricity at a low turn round efficiency [28]. The hydrogen may alternatively be dedicated to existing hydrogen markets to displace the use of hydrogen reformate. It is anticipated that in the short term such zero-carbon or ‘green’ hydrogen would best be used for merchant industrial applications where hydrogen market prices are greatest, but in the long term it could be applied to hydrogen transport applications or even to power generation. In regions of high wind resource and network constraints, this approach could help mitigate the financial penalties associated with wind curtailment, increase the economic returns from deploying new wind power generation, and reduce the carbon footprint of existing merchant hydrogen use.

In [20, 17, 9], variable generation forecasts are prepared with a combination of data from large-scale numerical weather prediction (NWP) models maintained by public meteorological agencies and meteorological and generation data from individual wind plants. The statistical models establish a relationship between predictor (input) and forecast (output) variables, based on a training sample of historical data. (Statistical models can learn from experience without having to model the supporting physical and atmospheric relationships.) The typical approach is to rely upon output from the NWP models and measured data from the wind plant to forecast the output (power production, wind speeds, etc.) at the location of the plant. The statistical models help represent the effects of local terrain and other geographic details that cannot be realistically represented in the NWP models. But because statistical models need to learn from historical examples, the models generally predict typical events more successfully than rare events, unless the models are specifically designed for predicting such events and are trained on a sample that includes them. The methods improving weather, wind forecasting is mentioned to help grid operators monitor system conditions, schedule or commit fuel supplies and power plants in anticipation of changes in wind generation, and prepare for extreme high and low levels of wind output. [6]

1.2 Challenge

Wind power generation is inconsistent and intermittent energy source, the wind speed variation causes the fluctuation of wind power output. High wind power penetration can lead to higher risk level for power system security and reliability. Due to its high fluctuation, the output of wind generator is often need to be curtailed to keep within the security of system operation. It also poses several challenges in its integration in current electricity markets.

System operators have developed a variety of strategies to minimize curtailment of wind energy sources. From [6,7] and above strategies are part of a broader and extended collection of practices to manage this variability and uncertainty of renewable generation and thereby reduce related curtailments. [6] concentrates on the flexibility for existing and new generating plants, it contains on how to frequent start, stop, change production output, quick ramp output up or down, operate above and below standard utilization rates without significant loss in operating efficiency.

A significant challenge is in assessing how much flexible capacity already exists and how much move and when it will be needed. It is expected that the combined power market strategies can give an evaluated solution to reduce the curtailment of wind power. Flexible generator sources are needed to meet the high level of wind and solar generation to increase utilization of zero variable-cost resources and lower overall system operating costs.

The research in this thesis concentrated on the maximum integrating wind power generation into the system through power market trading strategies is investigated. This work will develop the combined pool/bilateral trades for the proposed methods to integrate all of the wind power outputs into the system operation considering security. Also, the associated economic performance of the proposed cooperation under different price mechanism will be discussed.

The main investigated areas as following:

1. ***Determine the impacts on the transmission capacity and congestions management integrating wind power into the system operation***

From [14] “Nodal pricing is a method in which market prices are calculated for a number of locations on the transmission network (nodes) that represent physical locations on the system. These locations can include both generators and loads. The price at each node represents the incremental cost of serving one additional megawatt of load at that location subject to system constraints.” Wind farm is integrated into the system operation, with transmission line limits imposed and congestion appears. The introduction of the wind farm changes the nodal price, significantly in some situation, leading to a much higher electricity price for the customers. Thus when wind farm is integrated into a power system it is important to investigate and reinforce transmission capacity to avoid congestion appears in the system. Furthermore congestion in a transmission network also means wind generation output curtailment.

2. ***Determine the impacts of integrating wind power into the system operation under the combined pool/bilateral trades market***

The firm scheduled bilateral contracts from the conventional generator need sufficient transmission capacity for the trades. When the power system is operating under the optimal power flow, additional free wind energy will need to be accepted by the system operator. This process will cause the transmission congestion and free wind power cannot be integrating into the power system operation sufficiently. Hence to maximize the benefit of wind generation for both the utility and the customers, transmission congestion must be carefully investigated.

3. ***Propose an operational model to reduce the curtailment of wind energy with the minimums costs***

Under the combined pool/bilateral dispatch model, the market trading strategies will show the optimal relative level between pool versus bilateral trading and the influences on the individual power levels, costs and nodal prices. Integrating into the system operation the intermittency and non-forecast wind power output into this market process decision have not been investigated widely. The proposed power market model need focus on how to trade between pool and bilateral trades, considering their different pricing mechanisms and network constraints, enhancing penetration of wind power into the system operation, the ultimate goal being to obtain good profits at low risk.

Accordingly, new power market strategy will be required to provide possible solutions for the existing challenges. Moreover, the proposed combined pool/bilateral dispatch should be viewed from both the system operation perspective and power market operator.

1.3 Objectives and Research Questions

The eventual goal of this proposed method is to integrate maximum wind energy into the power system while help generator and load serving entities choose appropriate relative levels between pool and bilateral trades considering risk, economic performance and transmission bottleneck. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated.

The proposed method proposes a one-step optimal power flow model that dispatches the pool in combination with curtailed part of fixed bilateral contracts from conventional generators to try to increase utilisation of wind farms that are currently constrained by the transmission congestion while minimizing costs.

The objectives of this thesis are realized by addressing four research questions. These research questions are outlined as follows:

RQ 1: How to evaluate the impacts on power system operation with increasing wind penetration?

Answering this question requires an adequate knowledge of power systems security assessment. And to test the impacts on the system operation caused by the wind power, the relationship between wind speed variation and wind power output is analyzed in details as well.

The specific processes required to respond to this question include:

- ✓ Reach a deeply understanding of the system security, stability and reliability for future analysis.

- ✓ Conduct a relevant literature review to list the issues of wind power integration. Such as impacts of wind power integration on power system reliability, operational methods, transmission capacity consumption and power markets.

- ✓ Construct a wind power output model by considering the wind speed profile, Monte Carlo Simulation, Weibull distribution function and wind turbine output model.

- ✓ Study the software *MATPOWER on how to* analyses the electric network power-flows at different wind penetration levels.

- ✓ Perform test simulation with the *IEEE-14* bus system integrating the wind power generation model into existing power system operation under the different conditions (constrained or unconstrained) in *MATLAB* and identify the key impacts.

RQ 2: What function does the bilateral contract do in the power market and how does it affect the power system operation and power market?

The energy purchasing progress is done through bilateral contract with agreed price between a load and a selected generator, and at specified time period the amount of contractual energy would be delivered. To relieve an overloaded line will reduce the power flow through the line by curtailing the contractual energy of bilateral transactions.

The specific processes required to answer this question include:

- ✓ Understand the definition and mathematical model of bilateral contract trade in power market and the related strategy, to prepare for the proposed methods.

- ✓ Investigate the impact of integrating different wind power penetration levels into the system operation when the transmission line is constrained under pool/bilateral contract market using *MATPOWER* software.

- ✓ Investigate how to price the flexible volume of bilateral contract (involved scheduling problem) and maintain the profit of the conventional generators; the conventional generators with fixed bilateral contracts, and the volume of the contracts will be curtailed to allow more wind power to be used in the power system.

RQ 3：How to reduce the curtailment of wind power integration under the bilateral market?

The main propose is to Integrate wind power into the system operation while many of them have been curtailed due to the system security operation constraints. The proposed method proposes an optimal power flow model that dispatches in combination with curtailed part of fixed bilateral contracts from conventional generators to try to increase utilisation of wind farm that are currently constrained by the transmission congestion while minimizing costs.

The specific processes required to answer this question include:

- ✓ Model the proposed optimal power flow formulation with *MATPOWER* software to analysis the electric network power-flows when the selected conventional generator is at different bilateral contract curtailment strategies.

- ✓ *IEEE 9-Bus* system is used to verify the proposed theory. Selected conventional generators may fail to re-sell their curtailed energy contracts and reduced profits, they will be paid by the ISO to increase utilisation of wind farm that are currently constrained by the transmission congestion while minimizing costs.

RQ 4: How does the proposed combined pool/bilateral dispatch enhance penetration of wind power integration?

To integrate maximum wind power into the system operation, the aim here is to investigate a new market structure where firm contracts may voluntarily agree to be curtailed for economic reasons. It is proposed that each firm bilateral agreement be allowed to submit a request for compensation in case of curtailment (except in emergency situations). This curtailment and associated payment will be scheduled by the ISO and by doing so, the overall generation costs plus curtailment payments are minimized.

The specific processes required to answer this question include:

- ✓ Develop a deep understanding of the proposed combined pool/bilateral dispatch and analyze the impacts on the related system operation issues.

- ✓ Test the proposed combined pool/bilateral dispatch with *MATPOWER* software, different request values for curtailment bid and analyze the changes on economic performance.

1.4 Contribution

Contribution 1: The first main contribution of this thesis is introducing a dynamic wind turbine model to identify the impacts of integrating wind power into system operation. The Weibull Distribution Function is used to analyse the problem of wind distribution and Monte Carlo simulation method is also introduced to simulate the output of wind power generation. This involved the following specific contributions:

- ✓ The dynamic wind turbine model can be simulated in a continuous operating state, the simulation results of the impacts on participants will be easier to understand.

- ✓ The operation model of each component in the system is constructed by using *MATLAB* software tool with the dynamic wind model. It is an effective tool to analyse the intermittent nature of wind power and the impacts of wind penetration on system security operation.

Contribution 2: The major contribution of this thesis is the proposed combined pool/bilateral trade model to cooperate with wind power output fluctuations. The method will increase utilisation of wind farm which are currently constrained by the transmission networks. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. In particular the incorporation would look at instances when conventional (typically coal fired) plants have fixed bilateral contracts. These generators are not willing to reduce their output because they will lose earnings. This incorporation will look at maintaining the profit of the generators even if they are curtailed to allow more wind power to be used.One innovative feature of my proposed method is the dispatch of a generation subject to the constraints imposed by the physical bilateral contracts, to alleviate the curtailment of wind power generation. The effects of this optimal power flow model that dispatches the pool in combination with curtailed part of fixed bilateral contracts from conventional generators will be analysed and discussed. The aim is integrating maximum wind energy into the power system while minimizing costs.

Contribution 3: The final contribution of this thesis is a comparison proposing the compared study of the proposed one-step combined pool/bilateral trade model under different compensation prices for the generator. The simulation results will show the performance in terms of individual power levels and costs. Consideration will include fixed bilateral contracts under various curtailment strategies in a mixed pool/bilateral operation with network constraints. The aim is to enhance penetration of wind power into the system operation, and to obtain good profits at low risk. All of the compared simulation studies are investigated by using *MATPOWER* software.

A consistent theme running through the thesis is the need for greater cooperation among utilities, states, power marketing participants to share resources, loads and transmission in order to take advantage of least-cost strategies to integrate renewable resources.

1.5 Thesis Structure

Based on the objectives and the proposed methodology, this thesis is organized into eight chapters. The contents are summarized below:

Chapter 2 provides an overview of wind power generation technology. Firstly, the current worldwide wind power generation development is introduced. Then, it proposes a calculation model of wind power generation output for evaluating the impact of wind power penetration on electric networks. Weibull distribution function is described in details. Then, the inverse transform method and Weibull distribution are used to generate the artificial wind speed profile. Wind farm output can be calculated by using the simulated artificial wind speeds. Furthermore, the power output characteristics of multiple wind farms are also investigated for later studies.

Chapter 3 presents an overview of wind integration issues, the main points are the associated integration impacts on power systems reliability, operational methods and markets. The impacts of wind power integration on power system operational methods and markets are discussed in details. These definite include increase in reserve requirements, estimating impacts on other generation and balancing, capacity value of wind power and increase in transmission due to wind power. In this chapter, a simple example is used to illustrate the impact of wind power on the transmission capacity consumption with different penetration and location.

Chapter 4 uses the dynamic wind power generation model integrated into the *IEEE 14-bus* system to do the simulation study. The impacts on the outputs of the combined conventional generators, the influence for the transmission congestion and the reinforcement for the operation costs are tested at two different wind penetration levels. This chapter is separated into two parts, with the first descripts each core element of the simulation and the second part discussing results for the compared simulation.

Chapter 5 presents background of the wind power generation curtailment in the system operation in China, and the synthesis of curtailment practices and trends all over the world. The main aspects of the research of my thesis is reinforced in this chapter and related fundamental knowledge especially flexible scheduling of bilateral contract will be discussed in details.

Chapter 6 proposes an operational practice to try to enhance penetration of wind power into the system operation whilst many of them may have been curtailed due to the system security operation constraints. The proposed method proposes a optimal power flow model that dispatches in combination with curtailed part of fixed bilateral contracts from conventional generators to try to increase utilisation of wind farm that are currently constrained by the transmission congestion while minimizing costs. The detailed explanation of the mathematical model and the entire simulation procedure including flow charts are presented. The modified *IEEE 9-Bus* system is used to verify the proposed theory in this chapter.

Chapter 7 presents the comparison studies using the proposed methods based on a *30-bus* test network (modified *IEEE 30-Bus* test system) and discusses the simulation results. The results will help with the basic strategic decision faced by independent generators and loads, namely. The strategy is on how to trade and what proportion between pool and bilateral trades, considering their different pricing mechanisms and network constraints. The aim is to enhance penetration of wind power into the system operation, and the goal being to obtain good profits at low risk.

Chapter 8 summarizes the conclusions of this thesis and discusses possible future works.

The main document is complemented by several Appendices.

1.6 Publications

Based on the results of the research work reported in this thesis, the following papers have been published:

Xin Li and K.L.Lo, “Evaluating the impact on transmission capacity due to wind power” in *Universities Power Engineering Conference (UPEC2012),* London, *47th International* 2012

Xin Li and Pengbiao Duan, “*Effects on transmission capacity with wind power participation*”, in *Universities Power Engineering Conference (UPEC2012)*, London, *47th International* 2012

Xin Li and K.L.Lo, *“Reduction of Wind Power Curtailment in Power System Operation”* under preparation for journal submission

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Chapter 2

Wind Power Characteristics and Wind Turbine Generator Performance

2.1 Introduction

The transformation of the global energy system has begun while more money has been invested in new renewables-based generation capacity than on non-renewables-based generation capacity. Investments in renewable energy are first and foremost investments in long-term ecological stability.

At an event in February 2014 in Indonesia, the US Secretary of State John Kerry said “climate change ranks among the world’s most serious problems”, such as disease outbreaks, poverty, terrorism and the proliferation of weapons of mass destruction and called on all nations to respond to “the greatest challenge of our generation”. Two weeks later in March 2014 the Chinese Premier at the annual opening session of the country’s Parliament said, “We will resolutely declare war against pollution as we declared war against poverty”.[1]

With the environmental benefits, technological advance, public support and government incentives, wind power capacity has experienced a great development in the past decade. Wind energy conversion systems convert the kinetic energy of the wind into electricity or other forms of energy, which has been recognized as an environmentally friendly and economically competitive means of electric power generation.

From the published calculations of [1] by 2035, renewables will be generating more than 25% of world's electricity, with a quarter of this coming from wind, being the second largest renewable energy source after hydro power according to the International Energy Agency (IEA). This will lead to a substantial reduction in CO_2 emissions and create jobs for hundreds of thousands of people.

In this chapter, *Section 2.2* presents an overview of wind characteristics, and a brief comment of the wind power market will be introduced in *Section 2.3*. The main aim of this chapter is to discuss the characteristics of wind and wind turbine generation which influence the performances of wind generation and power system.

The research follows with assess the impact of wind power penetration on power system. This chapter will also introduce the methods that are used to get wind speed and wind generation output data for further study. In *Section 2.5*, Weibull distribution function is used to represent the wind speed variations by modifying Weibull scale and shape parameters. Weibull distribution has an important characteristic: no specific shape. It can be shaped to represent many distributions by changing its parameters, as long as they are positive. The details of Weibull distribution are discussed in *Section 2.5.1*. The complementary cumulative Weibull probability distribution combined with inverse transform method are used in *Section 2.5.2* and *Section 2.5.3* to obtain the artificial wind speed model. The power output model of the wind turbine is described in *Section 2.4.3* and an example simulated output of wind turbine is described in *Section 2.5.4*.

2.2 The Characteristics and Benefits of Wind Resource

Almost every country in the world gives more public expenditure to increase the renewable energy utilization. Energy-saving and emission-reduction is of the top priority. Wind is a clean and inexhaustible form of energy and as a result the installed capacity of wind power generation is increasing rapidly. But it is difficult to forecast the output of wind generation, the distribution of this energy source is depending on climate, season and many other elements.

In the absence of a global price on carbon, or anything close to it, wind energy's other attributes come to the fore. Today in many countries , for the energy markets, the most compelling selling point is cost competitiveness, and wind is already competing successfully against heavily subsidized incumbents in a growing number of markets around the world, as the technology and its implementation steadily improve.[1]

Wind energy also offers major advantages for geopolitical reasons: wind is widely available throughout the world and can help reduce energy and fuel import dependency. Since it entails no fuel price risks or constraints, it also improves the security of supply, thus stabilizing the cost of power generation over the long term. [1]

2.3 International Development Situation of Wind Power

2.3.1 The Wind Energy Market

The market for wind energy is growing and is making a significant impact on global energy supply. At the beginning of 2014, wind generating capacity of 318.1 GW was installed worldwide, which is shown in *Figure 2.1*. During the past 10 years, wind energy installed capacity has grown at about 22%/year.

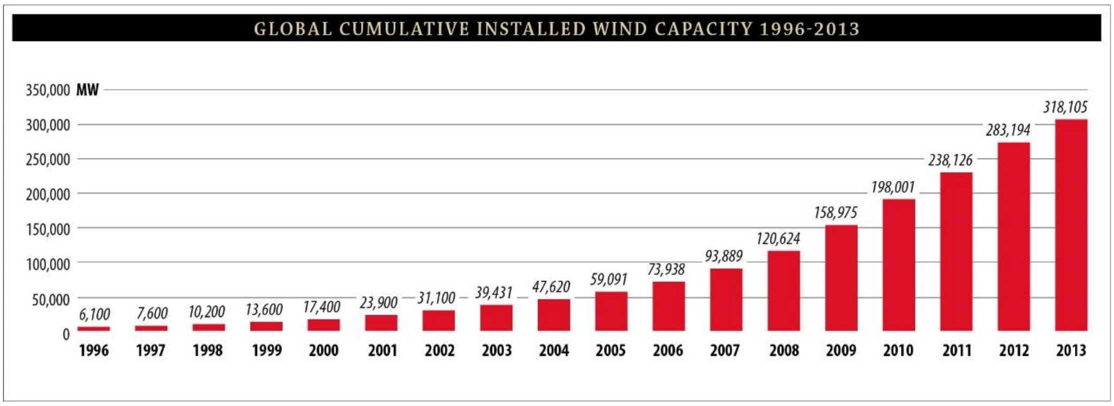
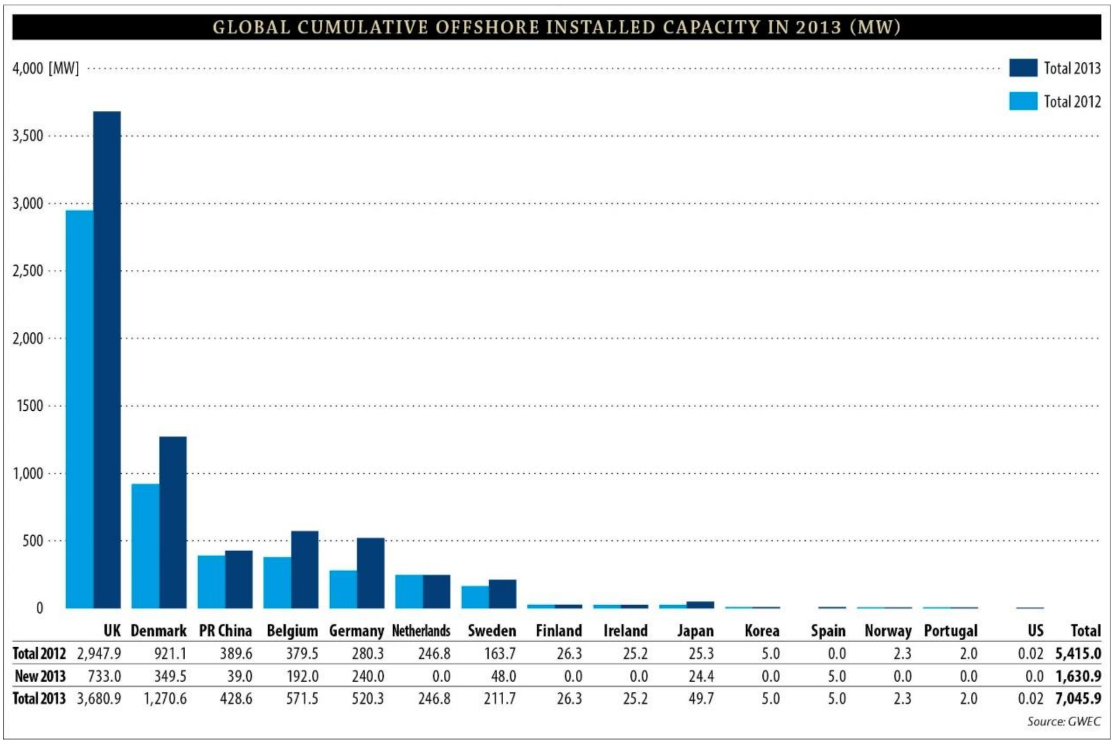


Figure 2.1. Global Cumulative Installed Wind Capacity 1996–2013 [1]

Offshore wind is playing a larger role in the market. In Global market, 2013 saw completion of 1630MW new offshore wind turbines, see *Figure.2.2* [1], Europe has always been the leader in offshore wind technology and has developed much faster than other regions. The largest offshore wind farms are all distributed in Europe. With the best wind resources in Europe, from *Figure 2.2*, it is obvious that United Kingdom is the leader in offshore wind energy development, which has the largest installed capacity. The newly installed capacity of UK in 2013 is 733 MW, which is 45% of the world's total annual installed capacity [1]. It is predicted that the total installed capacity of offshore wind in the UK will reach 20 GW in 2020 [5].



	UK	Denmark	PR China	Belgium	Germany	Netherlands	Sweden	Finland	Ireland	Japan	Korea	Spain	Norway	Portugal	US	Total
Total 2012	2,947.9	921.1	389.6	379.5	280.3	246.8	163.7	26.3	25.2	25.3	5.0	0.0	2.3	2.0	0.02	**5,415.0**
New 2013	733.0	349.5	39.0	192.0	240.0	0.0	48.0	0.0	0.0	24.4	0.0	5.0	0.0	0.0	0.0	**1,630.9**
Total 2013	3,680.9	1,270.6	428.6	571.5	520.3	246.8	211.7	26.3	25.2	49.7	5.0	5.0	2.3	2.0	0.02	**7,045.9**

Figure. 2.2. Global Cumulative Offshore Installed Capacity in 2013 [1]

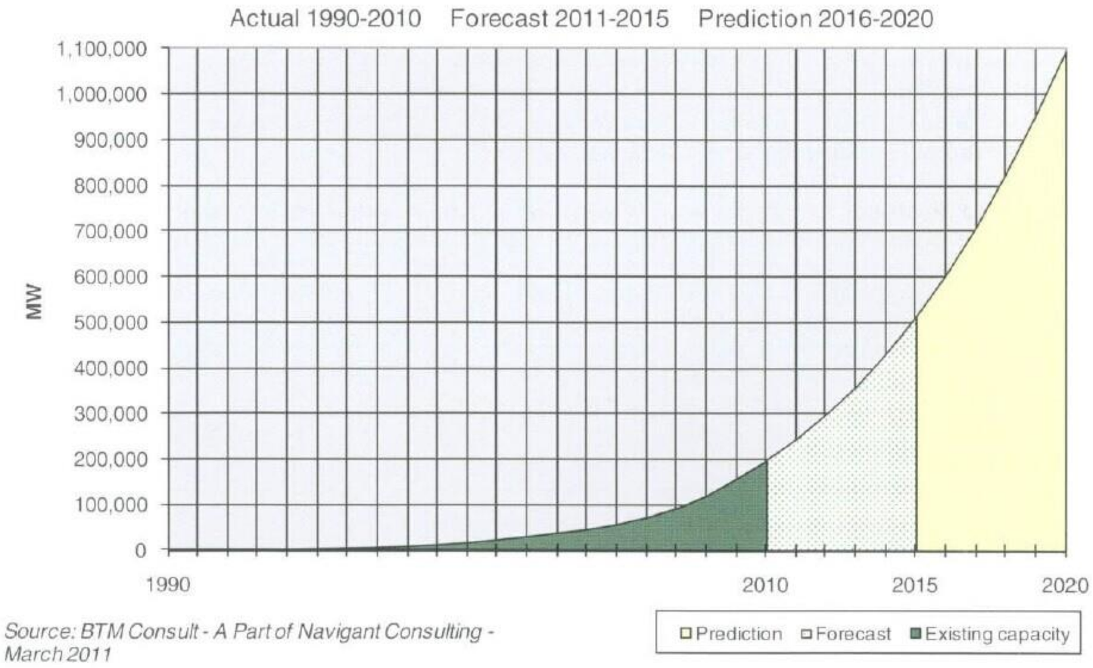
Small wind applications and hybrid technologies are operating in many countries with good market prospects. At the close of 2010, the installed capacity of small wind systems was estimated at 443 MW worldwide with more than 650,000 units in operation. By the end of 2011, more than 330 small wind manufacturers were offering commercial generation systems. An additional 300 firms were supplying parts, technology, consulting, and sales services. [3]

2.3.2 Future Markets

In 2011, most of the high-growth markets were outside of Europe and North America. The Chinese market had stabilized somewhat and markets in India, Brazil, and Mexico were growing rapidly. Emerging markets in Eastern Europe offer hope, as the European Union marches towards its 2020 renewable energy targets. Canada and Australia are potentially substantial markets which could add significantly to global growth figures;

and South Africa has now entered the market in earnest [1].

Annual market growth rates of about 8% have been forecast, which would add about 255 GW in the 2012–2016 period. Overall, wind energy is expected to reach a total capacity of just under 600 GW by the end of 2016, which is shown in *Figure 2.3*.



Source: BTM Consult - A Part of Navigant Consulting - March 2011

Figure 2.3 Prediction of Cumulative Global Wind Power Development (1990–2020) [9]

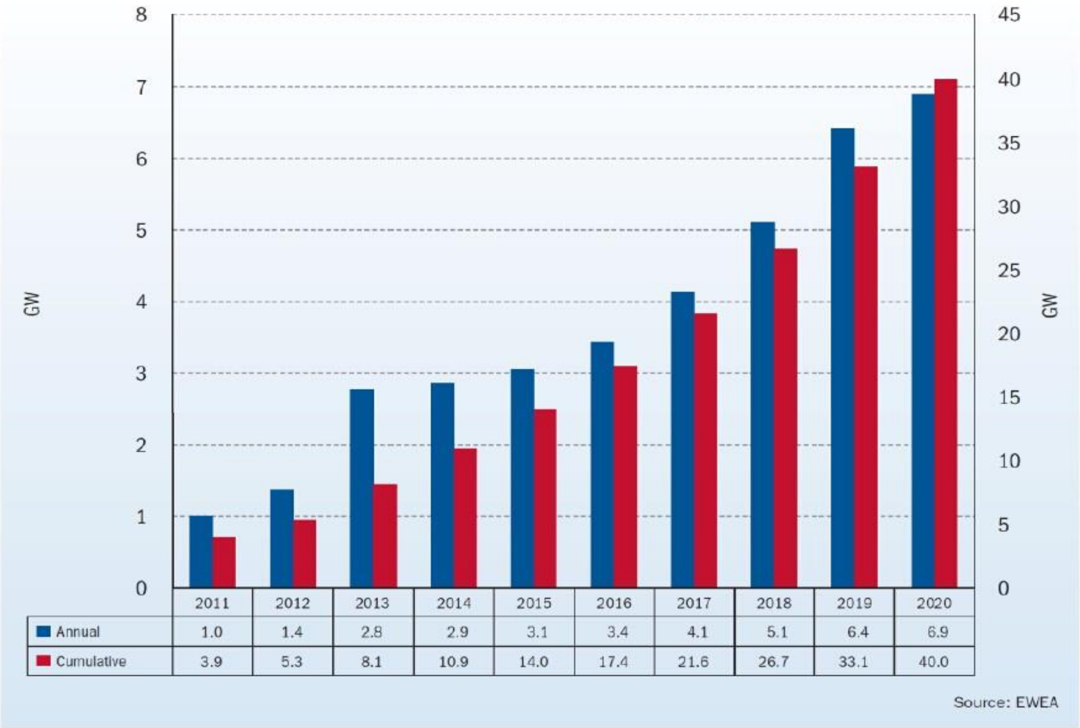


Figure 2.4. Predictions of Offshore Wind Annual and Cumulative Installations in Europe (2011–2020) [5]

Between 2011 and 2020, EWEA expects the annual offshore market for wind turbines to grow steadily from 1 GW in 2011 to 6.9 GW in 2020, which is shown in *Figure 2.4*. In 2010, offshore wind power made up 9.5% of the annual wind energy market. By 2020, offshore is expected to make up 28% of the annual wind energy market [7].

Wind markets in areas considered as cold climates are also increasing. Cold climate areas are characterised by good wind resources and low population, which together makes cold climates areas attractive for wind energy generation. It has been estimated that installed capacity in cold climate areas is approximately 60 GW [4] and represents about 25% all wind energy markets. Market in areas with high likelihood of icing is smaller, estimated at almost 10% of all markets.

Small wind turbine installations are expected to increase due to continuing political support. In recent years, global installed capacity of small wind turbines has increased

35% each year. This rate of growth is forecast to continue through 2015, reaching an annual installation of 288 MW of small wind turbines. Responding to this expansion, individual countries and the international small wind community are establishing more rigorous and structured standards and policies to regulate the market and support investments. Based on a conservative assumption, the market could subsequently see a steady compound growth rate of 20% from 2015 to 2020. The industry is forecasted to add 750 MW annually in 2020 and achieve a cumulative installed capacity of 3,817 MW by 2020 [3].

2.4 Wind Turbine Technology

Wind energy conversion systems convert the kinetic energy of the wind into electricity or other forms of energy. Wind power generation has experienced a tremendous growth in the past decade, and has been recognized as an environmentally friendly and economically competitive means of electric power generation.

The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems, as shown in Figure 2.5.[18]

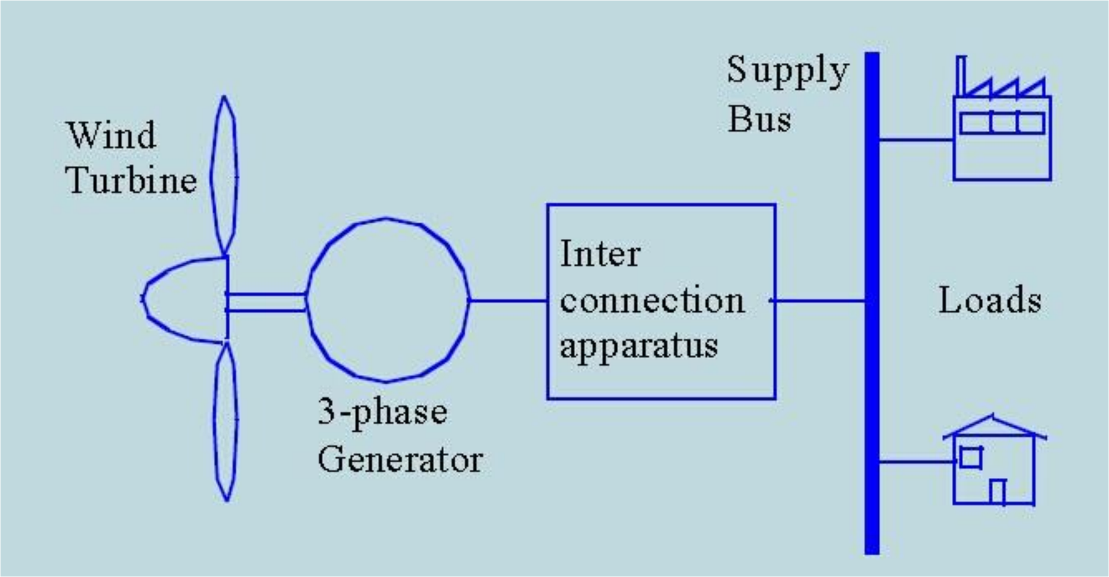


Figure.2.5 Structure of a Typical Wind Energy System [18]

2.4.1 Wind Turbine Basics

Wind turbines can be classified into vertical axis type and horizontal axis type. Most modern wind turbines use a horizontal axis configuration with two or three blades, operating either down-wind or up-wind. (*Figure.2.6*)

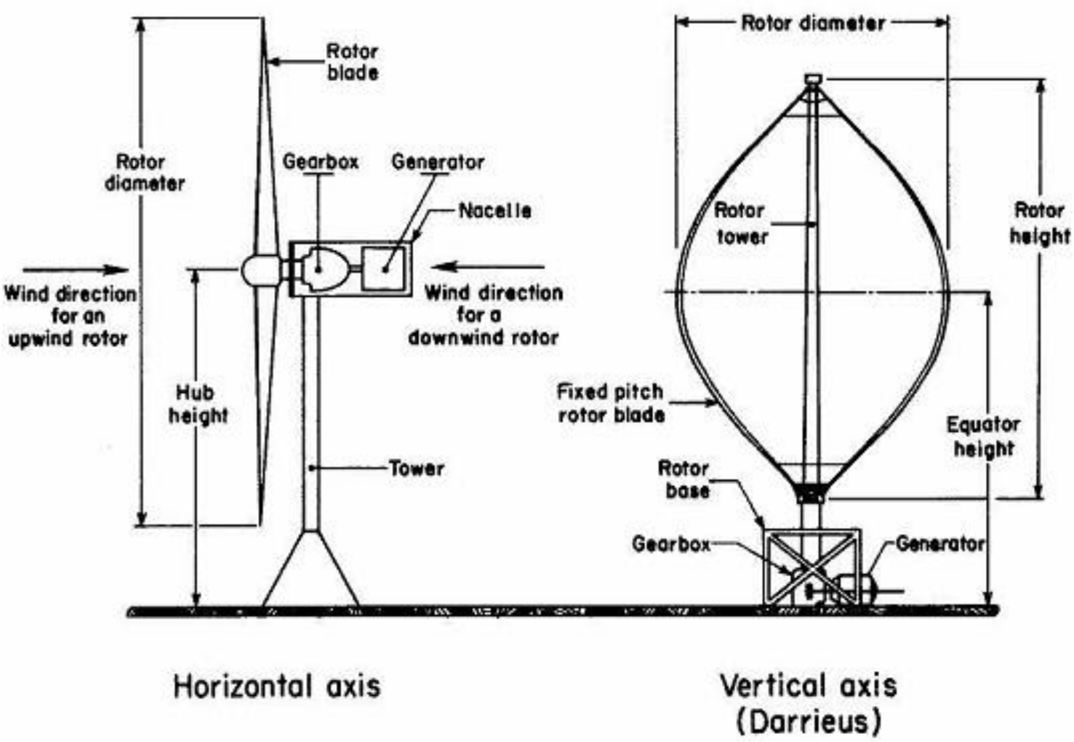


Figure.2.6 Illustration of Horizontal Axis Wind Turbine and Vertical Axis Wind Turbine [14]

HAWTs are the most commonly produced utility-scale wind turbines today, which have an advantage over VAWTs in that the entire rotor can be placed atop a tall tower, where it can take advantage of larger wind speeds higher above the ground. Some of the other advantages of HAWTs over VAWTs for utility-scale turbines include pitchable blades, improved power capture and structural performance, and no need for guy wires (which are tensioned cables used to add structural stability). VAWTs are much more common as smaller turbines, where these disadvantages become less important and the benefits of reduced noise and omni-directionality become more pronounced.

2.4.2 Wind Turbine Components

The main components of a horizontal-axis wind turbine that are visible from the ground are its tower, nacelle, and rotor, as can be seen in *Figure. 2.7*. The nacelle houses the generator, which is driven by the high-speed shaft. The high speed shaft is in turn usually driven by a gear box, which steps up the rotational speed from the low-speed shaft. The low-speed shaft is connected to the rotor, which includes the airfoil-shaped blades. These blades capture the kinetic energy in the wind and transform it into the rotational kinetic energy of the wind turbine.

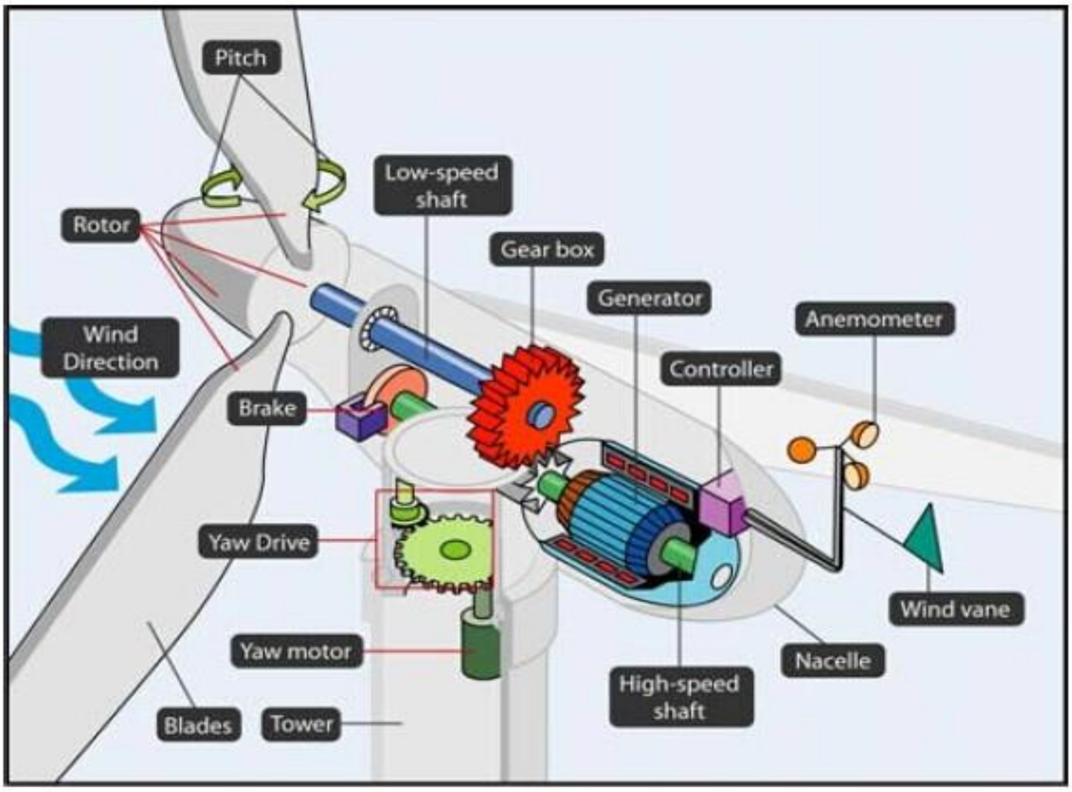


Figure.2.7 Wind Turbine Components [13]

Wind turbine control goals and strategies are affected by turbine configuration. HAWTs may be “upwind,” with the rotor on the upwind side of the tower, or “downwind.” The choice of upwind versus downwind configuration affects the choice of yaw controller and the turbine dynamics, and thus the structural design. Wind turbines may also be variable pitch or fixed pitch, meaning that the blades may or may not be able to rotate along their longitudinal axes. Although fixed-pitch machines are less expensive initially, the reduced ability to control loads and change the aerodynamic torque means that they are becoming less common within the realm of large wind turbines. Variable-pitch turbines may allow all or part of their blades to rotate along the pitch axis. [13]

Moreover, wind turbines can be variable speed or fixed speed. Variable-speed turbines tend to operate closer to their maximum aerodynamic efficiency for a higher percentage of the time, but require electrical power processing so that the generated electricity can be fed into the electrical grid at the proper frequency. As generator and power electronics technologies improve and costs decrease, variable-speed turbines are becoming more popular than constant-speed turbines at the utility scale.

2.4.3 Wind Turbine Output Model

The below *Figure 2.8* shows a sketch a how the power output from a wind turbine varies with steady wind speed.

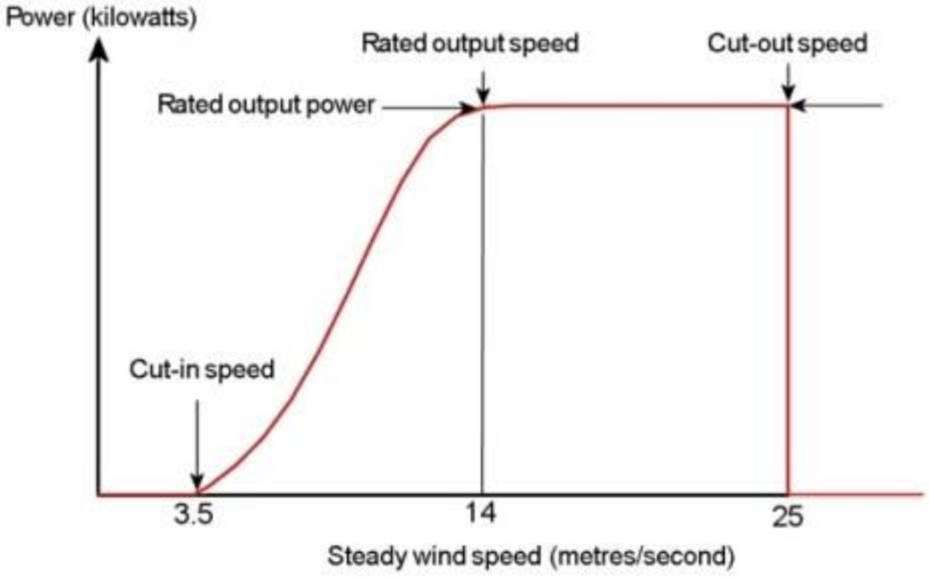


Figure.2.8 Typical Wind Turbine Power Output with Steady Wind Speed [6]

At very low wind speed, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. As the wind speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the ***cut-in speed***, in the above *Figure.2.8* is between 3 and 4 meters per second.

As the wind rises above the ***cut-in speed***, the output of electrical power increase rapidly as shown. However, typically somewhere between 12 and 17 meters per second, the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the ***rated power output*** and the wind speed at which it is reached is called the ***rated output wind speed.*** At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power.

As the speed increases above ***the rate output wind speed***, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a results, a braking system is employed to bring the rotor to a standstill. This is called the ***cut-out speed*** and is around 25 meters per second in *Figure.2.8.*

The wind power output characteristics have two distinct regions: one is the interval between cut-in and rated wind speeds in which the power output increases with wind speed (known as maximum power output region); another is the interval between rated and cut-out wind speeds when the power output is maintained constant at the rated value (known as power regulation region) [10]

The wind power output characteristics can be described in a general expression as *Equations 2.1.* [12]

$$P_w = \begin{cases} 0 & W_s < V_{ci} \\ (A + B \times W_s + C \times W_s^2) \times P_{wr} & V_{ci} \le W_s < V_r \\ P_{wr} & V_r \le W_s < V_{co} \\ 0 & V_{co} \le W_s \end{cases} \qquad （2.1）$$

Where:

W_s = the wind speed (m/s)

V_{ci} = designed cut-in speed of wind turbine (m/s)

V_r = designed rated speed of wind turbine (m/s)

V_{co} = designed cut-out speed of wind turbine (m/s)

P_{wr} = rating power output of wind turbine (MW)

While A, B and C are constant parameters in [12] which can be determined using the following *Equations*:

$$\begin{aligned}
A &= \frac{1}{(V_{ci}-V_r)^2}\left[V_{ci}(V_{ci}+V_r)-4V_{ci}V_r\left(\frac{V_{ci}+V_r}{2V_r}\right)^3\right] \\
B &= \frac{1}{(V_{ci}-V_r)^2}\left[4(V_{ci}+V_r)\left(\frac{V_{ci}+V_r}{2V_r}\right)^3-3(V_{ci}+V_r)\right] \qquad (2.2) \\
C &= \frac{1}{(V_{ci}-V_r)^2}\left[2-4\left(\frac{V_{ci}+V_r}{2V_r}\right)^3\right]
\end{aligned}$$

2.5 Wind Speed Probability Distribution

In order to research the wind power generation, a model of wind speed is essential. Because of the variability of wind speed, the behavior of wind speed was studied based on its characteristics and historical data based on daily, monthly, season and yearly data collection. Wind speed variation during a certain period can be well characterized in terms of a probability distribution function (pdf) through lots of statistical data. This probability function is called Weibull probability distribution. [15, 16]

2.5.1 The Weibull Distribution Function

The Weibull distribution function is discussed for representation of the wind speed frequency distribution. Two Weibull parameters (scale factor α and shape factor β) can be estimated from simple wind statistics. One of the important characteristic of this method is that, the Weibull distribution function has no specific shape, it can be shaped to represent many distributions by modified the value of α and β， as long as they are positive. Therefore, the Weibull distribution can be applied to fit the experimental data which cannot be described with a particular distribution such as normal distribution or exponential distribution. This feature makes Weibull distribution a popular tool in statistical analysis of experimental data. For example, in many published papers, it is common to use Weibull distribution to characterize the wind speed. [17, 12, 8, 20, 2]

The density function of Weibull distribution is as follow,

$$f(x)=\frac{\beta x^{\beta-1}}{\alpha^{\beta}}\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad (2.3)$$

Where: $f(x)$: the probability of occurrence of wind speed x ($x \geq 0$)

α : the Weibull scale parameter

β : the Weibull shape parameter

and $\alpha, \beta \geq 0$.

And the complementary cumulative Weibull distribution function *F(x)* gives the probability of the wind speed exceeding the value *x*. The expression is given as *Equations 2.4*.

$$F(x)=\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad (2.4)$$

So, the cumulative Weibull probability distribution function is expressed as *Equations 2.5.*

$$F(x)=1-\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad (2.5)$$

Therefore, the distribution characteristic of the cumulative Weibull distribution function is apparently monotonically increasing as shown in *Figure 2.9*.

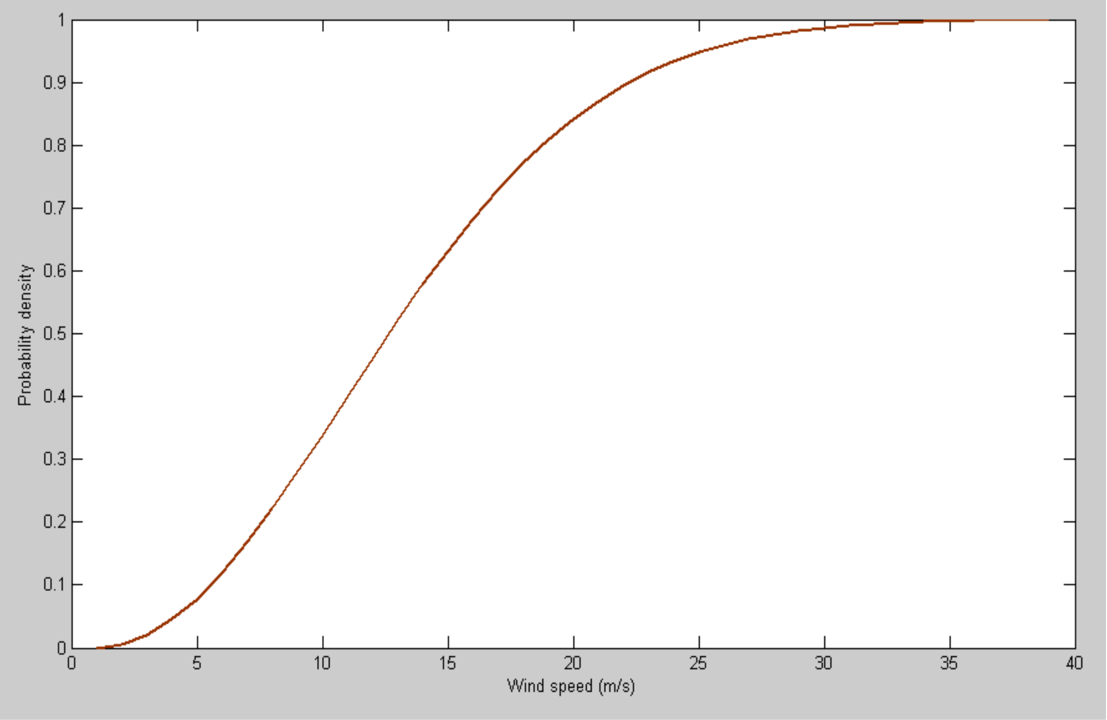


Figure. 2.9: Cumulative Weibull Probability Distribution (α = 7 & β = 2)

2.5.2 Distribution for Different Shape and Scale Parameters

The Weibull Scale parameter α

α is the scale parameter of the Weibull distribution. In the simulation of the wind speed, α is the mean wind speed in m/s. A change in the scale parameter α has the same effect on the distribution as a change of the abscissa scale. Changing the value of α when β 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 α, as indicated in *Figure.2.10*. [15, 19, 11]

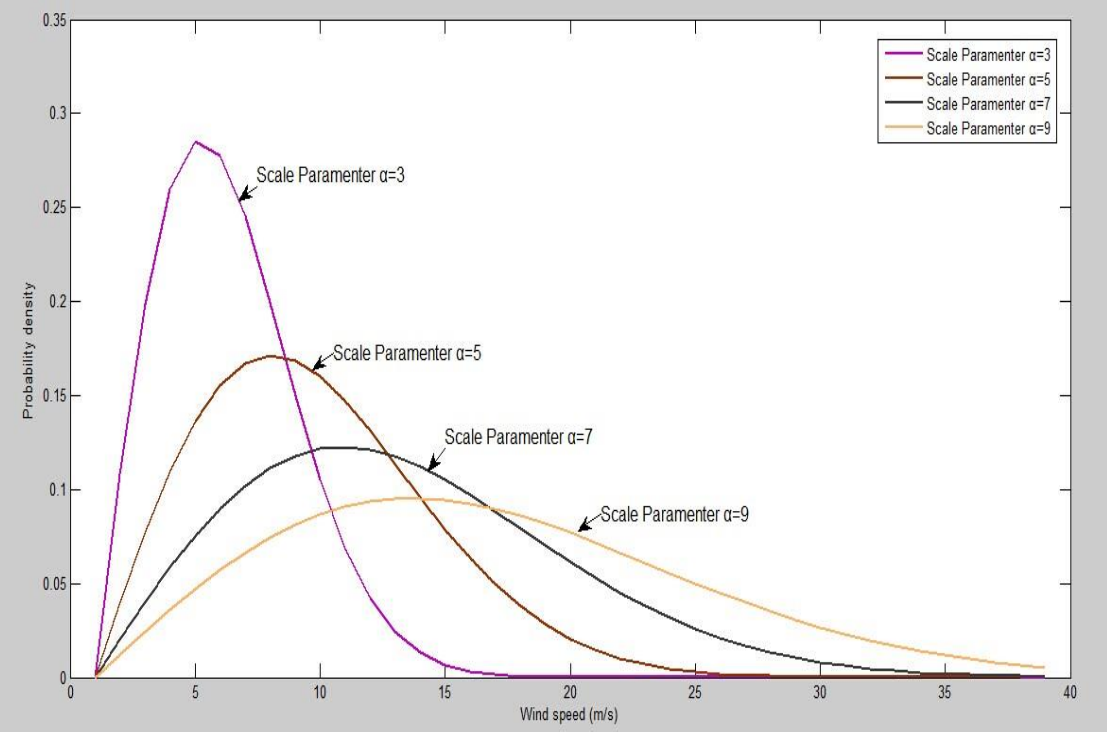


Figure.2.10 Weibull Distribution Density versus Wind Speed under a Constant Value of β =2 and Different Values of α

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

The Weibull Shape parameter β

In Weibull probability density function, $\beta \geq 0$ 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. *Figure.2.11* shows a Weibull pdf with constant value of α and values of $\beta = 0.5$, $\beta = 1$, $\beta = 2$, $\beta = 3$.

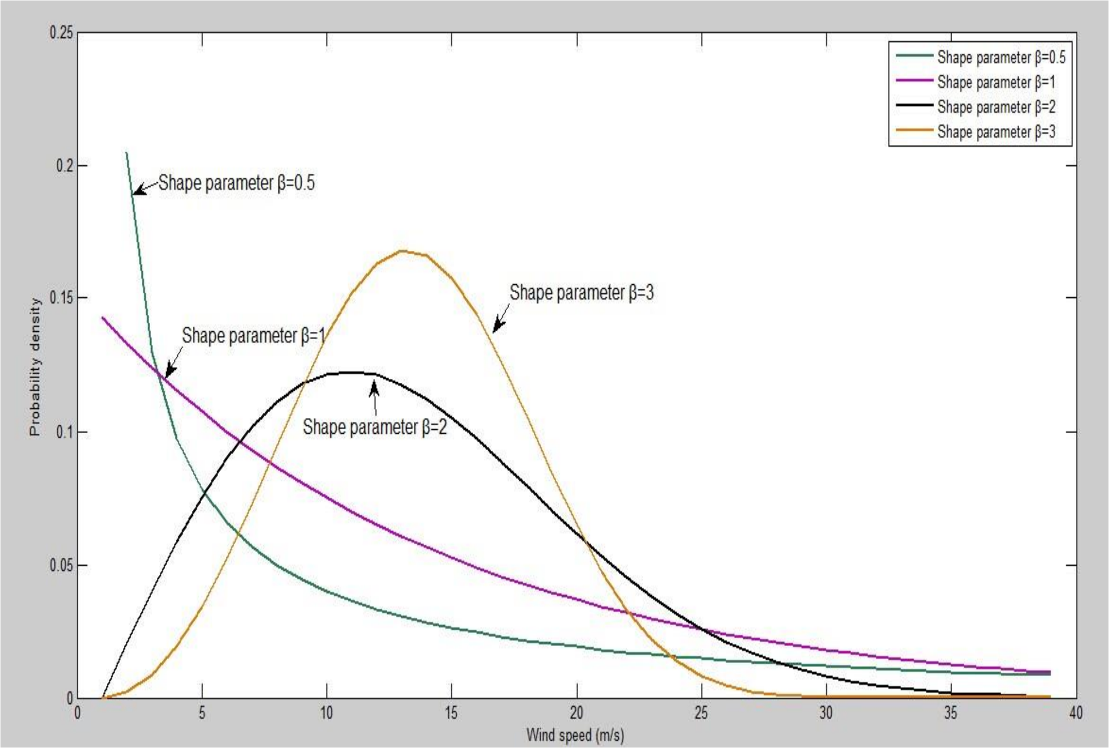


Figure.2.11 Weibull Distribution Density versus Wind Speed under a Constant Value of α =7 and Different Values of β =0.5, 1, 2, 3

These are shown on *Figure.2.11*, when $\beta = 1$, 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 $\beta = 2$, it becomes equivalent to the Rayleigh distribution[19,11] which more wind speed date is lower than mean speed in data collection period; when $\beta = 3$, it appears similar to the normal distribution, the distribution curve is more like bell shape or Gaussian distribution[19,11] and which more wind speed data is around mean speed in a certain period.

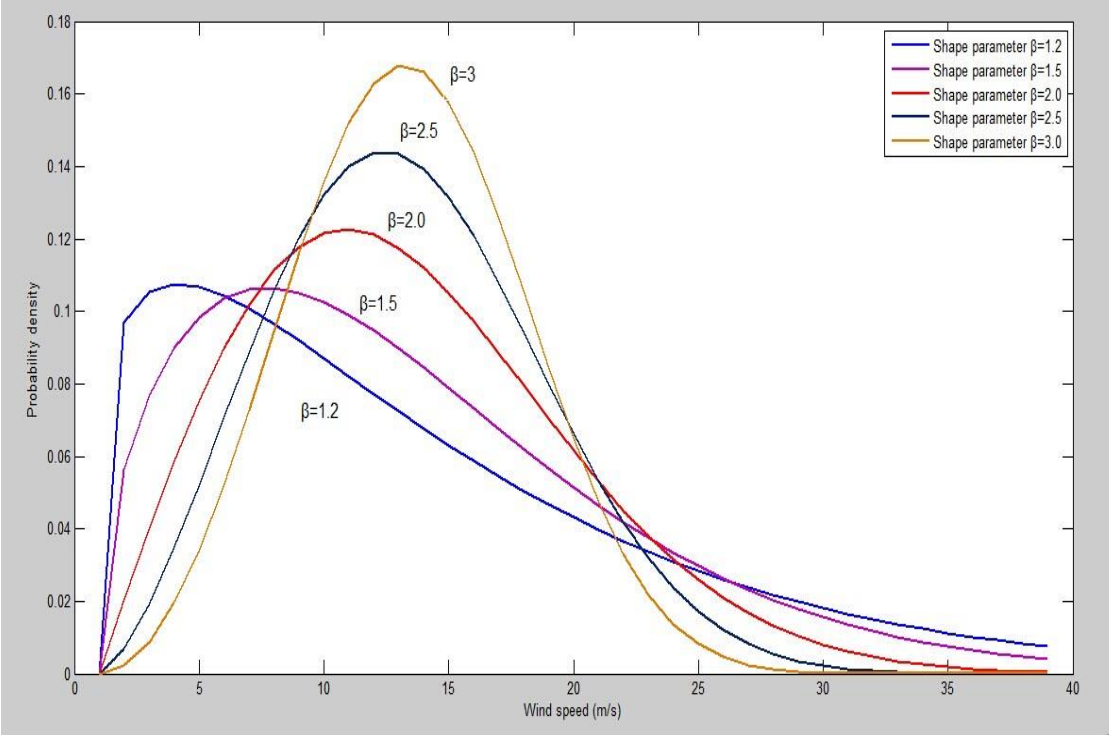


Figure.2.12 Weibull Distribution Density of Different Wind Speed under a Constant Value of α =7 and Different Values of β =1.2,1.5,2,2.5,3.

Figure.2.12 shows the changes of shape parameter β . A higher value of β , such as2.5 and 3, indicate 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 β , such as 1.2 or 1.5, indicates a greater deviation away from mean value.

2.5.3 Artificially Generated Wind Speed

To assess the operation of power system with wind power requires the data of wind power generation output. In order to modelling the wind turbine output, it is necessary to build a wind speed model. The wind speed is simulated by combining the Weibull distribution and random variables.

Monte Carlo simulation methods are stochastic techniques, based on the use of random numbers and probability statistics to investigate problems. Monte Carlo simulation methods estimate the indices by simulating the actual process and random behavior of the system; it treats the problem as a series of experiments instead of the conventional numerical methods studying the analytical models of systems.

Applying random number and different kinds of probability distribution function, Monte Carlo simulation methods is widely used in the simulation of generators operation, the output calculation of wind turbine and some other components of power system.

The integral Weibull distribution is shown by the following equation

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad (2.6)$$

Then let

$$U = F(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad (2.7)$$

The U is a uniformly distributed random variable between [0, 1].
By the inverse transform method

$$x = \alpha\left[-\ln\left(1-U\right)^{\frac{1}{\beta}}\right] \qquad (2.8)$$

Because every (1- U) represents an random number uniformly distributed within the interval of [0, 1] same as U, then this equation can also becomes

$$x = \alpha\left[-\ln(U)^{\frac{1}{\beta}}\right] \qquad （2.9）$$

Then it is possible to generate the artificial wind speed.

$$W_s = x = \alpha\left[-\ln(U)^{\frac{1}{\beta}}\right] \qquad （2.10）$$

The wind speed W_s can be generated artificially by using *Equations 2.10.* Then, the power output of the wind turbine can be obtained by applying the wind speed into wind turbine output model.

Applying the Weibull distribution function with *Equations 2.10*, where the Weibull parameters set to $\alpha = 7$ & $\beta = 2$. The simulated wind speed profile for 240 hours is shown in *Figure. 2.13*. It can be seen that the wind speed is constantly changing; most of them are moderate winds, strong winds and weak winds are rare, From *Figure 2.13*, it is clear that most wind speeds are mainly distributed between 4 m/s and 10 m/s. Therefore, Weibull distribution can have an excellent performance on simulating the wind speed profile by modifying its scale and shape parameters.

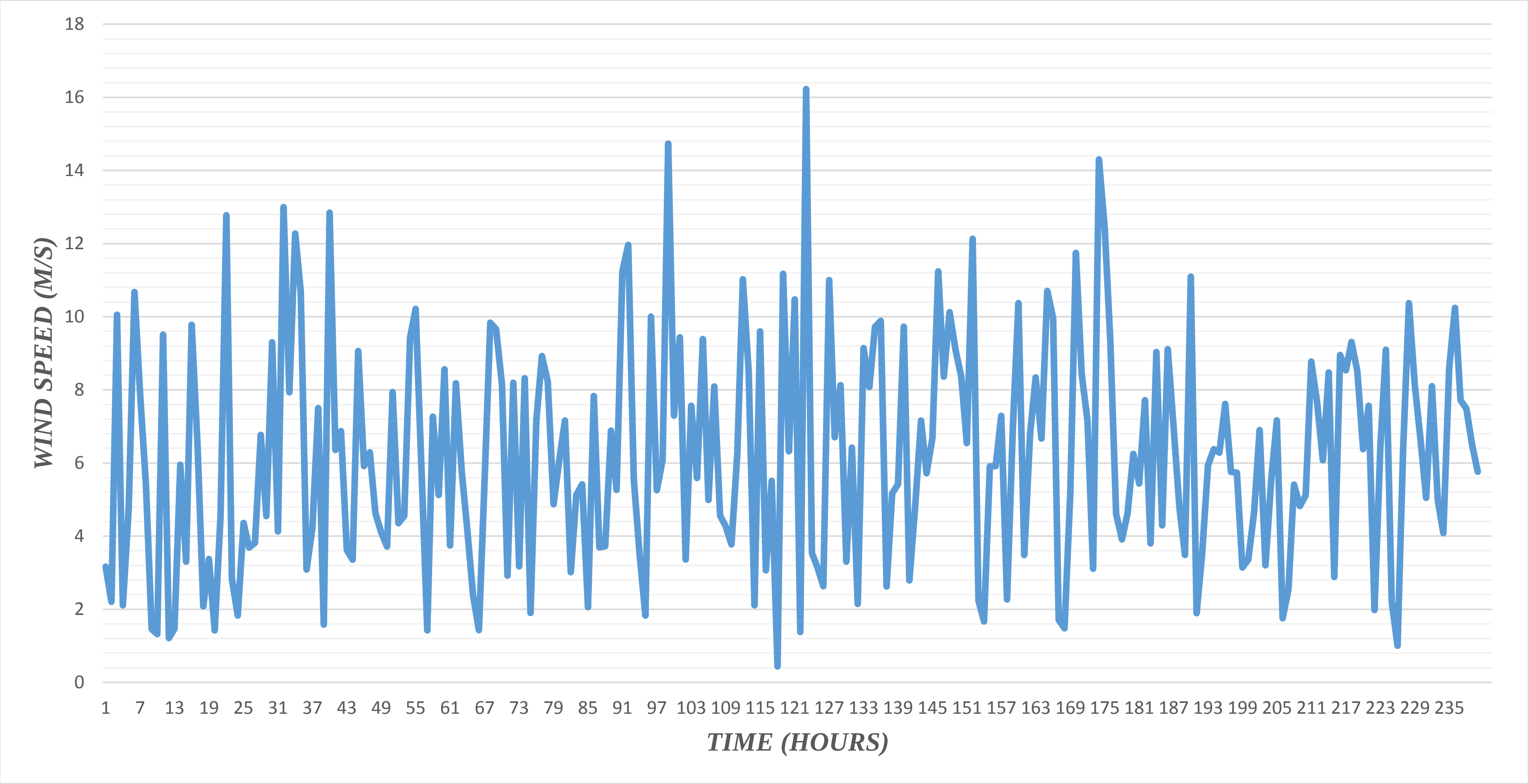


Figure. 2.13: Snapshot of Simulated Wind Speed (240 hours)

2.5.4 Wind Turbine Output Calculation

The wind turbine output model and the model details have been described in *section 2.4.3*.

The calculation procedures of wind turbine output with artificially generated wind speed profile are summarized as follows

Step1: Set the scale parameter α and shape parameter β for Weibull distribution, normally the values are 7 and 2 respectively.

Step2: Generate a uniformly distributed random number U between [0, 1];

Step3: Calculate the artificial wind speed W_s by *Equations 2.9,* with inverse transform of integral Weibull distribution function which is calculated by *Equations 2.6.*

Step4: Set the cut-in, cut-out and rating wind speed and rating output for wind turbine.

Step5: Calculate constant parameters A, B and C. with *Equations 2.2*

Step6: Calculate the wind turbine output with *Equations 2.1*

.

Example

The data shown in *Table 2.1 is for the* wind turbine, the scale and shape parameters α & β will be set to 7 and 2, which is the typical configuration for the wind turbine output calculation.

Table 2.1 Wind Turbine Parameter Data

Rated Power Output	3MW
Cut-in speed	4m/s
Rated speed	12m/s
Cut-out speed	25m/s

For one single wind turbine, *Figure 2.14* is the 240 hours snapshot of simulated wind turbine output. The wind speed can be simulated by Weibull distribution. In this example, the wind turbine output is calculated based on the wind speed profile in *section 2.4.1*.

There are 10 wind turbines in a single wind farm with a total installed capacity of 30 MW. *Figure. 2.15* is the 240 hours snapshot of simulated wind farm power output. Therefore, the following research on the operation of power system with wind power integrating can be evaluated with the wind farm output results in this section.

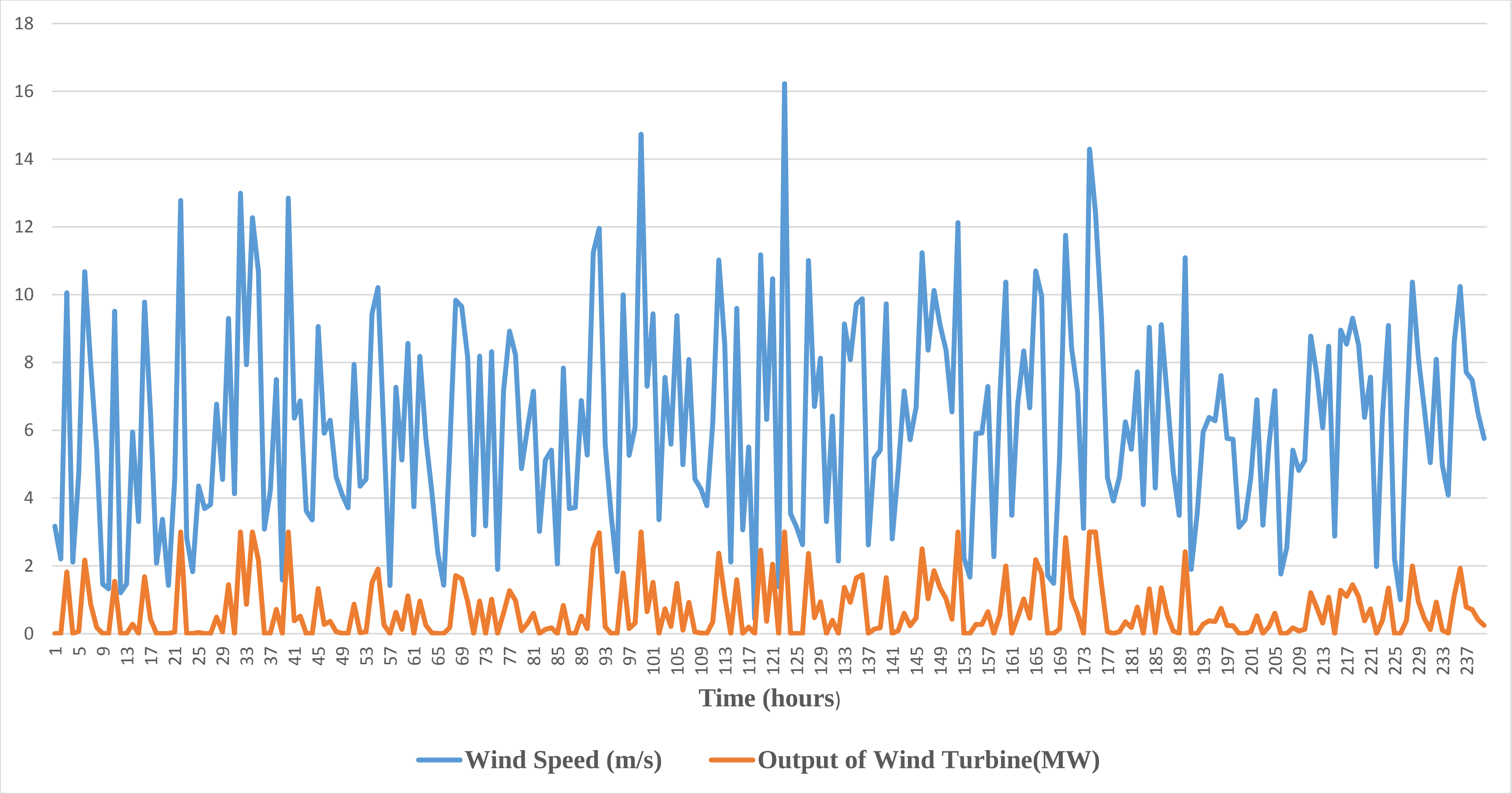


Figure 2.14: Snapshot of Simulated Wind Turbine Output (240 hours)

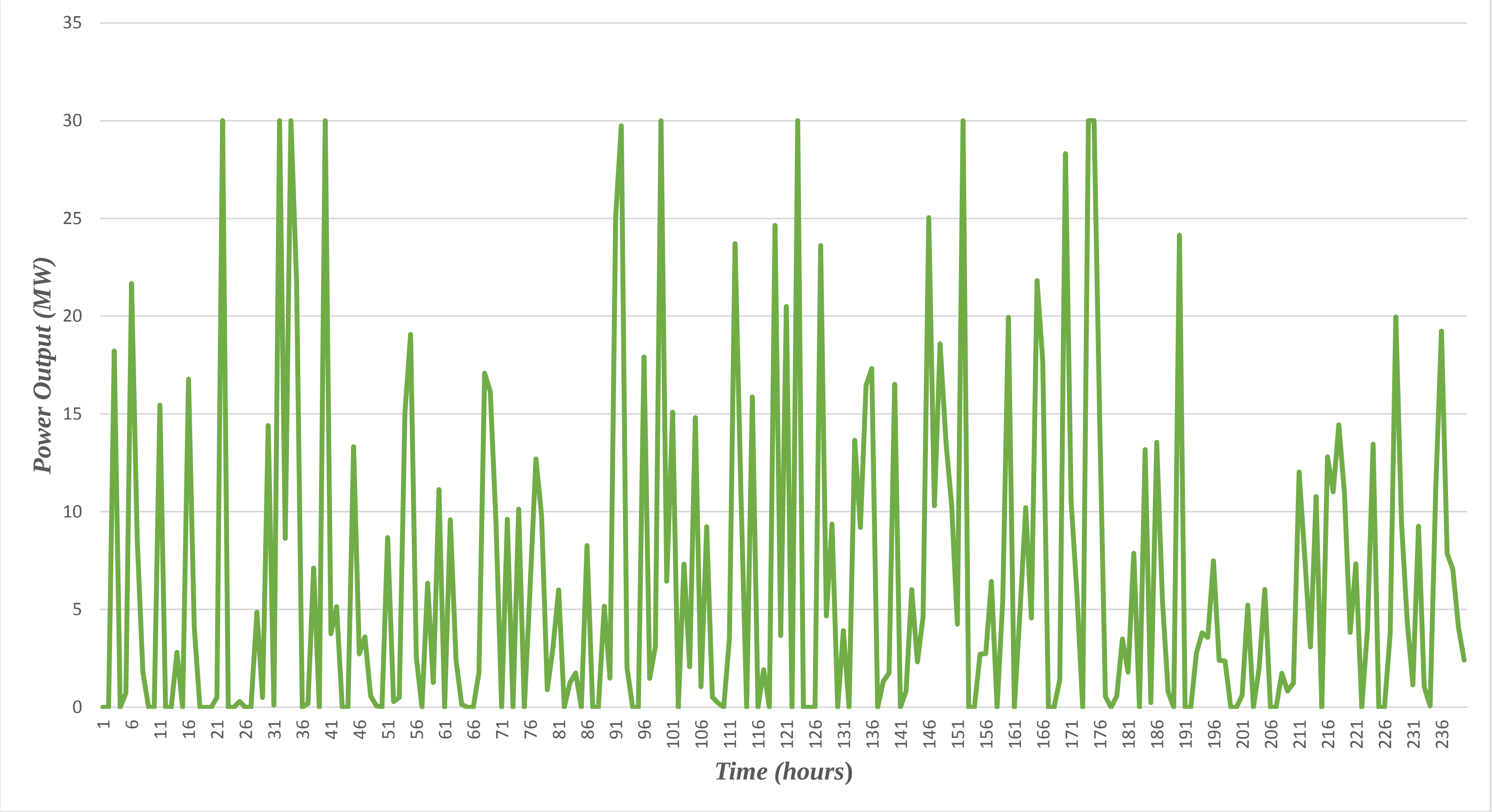


Figure 2.15: Snapshot of Simulated Wind Farm Power Output (240 hour)

2.6 Summary

This chapter discussed the related areas about wind energy, including wind power market, wind speed variation, Weibull distribution, and wind turbine power output calculation.

The first part of this chapter presented the development of wind energy and the benefits of wind power generation. Wind power is a main pillar of tomorrow’s energy supply. It generates clean and climate-friendly electricity, creates jobs and reduces risks on several levels, such as exposure to particulate matter and susceptibility to the price volatility of imported fuel.

The second 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, Then it introduced the method of developing wind speed data and the simulation of produce wind speed data as an example. Finally, the wind turbine power output can be calculated through simulated wind speeds.

In conclusions, 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 generation models in any further research about wind power generation integrating into the power system.

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Chapter 3

Some Issues of Wind Power Integration and an Overview of Power Market

3.1 Introduction

Integration specifically means the physical connection of the generator to the network with due regard to the secure and safe operation of the system and the control of the generator, so that the energy resource is exploited optimally. [10]

The proper integration of any electrical generator into an electrical power system requires knowledge of the well-established principles of electrical engineering. The integration of generators powered from renewable energy sources is fundamentally similar to that of fossil fueled powered generators and is based on the same principles, but, renewable energy sources are often variable and geographically dispersed. [10]

Integrating wind power generation into electric networks can create operational difficulties for power system operator. The existing power system was built to meet the operational characteristics of conventional generators and not for an intermittent source of energy such as wind generators. In recent years, numerous reports and papers have been published in many countries investigating the power system impacts of wind generation. The results on the technical constraints and costs of wind integration differ, and comparisons are difficult to make due to different methodologies, data and tools used, as well as terminology and metrics in representing the results.

Wind integration studies usually involve investigations of transmission adequacy, simulations of the power plants operation in the system and calculations of the capacity needed to meet resource adequacy requirements in the peak load situations.

Grid simulations (load flow and dynamics) involve contingency analysis and stability studies. Dynamic simulations and flexibility assessment are necessary, especially when studying higher penetration levels of wind power.

Reliability constraints from transmission or capacity adequacy or reserve margins will require iteration on the initial results to adjust the installed capacity of the remaining power plants (the portfolio), the transmission grid, and the operational methods of system management (like reserves).

This chapter presents an overview of wind integration issues, the main points are the associated integration impacts on power systems reliability, operational methods and markets. A brief review of integration impacts is presented in *Section 3.2.* The basic concepts and reliability indices of power system reliability evaluation are explained in details in *Section 3.3*. *Section 3.4* presents the impacts of wind power integration on power system operational methods and markets, such as increase in reserve requirements, estimating impacts on other generation and balancing, capacity value of wind power and increase in transmission due to wind power. A simple introduction of power market is shown in *Section 3.4.1*. *Section 3.5* is a simple example made to illustrate the impact of wind power on the transmission capacity consumption with different penetration and location.

3.2 Overview of Wind Integration Issues

All new power plants will need to be integrated in the power system by assessing the grid adequacy in longer time scales and implications to system balancing and dynamic stability in shorter time scales. Implementing wind power has impacts on power system management, economics, and efficiency. To keep the operational security and reliability at an acceptable level, some measures may need to be taken.

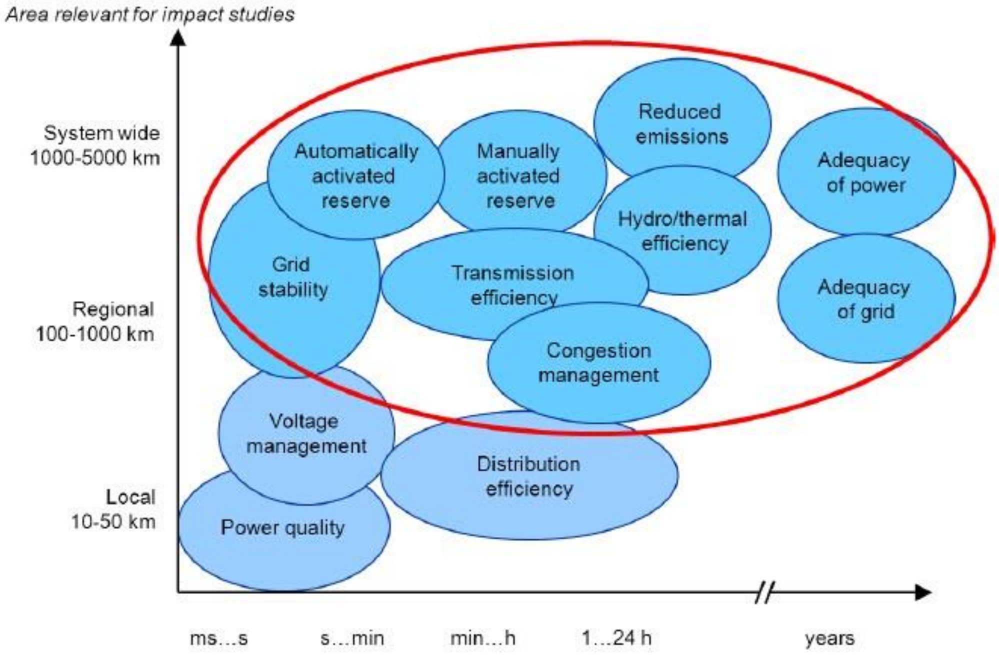

Figure 3.1. Impacts of wind power on power systems [2]

When we consider the impacts of wind power generation on power systems, with different time scales and geographic width of area relevant for the studies, the issues is shown as *Figure 3.1.* from [2] . Operating reserve can be divided into two categories: automatically activated reserves in seconds (frequency activated, primary/secondary reserve, regulation) and manually activated reserve in 5–15 minutes (minute reserve, load following reserve). [2] Transmission and distribution efficiency refers to grid losses.

To investigate wind integration impacts on power system, the operation (scheduling and dispatch) of power system and the generation resource need to be looked into. Power flow on transmission system and dynamic/transient of the whole system are the main aspects.

Owing to the operational characteristics of the installed generation plants, the inherent variability of generator itself, the rules and strategies practiced in relation to transmission capacity, the treatment of imbalances, and the network topology (well-meshed versus radial grids), power systems are quite different from each other. Physical flexibility, for example the existing generation capabilities, and administrative flexibility such as market structure, they are both affect the ability to balance increased variability and uncertainty from wind power.

How to conduct wind integration studies will depend to some extent on the penetration level to be studied. As a metric of penetration level for normally used is the share of wind electricity from annual electrical energy (i.e., gross demand). There is no standard practice regarding what share of wind power in electric energy is considered low or high penetration. How low penetration is defined depends on power system characteristics: 5% is considered a low penetration level in most systems, whereas for more flexible systems, 10% can be considered a high or low penetration level, depending on the system. High penetration levels generally refer to penetration levels exceeding 20% of gross demand. [2]

Another important aspect is how wind power is added to the system; by replacing existing generation or by adding wind power to the existing system. When studying small amounts of wind power (penetration levels where wind share in energy < 5-10%), wind power can be studied by adding wind to an existing, or foreseen system. For larger penetration levels, changes in the remaining system may be necessary, taking into account flexibility needs and additional network infrastructure. [2]

3.3 Impacts of Wind Power Integration on Power System Reliability

The primary function of the power system is to provide electrical power to its customers as economically as possible with an acceptable degree of quality. Reliability of power supply is one of the most important features of power quality [5]. Wind integration studies of power system reliability focus on the electrical behavior of wind power plants in interaction with the grid.

3.3.1 Basic Concepts of Power System Reliability Analysis

Power system reliability analysis usually has two subjects: system adequacy analysis and system security analysis. System adequacy deals with the problem that whether system facilities are sufficient to maintain the continuous power supply. Such facilities generally include generation units, transmission and distribution system network and associated assets to transport the generated electrical power to end – user.

A whole power system can be divided into three segments defined as three functional zones: generation, transmission and distribution as shown in *Figure 3.2* and adequacy studies are therefore based on one or all of these functional zones. [26]

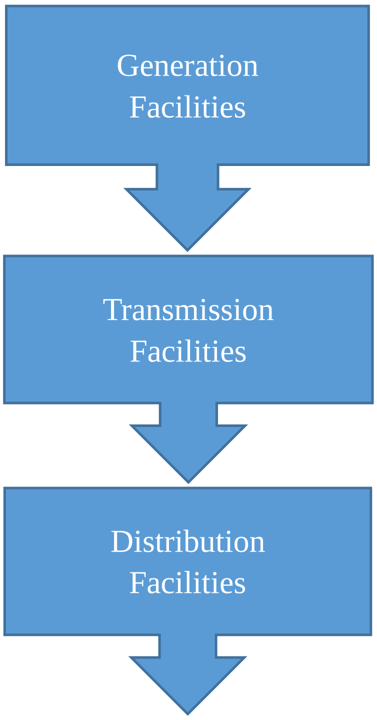

Figure 3.2 Functional Zones

System security means the ability of power system to tolerate the disturbance on generation, transmission facilities which can develop into dynamic, transient, voltage or frequency instability.

The reliability analysis in this thesis are focused on the generation adequacy issues within respect to the impact of wind power generation when the wind penetration level is significant. The term “reliability” used in this thesis means the system adequacy.

3.3.2 Elements in Generating Unit Model

There are some important elements for modelling generating units. In this section, four of the most representative factors will be discussed [25, 1].

I. Mean Time to Failure (MTTF)

MTTF means the system components' average 'up time' of a failure-repair cycle in an operating duration, when applied in a power system reliability analysis. The multiplicative inverse of MTTF is the component's failure rate λ.

II. Mean Time to Repair (MTTR)

MTTR is the average repair time for a system component. In addition, the multiplicative inverse of MTTR is the component's repair rate μ.

III. Mean Time between Failure (MTBF)

MTBF is the average time between each occurrence during an operating duration. It has significant conceptual difference with MTTF. The difference is shown clearly in *Figure 3.3*. It can be seen that MTBF= MTTF+ MTTR, which depends on MTTR (normally very small).

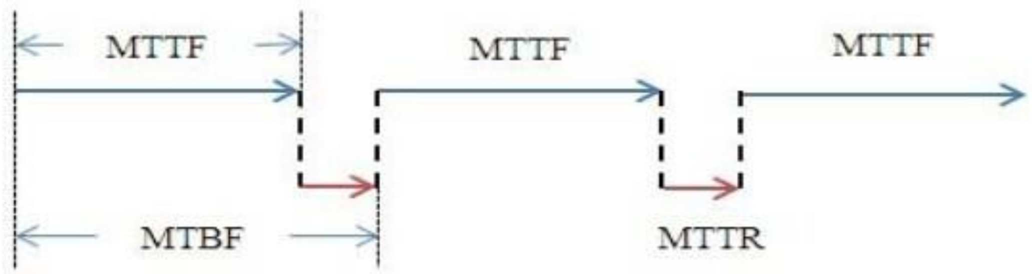

Figure 3.3: The Relationship between MTTF, MTTR and MTBF

IV. Forced Outage Rate (FOR)

FOR is defined as a ratio of two time values that represents the expected unavailability of a system in some distant time in the future.

Unavailability (FOR):

$$\mathrm{U} = \frac{\lambda}{\lambda+\mu} = \frac{r}{m+r} = \frac{r}{T} = \frac{\sum[down\ time]}{\sum[up\ time]+\sum[down\ time]} \qquad (3.1)$$

Availability:

$$\mathrm{A} = \frac{\mu}{\lambda+\mu} = \frac{m}{m+r} = \frac{m}{T} = \frac{\sum[up\ time]}{\sum[up\ time]+\sum[down\ time]} \qquad (3.2)$$

Where

λ= expected failure rate

μ= expected repair rate

m= mean time to failure= MTTF= 1/ λ

r= mean time to repair= MTTR= 1/ μ

m+ r= mean time between failure= MTBF= T

T= cycle time.

3.3.3 Generating Unit State Model

In power system reliability evaluation, generating units can be defined to have two states or multiple states.

Two-State Model

Two-state model means the unit has only two operating states, considered either fully available (up state) or fully out of service (down state). The state model is shown in

Figure 3.4, where λ and μ are unit failure rates and repair rates respectively.

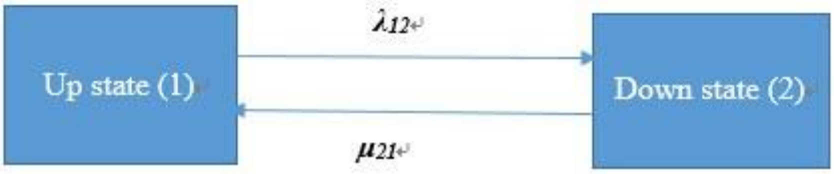

Figure 3.4: Two-State Transition

Multiple-State Model

Sometimes generating units can be in the up-state, but only able to generate part of their rated output. Therefore, it is necessary to consider the generating units have multiple states. This situation is called derated state. A three-state model is shown in *Figure 3.5*.

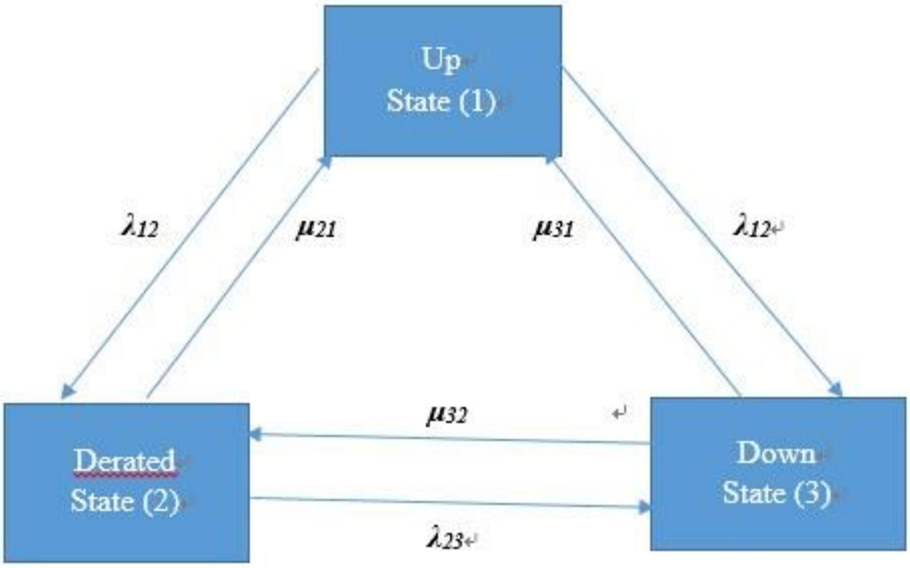

Figure 3.5: Three-State Transition

It is clearly that increasing number of derated states will increase the complexity of the reliability assessment. The work in this thesis is focused on the impacts of wind power integration, so the conventional generating units used for computations are considered as two-state model, either fully generate rated output or fully out of service. Moreover, a wind turbine generator can be considered as a multiple-state model with an infinite number of states.

3.3.4 Generating System Reliability

The function zones introduced in section 3.3.1 can be used to define three hierarchical levels (HL). Generation reliability study focuses on generation facilities, also known as hierarchical level 1 (HL1). The objective of generation system reliability evaluation is examining whether the generating system has sufficient capacity to fulfil the total system load with respect to the effect of generators' rated capacity, generators' forced outage, load forecast error and etc. The network topology, transmission congestion and security constraints are usually the main concern. This section presents some of the most widely used adequacy indices in reliability analysis [4, 9, 26, 25, 24].

The basic adequacy index used in HL1 studies are concluded as follows:

a) Loss of Load Probability, LOLP

It is the oldest and most basic probabilistic index. It is the probability that the load will exceed the available generation. But it does not consider the level of capacity or energy shortage.

b) Loss of Load Expectation, LOLE(days/yr or hours/yr)

LOLE is the loss of load probability of a generating system measured in time (days or hours) during a research period, expressed as [27]:

$$\text{LOLE} = \sum_{i \in S} p_i \, T_i \qquad (3.3)$$

Equations 3.3 is the expression of LOLE in analytical reliability analysis p_i is the probability of loss of load state *i*, *S* is the number of all evaluated system states in research period and *T* is the duration time for state *i*.

However, the expression of LOLE is different in simulation reliability analysis. It is defined as follows [28]:

$$\mathrm{LOLE} = \frac{\sum_{y=1}^{Y_S} LLD_y}{Y_S} \qquad (3.4)$$

In *equations 3.4*, Y_S is sampling time, normally in years and LLD_i is sampled loss of load duration in hour for year *i*.

c) ***Loss of Energy Expectation, LOEE (MWh/yr)*** [27]

$$\mathrm{LOEE} = \sum_{i \in S} 8760 C_i \, p_i \qquad (3.5)$$

In *equations 3.5*, p_i is the probability of loss of load state *i*, *S* is the number of all evaluated generating system states and C_i is the loss of load for state *i* in MW.

Similar to LOLE, the expression of LOEE in simulation reliability analysis is also different [28]:

$$\mathrm{LOEE} = \frac{\sum_{y=1}^{Y_S} ENS_y}{Y_S} \qquad (3.6)$$

Y_S is sampling time as in *equations 3.4*, *ENS$_i$* is sampled energy not supplied in MWh obtained by observing the available generation margin.

d) ***Loss of Load Frequency, LOLF(occ./yr)*** [27]

$$\mathrm{LOLF} = \sum_{i \in S} (F_i - f_i) \qquad (3.7)$$

In *equations 3.7,* F_i is the frequency that generators' state departing from state i and f_i is a portion of F_i which represents the frequency of those who departing from state i but not entering "down" state.

And the LOLF in simulation reliability analysis can be obtained by following equation [28]:

$$\mathrm{LOLF} = \frac{\sum_{y=1}^{Y_S} LLO_y}{Y_S} \qquad (3.8)$$

Where LLO_i is sampled loss of load occurrence in year *i.*

e) Loss of Load Duration, LOLD (hours/occurrence)

$$\mathrm{LOLD} = \frac{LOLE}{LOLF} \qquad (3.9)$$

Equations 3.9 defines the Loss of Load Duration. Denotes the LOLD is the average value of expected loss of load duration.

3.3.5 Reliability Cost/Worth Assessment

In the current worldwide electricity market environment, it is becoming significantly important to justify capital, operating and maintenance expenditures based on the benefits of utilities and customers. There are two issues of crucial importance: relate the economics with reliability and evaluate the worth of investment on increasing the system reliability. The reliability worth can be calculated directly or indirectly. However, it is difficult to assess the reliability worth directly.

In reliability cost and worth analyses of power systems, customer interruption cost (CIC) is used as a substitute in the reliability worth assessment. Therefore, the generally preferred indirect method is that using the CIC of losses of expected power supply to represent the value of power systems reliability [29]. It is known as a customer damage function (CDF). According to the Standard Industrial Classification (SIC), there are seven main types of customers: industrial, residential, agriculture, government, commercial, large user and office. *Figure 3.6* shows the proportion of the components based on the data in [25]. The CDF is built on survey of actually loss reported by customers as shown in *Table 3.2*. [1]

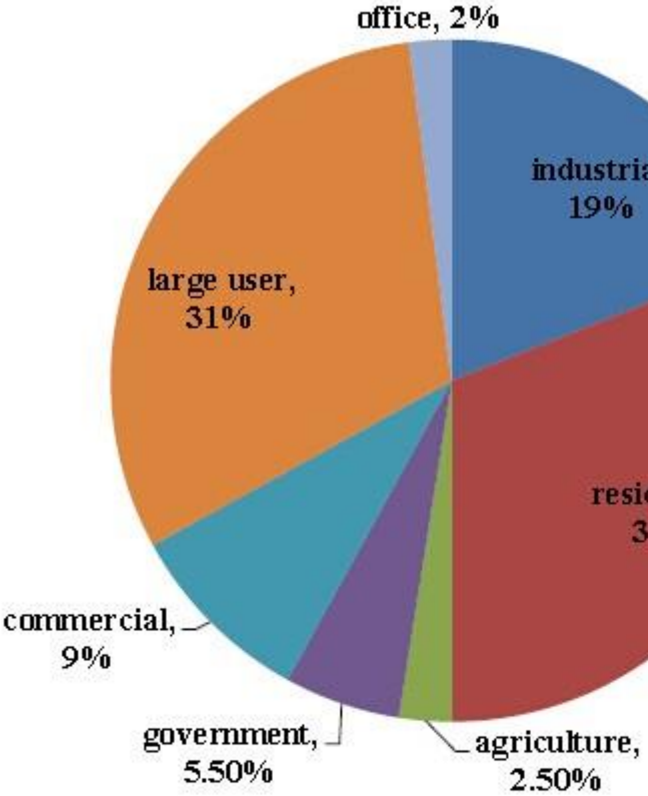

Figure 3.6: Seven Components used in Canadian Electricity Market [25, 1]

Table 3.2: Customer Damage Function for Seven Components [25, 1]

Customer Damage Function (£/kWh)							
Duration	Large user	Res.	Agri.	Govern.	Indus	Com.	Office
1 min	1.005	**0.001**	0.060	0.044	1.625	0.381	**4.778**
20 mins	1.508	**0.093**	0.343	0.369	3.868	2.969	**9.878**
1 hour	2.225	**0.482**	0.649	1.492	9.083	8.552	**21.038**
4 hours	3.968	4.914	**2.064**	6.558	25.163	31.317	**68.83**
8 hours	8.240	15.69	**4.120**	26.040	55.808	83.008	**119.16**

As the results in *Table 3.2*, Office has the highest value in all time intervals. When the duration is less than 1 hour, Residential has the minimum value; however, when the duration continues to go up, Agriculture has the lowest value amongst all seven categories.

3.3.6 Effect of Wind Energy on System Reliability and reserve requirements

It is well understood that wind power generation is a variability and uncertainty energy source. Therefore, the power outputs from wind turbines have fluctuations. These fluctuations can cause negative influences on the overall system health. As discussed in *Section 3.3.3*, the wind turbine unit is a multiple-state model with an infinite number of states, which is very different from the conventional generating unit. It makes the output models of wind power generating units difficult to build in reliability evaluation.

The values of reliability indices (LOLE, LOEE and LOLF) will become bigger than before due to wind power integration. Accommodating wind power generation will cause impact on generating system reliability and such impact will increase as the wind penetration level is increased. Therefore, it is necessary to provide additional operating reserve to overcome the fluctuation from wind and maintain the reliability level. [1]

The operating reserve requirement addresses the short-term flexibility for power plants that can respond to load and generation unbalances. These are caused mainly by unpredicted variations. The impact that wind energy has on procuring operating reserves is an on-going area of research, taking the uncertainty of wind power into account while aiming for both reserve adequacy and economic provision [3]. System operators carry reserves to balance load and generation, and to respond to outages.

3.4 Impacts of Wind Power Integration on Power System Operational Methods and Markets

Operational methods and markets may need to be assessed to determine whether current approaches to operate the system and current market practice allow for reliable and cost-efficient integration of wind power. This part involve investigations of transmission grid, simulations of the operation of power plants in the system, and calculations of the capacity needed to meet resource adequacy requirements in the peak load situations. Market structures/design still should be assessed to enable operational flexibility. Where market structures are inhibiting access to flexibility they need to be changed. And markets need to incentivize also adequate capacity.

3.4.1 Review of Deregulated Power Market

Role of Independent System Operator

In deregulated electricity market, the ISO must be independent to give the market participants, for example generators and loads, a fair and non-discriminatory access to transmission services. The roles of Independent System Operator (ISO) differ for different market model.

In bilateral market, the ISO does not involve in the energy market and its role is limited to purely ensuring that power transactions can be carried out between generators and loads. In the operational timeframe, the main function of the ISO is to maintain energy transfer balance and system operation balance. Energy transfer balance relates to the adequacy of the generation to match the load. System operation balance is linked to satisfactory levels of reactive power, operating reserves and other Ancillary Services (AS). It also coordinates measures to alleviate transmission congestion and perform contingency analysis for security analysis.

In pool market, in addition to the above the ISO is also responsible in energy trading. Its roles would include generation and AS scheduling, pricing of transmission facilities, dispatching generation in cases of imbalance, and facilitate the energy and AS markets.

Pool Market

In the pool market, all energy supply is controlled and coordinated by a single pool operator who is normally known as Independent System Operator (ISO). The generators submit their energy capacity and bid price of their energy into the pool. Respecting the constraints of the system operation, the ISO will use these information and choose the cheapest generator for dispatching the energy to the customers/distribution companies. The old England and Wales (E&W) pool is an example of a mandatory pool market and all energy must be traded through the pool. Nordpool in Norway [22] is an example of voluntary pool market where market participants are free to trade either in pool or bilateral market.

Bilateral Market

In bilateral-market with respect to their own financial interest, market participants arrange the electricity trading through bilateral contracts with each other. The ISO doesn't know the price of the bilateral contract, and they do not need to be responsible in determining the optimum power output of the participant generators. The role of ISO is narrowed to maintain security and provide ancillary services. Once bilateral contract has been agreed, the participants submit their quantities and delivery period to the ISO. The ISO task is either to accept or reject the submitted contract given by the participant. It is generator and load responsibility to ensure that the agreed contract does not violate system security and physical constraints or risking rejection from the ISO. BETTA (British Electricity Trading and Transmission Arrangement) [14, 20] in United Kingdom is a practical example of bilateral market model.

Hybrid Bilateral-Pool Market

In practice, most of the electricity markets in the world are combination of bilateral and pool market. In this model, market participates not only bid into the Pool but also may have the bilateral contract with each other. So this model provides more flexible options for energy trading. NordPool, NY (New York), PJM (Pennsylvania, New Jersey, Maryland) and California ISO are examples of this model [22, 18, 15, 19]

Balancing Market

Balancing Market is designed to cater any energy deficit or excess in the system due to mismatches between contractual and actual power demand in bilateral market. The generators and loads that participate in Balancing Market submit their incremental/decremental bid to the ISO. The ISO will then use these bids to adjust generator/s output or load/s demand at minimum cost [17]. Practical examples of Balancing Markets are BETTA Balancing Mechanism [13] and Nordpool Balancing

Market.

3.4.2 Optimal Displacement of Conventional Generators

Because wind power output is regarded as “must-take” generation, once the wind penetration level is significant, one of the major impacts of wind on generation system is that its output will lead to displacement of conventional generator to maintain the generation- demand balance.

The displacement can base on many viewpoints and create relevant objective function for optimization. The displacements of conventional generators reported in this thesis are optimized in order to have minimum impact on conventional generations’ profits for maximum wind penetration level.

The optimization approach in this thesis is based on different location and penetration of wind turbine, the Bilateral Contract of conventional generator in the trade affecting the curtailment of wind energy. The detailed case studies and results will be presented in *chapter 4 and 5*. This section and the following ones aim to introduce the concept of involved elements, methodology and the steps of the research.

3.4.3 Optimal Power Flow (OPF) Formula Formulation

In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. OPF algorithm was formulated in the 1960’s [21], to minimize some objective function subject to a number of equality and inequality constraints. The objective of OPF is to determine the most cost efficient generations from all available resources to operate a power system with an objective function of minimizing operating cost subject to power flow equations and network constraint. OPF functionally combines the power flow (PF) with Economic Dispatch(ED) with the objective function of minimizing a cost function (operating cost) taking into account realistic equality and inequality constraints. [12]

The optimization is applied in the spot pricing theory to dispatch generation and load in an economic manner where suppliers submit bid curves to the pool operator and an optimization routine is carried out to determine the dispatch results. Suppliers are then paid a price according to their bus price and consumers pay at their bus price. Several methods have been used to solve optimal power flow; these include lambda iteration method, gradient method, Newton’s method, linear programming method and interior point method. [12] In general, OPF problem for real power can be expressed as:

$$Min \sum_{k=1}^{N} C_{gen,k}(P_{gen,k}) \qquad (Energy\ Bids) \qquad (3.10)$$

Subject to

$$\sum_{k=1}^{N} P_{gen,k} = \sum_{k=1}^{N} P_{load,k} + P_{Loss} \qquad (Active\ Power\ Balance) \qquad (3.11)$$

$$P_{gen,k}^{\min} \le P_{gen,k} \le P_{gen,k}^{\max} \qquad (Active\ Power\ Limit) \qquad (3.12)$$

$$g_{line,l} \le g_{line,l}^{\max} \qquad (Line\ limit) \qquad (3.13)$$

The generator cost function model at bus k, is given as

$$C_{gen,k}(P_{gen,k}) = a + bP_{gen,k} + cP_{gen,k}^{2} \qquad (£/h) \qquad (3.14)$$

where a, b and c are the cost coefficients with their unit in £/MWh, £/(MWh)^2 and £/(MWh)^3 respectively. The equality constraint in *Equations 3.11* is the active power balance Equation, where total supply is equal to total demand plus system losses. The inequality constraint in *Equations 3.12* corresponds to the active power generation limit. *Equations 3.13* is the inequality constraint for line flow limits of the system. *Equations 3.14* is the generator cost function at bus *k*. [12]

The aim of the following research is evaluating the impact on transmission system due to wind power generation integrating into the power system. So in the case study, wind turbine is assumed that 'wind farm owners' offer their energy production price being equivalent to zero and the wind farm is treated as first used generation in the power market.

The objective function in a centralized dispatch is to minimize the system operating cost subject to equality and inequality constraints. Hence the Lagrange function of the OPF problem can be written as [12]:

$$\begin{aligned} L = {} & \sum_{k=1}^{N} C_{gen,k}(P_{gen,k}) + \sum_{k=1}^{N} \lambda_k \left[\sum_{k=1}^{N} P_{gen,k} - \sum_{k=1}^{N} P_{load,k} - P_{loss} \right] \\ & + \sum_{l=1}^{nl} \mu_l \left[g_{line,l} - g_{line,l}^{\max, flow} \right] + \sum_{k=1}^{N} \pi_k^{\max} \left[P_{gen,k} - P_{gen,k}^{\max} \right] \\ & + \sum_{k=1}^{N} \pi_k^{\min} \left[P_{gen,k}^{\min} - P_{gen,k} \right] \end{aligned} \tag{3.15}$$

where

$C_{gen,k}(P_{gen,k})$	denotes the energy bid function of bus *k*
λ_k	denotes the Lagrange multiplier for the marginal value of the active power balance constraint at bus *k* (i.e. LMP active power at bus *k*)

π_k^{max}	denotes the Lagrange multiplier of upper limit of active power at bus *k*
π_k^{min}	denotes the Lagrange multiplier of lower limit of active power at bus *k*
π_l	denotes the Marginal (shadow) cost of transmission constraint at line *l*
$P_{gen,k}^{max}$	denotes the Upper limit of active power injection at bus *k*
$P_{gen,k}^{min}$	denotes the Lower limit of active power injection at bus *k*

Applying Karush-Kuhn-Tucker(KKT) theorem[29], the LMP can be expressed as follows:

$$\lambda_k = \lambda_k^{energy} + \lambda_k^{loss} + \lambda_k^{cong} \qquad (3.16)$$

or

$$\lambda_k = \lambda_0 - \lambda_0 \frac{\partial P_{loss}}{\partial P_k} - \sum_{l=1}^{nl} \mu_l T_{l,k} \qquad (3.17)$$

where	λ_k	is the marginal price or Locational Marginal Price at bus *k*
	λ_0	is the marginal cost of energy
	λ_k^{loss}	is the marginal cost of loss component at bus *k*
	$\frac{\partial P_{loss}}{\partial P_k}$	is the real power loss sensitivity factor at bus *k*, denotes as L_k
	μ_l	is the vector of Lagrange multiplier associated to network constraint of line *l*
	$T_{l,k}$	is the sensitivity factor of the network at bus *k* due to network constraint on line *l*

The bus of marginal price in *Equations 3.17* can be summarized into two parts

1) λ_0 represents marginal generation cost, also called ‘system lambda’ or ‘system marginal price’.

2) Second and third terms in *Equations 3.16* are called ‘lambda differential’ also known as ‘delivery cost’ that varies within a network which are dependent to the cost of marginal losses and network constraint congestion. Under unconstrained condition, where there is no line overloading, the third term will be equal to zero leaving the cost of lambda differential just depending on the cost of marginal losses as:

$$\lambda_k = \lambda_k^{energy} + \lambda_k^{loss} \qquad (3.18)$$

The Lagrange multipliers determined from the solution of the optimum power flow provide important economic information regarding the power system. A Lagrange multiplier can be interpreted as the derivative of the objective function with respect to enforcing the respective constraint. Therefore, the Lagrange multipliers associated with enforcing the power flow Equations of the OPF can be interpreted as the marginal cost of providing energy service (£/MWh) to that bus in the power system.

This marginal cost is also known as locational marginal price and sometimes is called the shadow price of the power injection at the node. The locational marginal price is then decomposed into three components which are the cost of energy, cost of marginal losses and cost of marginal congestion to reflect the effects of system marginal cost, loss compensation and congestion management as well as voltage support. These components are all important cost terms in the deregulated electricity market and can be forwarded to the generators and consumers as control signals to regulate the level of their generation and consumptions. [12]

In the following *Chapter 4*, the case study which is the dynamic stochastic output of wind turbine affecting the power system performance. The results of generators with economic dispatch, power flow at each transmission line and locational marginal price at each bus will be compared under two system operating conditions (congestion and without congestion).

3.4.4 Effect of Wind Energy on Transmission Adequacy

As electric power industry continues to restructure, for example integrating new power generation into the existing power system, there is an increased need by many system operators to accurately determine the cost of various components associated with the network properties. These components are the system losses and the transmission congestion. The most important issue is the transmission congestion. It is defined as the short-term costs associated with having to re-dispatch the system generation or possibly other controls to avoid exceeding transmission system limits. [12]

Congestion Management

This section discusses transmission congestion for pure pool-based market. The first stage is called unconstrained dispatch and the second one is called security constrained re-dispatch. During unconstrained dispatch, generators are placed in an ascending order according to their bid prices without considering any system constraints. A number of the least expensive generators are selected for dispatching to meet system predicted demands. The bid price of the last dispatched generator determines the system marginal price (SMP). Next, the ISO evaluate if transmission constraint would occur under the unconstrained dispatch stage is executed. If there is constraint violation, the ISO would re-dispatch the generators using security-constrained dispatch.

Unconstrained Dispatch

This dispatch also known as Market Dispatch. The SMP gained at this stage is the marginal cost of the marginal unit in the absence of transmission constraints. That is, the SMP is only determined from the generators bids but independent of transmission constraints. If the price elasticity effects are neglected, the unconstrained dispatch algorithm in the absence of system losses and constraints may be stated as:

$$\min \sum_{i=1}^{N_G} C_{G_i} P_{G_i} \qquad (3.19)$$

$$\text{Subject to } \sum_{i=1}^{N_G} P_{G_i} = \sum_{j=1}^{N_D} P_{D_j} \qquad (3.20)$$

$$0 \le P_{G_i} \le P_{G_i}^{max} \qquad (3.21)$$

Where :

C_{G_i} : Bid price of generator i in £/MWh

P_{G_i} : Power produced by generator i

$P_{G_i}^{max}$: Maximum generation capacity of generator i

N_G : Number of generators

N_D : Number of loads

Equations 3.20 states that the total supply must meet the total demand. *Equations 3.21* is the constraints relates to the generation capacity (i.e. the generation output must not exceeds its maximum output capacity).

Security-constrained Dispatch

In this dispatch, the ISO resolves the transmission constraint though generators re-dispatching. When transmission constraint occurs, the objective function of *equations 3.19* is supplemented by an additional inequality constraint equation. The inequality constraint for MW flow constraint on line k-l is given by:

$$P_{kl} \leq P_{kl}^{max} \tag{3.22}$$

$$P_{kl} = P_{kl}^{0} + \sum_{i=1}^{N_G} PTDF_{kl,i} * (P_{G_i}^{adj} - P_{G_i}^{0}) \tag{3.23}$$

Where:

P_{kl}^{0} : Initial power flow on the constraint line k-l

P_{kl}^{max} : Maximum power flow limit on the constraint line k-l

$P_{G_i}^{0}$: Initial power output for generator i

$P_{G_i}^{adj}$: Final adjustment power output for generator i

N_G : Number of generator buses

$PTDF_{kl,i}$: DC-Power Transfer Distribution Factor, the sensitivity of the flow on line k-l to a change in generation at bus i

Power Transfer Distribution Factor (PTDF) [23] is used to approximate the change in power flow in the transmission network due to a change in power injection at any node. PTDF is a very useful tool for redispatch and curtailment procedure. The definition and calculation details of PTDF are presented in many publications.

It is generally believed, wind power generator has much lower capacity factor than conventional ones. From Wikipedia, The net capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time. Then, in reality, to support the same amount of load the installed capacities of wind farms should be fairly higher than the conventional units to maintain the generation adequacy. Therefore, with the wind penetration level is getting higher; it becomes an issue that whether the existing capacity of a line is sufficient to transport the power from wind especially during the peak output period. The incremental generation output from wind power will increase the line capacity consumption and have the potential to result in an over loading on a transmission line which will lead to transmission congestion, thermal risk, stability risk, over voltage risk and other relevant security problems.

On the other hand, the intermittent nature of wind makes the wind farms unable to generate at their rating output in the most times. The necessity to conduct the additional investment on network reinforcement due to wind power output and the effect on transmission cost calculation is needed to be evaluated.

3.4.5 Related Costs of Wind Power

The cost of wind power varies according to many aspects; it depends on the location of wind farms, the size of wind farms installed capacity, duration of generating, investment of wind farm construction, associated ancillary service and so on.

Wind Generation Cost

Compared with conventional plants, wind power generator requires lower operation cost and higher investment, that means a longer capital recovery period will be need. The cost of each kWh wind power can be calculated by *equations 3.24.* [9]

$$\mathrm{C} = \frac{r(1+r)^n}{(1+r)^n - 1}\left(\frac{Q}{8760 * F}\right) \qquad (3.24)$$

C is the cost of wind generation in £/kWh

Q is the capital investment in £/kW

r is the annual capital recovery rate

n is the wind turbine’s operating time in years

F is the power generation factor of the wind turbine, which can be determined by *equations 3.25*

$$\mathrm{F} = {}^{P_{wa}}/_{P_{wr}} \qquad (3.25)$$

Where P_{wa} is the wind turbine's annual mean output, P_{wr} is wind turbine's rated power output

By observing *equations 3.24*, it can be discovered that increasing the generation efficiency and reducing the investment can effectively reduce the wind generation cost.

Additional Reserve Cost

Integrating wind generation into the power system operation, amount of additional operating reserve will be required. Normally, the cost of reserve consists of two parts:

- The cost of spinning reserve

The spinning reserve is usually provided by the generators with low marginal costs, such as coal or gas units. In order to provide contracted reserve amount, these generators are working part-loaded, therefore the additional payment will be made to compensate their efficiency losses as they are working outside the optimal conditions.

- The cost of standing reserve

Conversely, the standing reserve is normally provided by high marginal price unit. The reserve level is determined by ISO according to the availability and price offers made by market participants as well as the price and availability of spinning reserves.

Electrical Network Reinforcement Cost

Many published papers [16, 6] show that high level wind penetration leading to additional investment in transmission and distribution network reinforcement. It always rest with the location of wind farm and the distance from wind farm to the demand.

In the past century, the development of the electrical network has been dominated by the following concept, with the favorable location and respected to safety primary energy resources, conventional generator provide the optimal cost-effective electricity. Hence the power network was developed hierarchically to transport the electrical energy from the conventional generators to the demand through the structure of transmission networks, distribution networks and “last-mile” network. The existed power network can only satisfy the conventional plants source well. However, wind is a kind of specific energy source; the location of wind farm primarily depends on the availability of wind. If the wind farm coincidently need to be located at weak side of transmission network (low voltage level, insufficiently line capacity), reinforcement of network will be needed for the energy delivery.

Re-dispatch Cost

As explained previously, the intermittent characteristic of wind will have significant impact on power system reliability when integrating into the system operation, especially with the high penetration level. In order to provide sufficient operating reserve that maintains the reliability, some conventional generators need to operate as part-loaded., and some generators will be used to provide standing reserve. And trying to engage more wind energy being used in the system operation, SO will change the schedule of system operation and some of the conventional generators will be cut. The additional cost is known as the re-dispatch cost.

3.4.6 Effect of Wind Energy on Power Market

From [3] there is good experience from Denmark, Spain, Ireland, and New Zealand with balancing wind power variations through forecasting and liquid day-ahead and balancing markets. [7]. For West Denmark, the balancing cost from the Nordic day-ahead market has been 1.4-2.6 €/MWh for 24% wind penetration of gross demand. (the penetration in the market is much lower, less than 55%)[8].

Wind integration through markets has many positive impacts. Markets can help managing larger balancing areas, and can pool balancing and flexibility bids. Wind power will also give rise to challenges in electricity markets regarding flexibility, capacity adequacy, and also regarding the participation of wind and solar generators to markets. There are two aspects of flexibility markets: 1) Long-term market signals must be sufficient to induce the needed flexibility to be built, and 2) Once built, the operational market must provide a sufficient revenue stream to ensure the financial viability of the flexible unit (or load). All of this should be accomplished in an economically efficient manner. [3]

3.5 Simple Model for Impacts on Transmission Capacity Consumption with Wind Energy

Similar to any other electricity sources, the outputs from wind power generators will increase the transmission capacity consumption of the existing power system. However, the wind is an inconsistent and intermittent energy source not the same as conventional power plants, which is discussed in section 3.4, the wind farm location depends on the availability of wind resource.

For example, UK is the country which possesses the most plentiful wind resource in Europe. According to the wind power development plan from UK governments, the majority of wind farm will be located in Scotland and the North of England. The integration of wind power generation in the UK system may require considerable reinforcement in the transmission network.

3.5.1 Simple Illustrative Example

A simple example is made to illustrate the impact of wind power on the transmission network. A 6-bus transmission power system was built with *POWERWORLD* Simulation. The structure is as following *Figure 3.7. Table 3.3* is the simulated power flow on each line and the percentage of the lines' capacities. This test system has 6 buses, 7 transmission lines, 6 load points and 4 conventional generators.

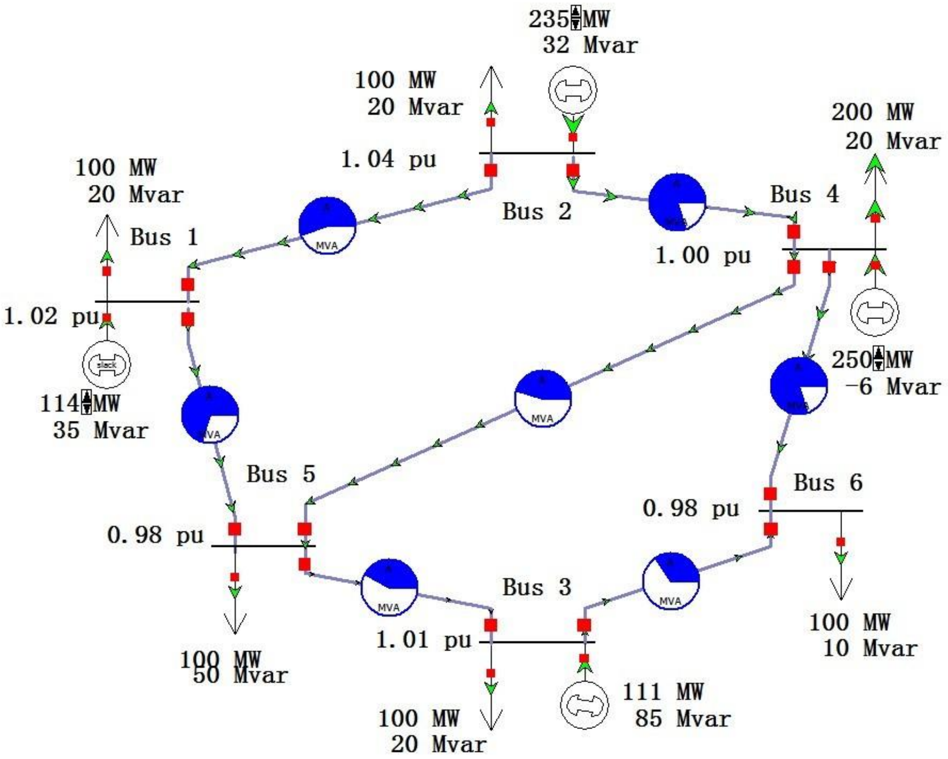

Figure 3.7 6-Bus System for Illustration

Table 3.3 Power Flow and the Percentage of Line Limit for No Wind Case

From Bus	***To Bus***	***MW***	***MVA***	***Line Limit MVA***	***% of Limit***
1	2	-55.1	55.1	100	56.3
1	5	69.2	70.4	100	70.4
2	4	78.5	79.7	100	79.7
3	5	-11.5	41.0	100	41.8
3	6	22.7	34.1	100	34.6
5	4	-44.9	45.0	100	45.8
6	**4**	-77.8	**79.5**	100	**79.6**

When wind penetration level is 8% (wind farm with average output of 50MW on bus 4), the total power output with wind farm will exceed the nodal demand on node 4 as shown in *Figure 3.8*. Therefore, compared with *Figure 3.7*, bus 4 will export more electrical power to the network, and the increasing output from wind farm will consume the line capacity and eventually cause transmission loading to reach its capacity limits as shown in *Figure 3.8*. This effect is especially significant on the line connecting bus 4 and bus 6. Meanwhile some of the energy generation from conventional generator are displaced by wind power, and compared with no wind scenario, the total consumption on transmission capacity still have a change.

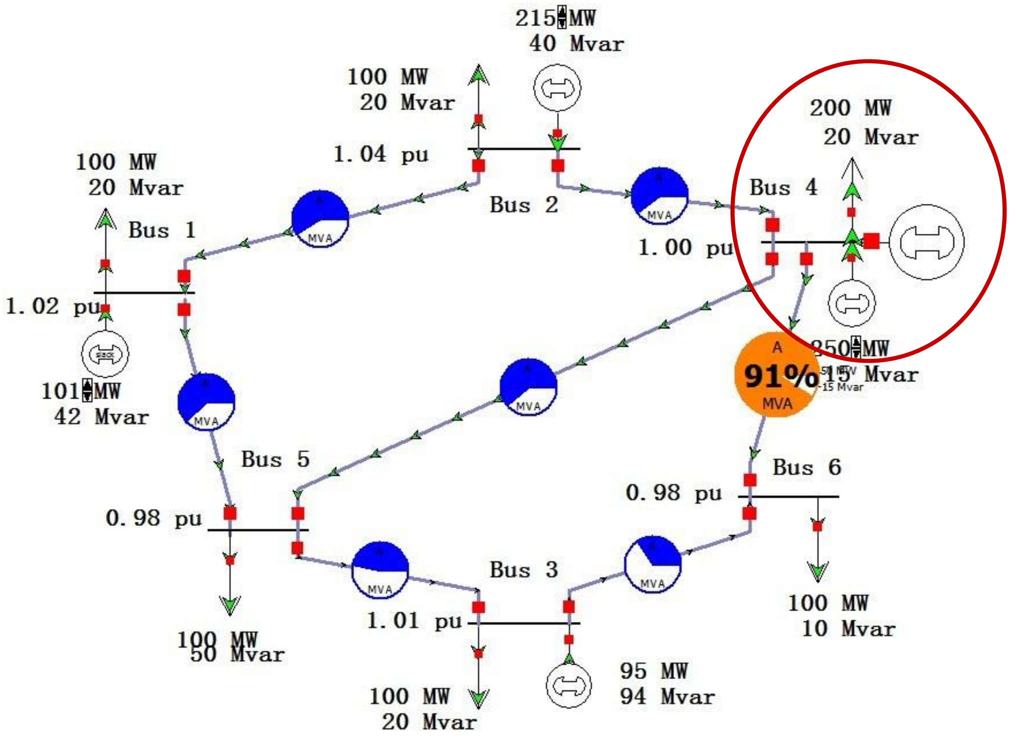

Figure 3.8 6-Bus System adding one Average Output 50MW Wind Farm on Bus 4

Table 3.4 Power Flow and the Percentage of Line Limit adding one average output 50MW Wind Farm on Bus 4

From Bus	***To Bus***	***MW***	***MVA***	***Line Limit MVA***	***% of Limit***
1	2	-58.8	58.9	100	60.2
1	5	59.3	61.9	100	61.9
2	4	55.1	60.1	100	60.1
3	5	17.3	46.0	100	46.6
3	6	12.1	33.6	100	34.4
5	4	60.3	61.1	100	62.5
6	**4**	-88.3	**91.1**	100	**91.1**

In reality, the distribution lines and some transmission lines are designed to provide connection for the power demands. Their capacities are corresponding to the size of demands, therefore when wind farms are coincidently connected to these buses, related lines will be easier to overload than others, which is shown in the example.

3.5.2 The Effect of Wind Farm Location

This section aims to discuss the effect of wind farm location on the usage of line capacity with simple 6-Bus test system.

No Wind

In section 3.5.1, the structure of a 6-bus transmission power system is shown as *Figure 3.7. Table 3.3* is the simulated power flow on each line and the percentage of the lines' capacities.

Single Wind Farm

Figure 3.9 is the simulation results when a wind farm with an average output as 50MW is added to bus 5 on the *6-Bus* test system. The line from bus 4 to bus 6 is highlighted in following figure and indicates that the transmission capacity on this line almost reaches its capacity limit when the wind farm is connected to bus 5.

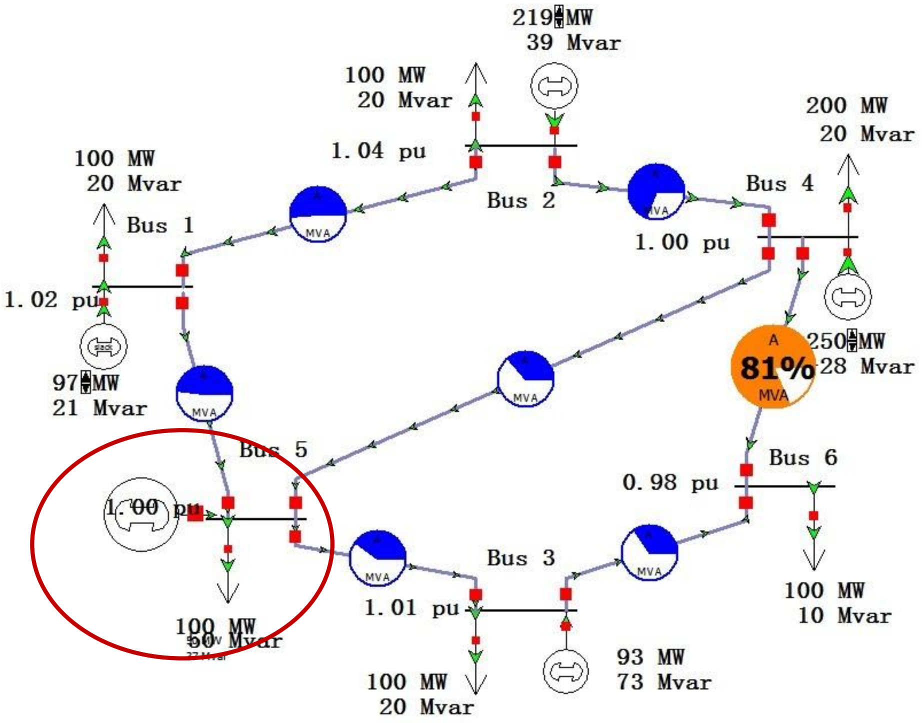

Figure 3.9 6-Bus System add one 50MW wind farm on bus 5

Table 3.5 shows the power flow and percentages of lines' capacities with single wind farm connected to the system.

Table 3.5 Power Flow and the Percentage of Line Limit adding one Average Output 50MW Wind Farm on Bus 5

From Bus	*To Bus*	*MW*	*MVA*	*Line Limit MVA*	*% of Limit*
1	2	-51.4	51.4	100	52.4
1	5	48.0	48.0	100	48.0
2	4	66.5	69.1	100	60.1
3	5	-28.6	39.1	100	40.1
3	6	21.2	33.8	100	34.3
5	4	32.2	35.8	100	36.7
6	**4**	-79.2	**81.1**	100	**81.1**

Two Wind Farms

As shown in *Figure 3.10*, the second wind farm with an average output as 100MW is connected to bus 6. The load from demand side on bus 6 is 100MW, in this simulation, the installed 100MW wind farm can efficiently support the local power demand and contribute in reducing the transmission capacity consumption.

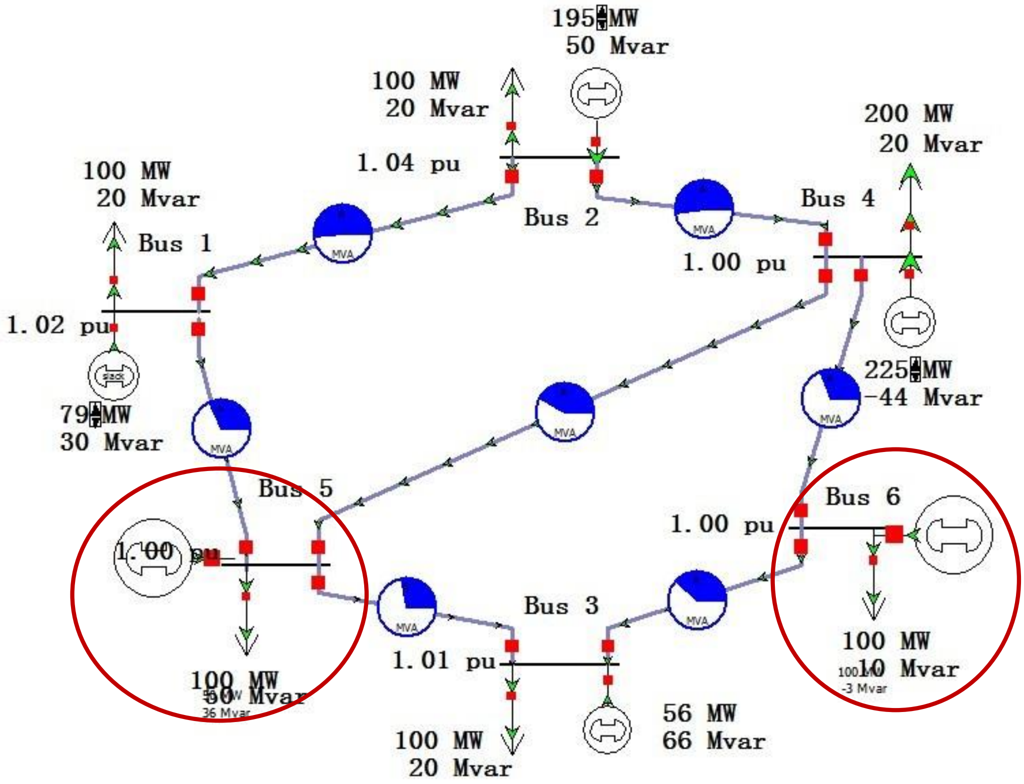

Figure 3.10 6-Bus System adding Two Wind Farms on Bus 5 and Bus 6

With the installation of the second wind farm, there is a reduction of the loading consumption on the transmission line from bus 4 to bus 6, which is congested in the previous scenario. The power flow and the percentage of line limits for 2 wind farms connected are shown in following table.

Table 3.6 Power Flow and the Percentage of Line Limit for 2 Wind Farms (Adding Wind Farms to the System on Bus 5 and Bus 6 respectively)

From Bus	*To Bus*	*MW*	*MVA*	*Line Limit MVA*	*% of Limit*
1	2	-51.4	51.4	100	52.4
1	5	30.1	31.6	100	31.6
2	4	42.5	52.0	100	52.0
3	5	-16.9	26.4	100	27,7
3	6	-27.6	37.3	100	38.3
5	4	-37.5	41.8	100	42.7
6	**4**	-27.5	**30.5**	100	**31.4**

Based on the simulation results and discussions conducted in following *Figure 3.11*, generally, with increasing number of wind farms accommodated into the power system, the usage of the lines’ capacity may be decreased. That is because the wind farms can support the local loads and reduce the power transmission requirements from the network. However the results presented in *Figure 3.11* also indicate, some transmission lines will bear a significant increase in power flow due to the connection of wind farm. The impact of wind generation on the power flow and associated transmission capacity consumption varies from line to line. Elements such as the individual line’s capacity, location of wind farms and the power flow limitation on the transmission line need to be carefully considered.

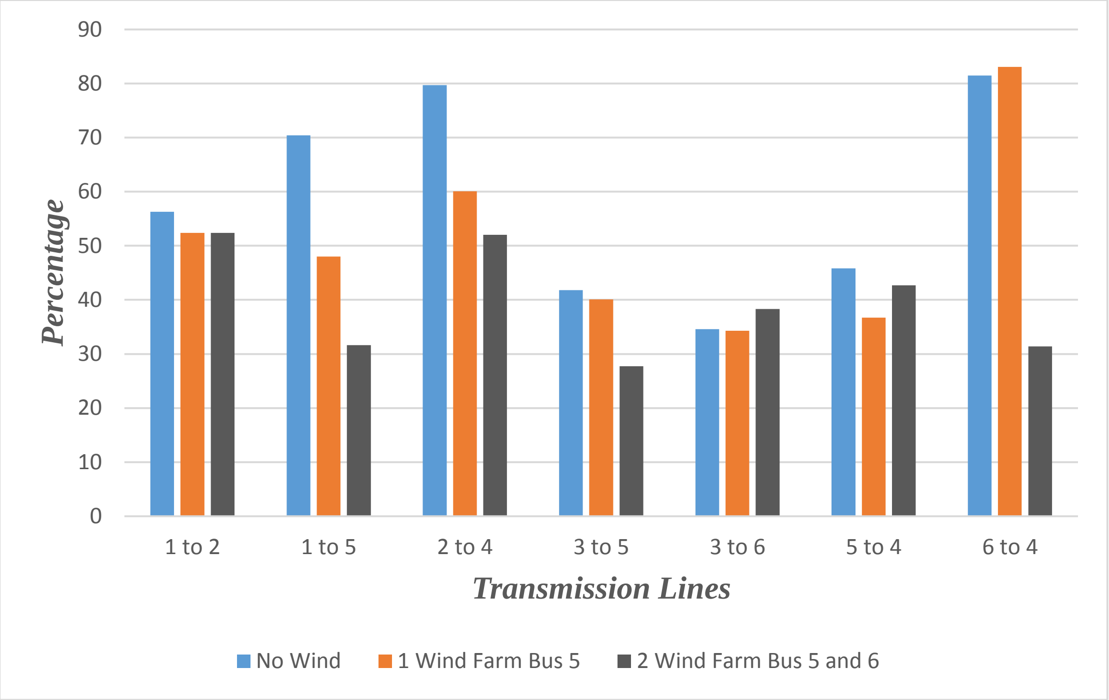

Figure 3.11. The Loading as Percentage of Transmission Lines' Capacity for Three Different Scenarios

3.6 Summary

The (future) portfolio of generation plants, transmission capacity and operational practices are all important aspects for the wind integration study. This chapter emphasize the related issues caused by wind power generation and discusses the approaches to evaluate the impact of wind power generation integration. The discussion is focused on following areas:

Optimal displacement of conventional generators

As wind power output continues to be the "must-take" generation, once the wind penetration level is significant, certain amount of displacement needs to be conducted on conventional generation unit to accommodate the output from wind power. Since the very different characteristic between wind power and conventional generation, such displacement will create impact. The study reported in this thesis focuses on the impact on operation methods and power market.

Impact on generation system reliability evaluation

It is generally agreed that the intermittent nature wind will lead to fluctuating generation output and jeopardize the generating system reliability. The reliability study reported in many paper uses modified Monte Carlo simulation by combining the simulated wind turbine output and simulated conventional generators using system duration sampling technique. Additional reserve requirement compensate the fluctuation from wind are needed to maintain the reliability level of the existing power system,.

Impact on transmission capacity consumption and operation cost

When the wind power penetration become high, it become necessary to determine whether the existing capacity of a line is sufficient to transport the power from wind especially during the peak output period or whether it is necessary to conduct the additional investment on network reinforcement since the wind farms output is highly intermittent. This chapter discusses the impacts that wind power output will have on the power flow, the scheduling and dispatch of conventional generation, and operational costs of the system.

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[29] Dzobo, O., C.T. Gaunt, and R. Herman, *Investigating the use of probability distribution functions in reliability-worth analysis of electric power systems.*

Chapter4

Design and Operation of Power System with Wind Power Integration

4.1 Introduction

Wind power is introduced in *Chapter 2*, it is the most promising renewable energy source for the sustainable development due to its advanced and mature technologies. Wind power generation is inconsistent and intermittent energy source, the wind speed variation causes the fluctuation of wind power output. High wind power penetration can lead to high risk levels of the power system reliability. *Chapter 3* presented the review of study integrating wind power generation into the power system and briefly introduced the related notion of impacts on system operation. This chapter will use the simulation models and simulated details to explain the impacts.

This chapter presents the simulation research with a dynamic wind power generation model integrating into the *IEEE 14-bus* system. The dynamic wind power generation model was introduced in *Chapter 2,* with the Weibull Distribution Function being used to analysis the wind distribution and the Monte Carlo simulation method is applied to consider random output of wind power generation. The average mean wind speed is set to 7 m/s, and the Weibull shape parameter is defined as 2. The output of the wind farm model have 240 random values to generate 240 wind speeds which are transferred to the wind generation outputs. Wind is a kind of free energy, the “must-take” wind power generation is integrating into the system operation. The impacts on the combined conventional generators, the transmission lines and the operation costs will be tested under different system operation conditions (constrained and unconstrained).

The nodal prices ensure a competitive market and efficient allocation while the access charge allows the transmission provider to recover the full embedded cost of the transmission system. Locational Marginal Price is focused in the simulation, using the wind power generation model and a small test power system, with different wind power penetration levels. The impacts on each transmission line will be easier to understand. For example, the tendency of the power flow on each line, the trend of the LMPs, the output changes of each generator with the installed wind generation integrating into electric network as well as congestion adding on the transmission lines, the above areas will be compared. The *IEEE 14 bus* system will be used in this chapter, its aim is to maximize the use of wind power generation to meet grid security.

Firstly, the content of the wind power integration study and flow chart for this research will be presented in *Section 4.2*, *Section 4.3* is a description of each core element for this simulation study. *Section 4.4* introduces the dynamic wind power generation model which has been discussed in *Chapter 2* for wind power integration study. In *Section 4.5*, three comparison scenarios showing simulation results are presented in graphical form to explain the effects.

4.2 Content of the Wind Power Integration Study and Flow Chart

A full wind power integration study is a complicated process, it is impossible to take into all possible related aspects. An overview of a comprehensive study integrating wind power into power system is given as a flow chart in *Figure.4.1*. [4] It shows the content of wind power integration study, the details include integrating wind power generation on power system operation (scheduling and dispatch), power system adequacy (resource), power flow and the dynamic/transient conditions.

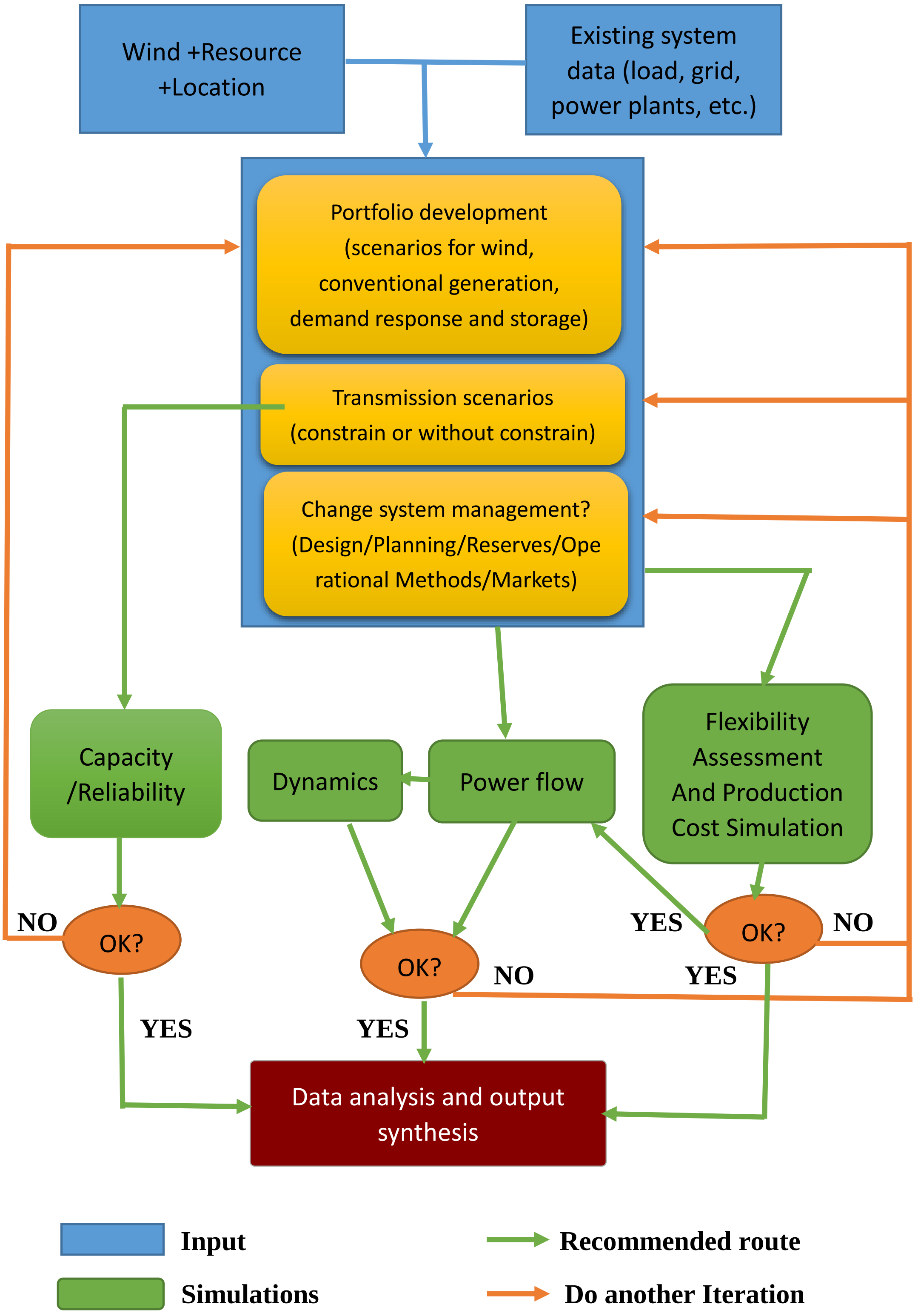

Figure. 4.1 Wind Integration Study Components [4]

4.3 Description Each Core Elements of Simulation

4.3.1 Production Cost Simulation

Simulation of the production cost is the main research vehicle used to assess the impacts of wind power integration. The simulation are always linked to operation flexibility, operating costs, and emissions. It involves integrating the wind power and optimizing the scheduling of load and generation resources to meet expected demand over various time frames, as well as the need to consider the system operating conditions, such as constraints on system, physical, and operational. Production cost simulation is comprised of Unit Commitment and Economic Dispatch (UCED), to simulate optimal short-term energy balance in the power system. The study in this chapter is connected with dispatch.

Most results on production costs are based on comparing costs of system operation without wind and adding different amounts of wind. In the simulation model, the constraints in the optimization ensure the physical feasibility of the short-term operational plans and reliability under uncertainty. To assess the true capacity of the system to respond to changes, the limitations and constraints of the system must be accurately modelled. Wind power also introduces additional uncertainty, which needs to be considered. At higher wind penetration levels, the day-ahead uncertainty from wind power will get larger than uncertainty from loads.

4.3.2 Flexibility Assessment

Flexibility can be described as the ability of the power system to respond to changes in different time scales. The capability to respond to these changes is limited by physical constraints on generation resources and the power system in general. [10] When we consider the wind power integration, flexibility is required to manage the resulting variability and uncertainty to ensure the balance between supply and demand, security of system operation, and reliability constraints of system. Typical sources of flexibility include conventional generations dispatched up and down and power market strategies. Meanwhile, wind power can also be a source of flexibility. However, as this requires energy to be held back to enable reserve and/or frequency response, wind power could be an expensive one.

From [10] flexibility needs can be divided into planning and operational horizon flexibility. Planning horizon is focused on how to determine the future need for flexibility and how to get it. It is needed to build new power stations or design power market so as to incentivize all flexibility to be used by system needs. Operating horizon is focused on how best to use the flexibility that is available from installed generation/storage/demand side. That will include Unit Commitment and possibly some form of stochastic Unit Commitment is needed in order to minimize the risk of getting caught short.

So far, flexibility assessment in the operating horizon is generally conducted implicitly within production cost simulations. Production cost simulation is comprised of UCED. Various methods have been proposed to assess the adequacy of power systems and develop adequacy metrics with respect to their flexibility. In this thesis, a proposed planning horizon of flexibility in power market design will be introduced in chapter 6, operational horizon flexibility will be used in this method in order to enhance the wind energy usage in power system operation. In this chapter, only the economic dispatch issue will be investigated.

4.3.3 Impacts on Conventional Generations and Transmission Grids: Losses and Bottleneck Situations

Transmission planning with wind power integration is becoming an iterative process consisting of generation expansion planning, economic-based transmission planning, system operation reliability analysis, and wind power integration studies. [4]

The variability and uncertainty of wind power will impact the operation of the conventional power plants. Changing the output level of the conventional generator, additional ramping, and increasing amount of starts/stops will incur costs. To assess the impact of integrating wind power on the operation of power systems, simulation model runs are made that optimize the dispatch of all power plants to meet varying load. Most results are based on the system operation without wind and then adding different wind penetration levels.

In some cases the impacts of wind power integration on the transmission losses and grid bottleneck (constraint) situations can be significant and so may need to be assessed. The changes of capacity on the transmission lines as a result of increasing wind power production can bring about power losses, as well as benefits or enhances in bottleneck situations of the transmission system. As the simulation results in *section 3.5*, depending on its location, wind power may at its best reduce bottlenecks, but when changed to another location, may result in more frequent bottlenecks.

4.3.4 Locational Marginal Prices

There are few references which describe the relationship between the wind source and the electricity prices. With the unpredictability of wind energy, the output of a wind turbine fluctuates. Even though the technical literature offers a number of studies providing the influence of wind power generation on energy prices [6] [10], there is still a lack of mathematical models able to quantify the associated impact.

In paper [9], the author uses nine months of actual data and simulated the LMP prices with three different levels of generation capacity factors for three different percentages of wind energy penetration. In his report, it is interesting to note that the highest LMP values are slightly off peak. The study presented [5] shows the impact of wind power on LMPs, wind power is modelled as negative loads in the market and is characterized by historical data records. A number of wind power plants are located at different buses as demands. The paper provides a methodology that for any given demand level it simulates the effect of a variety of wind power conditions on market clearing outcomes, and thus allows a statistical characterization of locational marginal prices (LMPs) throughout the network.

[1] uses a model which accounts for the uncertain character of wind by using a modelling framework based on stochastic optimization to simulate market barriers by means of a bi-level structure, and considers the financial risk of investments in transmission through the conditional value-at risk. In [2], a mathematical program with equilibrium constraints (MPEC) is introduced to seek to identify the optimal wind projects to be developed and the required network reinforcements.

In this chapter the power flow and LMPs will be the signals for the electricity market participants to investigate impact caused by integrating wind power generation into the electric networks. Different wind power penetration levels effect on the power system will be studied; by considering the changing of power flow and LMPs under different operating conditions of the power system. The impacts on power system operation costs will be analyzed as well.

4.4 Illustrative Example

As introduced previously in this chapter, in the designed case study is a wind farm simulated with different integration penetration levels. The following example will focus on the system simulation with the cooperation of wind power generation and conventional generation under different system operating conditions (with constraints and without constraints). Two wind penetration levels are employed in this section.

For this wind turbine model the Weibull Distribution Function will be used to analyse the problem of wind distribution and Monte Carlo simulation method is also introduced to simulate the output of wind power generation. The output of the wind farm using the model introduced in *Chapter 2,* have 240 random values to generate 240 wind speeds. The computed wind power output is shown in *Figure 2.14*.

4.4.1 Data and Assumptions for the Test System

Results from the case study based on test *IEEE 14-bus* system as shown in *Figure 4.2* and the *MATPOWER* simulation package will be used to run *ACOPF* simulation. The basic system data are shown in *Table 4.1*. A five generators system is used to analyse the effects due to wind power integration with changing system operating situations. The power flow on each transmission lines and LMPs on each bus are calculated using standard OPF formulation of the *MATPOWER* simulation package. Using the assumption that pool-based electricity market is perfectly competitive, offers submitted by generating units correspond to their marginal costs of energy production.

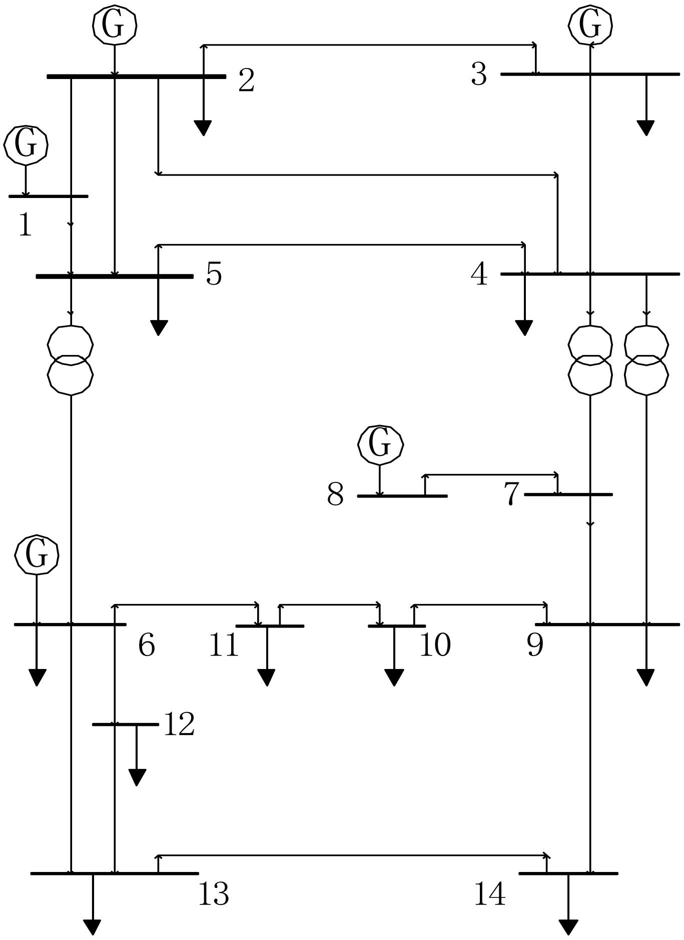

Figure 4.2. IEEE 14-Bus System Diagram

Table 4.1. Test System Data

Generators	**5**
Buses	14
Load points	11
Total generation capacity	772.4MW
Fixed load	259.0MW

The wind power penetration level in this thesis is defined as the ratio of the installed wind generation capacity to the total-installed system generation capacity (includes installed wind capacity and other conventional generation capacities). The wind power output is considered as must take units; as a consequence, a certain amount of conventional generating units will have to be displaced. In this case study, the wind penetration levels are 5% (*Figure 4.3*) and 10% (*Figure 4.4*), and accordingly, the installed wind generation capacity is 30 MW and 60MW, respectively. This means the displacement of conventional generation is a maximum as 30 MW and 60 MW respectively.

The average mean wind speed is set to 7 m/s, and the Weibull shape parameter is defined as 2. The wind speed variations are represented by the Weibull probability distribution. Then, the power output of the wind turbine can be obtained by using wind speed profile and Monte Carlo simulation, which were presented in *Chapter 2*.

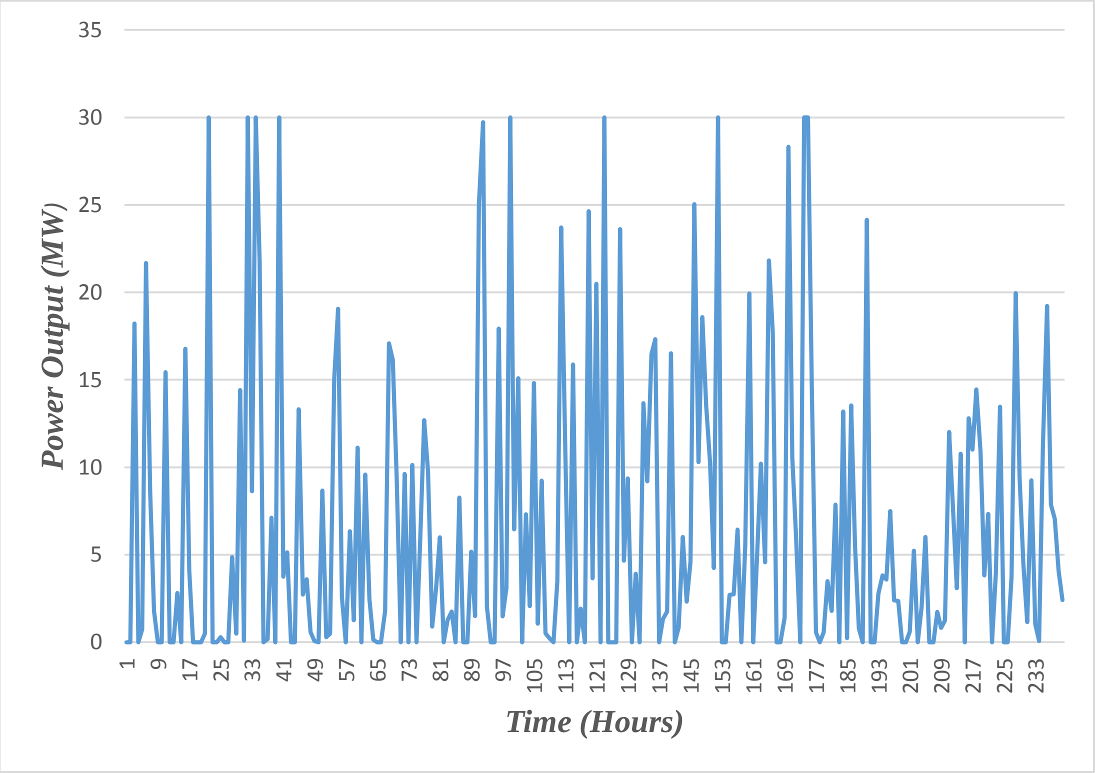

Figure 4.3. Snapshot of Simulated Wind Farm Power Output

(240 hours, maximum 30MW)

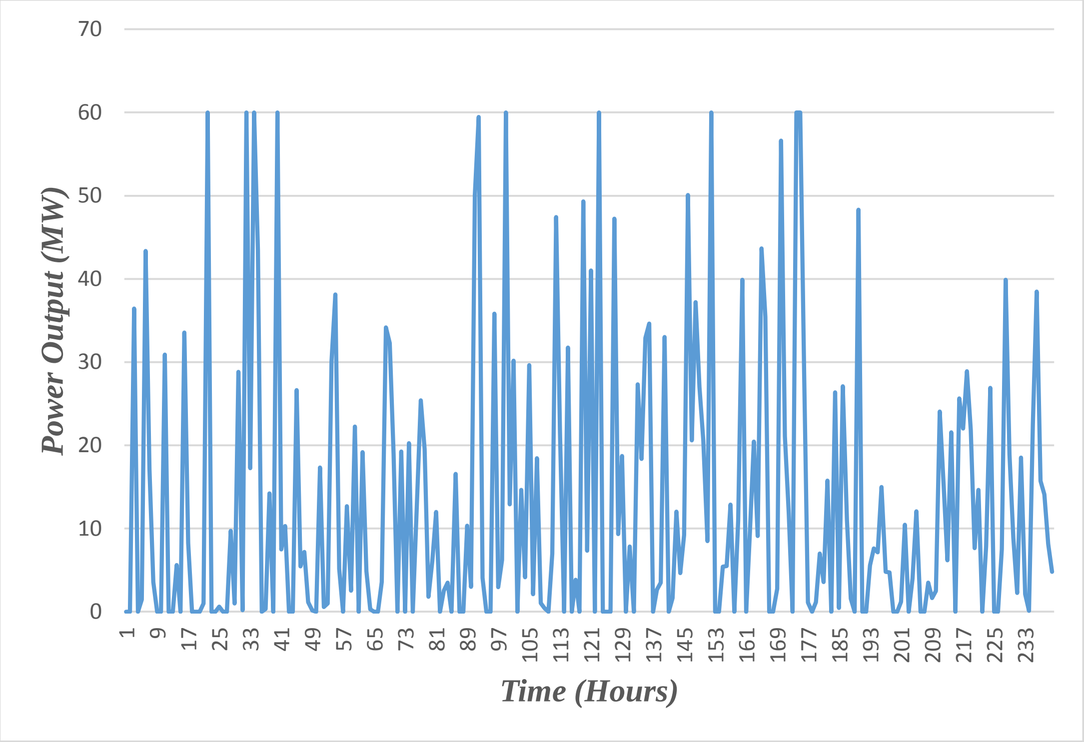

Figure 4.4. Snapshot of Simulated Wind Farm Power Output

(240 hours, maximum 60MW)

4.5 Results and Discussions

4.5.1 Scenario 1: Base Case for an Unconstrained Network without Wind Power Integration

The network operation without wind power generation is being used as the base case for comparison study. *Table 4.2* is the optimal power flow on each branch when the power system is operating without congestion, equation and in this scenario, wind power generation is not included in.

Table 4.2. The Optimal Power Flow on Each Branch without Wind Farm System Operation without Congestion

Branch	***From Bus***	***To Bus***	***Active Power Flow (MW)***	***S(MVA)***
1	1	2	125.88	**126.1135**
2	1	5	69.74	**70.16531**
3	2	3	38.33	**38.3791**
4	2	4	54.87	**54.87117**
5	2	5	45.05	**45.12861**
6	3	4	13.5	**13.89612**
7	4	5	-41.95	**43.23754**
8	4	7	22.54	**22.92729**
9	4	9	18.23	**18.29021**
10	5	6	51.53	**53.46656**
11	6	11	12.83	**14.02674**
12	6	12	14.44	**14.91601**
13	6	13	23.23	**24.64953**
14	7	8	-26.62	**28.20803**
15	7	9	49.16	**49.33252**
16	9	10	19.97	**20.13749**
17	9	14	17.93	**18.13203**
18	10	11	0.85	**3.601798**
19	12	13	-1.90	**2.50035**
20	13	14	7.46	**8.175476**

In this test system, the generation costs of generator 3(on bus 3), generator 4 (on bus 6) and generator 5 (on bus 8) are the most expensive with the same values; generator 1 (on bus 1) and generator 2 (on bus 2) are much cheaper than others;

Table 4.3. The Data of IEEE 14-Bus System with OPF Unconstrained

Bus No.	***Generation(MW)***	***Load(MW)***	***Lambda(£/MVA-hr)***
1	**195.62**	-	**36.835**
2	**36.81**	21.70	**38.403**
3	**0.00**	24.20	**39.805**
4	**-**	67.80	**40.572**
5	**-**	17.60	**40.090**
6	**10.17**	11.20	**40.203**
7	**-**	-	**40.539**
8	**26.62**	-	**40.532**
9	**-**	29.50	**40.539**
10	**-**	19.00	**41.035**
11	**-**	13.50	**41.097**
12	**-**	16.10	**41.615**
13	**-**	13.50	**41.324**
14	**-**	24.9	**42.375**
Total	**269.23**	259	-
Total Cost	-	-	***8113.94£/hr***

Table 4.3 shows the output of each conventional generator with OPF. In this case, because of high generation cost, output of generator 3 connected on bus 3 is almost equal to zero. The LMP value on each bus is shown as well, the differences of price in spot market are due to the lines losses in the unconstrained system. Total generation costs of the base case is 8113.94£/hr.

The LMPs on each bus are graphical displayed in *Figure 4.5*, the prices on each bus in the system are due to the cost of energy plus the cost for sending the energy across the transmission system. So variable losses causing the different prices on each node.

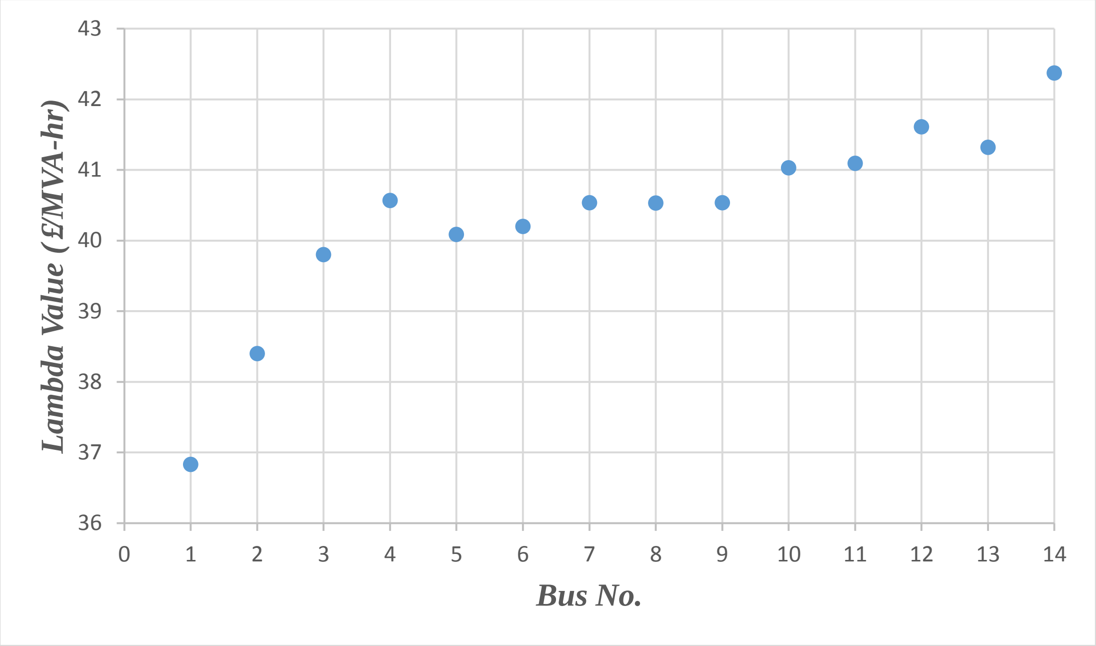

Figure 4.5. Snapshot of Simulated Lambda (£/MVA-hr) Value on Each Bus

4.5.2 Scenario 2: Effect of Different Wind Power Penetration Integration under Unconstrained Network

The wind farm installed generation capacity 30 MW (*Figure 4.3*) is 5% wind power penetration and the wind farm installed generation capacity 60 MW (*Figure 4.4*) is 10% wind power penetration will be introduced into the system operation to displace the conventional generator on bus 3 respectively. The aim of the simulations is to assess the impacts on conventional generators and transmission system due to wind power generation integrating into the power system. So in this test study, wind turbine is assumed that wind farm owners offer their energy production and the price is equivalent to zero. In this way the wind farm can be treated as firstly used generation in the power market. The cases in this scenario are operating with unconstrained network.

In the diagrams to follow, the blue curve is the result of the base case mentioned in *section 4.5.1*. The orange curve and grey curve represent the 'generator' outputs with 5% and 10% wind penetration respectively, with the network transmission constraints ignored. The green curve is the output of the wind generator (30MW).

Figure 4.6 are the results of generator 1' outputs compared under three different system operating conditions, unconstrained network without wind power, with integration of 5% wind power penetration and with integration of 10% wind power penetration.

Wind power output is regarded as "must-take" energy, once the wind penetration level is significant, one of the major impacts of wind integration on generation system is that its output will lead to reducing energy from conventional generator to maintain the generation-demand balance. It is very clearly shown in *Figure 4.6,* with the increased wind power penetration integrated into the test *IEEE 14-bus* system, output of generator 1 will decrease, and the correlation coefficient between these two simulated results will be more precise.

Figure 4.7 is the compared simulation results for generator 2, which yields the same conclusion as generator 1' results. *Figure 4.9* and *Figure 4.10* explain similar changes for generator 4 and generator 5 respectively. During the whole simulation process, all of the "zero price" wind energy will be accepted by the system operator. In *Figure 4.8,* the yellow curve is the output of wind farm whose installed generation capacity is 60 MW, and the green one is the output of wind farm installed generation capacity is 30 MW.

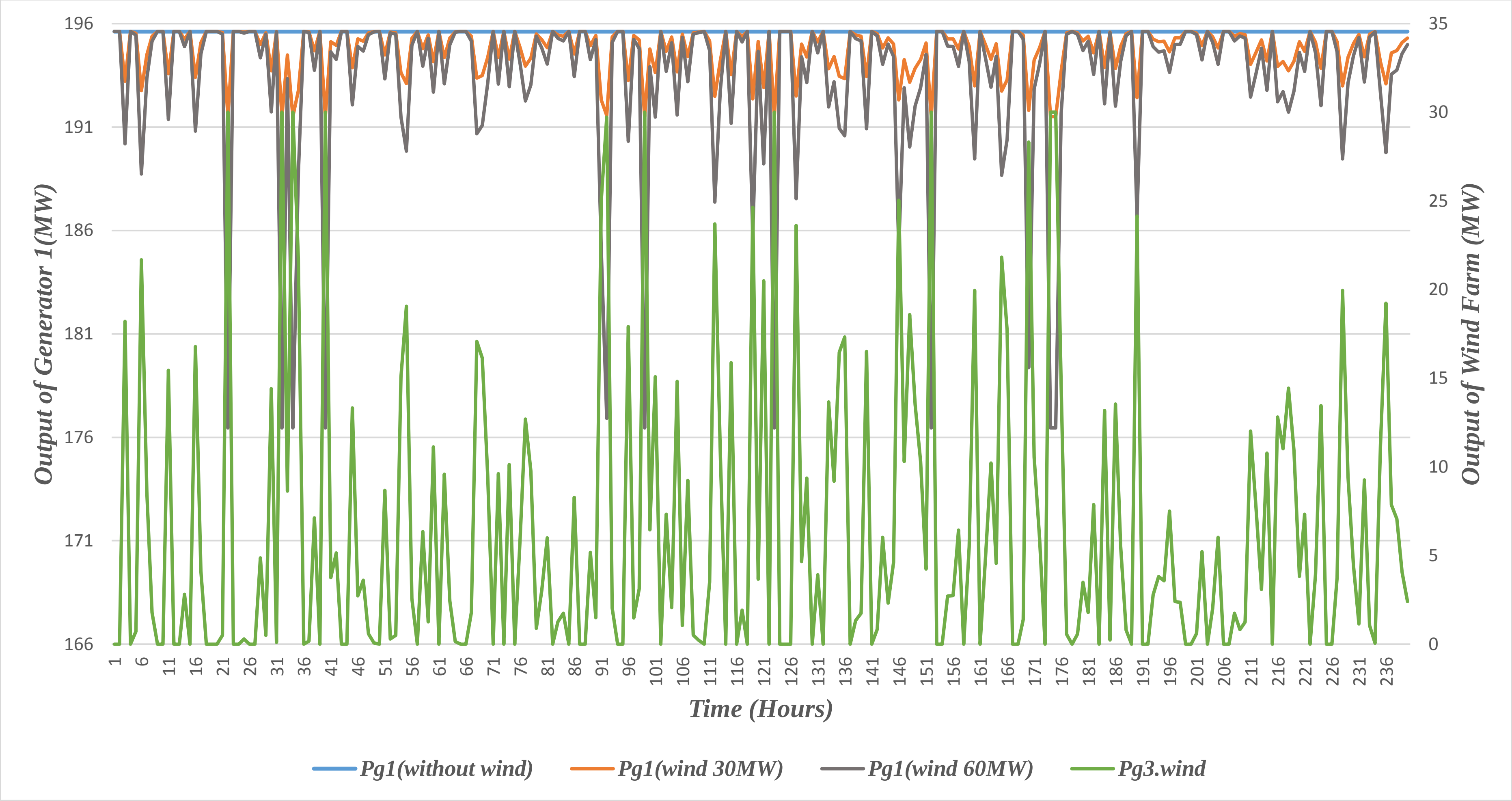

Figure 4.6. Snapshot of Simulated Generator 1's Outputs with Different Wind Power Penetration

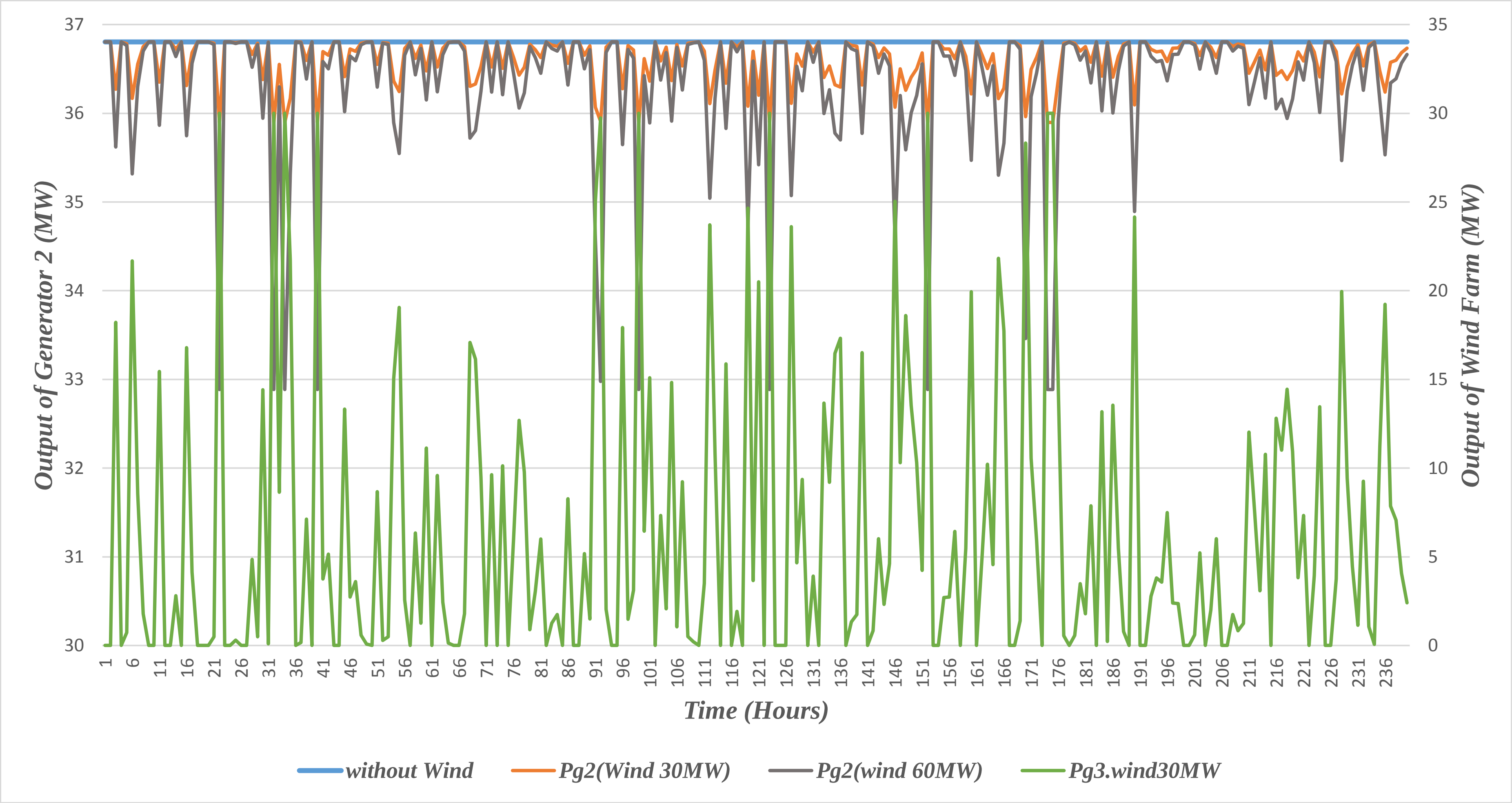

Figure 4.7. Snapshot of Simulated Generator 2's Outputs with Different Wind Power Penetration

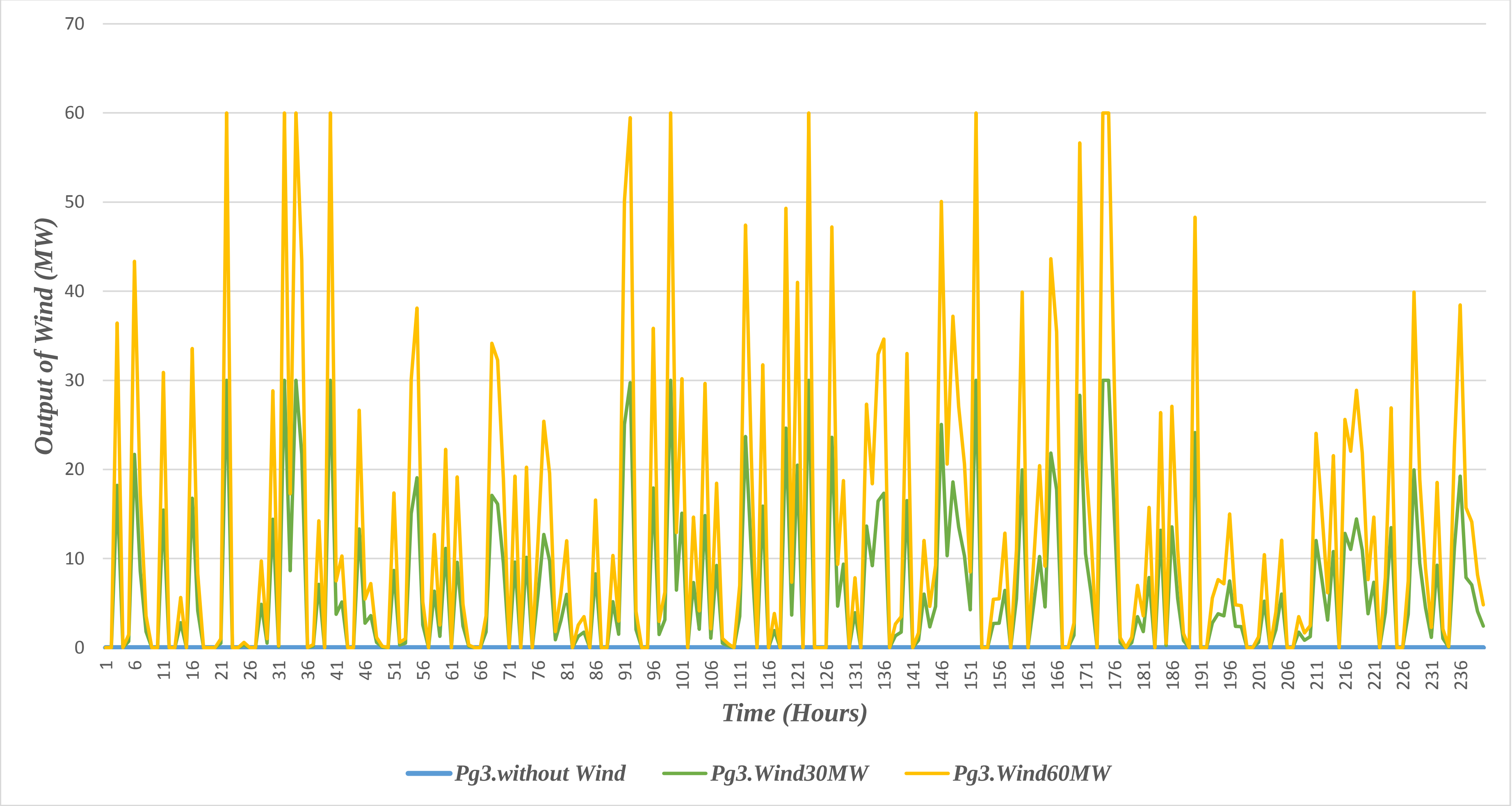

Figure 4.8. Snapshot of Simulated Generator Located on Bus 3's Outputs with Different Wind Power Penetration

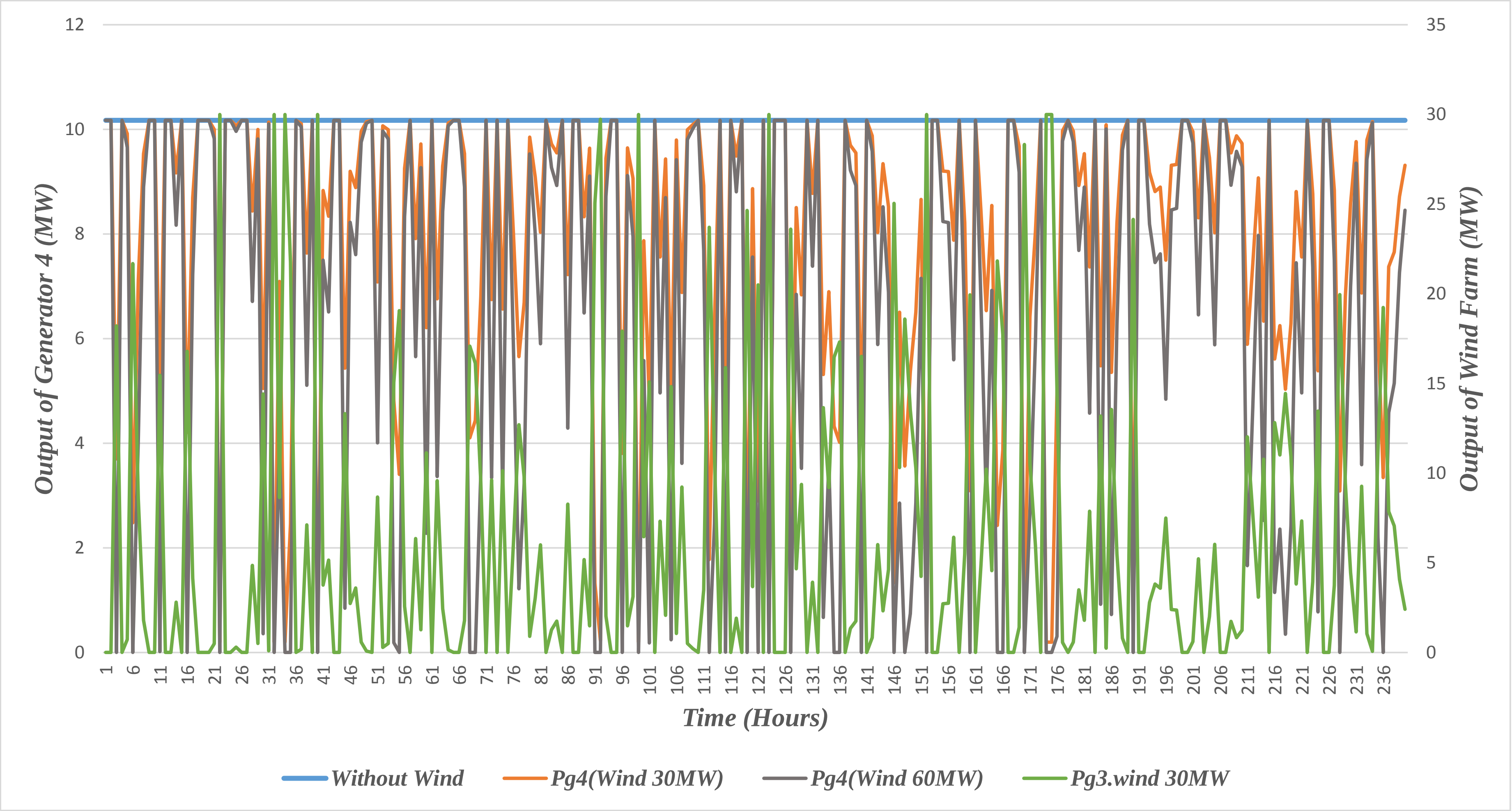

Figure 4.9. Snapshot of Simulated Generator 4's Outputs with Different Wind Power Penetration

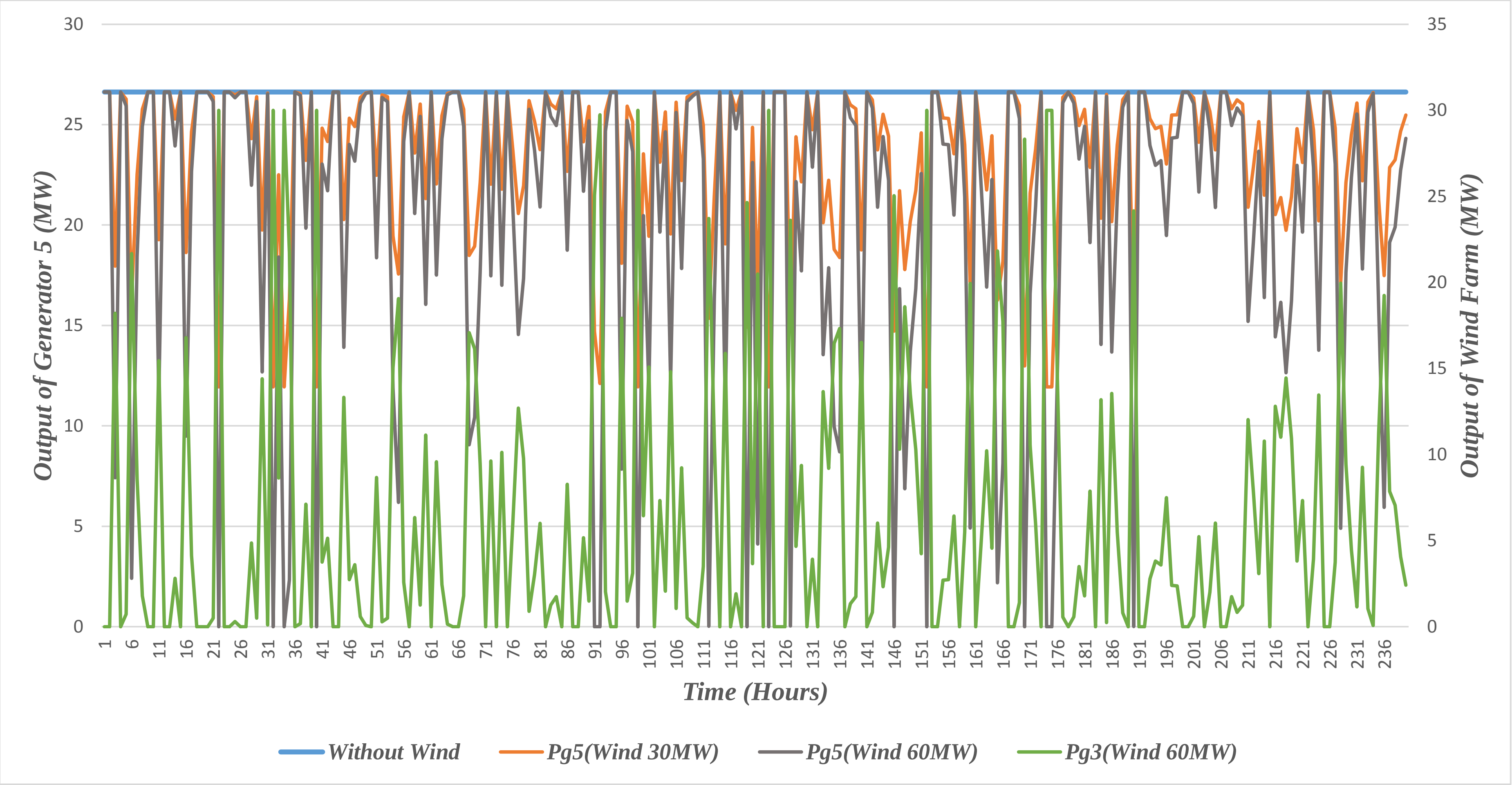

Figure 4.10. Snapshot of Simulated Generator 5's Outputs with Different Wind Power Penetration

Consideration of electricity market naturally leads to the notion of *locational marginal pricing* of electricity. According to which the electricity prices at each node of the system should be different. These differences stem from the active power losses and network bottlenecks (congestion), which are discussed in *Chapter 3*. The performing analysis in this section is intended to evaluate the random behavior of the electricity price in terms of expected value and volatility altered by the potential uncertainty of wind generation.

In this scenario, the network absorbs the amount of wind energy that can be transferred from node 3 to the rest of buses in the system. On the bus 3 there is a load of 24.2 MW, and as a result, wind farm supports this whole load, and the effect of wind generation on LMPs becomes *locally* relieved. As shown in *Figure 4.11,* with the increasing of wind power penetration, the LMP on bus 3 will decrease.

In unconstrained network, integrating “must-take” wind power, the output of conventional generator will be reduced to maintain the generation-demand balance. *Figure 4.12* is the simulated lambda (£/MVA-hr) on Bus 1 with different wind power penetration, the results of three simulation conditions are compared, unconstrained network without wind power integration, 5% wind power penetration integration and 10% wind power penetration integration. In *Figure 4.12,* it shows that, with the increasing wind power penetration, LMP on bus 1 will decrease, and this tendency is due to the output of generator 1’s reduction in output. The performances of simulated results are similar in *Figure 4.12*, the variation tendency of LMPs on bus 2(*Figure 4.13*), bus 6(*Figure 4.14*) and bus 8(*Figure 4.15*) are very similar.

Operating with an unconstrained network as in this test system and because of increasing free wind energy, this leads to a sharp decrease on the value of the corresponding LMPs for each bus.

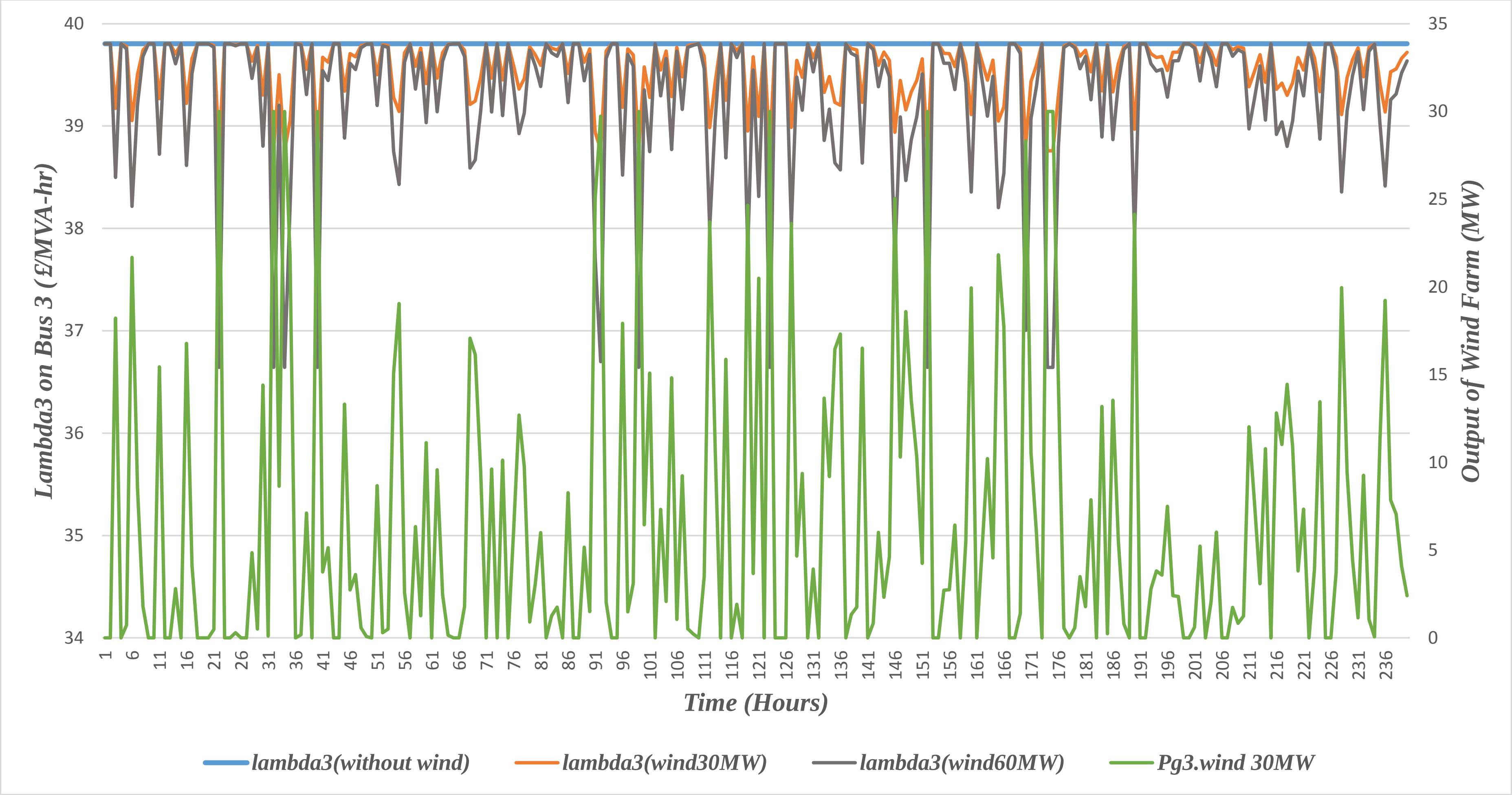

Figure 4.11. Snapshot of Simulated Lambda (£/MVA-hr) on Bus 3 with Different Wind Power Penetration

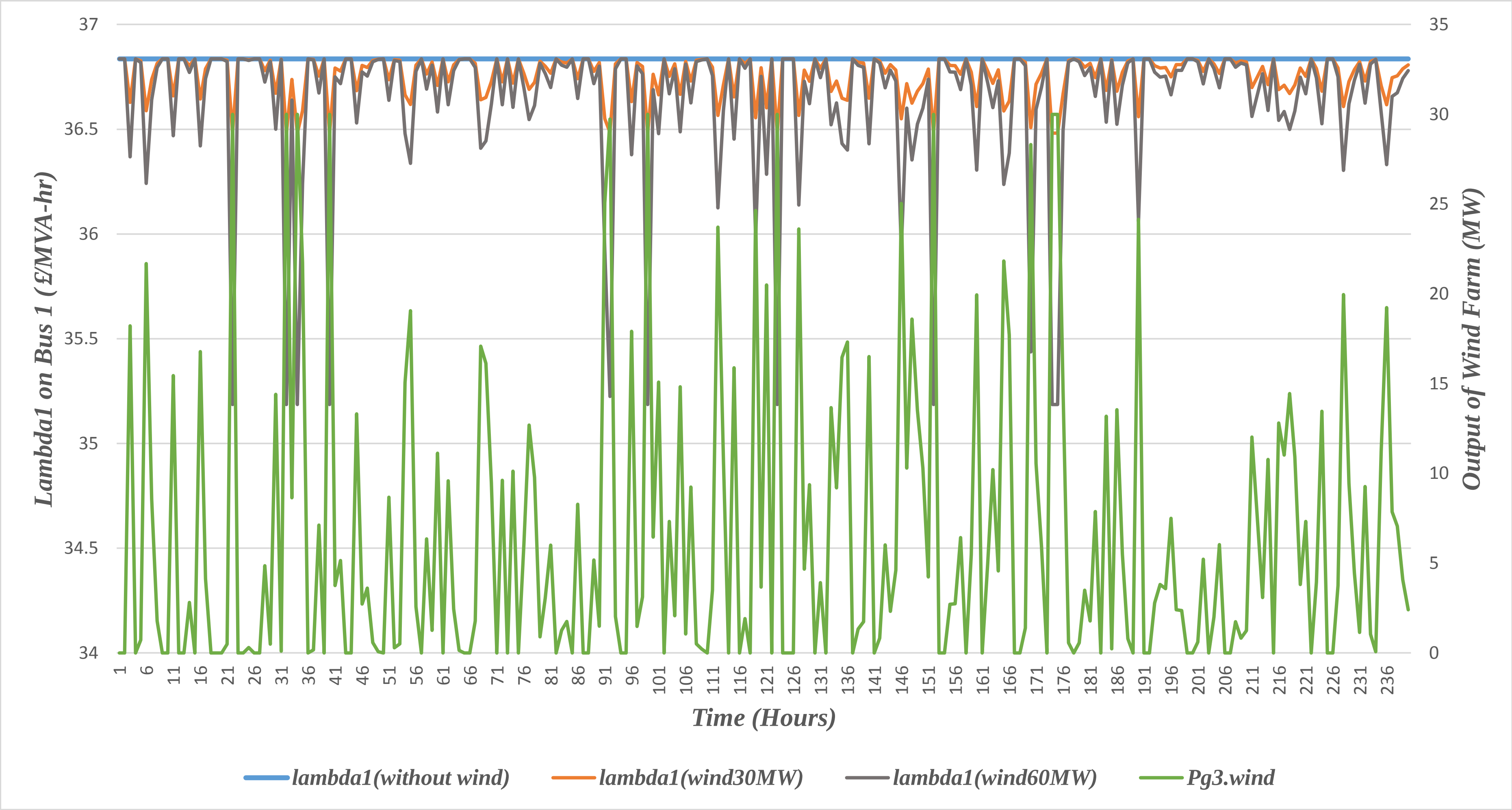

Figure 4.12. Snapshot of Simulated Lambda (£/MVA-hr) on Bus 1 with Different Wind Power Penetration

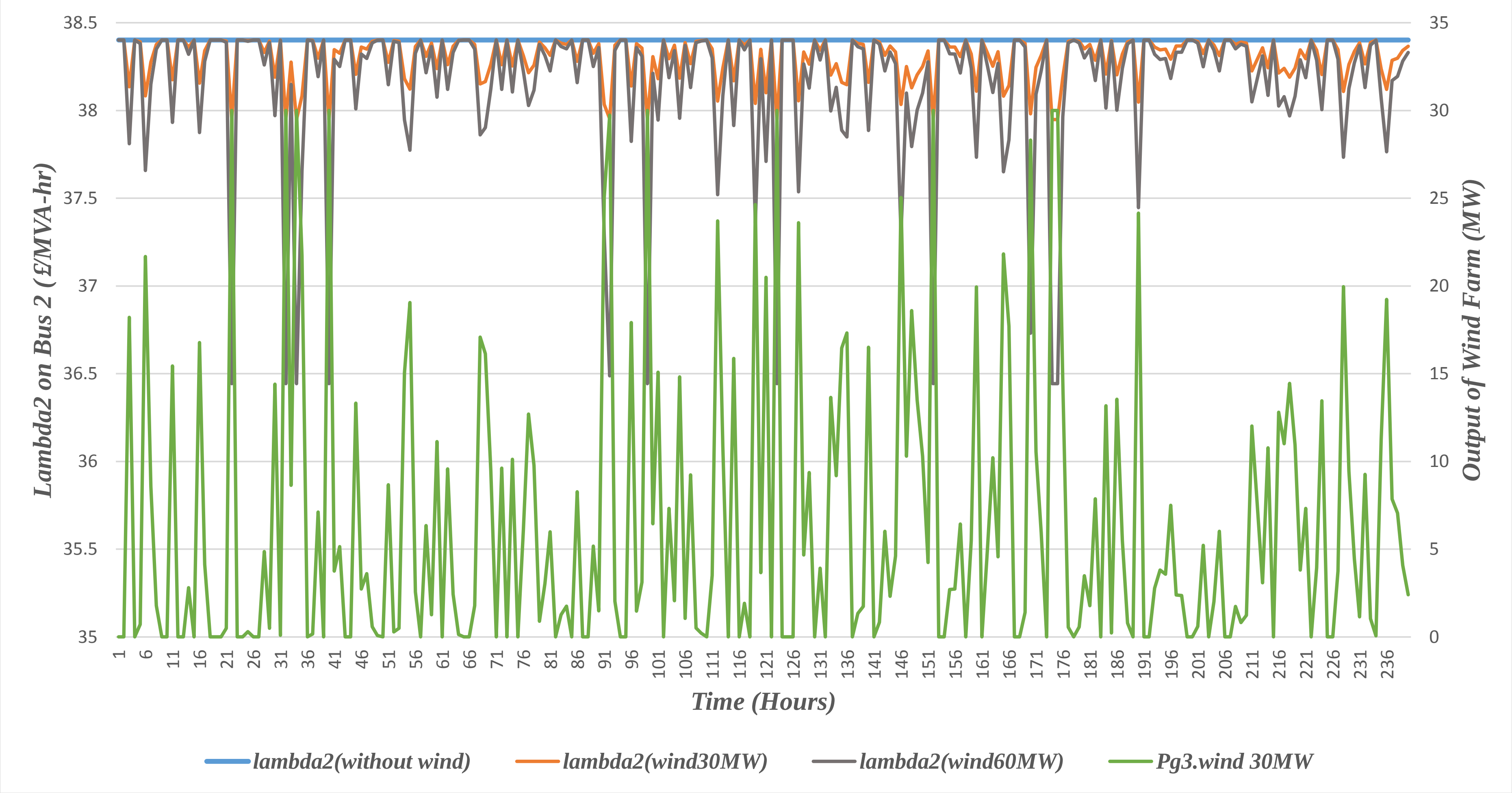

Figure 4.13. Snapshot of Simulated Lambda (£/MVA-hr) on Bus 2 with Different Wind Power Penetration

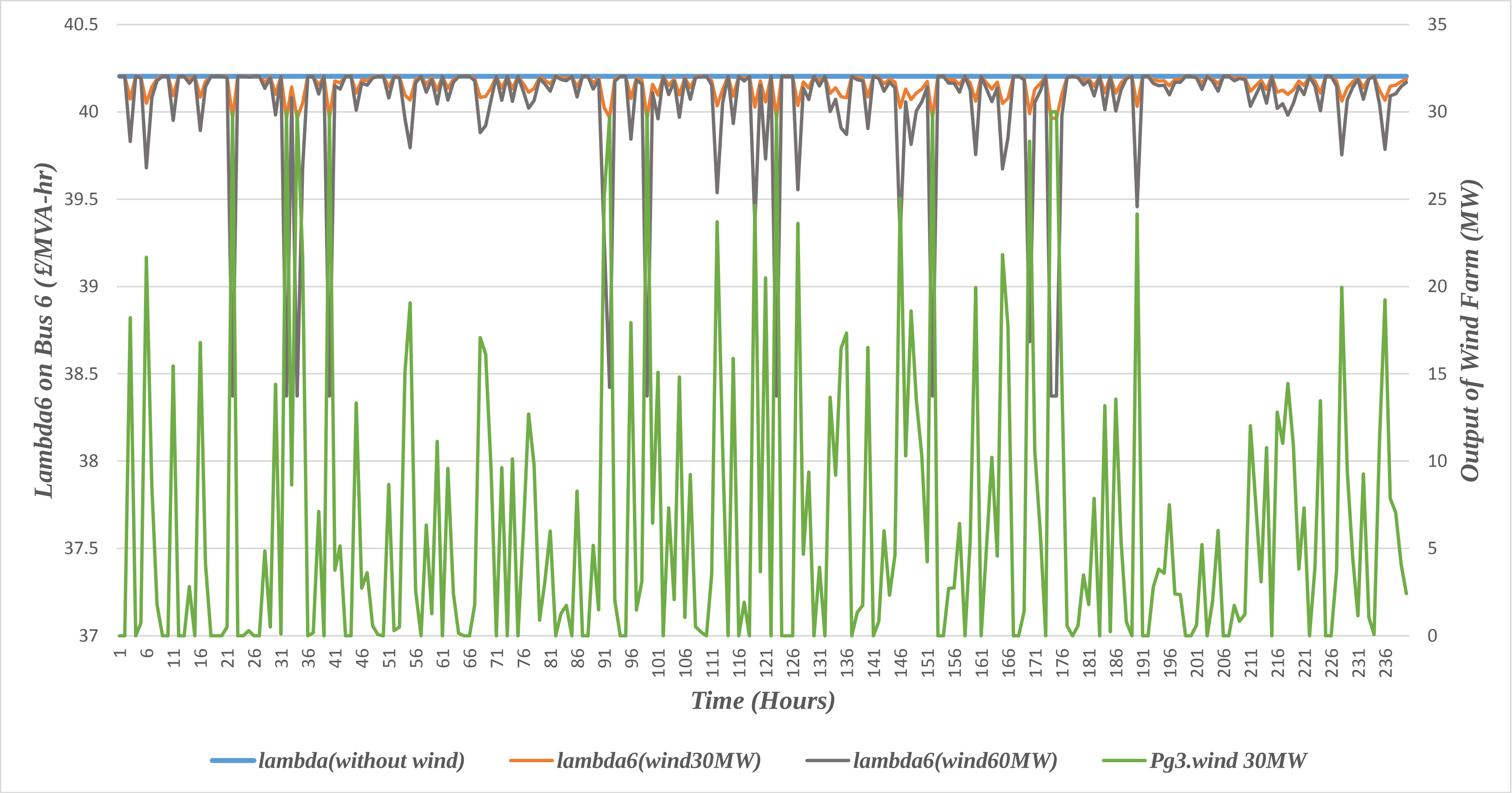

Figure 4.14. Snapshot of Simulated Lambda (£/MVA-hr) on Bus 6 with Different Wind Power Penetration

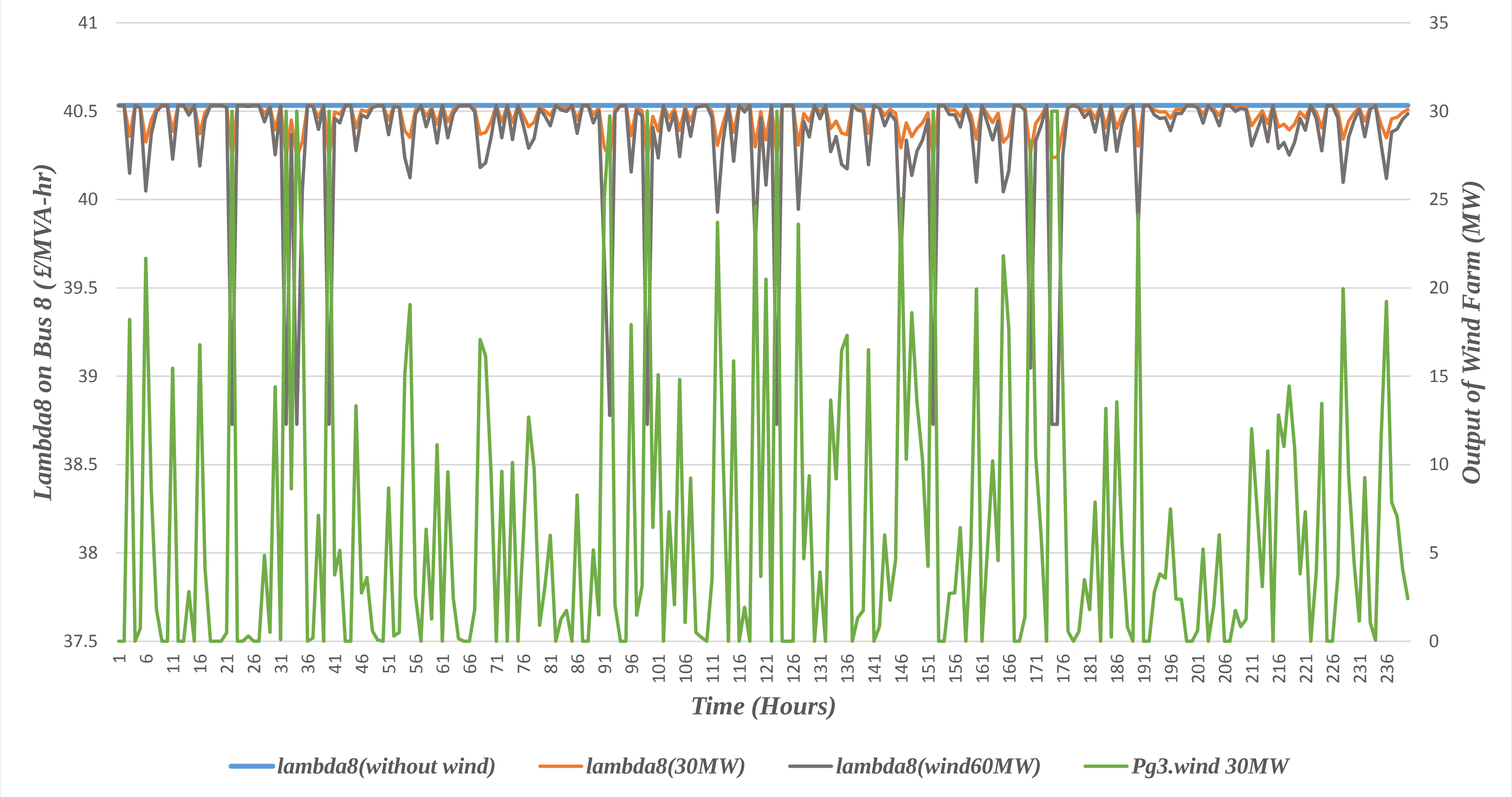

Figure 4.15. Snapshot of Simulated Lambda (£/MVA-hr) on Bus 8 with Different Wind Power Penetration

4.5.3 Scenario 3: Effect of Variable Wind Power Penetration Integration under System Operating Condition with Constraint and without Constraint

Wind farm mentioned in *Scenario 2* will still be used in this scenario study, with the wind farm installed generation capacity of 30 MW (*Figure 4.3*) as 5% of wind power penetration and the wind farm installed generation capacity 60 MW (*Figure 4.4*) as 10% of wind power penetration respectively. The conventional generator on bus 3 will be displaced respectively in the test.

In this scenario, the aim is to assess the impact on conventional generators and transmission system due to wind power integration with different system operating conditions (with constraints and without constraints). Congestion on the transmission system will be considered, one transmission line from bus 3 to bus 4 has overloaded in this scenario. The solution is obtained by ACOPF by enforcing the line limits with all generators bidding at their marginal cost.

Figure 4.16 is the simulation results of power flow on selected branch. Green dotted curve is the power flow with constrained transmission limits from bus 3 to bus 4 when the wind farm installed generation capacity is 60 MW. The orange curve is original power flow without transmission constraints during the system operation. In this scenario, four system operating situations will be compared, the blue curve is the simulation result of base case mentioned in *section 4.5.1*, unconstrained network operation without wind power integration. The orange curve means 5% wind power penetration is integrated into the unconstrained network, and with the dark grey curve means 5% wind power penetration is integrated into the constrained network. The green dotted line means simulation result as increasing wind power penetration into the constrained network to 10%. In all of the simulation studies, wind turbine is treated as first used generation in the power market, that wind farm owners offer their energy production price as zero.

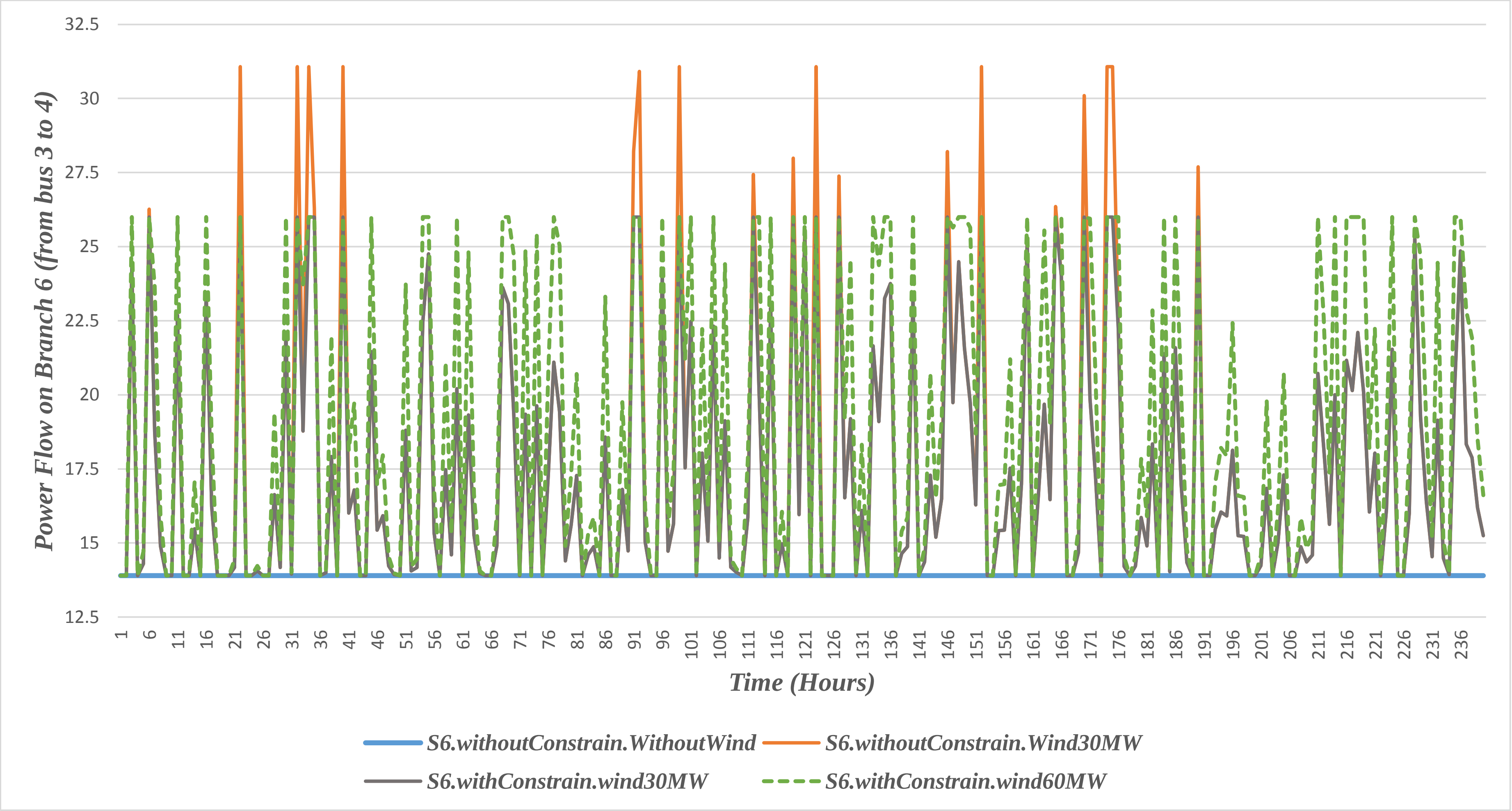

Figure 4.16 Power Flow on Branch 6 (from Bus 3 to Bus 4) with OPF

Chapter 3 has briefly discussed the study of wind power integration affecting optimal displacement of conventional generators. As wind power output continues to be the "must-take" generation, once the wind penetration level is significant, certain amount of displacement needs to be conducted on conventional generation unit and taken out of the system to accommodate the output from wind power.

Figure 4.17 is the snapshot of simulated generator 1's outputs with variable wind power penetration under different system operating conditions. Using OPF with unconstrained network with no wind power, the output of generator 1 is 195.62MW as shown in the blue line. When wind power penetration level is increased with unconstrained network, simulation results show that output of conventional generator 1 will decrease (*Figure 4.6)* in *Scenario 2*. If capacity limits of transmission line is introduced, enforcement of the transmission line constraint has resulted in a re-dispatch of generators in the power system operation in order to relieve the line constraint.

As shown in *Figure 4.17*, reduction of more expensive conventional generator will be intensive with the same wind power penetration level under different power system operating conditions. This variation depends on wind power connection location and taken of all location of congested transmission lines. With increasing wind power penetration, the outputs of conventional generator will be decreased with a constrained network. Similar changing tendency for generator 2 is shown in *Figure 4.19,* it is the simulated results of generator 2's outputs with variable wind power penetration under different system operating conditions.

Re-dispatch of generators in the power system operation will relieve the line constraints. As a result, the presence of congestion has altered the locational marginal prices. *Figure 4.18* is the snapshot of simulated lambda (£/MVA-hr) on bus 1 with variable wind power penetration under different system operating conditions (with transmission constraints and without transmission constraints). The changing tendency of locational marginal prices are related with the outputs of connected generation. *Figure 4.20* is a snapshot of simulated lambda (£/MVA-hr) on bus 2 with variable wind penetration under different system operating conditions (with transmission constraints and without transmission constraints).

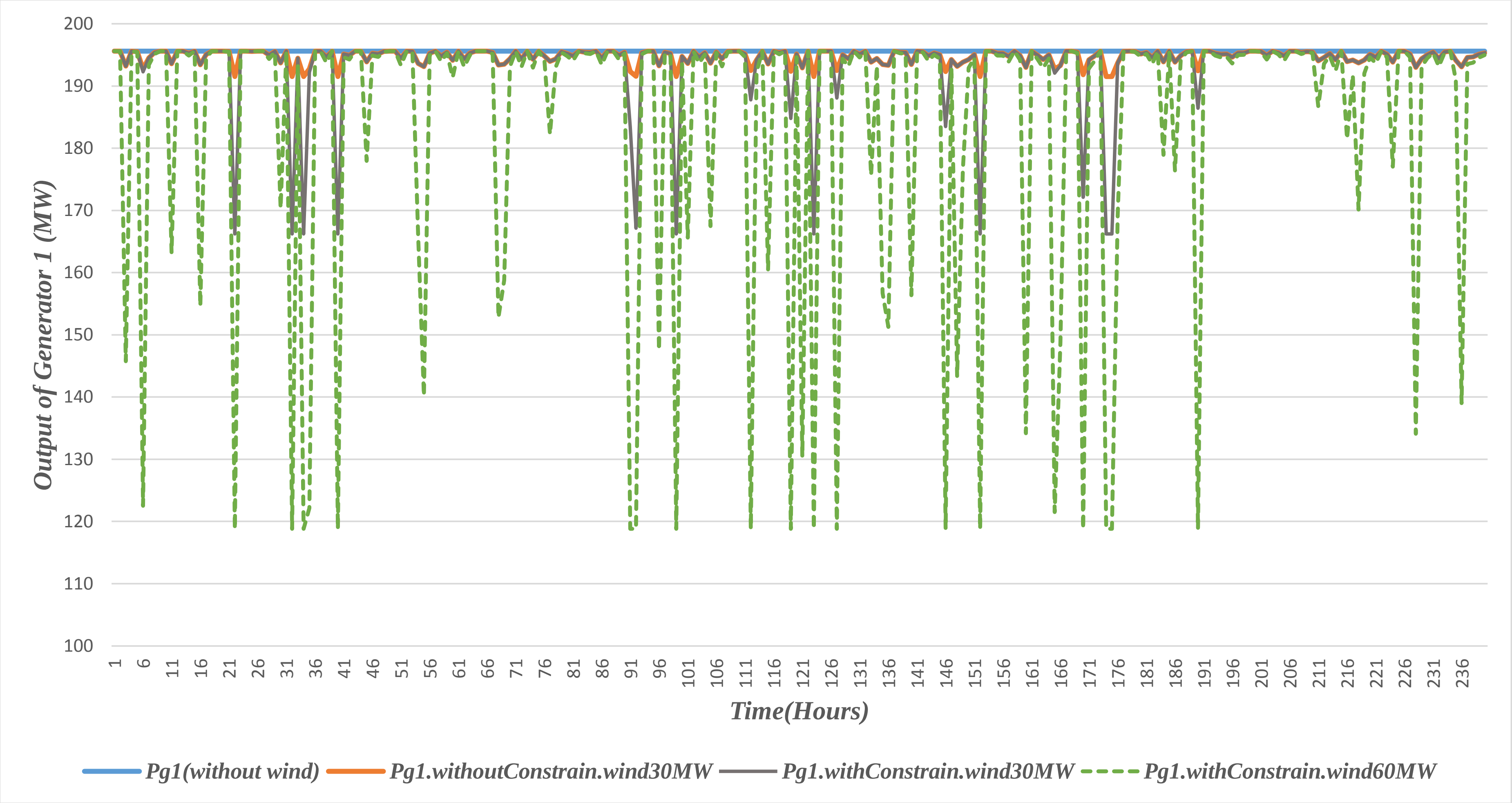

Figure 4.17. Snapshot of Simulated Generator 1's Outputs with Variable Wind Penetration under Different System Operating Conditions

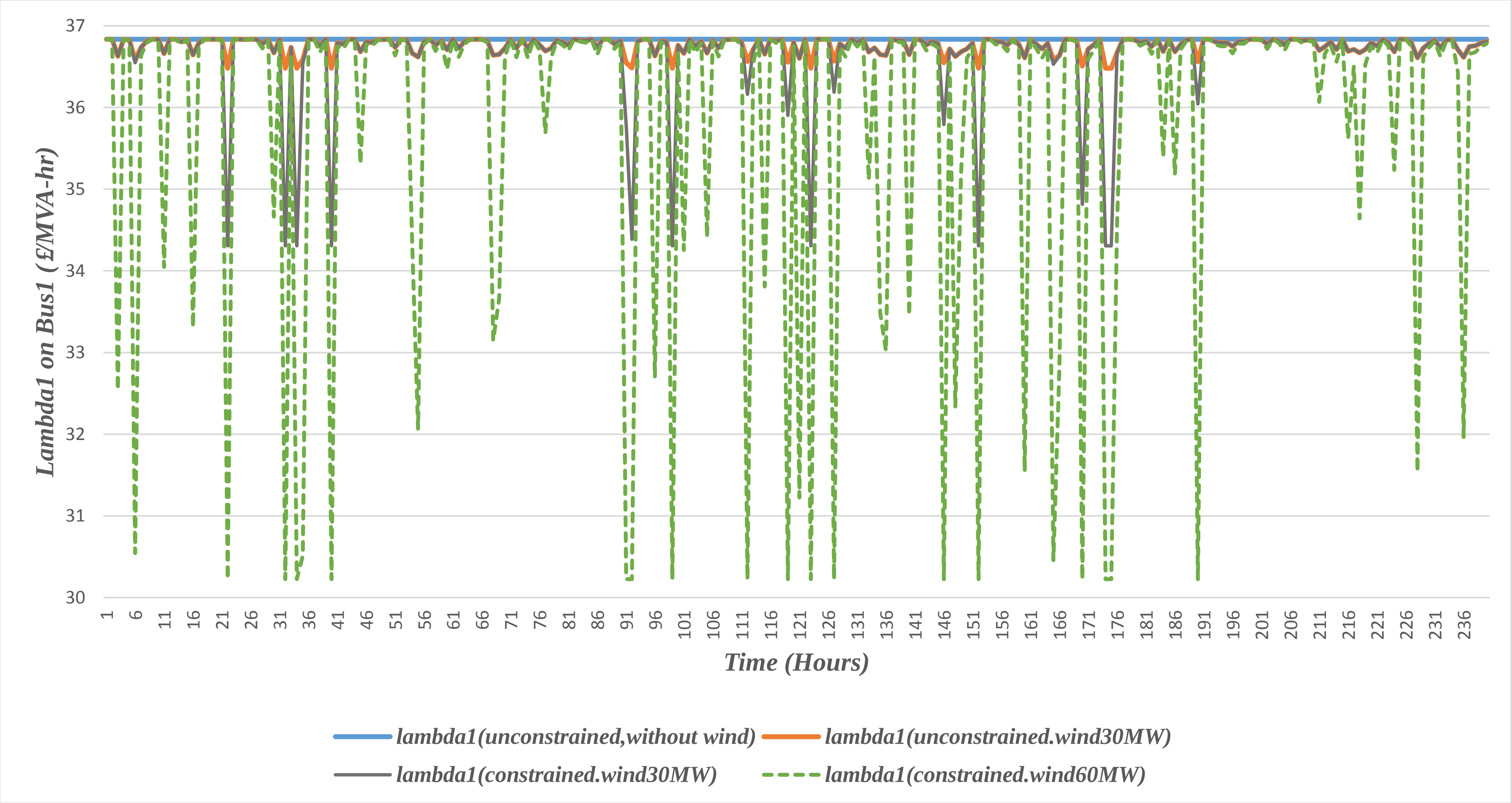

Figure 4.18 Snapshot of Simulated Lambda(£/MVA-hr) on Bus 1 with Variable Wind Penetration under Different System Operating Conditions

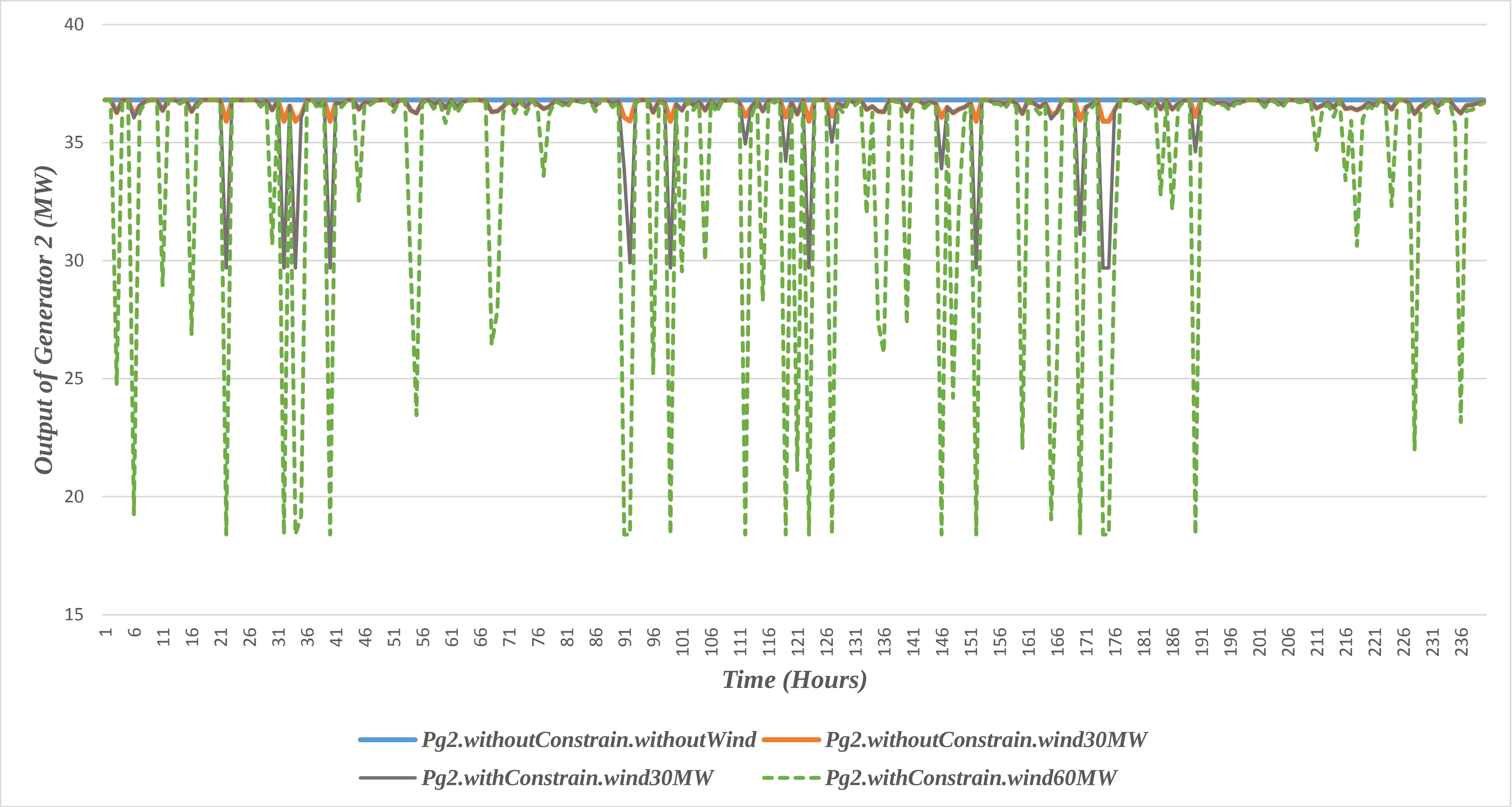

Figure 4.19. Snapshot of Simulated Generator 2's Outputs with Variable Wind Penetration with Different System Operating Conditions

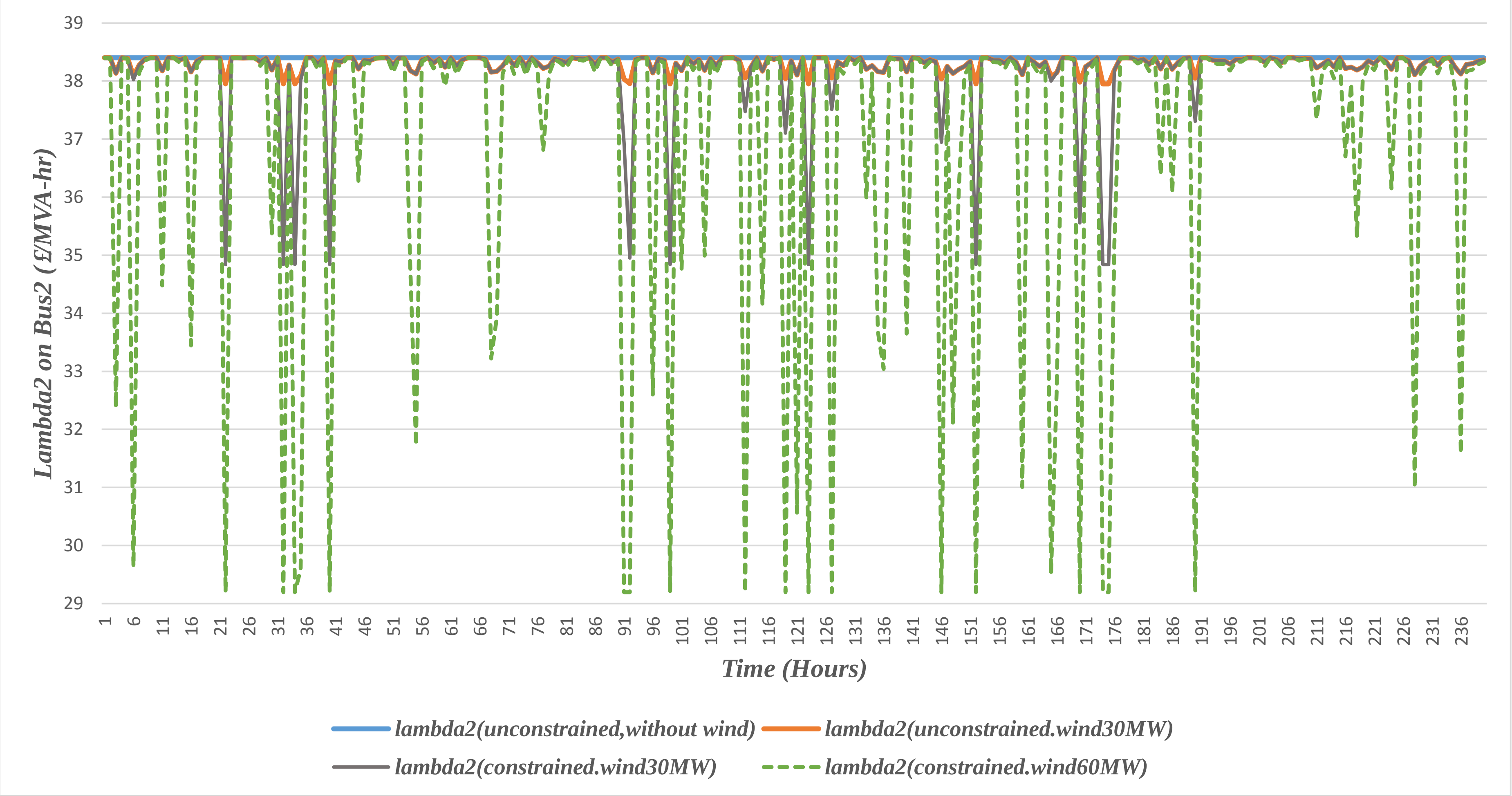

Figure 4.20 Snapshot of Simulated Lambda(£/MVA-hr) on Bus 2 with Variable Wind Penetration under Different System Operating Conditions

Comparing simulated results of wind power in *Figure 4.21* one can see fluctuation output though it is a *"zero price"* generator. Total output energy from installed wind farm can be accepted by unconstrained network as shown with the orange curve. In this test system, the total demand is much higher than the maximum output of the wind generator, so wind farm installed generation capacity of 30MW as 5% wind power penetration is still totally accepted by the system operator with the constrained network. The two curves overlapped (with congestion as dark grey dotted curve and without congestion as orange curve).

The variation of lambda value at bus 3 is shown in *Figure 4.23*. It shows that when the power system is operating with constraints, the value of lambda varies over a big range. This phenomenon will appear on every bus in the test system due to re-dispatch operation.

But with the increased penetration of wind to 10%, under constrained system operation, output of wind farm will be curtailed. The green dotted line in *Figure 4.21* is the output of wind farm with 10% penetration level under constrained network. This curtailment of wind farm is shown in simulated comparative results in *Figure 4.22*. The blue curve is the curtailed output of wind farm with OPF under constrained network. The orange dotted line is the output of wind farm with no curtailment.

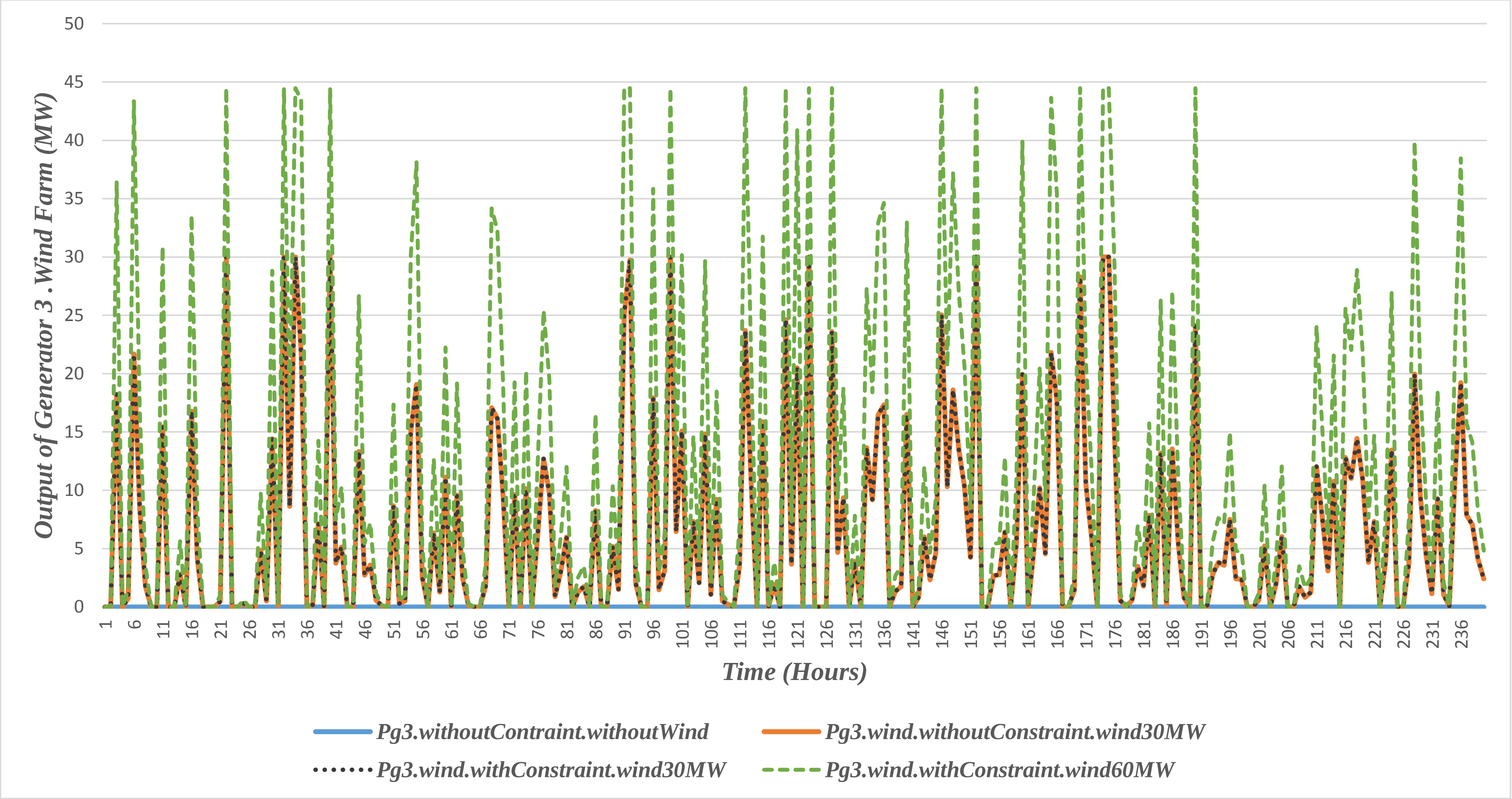

Figure 4.21. Snapshot of Simulated Wind Farm's Outputs with Variable Wind Penetration under Different System Operating Conditions

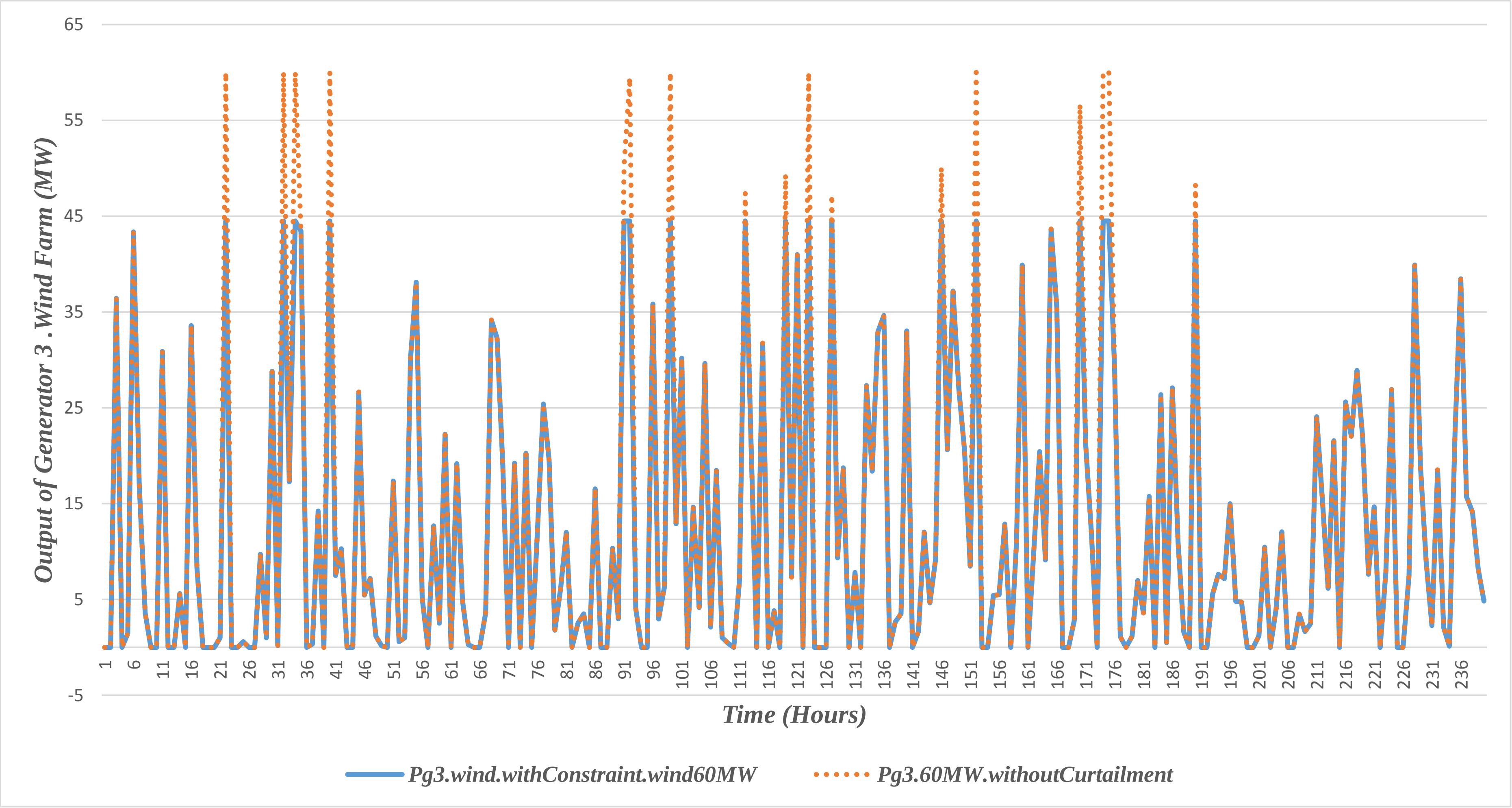

Figure 4.22 Snapshot of Comparing Simulated Results between Installed Wind Farm and it's Output with OPF under Constrained Network

It is important to note that LMP price will reflect the system conditions by the data and assumptions used in the studies. Differences in the system conditions will produce differences in LMP prices and other variations in the system conditions would also produce different results.

Figure 4.23 is a snapshot of simulated lambda (£/MVA-hr) on bus 3 with variable wind penetration under different system operating conditions. Output of 60MW wind farm as 10% penetration will be curtailed with the constrained test system. When curtailment appears, locational marginal price on bus 3 will almost equal to be zero, as shown in *Figure 4.23* with green dotted curve.

Figure 4.24 is a snapshot of simulated lambda (£/MVA-hr) on bus 4 with variable wind penetration under different system operating conditions (with constraints and without constraints). With the wind farm curtailment appears on bus 3 and constrained enforcement on branch 6 (between bus 3 and bus 4), location marginal price on bus 4 will increase due to re-dispatch. The simulated results highlight the key characteristics of the prices resulting from the impacts of transmission constraints that affect system dispatch.

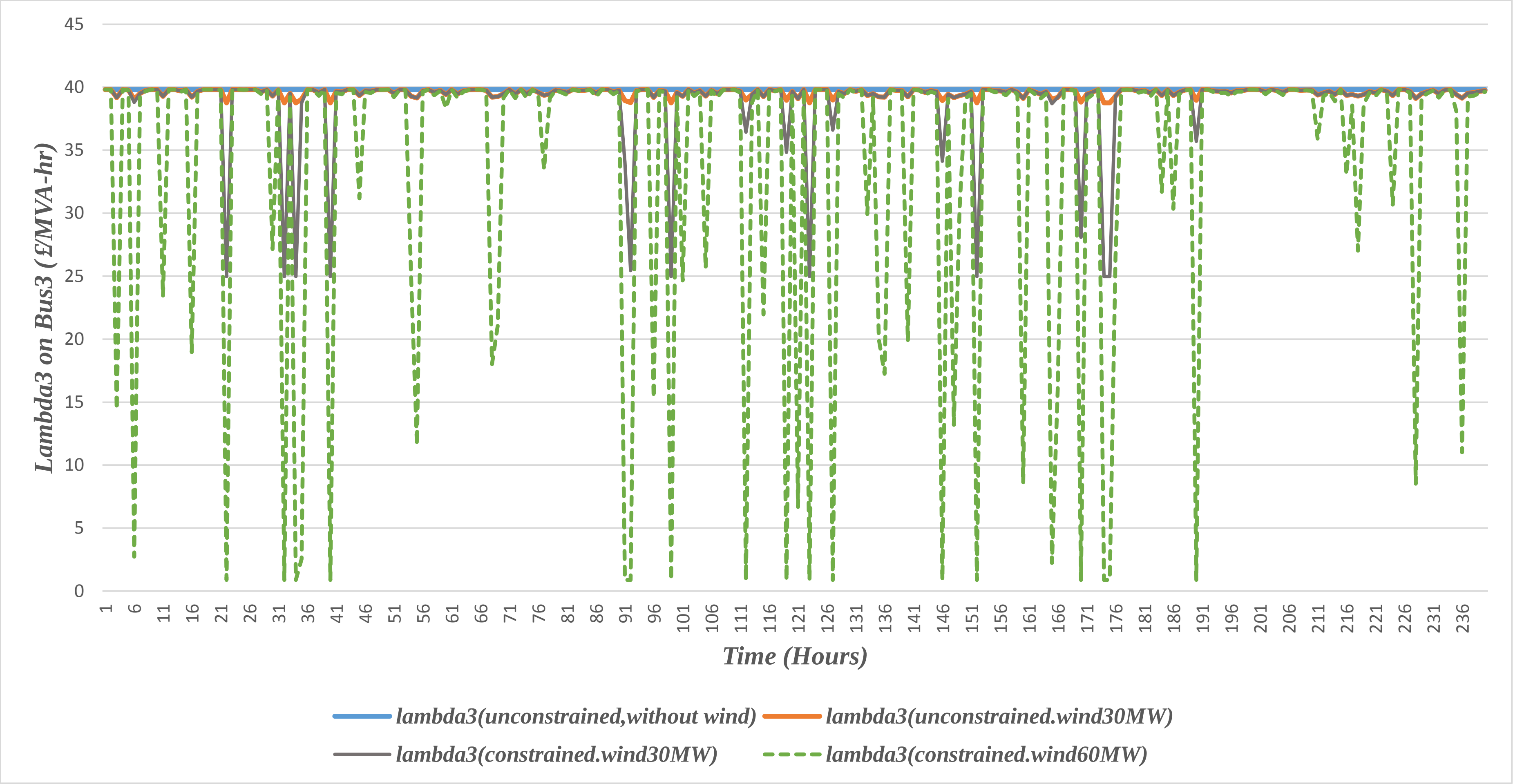

Figure 4.23 Snapshot of Simulated Lambda(£/MVA-hr) on Bus3 with Variable Wind Penetration under Different System Operating Conditions

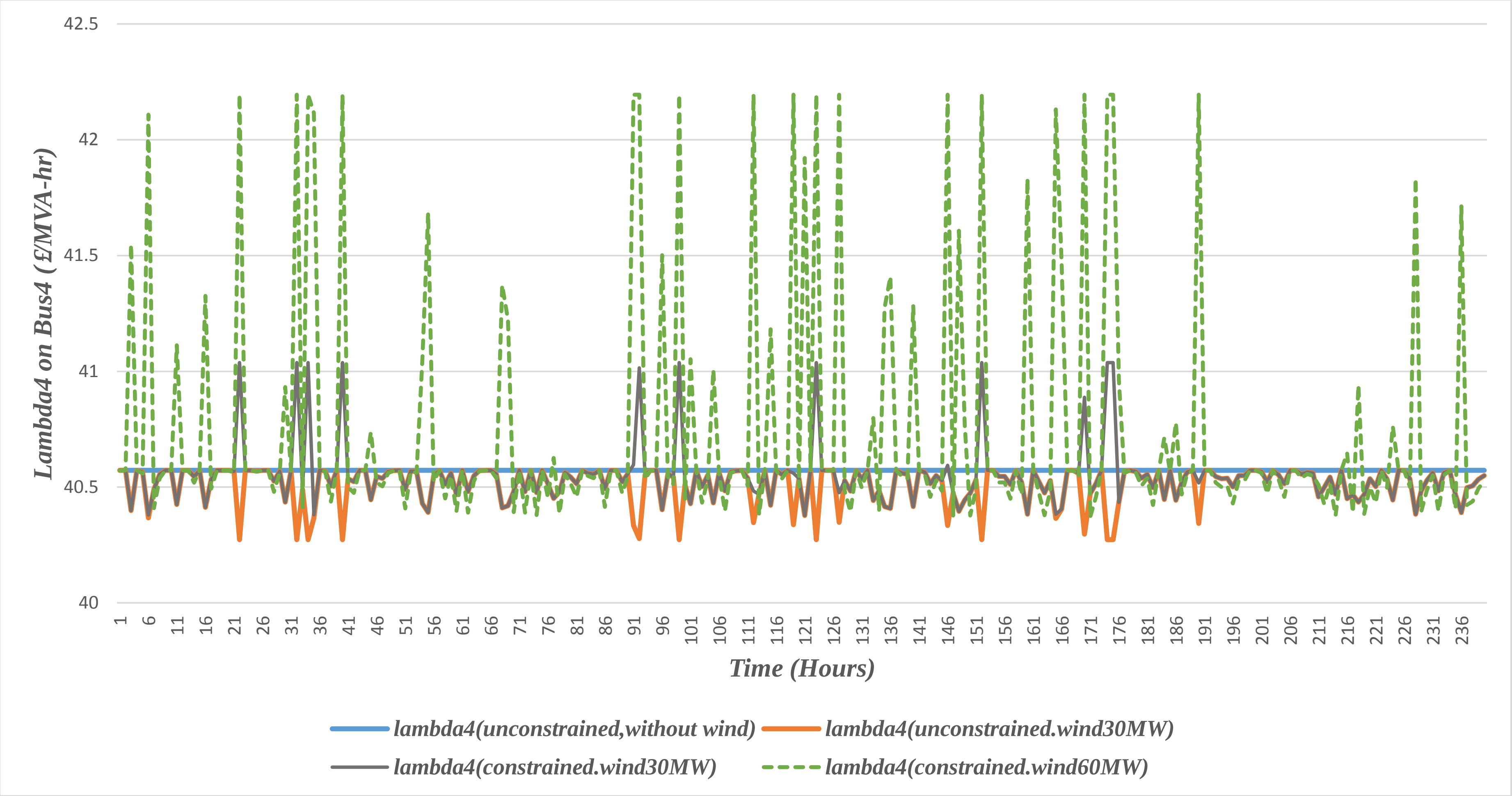

Figure 4.24 Snapshot of Simulated Lambda(£/MVA-hr) on Bus4 with Variable Wind Penetration under Different System Operating Conditions

The power flow on branch 6 from bus 3 to bus 4 must be constrained and cannot be exceeded for security and stability purpose. Therefore, the decrease in generation from G1 (on bus 1), G2 (on bus 2) and curtailed wind farm must be compensated by increase in generation from G5 (on bus 8), so that the resulting flow in branch 6 remains at its limit of 26MW. *Figure 4.26* is a snapshot of simulated generator 5's outputs with variable wind penetration under different system operating conditions (with constraints and without constraints). In *Figure 4.26*, output energy from G5 (on bus 8) will increase with the re-dispatch under constrained network as shown with the green dotted curve. Because of location and constrained branch, output from generator 4 (on bus 6) will decrease under constrained system operation with increasing wind power penetration as shown in *Figure 4.25* with the green dotted curve.

LMP is an aggregation of cost of energy, loss and congestion components as discussed in *Chapter 3*. *Figure 4.27* is a snapshot of simulated lambda (£/MVA-hr) on Bus 6 with variable wind penetration under different system operating conditions (with constraints and without constraints). Generator 4 is connected on bus 6 in the test system, the variable tendency of LMP on bus 6 is much chosen to the variable output of G4. The LMP on bus 8 has the similar simulated results with output of G5, which is connected on it, with transmission constraints and without transmission constraints and are shown in *Figure 4.28.*

All of the simulated results explain the impact of wind power on LMP with variable penetration under different system operation conditions are presented in graphical form in this scenario. Results of others are listed in the appendices.

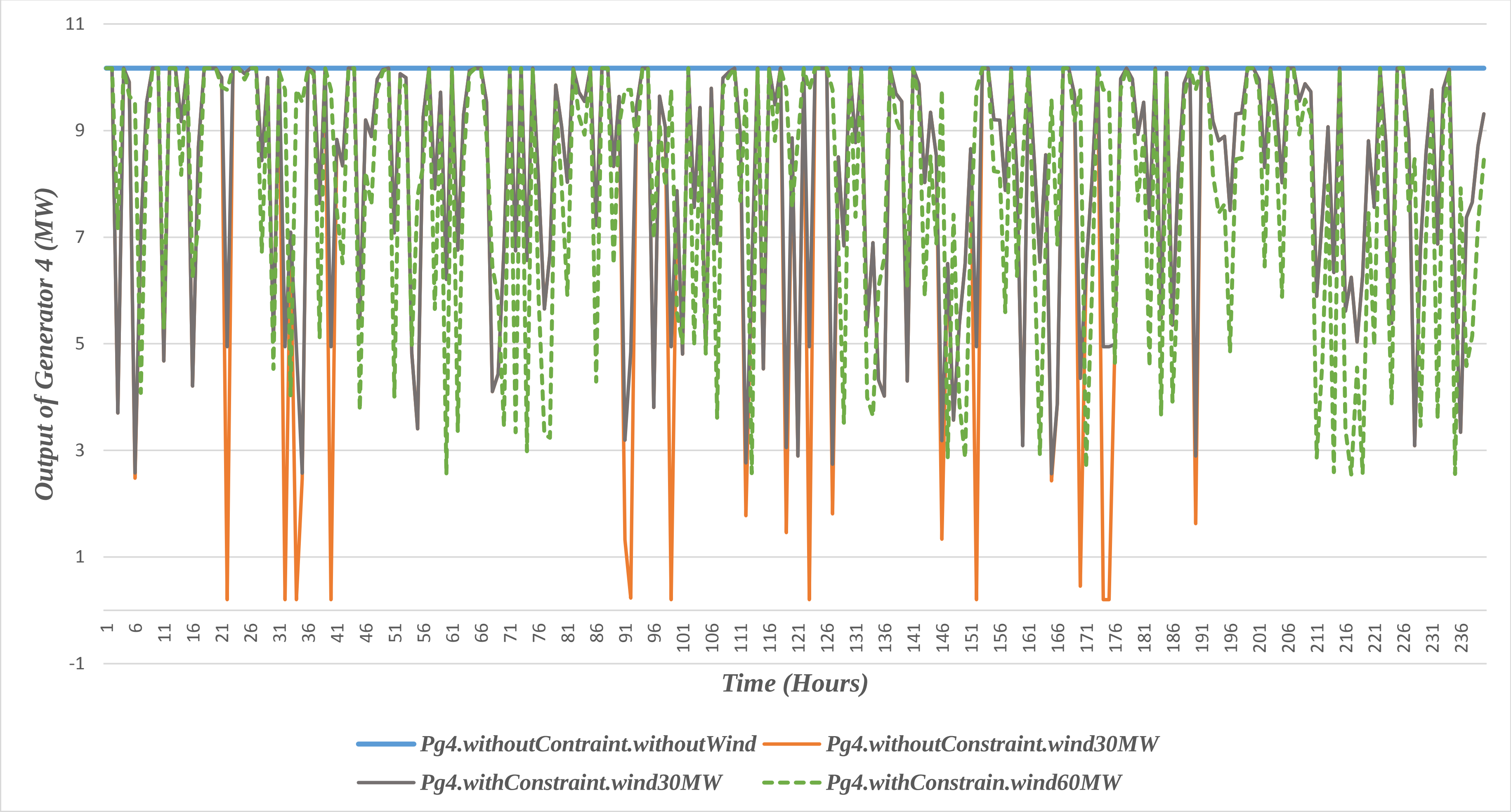

Figure 4.25. Snapshot of Simulated Generator 4's Outputs with Different Wind Penetration under Different System Operating Conditions

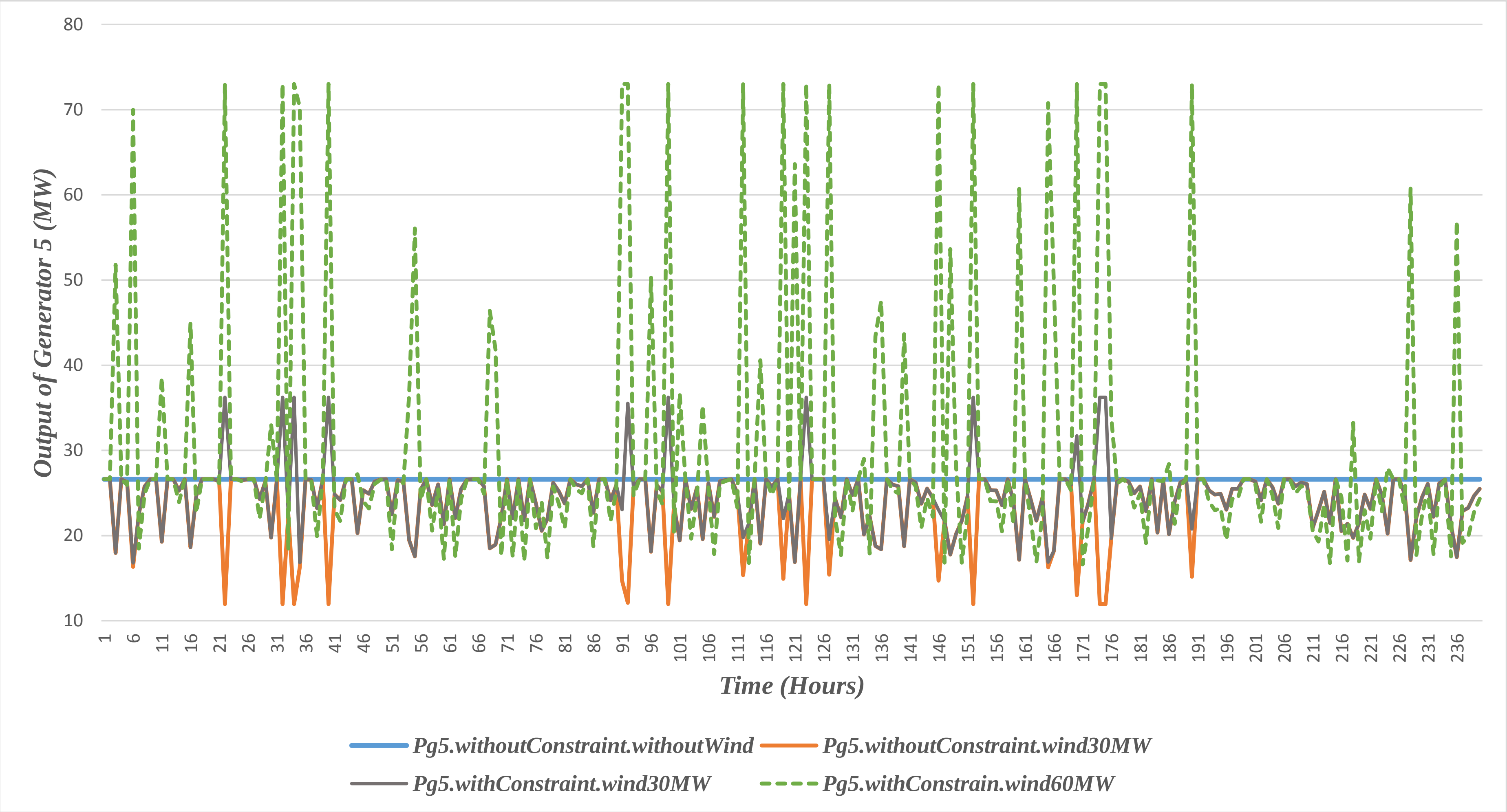

Figure 4.26. Snapshot of Simulated Generator 5's Outputs with Variable Wind Penetration under Different System Operating Conditions

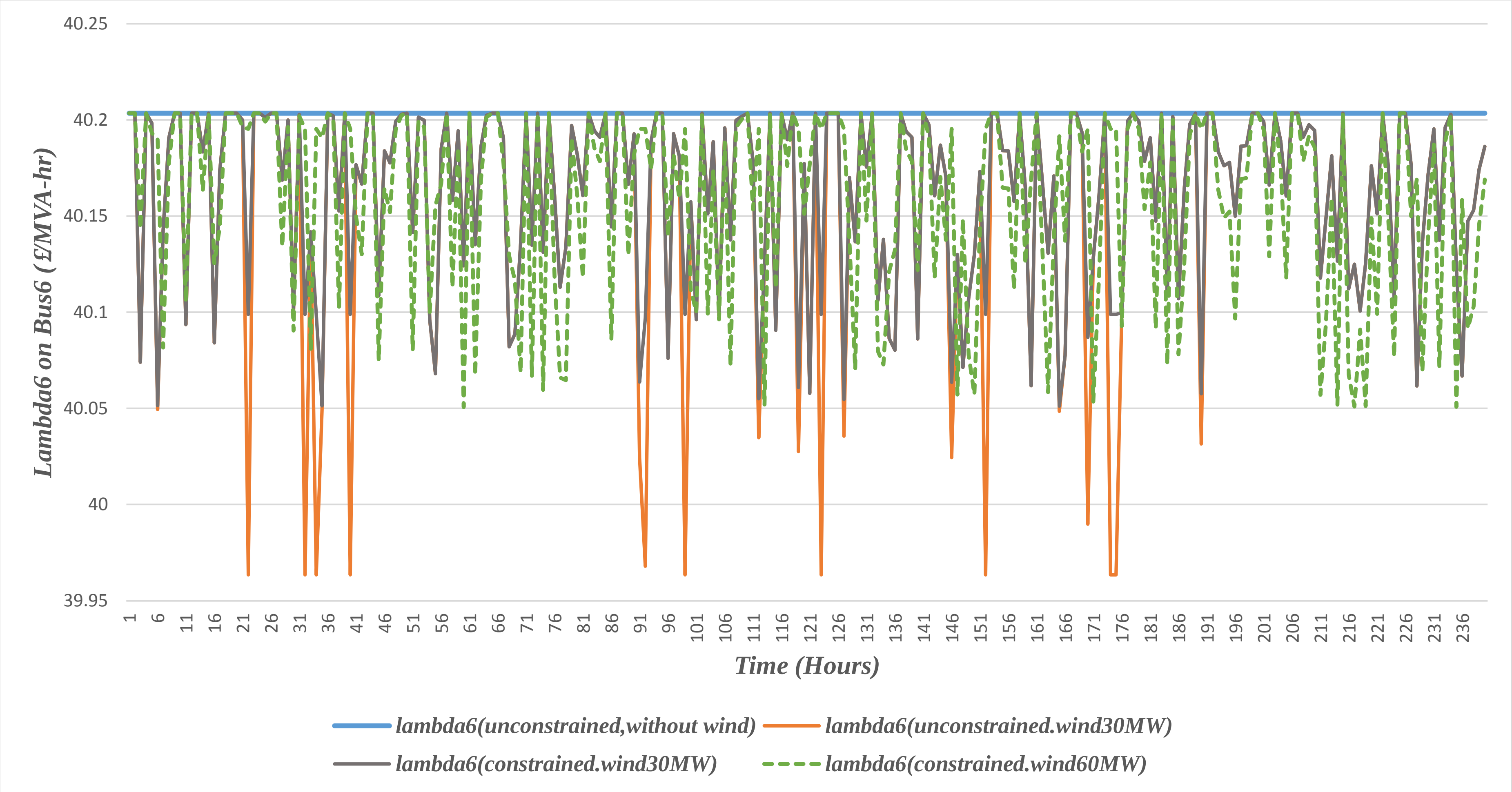

Figure 4.27 Snapshot of Simulated Lambda(£/MVA-hr) on Bus6 with Variable Wind Penetration under Different System Operating Conditions

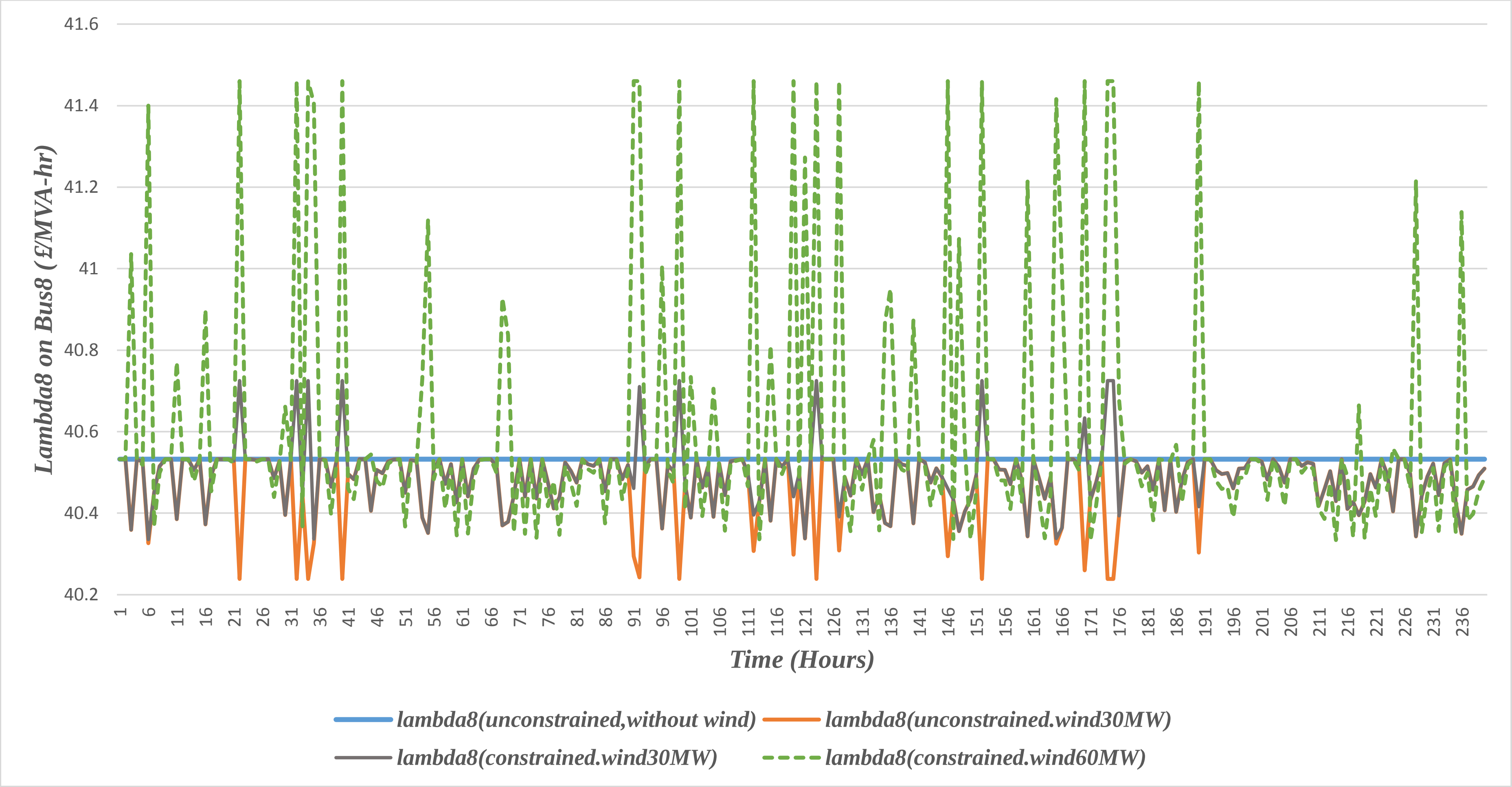

Figure 4.28 Snapshot of Simulated Lambda(£/MVA-hr) on Bus8 with Variable Wind Penetration under Different System Operating Conditions

4.5.4 Effect on Operating Costs with these Three Scenarios

Operating costs is one of the main criteria used to assess the impacts of wind power integrating into the power system. All the simulations involve integrating wind power, optimizing generation resources and scheduling of load to meet expected demand over various time frames, taking into account the system operating conditions.

Figure 4.29 is a snapshot of simulated operating costs (£/hr) in the previously three scenarios. The blue line is the 8113.94 £/hr line which is the operating cost in the base case, unconstrained network operation without wind power generation. With the comparison simulated results, when wind power penetration is increased for the unconstrained network, operating costs will decrease sharply. *Figure 4.30* is a snapshot of selected hour points of simulated operating costs (£/hr) in these three scenarios. In *Figure 4.30,* the dark grey curve is the operating cost of the unconstrained network with wind power penetration at 10%. With congestion in the power system, some related elements will have added operating cost, such as re-dispatch for system operation. The green curve in *Figure 4.30 is* the operating cost of wind power penetration at 10% considering constraints.

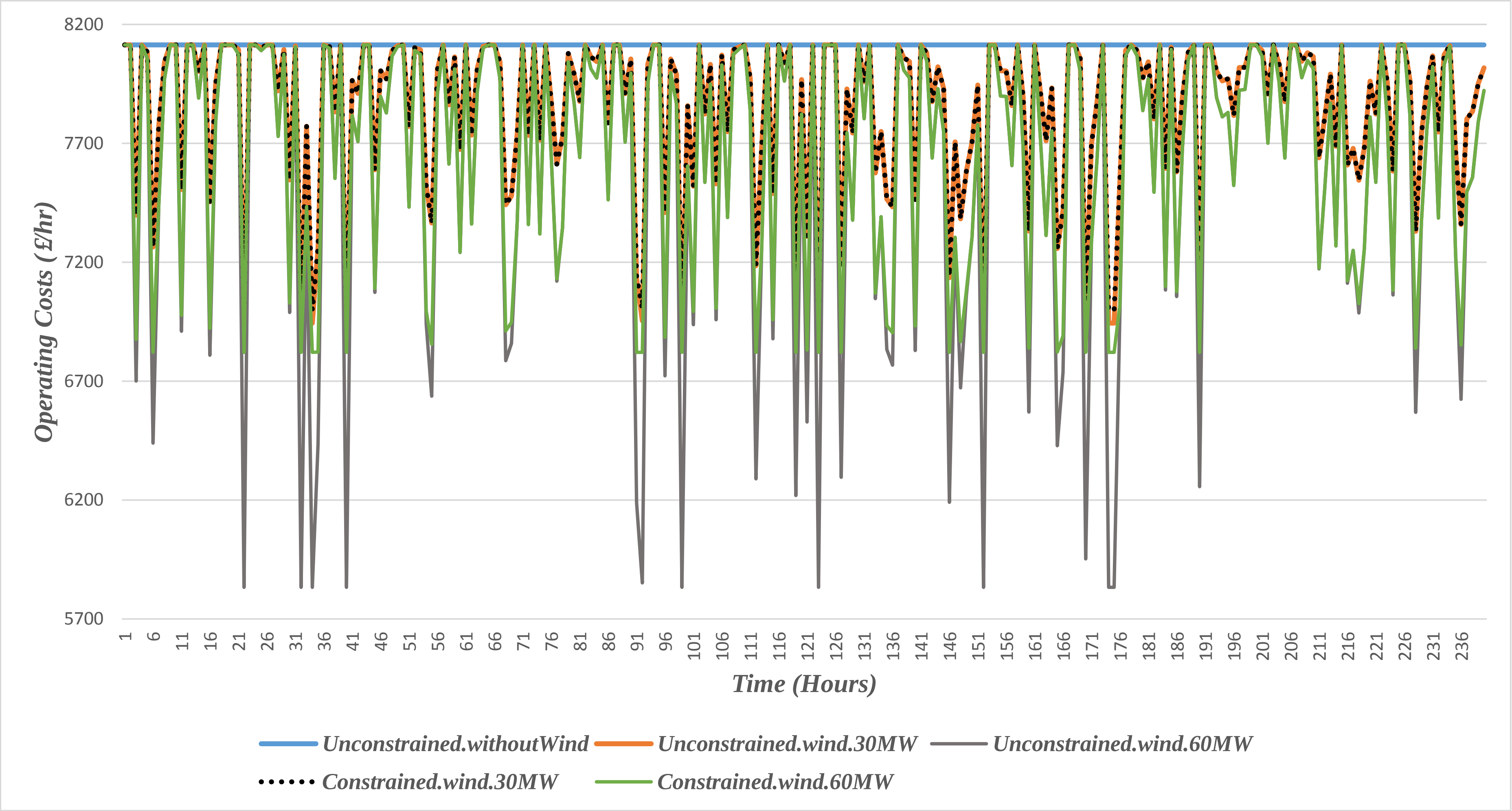

Figure 4.29 Snapshot of Simulated Operating Costs (£/hr) in these Three Scenarios

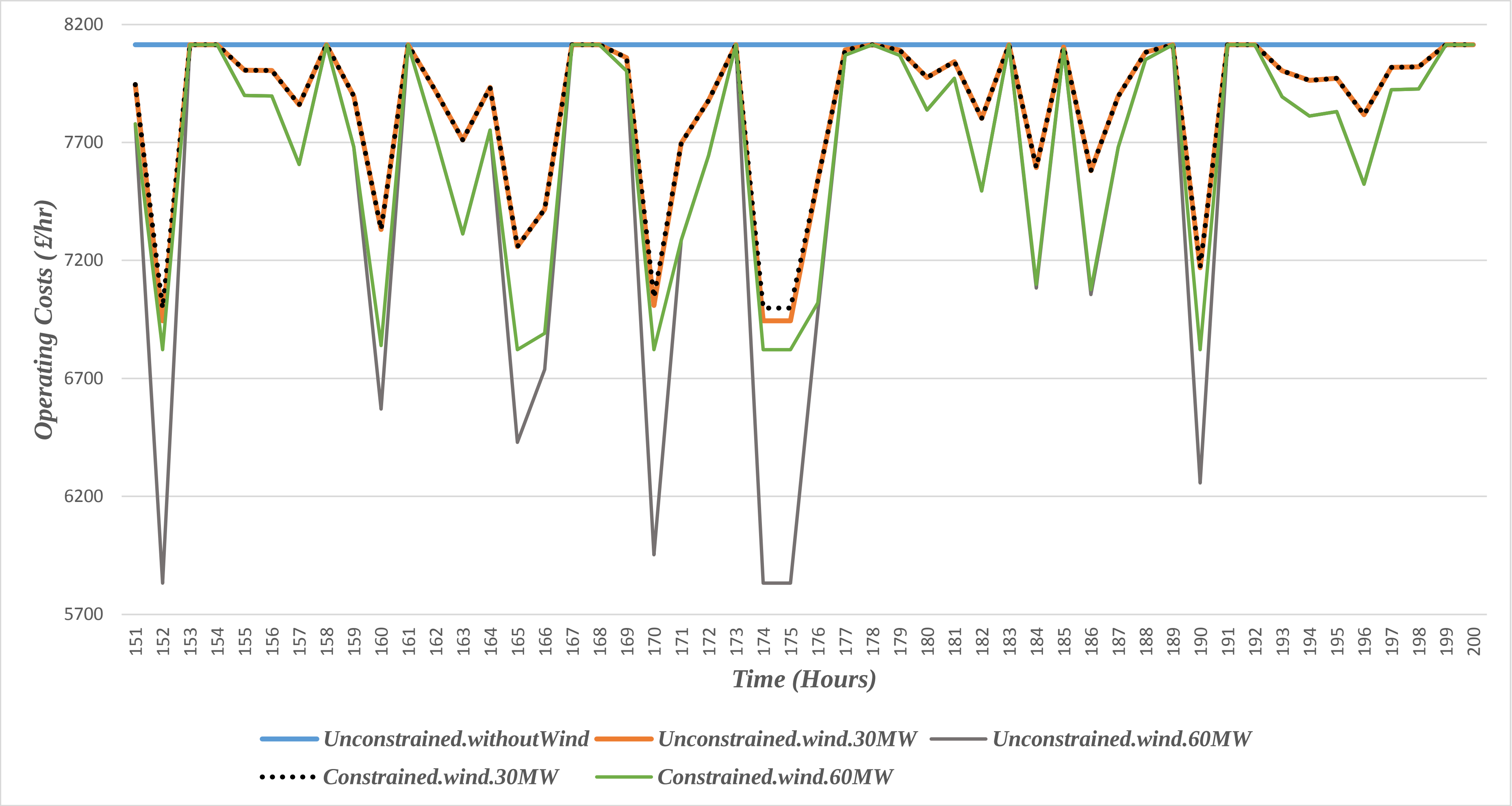

Figure 4.30 Snapshot Selected Hours Points of Simulated Operating Costs (£/hr) in these Three Scenarios

4.6 Summary

Wind source is an intermittent energy source and it is important to have means to maintain system security when wind farms are connected to a power system. A sudden change in wind speed will significantly change a wind farm's power output. When such a variation lasting for a very short time interval the fluctuating output will still affect the power flow, system generation – load balance, generating system reliability and hence the power system operation and the power market.

During the case studies in this chapter, wind farm with variable penetration is used in the simulation. The performance of the system is analysed with three scenarios, and the simulation results are presented in graphical forms.

The introduction of the wind farm changes the output of conventional generator and the lambda values, significantly in some cases, leading to a much higher electricity price for the customers.

When investigating wind farm integrating into a power system it is important to investigate and reinforce transmission capacity to avoid congestion appears in the system. Furthermore congestion in a transmission network also means wind generation output will be curtailment during power system operation. Hence to maximise the benefit of wind generation for both the utility and the customers, transmission capacity reinforcement must be carefully investigated.

Reference

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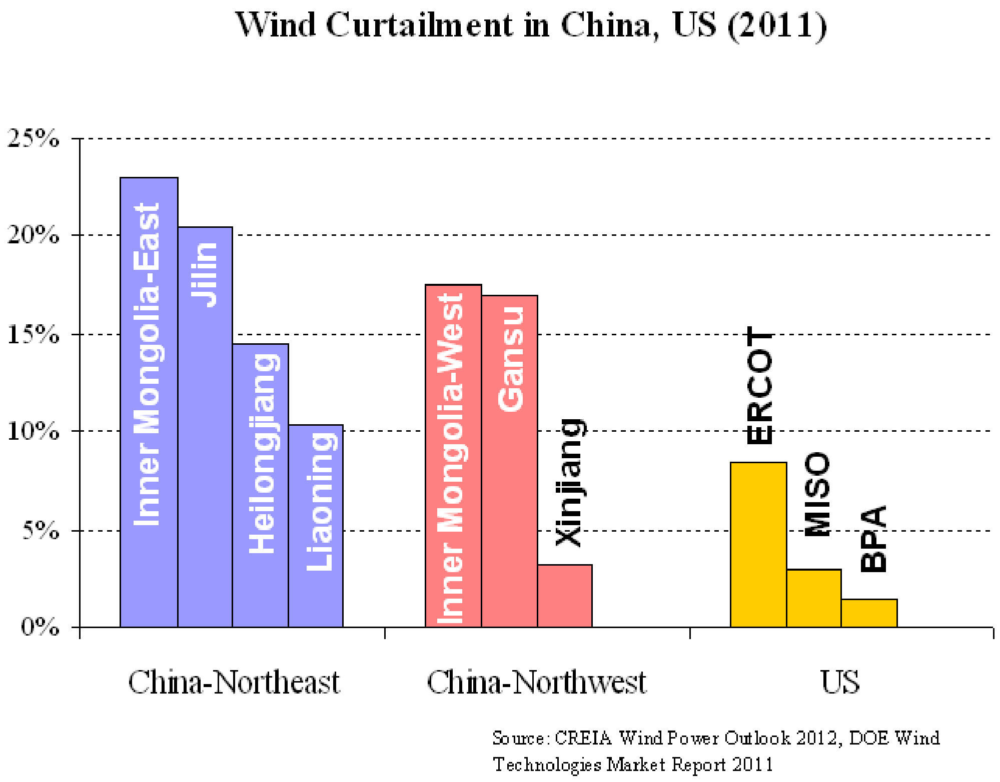
Chapter 5

Wind Power Curtailment and Associated Mechanisms of Bilateral Contract

5.1 Introduction

In recent years, wind energy has been identified as an important alternative power source to rebalance its energy mix by government. This development has been supported with many relevant regulations and policies.

For example, according to tallies by the National Energy Administration, China added 14 Gigawatt (GW) of wind power capacity to the grid in 2013, and now in the fifth consecutive year of over 10 GW installed. [6] In the same year, unused wind electricity hit record highs while wind connected to the grid was roughly half the size of Germany's. China is perhaps the largest yet the most inefficient wind power system in the world. [6] *Figure 5.1* shows the latest provincial figures for 2011, which is China's grid connected wind generation curtailment problems as much more than its peers, pegged at between 10~20%. Reports on 2012 show this has skyrocketed to as high as 50% in some regions. By comparison, ERCOT peaked at 17% in 2009 and was 3.7% last year. [6]



Source: CREIA Wind Power Outlook 2012, DOE Wind Technologies Market Report 2011

Figure 5.1 Wind Curtailment in China, US (2011） [6]

Curtailment here means that wind are available, but the system operators will not allow the wind farm to transmit power to the grid. In other words, the wind farm cannot dispatch power as the other plants doing power system operation. Two mechanisms affect curtailment levels. First, transmission constraints are an important cause; second, curtailment occurs during hours of oversupply of wind power generation.

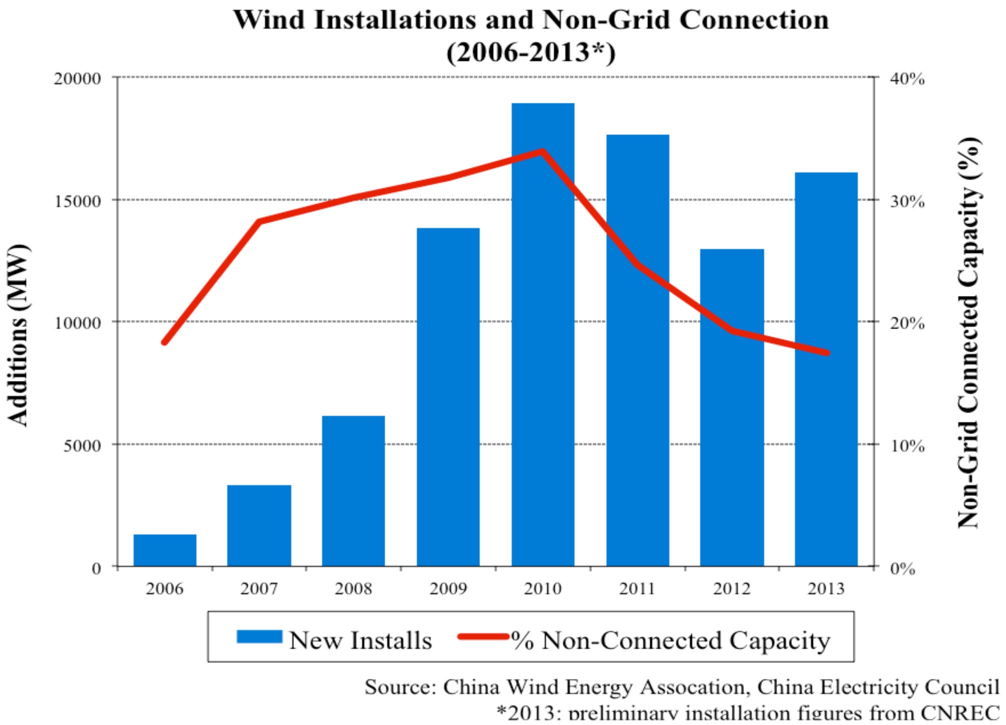
This chapter sets out contracts curtailment incorporated in this thesis, the details of the proposed method will be introduced in Chapter 6. Section 5.2 gives a brief description about the current phenomena of wind power curtailment. In section 5.3, reasons of wind power curtailment and the experiences of utilities and system operators for curtailment of wind power in some countries will be reported. The main aspects of the research will be introduced in section 5.4 and related fundamental knowledge especially flexible scheduling of bilateral contract will be discussed.

5.2 Background of Wind Power Curtailment

5.2.1 China

Compared with centralized fossil stations, wind has many disadvantages, as a variable and unpredictable energy resource, these unavoidable usage limitations are not unique to China, all of the countries in the world would need to face this phenomenon magnified by its geography. Unlike other countries with varying political support for renewable energy, wind in China enjoys a privileged status. A well-funded feed-in-tariff (FIT) and other government support since 2006 encouraged an annual doubling of wind capacity for five consecutive years, followed by 10-15 GW additions thereafter. [6]

Wind projects are typically far from the city and industrial centers where electricity is needed, and transmission network investments needed to connect to the grid are not always kept up in pace. This remarkable gap left wind turbines, as many as a third of them in 2010, languishing unconnected, unable to sell the electricity to the grid (*Figure 5.2*). [6]



Source: China Wind Energy Assocation, China Electricity Council
*2013: preliminary installation figures from CNREC

Figure 5.2 Wind Installations and Non-Grid Connection (2006-2013) [6]

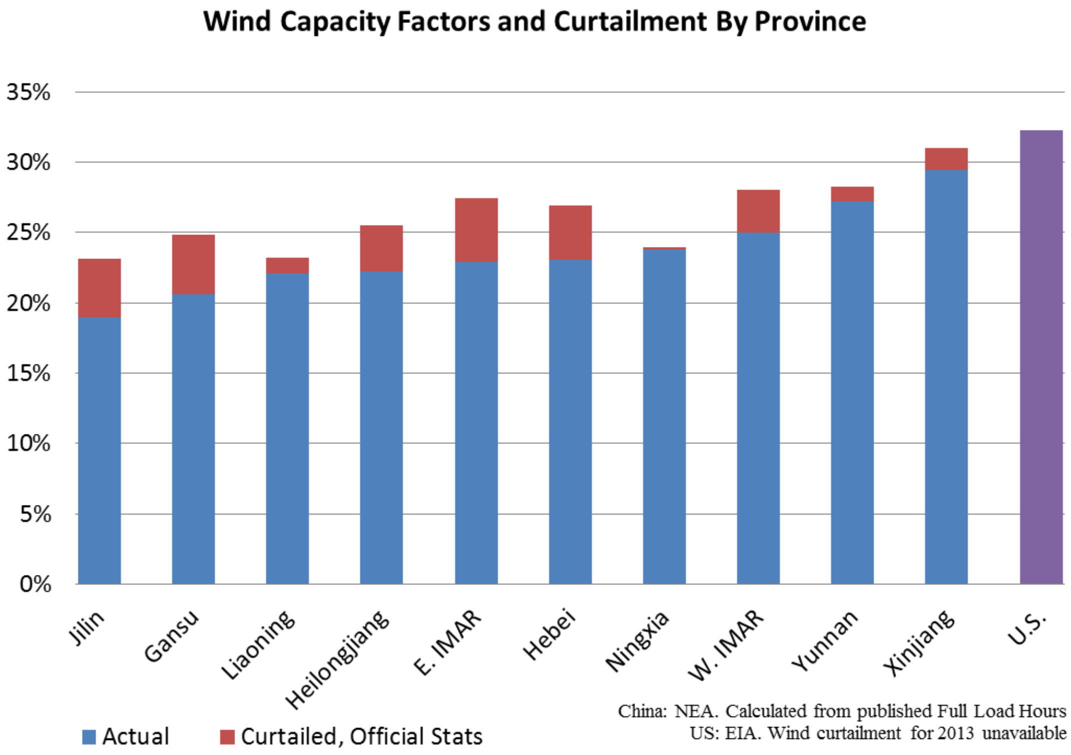
Because of system operation reliability or other constraints, system operator will decreased wind farm operators to reduce their outputs. In *Figure 5.2*, shows official estimates of wind curtailment in 2013, it shows some improvements in 2012, but the problem is far from being solved.

From Brazil to Germany, grid connection delays from primarily transformer and line right-of-way siting, permit and construction, these steps have occurred where there is rapid wind power development. China, however, had a unique policy (until mid-2011) that exacerbated the wind-grid mismatch: all projects smaller than 50 MW could be approved directly by local governments, bypassing more rigorous feasibility analyses, in particular, related to grid access.[6] The delay of central government reimbursement to overburdened local grids for construction may also be responsible. The level of non-grid connected capacity is hovering at around 15 GW as at the end of 2013. [6]

Although as a wind power generation owner, wind farms may have successfully connected to the grid, there are still have some related problems that needs to be researched when trying to transmit power to load centers. During power system operation, system operators make decisions a day ahead on which thermal plants to turn on, so if wind power penetration is at a very high level and the penetration is significant, the differences will be curtailed to maintain the stability for grid. And if a wind farm is connected at the end of a constrained transmission line, the system operator may also have to curtail the output from wind generation, as has happened in ERCOT (Texas' grid) and northwest China. Finally, to manage hourly variation, system operators will ramp up and down other generators to accept as much as output from wind power generation, they need to maintain supply and demand balance with limits on flexibility of conventional generators.

China's energy mix is coal-heavy which will be more sluggish when changing output. It is one of the main aspects that led to the third year in a row of the unfavorable situation of China which leading the world in wind capacity yet still trailing in terms of wind generation. From [8] the increased size of coal plants makes this effect more pronounced.

As in previous years, northeastern provinces of China with large coal-fired power capacities and the transmission-constrained northwestern region topped the list for curtailed wind. Inner Mongolia has two separate grid regions: the northwest (W. IMAR) and the northeast (E. IMAR). In the *Figure 5.3*, it shows the actual capacity factor as well as its reduction compared to the potential capacity factor according to official curtailment statistics. [6]


Wind Capacity Factors and Curtailment By Province

China: NEA. Calculated from published Full Load Hours
US: EIA. Wind curtailment for 2013 unavailable

Curtailment continued to take a big chunk out of potential wind generation in 2013. Reported capacity factors are still much below U.S. levels.

Figure 5.3 Wind Capacity Factors and Curtailment by Province (2013) [6]

With the development and project planning from Chinese government, the wind construction sector is likely to keep going strong in 2014, as an additional 56 GW of wind has already been permitted according to government statistics, and analysts expect 14 GW of solar also will be added to Chinese power system in 2014. [7] How to increase utilization of wind farm which are currently curtailed by system operation will be the main point for China’s currently wind power development.

5.2.2 UK

The European Union (EU) is currently in the process of moving towards ‘greener’ technologies with a drive to encourage the adoption of renewable energy technologies.

From [17] EU Directive 2009/28/EC (The European Parliament and the Council of the European Parliament, 2009) sets renewable energy targets for all member states to achieve by 2020 in overall energy production and transport. The targets state that 20% of energy generated in the EU and 10% of energy used in transport should be from renewable means. The directive requires member states to set their own personal targets; these must however be consistent with 2009/28/EC.

From [18] UK Government targets outlined in the UK Government Low Carbon Transition Plan state that around 30% of electricity will be generated from renewable energy sources by 2020. The Scottish Government has also set its own ambitious targets, aiming for 100% of electrical demand to be met from renewable energy by 2020[15].

To encourage the connection of renewables, a number of incentives were introduced by the UK Government including the Feed-in Tariffs (FITs) [1] and Renewable Obligation (RO) [2]. The RO is the most significant incentive for renewable generation development in the UK, where generators are rewarded Renewable Obligation Certificates (ROCs) for each MWh of energy produced by renewable energy sources.

The value of ROC has an important impact on the price paid to the renewable generator for electricity produced. The ROC price is set at a fixed rate for each year, while the market price of electricity fluctuates, and the long term value of the power purchase agreement is typically lower than the average market rate.[20]

The number of ROCs awarded varies depending on the technology, namely to encourage investment in less developed technologies.[12] The value of ROCs is set by Ofgem each year and will change over the years in line with the Retail Price Index (RPI). An example of ROC prices can be found online at the e-ROC website [3]. The current Electricity Market Reform (EMR) [a9] will introduce Contracts for Difference (CfDs) and these will replace ROCs by 2017. The aim of CfDs is to remove the long term exposure of low carbon technologies to volatile electricity prices. CfDs ensure that generators receive payments for energy produced at a fixed price, known as the ‘strike price’. If the electricity price is lower than the strike price, low carbon generators will receive a top-up payment to make up the difference from suppliers. However, if the electricity price is higher than the strike price, then low carbon generators must pay back the difference.

Feed in Tariffs (FITs) apply to any generators smaller than 5 MW and the rates vary depending on the size of installation and the technology used. FIT prices are set by Ofgem each year. Prices for the 2013/2014 period are available on the Ofgem website [4].

5.3 Synthesis of Curtailment Practices and Trends

5.3.1 Reasons for Curtailment

The reasons for curtailment include transmission system constraints, and congestion because of system balancing challenges related to oversupply situations and ramp limitations.

Transmission constraints have been the most common reason for wind curtailments. The construction of new transmission and the adoption of new transmission to increase the transfer capacity on existing transmission system, often lags behind the pace of wind power development. This has researched in an infrastructure that is insufficient to support wind generation on line.

For example, curtailments of wind generation occur when local lines are unable to accept all available wind generation. Consequently, the wind farm owners may choose to undertake an interconnection review that provides sufficient information to ensure a safe interconnection, but it does not indicate whether the wind resource can be delivered into the market while other local resources are also generating. The phenomena has been simulated in *Section 4.5.3*, with the simulated result in *Figure 4.21* of *Chapter 4*. This is particularly problematic for wind generators as the available wind resource tends to compete with other wind generators for limited transmission capacity.

Some wind power generation curtailment has been attributed to challenges in balancing the system operation with higher penetrations of wind energy due to oversupply of generation, typically during low load periods. Some utilities or system operators have curtailed generation from wind plants when minimum generation levels on conventional plants are reached, that is because the payment of stopping and restarting fossil units within a few hours will be significantly more expensive than payment for a few hours of wind curtailment. This type of situation will always occur at night when substantial amounts of wind power output are available but loads are at very low levels. This phenomena will be exacerbated in some small balancing areas.

There are also other reasons for wind power curtailment, such as addressing voltage issues, interconnection issues, and maintain frequency and stability requirements. [9] In this thesis the main focus is the curtailed wind power output caused by transmission congestion.

5.3.2 Compensation of Curtailed Generators

Compensation to curtailment of wind power generations varies across balancing authorities, off takers and typically depends on the cause of curtailment. From Lew et al. (2013) [10,11], internationally, many countries compensate curtailed renewable generators to encourage its development. Compensation varies by types of curtailment, amount compensated, and specific renewable technologies and jurisdictions. [9] Most commonly, generators are compensated at the prevailing market value for the electricity curtailed, but this does not usually include revenue lost from green energy credits or other types of support mechanisms. Examples of this include Ireland and Romania. In other countries, generators are compensated for a fraction of the energy lost—varying from 15% to 50% or more. For example, Greece compensates for 30% of annually curtailed energy, but the compensation only applies to wind facilities. Sometimes, compensation only applies to specific types of curtailments. An often-used dichotomy is that congestion curtailments are compensated while those related to security are not. This is the case in Belgium and Germany. Spain uses another dichotomy: real-time curtailments are compensated (albeit only 15%) while scheduled curtailments due to technical constraints are not. Table 5.1 is the summaries from the interviews about compensation practices for the grid operators and utilities in the United States, the information is reported in [9].

Table 5.1 Summarizes Compensation Practices for the Grid Operators and Utilities in the United States [9]

Utility or Grid Operator	*Compensation Provided?*	*Limits Specified in Contracts*	*Reasons for Compensation*	*Limits to Compensation*
AESO	No		Wind generators are not compensated.	
APS	Yes	x		Limited annually; do not pay if directed by other transmission operators
BPA	OMP curtailment is compensated; DSO is not			Wind generators may absorb costs for OMP.
CAISO	Varies	x	Some contracts for RE brought online before sufficient transmission include compensation	
ERCOT	No		Wind generators are not compensated.	
HECO,HELO ,MECo	No			
ISO New England (ISO-NE)	No	x		No market-based compensation, but off-taker contracts could have some

Utility or Grid Operator	***Compensation Provided?***	***Limits Specified in Contracts***	***Reasons for Compensation***	***Limits to Compensation***
MISO	Yes	x	Wind generators eligible for MISO's make-whole payments; off-taker contracts may specify	
NV Energy	Yes		Compensated for non-emergency situations, or those unrelated to reliability requirements	Curtailment not compensated under specific scenarios
PacifiCorp	Unknown		Unknown	
PJM	Yes		If wind curtailed below economic base point	No compensation if wind resource is not providing required data and following PJM dispatch signals
PSCO	Yes	x	Balancing purposes	Transmission causes beyond control; limited annually
Puget Sound Energy	Follow BPA rules			
Salt River Project	Yes		Take-or-pay contracts	

Utility or Grid Operator	*Compensation Provided?*	*Limits Specified in Contracts*	*Reasons for Compensation*	*Limits to Compensation*
SMUD	Yes		If CAISO curtails due to oversupply, SMUD compensates.	
SPP	Yes (changing with new market rules)	x	Congestion-based curtailment has been compensated.	No compensation for reliability-based curtailment
Tucson ElectricPower	Yes	x	For reasons under TEPs control	No compensation for curtailments caused by others
WAPA	No			

5.3.3 Strategies to Mitigate Curtailment

System operators have developed a variety of strategies to minimize curtailment of wind energy sources. From [8.9] these strategies are part of a broader and extended collection of practices to manage this variability and uncertainty of renewable generation and thereby reduce related curtailments. *Table 5.2.* is a summary of strategies that mitigate wind energy curtailment in the United States , they include management of the changes in the way reserves and conventional generations, automation of curtailment signals, market design issues such as negative pricing, changing transmission planning, and improved renewable energy forecasting.

Table 5.2. Strategies that Mitigate Wind Energy Curtailment in the United States [9]

Reserves and Generation Management	***Utilities or ISOs That Implement***
Automation (i.e., AGC)	ERCOT, PSCO
Use curtailed generators for positive reserves	PSCO
Reduction of minimum generation levels	HECO (Maui) WAPA (adopting)
Increase scheduling frequency	
Market Integration and Negative Bidding	***Utilities or ISOs That Implement***
Economic dispatch	ERCOT, MISO, SPP (adopting)
Negative pricing	CAISO, ERCOT, MISO, PJM, SO-NE (adopting)
Energy imbalance market	CAISO, PacifiCorp
Other Strategies	***Utilities or ISOs That Implement***
Wind power ramp management system	AESO
Increase transmission capacity	ISO-NE, ERCOT, MISO, PJM, SPP
Improve forecasting	ISO-NE, PSCO, NV Energy, SMUD

One of the objectives of the thesis is to try to increase utilisation of wind farm that are currently constrained by the transmission networks. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. In particular the incorporation would look at instances when conventional (typically coal fired) plants have fixed bilateral contracts. These generators are not willing to reduce their output because they will lose earnings. The thesis will investigate maintaining the profit of the generators even if they are curtailed to allow more wind power to be used.

5.4 Flexible Scheduling of Bilateral Contract in the Competitive Electricity Markets

5.4.1 Definition of Bilateral Contract

In bilateral-based market, the load from demand side is free to purchase electrical energy with any generators in the whole power system. The energy purchasing progress is done through bilateral contract with agreed price between a load and a selected generator, and at a specified time period the amount of contractual energy would be delivered. For example, bilateral contract can exist between a generator and a load for 100MW, which should be delivered say on Monday from 9:00 to 9:30 delivery period. That means, on Monday at 9:00 to 9:30, the generator node should generate 100MW to meet the load which required 100MW.

Normally trade in electricity has been modeled as two main forms in the wholesale markets. They are a day-ahead (spot) trade with an hourly coordination of demand side and energy supplier, and a medium or long-term forward trade based on bilateral forward contracts (BCs) between demand and supplier. Bilateral contracts for physical delivery are widely applied in the competitive electricity markets in many countries, and some of them let bilateral trade covering the main portion of electricity delivery.

For stable prices and to reduce the possibility of market power abusing in the "day-ahead" (spot) market, bilateral contracts are commonly used to hedge or mitigate a market price risk. A bilateral contract needs two parties, an electricity energy supplier and a buyer. The suppliers are always the generation companies (GC) or independent power producers, and the buyers are always the electricity supply companies (ESC) on the demand side that sell electricity to local consumers. Both of them forecast the price levels for electricity trading in the spot market and energy demand. [19]

5.4.3 Mathematical Model for Bilateral Contract

Power flow in a network is mainly determined by power consumed by load, power generated by generator and network configuration. If a bilateral contract T_i is added to the power system, energy generation at supply side and consumption at demand side will all increase, and thus changing the power flow in the network. To choose a line between bus *k* and bus *l* (line *k*-*l*), the difference in power flow in line *k*-*l* without T_i and with T_i determines power flow due to T_i, it is denoted as f_{kl,T_i}.

In a pure bilateral market, a number of bilateral transaction would take place. Thus, it can be said the power flow though the transmission system is a combination of power flow caused by various bilateral transactions. The various bilateral transactions are unreached, the simplest way to deal with this is to consider a linear DC based power flow [19,21].

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A DC-based distribution factor, PTDF [21] is used to determine the sensitivity of the flow of a particular line due to a change in power injection at any bus, as follows;

$$\Delta f_{kl,m} = PTDF_{kl,m}\Delta P_m \qquad (5\text{-}1)$$

Where,

$\Delta f_{kl,m}$: change in power flow in line *k*-*l*

$PTDF_{kl,m}$: sensitivity of power flow due to a unit change in power injection at bus m

ΔP_m : change in power injection at bus m

Mathematically, a bilateral transaction between a generator and a load can be modelled by positive power injection at one bus (generator bus) and negative power injection of the same magnitude at another bus (load bus). Thus, the flow of a particular line due to transaction i, T_i (between generator at bus m and load at bus n), is calculated as follows:

Changing in power flow in line *k*-*l* due to a change at bus m;

$$\Delta f_{kl,m} = PTDF_{kl,m}\Delta P_m \qquad (5\text{-}2)$$

Changing in power flow in line *k*-*l* due to a change at bus n;

$$\Delta f_{kl,n} = PTDF_{kl,n}\Delta P_n \qquad (5\text{-}3)$$

Similarly:

$$\Delta f_{kl,n} = PTDF_{kl,n}(-\Delta P_m) \quad \text{as} \;\; \Delta P_n = -\Delta P_m \qquad (5\text{-}4)$$

Thus, change in power flow in line *k*-*l* due to transaction i (change at bus m and bus n simultaneously);

$$\Delta f_{kl,T_i} = \Delta f_{kl,m} + \Delta f_{kl,n} = (PTDF_{kl,m} - PTDF_{kl,n})\Delta P_m \qquad (5\text{-}5)$$

Rewritten the equation:

$$f_{kl,T_i} = (PTDF_{kl,m} - PTDF_{kl,n})P_{T_i} \qquad (5\text{-}6)$$

Where:

f_{kl,T_i}: contribution of transaction T_i, between generator at bus m and load at bus n to the power flow in line *k-l*

P_{T_i} : amount of contractual energy of bilateral transaction T_i

5.4.3 Contracts with Flexible Scheduling

Price of electricity is an important issue in competitive market. The primary aim of electricity pricing is to achieve market efficiency. The spot market and bilateral contract market may influence and interact with each other. The volumes and prices stipulated in bilateral contract may influence the trade volumes and prices in the spot market. And the spot market risks and price behavior have resulted in the contract arrangement strategy.

Bilateral contracts can serve purposes beyond merely supplying electricity energy. These contracts can also be used to manage risk and reduce the impact of market power in the electricity market. Typical contracts for the allocation of risk are futures and options contracts. The options contract, by nature, has some flexibility in that the buyer of the contract must make a decision on whether or not to exercise the options. To achieve greater flexibility in contracts, the scheduling decisions become more complex.

A flexible bilateral contract requires scheduling of demand side or energy supplier. In other words, the buyer or seller will have to make decisions on the usage of contracts for some particular market condition, for example, scheduling of the amounts to buy or sell and their timing depending on the market environments.

This scheduling problem can be formulated as a sequential decision-making process that depends on the realization of random variables. In some publication, these random variables can be the electricity spot price or equipment failure. Here the focus is on how to price the flexible volume of bilateral contract (involved scheduling problem) and maintain the profit of the conventional generators; the conventional generators with fixed bilateral contracts, and the volume of the contracts will be curtailed to allow more wind power to be used in the power system.

5.4.4 Compensative Price for the Bilateral Contract Curtailment

To relieve an overloaded line is to reduce the power flow through the line by curtailing the contractual energy of bilateral transactions. In the electricity market, nobody wants their energy contracts to be curtailed by the ISO. If curtailment of bilateral transaction is unavoidable, the curtailed transactions should receive compensation money from ISO. Compensative price here means the compensation money per unit MW curtailment that the ISO pays bilateral transactions that been curtailed.

In the event of security problem occurrence, which needs for transaction curtailment, as curtailment of each transaction has different sensitivity in reducing the overloaded line, the ISO would try to minimize the total cost of energy curtailment of all transaction, while keeping the flow on the overloaded line below its limit. In other words, the ISO tries to minimize the compensation cost that the ISO has to pay to the curtailed transactions.

Mathematically, it can be formulated by the following optimization problem;

$$\min \sum_{all\, T_j} CP_{T_j}\, P_{T_j}^{curtail} \qquad (5\text{-}7)$$

Subject to:

$$f_{kl} - \sum_{all\, T_j} f_{kl,T_j}^{curtail} \leq f_{kl}^{lim}$$

$$\sum_{all\, T_j} f_{kl,T_j}^{curtail} = \sum_{all\, T_j} (PTDF_{kl,T_j}) P_{T_j}^{curtail}$$

$$PTDF_{kl,T_j} = PTDF_{kl,m} - PTDF_{kl,n}$$

Where,

CP_{T_j}: Compensative price of transaction j

T_j : the transaction between generator at node m and load at node n

$PTDF_{kl,T_j}$: the sensitivity of the flow of line k-l due to transaction j, T_j

5.5 Summary

Wind power to be curtailed mostly because it generates power during hours of low load. Most curtailment has occurred when insufficient transmission capacity for power flow caused by wind power integration. Some generators are not dispatched by the market and can be subject to manual curtailments primarily due to congestion. As penetrations of wind energy increase, curtailment practices and the use of strategies to mitigate the potential for curtailment become increasingly significant and may impact wind energy project economics.

While almost every country is experiencing some forms of curtailing for wind power resources, with more attention being paid for the technologies and strategies. The relative magnitude of curtailment is dropping but the amount of wind power integration is increasing. Rebuild or construction of transmission system, new transmission capacity and better operating practices, are now resolving challenges for system operators. Some of the reduction could be attributed to market changes.

Some of the curtailment order is often based on plant economics or the ability to alleviate local congestion. An important objective is to try to increase utilisation of wind farm that are currently constrained by the transmission networks. Contracts between conventional generators and off-takers have in some cases included fixed bilateral contract volumes. There will be compensated for curtailment for reasons used to match the limitation of flexible schedule in the competitive power market. These conventional generators are not willing to reduce their output because they will lose earnings. The approach is looking at maintaining the profit of the generators even if they are curtailed to allow more wind power to be used. In wholesale power markets, the system operator need to compensate if it calls for units to deviate from initial dispatch orders.

To increase wind generators’ participation alongside conventional generators and minimize the curtailments, market solutions that base dispatch levels on economics offer the advantages of creating transparency and efficiency in curtailment procedures. The details involved is the market-based approaches and their associated automation will be covered in the following chapter.

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Chapter 6

Proposed Operational Practice and Market Decision to Enhance Penetration of Wind Power

6.1 Introduction

In the *Chapter 4*, the impacts of wind power integrating into the power system have been discussed. Wind is variable and unpredictable, a sudden change in wind speed will significantly change a wind farm's power output. System generation – load balance, generating system reliability and system operation security are the main points for the power network operation. Although most countries in the world do support wind power development, yet when it comes to consider the system operating security, many of the wind energy is still being curtailed. In the *Chapter 5,* a brief description about the current phenomena of wind power curtailment in the world has been included, the reasons of wind power curtailment, the experiences of the utilities and system operators for curtailment of wind power in some country have been mentioned.

In the *Chapter 5*, bilateral contract curtailment methods are discussed, curtailments of conventional generator energy contracts affect both loads and generators business strategies. In this thesis, the proposed operational practice is to try to enhance penetration of wind power into the system operation while many of them have been curtailed due to the system security operation constraints. Conventional generators may fail to re-sell their curtailed energy contracts resulting in reduced profits. The proposed approach is looking at maintaining the profit of the conventional generators even if they are curtailed to allow more wind power to be used. The proposed operational method is introduced initially to be operating with mixed bilateral market to solve energy imbalances problem due to mismatch between contractual and actual energy demand.

Theoretically, in the Optimal Power Flow (OPF) with security constrained, the basic objective is to minimize the cost of meeting the load, and at the same time, the system is able to respond to the contingencies. Contingencies are treated as a set of physical constraints on the optimization problem. In this chapter, an alternative way is proposed to determine the optimal dispatch in the market. The proposed objective function minimizes the total production costs of energy with the curtailment of conventional generators' bilateral contract. In the proposed objective function, the optimal pattern of compensation for the curtailment bilateral contract from selected conventional generators is defined endogenously and it adjusts to the changes in the physical and market conditions of the network.

This chapter begins with *a* discussion on the use of conventional generator's bilateral contract for managing congestion to relieve the curtailment of wind power generation. *Section 6.3* describes the methodology of the proposed method and its mathematical model details are presented in this section. Finally, two simulation scenarios are presented in *Section 6.4*. The modified *IEEE 9-Bus* system is used to verify the proposed theory.

6.2 The Proposed Operational Practice

The main problem in managing transmission constraint in pure bilateral-based market is that the ISO doesn't have control on outputs of generators. The schedules of each generator in transaction depend on their bilateral contracts. For example, if a generator has a bilateral contract of 200MW to be delivered at 10:00am on Monday, its generation schedule is 200MW at that period. If a transmission line is overloaded at that moment, the ISO deals with this phenomena through curtailment of the bilateral contracts.

The new method is proposed for managing congestion problem and relieve curtailment of wind power. There are two key elements of the proposed method: 1) to relieve congestion problem; 2) how to deal with the curtailment of wind power.

6.2.1 Generation Adjustment Using Linear Programming

In practice, for the real power system, it consists of hundreds or even thousands of buses interconnected together with thousands of transmission lines. The objective is to adjust generation schedules that relieve all overloaded transmission lines. Linear programming is a mathematical programming technique and maintain a linear objective function subjective to a set of linear constraints. In [5], this mathematical programming technique has been applied for the calculation of power system security control. In the reference [3], the application of linear programming for economics, planning and operations for the power system has been discussed. From [2, 4], the algorithm of Linear programming generation adjustment can be expressed as in the following.

Objective Minimizes:

> The total cost of generation adjustment (sum of total MW increment/decrement of generation cost)

Subject to (constraints):

1. The total MW increment of the generators must be equal to the total MW decrement of the generators.
2. All power flow on transmission lines must be within limits.
3. The generators must remain within their MW increment and decrement limits.

The objective function of generation adjustment can be mathematically expressed as:

Minimizes: $\sum_{all\ G_i} C_{G_i}^{+} \Delta P_{G_i}^{+} + C_{G_i}^{-} \Delta P_{G_i}^{-}$ (6.1)

Where

$\Delta P_{G_i}^{+}$ is the MW increment variables of generator *i*

$\Delta P_{G_i}^{-}$ is the MW decrement variables of generator *i*

$C_{G_i}^{+}$ is the cost of MW increment of generator *i*

$C_{G_i}^{-}$ is the cost of MW decrement of generator *i*

The first constraint: $\sum_{all\ G_i} \Delta P_{G_i}^{+} = \sum_{all\ G_i} \Delta P_{G_i}^{-}$ (6.2)

Where

$\sum_{all\ G_i} \Delta P_{G_i}^{+}$ is the total MW increment of generators

$\sum_{all\ G_i} \Delta P_{G_i}^{-}$ is the total MW decrement of generators

Assuming that the system losses and total loads are fixed, the constraint above indicates the total MW increment of all generators must be equal to the total MW decrement of all generators, and during this progress system is kept in balance.

The second constraint (DC-load flow model):

$$f_l = f_l^0 + \sum_{all} DF_{l,G_i} \Delta P_{G_i} \qquad (6.3)$$

$$-f_l^{max} \leq f_l \leq f_l^{max} \qquad (6.4)$$

The linear transmission line flow function can be expressed as above, where

f_l^0 is the initial flow of line *l*

DF_{l,G_i} is the distribution factor(sensitivities) of the power flow of line *l* due to the power injection at generator on bus *i*

ΔP_{G_i} is the change of output of generator on bus *i*

f_l^{max} is the maximum limit of power flow on line *l*

Equation 6.4 can be expanded as follow:

$$-f_l^{max} \leq f_l^0 + \sum_{all} DF_{l,G_i} \Delta P_{G_i} \leq f_l^{max} \qquad (6.5)$$

And then, this two-sided inequality is expressed as two one-sided inequalities as follows:

$$\sum_{all} DF_{l,G_i} \Delta P_{G_i} \leq f_l^{max} - f_l^0 \qquad (6.6)$$

and $$\sum_{all} DF_{l,G_i} \Delta P_{G_i} \geq -f_l^{max} - f_l^0 \qquad (6.7)$$

And for the *Equation 6.6* and *Equation 6.7,* ΔP_{G_i} can be substituted by $\Delta P_{G_i}^{+}$ and $\Delta P_{G_i}^{-}$, so the inequalities can be expressed as follows:

$$\sum_{all} DF_{l,G_i} (\Delta P_{G_i}^{+} - \Delta P_{G_i}^{-}) \leq f_l^{max} - f_l^0 \qquad (6.8)$$

and $$\sum_{all} DF_{l,G_i}(\Delta P_{G_i}^{+} - \Delta P_{G_i}^{-}) \geq -f_l^{max} - f_l^{0} \tag{6.9}$$

The third constraint:

$$0 \leq \Delta P_{G_i}^{+} \leq \Delta P_{G_i}^{offer} \tag{6.10}$$

$$-\Delta P_{G_i}^{bid} \leq \Delta P_{G_i}^{-} \leq 0 \tag{6.11}$$

Where

$\Delta P_{G_i}^{offer}$ is the submitted energy offers from generator on bus *i* to ISO

$\Delta P_{G_i}^{bid}$ is the submitted energy bids from generator on bus *i* to ISO

Equation 6.10 and *Equation 6.11* are the constraints concerning generators' MW increment and decrement limit, these limits depend on the energy incremental bids (offers) and decrement bids (offers) submitted to the system operators. For example, in the power market, a generator submitted energy incremental offers of 20MW and decrement bids 30MW to the ISO, the increment limit of this generator is 20MW and its decrement limit is 30MW. In other words, the ISO can only increase the output of this generator at a maximum of 20MW, as well as decrease its output within 30MW from its initial generation dispatch.

6.2.2 The Proposed Market Decision to Enhance Wind Power

To solve wind power curtailment problem caused by transmission congestion in bilateral-based market, it is hopeful that the ISO action would be sufficient to solve congestion provided that all generators participate in Power Market and all generators submitted their incremental bid energy (offers) up to their maximum generation capacity and their decremental bid energy (Bids) equal to its scheduled generation. Thus the generators can be adjusted from zero generation up to the maximum generation capacity.

The proposed bilateral contract curtailment method for mixed bilateral-based market can be illustrated in a diagram shown in *Figure 6.1.* A conventional generator and a load that has signed a bilateral contract formed a bilateral transaction. Each transaction must submit the details of their bilateral trading to the ISO, which includes the amount of contractual energy and the delivery period. Also, all conventional generators submit their incremental/decremental bids to power market. Using information from the submitted bilateral trading, the ISO would then run power flow analysis to check the security of the system. The ISO would use the incremental/decremental bids from conventional generators to optimally adjust the total expected cost (the combined production costs of energy and compensation for the curtailment of conventional generators' bilateral contract) to a minimum.

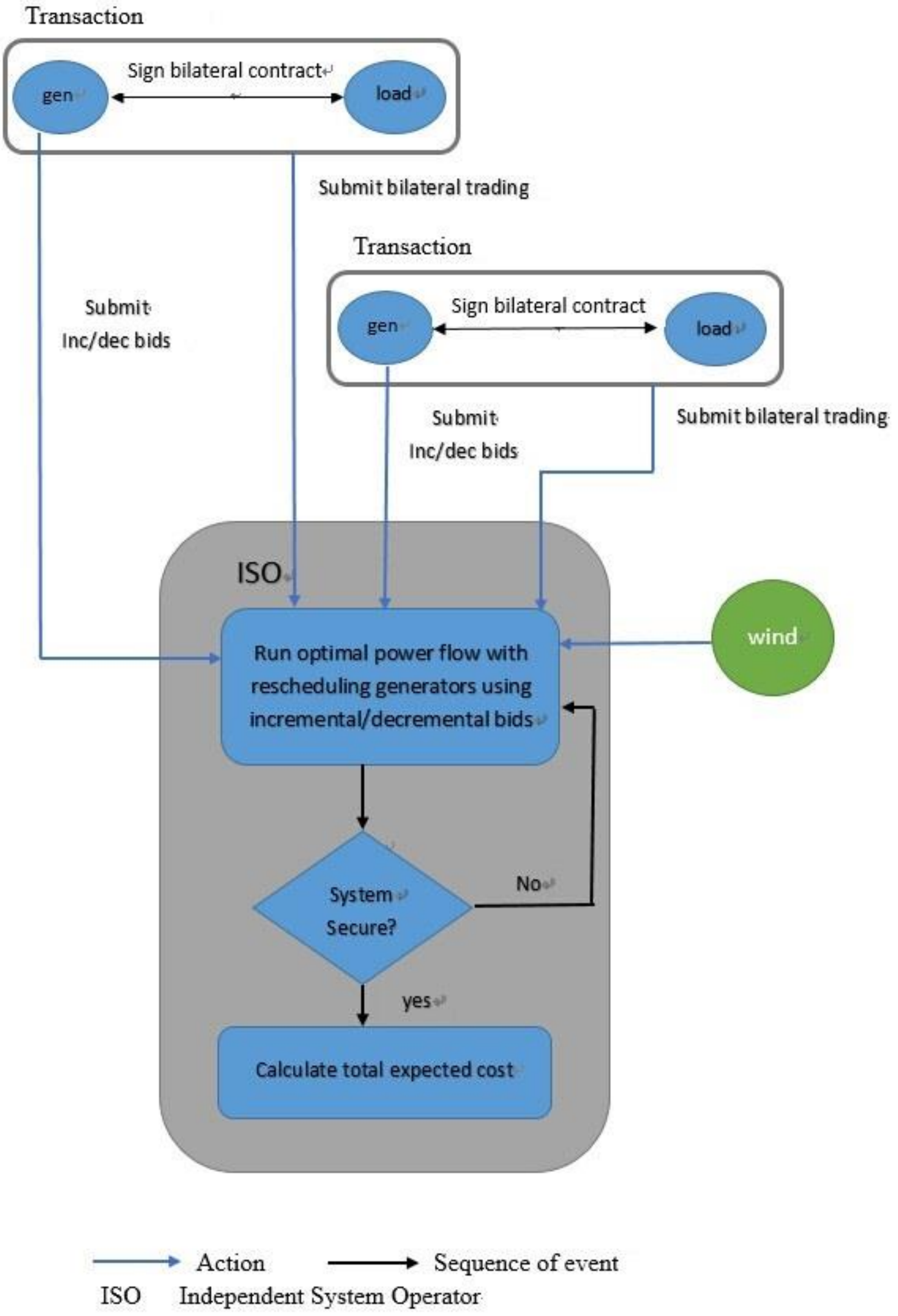

Figure 6.1 Illustration of the proposed bilateral contract curtailment method [1]

6.3 Mathematical Model for the Proposed Approach

The proposed method will adopt the Linear Programming (LP) approach presented in section 6.2.1 to find the optimum generation adjustments that would relieve curtailment of wind power at minimum cost. The following subsections discuss the mathematical model that has been adopted for the LP optimization problem

6.3.1 Incremental/Decremental Bids

Incremental bids are the price at which a generator is willing to increase its generation while decremental bids are the price at which a generator is willing to decrease its generation from the scheduled generation in bilateral market. In this chapter, incremental/decremental bids are known as the forced bilateral contracts on conventional generators by the ISO to enhance more wind power generation integrating into the power system. In power market, incremental/decremental bids are also known as Offer/Bids, thus to avoid confusion, the words “incremental/decremental bids” are used throughout this thesis.

In the proposed method, the curtailment of wind power energy is caused by transmission congestion, and in the mixed transactions, some conventional generation have the bilateral contracts with demand side, and all generators must participate in the market by submitting Offers/Bids. For a specific delivery period, each generator can submit more than one incremental/decremental bid for different incremental/decremental energy. However the total submitted incremental energy of a generator must be equal to its available supply capacity and the total submitted decremental energy must be equal to its scheduled generation. For example, if a conventional generator with a generation capacity of 250MW is scheduled to generate

160MW at a specific delivery period, at the same time, it should submit in total of 90MW incremental energy and in total of 160MW decremental energy to the ISO. This would allow the ISO to adjust the output of generator from zero or up to its maximum output to relive the transmission congestion and to let total wind power energy integrating into the power system. From 160MW of submitted decremental energy, the conventional generators submit their incremental/decremental bid with price, for example, the ISO should pay the first 30MW decremental energy at £30/MW, the next 20MW decremental energy at £35/MW and the remaining at £40/MW.

6.3.1.1 Incorporating Incremental/Decremental Bids

Considering a generator with a capacity of P^{max} scheduled to generate P^0 at a specific delivery period. It submits N_i incremental bids and N_d decremental bids. BP^{+i} represents incremental bid price of each submitted incremental energy and BP^{-d} represents decremental bid price of each submitted decremental energy.

The relationship can be illustrated in a graph shown in *Figure 6.2*. [1]

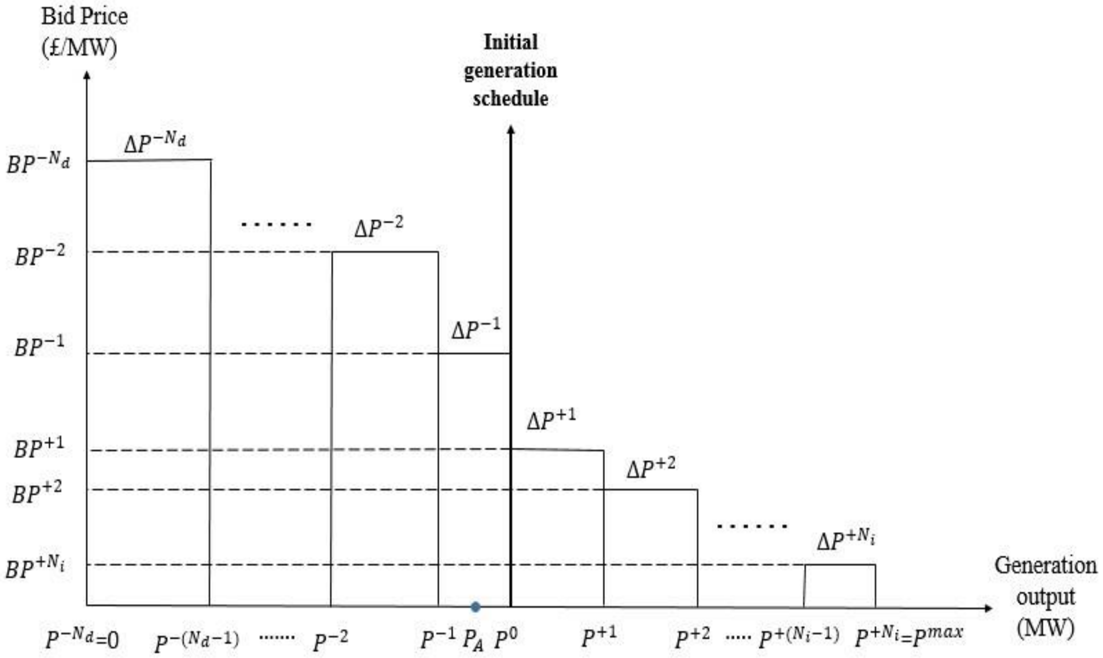

Figure 6.2 Illustration of Incremental/Decremental Bids

Figure 6.2 is the illustration of incremental/decremental bids, where,

$$\begin{array}{ll} \Delta P^{+1} = P^{+1} - P^0 & \Delta P^{-1} = P^0 - P^{-1} \\ \Delta P^{+2} = P^{+2} - P^{+1} & \Delta P^{-2} = P^{-1} - P^{-2} \\ \vdots & \vdots \\ \Delta P^{+N_i} = P^{+N_i} - P^{+(N_i-1)} & \Delta P^{-N_d} = P^{-N_d} - P^{-(N_d-1)} \end{array} \tag{6.12}$$

In order to model the submitted incremental/decremental bids shown in *Figure 6.2* into new objective function, the increment/decrement limit for each incremental/decremental price must be defined. Consider a generator output of P_A in *Figure 6.2,* which is between P^0 and P^{-1}. P_A is a result of P_A^- decrement from P^0, thus $P_A = P^0 - P_A^-$.

In order for P_A^- to have decremental price of BP^-(£/MW), the output of the generator must be between P^0 and P^{-1}. Thus;

$$P^{-1} \leq P_A \leq P^0 \qquad (6.13)$$

While $P_A = P^0 - P_A^-$ and $P^{-1} = P^0 - \Delta P^{-1}$, thus *inequality (6.13)* becomes;

$$P^0 - \Delta P^{-1} \leq P^0 - P_A^- \leq P^0 \qquad (6.14)$$

Substract P^0 from the *inequality 6.14,* thus

$$P^0 - \Delta P^{-1} - P^0 \leq P^0 - P_A^- - P^0 \leq P^0 - P^0 \qquad (6.15)$$

$$0 \leq P_A^- \leq \Delta P^{-1} \qquad (6.16)$$

As P_A^- is a decrement from 0, rewritten *inequality 6.16* into standard form, thus the decrement limit for decremental price of BP^{-1} is:

$$0 \leq P^{-1} \leq \Delta P^{-1,lim} \qquad (6.17)$$

Now consider if P_A is between P^{-1} and P^{-2}, thus;

$$P^{-2} \leq P_A \leq P^{-1} \qquad (6.18)$$

P_A now is a result of P_A^- decrement from P^{-1}, thus $P_A = P^{-1} - P_A^-$

Or similarly,

$$P_A = P^0 - \Delta P^{-1} - P_A^- \qquad (6.19)$$

We also know that $P^{-1} = P^0 - \Delta P^{-1}$ and $P^{-2} = P^0 - \Delta P^{-1} - \Delta P^{-2}$, thus *inequality 6.18* becomes;

$$P^0 - \Delta P^{-1} - \Delta P^{-2} \leq P^0 - \Delta P^{-1} - P_A^- \leq P^0 - \Delta P^{-1} \qquad (6.20)$$

Substract $P^0 - \Delta P^{-1}$ from the inequality in 6.20, thus

$$P^0 - \Delta P^{-1} - \Delta P^{-2} - (P^0 - \Delta P^{-1}) \leq P^0 - \Delta P^{-1} - P_A^- - (P^0 - \Delta P^{-1}) \leq P^0 - \Delta P^{-1} - (P^0 - \Delta P^{-1}) \qquad (6.21)$$

So $0 \leq P_A^- \leq \Delta P^{-2}$ (6.22)

As P_A^- is a decrement from P^{-1}, rewritten equation 6.22 into stand form, thus the decrement limit for decremental price of BP^{-2} is:

$$0 \leq P^{-2} \leq \Delta P^{-2,lim} \qquad (6.23)$$

The incremental/decremental limit for generator i, G_i for all inc/dec bid prices can be found in a similar manner. The limits are as follows:

Incremental Bids:

$$0 \leq \Delta P_{G_i}^{+1} \leq \Delta P_{G_i}^{+1,lim}, 0 \leq \Delta P_{G_i}^{+2} \leq \Delta P_{G_i}^{+2,lim}, \cdots\cdots, \ 0 \leq \Delta P_{G_i}^{+N_i} \leq \Delta P_{G_i}^{+N_i,lim} \quad (6.24)$$

Decremental Bids:

$$0 \leq \Delta P_{G_i}^{-1} \leq \Delta P_{G_i}^{-1,lim}, 0 \leq \Delta P_{G_i}^{-2} \leq \Delta P_{G_i}^{-2,lim}, \cdots\cdots, \ 0 \leq \Delta P_{G_i}^{-N_d} \leq \Delta P_{G_i}^{-N_d,lim} \quad (6.25)$$

6.3.1.2 Generators Bidding Strategies

The incremental/decremental bid prices depend on the generators' bidding strategy. However it should reflect the cost curve of a generator. *Figure 6.3* shows an example of generation cost curve. The generation cost increases as MW output increases.

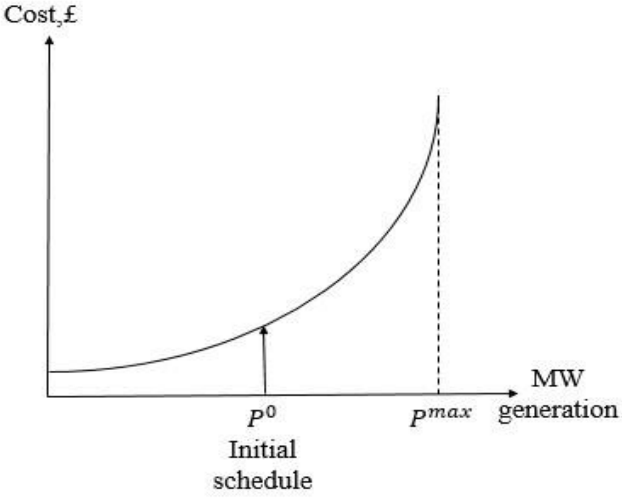

Figure 6.3. An Example of Generation Cost Curve

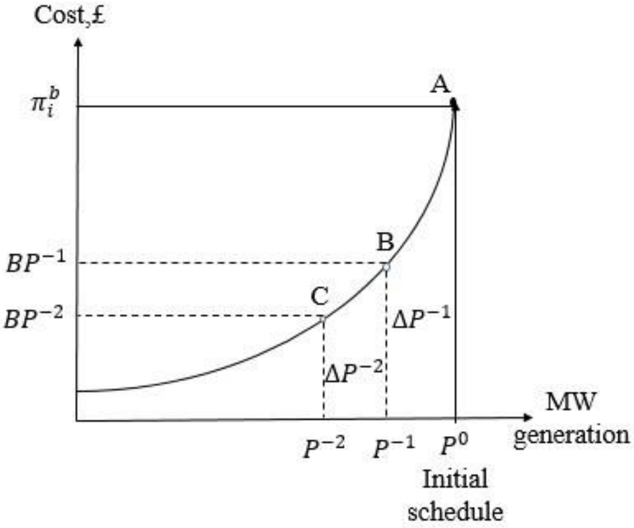

Figure 6.4 Selection of Points on Generation Cost Curve for Enforced inc/dec Bids

It is proposed that each generator selects a number of points in its generation cost curve which would best represent its forced curtailed parts of bilateral contracts. The corresponding MW generation and paid for these points could be used as the generators inc/dec bids. To illustrate this, a generation cost curve of a generator as shown in *Figure 6.4* is considered. The generator is schedule to generate P^0 with the price of bilateral contract as π_i^b during deliver period, which is shown in the *Figure 6.5* as the point A. In order to enhance penetration of wind power generation integrating into the power system, relieve the curtailment of wind generation, the proposed strategy of power market will force to reduce the bilateral contract of conventional generator. In order to submit an inc/dec bids to the ISO, the conventional generator may operate at point B and C on its generation cost curve as shown in *Figure 6.4.* ΔP^{-1}, ΔP^{-2} is the two decremental energy bids for the conventional generator with decremental bid price of BP^{-1}, BP^{-2} respectively. If a conventional generator is selected to decrease it output down to P^{-1}, the shaded area shown in *Figure 6.5* represent the profit lost by the generator.

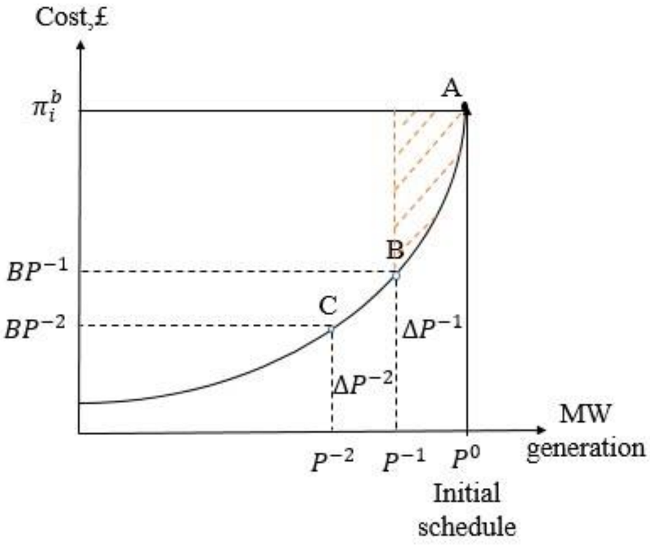

Figure 6.5 Profit Lost by Conventional Generator When the Decrease Bids is BP^{-1} (Represented by the Shaded Area)

6.3.2 Proposed Optimization Function

The proposed method will adopt the Linear Programming approach presented in *Section 6.2.1* to find the optimum conventional generation adjustments that would relieve curtailment of wind power generation at minimum cost. The objective of the proposed method is to try to increase utilisation of wind farm that are currently constrained by the transmission networks. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. In particular the incorporation would look at instances when conventional (typically coal fired) plants have fixed bilateral contracts. These generators are not willing to reduce their output because they will lose earnings. This incorporation will look at maintaining the profit of the generators even if they are curtailed to allow more wind power to be used.

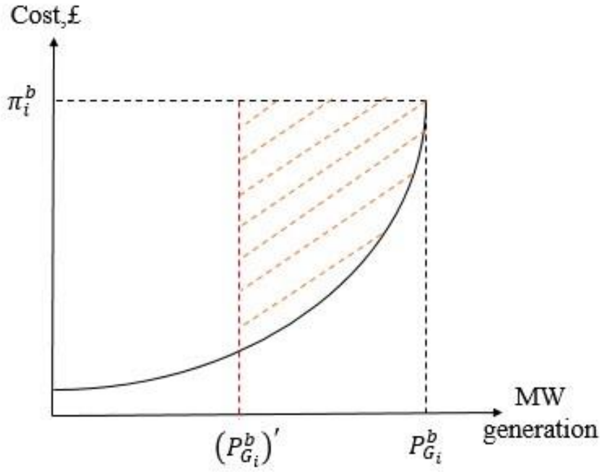

Figure 6.6 Profit Lost by the Selected Conventional Generator (Represented by the Shaded Area)

As shown in *Figure 6.6*, when the operation of generator i is under the full Bilateral Contract, the profit of it is shown as following,

$$\mathrm{P}\varepsilon_i = \pi_i^b {\mathrm{P}_{\mathrm{G}}}_i^b - C({\mathrm{P}_{\mathrm{G}}}_i^b) \tag{6.26}$$

π_i^b is given as constant, this is the price of the bilateral contract. $C({\mathrm{P}_{\mathrm{G}}}_i^b)$ is the generation cost when the selected conventional generator' output is ${\mathrm{P}_{\mathrm{G}}}_i^b$, ${\mathrm{P}_{\mathrm{G}}}_i^b$ will be delivered at one period for the bilateral contract.

After curtailment of the selected conventional generation, the profit of it will be shown as follow,

$$\begin{aligned}\mathrm{P}\varepsilon_i{}' &= \pi_i^b (\mathrm{P_G}_i^b)' - C\left[\left(\mathrm{P_G}_i^b\right)'\right] \\ &= \pi_i^b\left(\mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i\right) - C\left[\left(\mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i\right)\right] \qquad (6.27)\end{aligned}$$

In the *Equation 6.27*, $(\mathrm{P_G}_i^b)' = \mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i$, $\Delta\mathrm{P_G}_i$ is the curtailed part for the output of conventional generation which is forced by the ISO to relieve the curtailment of wind power generation.

As shown in *Figure 6.6*, represented by the shaded area is the change in profit of selected conventional generator due to curtailment and is presented as *Equation 6.28*.

$$\begin{aligned}\pi_i^c \Delta\mathrm{P_G}_i &= \mathrm{P}\varepsilon_i - \mathrm{P}\varepsilon_i{}' \\ &= \pi_i^b \mathrm{P_G}_i^b - C\left(\mathrm{P_G}_i^b\right) - \pi_i^b\left(\mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i\right) + C\left[\left(\mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i\right)\right] \\ &= \pi_i^b \mathrm{P_G}_i^b - \pi_i^b\left(\mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i\right) - \left\{C\left(\mathrm{P_G}_i^b\right) - C\left[\left(\mathrm{P_G}_i^b - \Delta\mathrm{P_G}_i\right)\right]\right\} \qquad (6.28) \\ &= \pi_i^b \Delta\mathrm{P_G}_i - \Delta C_i\end{aligned}$$

π_i^c is the minimum price for the generators who asked for the curtailment. Therefore, π_i^c will cover loss and profit and will be as follow,

$$\begin{aligned}\pi_i^c &= \frac{\pi_i^b \Delta\mathrm{P_G}_i - \Delta C_i}{\Delta\mathrm{P_G}_i} \\ &= \pi_i^b - \frac{\Delta C_i}{\Delta\mathrm{P_G}_i} \qquad (6.29)\end{aligned}$$

Now the proposed objective function for this problem is

$$\min\left[C\left(\mathrm{P_G}_i\right) + \pi_i^c \Delta \mathrm{P_G}_i\right] \tag{6.30}$$

i.e.

$$\min\left[C\left(\mathrm{P_G}_i\right) + \left(\pi_i^b - \frac{\Delta C_i}{\Delta \mathrm{P_G}_i}\right)\Delta \mathrm{P_G}_i\right]$$

$$= \min\left[C\left(\mathrm{P_G}_i\right) + \pi_i^b \Delta \mathrm{P_G}_i - \Delta C_i\right] \tag{6.31}$$

$\Delta \mathrm{P_G}_i$ is the curtailed part for the output of conventional generation which is forced by the ISO to relieve the curtailment of wind power generation.

New problem to solve

$$\min\left[C\left(\mathrm{P_G}_i\right) + \pi_i^b \Delta \mathrm{P_G}_i - \Delta C_i\right] \tag{6.32}$$

where

$$\Delta C_i = C\left(\mathrm{P_G}_i^b\right) - C\left[\left(\mathrm{P_G}_i^b - \Delta \mathrm{P_G}_i\right)\right] \tag{6.33}$$

For the Optimal Power Flow (OPF) with security constrained, the basic objective is to minimize the cost of meeting load, and at the same time, the operation is able to respond to the contingencies. Covering the contingencies is treated as a set of physical constraints on the optimization. These constraints are as follow:

$$\mathrm{P}_{G_i} - \mathrm{P}_{d_i} = \mathrm{P}(\delta, \mathrm{V}) \tag{6.34}$$

$$\mathrm{Q}_{G_i} - \mathrm{Q}_{d_i} = \mathrm{Q}(\delta, \mathrm{V}) \tag{6.35}$$

$$\mathrm{P_G}_i^{min} \le \mathrm{P_G}_i \le \mathrm{P_G}_i^{max}$$

$$\mathrm{Q_G}_i^{min} \le \mathrm{Q_G}_i \le \mathrm{Q_G}_i^{max}$$

$$V_i^{min} \le V_i \le V_i^{max}$$

$$-\mathrm{P}_{f_{ij}}^{max} \le \mathrm{P}_{f_{ij}} \le \mathrm{P}_{f_{ij}}^{max}$$

Where:

P_{G_i} : Power produced by generator i

$P_{G_i}^{max}$: Maximum generation capacity of generator i

$P_{G_i}^{min}$: Minimum generation capacity of generator i

Q_{G_i} : Reactive Power produced by generator i

$Q_{G_i}^{max}$: Maximum reactive generation capacity of generator i

$Q_{G_i}^{min}$: Minimum reactive generation capacity of generator i

V_i: Voltage at bus i

V_i^{max}: Maximum voltage value at bus i

V_i^{min}: Minimum voltage value at bus i

$\mathrm{P}_{f_{ij}}$: Power flow between bus i to bus j

$\mathrm{P}_{f_{ij}}^{max}$: Maximum power flow between bus i to bus j

The proposed objective function minimizes the total expected cost (the combined production costs of energy and compensation for the curtailment of conventional generators' bilateral contract) for the base case (intact system), which is presented in mathematical model as shown in *Equation 6.32* and 6.33. In the proposed objective function, the optimal pattern of compensation for the curtailment of conventional generators' bilateral contract is determined endogenously and it adjusts to changes in the physical and market conditions of the network. The new optimal function need to consider the following aspects.

Need to include constraints:

$$\mathrm{P}_{\mathrm{G}_i}^{b} - \Delta\mathrm{P}_{\mathrm{G}_i} \leq \mathrm{P}_{\mathrm{G}_i} \leq \mathrm{P}_{\mathrm{G}_i}^{max} \tag{6.36}$$

$$0 \leq \Delta \mathrm{P}_{\mathrm{G}_i} \leq \Delta \mathrm{P}_{\mathrm{G}_i}^{max} \tag{6.37}$$

Where:

$\mathrm{P}_{\mathrm{G}_i}^{b}$	Power output of conventional generator i with bilateral contract
$\mathrm{P}_{\mathrm{G}_i}$	Power produced by conventional generator i
$\mathrm{P}_{\mathrm{G}_i}^{max}$	Maximum generator capacity of conventional generator i
$\Delta \mathrm{P}_{\mathrm{G}_i}$	Change of power output for conventional generator i due to forced curtailment
$\Delta \mathrm{P}_{\mathrm{G}_i}^{max}$	Maximum change of power output for conventional generator i due to forced curtailment

6.3.3 Flowchart

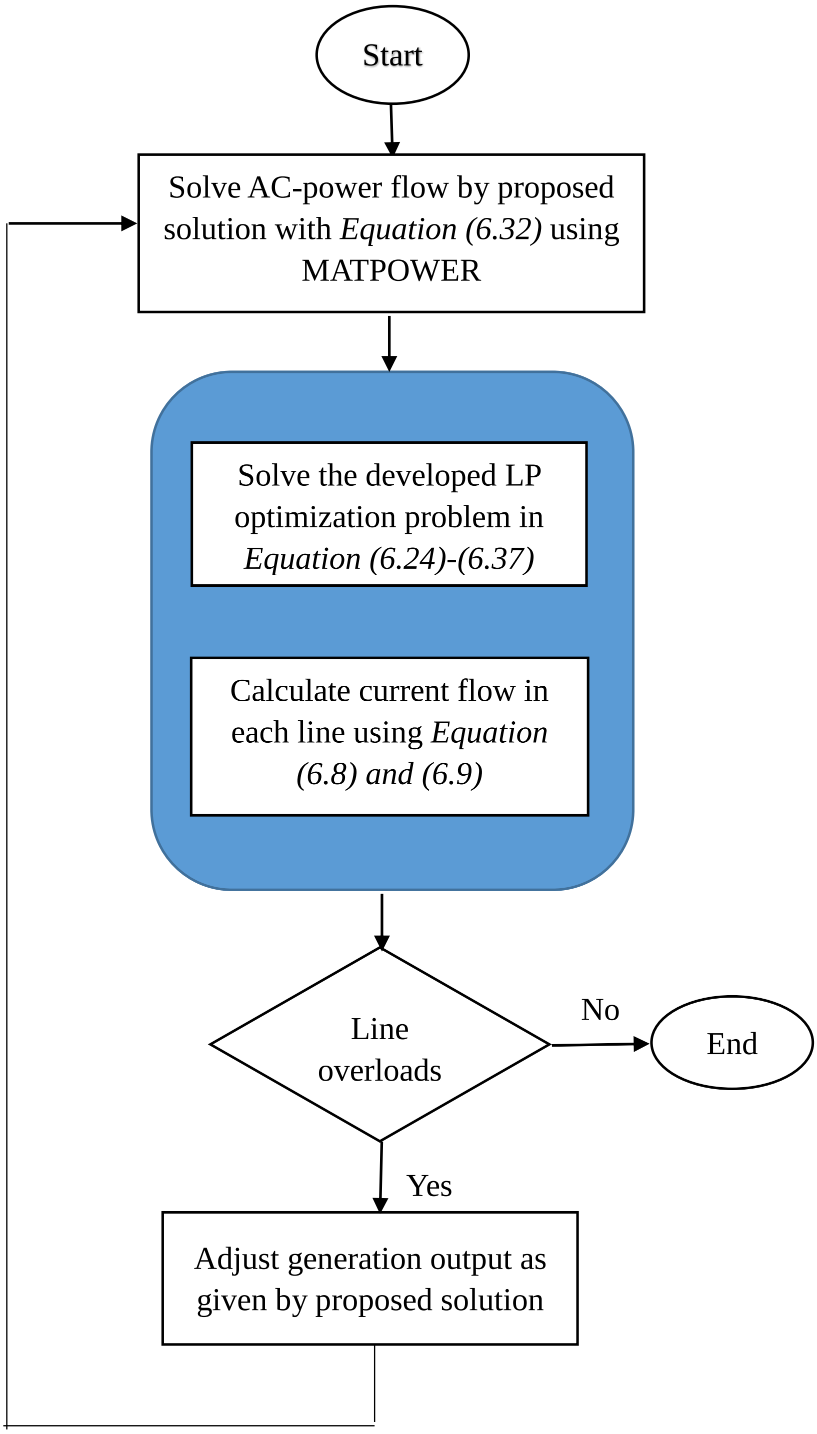

Figure 6.7 Flowchart of the Generation Adjustment Algorithm

6.4 Case Studies

6.4.1 Data and Assumptions for the Test System

These case studies are based on a *9-bus* test network (*Figure 6.8*) that has been used extensively in my research to test the performance of different market designs using the *MATPOWER* platform. The basic system data are shown in *Table 6.1*. and is a four generators system. Wind power generation is connected to bus 8. Using the assumption that mixed bilateral power market is perfectly competitive, offers submitted by generating units correspond to their marginal costs of energy production.

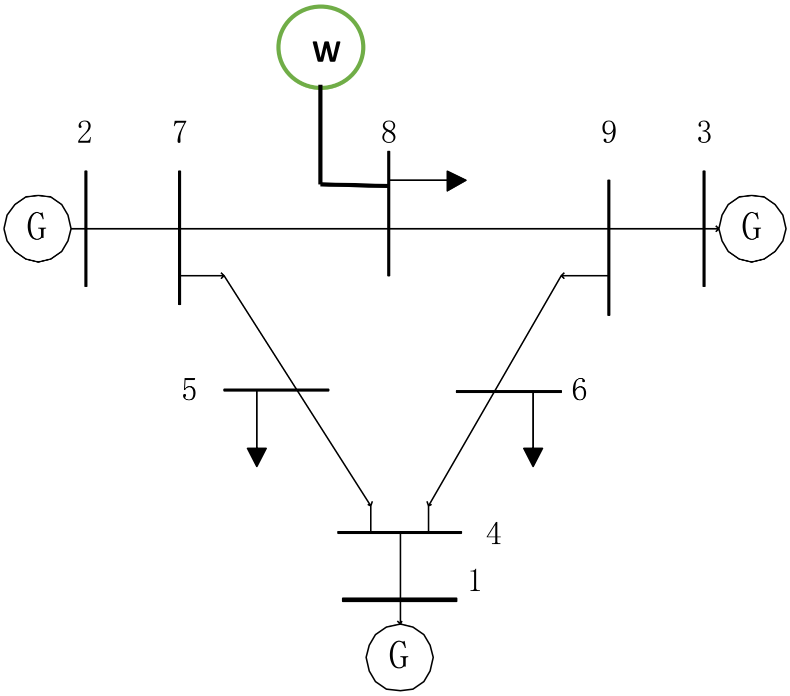

Figure 6.8 IEEE 9-bus Test System

Table 6.1. Test System Data

Generators	4
Buses	9
Load points	3
Total generation capacity	850MW
Fixed load	315MW

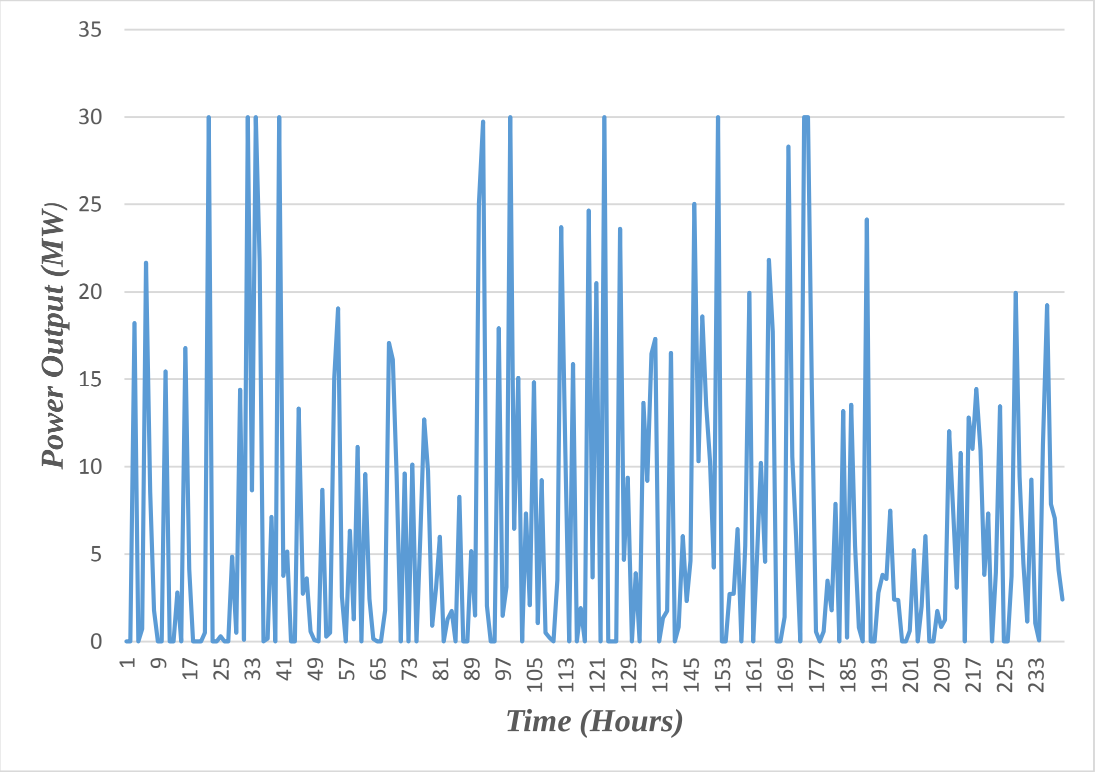

Figure 6.9. Snapshot of Simulated Wind Farm Power Output

(240 hours, maximum 30MW)

To carry out the analysis reported in this chapter, the actual, installed wind generation capacity is 30 MW. The output of the wind farm using the model is introduced in *Chapter 2*, which has 240 random values to generate 240 wind speeds. The average mean wind speed is set to 7 m/s, and the Weibull shape parameter is defined as 2. The wind speed variations are represented by the Weibull probability distribution. Then, the power output of the wind turbine can be obtained by using wind speed profile and Monte Carlo simulation. The computed wind power output is shown in *Figure 6.9*. Transfer the wind generation output into every 1hr, and which gives 240 data points.

6.4.2 Scenario 1: Base case for an Unconstrained Network with Wind Power Integration Considering the Bilateral Contract of Conventional Generator

In this chapter, it analyzes the problem of the wind curtailment due to transmission congestion. Furthermore, it proposes a methodology to relieve the curtailment of wind power energy by reducing the bilateral contract from selected conventional generator. And in this section, an unconstrained network operation with wind power generation is used as the base case for comparison study.

In this test system, a wind farm with the installed generation capacity of 30 MW will be introduced into the system operation, which will be connected to bus 8. The aim of the simulations is to assess the impacts on conventional generators and transmission system due to wind power generation integrating into the power system. So in this test, wind turbine is assumed that wind farm owners offer their produced energy at a price is equivalent to zero. In this way the wind farm can be treated as firstly used generation in the power market. The cases in this scenario are operating with unconstrained network.

In this case study, the conventional generator 2 with the bilateral contract is selected for the compared study. The energy purchasing progress is done through bilateral contract with agreed price between a load and generator 2, and at specified time period the amount of contractual energy would be delivered. In this scenario, two different volumes of the bilateral contract with the same price for generator 2 will be used in the simulation. A bilateral contract exists between generator 2 and a load for 140MW, which should be delivered for ten days at delivery period. And another bilateral contract exists between generator 2 and a load for 150MW, which should be delivered for ten days at another delivery period.

The following three operating situation will be considered:

1) The network operation with wind power generation integrated regardless of transmission congestion is being used as the first simulation step in this scenario;
2) Considering this bilateral contract from conventional generator 2 as 140MW;
3) Change the volume value of the bilateral contract on conventional generator 2 to 150MW to see the different simulation results for the same system operation.

In the diagrams of results, the purple red curve is the result of the simulation when system operation with wind power integrating without considered to transmission congestion and with no bilateral contract for the basic market. The blue curve and yellow curve represent the generator' outputs when selected conventional generator 2 with 140MW and 150MW bilateral contract loads respectively, with the network transmission constraints ignored.

Figure 6.10 is the salutation results of generator 1' outputs compared under three different system operating conditions, unconstrained network with wind power integration, selected conventional generator without bilateral contract, with 140MW bilateral contract and with 150MW bilateral contract respectively.

Wind power output is regarded as "must-take" energy, once the wind penetration level is significant, one of the major impacts of wind integration on generation system is that its output will lead to reducing energy from conventional generator to maintain the generation-demand balance. It will be seen in *Figure 6.10,* that with the increased wind power penetration integrating into the test *IEEE 9-bus* system, output of generator 1 will decrease, as while when other conventional generator got the bilateral contract, the impacts on the output of generator 1 still will be effected.

Figure 6.11 is the compared simulation results for generator 2, which have the bilateral contract with load. It can be seen that when conventional generator 2 has the bilateral contract, the output of it will be constant. The blue straight line is the output of conventional generator 2 when it has the bilateral contract as 140MW, the yellow one is the output of conventional generator 2 when it has the bilateral contract as 150MW.

Figure 6.12 is the simulation results for generator 3, which can get the same conclusion as generator 1. During the whole simulation process, all of the “zero price” wind energy will be accepted by the system operator. In *Figure 6.13,* the purple red curve is the output of wind farm whose installed generation capacity is 30 MW. The base case for the simulation is an unconstrained network with wind power integration, so although considering the different bilateral contracts of conventional generator, there is no effect on the outputs of wind power.

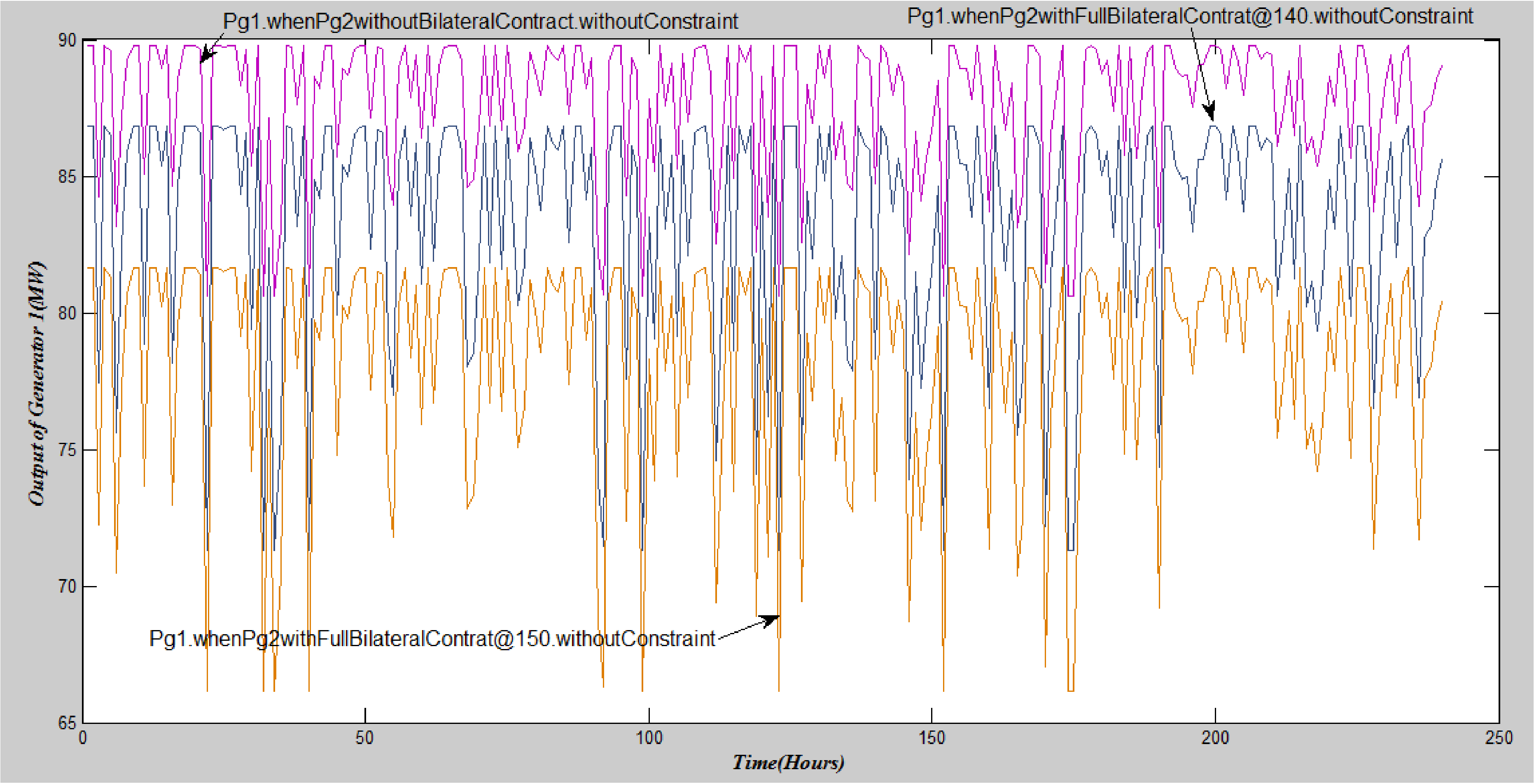

Figure 6.10. Snapshot of Simulated Generator 1's Outputs with Different Bilateral Contract Conditions from Generator 2

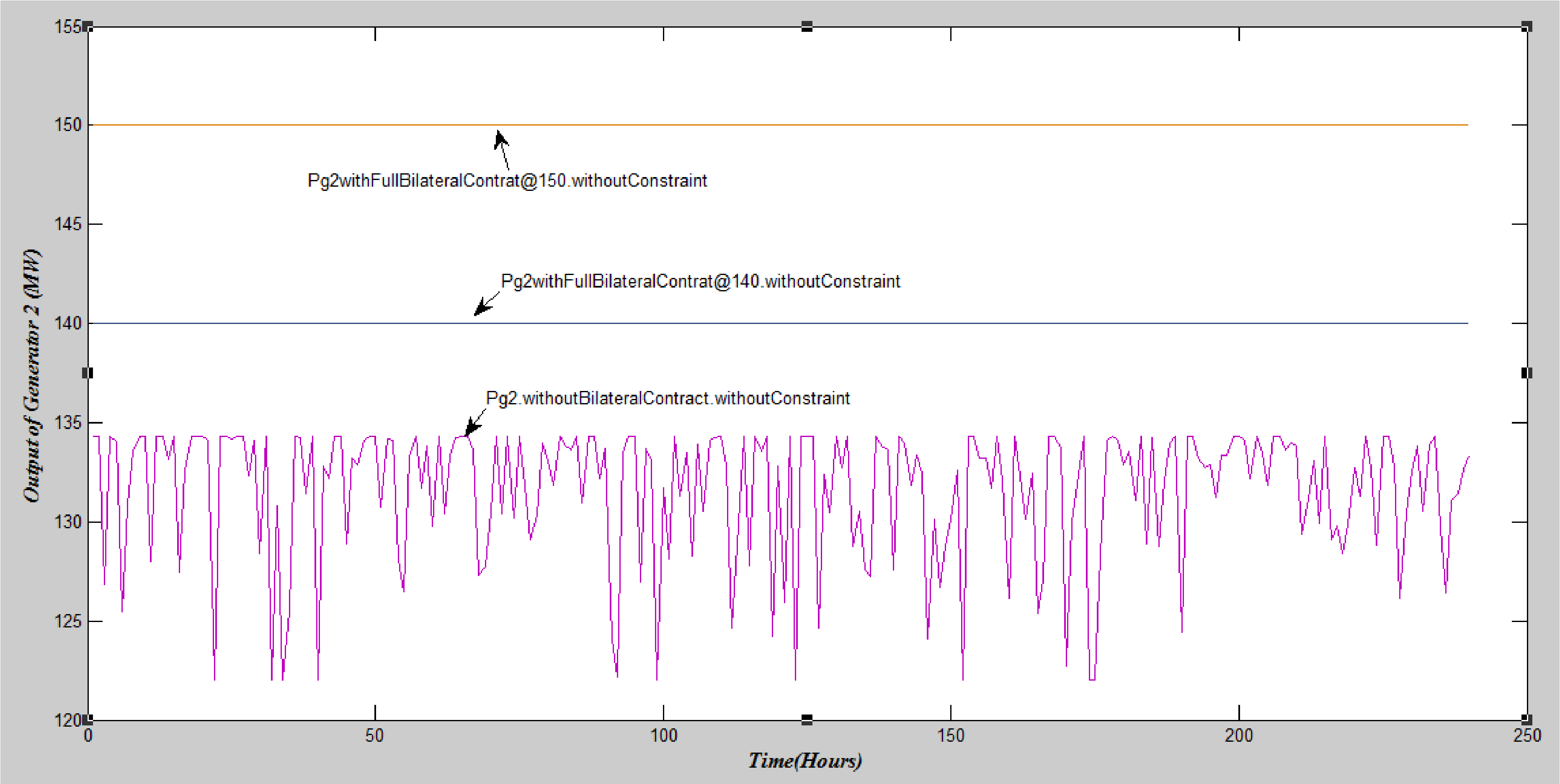

Figure 6.11. Snapshot of Simulated Generator 2's Outputs with Different Bilateral Contract Conditions

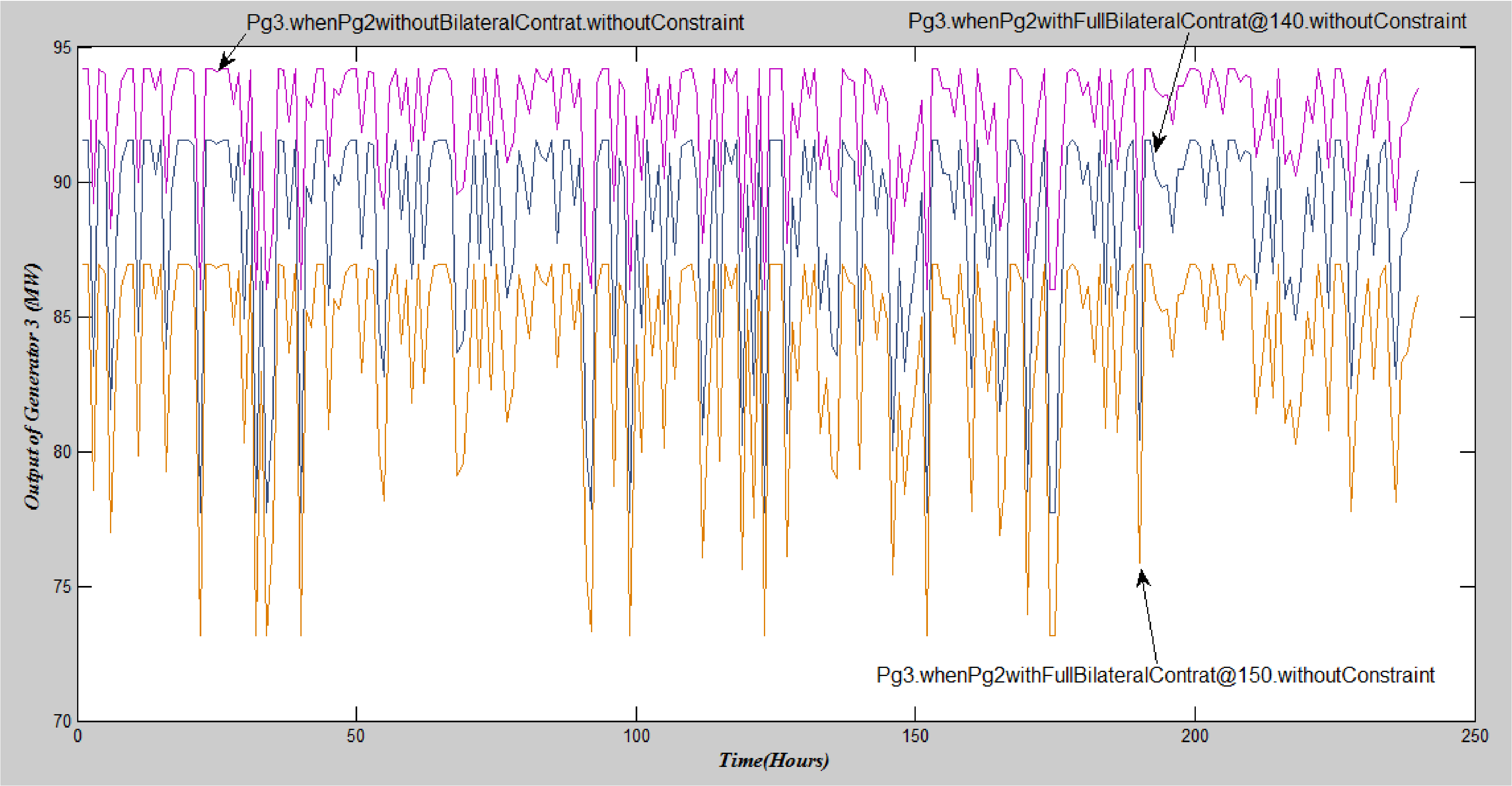

Figure 6.11. Snapshot of Simulated Generator 3's Outputs with Different Bilateral Contract Conditions from Generator 2

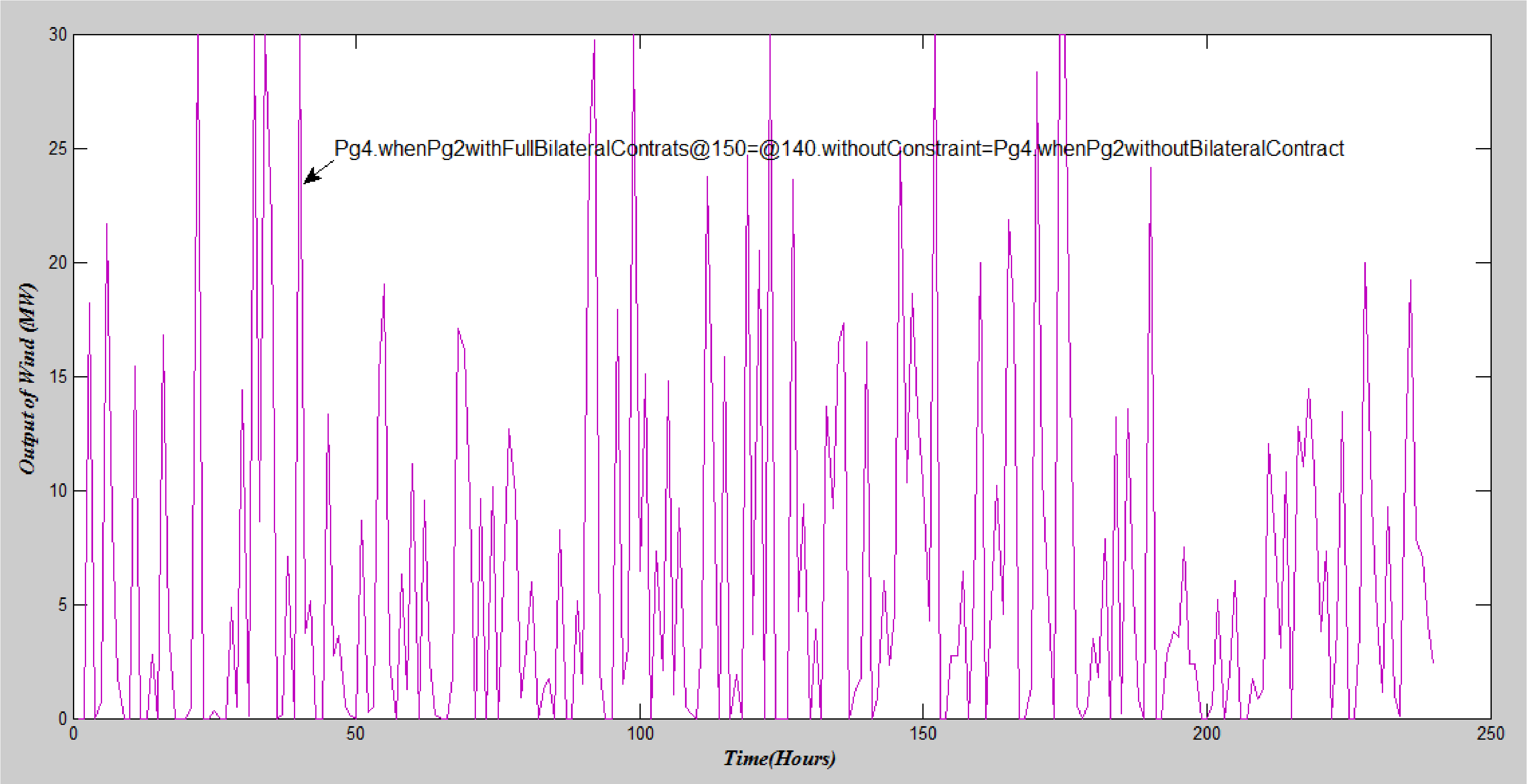

Figure 6.12. Snapshot of Simulated Generator Wind's Outputs with Different Bilateral Contract Conditions from Generator 2

Operating costs is one of the main criteria used to assess the impacts of cooperative operation for the power system. All the simulations involve integrating wind power, the bilateral contract for the selected conventional generator, optimizing generation resources and scheduling of load to meet expected demand over various time frames, and it still needs to take into account the system operating conditions.

Figure 6.13 is a snapshot of simulated operating costs (£/hr) in this scenario. The purple red line is the operating cost in the base case, unconstrained network operating with wind power generation, with no the bilateral contract from the conventional generation. With the comparison simulated results, with the wind power integration for the unconstrained network, when one of the conventional generators is on bilateral contract, operating costs will increase. *Figure 6.14* is a snapshot of selected hours points of simulated operating costs (£/hr) in these three situations. In *Figure 6.14*, the blue curve is the operating cost of unconstrained network with wind power integrated while the bilateral contract of selected conventional generator is 140MW. While enforcing increase volume of bilateral contract into the power system, some related elements will add operating cost, such as re-dispatch for system operation. The yellow curve in *Figure 6.14* is the operating cost with the same system operating conditions but with the volume of bilateral contract limited to 150MW.

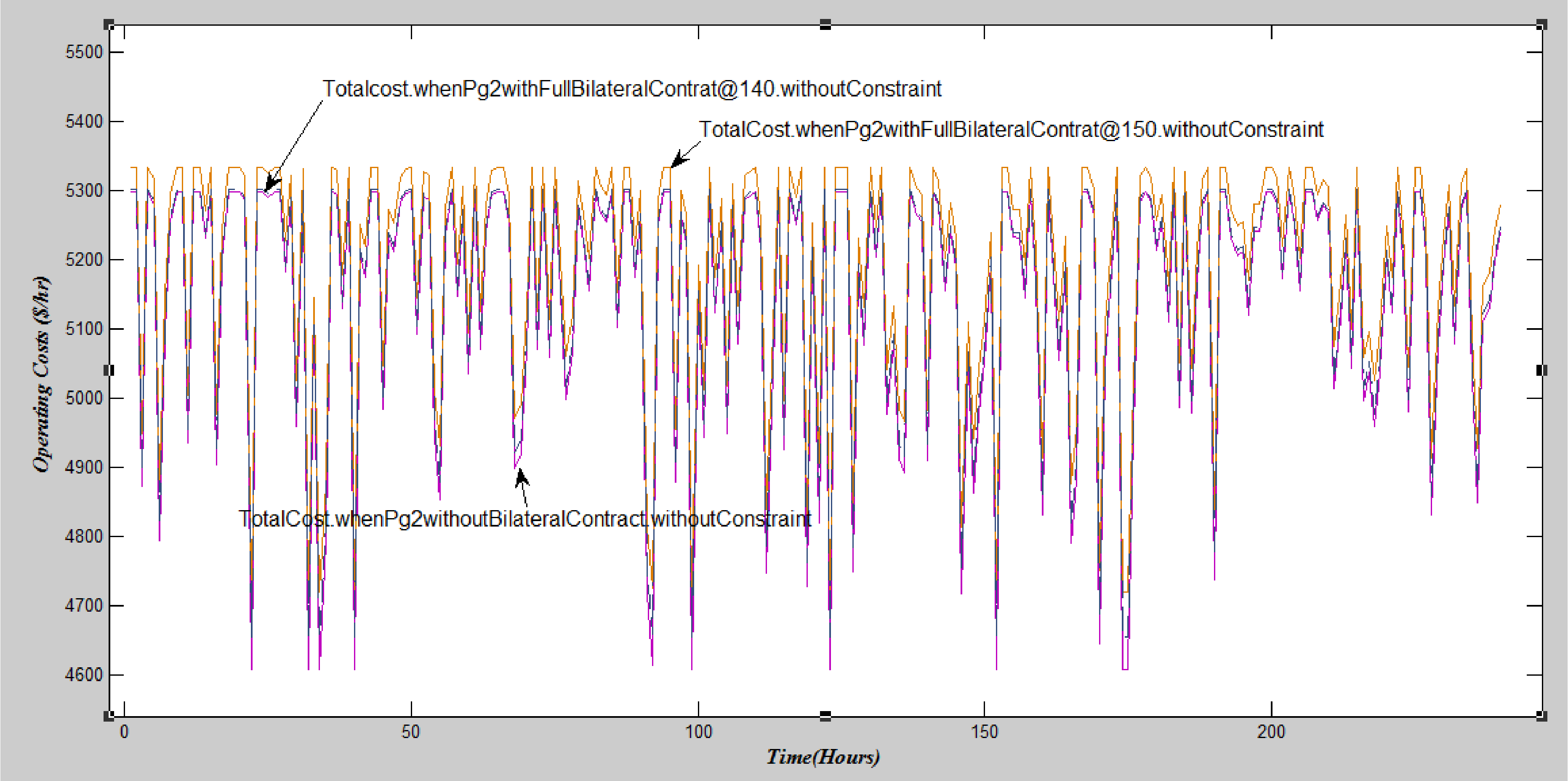

Figure 6.13. Snapshot of Simulated Operating Costs (£/hr) in this Scenario

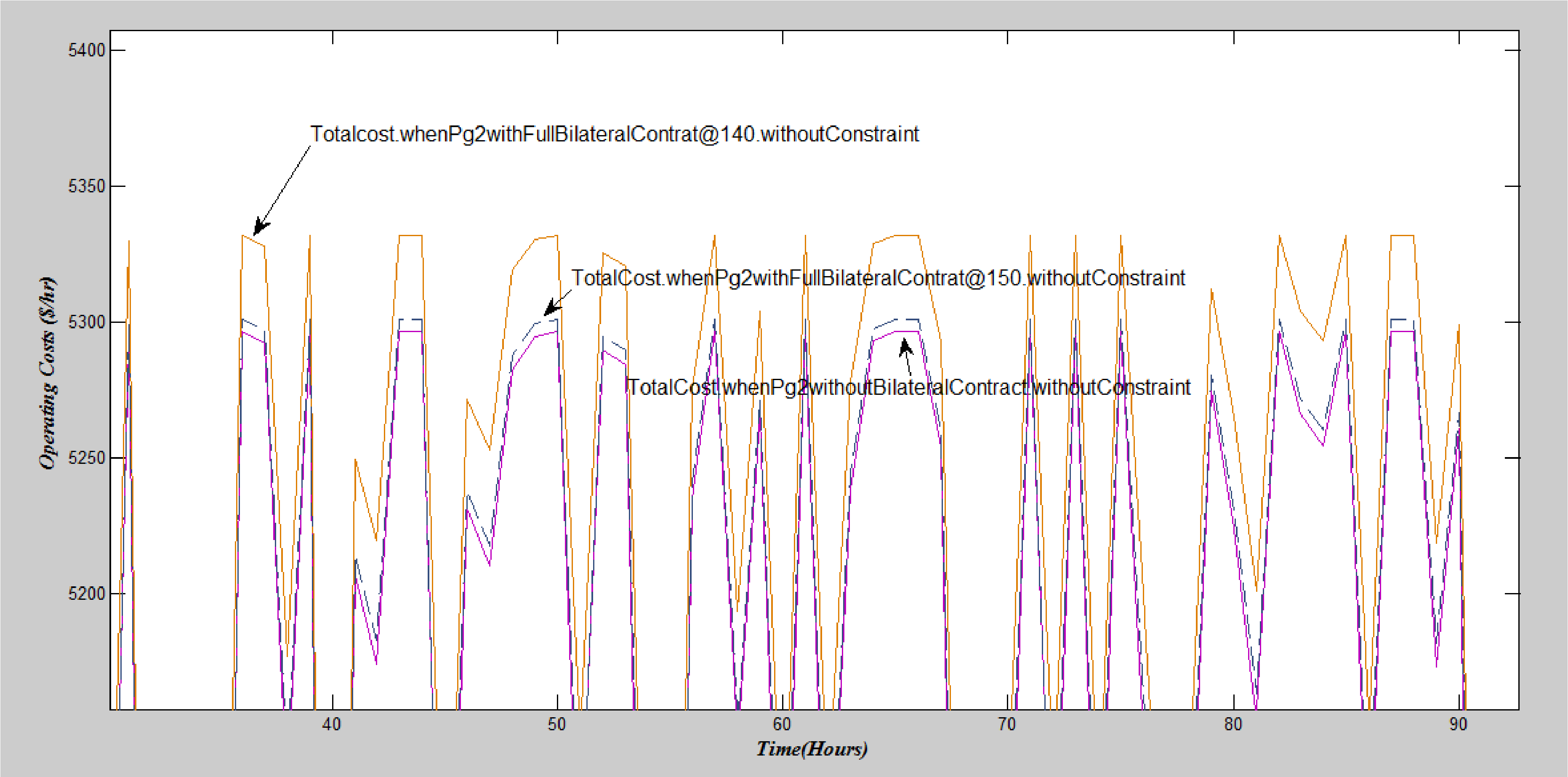

Figure 6.14 Snapshot Selected Hours Points of Simulated Operating Costs ($/hr) in this Scenario

6.4.3 Scenario 2: The proposed Method for Marketing Strategy to Relieve the Curtailment of Wind Power

In this part, two cases are studied. The first case is a system with wind power generation integrating into the power system which the transmission constraints are taken into consideration, and the second case is using the proposed optimal function to improve the system operation. In the simulation study the main focus is the power flow constraints on the transmission lines. The first case is selected in order to show the effect of transmission congestion leading to the curtailment of wind power generation. However, the second one is done to verify the proposed method according to the cooperative reduction of the selected conventional generator’s bilateral contract to relieve the curtailment of wind energy.

Wind farm mentioned in *Scenario 1* in this chapter will still be used in this scenario, with the wind farm installed generation capacity remaining at 30 MW (*Figure 6.9*) .The conventional generator on bus 2 with the bilateral contract at 150MW will be selected to verify the proposed method in the test system.

In the first case, the aim of simulation is to assess the impact on wind power generation and the output of conventional generators with the bilateral contract. During this simulation wind power integration with different system operating conditions (with constraints and without constraints) will be compared. And congestion of the transmission system will be considered, two transmission line, one is from bus 7 to bus 8, and another one from bus 8 to bus 9 are overloaded in this scenario. The solution is by ACOPF by enforcing the line limits with all generators bidding at their marginal cost.

For the first case three system operating situations will be compared. In the following simulated results, the purple red curve is the result of the simulation unconstrained network operation with wind power integrated and no bilateral contract for the market. The yellow curve means wind power integrated into the unconstrained network and the selected conventional generation with 150MW bilateral contract. The pink curve represents the generator' outputs when transmission congestion is considered. In all of the simulation studies, wind turbine is treated as first used generation in the power market, that wind farm owners offer their energy production price being equivalent to zero.

Chapter 5 has briefly discussed the curtailment of wind power integration affected by the transmission congestion, and some basic knowledge about the impact on system optimal operation due to the bilateral contract reduction from conventional generators. As wind power output continues to be the "must-take" generation, once the wind penetration level is significant, certain amount of displacement needs to be conducted on conventional generation units to accommodate the output from wind power. But with the transmission congestion, and for the security of system operation, some of the wind power will be curtailed. In the following simulation results of the first case, these will be shown in the graphs.

Figure 6.15 is the snapshot of simulated generator 1's outputs with wind power integrated under different system operating conditions (with transmission constraints and without transmission constraints) while conventional generator 2 has the bilateral contract at 150MW. OPF with wind power integrated into the unconstrained network and conventional generator without bilateral contract, the output of generator 1 is shown in the purple red curve. When the bilateral contract from the selected conventional generator is introduced with the unconstrained network, simulation results show that output of the other conventional generator will decrease (*Figure 6.16 and Figure 6.17)* in *Scenario 2*. If capacity limits of transmission line is introduced, enforcement of the transmission line constraint has resulted in a re-dispatch of generators in the power system operation in order to relieve the line constraint.

As shown in *Figure 6.15*, reduction of more expensive conventional generator will be intensive with the same wind power penetration level under different power system operating conditions. This variation depends on wind power connection location and taken of all location of congested transmission lines. In the *Figure 6.16*, the selected conventional generator 2 with the bilateral contract at 150MW with the constrained test system and the unconstrained test system, so the output of generator 2 will be overlap although transmission constraints will lead to the optimal dispatch operation for the system.

Re-dispatch of generators in the power system operation will relieve the line constraints. The presence of congestion has altered the output of each generator. *Figure 6.17* is the snapshot of simulated outputs of generator 3, with wind power integrated under different system operating conditions with transmission constraints and without transmission constraints respectively. The output of generator 3 will decrease when the selected conventional generator's bilateral contract is introduced into the system and with transmission congestion, the output of generator 3 will increase as the result of economic dispatch.

Comparing simulated results of wind power in *Figure 6.18*, it can be seen that fluctuation output of wind as a *"zero price"* generator. Total output energy from installed wind farm can be accepted by unconstrained network as shown with the yellow curve. When the bilateral contract of generator 2 is introduced into the simulation, no effect on the acceptable wind energy. Under these two situation, the two curves overlapped. But with the transmission congestion introduced into the power system, under constrained system operation, output of wind farm will have to be curtailed. The pink curve in *Figure 6.18* is the output of wind farm under constrained network. The proposed method in this chapter is to relieve this curtailment.

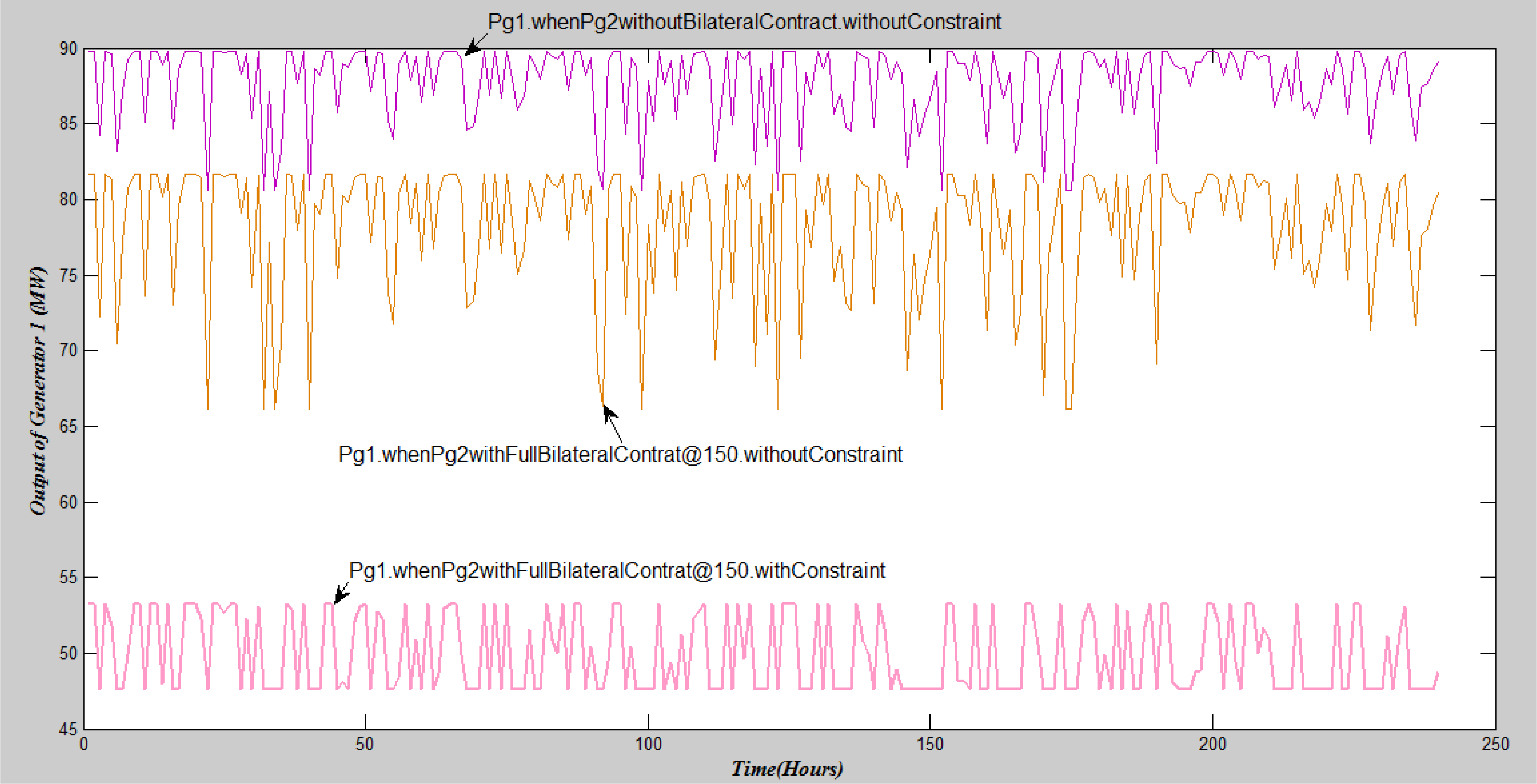

Figure 6.15. Snapshot of Simulated Generator 1's Outputs with Wind Power and Selected Convectional Generator with Bilateral Contract under Different System Operating Conditions

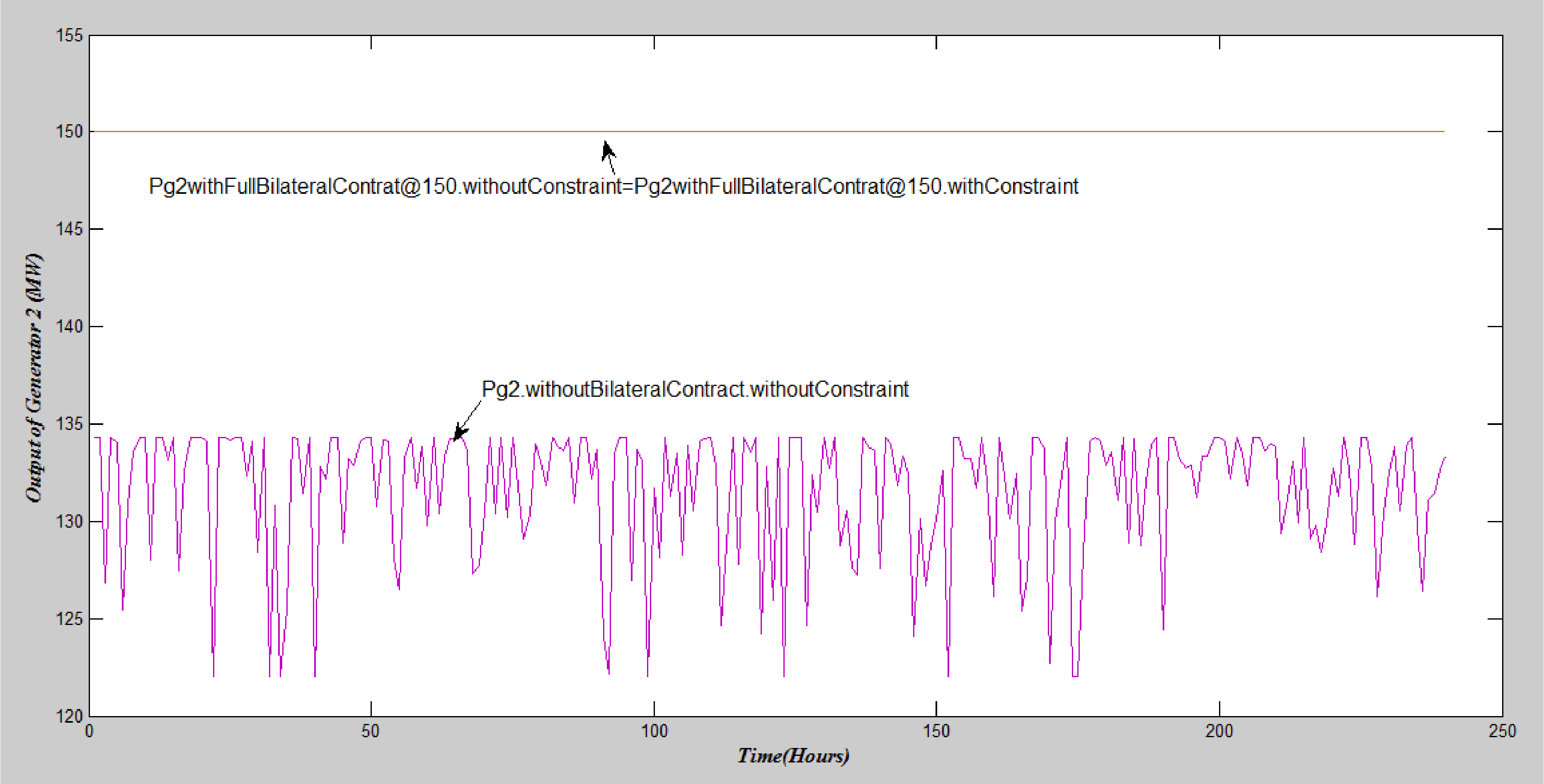

Figure 6.16. Snapshot of Simulated Generator 2's Outputs with Bilateral Contract and Wind Power integration under Different System Operating Conditions

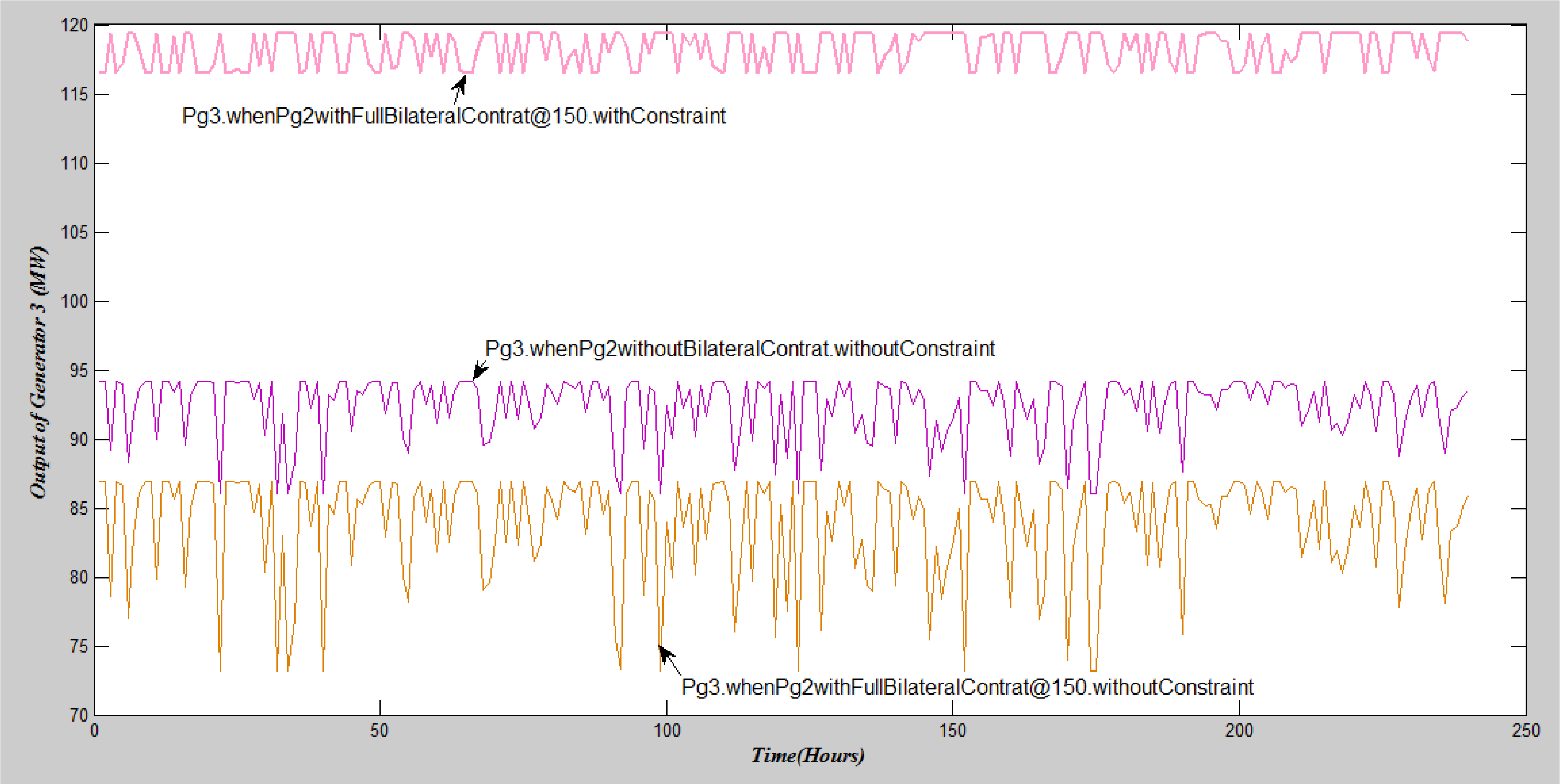

Figure 6.17. Snapshot of Simulated Generator 3's Outputs with Wind Power and Selected Convectional Generator with Bilateral Contract under Different System Operating Conditions

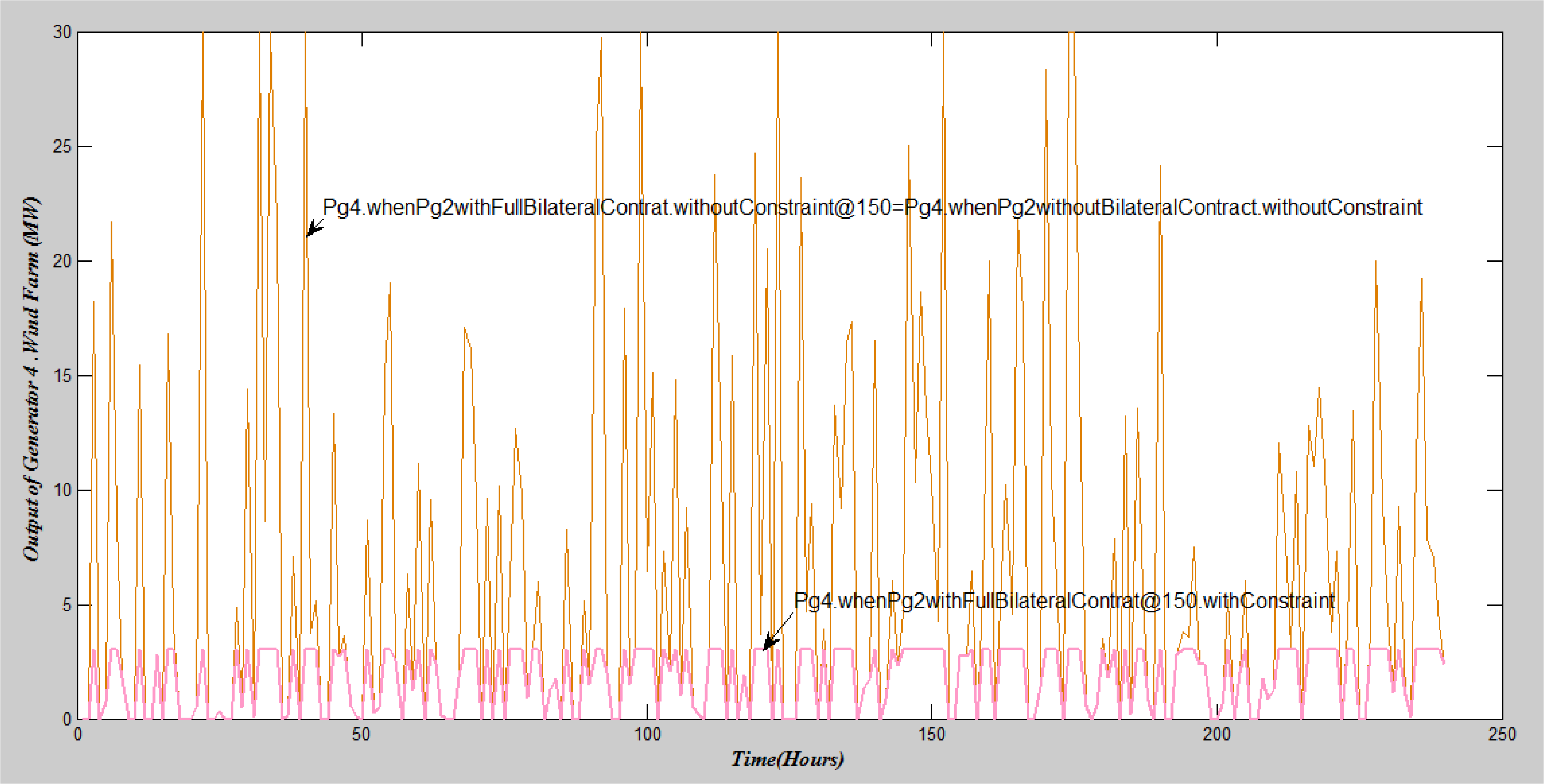

Figure 6.18. Snapshot of Wind Power's Outputs and Selected Convectional Generator with Bilateral Contract under Different System Operating Conditions

The aim of the second case simulation in this scenario is done to prove the proposed method according to the flexible scheduling of the selected conventional generator’s bilateral contract to relieve the curtailment of wind energy. The curtailment of wind power is caused by transmission congestion. *Section 6.2* and *Section 6.3* have described the detail of the proposed method.

The proposed method is to try to increase the utilisation of wind farm that is constrained by the transmission networks. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. In particular the incorporation would look at instances when conventional (typically coal fired) plants have fixed bilateral contracts. These generators are not willing to reduce their outputs because they will lose earnings. This incorporation will look at maintaining the profit of the generators even if they are curtailed to allow more wind power to be used. The *Equation 6.32* is the new proposed objective function that minimizes the total expected cost (the combined production costs of energy and compensation for the curtailment of conventional generators’ bilateral contract) for the base case (intact system) and a specified set of credible corresponding probabilities of occurring (to keep the conventional generator’s profit and curtailed their fixed bilateral contracts to relieve the curtailment of wind power generation). In the proposed objective function, the optimal pattern of compensation for the curtailment of conventional generators’ bilateral contract is determined endogenously and it adjusts to changes in the physical and market conditions of the network.

The results of the simulation, shown in *Figure 6.19,* illustrate that the fixed bilateral contract of conventional generator 2 is reduced for the proposed objective function to relieve the curtailment of wind power. The output curve under this situation as shown as the green dotted curve, and this reduction of the output will be paid for by the ISO. In *Figure 6.19,* the purple red curve is the base case when the unconstrained network with wind power integrated, the conventional generator’s bilateral contract is not attend.

The blue curve presents that, with the fixed bilateral contract at 140MW, the output of generator 2 will be 140MW.

The curtailment of wind power generation caused by the transmission congestion is shown in the *Figure 6.20* as the blue curve; the wind farm installed generation capacity is still 30 MW (*Figure 6.9*), and the conventional generator on bus 2 with the fixed bilateral contract at 140MW. The proposed method is to relieve this phenomenon is trying to reduce the volume of conventional generator' bilateral contract to meet the total available wind power output integrated into the power system operation while the ISO will pay this lost of profits for the contract. With the simulation results in this scenario, conventional generator 2 being paid at the price 50 £/MW (one of the submitted decremental bids) to reduce its bilateral contract, as while all of the wind power generation will be accepted into the system operation (yellow curve). The test constrained power system is operating in a secured condition. *Figure 6.20* and *6.21* are the simulated output results of generator 1 and generator 3 respectively, using the proposed optimal function and economic dispatch, their power outputs will be changed. These are shown in the green dotted curves.

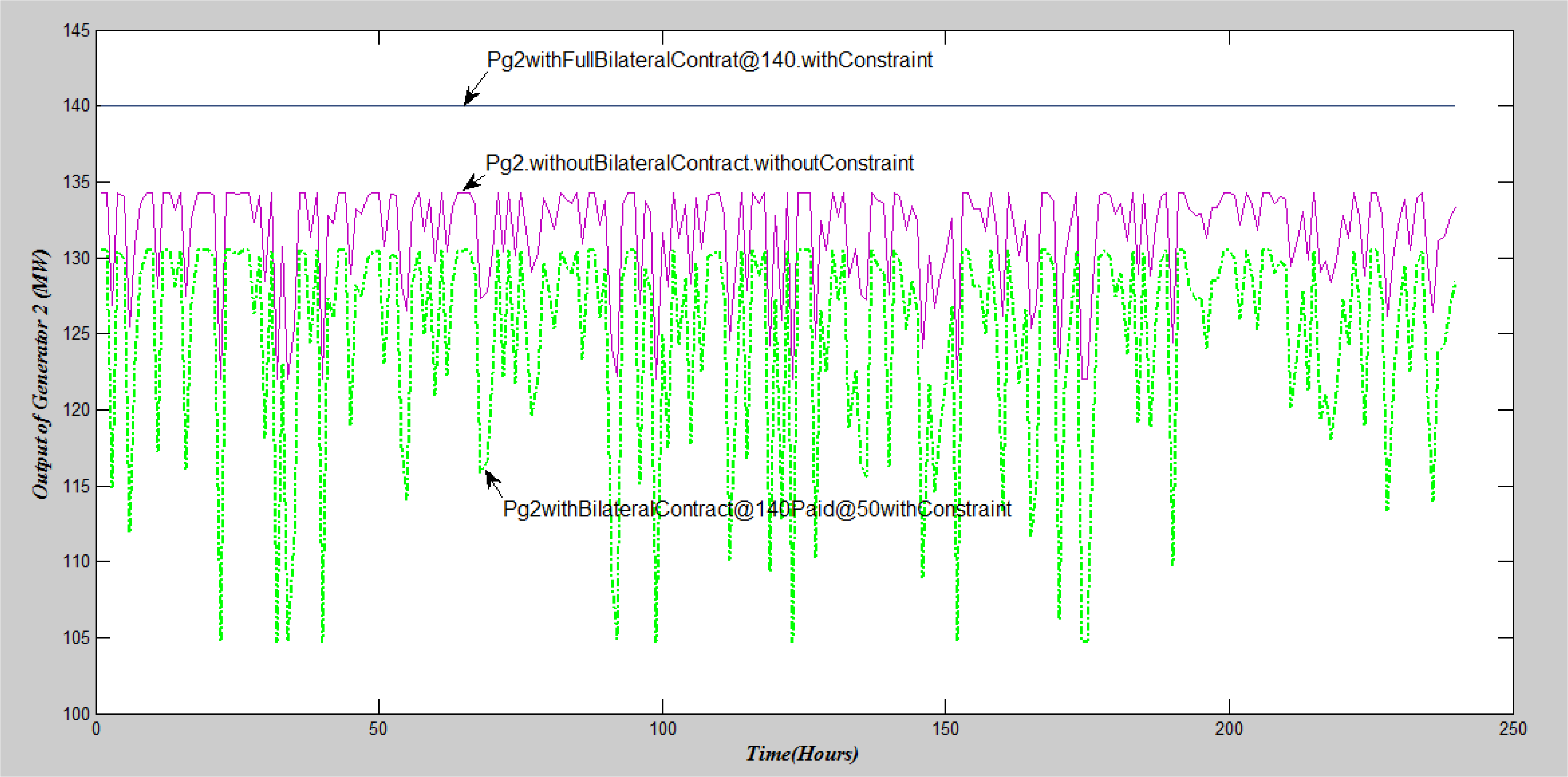

Figure 6.19. Snapshot of Simulated Generator 2's Outputs with Proposed Method

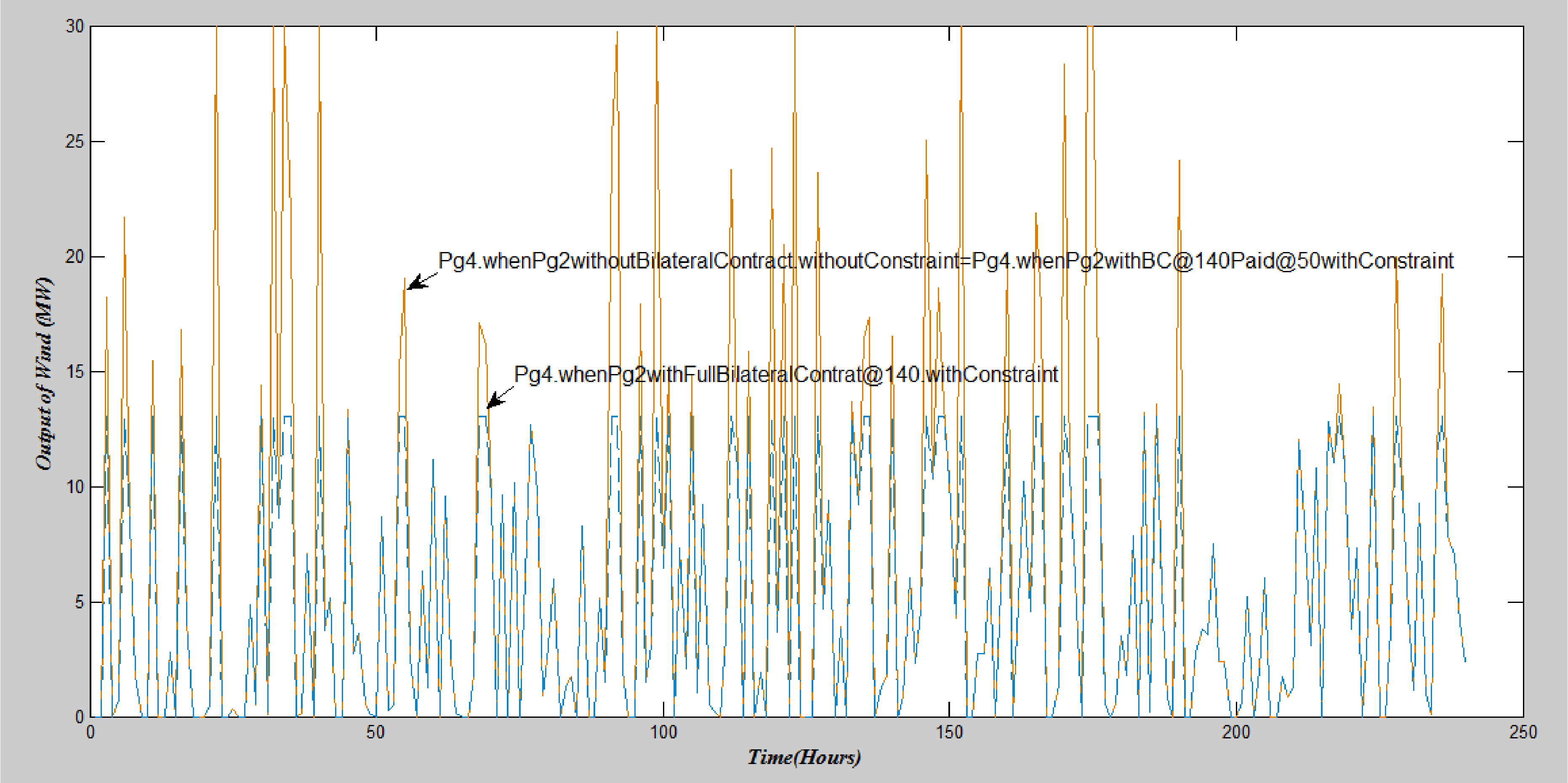

Figure 6.20. Snapshot of Simulated Wind Farm's Outputs with Proposed Method

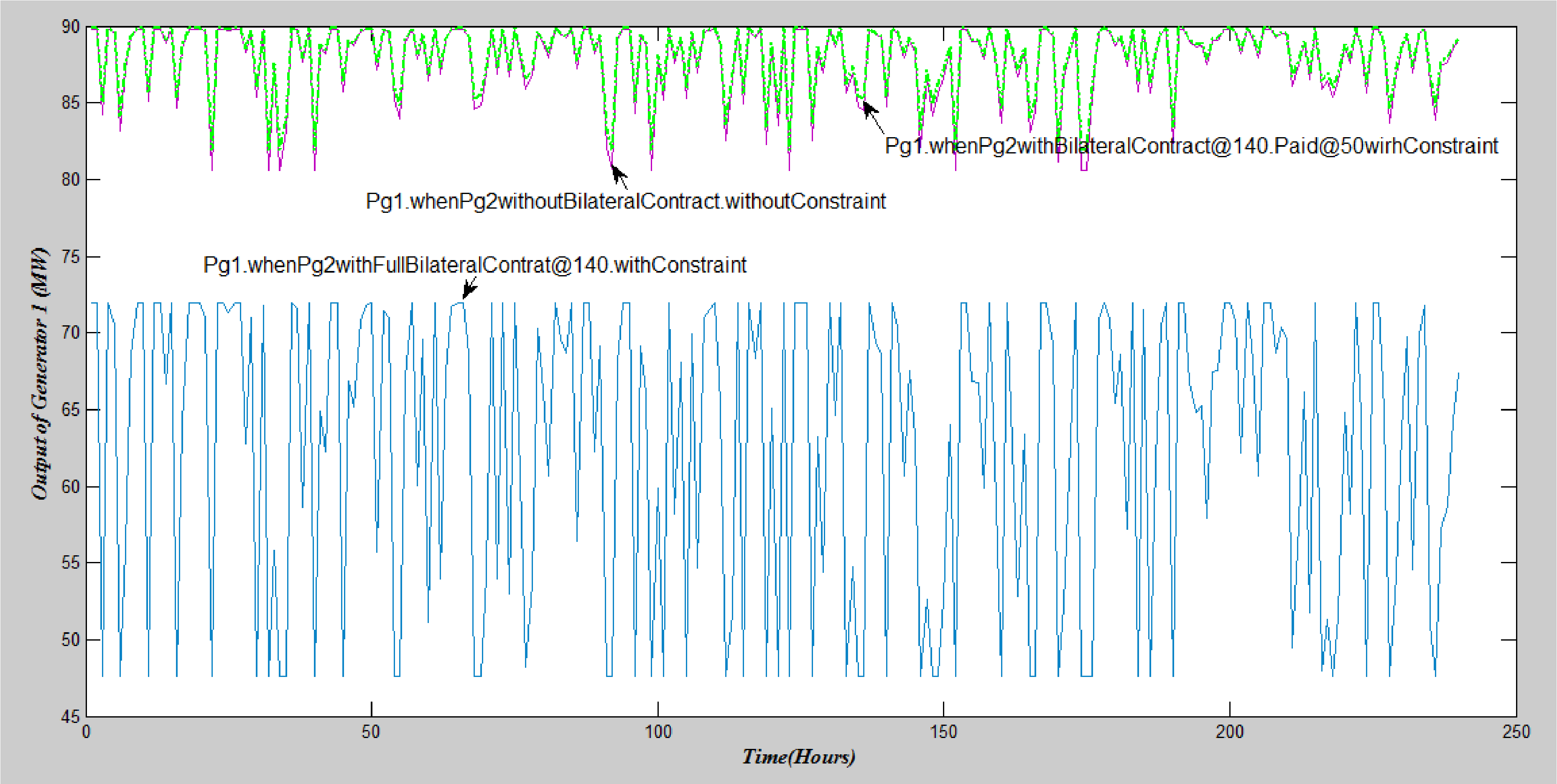

Figure 6.20. Snapshot of Simulated Generator 1's Outputs with Proposed Method

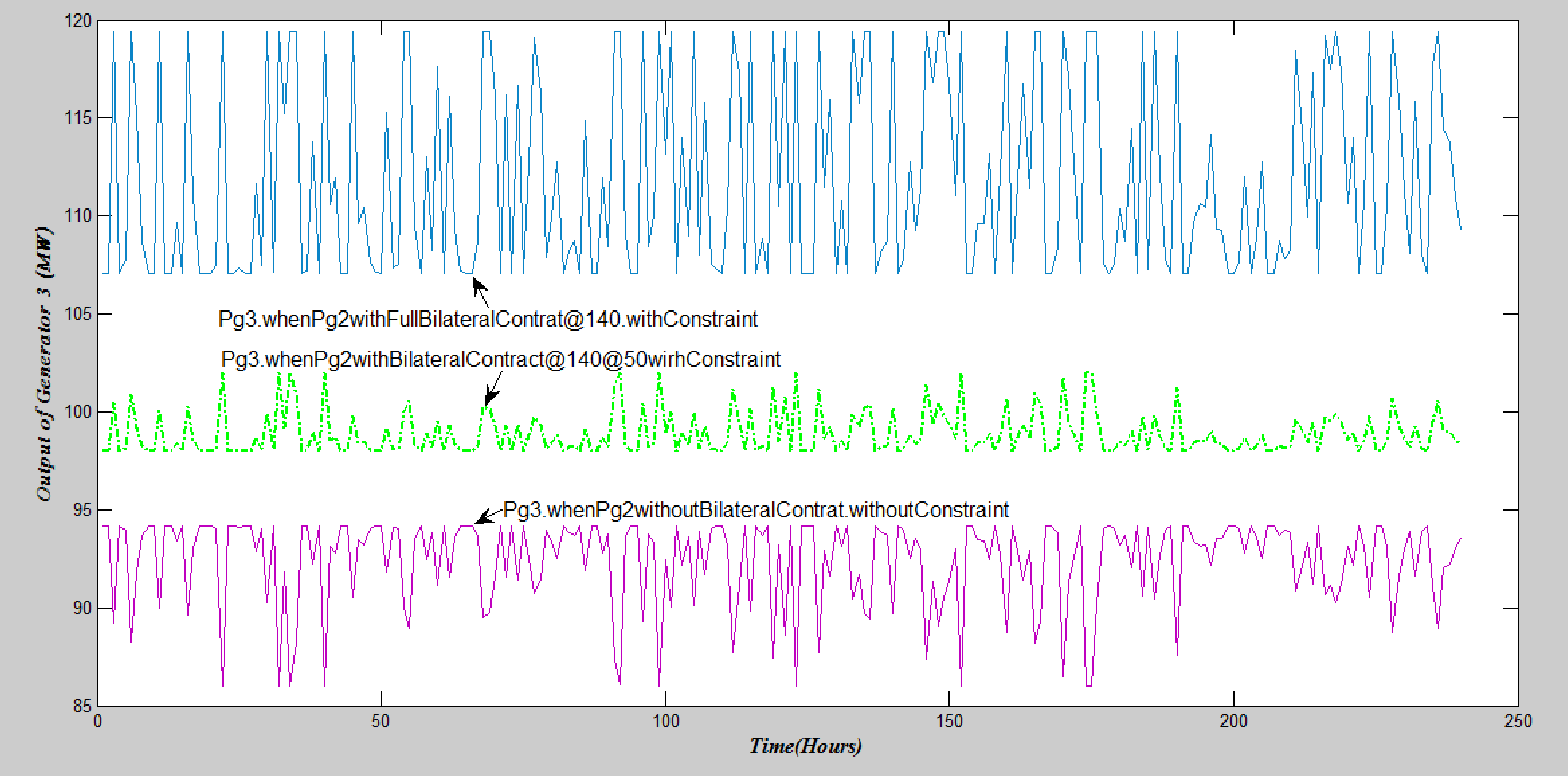

Figure 6.21. Snapshot of Simulated Generator 3's Outputs with Proposed Method

6.5 Summary

During the past decade, there has been tremendous development in wind energy all over the world. However, due to power system operational constraints, reliability requirement as well as other technical limitations, significant portions of the wind generation resources are curtailed in real-time operations. Among various power system operating constraints, transmission congestion plays a significant role. In this chapter, it analyzes the problem of wind curtailment due to transmission congestion. Furthermore, it proposes a methodology to relieve the curtailment of wind power energy by reducing the bilateral contract from selected conventional generator at minimum costs. An analytical expression of the proposed bilateral contract curtailment method for mixed bilateral-based market is derived based on the network theory of power system. The modified *IEEE 9-Bus* system is used to verify the proposed theory.

The proposed could help decision makers to analytically assess impact of wind curtailment due to transmission congestion, as well as to pinpoint potential key transmission bottlenecks to alleviate wind curtailment.

The proposed bilateral contract curtailment method allows conventional generators to take part in security action by submitting incremental/decremental bids in power market. The ISO can choose the volume of reduction from the conventional generator’ bilateral contract that would minimize the overall cost generation adjustment cost (security cost) to adjust their output. The expected simulation results prove that the proposed method works satisfactory.

Further work will be discussed in the *Chapter 7*, using the proposed methodology, with different payment for the curtailed part of the conventional generator’ bilateral contract, to access the impacts on the combined production costs of energy and the compensation for the curtailment of conventional generators. The related changes for the locational marginal prices will be compared. *IEEE 30-Bus* system will be used for the analysis.

Reference

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Chapter 7

Economic Performance Measures with Wind Power Integration According to the Proposed Methods

7.1 Introduction

Chapter 5 analyzes the problem of the wind curtailment due to transmission congestion. C*hapter 6* proposes a methodology to relieve the curtailment of wind power energy by reducing the amount of bilateral contracts from selected conventional generators. The conventional generators may fail to re-sell their curtailed energy and hence resulted in reduced profits. The approach in this chapter is to looking at maintaining the profit of the conventional generators even if they are curtailed to allow more wind power to be used.

The modified *IEEE 9-Bus* system is used to verify the proposed theory in the previous chapter. In *section 6.4.3*, the case simulation is done to prove the proposed method in *Chapter 6* according to the flexible scheduling of the selected conventional generator's bilateral contract to relieve the curtailment of wind energy. The curtailment of wind power is caused by transmission congestion.

Under the proposed combined dispatch model in this chapter, the simulation results will show the relative bilateral trading influence performance in terms of individual power levels, costs and nodal prices. The comparative performance of fixed bilateral contracts under various curtailment strategies in mixed pool/bilateral operation will be discussed. The compensation of the curtailment part from the pre-arranged bilateral contracts derived from the pool and bilateral trading consistent with the corresponding costs for these services will also be discussed.

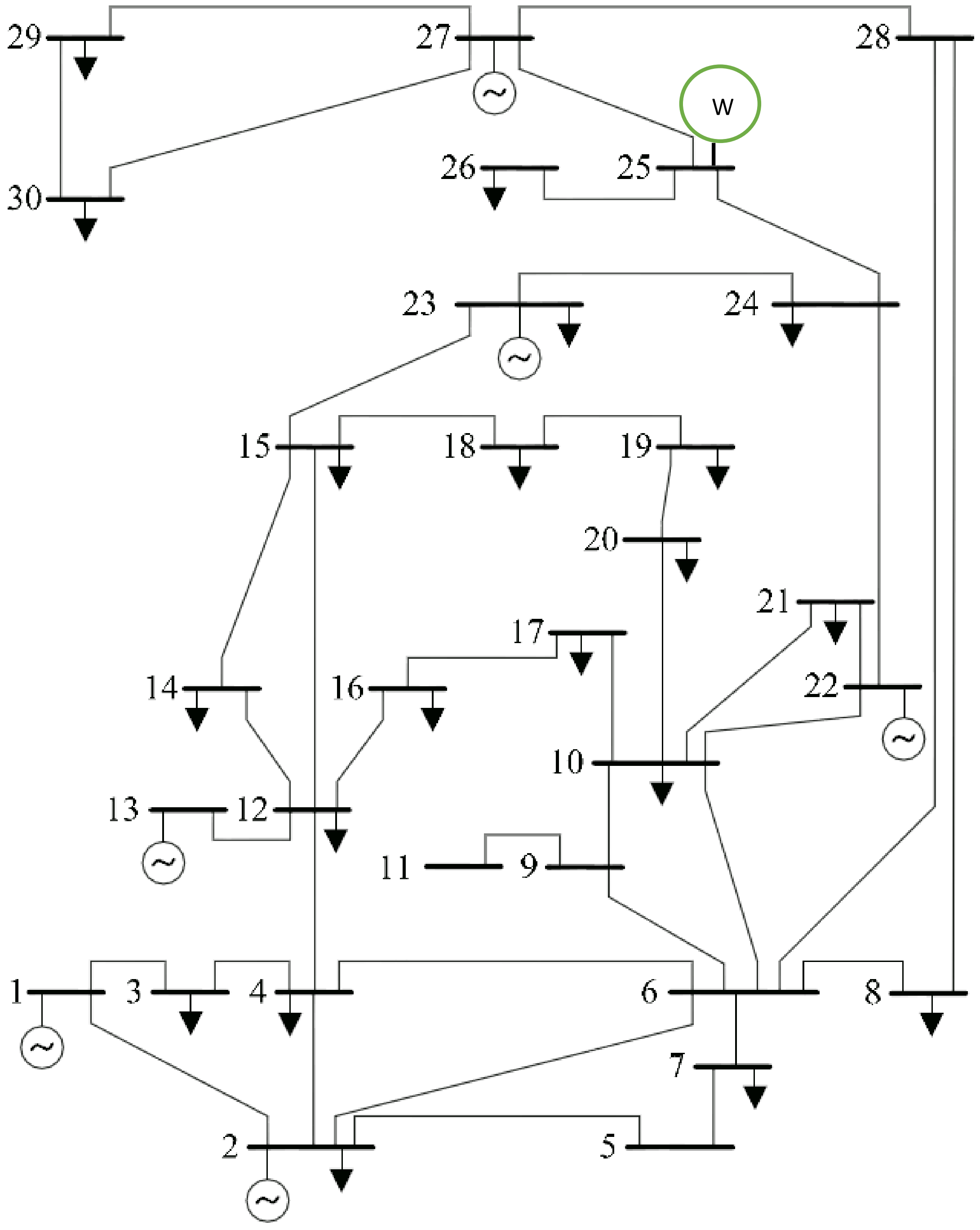
The above issues will be sequentially addressed in each section. The results will help with the basic strategic decision faced by independent generators and loads, namely, how to trade between pool and bilateral trades, considering their different pricing mechanisms and network constraints, enhancing penetration of wind power into the system operation, and the goal being to obtain good profits at low risk.

The details of the simulation test system will be introduced in Section 7.2. In this Chapter the *IEEE 30-bus t*est network (*Figure 7.1*) is used which has been used extensively in my research to test the performance of different market designs. The firm scheduled bilateral contract from the conventional generation can cause transmission congestion and free wind power cannot be integrated into the power system operation sufficiently. Two case studies through the proposed methods will be introduced in *Section 7.3*, 1) the volume values of conventional generator' scheduled bilateral contracts are varied; 2) the request payment for the curtailment bids submitted by the selected conventional generators are varied. The impact on system operation (generation levels, costs, and nodal prices) will be discussed. This will affect economic performance via individual or total revenues and expenditures for system participants. The performance measures analyzed here are of two types (operation costs and compensation for the curtailed part of scheduled bilateral contracts).

7.2 Evaluation of Modified IEEE 30-Bus Test System: Combined Pool/Bilateral Dispatch

The eventual goal of the proposed method is to integrate maximum wind energy into the power system whilst helping generator and load serving entities choose appropriate relative levels of pool and bilateral trades, considering risk, economic performance and transmission bottleneck. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. The proposed method proposes a one-step optimal power flow model that dispatches the pool in combination with curtailed part of fixed bilateral contracts from conventional generators to try to increase utilisation of wind farm that are currently constrained by the transmission congestion while minimizing costs.

7.2.1 Data and Assumptions for the Test System



7.1 One Line Diagram of IEEE 30 bus System

In this chapter, the simulation is based on a *30-bus* test network (*Figure 7.1*) that has been used extensively in my research to test the performance of different market designs using the *MATPOWER* platform. The basic system data are shown in *Table 7.1*. Six conventional generators are to be used. Wind power generation is connected to bus 25. In the test, wind turbine is assumed that wind farm owners offer their energy production and the price is equivalent to zero, so the wind farm can be treated as firstly used generation in the power market to assess the impacts on conventional generators and transmission system. Using the assumption that Combined Pool/Bilateral power market is perfectly competitive, offers submitted by generating units correspond to their marginal costs of energy production.

Table 7.1. Test System Data

Generators	**6**
Buses	**30**
Load points	**20**
Total generation capacity	**365MW**
Fixed load	**107.2MW**

To carry out the analysis reported in this chapter, the actual production of wind farm, the installed wind generation capacity is 30 MW. The output of the wind farm using the model introduced in *Chapter 2*, have 240 random values to generate 240 wind speeds. The average mean wind speed is set to 7 m/s, and the Weibull shape parameter is defined as 2. The wind speed variations are represented by the Weibull probability distribution. Then, the power output of the wind turbine can be obtained by using wind speed profile and Monte Carlo simulation. The computed wind power output is shown in *Figure 7.2*. Transfer the wind generation output into 1hr periods, and this gives 240 data points.

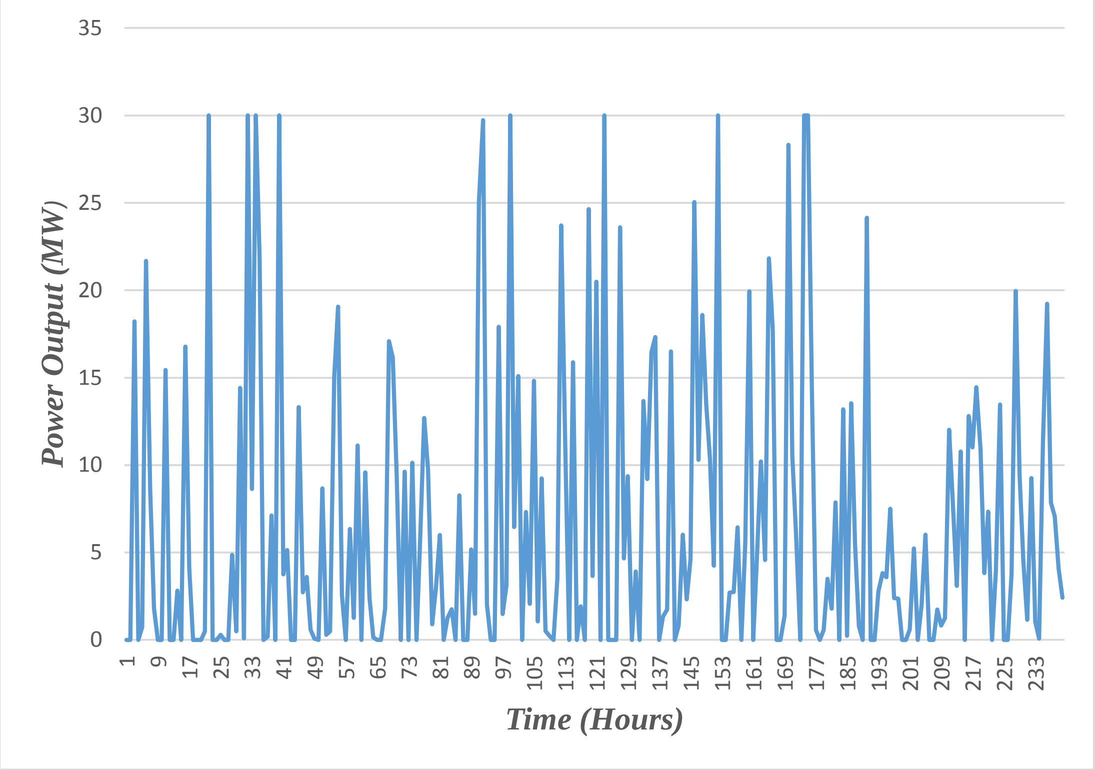


Figure 7.2. Snapshot of Simulated Wind Farm Power Output

(240 hours, maximum 30MW)

7.3 Combined Pool/Bilateral Dispatch: Results and Discussions

An important goal behind the restructuring of the electricity industry is not only to bring more choice of free green energy to supply load demands, but also permitting them to buy electricity either from a centralized spot market, or directly from generators or market participates through pre-arranged bilateral contracts.

In [1], the paper mentioned that the trend toward increased bilateral trading without sufficient combined coordination with the pool operation is risky, in the sense that it can lead to unnecessary congestion and higher nodal prices, as well as to nodal price differences with excessive associated power transfer costs. As a result, what may appear to be economically advantageous bilateral trading may become unprofitable after the power transfer costs due to congestion and losses are accounted for.

The method in this chapter proposes a one-step optimal power flow model that dispatches the pool in combination with curtailed part of scheduled bilateral contracts from conventional generators to try to increase utilisation of wind farm that are currently constrained by the transmission congestion while minimizing costs. The pool is the balancing market in this chapter. The nodal prices in this approach are not assumed to be known, but are obtained from the optimization. The calculated prices therefore are affected by and reflect the combined mixed pool/bilateral operation with all its constraints, and the dispatch is economically efficient in the sense that the total generation cost is minimized.

The model presented here uses the formulation mentioned in *section 6.3,* this notation allows us to define the notions of trades as well as a number of technical and economic performance measures for each competing entity. This dissection of financial measures according to pool or bilateral trading allows market participant to evaluate the profitability of each component of its chosen pool/bilateral mix, which serves as a signal to improve earnings in future by modifying its mixed trading strategy. The eventual goal of this proposed method is to integrating maximum wind energy into the power system.

7.3.1 Bilateral contracts cause the curtailment of wind power

In this section, an unconstrained network operating under the pure pool market with wind power integration will be the base case, the scheduled bilateral trades are ignore. In this part, for the test system, a wind farm with installed generation capacity as 30MW will be added at bus 25, the conventional generator 4 connected on bus 27 is selected to concert the compared study. The following three operating situation will be considered in the compared simulation. Firstly, the network operation with wind power generation integrating under pool market only regardless bilateral trades is being used as the first simulation step; Secondly, assumed the conventional generator 4 with scheduled bilateral contract as 30MW during the system operation under combined Pool/Bilateral market. So the system operation situation will be changed. In the third step, the volume value of the scheduled bilateral contract on conventional generator 4 is changed to 50MW.

The aim of the simulations in this section is to assess the impacts on conventional generators and transmission system due to wind power generation integrating into the power system when the scheduled bilateral contract is significant during the power system operation. So in this test study, wind turbine is assumed that wind farm owners offer their energy at a price equivalent to zero. In this way the wind farm can be treated as firstly used generation in the power market. The cases in this section are operating with unconstrained network.

Figure 7.3 is the simulation results of all generators' outputs under unconstrained network with pure pool market. Wind power output is regarded as "must-take" energy, once the wind penetration level is a significant for the supply side, one of the major impacts of wind integration on generation system is that the output will lead to the energy changing for the conventional generators to maintain the generation-demand balance. It is very clearly showing in *Figure 7.3*, the green dotted curve is the output of wind power, its maximum output is almost equal to 30MW. The red curve in *Figure 7.3* is the output of generator 4 which is selected to be scheduled with bilateral contract in the comparison study which is as follow.

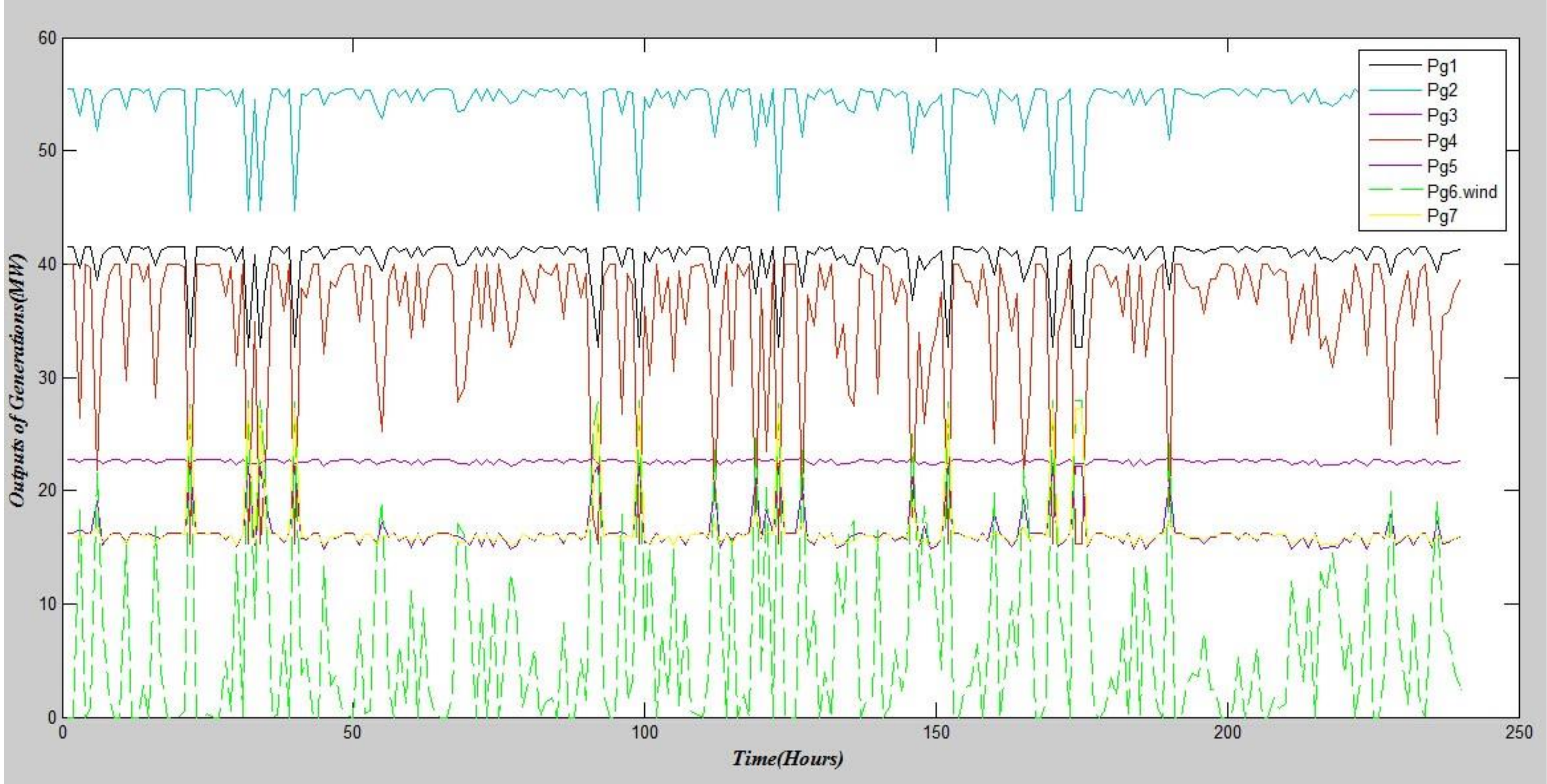


Figure 7.3. Snapshot of all Simulated Generator's Outputs under Pure Pool Market with Unconstrained Network

The conventional generator 4 is scheduled with bilateral contract of 30MW during the system operation under combined Pool/Bilateral market is introduced into the compared simulation. The simulation results in this section will show that, as the bilateral demand increases (while the pool demand declines), not only can some generators be forced to operate at their bilateral contract levels, but transmission congestion may also appear.

Figure 7.4 is the snapshot of wind power's outputs and the selected convectional generator 4 in the compared simulation have two different volume values of scheduled bilateral trades, 30MW and 50MW separately. With the simulation results in *Figure 7.4*, green dotted curve is the output of installed wind power generation, as maximum objective is 30MW. During the base case simulation process, all of the "zero price" wind energy will be accepted by the system operator. The scheduled bilateral trades lead to transmission congestion and the wind power generation will be curtailed. It can be seen in *Figure 7.4*, that the purple red curve which is the curtailed output of wind power when the selected generator 4 with 30MW scheduled bilateral trades, and power system is operating under the combined pool /bilateral dispatch. The black curve is the output of wind generation when the value of scheduled bilateral trades is increased to 50MW. More wind power will be curtailed when the scheduled bilateral trades on the conventional generator is increased.

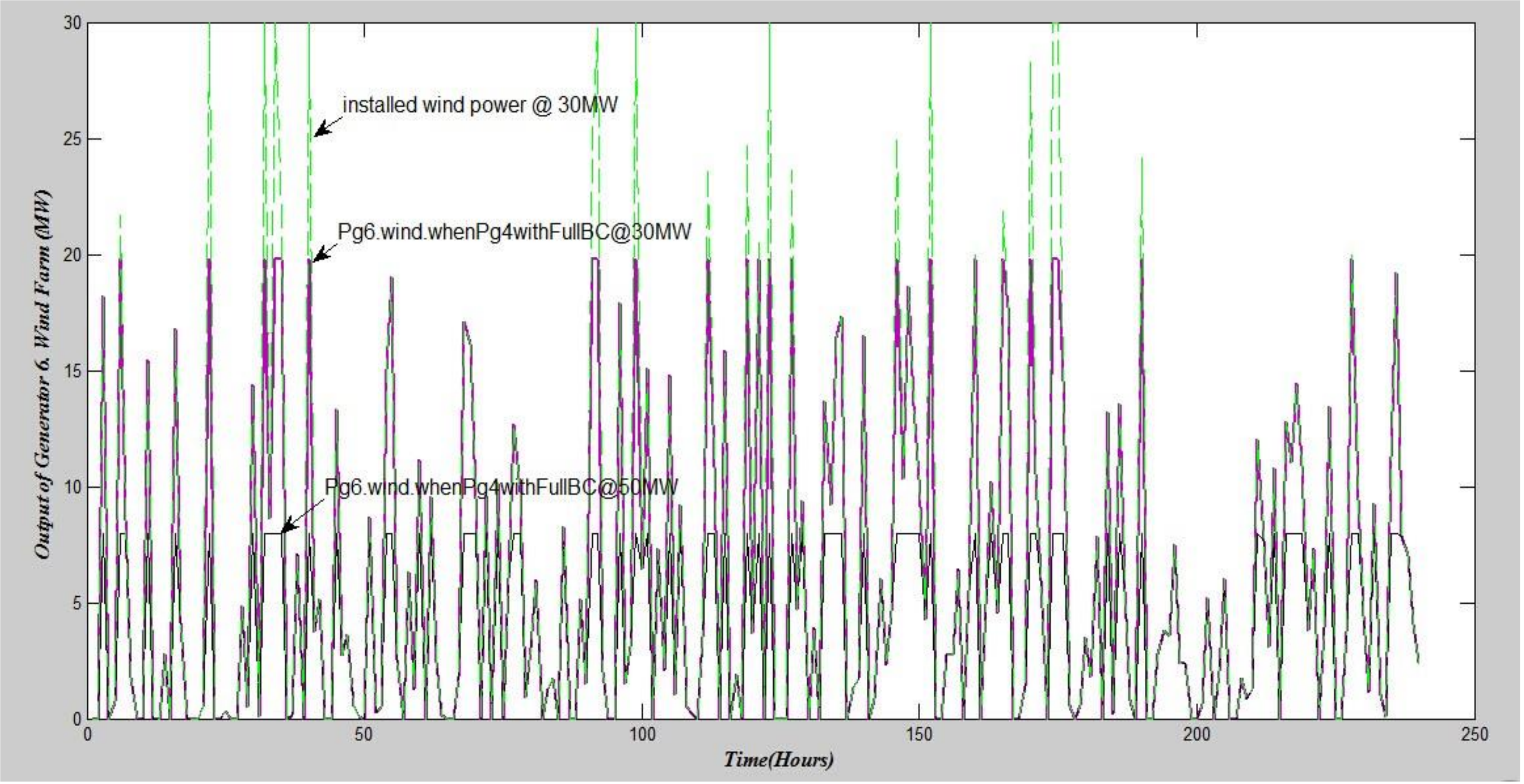


Figure 7.4. Snapshot of Wind Power's Outputs and the Selected Convectional Generator with Different Scheduled Bilateral Trades

7.3.2 Combined Pool/Bilateral Dispatch to Enhance Penetration of Wind Power

The ultimate goal of this proposed method is to integrate maximum wind energy into the power system while allowing generator and load serving entities to choose appropriate relative levels of pool and bilateral trades and taking into consideration risk, economic performance and transmission bottleneck. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. The optimization problem presented by *Equation 6.32* and *6.33* that coordinates these forms of trading is a necessary step toward this goal. The aim is to have better bilateral exchange planning and/or the introduction of coordinated bilateral contract curtailment.

The economic influences of system operation due to bilateral commitments is that nodal prices, generation revenues and load payments are altered. Under marginal pricing theory [6], the tariffs charged by generators and paid by loads (in ￡/MWh) are the nodal prices or bus incremental costs. Furthermore, it is assumed that the prices for the privately negotiated bilateral contracts can vary from one transaction to another. Since bilateral rates are private and confidential and non-unique, in this study, some reasonable but arbitrary values are used.

In the last *section 7.3.1*, the case study is selected in order to show the effect of transmission congestion leading to the curtailment of wind power generation. However, this part of the research is done to show the results of the proposed cooperative reduction of the scheduled bilateral trades from the selected conventional generator to relieve the curtailment of wind energy.

Additional dispatch flexibility is therefore required and this can be achieved in this way, establish firm contracts with curtailment bids for the selected conventional generator, for which a curtailed firm contract would receive payment from the ISO. While in this section, different volume values of the firm bilateral contracts and the different payments for the curtailment bids will be introduced in two comparison studies separately, and the impact on system operation (generation levels, costs, and nodal prices) will be discussed. The changing will affect economic performance via individual or total revenues and expenditures from system participants. The performance measures analyzed here are of two types: operation costs and compensation for the curtailed part of scheduled bilateral contracts.

Case 1 Change the volume of scheduled bilateral contract

Wind farm mentioned in *Section 7.3.1* will still be used in this simulation, with the wind farm installed generation capacity 30 MW (*Figure 7.2*) .The conventional generator on bus 27 with the scheduled bilateral contract at 30MW. Later the volume of the scheduled bilateral contract will be increased to 50MW.

In this study, firm bilateral contracts are allowed to coexist with the pool demand. As well an additional type of bids to the pool is introduced, namely, firm contract curtailment bids. They can be thought of as strategies to hedge against unfavorable nodal prices and power-transfer costs, particularly in the presence of congestion.

Also congestion management for pool and bilateral demand are provided centrally by the pool dispatch in one optimization step. The cooperative required one single optimal dispatch and it includes losses and congestion. In contrast to other curtailment models [2, 3, 4], in the approved method, the pool-scheduled bilateral contracts can be decreased from their requested values but cannot increase.

This study formulates the optimization problem of mixed pool/bilateral coordination with contract curtailment. A set of performance measures of the proposed model is then defined and tested.

One improved feature of my proposed method is the dispatch of a pool-based generation subject to the constraints imposed by the physical bilateral contracts.

Figure 7.5 is a snapshot of simulated generator 4's outputs with different volumes of scheduled bilateral contracts with wind power integrated in the system. Being the selected test conventional generator, three test operating situations will be compared. The black curve in the Figure 7.5 is the selected conventional generator operating with the full scheduled bilateral contracts of 50MW, which is the base case. The purple red curve is the simulation results if the generator 4 submit its own curtailment bid, the requested values is at 7 (£/MWh) while the scheduled bilateral contract is 30MW. The blue curve is the simulation results with the same requested payment for the curtailment of bilateral contract but the scheduled bilateral contracts is increased to 50MW.

When wind penetration level is significant, certain amount of displacement needs to be conducted on conventional generation unit to accommodate the output from wind power. But with the transmission congestion and for security of system operation, some of the wind power will also be curtailed. In *Figure 7.6,* the "must-take" generation wind power is curtailed because of transmission congestion which is caused by the conventional generator's scheduled bilateral contracts, as shown with the black curve. Using our approach in this chapter, better coordinated bilateral contract curtailment from the selected conventional generators will allow maximum wind energy into the power system. It is shown in the purple red curve in *Figure 7.6,* the requested values submitted by the selected conventional generator 4 is at 7 (£/MWh) while the scheduled bilateral contract is 30MW and 50MW separately, the total outputs from the installed wind power generation will be integrating into the system operation. In all of the simulation studies, wind turbine is treated as first used generation in the power market, that wind farm owners offer their energy production price being equivalent to zero.

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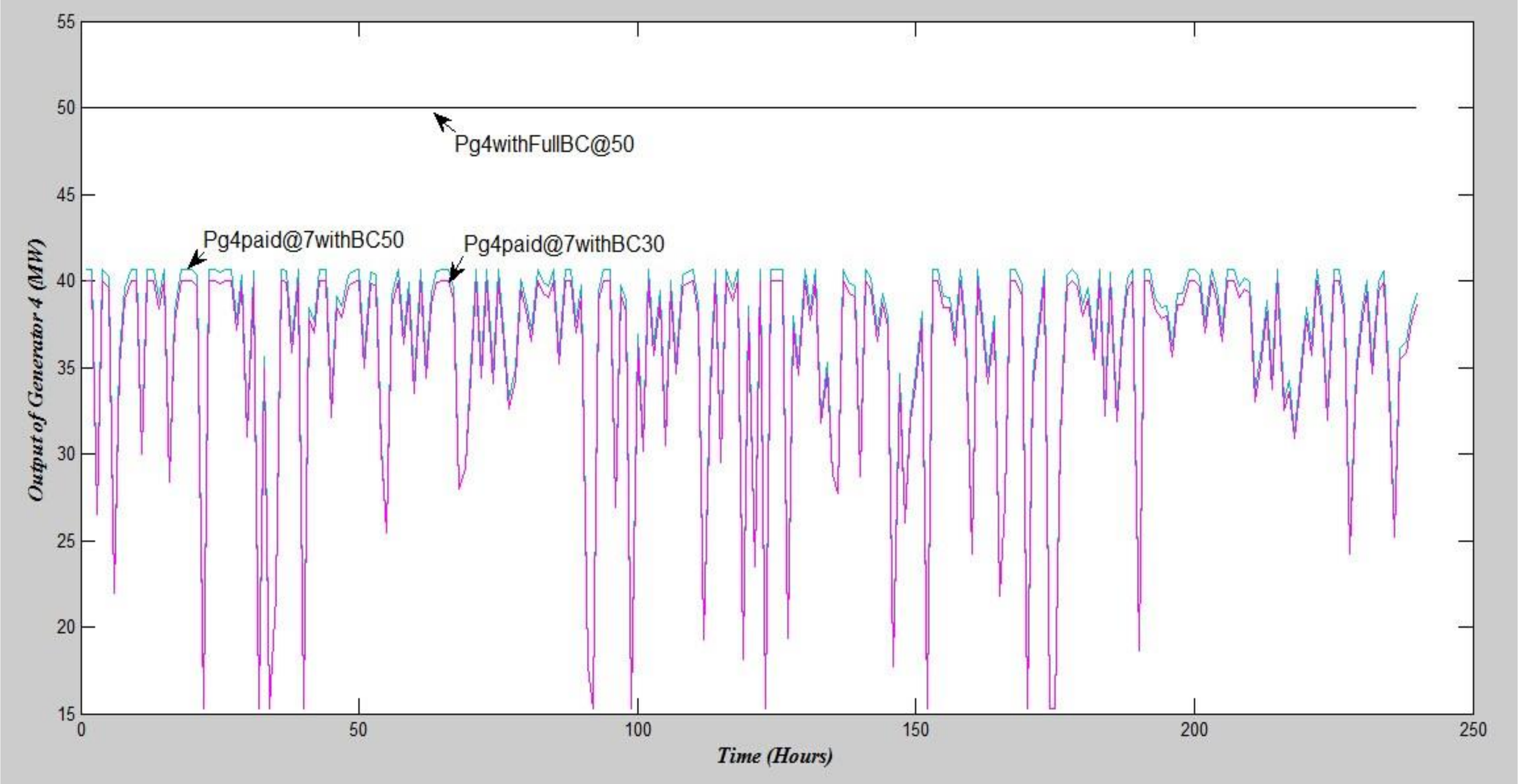

Figure 7.5. Snapshot of Simulated Generator 4's Outputs with Different Volumes of Scheduled Bilateral Contracts and Wind Power

integration

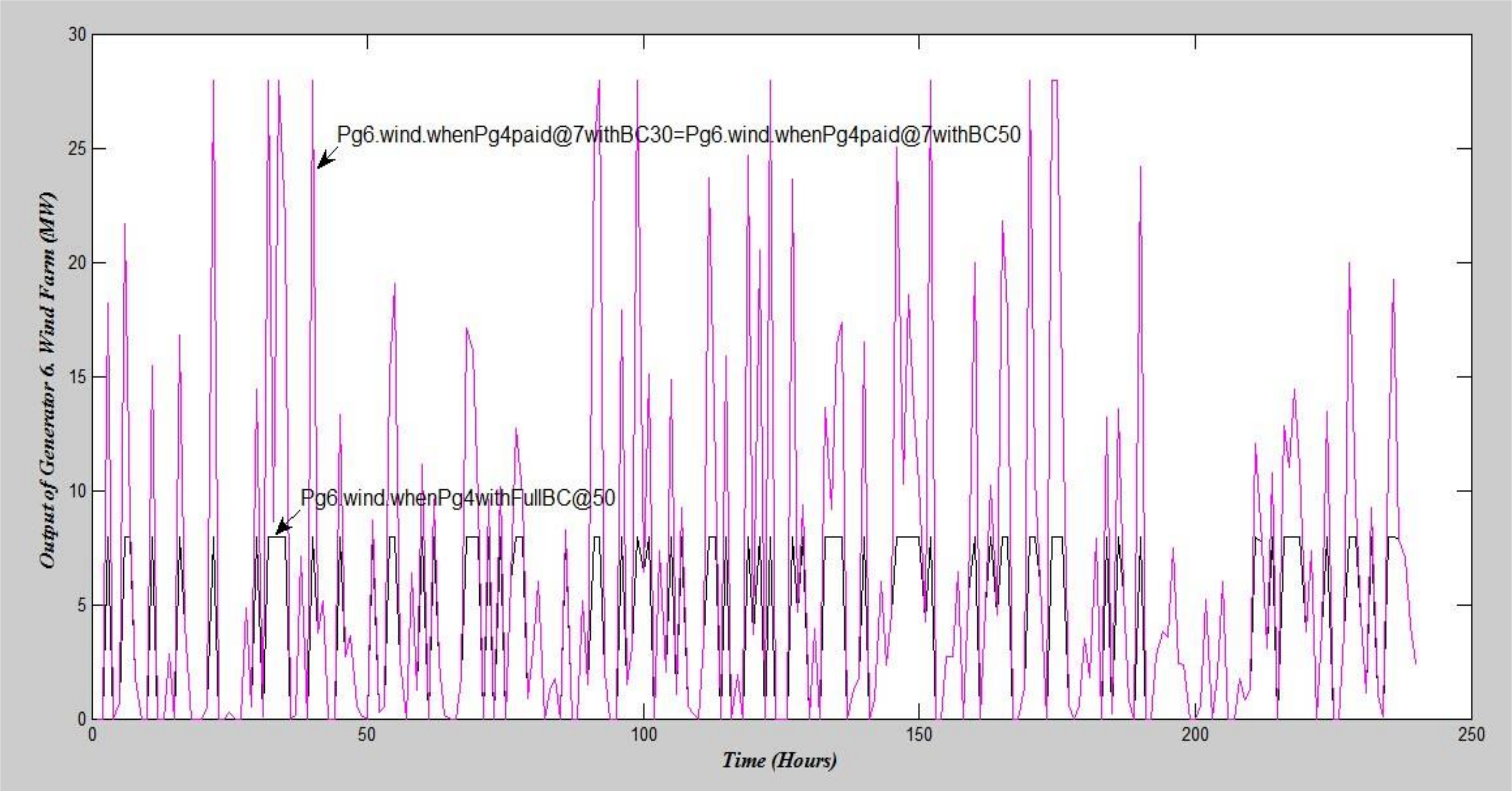

Figure 7.6. Snapshot of Simulated Wind Power's Outputs with Different Volumes of Scheduled Bilateral Contracts

A firm contract is one that has acquired the right to use the network for a requested power transfer. As originally defined [6], a firm contract can be reduced only in emergency situations, but not to improve system economic performance. To approve a firm contract, the ISO has to verify whether it can be transferred without violating system security limits. The transmission provider then assumes the obligation to transfer the power and would only decrease its transfer only under an emergency situation.

When confirming reservations for firm contracts, however, an ISO usually does not know the final system schedule. Thus, it may happen that some lines will operate at a limit, causing a significant increase in the power-transfer payments of certain market participants.

In this study, to integrate maximum wind power into the power system operation (which is curtailed by the transmission congestion caused by the firm bilateral contracts) with the optimization dispatch, firm bilateral contracts will receive compensation for unfulfilled transmission obligation.

In this chapter if a bilateral contract is responsible for congestion, resulting in large nodal price differences, the correspondingly large power-transfer charges send a first and necessary economic signal to holder of this contract. *Figure 7.7* is the simulation results of the total generation costs, the black curve is for the base case, and all of the schedule bilateral contracts are accepted by the ISO. The wind power curtailed by the transmission congestion cannot improve system economic performance.

This bidding mechanism in the proposed method allows bilateral parties to modify their operation and achieve more efficient overall system operation. In Figure 7.7, the purple red curve is the total generation costs if generator 4 submit its own curtailment bid, the requested values is at 7 (£/MWh) while the scheduled bilateral contract is 30MW. The blue curve is the simulation results with the same requested payment for the curtailment of bilateral contract but the scheduled bilateral contracts is 50MW. The results prove that the flexibility introduced by the bilateral contracts curtailment bids can improve financial performance measures of all market participants, not only those that are directly involved in curtailment bidding. To justify this statement, the market is more economically efficient shown as is *Figure 7.7*, system generation cost is reduced.

Figure 7.8 is a snapshot of compensation costs for the curtailment of scheduled bilateral contracts of generator 4 of different volumes. This additional terms that account for contract modification bids appear in the proved function $\min\left[C\left(\mathrm{P}_{\mathrm{G}_i}\right)+\pi_i^c\Delta\mathrm{P}_{\mathrm{G}_i}\right]$. $\pi_i^c\Delta\mathrm{P}_{\mathrm{G}_i}$ is the compensation costs for the curtailment of scheduled bilateral contracts of conventional generator. The ISO will curtail part of the scheduled bilateral contract from the selected conventional generator under the combined pool/bilateral dispatch and compensate them to the requested value.

In the *Figure 7.8*, The purple red curve is the compensation for the curtailment of scheduled bilateral contracts of generator 4 at a requested value as 7 (£/MWh) for a scheduled bilateral contract of 30MW. The blue curve is the simulation results with the same requested payment for the curtailment of bilateral contract but the scheduled bilateral contracts being increased to 50MW. With the higher volume of scheduled bilateral contract, the compensation for the curtailment will be more under the combined pool/bilateral dispatch. For the base case, the scheduled bilateral contracts caused the transmission congestion, that no compensation is agreed. This is shown in *Figure 7.8* as zero compensation.

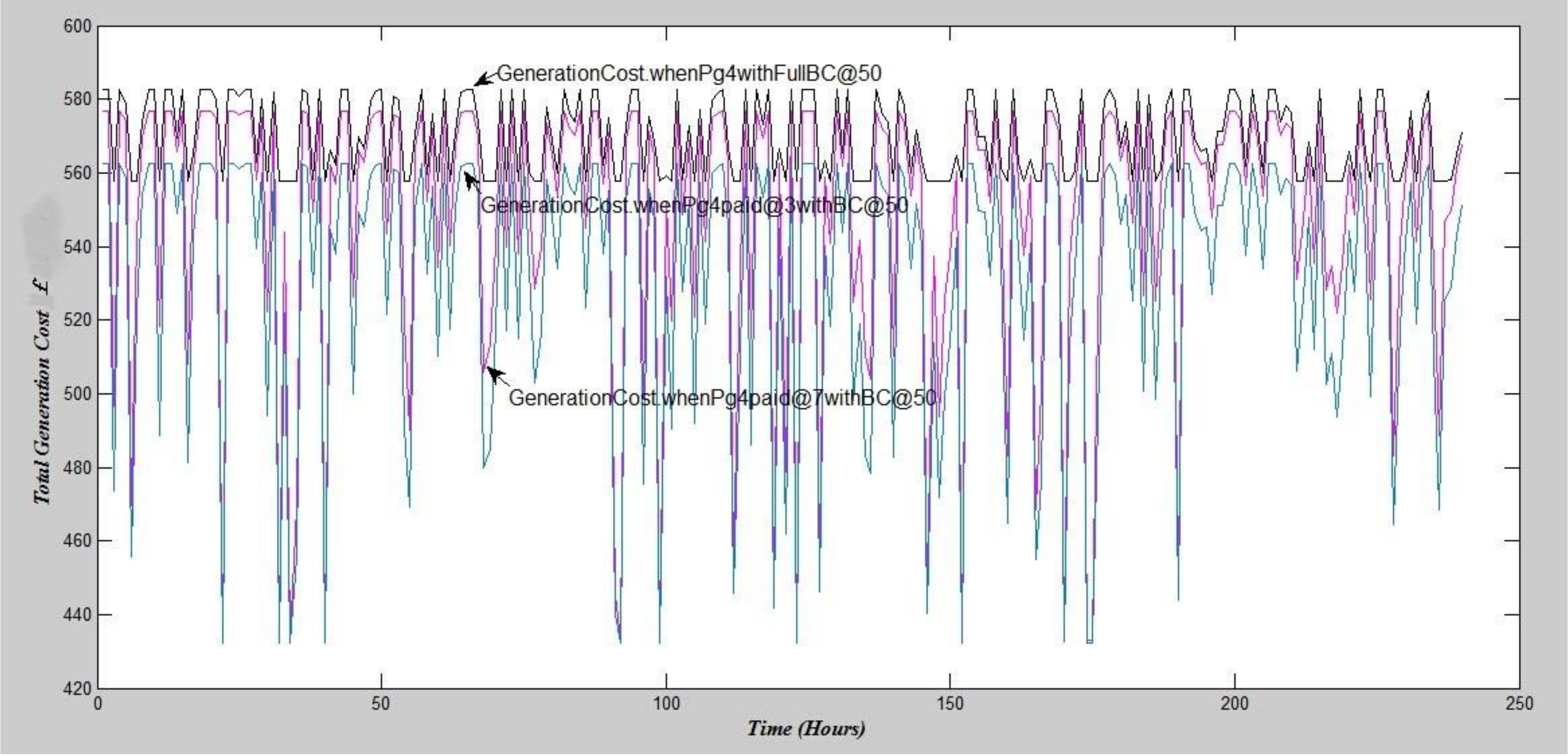

Figure 7.7. Snapshot of Total Generation Cost when Generator 4 with Different Volumes of Scheduled Bilateral Contracts and Wind Power integration

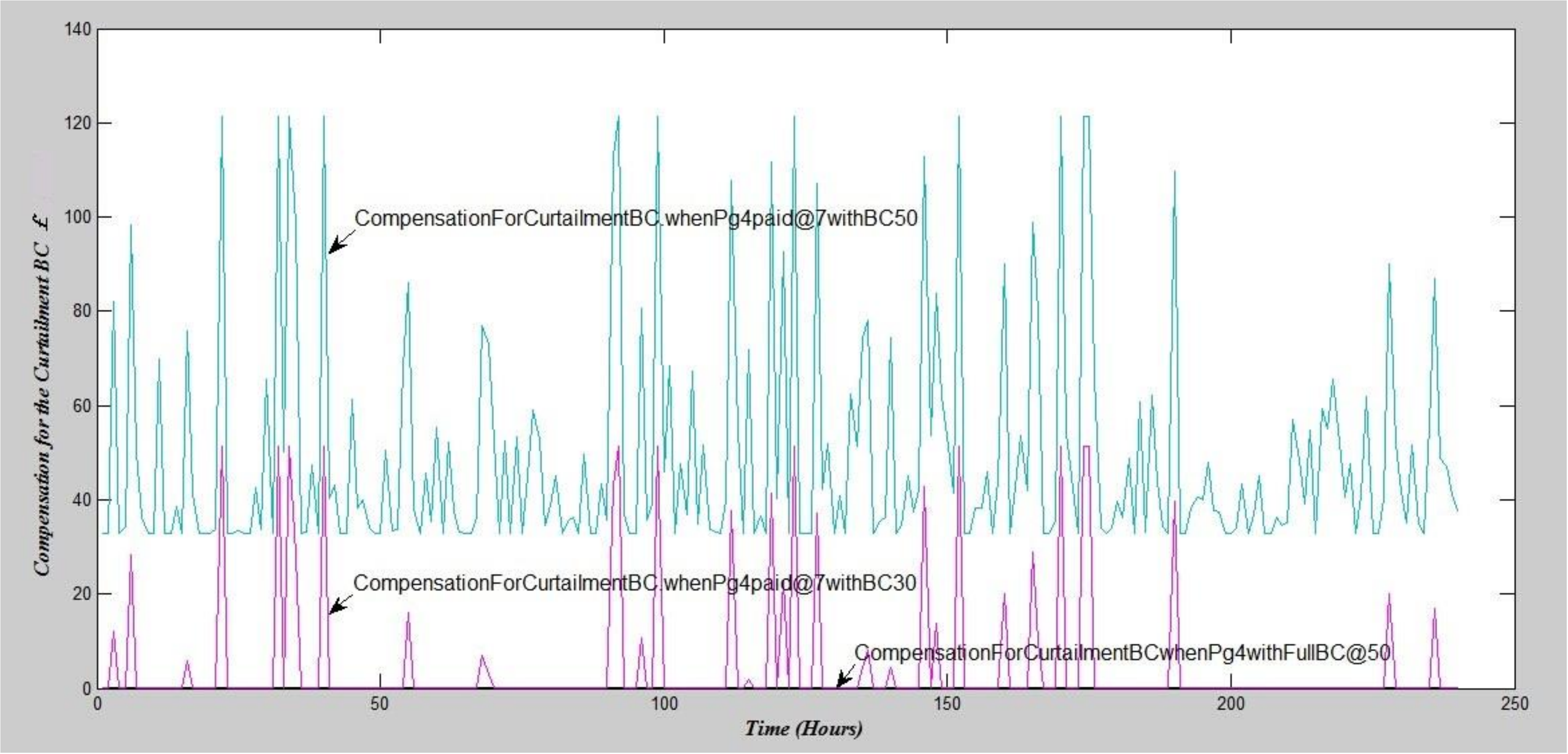

Figure 7.8. Snapshot of Compensation for the Curtailment of Scheduled Bilateral Contracts of Generator 4 with Different Volumes of it and Wind Power integration

Case 2 Change the curtailment bids of scheduled bilateral contract

To integrate maximum wind power into the system operation, the aim here is to investigate a new market structure where the firm contracts may voluntarily agree to be curtailed for economic reasons. In order to reconcile, on the one hand, the need for a centralized coordination of system operation and, on the other, the participants desire to “have a say” in the scheduling of their contracts, it is proposed that each firm bilateral agreement be allowed to submit a request for compensation in case of curtailment (except in emergency situations). This curtailment and associated payment will be administered by the ISO and by doing so, the overall generation costs plus curtailment payments are minimized. It is worth noting that since the ISO has no financial resources, these payments have to be collected from all market participants.

In the case study, a firm contract submits a requested values of 7 (￡/MWh) while the scheduled bilateral contract is 50MW. For comparison study, the requested values is lowered to 3 (￡/MWh) while the same volume of scheduled bilateral contract is 50MW is used.

Firm status payment guarantees that if a requested firm contract is curtailed, it will be compensated according to the curtailment bid, with the submitted requested values through curtailment bid payments.

Figure 7.9 is a snapshot of simulated generator 4’s outputs with different required values of curtailed scheduled bilateral contracts and wind power integration. The black curve in the *Figure 7.9* is the selected conventional generator operating with the full scheduled bilateral contract as 50MW, which is the base case. The blue curve is the simulation results that generator 4 submits a curtailment bid, the requested value is 3 (￡/MWh). The purple red curve is the simulation results when requested values for the curtailment being increased up to 7(￡/MWh) with the same volume of scheduled bilateral contract as 50MW. With the optimal operation under the combined pool/bilateral dispatch, the output of the selected conventional generator will be more if the requested values for the curtailment part of the scheduled bilateral contracts is higher.

Figure 7.10 is a snapshot of simulated wind power’s outputs with different required values for curtailed part of scheduled bilateral. Firstly, for the base case, the “must-take” generation wind power is curtailed because of the transmission congestion which is caused by the conventional generator’s scheduled bilateral contract which as shown as the black curve. Using the proposed approach, better coordinated bilateral contract curtailment from the selected conventional generators will allow maximum wind energy output into the power system. In *Figure 7.10*, the requested value submitted by the selected conventional generator 4 is at 3 (￡/MWh) and 7 (￡/MWh) respectively, a maximum outputs from the installed wind power generation can be accepted into the system and is shown as the purple red curve. In all of the simulation studies, wind turbine is treated as the first used generation, as the wind farm owner’s energy production price is treated as zero.

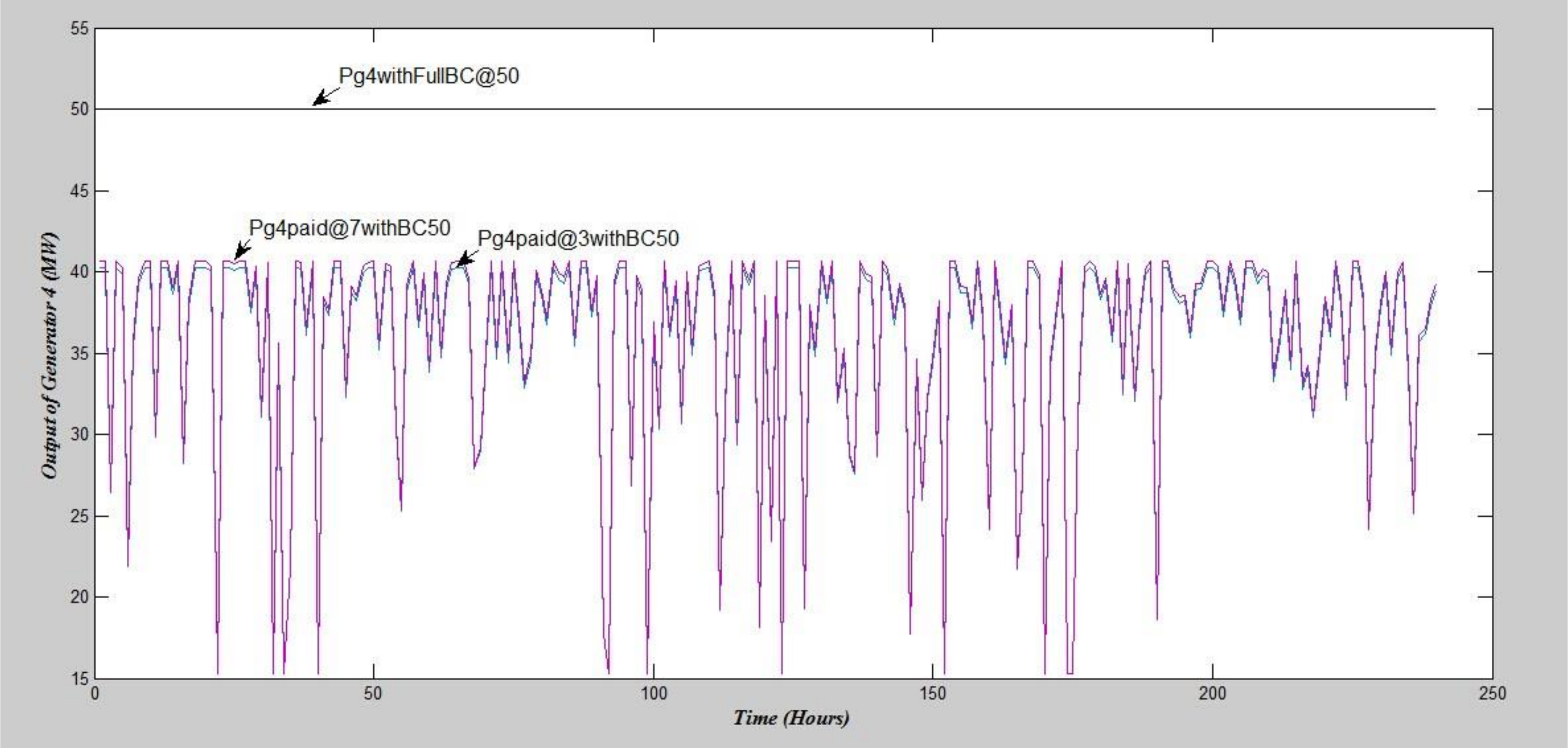

Figure 7.9. Snapshot of Simulated Generator 4's Outputs with Different Required values of Curtailed Scheduled Bilateral Contracts and Wind Power integration

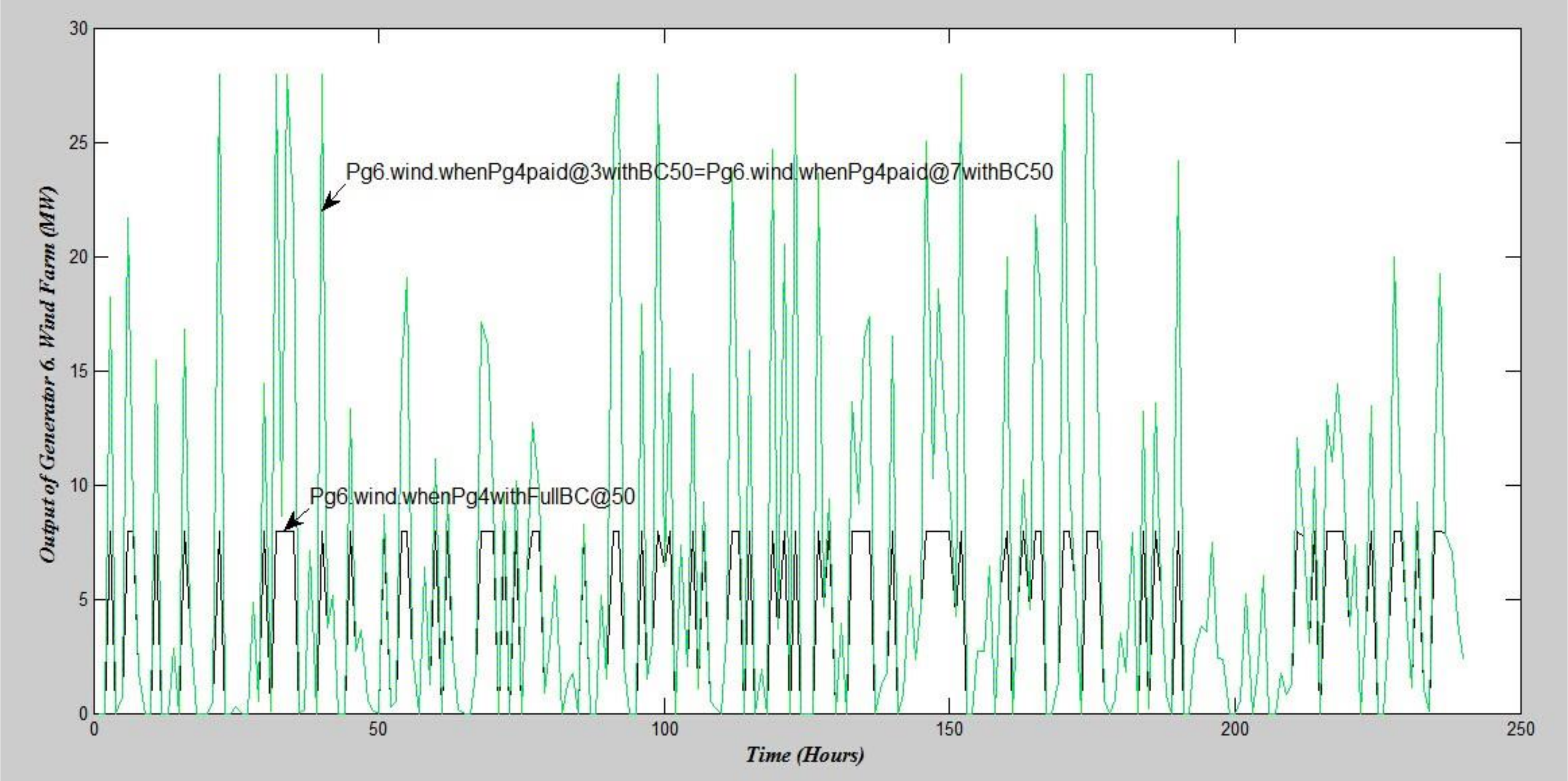

Figure 7.10. Snapshot of Simulated Wind Power's Outputs with Different Required values for curtailed part of Scheduled Bilateral Contracts

All the payments and revenues, however, depend on the market pricing mechanism and go through the ISO. The financial performance measures proposed here are structured such that the total generation costs or the compensation for curtailment payments are separated into components. These revenue and payment components are associated with specific portfolio-management decisions.

Figure 7.11 is a snapshot of total generation cost when selected conventional generator 4 with different requested value of curtailed part of scheduled bilateral contracts. The black curve is for the base case with all of the 50MW schedule bilateral contracts accepted by the ISO, and the wind power is curtailed when transmission congestion occurs. The total generation cost is the most expensive one for this case study.

In the *Figure 7.11*, the blue curve is the total generation costs when generator 4 submits its own curtailment bid at 3 (￡/MWh) with a scheduled bilateral contract of 50MW. The purple red curve is the simulation results with the same volume of scheduled bilateral contract when the selected conventional generator is to keep its profits and increases the requested value of the curtailment to 7 (￡/MWh). The simulation results of this comparison study shows that, with the higher requested value of the curtailment, lesser portion of the scheduled bilateral contract will be curtailed. The total generation cost will also be higher in this situation than the dispatch schedule with a requested value as 3 (￡/MWh).

Figure 7.12 is a snapshot of compensation for the curtailment of scheduled bilateral contract for the conventional generator 4, with different requested values. This bidding mechanism and the proposed method allows bilateral parties to modify their operation and achieve more efficient operation. The curtailment bid payments are important financial signal and incentive, the persuade bilateral contracts is in the schedule.

The blue curve is the compensation for the curtailment of generator 4 at a requested value of 3 (£/MWh).The purple red curve is the simulation results with the same volume of scheduled bilateral contract, but the requested value is increased to 7 (£/MWh). With the higher requested value for the curtailed part of the scheduled bilateral contract, the compensation for the curtailment will be more under the combined pool/bilateral dispatch. As the base case in this study, the scheduled bilateral contract causes transmission congestion, so in *Figure 7.12*, the compensation for it is equal to zero.

As shown by the results of this chapter, these contract price incentives are beneficial to the majority of participants in a mixed pool/bilateral market.

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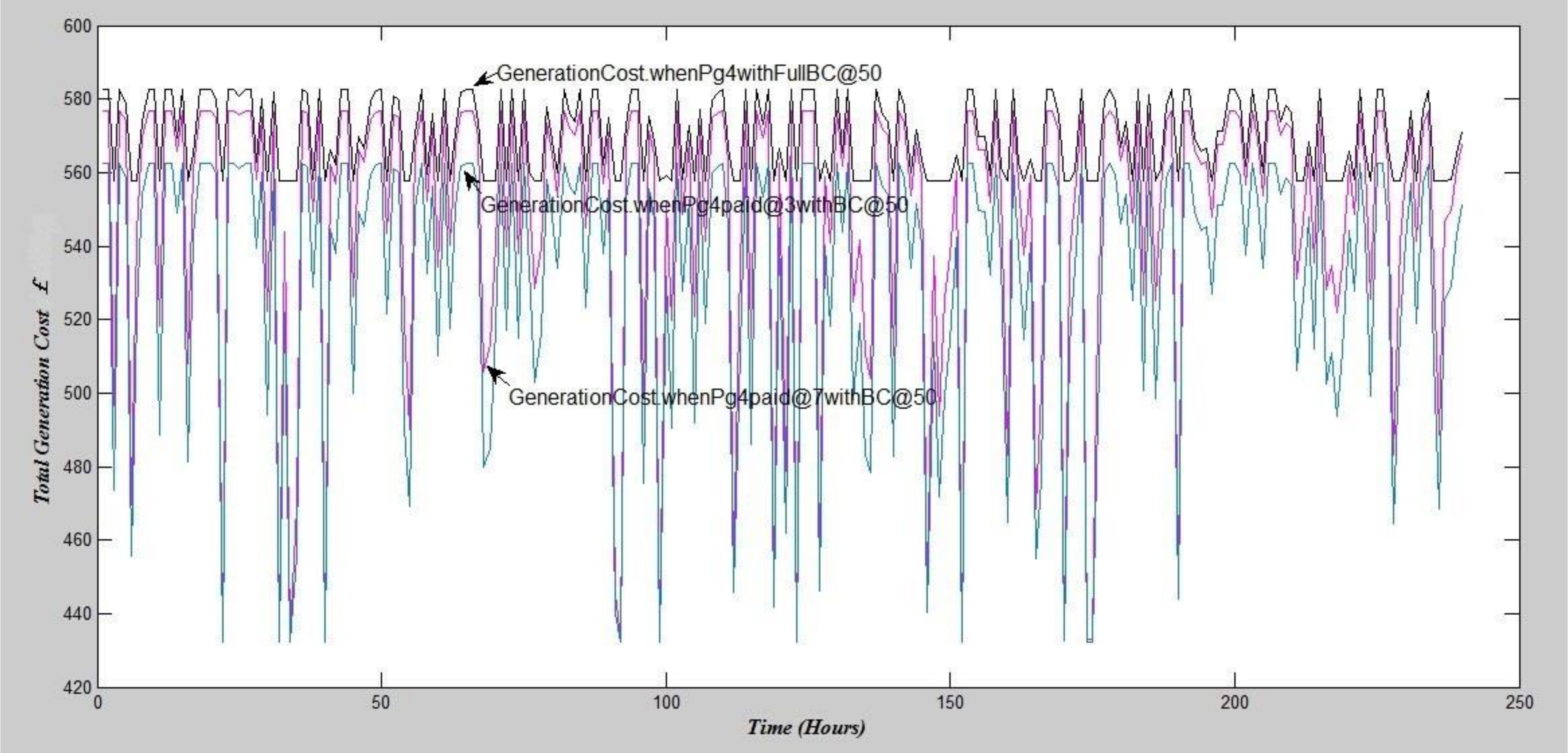

Figure 7.11. Snapshot of Total Generation Cost when Generator 4 with Different Required Value of Curtailed part of Scheduled Bilateral Contracts and Wind Power integration

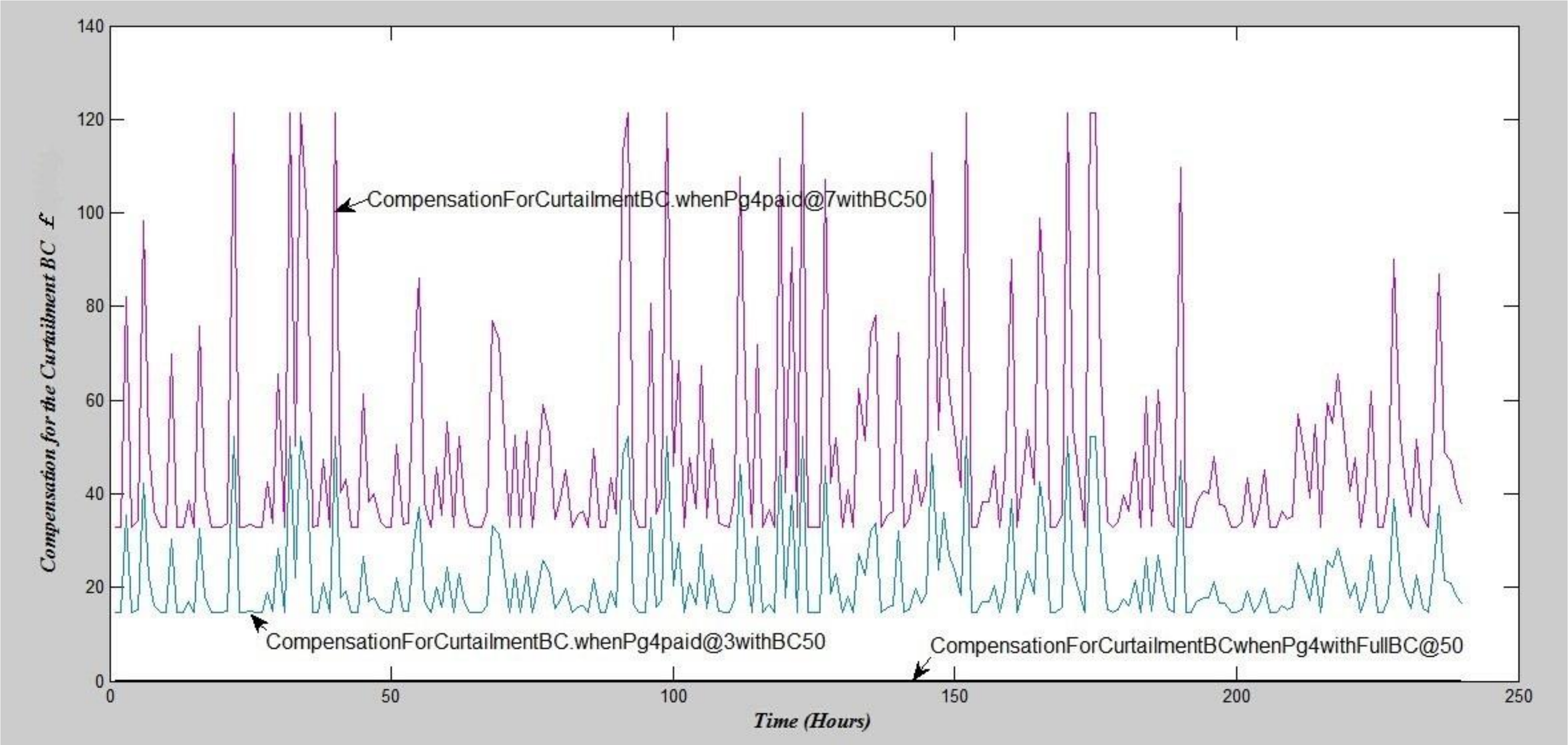

Figure 7.12. Snapshot of Compensation for the Curtailment of Scheduled Bilateral Contracts of Generator 4 with Different Required Value of Curtailed part of Scheduled Bilateral Contracts and Wind Power integration

7.4 Summary

This chapter formulates a comprehensive optimization model for mixed pool/bilateral markets to be used as part of a portfolio management strategy.

In section 7.3.1, the problem formulation and simulations carried out are based on the assumption that the bilateral contracts are firm without the possibility of curtailment. This firm scheduled bilateral contract leads to transmission congestion and the wind power output is curtailed under this situation. What ensues from that part is that high levels of firm bilateral demands can lead to poor economic performance for many participants due to “out-of merit” operation.

With the proposed method, the notions of pool and bilateral trades and generation are established first. Their coordination is then formulated as a cost minimization optimal power flow problem subject to transmission constraints and to enhance the maximum of wind power integration. The optimization procedure yields the generation outputs and the nodal prices, which serve to calculate individual financial measures such as operation cost and compensation for the curtailed part of scheduled bilateral contract according to pool or bilateral trading.

The eventual goal of these results is to help generator and load-serving entities choose appropriate relative levels of pool versus bilateral trades while considering risk, economic performance, and physical constraints. Simulation results illustrate how the performance measures can be used to assess the relative benefits of a chosen pool/bilateral mix. In addition, the results point to the importance of good bilateral contract planning, particularly when the contracts are firm.

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Chapter 8

Conclusions

8.1 Contributions and Findings of this Research

This thesis formulate an approach aiming to integrate maximum wind energy into the power system and to help generators and load to choose the appropriate relative levels between pool and bilateral trades taking into consideration risk, economic performance and transmission bottleneck. In order to efficiently use generation resources (wind power generation) and the transmission grid in a competitive environment optimal power flow is incorporated. The well-proven software tools *MATLAB* and *MATPOWER* support the study. The following section presents the key findings of this work in response to the detailed research question outlined in *Chapter 1.* This is then followed by the suggestions for future works.

✧ Wind power is one of the most promising renewable energy sources for sustainable development due to its advanced and mature technologies. Wind speed is inconsistent and intermittent; the speed variation causes the fluctuation of wind power output. High wind power penetration can lead to a high level of risk of the power system reliability. Many analysis methodologies and impacts have been presented in past works. A critical outcome of this work is using a dynamic simulation model to assess the related aspects of impacts on system operation.

The Weibull Distribution Function is used to analyze the problem of wind distribution and Monte Carlo Simulation (MCS) method is also introduced to simulate the output of wind power generation. It is an effective tool to analyze the intermittent nature of wind power and the impacts of wind penetration on system security operation. The simulation results prove that the Weibull Distribution Function is applicable for the proposed methodology.

With the dynamic model mentioned in the pricier paragraph the impacts of different penetration level of wind generation is investigated using the *IEEE-14 bus* system. The penetration level is increased from 5% to 10%.

When the power system is under unconstrained operation, with the price at “zero”, all wind power generation is accepted by the system operator. With the increasing wind power penetration, power energy from conventional generators will be reduced to maintain the generation-demand balance. And the increasing free wind energy leads to a sharp decrease on the value of the corresponding LMPs for each bus. For example, the bus which is connected with wind generation, to select one point of the simulation results, LMP decreases from 38.6*(£/MVA-hr)* to 36.5*(£/MVA-hr)*. With the simulation results, when wind power penetration is increased, operating costs will decrease sharply, to select one point of the simulation results, with the increase penetration of wind power, the operation costs will decrease from approximate 6900 £/hr to 5800 £/hr.

When the power system is under constrained operation, and with the increasing penetration of wind, the output of wind farm will be curtailed due to some transmission line is overloaded and transmission congestion occurs. LMPs vary over a big range. To select one point of the simulation results, the LMP on the bus which is connected with conventional generator 1, will be decreased from 36.5*(£/MVA-hr)* to 30.5*(£/MVA-hr)*. The LMP on the bus connecting wind farm and the power system will be zero when wind output curtailed; and with the simulation results, LMP on the overload lines' buses will increase. This Congestion and some related elements have added operating cost.

- ✧ The Main contribution of this thesis is proposing a combined pool/bilateral trade model to cooperate with wind power output fluctuations to increase the utilisation of wind farms which are constrained by the transmission networks. The proposed combined pool/bilateral trade method was applied to an extensive set of case studies and aimed to identify the validity of this cooperation in different sizes of power systems.

Theoretically, in the Optimal Power Flow (OPF) with security constrained, the basic objective is to minimize the cost of meeting the load, and at the same time, the system is able to respond to contingencies. These contingencies are treated as a set of physical constraints in optimization. The proposed trade model consists of both pool and bilateral contracts trades for the power market. In the proposed operational mode, the conventional generator with scheduled bilateral contracts are assigned to cooperate with wind power to offset the power imbalance caused by wind fluctuation and relieve the curtailed wind output caused by overloaded transmission lines. The detailed explanation of the mathematical model and the entire simulation procedure including flow charts are presented in *Chapter 6.*

The aim is to determine the optimal dispatch in a multi bilateral contract market. The ISO can choose the volume of reduction from the conventional generator' scheduled bilateral contract to integrate maximum wind energy into the power system and the proposed objective function minimizes the production costs of energy with the curtailment of conventional generators' bilateral contract. There are two test power systems in this thesis to illustrate the combined pool/bilateral trade cooperation: **1)** a smaller *IEEE-9 bus* test system is modified for validation purposes; **2)** a larger power system *IEEE-30* bus system is modified for the comparison case studies to analysis the effects of the proposed combined pool/bilateral trade method under different pricing mechanisms.

The operational mode was applied to the modified *IEEE-9* bus system for verification and validation. This optimal power flow model dispatches the pool in combination with curtailed part of scheduled bilateral contracts from conventional generators. This pool in my thesis is the balancing market. The aim is integrating maximum wind energy into the power system while minimizing costs. The results proved that it could guarantee the curtailed wind power to be relieved and all of the output of wind generation can be integrating into the power system operation. The main advantage of the proposed method is that, these conventional generators are not willing to reduce their output because they will lose earnings. This incorporation will look at maintaining the profit of the generators even if they are curtained to allow more wind power to be used.

- ✧ The final contribution of this thesis is proposing the comparison studies with the proposed one-step combined pool/bilateral trade model under different compensation prices for the generators. The details of the modified *IEEE 30-bus* is used as the test system have been presented. The firm scheduled bilateral contract from the conventional generation can cause transmission congestion and free wind power cannot be integrated into the power system operation sufficiently. Two case studies were introduced: **1)** the volume values of conventional generators' scheduled bilateral contracts are varied; **2)** the request payments for the curtailment bids which submitted by the selected conventional generators are varied.

For the first case, the modified *IEEE 30-bus* test system with changing the volume of conventional generators' scheduled bilateral contracts, one conventional generator with the scheduled bilateral contract was introduced and the volume of this scheduled bilateral contract was increased from 30MW to 50MW for the comparison tests. From the simulation results, output reduction of the selected conventional generator will be less if the volume of scheduled bilateral contract is higher. At the same time, the total generation cost will be reduced under constrained power system. With the higher volume of scheduled bilateral contract, the compensation for the curtailed part of this bilateral contract for the selected conventional generator will be more under the combined pool/bilateral dispatch.

For the second case the modified IEEE 30-bus test system is used with the different requested payments for the curtailment bids submitted by the selected conventional generators. It is proposed that each scheduled bilateral contract agreement to be allowed to submit a requested compensation in case of curtailed part of its scheduled bilateral contracts. In the case study, the conventional generator submits a requested value for the curtailed part from its scheduled bilateral contract. For the comparison study, the requested values would be 3 and 7 (£/Mwh) respectively for the same volume of scheduled bilateral contract from the selected conventional generator. If the requested scheduled bilateral contract is curtailed, the selected conventional generator would be compensated according to the curtailment bid. From the simulation results, the output reductions of the selected conventional generator will be less in the system operation, if the requested value for its curtailed part of scheduled bilateral contracts is higher such as 7 (£/Mwh), and lesser portion of its scheduled bilateral contract will be curtailed during the re-dispatch. The total generation cost will also be higher with the curtailment bids as 7(£/Mwh) from the selected conventional generator. With higher requested value for the curtailed part of the scheduled bilateral contract from conventional generator, the compensation for the curtailment will be more under the combined pool/bilateral dispatch.

All of the simulation results proved that the proposed combined pool/bilateral trade method could effectively relieve the curtailment of wind power under the constrained system operation. Consideration includes scheduled bilateral contracts from selected conventional generators under various curtailment strategies in a mixed pool/bilateral operation with network constraints. The simulation results prove that the flexibility introduced by the bilateral contracts curtailment bids can improve financial performance of all market participants, not only those that are directly involved in curtailment bidding. The aim is to enhance penetration of wind power into the system operation, and to obtain good profits at low risk.

All of the comparison simulation studies are investigated by using *MATLAB* and *MATPOWER* software.

8.2 Future Work

This thesis contributes to the integration and reduction of wind power curtailment in power system operation. However, the proposed method and associated case studies have been investigated in details; a consistent theme running through the thesis is the need for greater cooperation among utilities, states, power marketing participants to share resources, loads and transmission in order to take advantage of least-cost strategies to integrate renewable resources.

In this section, some possible directions for future research are presented.

- ✓ Presented works mainly focused on the power system, which are dominated by the thermal power generation. Due to the increasing various renewable energy sources, it is necessary to investigate the effect of using hydro as a reserve in the power system to reduce the various renewable energy fluctuations. With the hydro reserve and power market strategies, it is critical to find the optimal cooperation scenario to allow maximum wind power output into the power system.

- ✓ For the realistic, wind energy is not free, in the future researching work, the price of wind energy need to be considered into the optimal power flow simulation with the proposed methods.

- ✓ Due to a lack of real practical data and access to the up-to-data information, it is impossible to test these combined pool/bilateral contracts trade methods in real practical systems and power markets. Although the related simulation are based on the random numbers generated by the software and tested repeatedly for a significantly long period, and the accuracy and validity of theses simulation results have been proved; it is better to test the propose methodologies with real operational data and market information in practical power systems.

- ✓ How to pay the compensation for the curtailed part of selected conventional generator to create incentive need to be investigated in the future work.

Appendix

Appendix 1 Matlab Code of Wind Turbine Power Output Model

```
hour=1;
outwind=zeros(8736,2);
windoutput=zeros(8736,1);
i_wind=1;

Pwr=3; % rated power output of wind turbine
Vci=4; % cut-in speed
Vr=12; % rated speed
Vco=25; % cut-out speed
A=(Vci*(Vci+Vr)-4*Vci*Vr*((Vci+Vr)/(2*Vr))^3)/(Vci-Vr)^2;
B=(4*(Vci+Vr)*((Vci+Vr)/(2*Vr))^3-(3*Vci+Vr))/(Vci-Vr)^2;
C=(2-4*((Vci+Vr)/(2*Vr))^3)/(Vci-Vr)^2;

while hour<8737
     outwind(i_wind,1)=i;
     n1= wblrnd(7,2); % Weibull distribution
     outwind(i_wind,2)=n1

    if (outwind(i_wind,2)<Vci)
          Pw=0;
    elseif ((Vci<outwind(i_wind,2)) && (outwind(i_wind,2)<Vr))
        Pw=(A+B*outwind(i_wind,2)+C*outwind(i_wind,2)^2)*Pwr;
    elseif ((Vr<outwind(i_wind,2)) && (outwind(i_wind,2)<Vco))
        Pw=Pwr;

            else
         Pw=0;

   end;
  windoutput(i_wind,1)=Pw; % wind turbine power output

i_wind=i_wind+1;
hour=hour+1;

end
```

Appendix 2 OPF with bilateral contract

New variable:

$0 \leq \text{deltaP} \leq \text{deltaPmax}$

New constraints:

$\text{Pgib} \leq \text{deltaP} + \text{Pg}$

New input data:

deltaPmax => maxChange
Pgib => bilOutput
Πib – bilPrice

CASE9 – wind generator at bus 8

1. Run base case:

   ```
   mpc = loadcase(‘bilateral_case9’)
   r1 = runopf(mpc);
   ```

   and remember Pgi* optimal….

2. Change Pgib for one of generator such that Pgib > Pgi* and then run:

   ```
   mpc = loadcase(‘bilateral_case9’);
   mpc = bilateral_contract_final(mpc);
   r = runopf(mpc);
   ```

3. Find a problem in the network such that Pgi of wind generation can decrease

Appendix 3 Main part of Matlab Code changed on IEEE-9 Bus System

Added wind generator at bus 8 with max generation 100

Generator at bus 2 has bilateral contract 140MW with the price 50 £/MW

Congestion is made on lines 8-7 and 8-9

```
%% Max change in an output of a generator with bilateral contract,
deltaPmax
mpc.BilateralContract.maxChange = [100; 100; 100; 100];

%% Price in ($/MVA-hr) of generator with bilateral contract, Pib
mpc.BilateralContract.bilPrice = [100000; 50; 100000; 100000];

%% Output of generator with bilateral contract, Pgib
mpc.BilateralContract.bilOutput = [0; 140; 0; 0];
```

Appendix 4 Matlab Code

BILATERAL_CONTRACT Enable or disable curtailment of a conventional generators with firm bilateral contracts to increase output of renewables.

```matlab
function mpc = bilateral_contract(mpc)
%BILATERAL_CONTRACT Enable or disable curtailment of a conventioanl generators with
%                firm bilateral contracts to increase output of renewables.
%   MPC = BILATERAL_CONTRACT(MPC, 'on')
%   MPC = BILATERAL_CONTRACT(MPC, 'off')
%
%   Enables or disables a set of OPF userfcn callbacks to implement
%   optimization of a profit of conventional generators with a bilateral contract.
%
%   These callbacks expect to find a 'BilateralContract' field in the input MPC,
%   where MPC.BilateralContract is a struct with the following fields:
%      maxChange  (ng or ngr) x 1, max change in an output of a generator
%                              with bilateral contract in MW
%      bilPrice   (ng or ngr) x 1, price of generator with bilateral contract $
%      bilOutput  (ng or ngr) x 1, output of generator with bilateral contract in MW
%   where ngr is the number of generators with bilateral contract
%   and ng is the total number of generators.
%
%   The 'int2ext' callback also packages up results and stores them in
%   the following output fields of results.BilateralContract:
%      deltaP    - ng x 1, change in each gen in MW
%      deltaPmin  - ng x 1, lower limit on change in each gen, (MW)
%      deltaPmax  - ng x 1, upper limit on change in each gen, (MW)
%      mu.l      - ng x 1, shadow price on change lower limit, ($/MW)
%      mu.u      - ng x 1, shadow price on change upper limit, ($/MW)
```

```
%      mu.Pmax    - ng x 1, shadow price on deltaP + Pg <= Pmax
constraint, ($/MW)
%
%
%   See also RUNOPF_W_BC, ADD_USERFCN, REMOVE_USERFCN, RUN_USERFCN,
%   BILATERAL_CASE9.
%
%   Versions info: bilateral_contract.m V1.1
%   Author: Milana Plecas, Xin Li
%   Created: 17 June 2013
%   Last eddited: 10 July 2013

   %% check for proper bilateral contract inputs
   if ~isfield(mpc, 'BilateralContract') ||
~isstruct(mpc.BilateralContract) || ...
          ~isfield(mpc.BilateralContract, 'maxChange') || ...
          ~isfield(mpc.BilateralContract, 'bilPrice') || ...
          ~isfield(mpc.BilateralContract, 'bilOutput')
      error('bilateral_contract: case must contain a
''BilateralContract'' field, a struct defining ''maxChange'',
''bilPrice'', ''bilOutput''');
   end

   %% add callback functions
   %% note: assumes all necessary data included in 1st arg (mpc, om,
results)
   %%      so, no additional explicit args are needed
   mpc = add_userfcn(mpc, 'ext2int',
@userfcn_BilateralContract_ext2int);
   mpc = add_userfcn(mpc, 'formulation',
@userfcn_BilateralContract_formulation);
   mpc = add_userfcn(mpc, 'int2ext',
@userfcn_BilateralContract_int2ext);
   mpc = add_userfcn(mpc, 'printpf',
@userfcn_BilateralContract_printpf);
   mpc = add_userfcn(mpc, 'savecase',
@userfcn_BilateralContract_savecase);

%%-----  ext2int  ----------------------------------------------------
---
function mpc = userfcn_BilateralContract_ext2int(mpc, args)
%
%   mpc = userfcn_BilateralContract_ext2int(mpc, args)
%
```

```
%   This is the 'ext2int' stage userfcn callback that prepares the
input
%   data for the formulation stage. It expects to find a
'BilateralContract'
%   field in mpc as described above. The optional args are not
currently used.

%% initialize some things
bc = mpc.BilateralContract;
o = mpc.order;
ng0 = size(o.ext.gen, 1);          %% number of original gens (+ disp
loads)

%% check data for consistent dimensions
if size(bc.maxChange, 1) ~= ng0
   error('userfcn_BilateralContract_ext2int: the number of rows in
mpc.BilateralContract.maxChange (%d) must equal the total number of
generators (%d)', ...
       size(bc.maxChange, 1), ng0);
end
if size(bc.bilPrice, 1) ~= ng0
   error('userfcn_BilateralContract_ext2int: the number of rows in
mpc.BilateralContract.bilPrice (%d) must equal the total number of
generators (%d)', ...
       size(bc.bilPrice, 1), ng0);
end
if size(bc.bilOutput, 1) ~= ng0
   error('userfcn_BilateralContract_ext2int: the number of rows in
mpc.BilateralContract.bilOutput (%d) must equal the total number of
generators (%d)', ...
       size(bc.bilOutput, 1), ng0);
end

%% -----  convert stuff to internal indexing  -----
%% convert all BilateralContract parameters (maxChange, bilPrice,
bilOutput)
mpc = e2i_field(mpc, {'BilateralContract', 'maxChange'}, 'gen');
mpc = e2i_field(mpc, {'BilateralContract', 'bilPrice'}, 'gen');
mpc = e2i_field(mpc, {'BilateralContract', 'bilOutput'}, 'gen');

%% -----  formulation  -----------------------------------------------
----
function om = userfcn_BilateralContract_formulation(om, args)
%
```

```
%   om = userfcn_BilateralContract_formulation(om, args)
%
%   This is the 'formulation' stage userfcn callback that defines the
%   user costs and constraints for generators with bilateral
contract.
%   It expects to find a 'BilateralContract' field in the mpc stored
in om,
%   as described above.
%   The optional args are not currently used.

%% initialize some things
mpc = get_mpc(om);
bc = mpc.BilateralContract;
ng = size(mpc.gen, 1);     %% number of on-line gens (+ disp loads)

%% variable bounds
deltaPmin = zeros(ng, 1);            %% bound below by 0
deltaPmax = bc.maxChange;            %% bound above by maxChange
deltaPmax = deltaPmax / mpc.baseMVA;

%% constraints
I = speye(ng);                      %% identity matrix
Ar = [I I];
lr = bc.bilOutput / mpc.baseMVA;
% ur = bc.bilOutput / mpc.baseMVA;

%% cost
nb = size(mpc.bus, 1);
ng = size(mpc.gen, 1);
Cw = bc.bilPrice/2;    %% per unit cost coefficients
% gencost = mpc.gencost;
% [PW_LINEAR, POLYNOMIAL, MODEL, STARTUP, SHUTDOWN, NCOST, COST] =
idx_cost;
% Cw = - (gencost(:,COST+1) + 2 * gencost(:,COST) .* (bc.bilOutput /
mpc.baseMVA) - bc.bilPrice) * mpc.baseMVA;
% H = diag(gencost(:,COST) * mpc.baseMVA * mpc.baseMVA * 2);
N = speye(ng,ng);
cp = struct('N', N, 'Cw', Cw );%, 'H', H);

%% add them to the model
om = add_vars(om, 'deltaP', ng, [], deltaPmin, deltaPmax);
om = add_constraints(om, 'deltaP_plus_Pg', Ar, lr, [], {'deltaP',
'Pg'});
om = add_costs(om, 'usr', cp, {'deltaP'});
```

```
%% -----  int2ext  ---------------------------------------------------
----
function results = userfcn_BilateralContract_int2ext(results, args)
%
%   results = userfcn_BilateralContract_int2ext(results, args)
%
%   This is the 'int2ext' stage userfcn callback that converts
everything
%   back to external indexing and packages up the results. It expects
to
%   find a 'BilateralContract' field in the results struct as
described for mpc
%   above, including the two additional fields 'igr' and 'rgens'.
%   It also expects the results to contain a variable 'deltaP' and
linear constraint
%   'deltaP_plus_Pg' which are used to populate output fields in
%   results.bc. The optional args are not currently used.

%% initialize some things
bc = results.BilateralContract;

%% grab some info in internal indexing order
ng  = size(results.gen, 1); %% number of on-line gens (+ disp loads)

%% -----  convert stuff back to external indexing  -----
%% convert all bilateralcontract parameters (output, rgens)
results = i2e_field(results, {'BilateralContract', 'maxChange'},
'gen');
results = i2e_field(results, {'BilateralContract', 'bilPrice'},
'gen');
results = i2e_field(results, {'BilateralContract', 'bilOutput'},
'gen');
bc = results.BilateralContract;   %% update
o = results.order;              %% update

%% grab same info in external indexing order
ng   = size(results.gen, 1);  %% number of on-line gens (internal)
ng0  = size(o.ext.gen, 1);    %% number of gens (external)

%% -----  results post-processing  -----
%% get the results () with internal gen indexing
%% and convert from p.u. to per MW units
```

```
[deltaP0, deltaPl, deltaPu] = getv(results.om, 'deltaP');
deltaP      = zeros(ng, 1);
deltaPmin   = zeros(ng, 1);
deltaPmax   = zeros(ng, 1);
mu_l   = zeros(ng, 1);
mu_u   = zeros(ng, 1);
mu_Pmax = zeros(ng, 1);
deltaP    = results.var.val.deltaP * results.baseMVA;
deltaPmin  = deltaPl * results.baseMVA;
deltaPmax  = deltaPu * results.baseMVA;
mu_l   = results.var.mu.l.deltaP / results.baseMVA;
mu_u   = results.var.mu.u.deltaP / results.baseMVA;
mu_Pmax = results.lin.mu.u.deltaP_plus_Pg / results.baseMVA;

%% store in results in results struct
z = zeros(ng0, 1);
results.BilateralContract.deltaP       = i2e_data(results, deltaP, z,
'gen');
results.BilateralContract.deltaPmin    = i2e_data(results, deltaPmin,
z, 'gen');
results.BilateralContract.deltaPmax    = i2e_data(results, deltaPmax,
z, 'gen');
results.BilateralContract.mu.l        = i2e_data(results, mu_l, z,
'gen');
results.BilateralContract.mu.u        = i2e_data(results, mu_u, z,
'gen');
results.BilateralContract.mu.Pmax      = i2e_data(results, mu_Pmax, z,
'gen');
results.BilateralContract.totalcost    = results.cost.usr *
results.baseMVA;

%% -----  printpf  --------------------------------------------------
----
function results = userfcn_BilateralContract_printpf(results, fd,
mpopt, args)
%
%   results = userfcn_BilateralContract_printpf(results, fd, mpopt,
args)
%
%   This is the 'printpf' stage userfcn callback that pretty-prints
the
%   results. It expects a results struct, a file descriptor and a
MATPOWER
%   options vector. The optional args are not currently used.
```

```
%% define named indices into data matrices
[GEN_BUS, PG, QG, QMAX, QMIN, VG, MBASE, GEN_STATUS, PMAX, PMIN, ...
    MU_PMAX, MU_PMIN, MU_QMAX, MU_QMIN, PC1, PC2, QC1MIN, QC1MAX, ...
    QC2MIN, QC2MAX, RAMP_AGC, RAMP_10, RAMP_30, RAMP_Q, APF] =
idx_gen;

%% -----  print results  -----
bc = results.BilateralContract;
ng = length(bc.deltaP);
OUT_ALL = mpopt(32);
if OUT_ALL ~= 0
    fprintf(fd,
'\n==================================================================
==============');
    fprintf(fd, '\n|     BilateralContract
|');
    fprintf(fd,
'\n==================================================================
==============');
    fprintf(fd, '\n Gen   Bus   Status   deltaP  ');
    fprintf(fd, '\n  #    #             (MW)  ');
    fprintf(fd, '\n ----  ----  ------  -------- ');
    for k = 1:ng
        fprintf(fd, '\n %3d  %5d    %2d ', k, results.gen(k, GEN_BUS),
results.gen(k, GEN_STATUS));
        fprintf(fd, '%10.2f', results.BilateralContract.deltaP(k));
    end
    fprintf(fd, '\n                 --------');
    fprintf(fd, '\n          Total:%10.2f    Total Cost: $%6.2f', ...
        sum(results.BilateralContract.deltaP(1:ng)),
results.BilateralContract.totalcost);
    fprintf(fd, '\n');

    fprintf(fd,
'\n==================================================================
==============');
    fprintf(fd, '\n|     BilateralContract Limits
|');
    fprintf(fd,
'\n==================================================================
==============');
    fprintf(fd, '\n Gen   Bus   Status  deltaPmin mu    deltaPmin
deltaP    deltaPmax    deltaPmax mu    Pmax mu ');
```

```
    fprintf(fd, '\n  #    #            ($/MW)       (MW)       (MW)
(MW)        ($/MW)       ($/MW)  ');
    fprintf(fd, '\n----  -----  ------  ----------    ---------   ----
----   ---------    ----------    -------- ');
    for k = 1:ng
        fprintf(fd, '\n%3d %5d    %2d ', k, results.gen(k, GEN_BUS),
results.gen(k, GEN_STATUS));
        fprintf(fd, '%12.2f', results.BilateralContract.mu.l(k));
        fprintf(fd, '%14.2f', results.BilateralContract.deltaPmin(k));
        fprintf(fd, '%12.2f', results.BilateralContract.deltaP(k));
        fprintf(fd, '%13.2f', results.BilateralContract.deltaPmax(k));
        fprintf(fd, '%12.2f', results.BilateralContract.mu.u(k));
        fprintf(fd, '%13.2f', results.BilateralContract.mu.Pmax(k));
    end
    fprintf(fd, '\n                                        --------
');
    fprintf(fd, '\n                              Total:%14.2f',
sum(results.BilateralContract.deltaP(1:ng)));
    fprintf(fd, '\n');
end

%% -----  savecase  --------------------------------------------------
----
%%
function mpc = userfcn_BilateralContract_savecase(mpc, fd, prefix,
args)
%
%   mpc = userfcn_BilateralContract_savecase(mpc, fd, mpopt, args)
%
%   This is the 'savecase' stage userfcn callback that prints the M-
file
%   code to save the 'BilateralContract' field in the case file. It
expects a
%   MATPOWER case struct (mpc), a file descriptor and variable prefix
%   (usually 'mpc.'). The optional args are not currently used.

bc = mpc.BilateralContract;

fprintf(fd, '\n%%%%-----  BilateralContract Data  -----%%%%\n');

%% save output fields for solved case
if isfield(bc, 'deltaP')
    if exist('serialize', 'file') == 2
        fprintf(fd, '\n%%%% solved values\n');
```

```
        fprintf(fd, '%sBilateralContract.deltaP = %s\n', prefix,
serialize(bc.deltaP));
        fprintf(fd, '%sBilateralContract.deltaPmin = %s\n', prefix,
serialize(bc.deltaPmin));
        fprintf(fd, '%sBilateralContract.deltaPmax = %s\n', prefix,
serialize(bc.deltaPmax));
        fprintf(fd, '%sBilateralContract.totalcost = %s\n', prefix,
serialize(bc.totalcost));
    else
        url =
'http://www.mathworks.com/matlabcentral/fileexchange/12063';
        warning('MATPOWER:serialize', ...
            'userfcn_BilateralContract_savecase: Cannot save the
''BilateralCOntract'' output fields without the ''serialize''
function, which is available as a free download from:\n<%s>\n\n',
url);
    end
end
```