COMBINING THE WIND POWER GENERATION SYSTEM WITH ENERGY STORAGE EQUIPMENTS

by

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ABSTRACT

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WITH ENERGY STORAGE EQUIPMENTS

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With the advance in wind turbine technologies, the cost of wind energy becomes competitive with other fuel-based generation resources. Due to the price hike of the fossil fuel and the concern of the global warming, the development of wind power has rapidly progressed over the last decade. The annual growth rate of the wind generation installation has exceeded 26% since 1990s. Many countries have set goal for high penetration levels of wind generations. Recently, several large-scale wind generation projects have been implemented all over the world. It is economically beneficial to integrate very large amounts of wind capacity in power systems. Unlike

other traditional generation facilities, using wind turbines present technical challenges in producing continuous and controllable electric power. The distinct feature of the wind energy is its nature of "intermittent". Since it is difficult to predict and control the output of the wind generation, its potential impacts on the electric grid are different from the traditional energy sources. At high penetration level, an extra fast response reserve capacity is needed to cover shortfall of generation when a sudden deficit of wind takes place. However, this requires capital investment and infrastructure improvement. To enable a proper management of the uncertainty, this study presents an approach to make wind power become a more reliable source on both energy and capacity by using energy storage devices. Combining the wind power generation system with energy storage will reduce fluctuation of wind power. Since it requires capital investment for the storage system, it is important to estimate reasonable storage capacities for desired applications. In addition, energy storage application for reducing the output variation and improving the dynamic stability during the gust wind and severe fault are also studied.

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CHAPTER 1

INTRODUCTION

1.1 Background

After the Kyoto Protocol came in force automatically on February 16, 2005, the countries all over the world will face the challenges to reduce the emission of the greenhouse gases. Countries around the globe need to set targets and take actions to meet the goal in conformity with the Kyoto Protocol. The development of wind power has rapidly growth over the last decade, largely due to the improving in the technology, the provision of government energy policy, the public concern about global warming, and concerned on the limited resource of conventional fuel based generation [1].

As the fossil fuel causes the serious problem of environmental pollution, the wind energy is one of the most attractive clean alternative energy sources. Wind power is one of the most mature and cost effective resources among different renewable energy technologies. Wind energy has gained an extensive interest and become one of the most promising renewable energy alternatives to the conventional fuel based power resources. Despite various benefits of the wind energy, the integration of wind power into the grid system is difficult to manage. The distinct feature of the wind energy from other energy resources is that its produced energy is “intermittent”. Due to the wind power is an unstable source, its impact on the electric grid are different from the traditional energy sources.

1.2 Why Wind Power

Wind energy is a source of renewable power which comes from air current flowing across the earth's surface. The wind is influenced by the heat energy of the sun and the rotating of the earth. Figure 1.1 shows that wind is caused by the movement of air from areas of high pressure to low pressure. Air has mass, and when it is in motion, it contains the energy of that motion — this is called "kinetic" energy. Wind turbines harvest this kinetic energy and convert it into power. The electricity is sent through transmission and distribution lines to the end users. Wind energy is one of the fastest growing sources of electricity and one of the fastest growing markets in the world today.

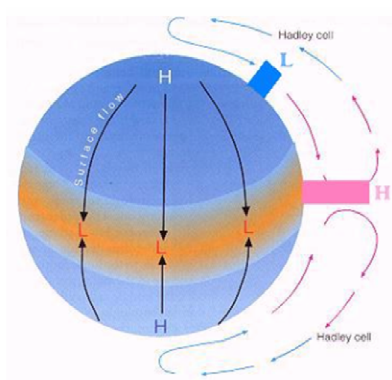

Figure 1.1 Wind movement from areas of high pressure to low pressure

Since it is a clean energy source, has lower impact to the environment, and never be used up, renewable energy is a hot issue in today competitive market. Because wind energy development is consumer and environmentally friendly, requires shorter construction time, is cost competitive, and are quicker to obtain permit, it becomes one of the most competitive sources among different renewable energy technologies [2].

1.2.1 Advantage

Wind power offers many advantages, which explains why it's the fastest-growing energy source in the world. Wind power is affordable, clean and sustainable. It also provides jobs and other sources of income. With an average annual growth rate of more than 26 percent over the past decade, wind is the fastest-growing sector of the energy industry all over the world. The advantages of wind energy are numerous and clear, and the technology itself has taken a leap forward in recent years.

First, wind power is the most mature and cost effective renewable energy technologies available today, costing between 3 and 5 cents per kilowatt-hour, depending upon the wind resource and project financing of the particular project. Since wind is free, the price of wind power is stable, unlike electricity from fossil fuel powered sources which depends on fuels whose prices are costly and may vary considerably. In the power market, the cost of generation is very important. Now, with the advance in wind turbine technologies, the cost of wind energy becomes competitive with traditional power plants.

Second, wind power can not be used up. Wind power is the renewable energy from the wind, which is inexhaustible and requires no addtional "fuel" to blow across the earth. Actually, wind is a converted form of solar energy. The sun causes some part of the atmosphere to warm differently. So, hot air rises and cooler air is down. Wind is movement of air from areas of high pressure to low pressure. Actually, if the sun is gone, the Earth also will be gone. Therefore wind energy always can not be used up within the foreseeable future.

Third, wind power is clean fuel source and environment friendly. Today, everyone concerns about the global warming due to the emission of greenhouse gases. Wind power is fueled by the wind. Since wind turbines don't produce atmospheric emissions that cause acid rain or the global warming, it is a clean fuel source. Wind energy can provide us with cleaner air and a healthier, safer environment.

Fourth, wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land.

1.2.2 Disadvantage

However, wind power still has some disadvantages. For example, noise used to be a big problem within the wind turbine and wind power is an intermittent power supply because wind doesn’t blow 100 percent of the time. Wind power is unstable and its electric characteristic and power quality of feeding into the grid are different from traditional coal, gas and hydro plants. Some disadvantages of wind generation are listed below:

First, good wind sites are often located in remote area, far from cities where the electricity is needed. For example, wind sites are often near coast. Therefore, it may require substantial infrastructure improvement to deliver the wind power to the load center.

Second, additional operation reserve requirement will increase operating cost. Wind power production induce more uncertainty in operating a power system due to its variable and partly unpredictable. To enable a proper management of the uncertainty, it requires more flexibility in the power system. It needs other fast response reserve capacity to cover the possible rapid fluctuation of the wind generation. It means that the cost of generation will be increased.

Third, although wind power plants have relatively little impact on the environment compared to other conventional power plants, there are concerns over the noise produced by the rotor blades, aesthetic (visual) impacts, and sometimes birds have been killed by flying into the blades. Fortunately, most of these problems have been resolved or greatly reduced through technological development or by properly siting wind plants [3].

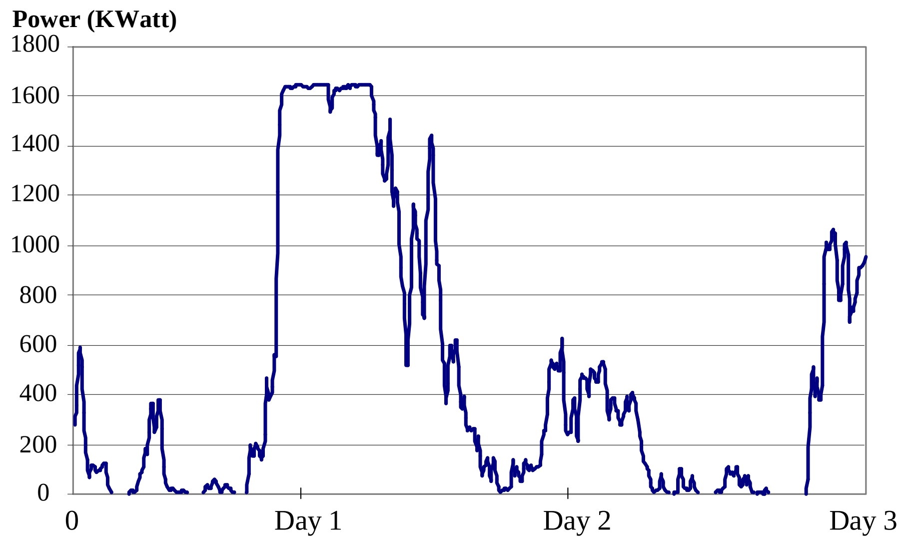

Figure 1.2 Intermittent wind power supply

Fourth, the major challenge to using wind as a source of power is that wind power is ”An intermittent power supply” and wind does not always blow when electricity is needed. The figure 1.1 illustrates the intermittent nature of wind power output. In other words, wind power is an uncertainty power supply and is controlled by the nature, not the power plant operator. It produces intermittent power and other generators on the grid can be throttled to match varying production from this renewable source. Further development of intermittent wind power will require some combination of grid energy storage equipments.

1.3 Challenge

Due to its intermittent in nature and partly unpredictable, wind power production introduces more uncertainty into operating a power grid. The major challenge to use wind as a source of power is that wind power may not be available when electricity is needed. Figure 1.2 shows the mismatch of the wind generation and system demand in the Electric Reliability Council of Texas (ERCOT) system. Figure1.3 shows the correlation between the real time market price and wind generation output. As one can see, the excess wind power has driven the wholesale electricity price to the negative territory in the morning while reduction of the wind generation has caused price spike in the afternoon. In the most recent incident, wind production from West Texas fell from more than 1,700 MW to 300 MW as the evening load was climbing has caused ERCOT to initiate the second stage of its “emergency grid procedures” on February 27, 2008. [4]

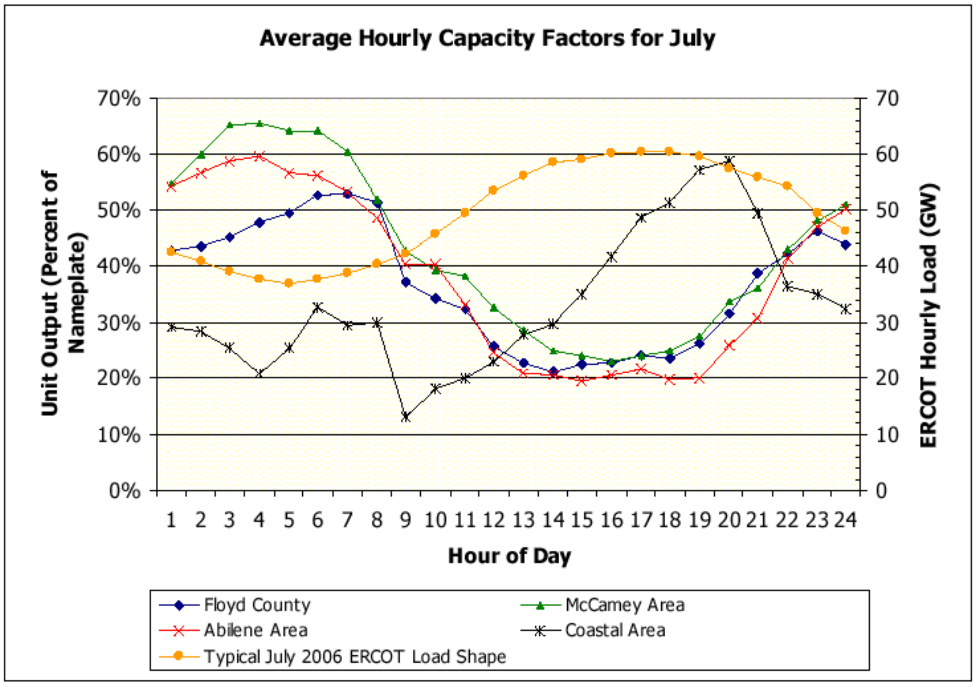

Figure 1.3 Average hourly capacity factors of wind farm with respect to the system load

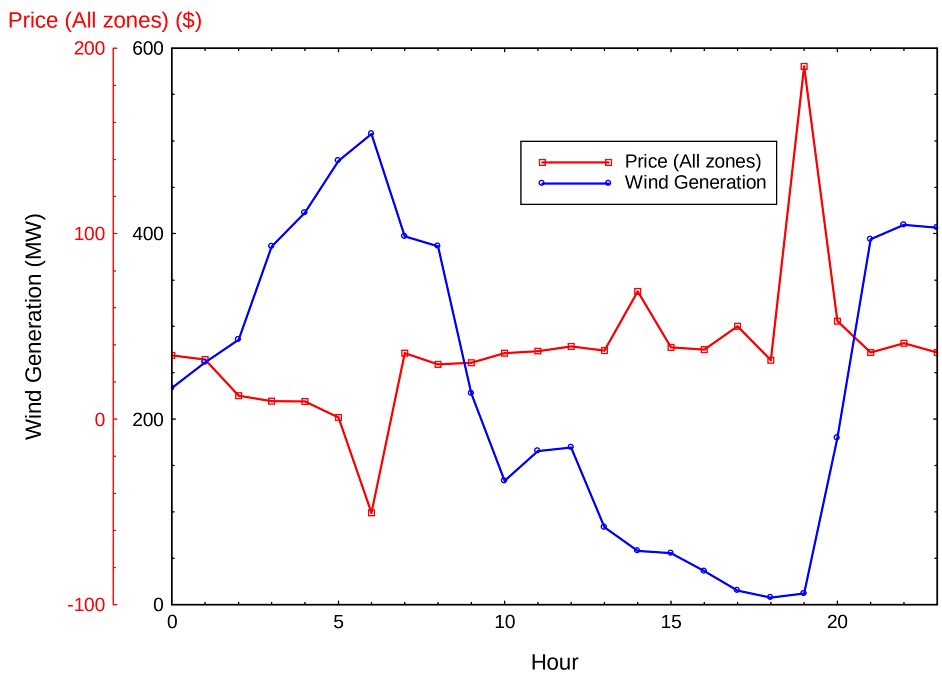

Figure 1.4 ERCOT market clearing price for energy and total wind generation on Feb. 22, 2005

Thus uncertainty wind power may create the other issues for power system operation. For that reason, this thesis studies the use of “Energy Storage Equipment” to reduce the uncertainty and negative impact of the wind generation. The integration of energy storage system and wind generation will enhance the grid reliability and security. Energy storage system can shift the generation pattern and smooth the variation of wind power over a desired time horizon. It is also be used to mitigate possible price hikes or sags. However, this requires significant capital investment and possible infrastructure improvement. It is important to perform cost benefit analysis to determine proper size of energy storage facilities for the desired operations.

This study discusses the benefits of combining the wind power generation system with energy storage to reduce both fluctuation of wind power and operating cost and make wind power with more reliable capacity. According to the wind quality, the study estimates the reasonable amount of energy storage capacities for the desired operations. Furthermore, energy storage for reducing the transient variations and improving the dynamic stability of the studied wind farm during the wind gust and three phases fault are also studied. Simulation results show the effect of the energy storage equipments on suppressing angle, voltage, and frequency fluctuations.

1.4 Organisation of This Thesis

This chapter has described an introduction which provides background, advantages, disadvantages, and challenge of wind power. The rest of this thesis is organized as follows. **Chapter 2** covers the wind turbine technology and gives an overview of several kinds of energy storage systems today. **Chapter 3** explains more detailed study procedure and study system description. The chapter discusses integration issues of wind power and describes the proposal wind farm configuration and the study case data. **Chapter 4** presents the different study results including storage capacity estimation, steady-state power flow, short circuit current, and transient stability study results. The chapter discusses and summary storage capacity estimation results for three different desired operation. Then it presents impacts of the interconnection of wind farm with energy storage system and simulates the transient stability. A comparison results with and without energy storage equipments is also discussed. Finally, **Chapter 5** concludes the work in this thesis and emphasizes contributions of this study.

CHAPTER 2

WIND TURBINE AND ENERGY STORAGE SYSTEM

2.1 Wind Power Generation

2.1.1 Wind Power Conversion System

The amount mechanical power of a wind turbine is formulated as:

$$P = \frac{1}{2}\rho\pi R^2 v^3 C_P = \frac{1}{2}\rho A v^3 C_P \qquad (1)$$

Where ρ is the air density, R is the turbine radius, v the wind speed and C_P is the turbine power coefficient which represents the power conversion efficiency of a wind turbine. Therefore, if the air density, swept area, and wind speed are constant, the power of wind turbine will be a function of power coefficient of the turbine.

C_P is a function of the tip speed ratio (λ), as well as the blade pitch angle (β) in a pitch controlled wind turbine. β may be considered as a constant for the optimal power capture when the machine speed is lower than the rated speed. λ is the ratio of linear speed of tip of turbine blades and linear wind speed, and given by:

$$\lambda = \frac{R \times \omega}{v} \qquad (2)$$

where ω (rad/sec) is the rotor angular speed, R is the blade length (m), and v is the wind speed (m/s) [5]. A typical C_P-λ curve is shown in Figure 2.1 [6]. It can be seen that there is a maximum power coefficient, C_{Pmax}. Normally, a variable speed wind turbine follows the C_{Pmax} to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at $\lambda_{optimal}$, then operates at the rated power with power regulation during the periods of high wind by the active control of the blade pitch angle or the passive regulation based on aerodynamic stall [7]. A typical power-wind speed curve is shown in Figure 2.2 [8].

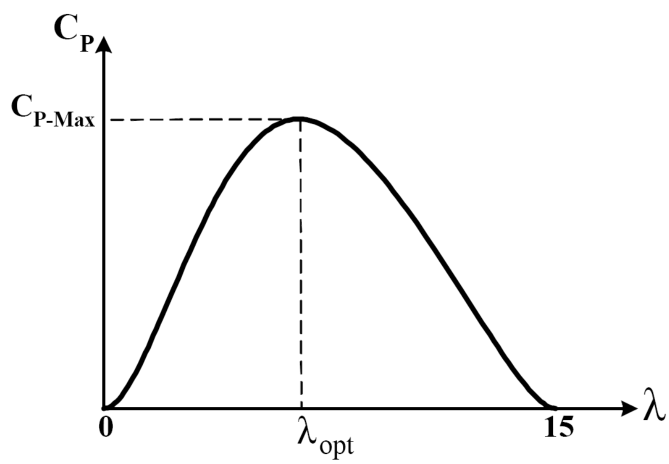

Figure 2.1 Typical power coefficient vs. tip-speed curve

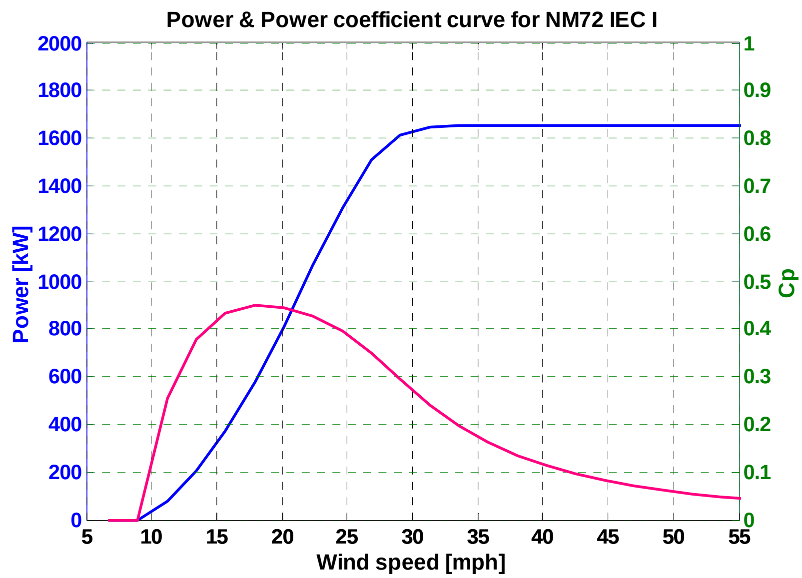

Figure 2.2 Power-wind speed curve

2.1.2 Wind Generator Modeling

There are many different generator technologies for wind-power applications in use today. The main distinction can be made between fixed-speed and variable-speed wind-generator concepts.

2.1.2.1 Fixed Speed Wind Generator: Induction Generator

A fixed-speed wind-generator is usually equipped with a squirrel cage induction generator whose speed variations are only very limited (see figure 2.3). Power can only be controlled through pitch-angle variations. Because the efficiency of wind-turbines (expressed by the power coefficient C_P) depends on the tip-speed ratio λ, the power of a fixed-speed wind generator varies directly with the wind speed. Since induction machines have no reactive power control capabilities, fixed or variable power factor correction systems are usually required for compensating the reactive power demand of the generator.

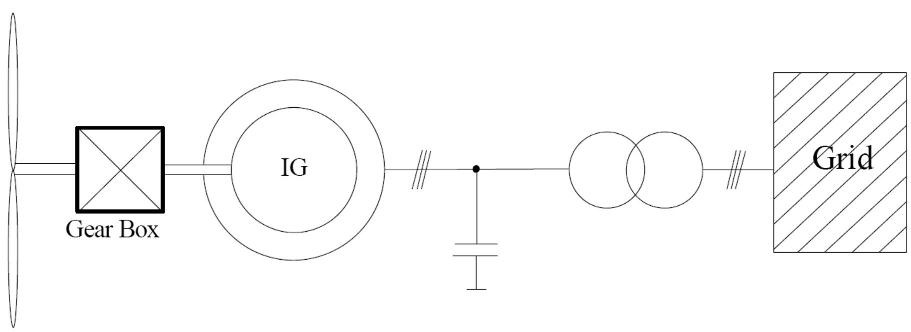

Figure 2.3 Fixed speed induction generator

2.1.2.2 Variable Speed Wind Generator: Doubly-Fed Induction and Converter-Driven Generator (DFIG)

In contrast to fixed-speed, variable speed concepts allow operating the wind turbine at the optimum tip-speed ratio λ and hence at the optimum power coefficient C_P for a wide wind-speed range. Varying the generator speed requires frequency converters that increase investment costs.

The two most-widely used variable-speed wind-generator concepts are the doubly-fed induction generator (figure 2.4) and the converter driven synchronous generator (figure 2.5 and figure 2.6). Active power of a variable-speed generator is controlled electronically by fast power electronics converters, which reduces the impact of wind-fluctuations to the grid. Additionally, frequency converters (self-commutated PWM-converters) allow for reactive power control and no additional reactive power compensation device is required.

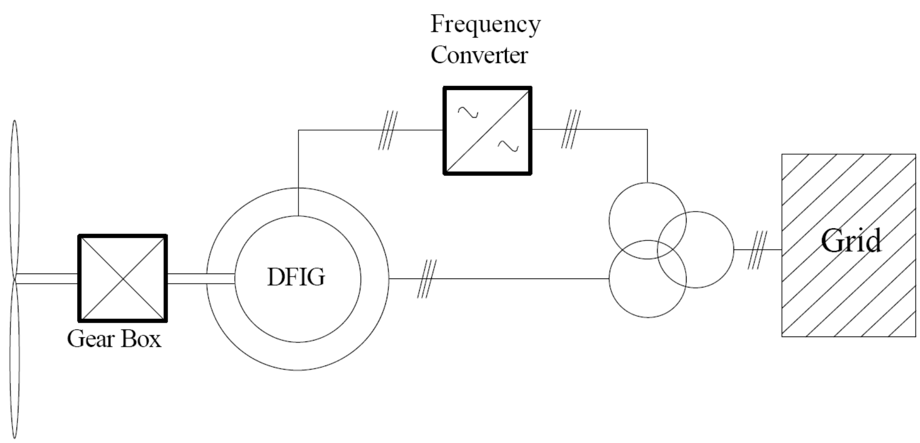

Figure 2.4 Doubly-fed induction generator

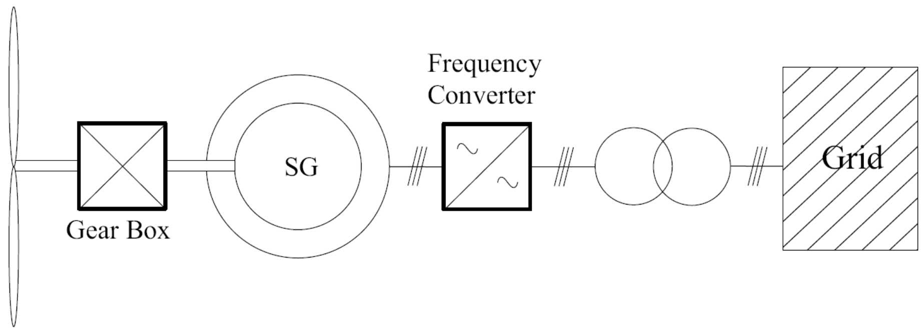

Figure 2.5 Converter-driven synchronous generator

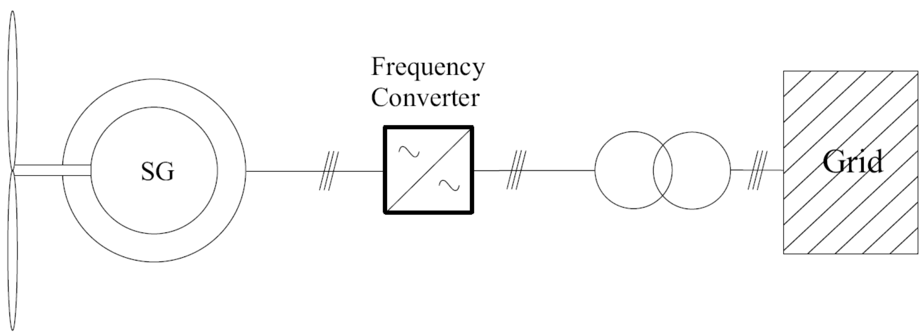

Figure 2.6 Converter-driven synchronous generator (Direct drive)

Figure 2.5 and figure 2.6 show two typical concepts using a frequency converter in series to the generator. Generally, the generator can be an induction or a synchronous generator. In most modern designs, a synchronous generator or a permanent magnet (PM) generator is used.

In contrast to the DFIG, the total power flows through the converter. Its capacity must be larger and cost more compare to the DFIG with the same rating. Figure 2.6 shows a direct drive wind-turbine that works without any gear box. This concept requires a slowly rotating synchronous generator with a lot of pole-pairs [9].

2.2 Energy Storage

Energy storage is the storing of some form of energy that can be drawn upon at a later time to perform some useful operations. “Energy storages” are defined in this study as the devices that store energy, deliver energy outside (discharge), and accept energy from outside (charge). Energy storage lets energy producers send excess electricity over the electricity transmission grid to temporary electricity storage sites that become energy producers when electricity demand is greater. Grid energy storage is particularly important in matching supply and demand over a 24 hour period of time. Energy storage system can shift the generation pattern and smooth the variation of wind power over a desired time horizon. These energy storages, so far, mainly include chemical batteries, pumped water, compressed air, flywheel, thermal, superconducting magnetic energy, and hydrogen.

2.2.1 Batteries

Battery storage has been used in the very early days of direct-current electric power networks. With the advance in power electronic technologies, battery systems connected to large solid-state converters have been used to stabilize power distribution networks for modern power systems. For example, a system with a capacity of 20 megawatts for 15 minutes is used to stabilize the frequency of electric power produced on the island of Puerto Rico.

Batteries are generally expensive, have maintenance problems, and have limited life spans. One possible technology for large-scale storage is large-scale flow batteries. For example, sodium-sulfur batteries could be implemented affordably on a large scale and have been used for grid storage in Japan and in the United States. Vanadium redox batteries and other types of flow batteries are also beginning to be adopted for energy storage including the leveling of generation from wind turbines. Battery storage has relatively high efficiency, as high as 90% or better.

2.2.2 Pumped Water

In many places, pumped storage hydroelectricity is used to even out the daily demand curve, by pumping water to a high storage reservoir during off-peak hours and weekends, using the excess base-load capacity from coal or nuclear sources. During peak hours, this water can be used for hydroelectric generation, often as a high value rapid-response reserve to cover transient peaks in demand. Pumped storage recovers about 75% of the energy consumed, and is currently the most cost effective form of mass power storage. The main constraint of pumped storage is that it usually requires two nearby reservoirs at considerably different heights, and often requires considerable capital expenditure.

Recently, a new concept has been proposed to use wind energy to pump water in pumped-storage. Wind turbines that direct drive water pumps for an 'energy storing wind dam' can make this a more efficient process, but are again limited in total capacity and available location.

2.2.3 Compressed Air

Another grid energy storage method is to use off-peak or renewably generated electricity to compress the air, which is usually stored in an old mine or some other kind of geological feature. When electricity demand is high, the compressed air is heated with a small amount of natural gas and then goes through expanders to generate electricity.

2.2.4 Flywheel

Mechanical inertia is the basis of this storage method. A heavy rotating disc is accelerated by an electric motor, which acts as a generator on reversal, slowing down the disc and producing electricity. Electricity is stored as the kinetic energy of the disc. Friction must be kept to a minimum to prolong the storage time. The ranges of power and energy storage technically and economically achievable, however, tend to make flywheels unsuitable for general power system application; they are probably best suited to load-leveling applications on railway power systems and for improving power quality in renewable energy systems. Flywheel storage is also currently used to provide Uninterruptible Power Supply (UPS) systems such as those in large datacenters for ride-through power necessary during transfer - that is, the relatively brief amount of time between a loss of power to the mains and the warm-up of an alternate source, such as a diesel generator.

2.2.5 Thermal

Design proposals have been made for the use of molten salt as a heat store to store heat collected by a solar tower so that it can be used to generate electricity in bad weather or at night. Thermal efficiencies of 99% for periods over one year have been predicted.

Off-peak electricity can be used to make ice from water, and the ice can be stored until the next day to cool either the air in a large building to shift the peak demand, or the intake air of a gas turbine generator to increase the on-peak generation capacity.

2.2.6 Superconducting Magnetic Energy

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. A typical SMES system includes three parts: superconducting coil, power conditioning system, and cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The power conditioning system uses an inverter to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter accounts for about 2-3% energy loss in each direction. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95%. The high cost of superconductors is the primary limitation for commercial use of this energy storage method.

2.2.7 Hydrogen

Hydrogen is also being developed as an electrical power storage medium. Hydrogen is created using electrolysis of water and then stored for later use with hydrogen based generating equipment. Hydrogen is not a primary energy source, but a portable energy storage method, because it must first be manufactured by other energy sources in order to be used. However, as a storage medium, it may be a significant factor in using renewable energies. Hydrogen may be used in conventional internal combustion engines, or in fuel cells which convert chemical energy directly to electricity without flames. Making hydrogen requires either reforming natural gas with steam, or, for a possibly renewable and more ecologic source, the electrolysis of water into hydrogen and oxygen. The former process has carbon dioxide as a by-product. With electrolysis, the greenhouse burden depends on the source of the power. The efficiency for hydrogen storage is typically 50 to 60%, which is lower than pumped storage systems or batteries.

With intermittent renewable energies such as solar and wind, the output may be fed directly into an electricity grid. At penetrations below 20% of the grid demand, this does not severely change the economics and system behavior; but beyond about 20% of the total demand, external storage will become important. If these sources are used for electricity to make hydrogen, then they can be utilized fully whenever they are available, opportunistically. Broadly speaking, it does not matter when they cut in or out, the hydrogen is simply stored and used as required [10].

CHAPTER 3

STUDY PROCEDURE AND STUDY SYSTEM DESCRIPTION

The study procedure is outlined in this chapter. It describes the system of proposed wind farm involved in the interconnection study, and identifies the wind generation system with the energy storage technology aspect that influence the results of these studies.

These studies include *Storage Capacity Estimation, Steady-State Power Flow, Short Circuit Current, and Transient Stability Studies.*

3.1 Study Procedure

3.1.1 Storage Capacity Estimation

The wind resource potential of Taiwan, as shown in figure 3.1, illustrates the annual average wind speed (meter per second) at 50 meter height [11]. A proposed wind farm with the total capacities of 39.6 MW is used in this study. The actual wind data between Feb. 1, 2006 and May 31, 2007 in the area of interest is obtained from Taiwan Power Company (TPC) [12].

Artificial Neural Network (ANN) wind capacity forecasting software developed in [13] is used to estimate wind power.

According to the ANN forecasting wind power results, A Matlab programming code (Appendix A) is developed to estimate the energy storage capacity and power rating. This study assumes that it is an ideal energy storage system with sufficient energy storage capacity and power rating to support entire wind farm. The program calculates the results and draws each graph when the desired energy storage time is one, two, six hours and one day respectively. And it also computes the storage maximum power. This study chooses three different variations of wind power from the results to illustrate the storage capacity requirements.

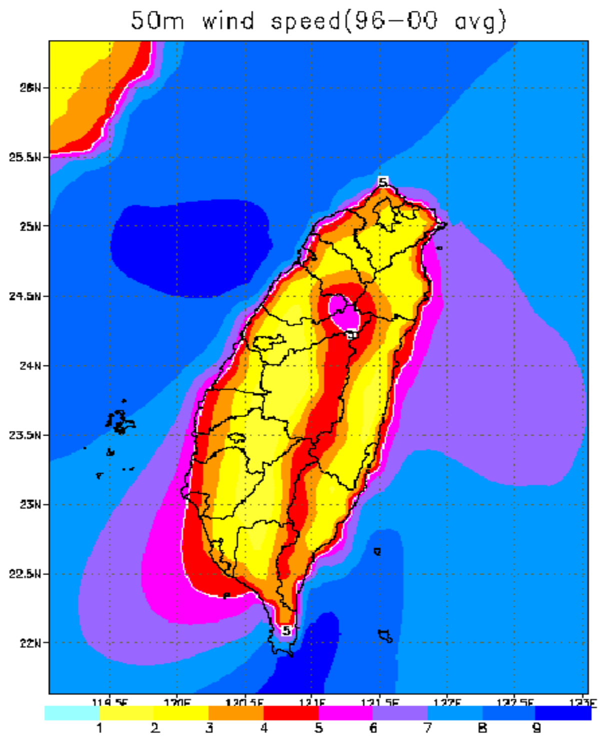

Figure 3.1 Wind resource potential of Taiwan

After estimating the energy storage system capacity, we have to evaluate impacts of the interconnection of wind farm with energy storage system. The impacts are evaluated through three following studies:

3.1.2 Steady State Power Flow Study

Steady state power flow study is performed through power flow simulations, normally with the wind plant dispatched at a power level expected to have maximum system impact (i.e., at rated output power) and with reactive power capabilities reflective of those of the proposed project. Power flow simulations are run for a list of system contingencies (e.g., transmission line outages, generator outages, etc.) to determine system impacts under all realistic abnormal operating conditions. Two primary planning criteria are examined in a power flow study: thermal and voltage criteria. The thermal analysis is to verify that transmission lines, transformers, and other equipment are not overloaded as a result of the project. The voltage analysis is to verify that the project does not have negative impact on voltage regulation at any buses in the transmission network.

This steady state power flow study is largely independent of wind turbine technology. Real power injected at the wind plant's Point of Common Coupling (PCC) with the grid system is a function only of project size (and any real power losses on the project side of the PCC). Reactive power capability may be provided by the wind turbines themselves, in the case of variable speed turbine technology, or by external means, such as capacitor banks or SVCs, in the case of constant speed technology. But from a steady-state perspective, both are modeled as reactive power injected at the PCC in response to the voltage at some control bus, with appropriate adjustments made for reactive power consumption on the project side of the PCC.

3.1.3 Short Circuit Current Study

Short circuit analysis is performed for both symmetrical and unsymmetrical faults on the transmission network in the neighborhood of the wind project to determine whether the addition of the wind generation results in equipment short circuit withstand or circuit breaker interrupting capabilities being exceeded. Unlike the steady-state power flow study, short circuit study is highly dependent on the wind turbine technology being used.

3.1.4 Transient Stability Study

Transient stability in its broadest sense may be described as the ability of a power system to return to a stable operating condition following a major disturbance such as a transmission line short circuit or a large generating unit trip. Transient stability study is carried out by computer-based time domain simulation of the response of generator excitation systems, turbine governor systems and other controlled devices in the power system to such disturbances. Planning criteria require that generator angular oscillations and voltage disturbances do not exceed specific values and are damped out within certain time periods, and, as in power flow study, these studies are run under various contingencies to verify that outages of specific transmission lines or generating units are considered. This analysis focuses on the time frame from several line cycles to up to approximately one minute after the initiation of the disturbance [14].

3.2 Study System Description

From the figure 3.1, it shows that the most of good wind resource are near the coast of Taiwan. A proposed wind farm (Datan) with the total capacities of 39.6 MW is used in this study. It is assumed that the GE 3.6MW wind turbine generators are installed. This study wind farm is located near the west coastal areas of North Taiwan.

3.2.1 New Wind Farm Configuration

The proposed wind farm comprises a number of wind turbines that are clustered and connected to a substation through underground cable and use a 22.8/161kV step-up transformer to the 161kV grid system. In this study case, the 2008 summer peak load predicting data of the Taipower is used and the zone load data of study case are shown in Table 3.1. Figure 3.2 shows the transmission lines configuration of Taiwan Power Company [15].

Table 3.1 Zone Load Data

	North	**Central**	**South**	**East**	**Total**
Load (MW)	14964	9076	10062	443	34545
Rate (%)	43.3	26.3	29.1	1.3	100.0

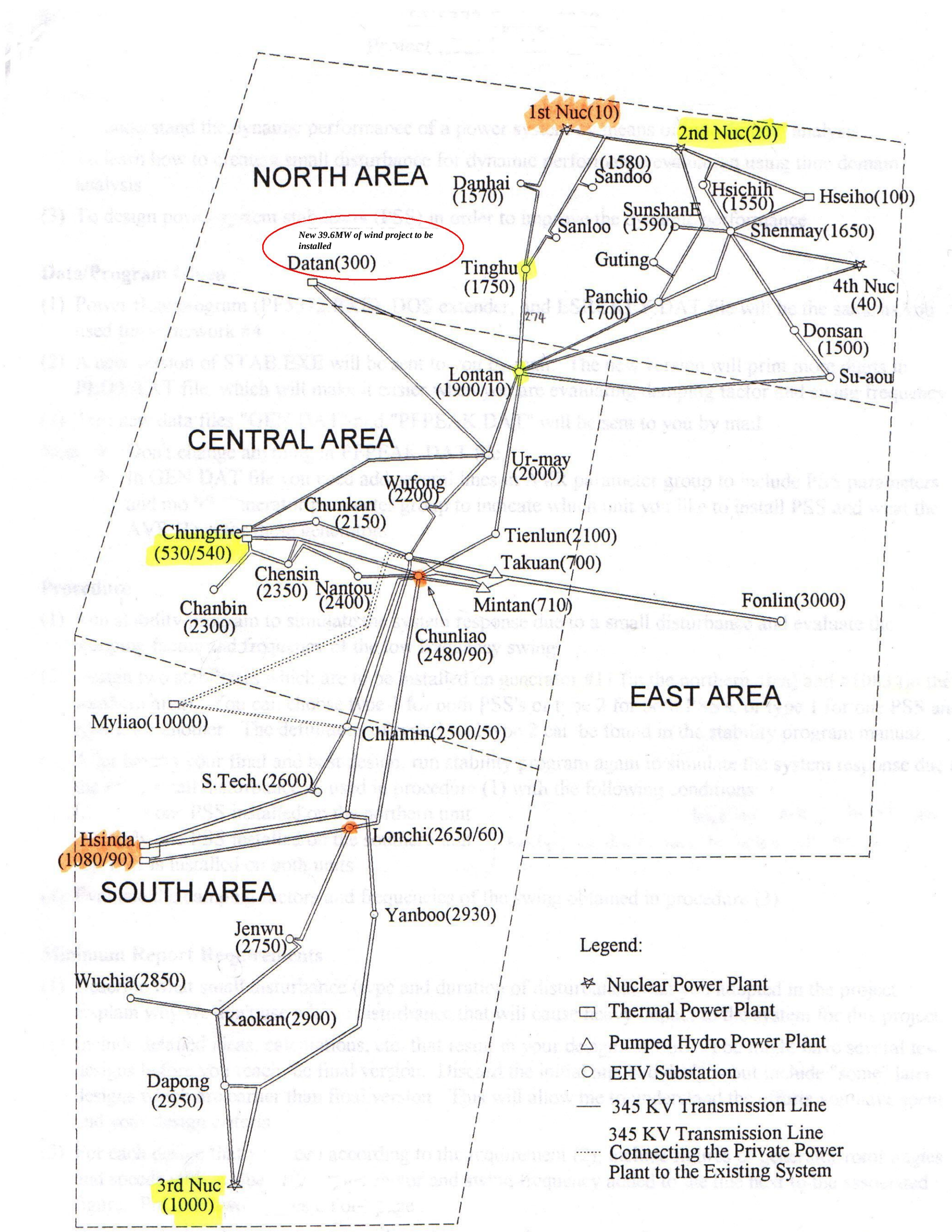

Figure 3.2 Taiwan Power System configuration and Datan-area where proposed new wind farm is installed

3.2.2 Model of the Wind Turbine and Energy Storage

A study system consisting of wind turbine and energy storage connected to a power system is modeled using the Power System Simulation for Engineering (PSS/E) software by Power Technologies Incorporation. In the PSS/E, the wind turbine model is equipped with an IPLAN program that guides the user in preparing the dynamic modules related to this model. The collection of wind turbines, wind speed information, wind turbine parameters, generator parameters, and the characteristics of the control systems are included [16]. This study uses the wind package of PSS/E to simulate and combine the wind power generation system with energy storage equipments integrated into a power grid.

The dynamic model is shown in Figure 3.3. A user-written model can be used to simulate a wind gust by varying input wind speed to the turbine model. The GE 3.6 machine has a rated power output of 3.6 MW. The reactive power capability of each individual machine is ±0.9 pf, which corresponds to Qmax = 1.74 MVAR and Qmin = -1.74 MVAR, and an MVA rating of 4.0 MVA. The minimum steady-state power output for the WTG model is 0.5 MW. In this study, the GE wind turbine models are used for simulation following the manufacturer's recommendations [17].

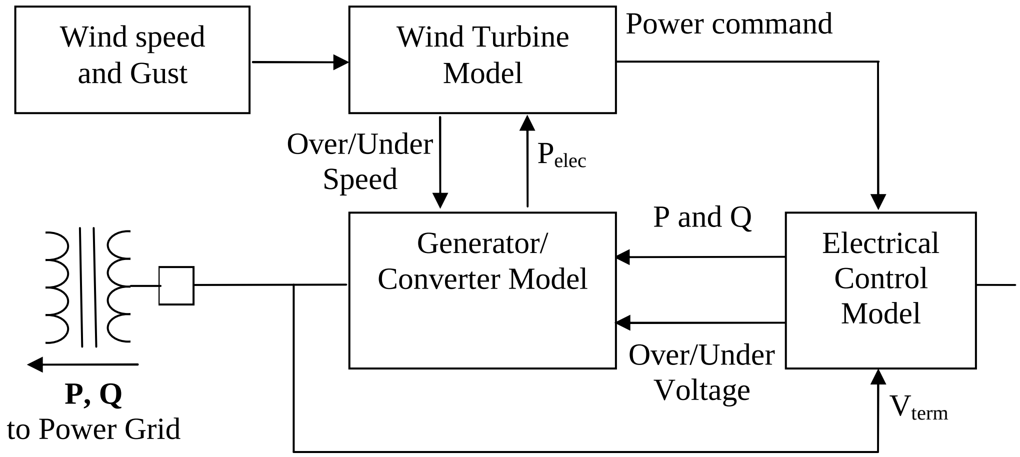

Figure 3.3 Dynamic model of GE 3.6 MW wind turbine

For energy storage model, EPRI battery model CBEST of PSS/E is used for simulation in this study. It simulates the dynamic characteristics of a battery. This model simulates power limitations into and out of the battery as well as AC current limitations at the converter. The model assumes that the battery rating is large enough to cover entire energy demand that occurs during the simulation [18].

CHAPTER 4

STUDY RESULT

4.1 Storage Capacity Estimation Result

In order to reduce the variation of wind power, combining the wind power generation system with energy storage study was performed as described and summarized in this section. Reasonable storage capacities for the desired operations are estimated.

The estimated results are shown in Figure 4.1 to 4.12. These figures show the different storage time, power rating, and storage capacity requirements. Blue line is wind power without storage device. Green area is the desired output with energy storage device. From the results, one can see different storage time requires different storage capacity and power rating. One of the most important factors is the quality of the wind. One can figure out easily that larger variation of wind generation as well as the longer storage time requires larger storage capacity and power rating. Though it can reduce more variation of wind power and make wind power becomes more reliable capacity of operation, the power and storage capacity reflects the requirement of capital investment.. This study chooses three different operation scenarios of wind power to illustrate the storage capacity requirements [19].

4.1.1 Typical Variation of Wind Power

Figure 4.1 to 4.4 show that storage capacity requirement to maintain the output of the wind farm as constant from one hour to one day under a typical variation of wind power. The storage capacities are 2.036MWh, 5.508MWh, 16.233MWh and 103.451MWh respectively. The maximum charging or discharging power ratings are 7.39MW, 10.66MW, 13.53MW and 17.58MW respectively for different desired operation scenarios. Summary of these estimated values relative to energy storage in typical variation of wind power scenario are shown Table 4.1.

Table 4.1 Estimated Values in Typical Variation of Wind Power

Desired Stable Power Output Time (hour)	**Storage Capacity (MWh)**	**Max. Charging/ Discharging Power (MW)**
1 H	2.036	7.39
2 H	5.508	10.66
6 H	16.233	13.53
24 H	103.451	17.58

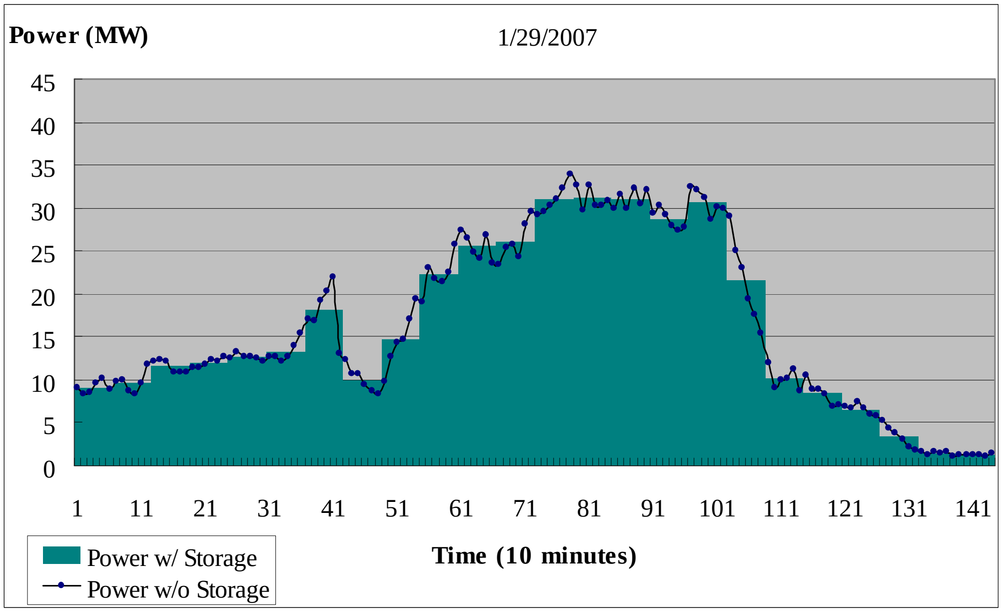

Figure 4.1 Storage Capacity and Time: 2.036 MWh, 1 hour

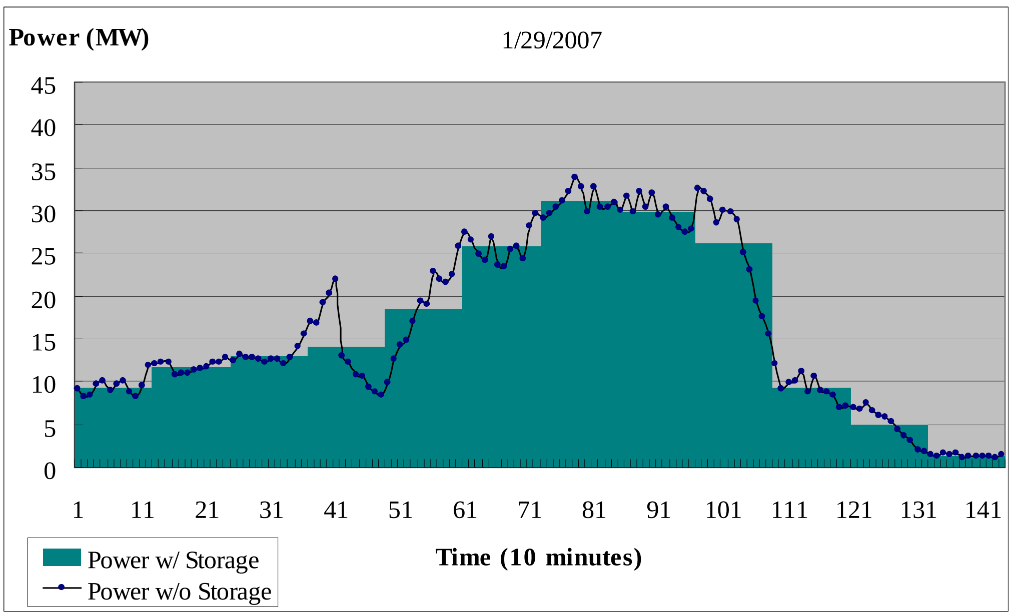

Figure 4.2 Storage Capacity and Time: 5.508 MWh, 2 hours

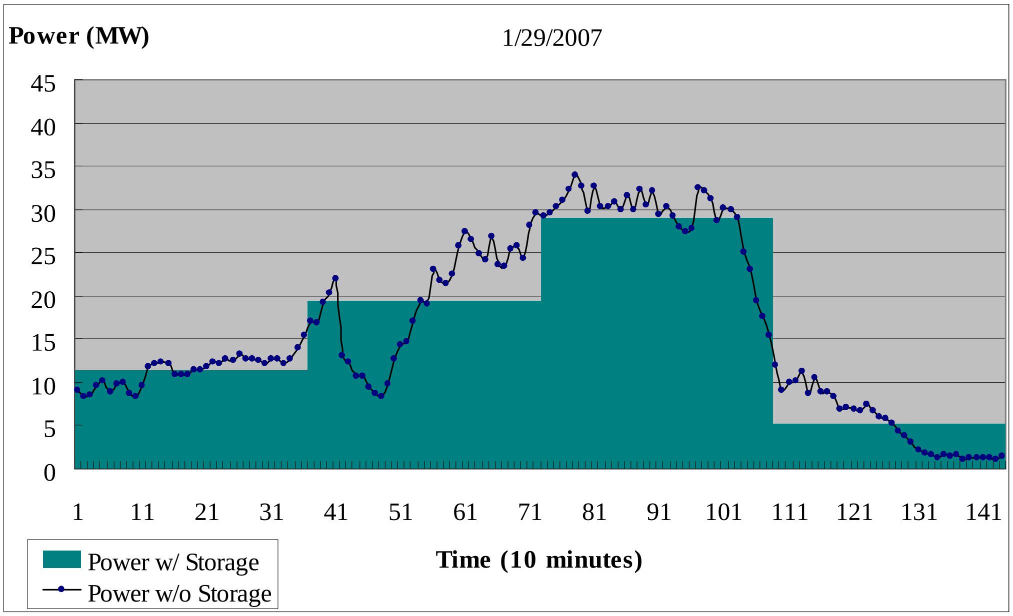

Figure 4.3 Storage Capacity and Time: 16.233 MWh, 6 hours

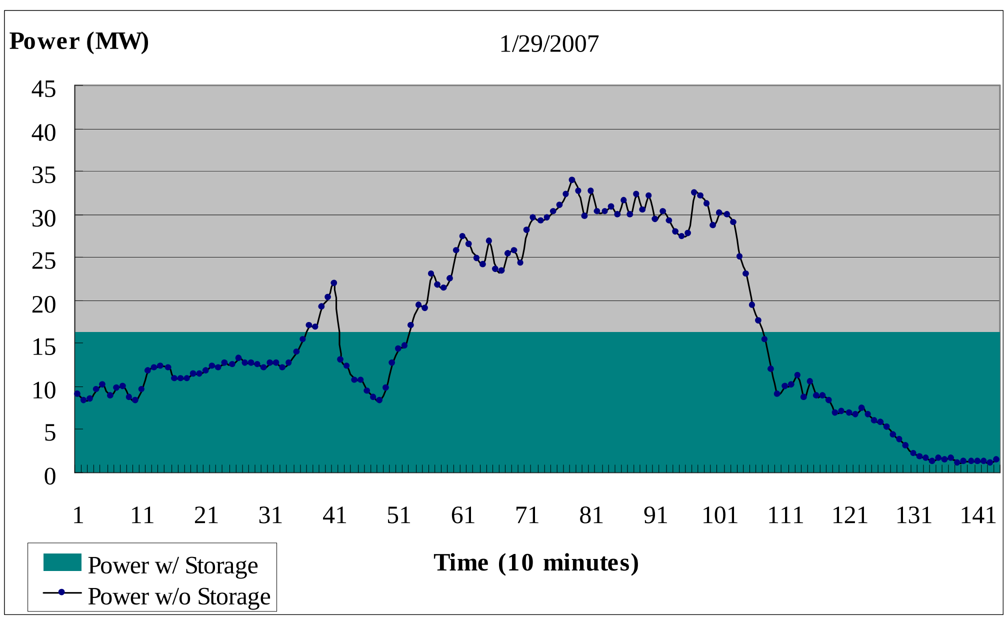

Figure 4.4 Storage Capacity and Time: 103.451 MWh, One Day

4.1.2 Smaller Variation of Wind Power

As shown in Figure 4.5 to 4.8, they present simulation results for the combined system with storage capacity from one hour to one day when the wind speed is relative stable. As one can see, the required storage capacities and charging/discharging power ratings are smaller than the previous case. The storage capacities are 0.870MWh, 1.690MWh, 3.160MWh and 10.435MWh and the charging/discharging power ratings are 4.63MW, 4.69MW, 5.74MW and 6.26MW respectively. Summary of these estimated values relative to energy storage in smaller variation of wind power scenario are shown Table 4.2.

Table 4.2 Estimated Values in Smaller Variation of Wind Power

Desired Stable Power Output Time (hour)	**Storage Capacity (MWh)**	**Max. Charging/ Discharging Power (MW)**
1 H	0.870	4.63
2 H	1.690	4.69
6 H	3.160	5.74
24 H	10.435	6.26

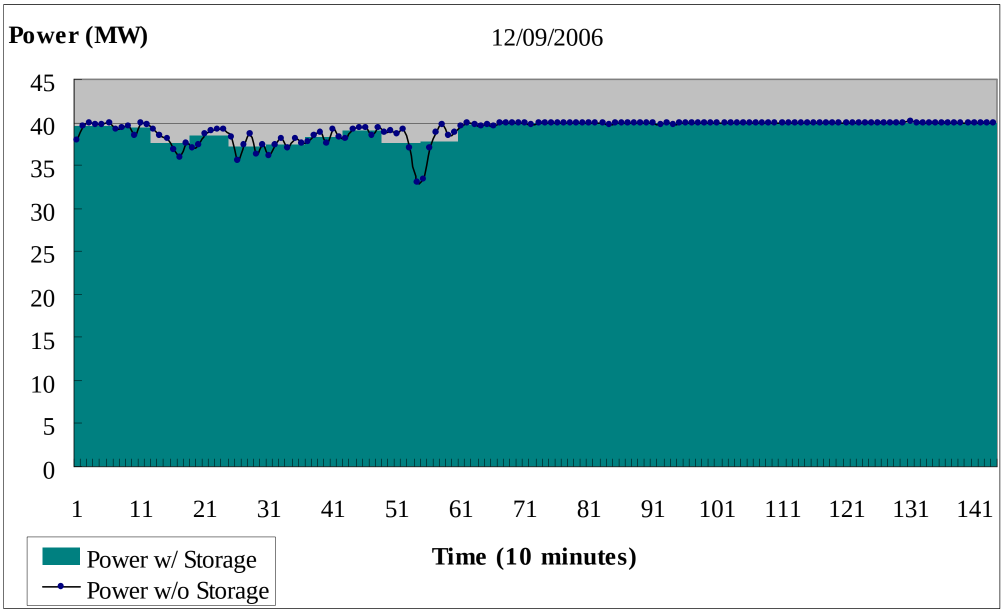

Figure 4.5 Storage Capacity and Time: 0.870 MWh, 1 hour

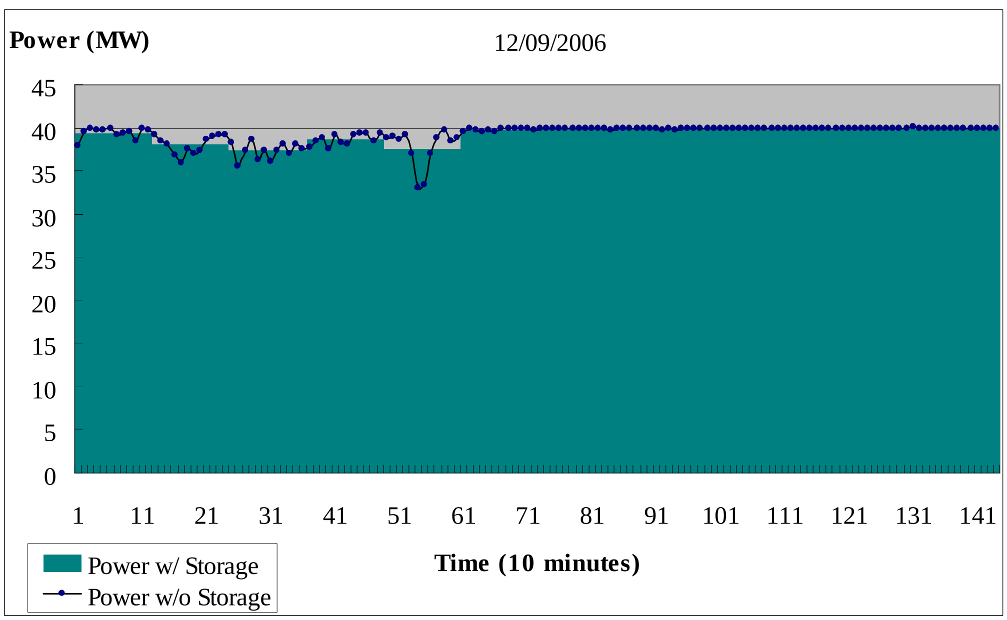

Figure 4.6 Storage Capacity and Time: 1.690 MWh, 2 hours

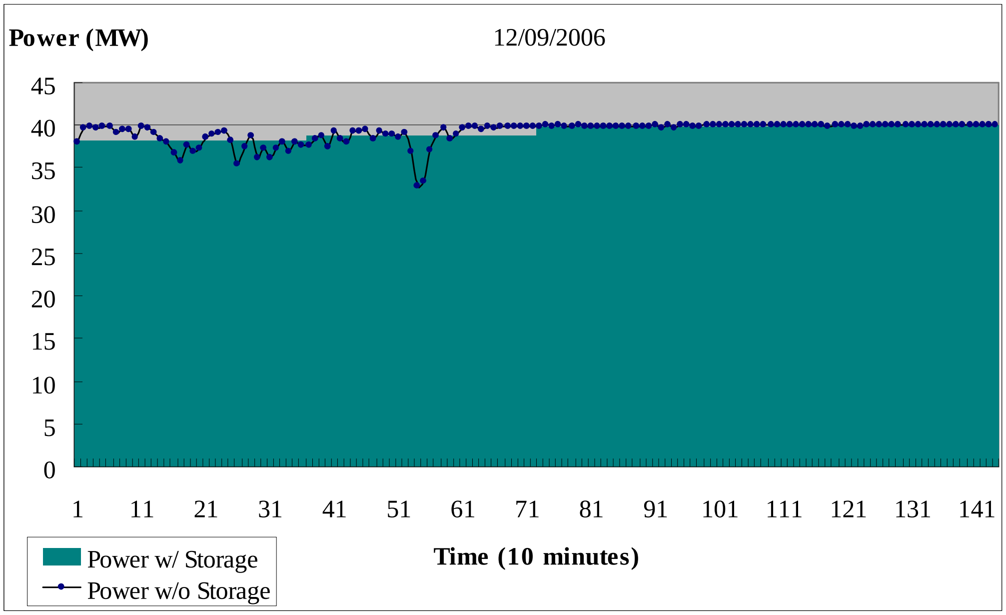

Figure 4.7 Storage Capacity and Time: 3.160 MWh, 6 hours

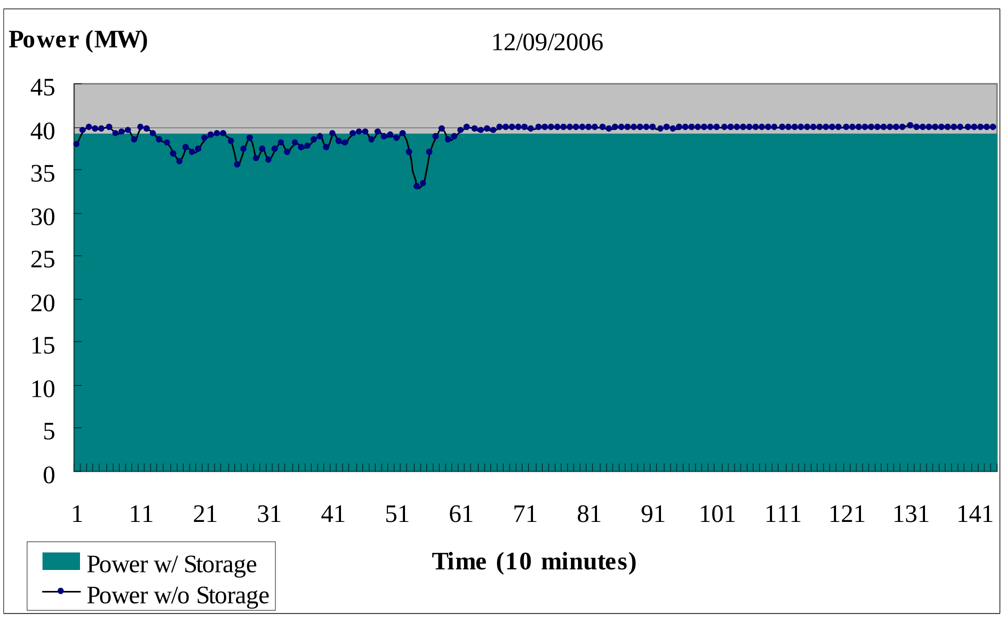

Figure 4.8 Storage Capacity and Time: 10.435 MWh, One Day

4.1.3 Larger Variation of Wind Power

Figure 4.9 to 4.12 show that the behavior of the system for one hour to one day storage capacity when there is large variation of the wind speed. The required storage capacities are 5.164MWh, 10.524MWh, 22.819MWh and 137.863MWh respectively. Maximum charging/discharging power rating requirements are 16.20MW, 23.31MW, 27.94MW and 26.69MW respectively. Summary of these estimated values relative to energy storage in smaller variation of wind power scenario are shown Table 4.3.

Table 4.3 Estimated Values in Larger Variation of Wind Power

Desired Stable Power Output Time (hour)	**Storage Capacity (MWh)**	**Max. Charging/ Discharging Power (MW)**
1 H	5.164	16.20
2 H	10.524	23.31
6 H	22.819	27.94
24 H	137.863	26.69

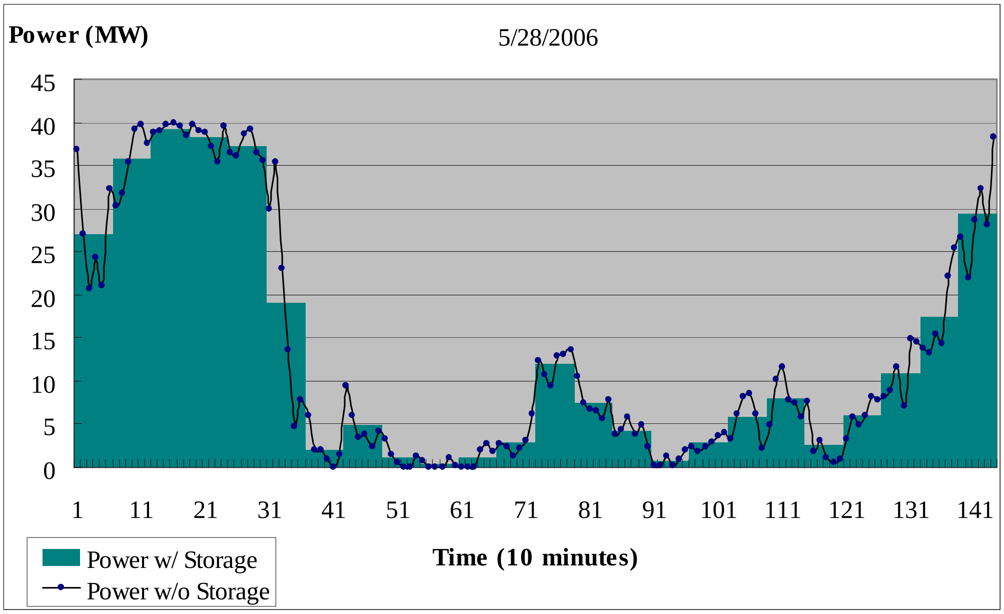

Figure 4.9 Storage Capacity and Time: 5.164 MWh, 1 hour

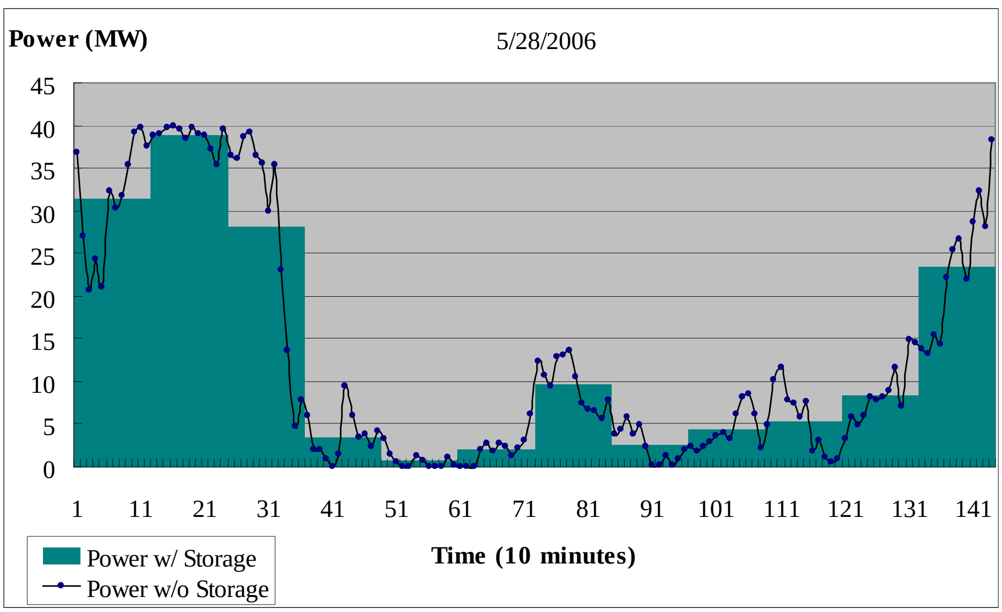

Figure 4.10 Storage Capacity and Time: 10.524 MWh, 2 hours

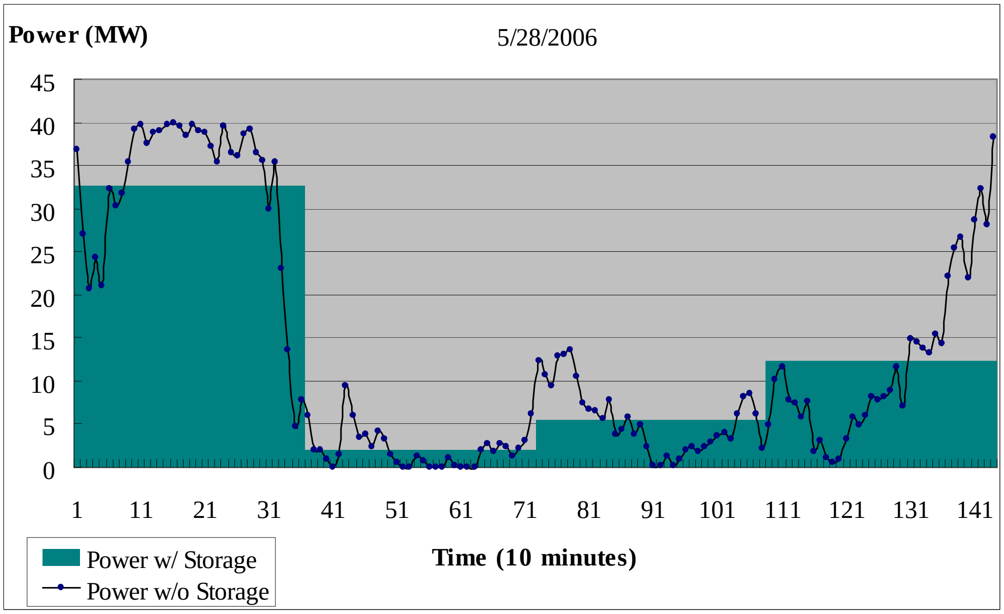

Figure 4.11 Storage Capacity and Time: 22.819 MWh, 6 hours

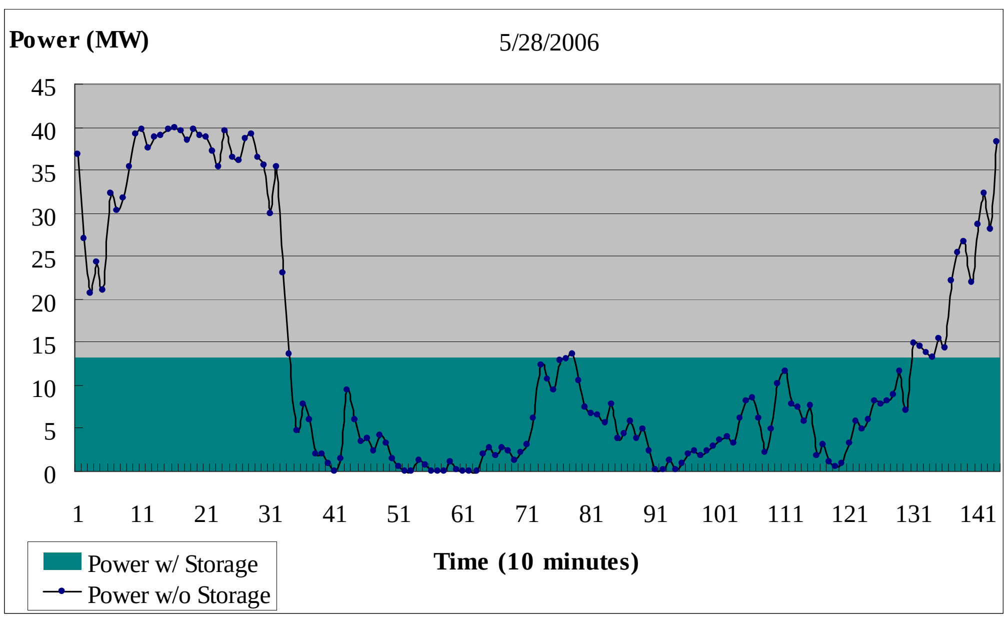

Figure 4.12 Storage Capacity and Time: 137.863 MWh, One Day

4.1.4 Summary

Summarize the above estimated results are shown Figure 4.13. This graph shows the storage capacity requirement for different operation scenarios for a period of one year. Bottom line shows the storage capacity for one hour dependable output. Pink line shows the storage capacity for 2-hour dependable output. Blue line shows the storage capacity for one day dependable output. As one can see, longer dependable output period requires more storage capacity and power rating.

In addition, the storage requirements are seasonal. One can install the largest requirement of the year to accommodate the all year round operating requirement or pick the capacity to cover the target months and switch to different operating strategies on other months.

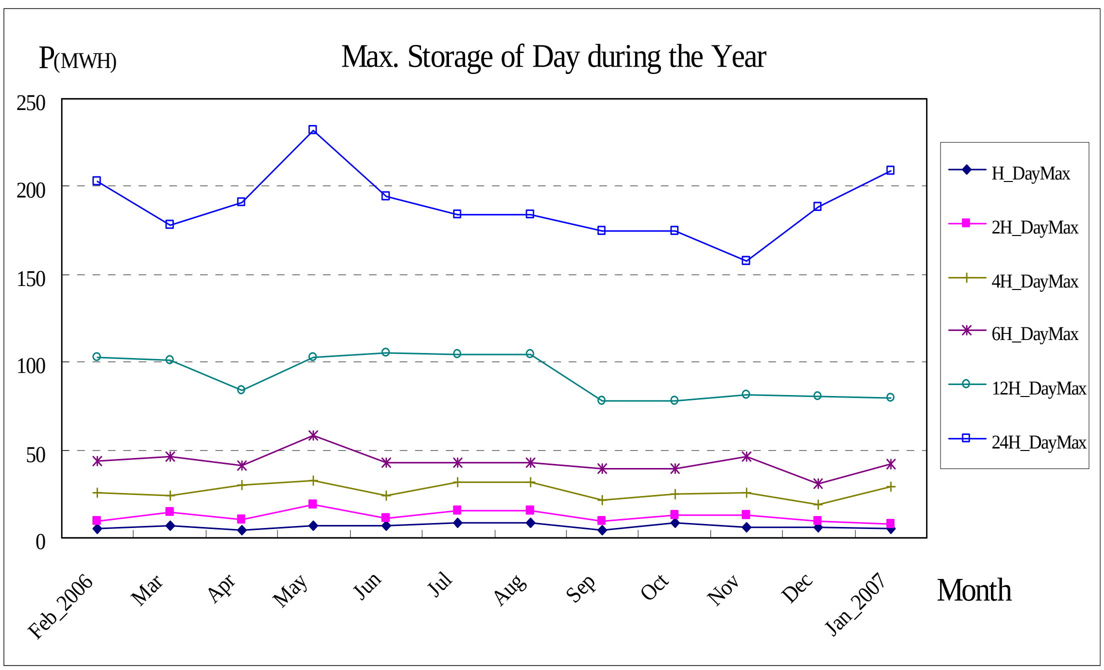

Figure 4.13 Max. Storage Capacity of Day every month during a Year

4.2 Steady State Power Flow Result

The purpose of this power flow study is to observe the potential system impact during normal and contingency conditions after the 39.6 MW proposed wind farm is interconnected with the grid system. The contingency analysis considers the impact of the new wind power on transmission line loading, transformer facility loading, and transmission bus voltage during outages of transmission line and/or transformers. The latest version of Taipower 2008 summer peak base case is used for this study. This study assumes that the energy storage systems is to keep 39.6 MW power output from wind collected bus 350 to grid. Therefore, the power flow result with energy storage equipments is the same as without them. To keep power system operates safely and reliably, the power flow result need to comply with the Taipower Grid Planning Standards [20]. The single line diagram of system near the wind farm is shown in Figure 4.14.

Table 4.4 compares the steady state and single contingency (N-1) power flow results before and after the installation of the wind farm. All power flows in the list are expressed in MVA. For N-1 analysis, the obtained result showed no negative impact of the wind farm on the power system. The analysis indicated that an installation of the 39.6 MW wind power has very little effect on the grid system.

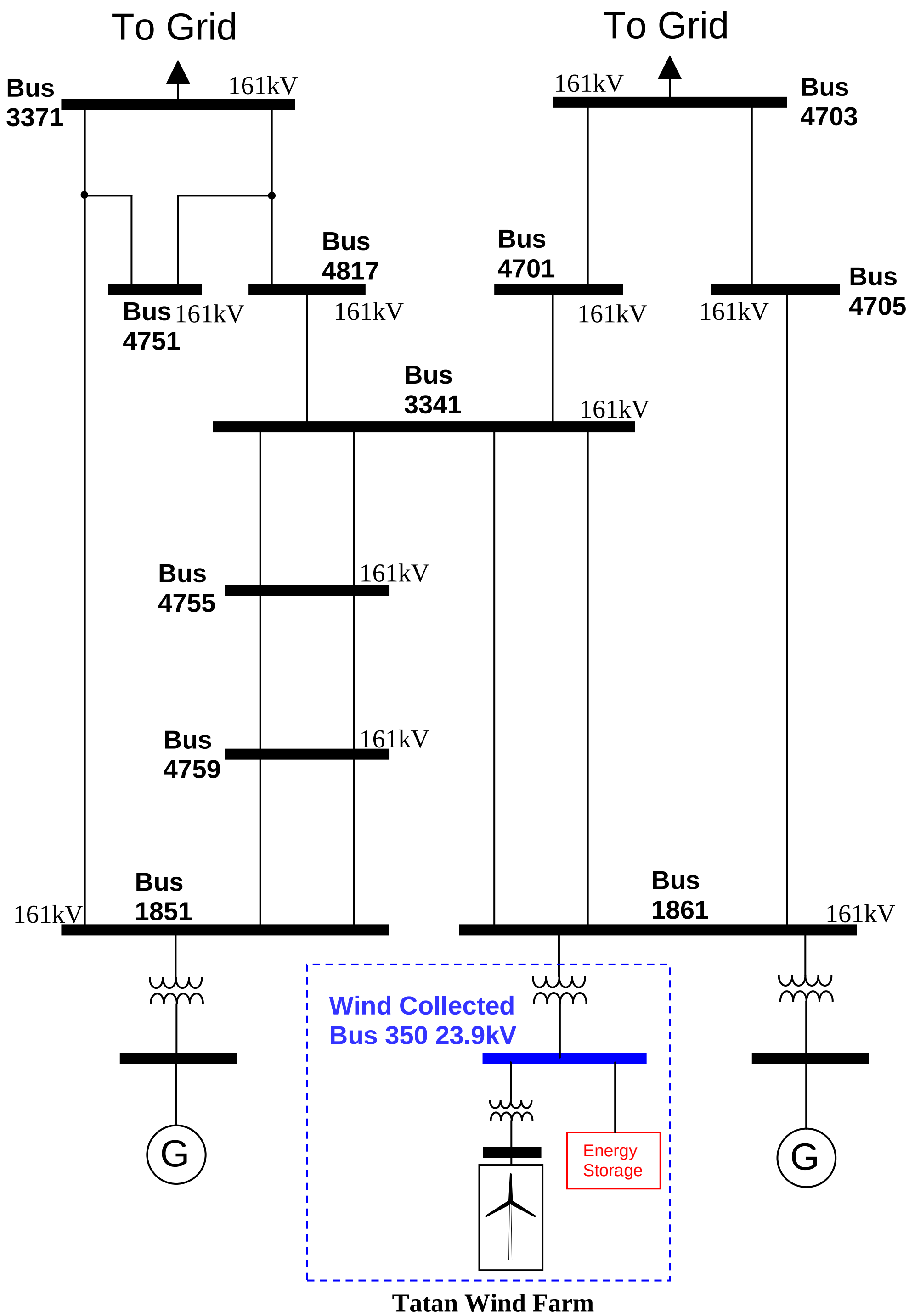

Figure 4.14 Single-line diagram of the power system near the proposed Datan wind farm

Table 4.4 Steady State Power Flow Current and Percentage Level at Neighboring 161 kV Lines of New Proposed Wind Farm

<table>
<tr><th colspan="10">Power Flow / Line</th><th rowspan="3">Is Flow over load ??</th></tr>
<tr><th colspan="3" rowspan="2">Line flow / System condition</th><th colspan="2">Line from bus 1861</th><th colspan="2">Line from bus 1851</th><th colspan="3">Line from bus 3341</th></tr>
<tr><th>To bus 3341</th><th>To bus 4705</th><th>To bus 4759</th><th>To bus 4751</th><th>To bus 4755</th><th>To bus 4701</th><th>To bus 4817</th></tr>
<tr><td colspan="2" rowspan="2">Base case N-0 (w/o wind farm)</td><td>MVA</td><td>303.4</td><td>143</td><td>410.2</td><td>39.5</td><td>188.6</td><td>112.7</td><td>31.6</td><td rowspan="2">—</td></tr>
<tr><td>%</td><td>30%</td><td>28%</td><td>37%</td><td>8%</td><td>18%</td><td>22%</td><td>6%</td></tr>
<tr><td rowspan="12">With wind farm</td><td rowspan="2">N-0</td><td>MVA</td><td>331.2</td><td>155.7</td><td>402.6</td><td>48.5</td><td>181.4</td><td>121.6</td><td>24.5</td><td rowspan="2">N</td></tr>
<tr><td>%</td><td>33%</td><td>31%</td><td>36%</td><td>10%</td><td>18%</td><td>24%</td><td>5%</td></tr>
<tr><td rowspan="2">N-1: Line from bus 1861 to 3341</td><td>MVA</td><td>289.1</td><td>198.3</td><td>403.8</td><td>49.8</td><td>186.8</td><td>80.2</td><td>31.6</td><td rowspan="2">N</td></tr>
<tr><td>%</td><td>58%</td><td>40%</td><td>37%</td><td>10%</td><td>18%</td><td>16%</td><td>6%</td></tr>
<tr><td rowspan="2">N-1: Line from bus 1861 to 4705</td><td>MVA</td><td>486.3</td><td rowspan="2">Out of service</td><td>395.2</td><td>60.3</td><td>181.8</td><td>261.1</td><td>31.2</td><td rowspan="2">N</td></tr>
<tr><td>%</td><td>48.5%</td><td>36%</td><td>12%</td><td>18%</td><td>53%</td><td>6%</td></tr>
<tr><td rowspan="2">N-1: Line from bus 1851 to 4759</td><td>MVA</td><td>331.3</td><td>155.7</td><td>399.2</td><td>52.2</td><td>176.4</td><td>120.1</td><td>26.8</td><td rowspan="2">N</td></tr>
<tr><td>%</td><td>33%</td><td>31%</td><td>72%</td><td>10%</td><td>17%</td><td>24%</td><td>5%</td></tr>
<tr><td rowspan="2">N-1: Line from bus 1851 to 4751</td><td>MVA</td><td>331.1</td><td>156.4</td><td>451.2</td><td rowspan="2">Out of service</td><td>223.2</td><td>117.3</td><td>27.6</td><td rowspan="2">N</td></tr>
<tr><td>%</td><td>33%</td><td>31%</td><td>41%</td><td>22%</td><td>24%</td><td>5%</td></tr>
<tr><td rowspan="2">N-1: Line from bus 3341 to 4701</td><td>MVA</td><td>239.2</td><td>253.4</td><td>392.2</td><td>59.2</td><td>174</td><td rowspan="2">Out of service</td><td>19.1</td><td rowspan="2">N</td></tr>
<tr><td>%</td><td>24%</td><td>51%</td><td>36%</td><td>12%</td><td>17%</td><td>4%</td></tr>
</table>

4.3 Short Circuit Current Result

Short circuit studies are performed to determine the possible changes of fault duty resulting from the added generation. In this study, the increment of the short circuit currents will be calculated to ensure that the circuit breakers in the neighborhood of the wind project still have enough ability to isolate the fault. In other words, this study is to check whether maximum short-circuit current of all neighboring buses is under circuit breaker interrupted capacity. If the maximum short-circuit current exceed the interrupted capacity of the circuit breakers, it requires infrastructure improvement to accommodate the new wind farm installation [1, 2]. This study supposes that energy storage has inherent current limitation as a result of the power electronic interface with the grid. To prevent damage to the converter, it has to be tripped during the fault. Therefore, short circuit current result of this study doesn’t consider influence of energy storage equipments on power system. Table 4.5 shows fault currents at different buses near the wind farm. All fault current in the list are expressed in kilo-amperes.

Table 4.5 shows that the largest increment in bus fault current occurs at TATANBH bus 1861 and increases by 0.347 kA. One more significant increasing of fault current locates at KUANINH1 bus 3341. The 0.282 kA increasing of fault current affected by the new generator was observed. However, they are still under the rated capacity of the existing circuit breakers. Therefore, no split-bus or circuit breaker upgrade is necessary for the new wind farm installation. The analysis indicated that an addition of the 39.6 MW wind farm is acceptable.

Table 4.5 Short-Circuit Current Level at Neighboring Buses of New Proposed Wind Farm

Bus Name	Bus No.	Voltage Level (kV)	Circuit Breaker IC (kA)	Short Circuit Current (kA)			Is under rated IC of circuit breaker?
				w/o wind farm	w/ wind farm	Increment	
TATANEE	300	345	63	23.132	23.134	0.002	Y
LUNTANE	1900	345	63	33.016	33.030	0.014	Y
LUNTASE	1910	345	63	42.415	42.424	0.008	Y
TATANAH	1851	161	50	37.728	37.848	0.120	Y
TATANBH	1861	161	50	41.645	41.993	0.347	Y
TATANCH	1871	161	50	16.899	16.899	0.000	Y
PAOSHENH	4759	161	50	37.711	37.833	0.122	Y
PAIYUH	4755	161	50	38.014	38.153	0.140	Y
KUANINH1	3341	161	50	45.124	45.406	0.282	Y
CHUNTA	4701	161	50	42.494	42.693	0.198	Y
SUNGWUH	4705	161	50	39.284	39.464	0.181	Y
FUKANGH	4751	161	50	33.515	33.578	0.063	Y
YANMEIH	4817	161	50	27.590	27.653	0.064	Y
MEIHUH	3371	161	50	34.879	34.917	0.039	Y
HSINKOUH	4703	161	50	44.407	44.610	0.202	Y
CHUNFUH	4715	161	50	44.544	44.731	0.187	Y
CHUNLIH	3321	161	50	44.709	44.887	0.178	Y

4.4 Transient Stability Result

4.4.1 Simulation Results during Wind Gust

When wind gust occurs like wind variation in wind farm, system power flow, generator angel, voltage and frequency will fluctuate. In this section, the wind turbine with energy storage during a short wind gust in study case to decrease the negative affect of power system fluctuation is simulated [21]. In this study case, it is assumed that the wind farm consists of a large number of wind turbine generators in a large area and the energy storage is connected to wind collector bus. The energy storage is modeled as the EPRI CBEST battery [18] of ±39.6MW, and ±22.8Mvar. The simulation results indicate that using the energy storage equipments can reduce most of power system fluctuation.

4.4.1.1 Reducing Wind Power Output Fluctuation

Figure 19 shows the response of the wind farm and energy storage device during wind gust variation. The green line is wind speed, yellow line is the power output of wind generator, blue line is the response of energy storage device, and pink line indicates the total power flow at Point of Common Coupling (PCC). As shown in Figure 4.15, the total active power injection from the wind farm (pink line) remains constant.

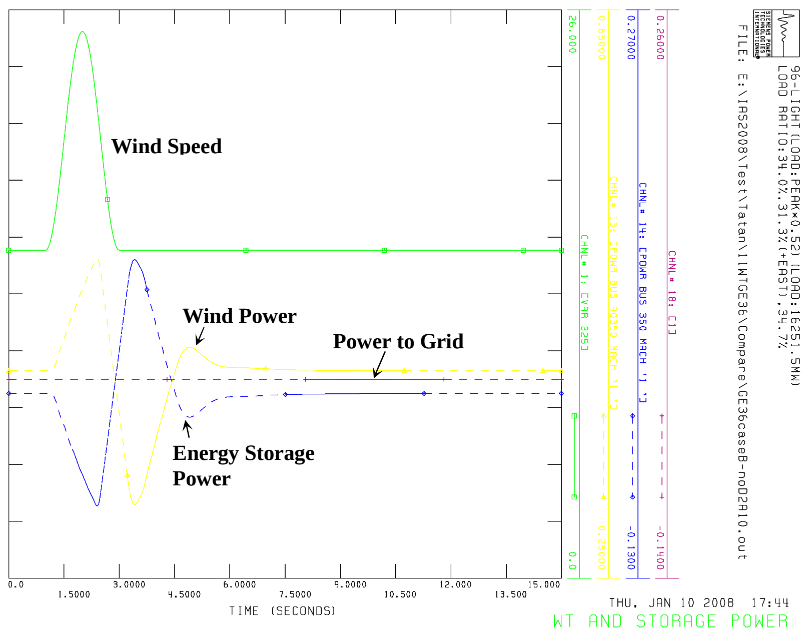

Figure 4.15 Wind farm and energy storage power output

4.4.1.2 Improving Power System Fluctuation

Figure 4.16 to 4.18 show the generator angle, frequency and voltage variation respectively during wind gust. The green, yellow and blue lines of these three figures indicate the system response without energy storage equipments. The other color lines show the improvement with energy storage devices. One can see that combining the wind power generation system with energy storage equipments is a good solution to improve power system fluctuation during the wind gust variation.

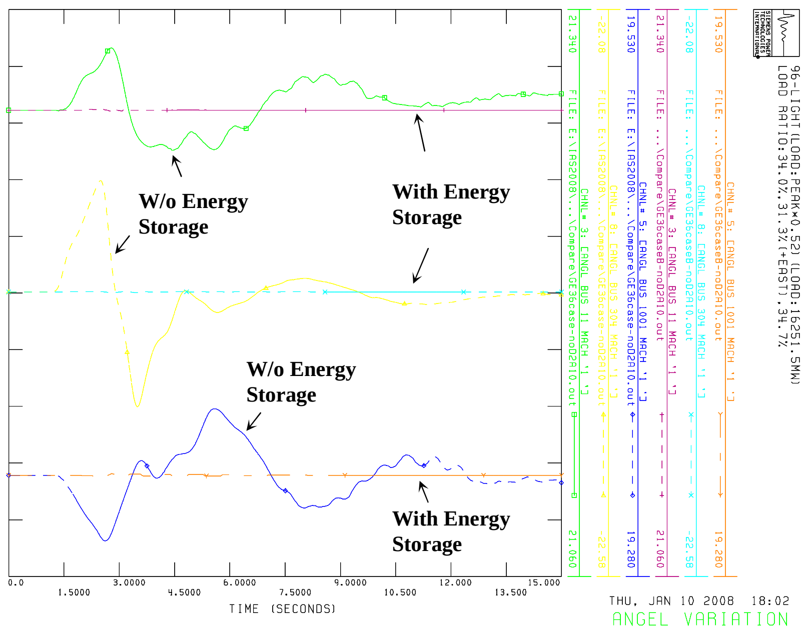

Figure 4.16 Simulation result about Generator Angle Variation

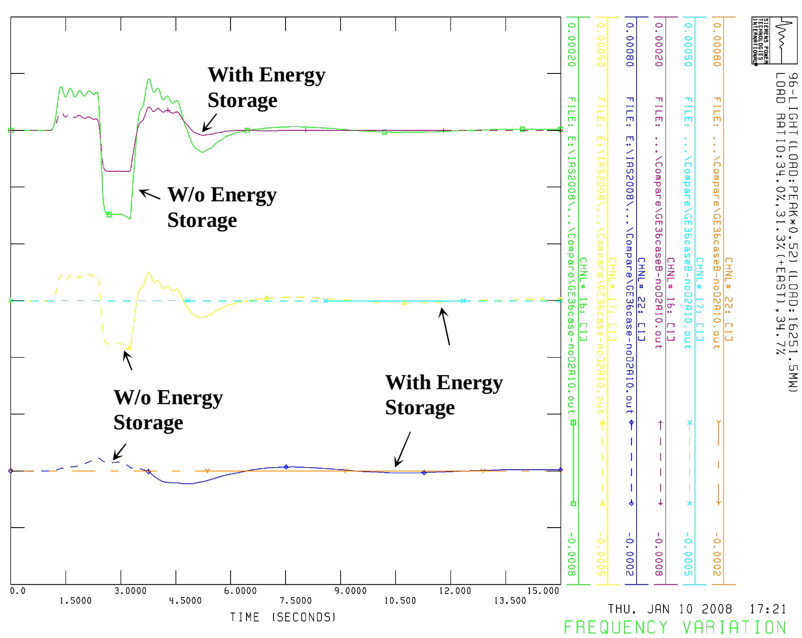

Figure 4.17 Simulation result about Frequency Variation

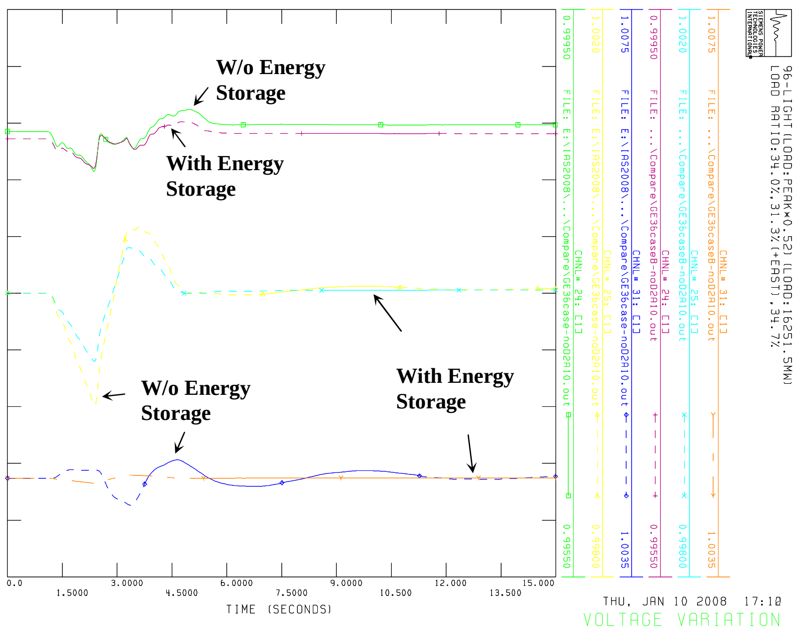

Figure 4.18 Simulation result about Voltage Variation

4.4.2 Simulation Results during the Fault

In this section, we simulate combining the wind turbine with and without energy storage equipments during the fault to describe as the ability of a power system to return to a stable operating condition following a major disturbance such as a transmission line short circuit or a large generating unit trip. Planning criteria require that generator angular oscillations do not exceed specific values and are damped out within certain time periods.

In this section, we simulate combining the wind turbine with energy storage during the fault to decrease the negative affect of power system transient stability. In this study case, it is assumed that the wind farm consists of a large number of wind turbine generators in a large area and the energy storage is connected to wind collector bus 350. The transmission line model used in this study is the TPC system 2008 winter load model. The energy storage model is identical to that in wind gust study modeled as the EPRI CBEST battery with the power rating of ±39.6MW, and ±22.8Mvar.

The simulation results show the generator angle of six different areas. In order to identify the potential stability problem, the angle of main generation units including the nuclear and thermal unit is observed. The following generator buses are monitored and shown in Table 4.6.

Table 4.6 Monitored of Generator Buses

Bus No.	**Generator Type**	**Area**
11	Nuclear	North
21	Nuclear	North
531	Thermal	Central
711	Pumped Water	Central
1001	Nuclear	South
90350	Wind	Proposed wind farm (North)

4.4.2.1 Cases Condition Description

To accomplish the stability study process, the transient stability studies for various studied-cases are designed to show the dynamic response of the system following critical disturbances in the neighborhood of the proposed new generator. According to Taiwan Power Company planning criteria, the disturbances are based on a three-phase fault on different buses near the new wind generator followed by removing the fault at 12-cycle through tripping the line at 7-cycle in 161 kV system. The other one is followed by clearing the fault at 8-cycle through tripping the line at 4-cycle in 345 kV system. The operating condition of each individual case is shown Table 4.7.

Table 4.7 Critical Clear Time of Dynamic Stability Study Cases

Fault Bus	Case No.	Trip Line (at 7-cycle)	Critical Clear Time (Cycle)	Is Stable?
No Fault	1	None	None	Y
350	2	A Transformer from bus 1861 to 350	□12	Y
1861	3	A Transformer from bus 350 to 1861	□12	Y
	4	A Line from bus 3341 to 1861	□12	Y
	5	A Line from bus 4705 to 1861	□12	Y
3341	6	A Line from bus 1861 to 3341	□12	Y
4705	7	A Line from bus 1861 to 4705	□12	Y
345kV Bus 1910	8	Two 345kV Lines from bus 2000 to 1910	□12	Y
	9	Two 345kV Lines from bus 1750 to 1910	□12	Y

The stability results are shown in figures 4.19 to 4.27. It is clear from the results that all cases remain stable after experiencing a three phase fault near Datan wind farm area.

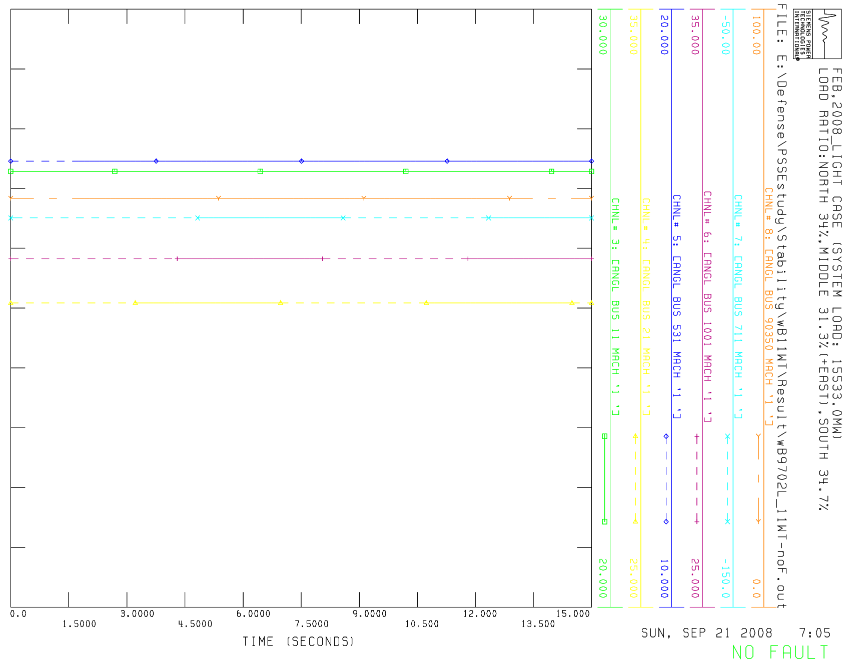

Figure 4.19 New wind farm is installed at bus 90350. (Case 1 No fault)

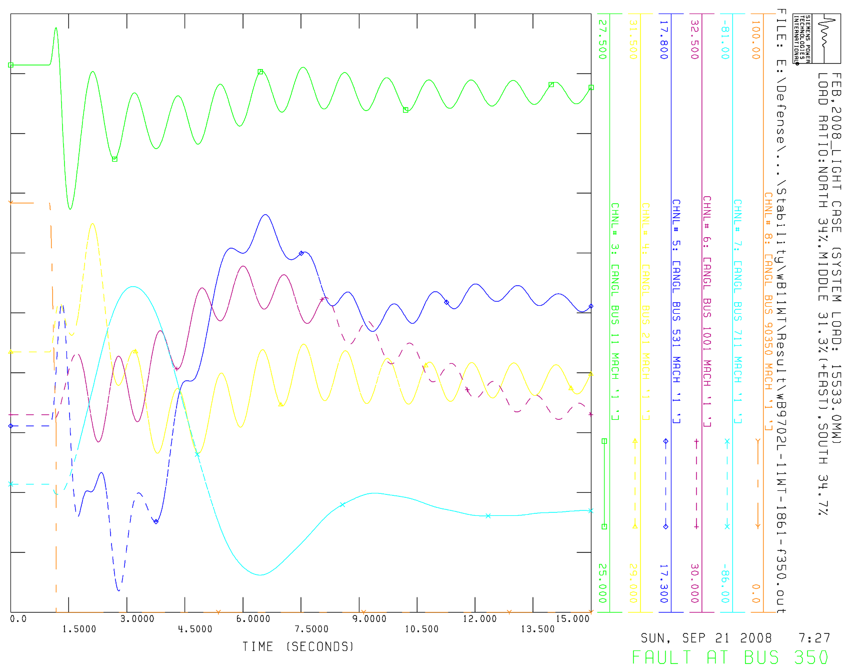

Figure 4.20 Three phase fault is occurred at Bus 350. A transformer between bus 1861 to 350 is tripped at 7-cycle to isolate the fault and clear the fault at 12-cycle. (Case 2)

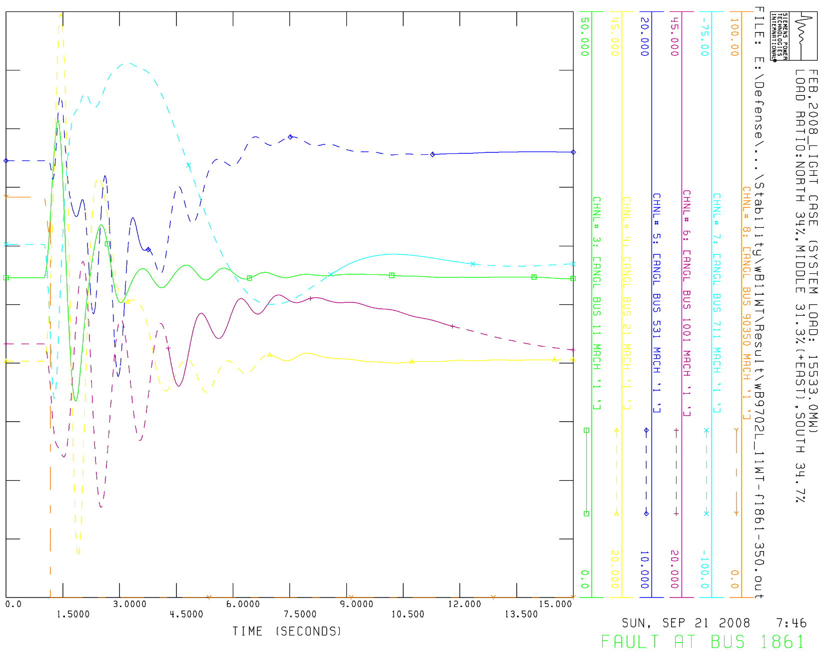

Figure 4.21 Three phase fault is occurred at Bus 1861. A transformer between bus 350 to 1861 is tripped at 7-cycle to isolate the fault and clear the fault at 12-cycle. (Case 3)

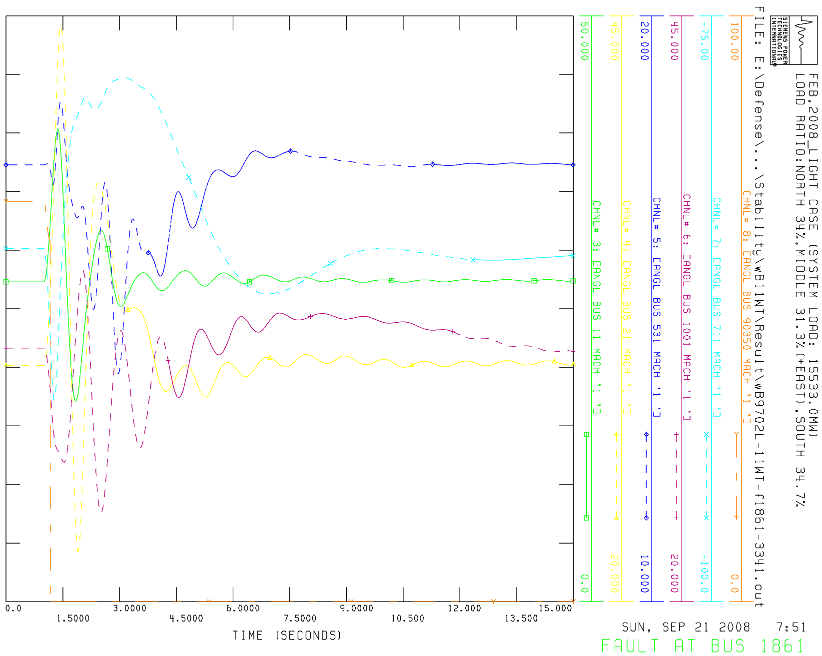

Figure 4.22 Three phase fault is occurred at Bus 1861. A line between bus 3341 to 1861 is tripped at 7-cycle to isolate the fault and clear the fault at 12-cycle. (Case 4)

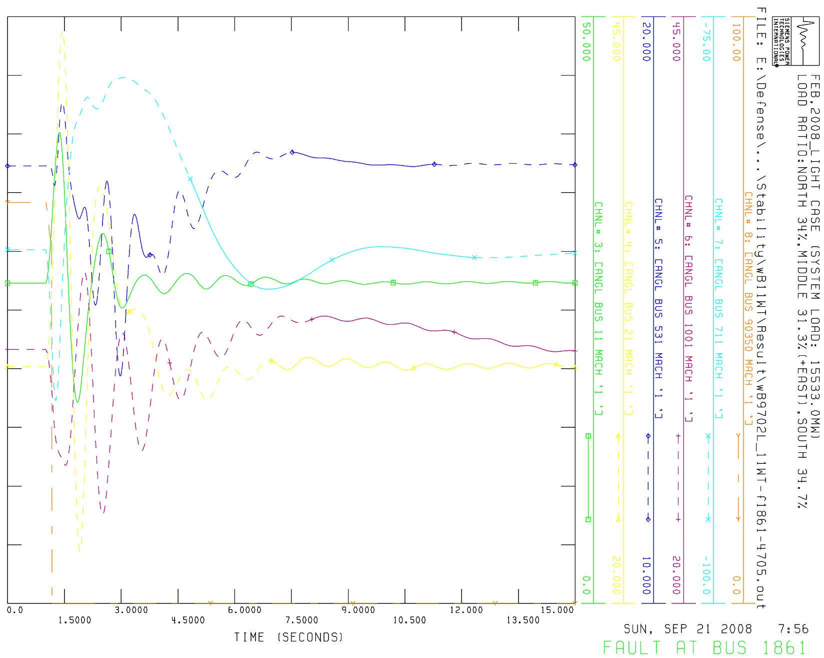

Figure 4.23 Three phase fault is occurred at Bus 1861. A line between bus 4705 to 1861 is tripped at 7-cycle to isolate the fault and clear the fault at 12-cycle. (Case 5)

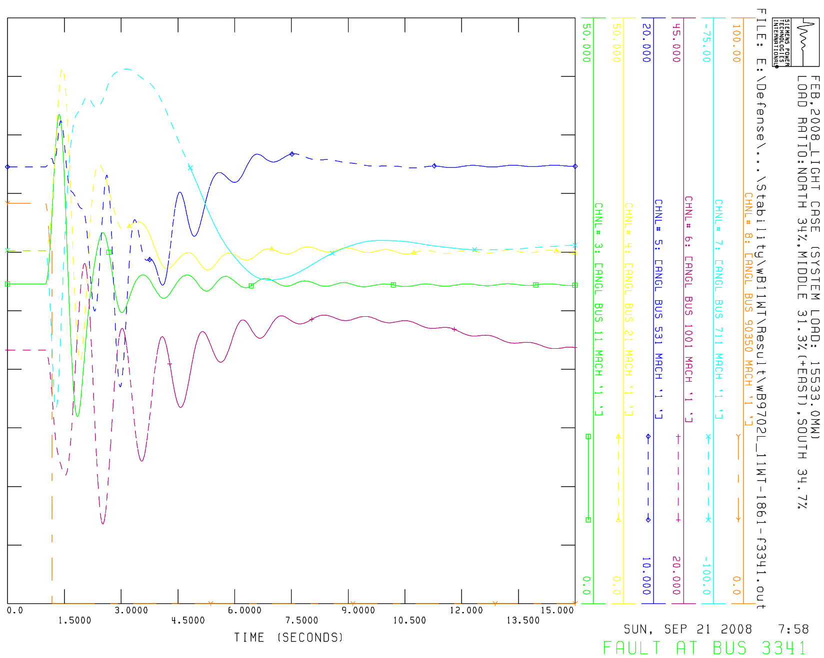

Figure 4.24 Three phase fault is occurred at Bus 3341. A line between bus 1861 to 3341 is tripped at 7-cycle to isolate the fault and clear the fault at 12-cycle. (Case 6)

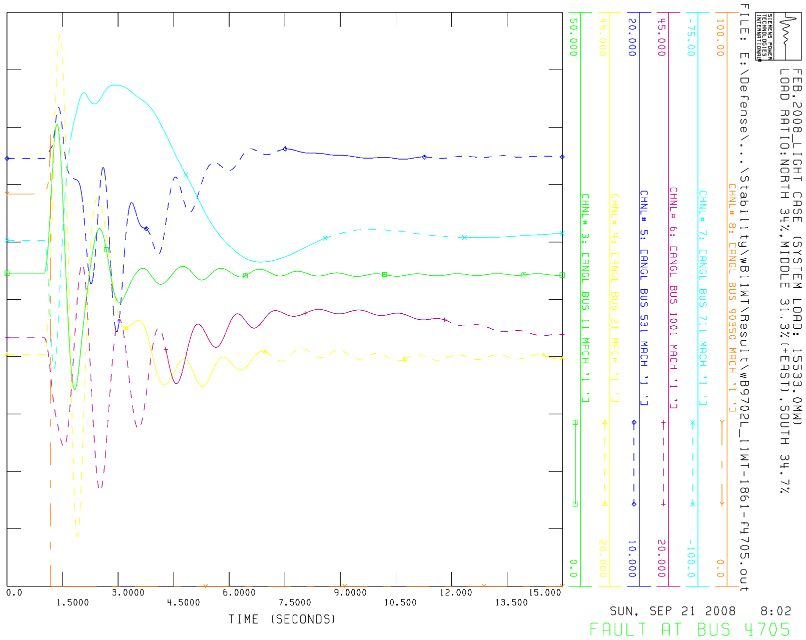

Figure 4.25 Three phase fault is occurred at Bus 4705. A line between bus 1861 to 4705 is tripped at 7-cycle to isolate the fault and clear the fault at 12-cycle. (Case 7)

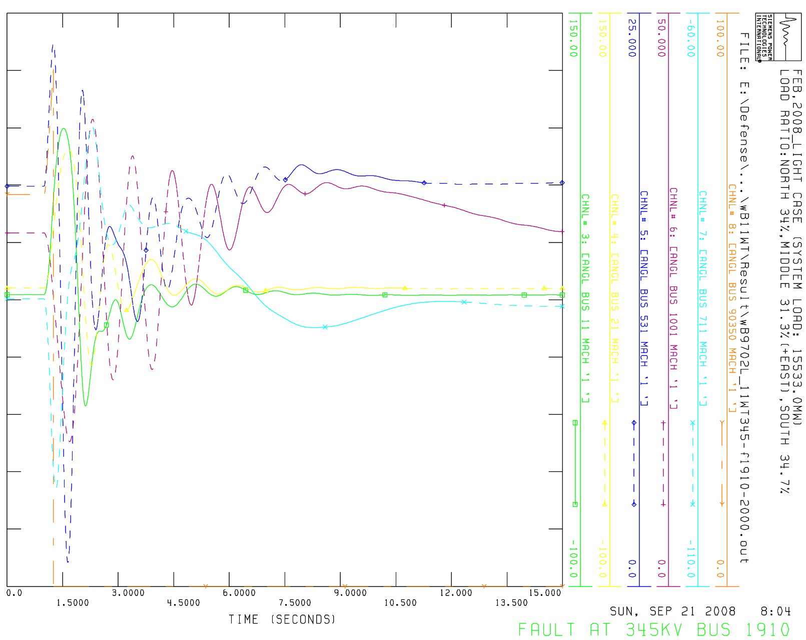

Figure 4.26 Three phase fault is occurred at 345kV Bus 1910. Two lines between 345kV bus 2000 to 1910 is tripped at 4-cycle to isolate the fault and clear the fault at 12-cycle. (Case 8)

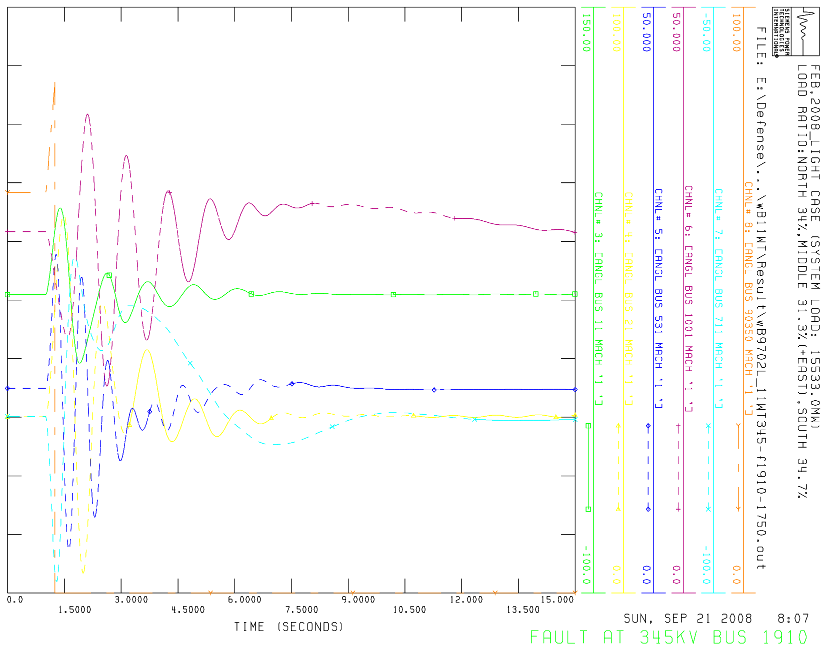

Figure 4.27 Three phase fault is occurred at 345kV Bus 1910. Two lines between 345kV bus 1750 to 1910 is tripped at 4-cycle to isolate the fault and clear the fault at 12-cycle. (Case 9)

4.4.2.2 Performance Comparison For System With and Without Energy Storage Equipments

Figure 4.28 to 4.43 show the generator angel of comparison for system with and without energy storage during a three phases fault. In all cases, the green, blue and yellow lines indicate the generator angel response without energy storage equipments. The other color lines show the improvement response with energy storage devices. Their operating conditions are identical to the former three phases fault study. The compared results indicate that using the energy storage equipments can improve the power system transient stability during the severe fault.

Case 2: Fault at **Bus 350** and trip one line between bus 1861 and 350.

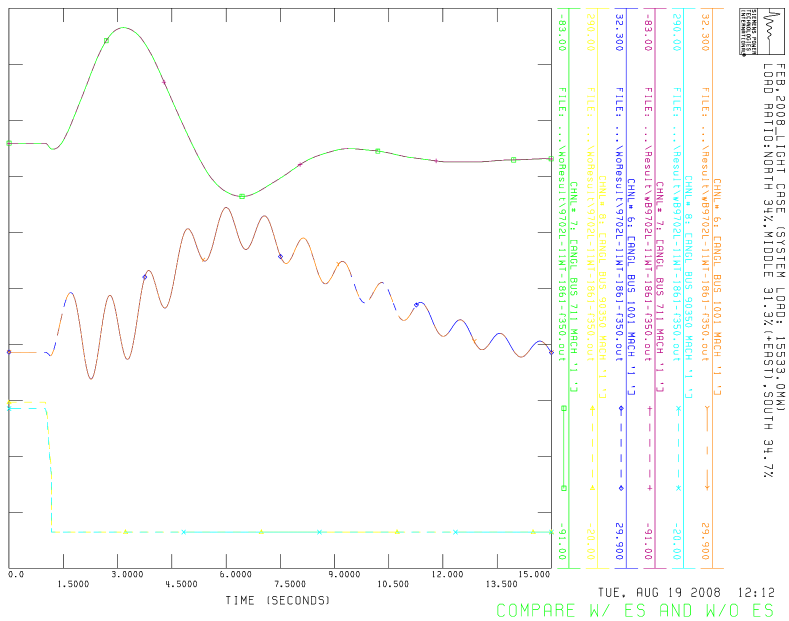

Figure 4.28 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 2)

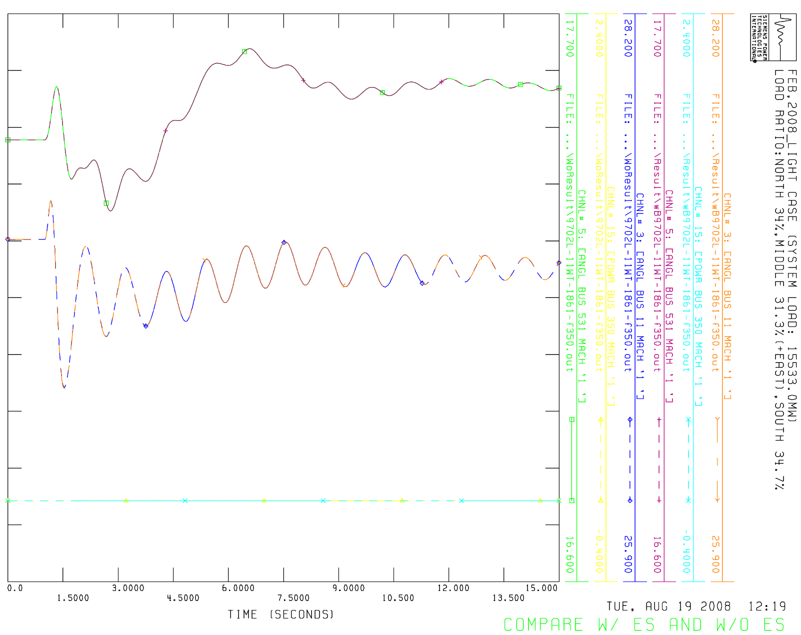

Figure 4.29 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 2)

Case 3: Fault at **Bus 1861** and trip one line between bus 350 and 1861.

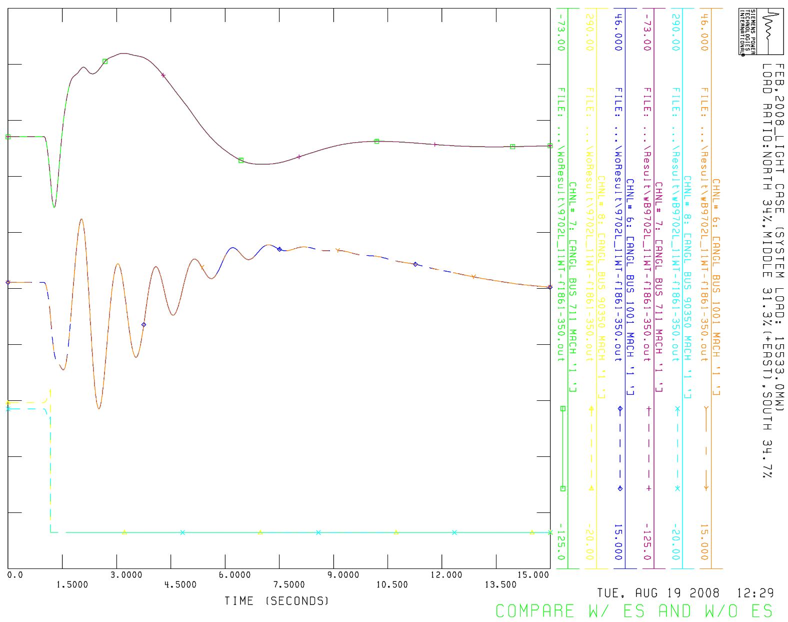

Figure 4.30 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 3)

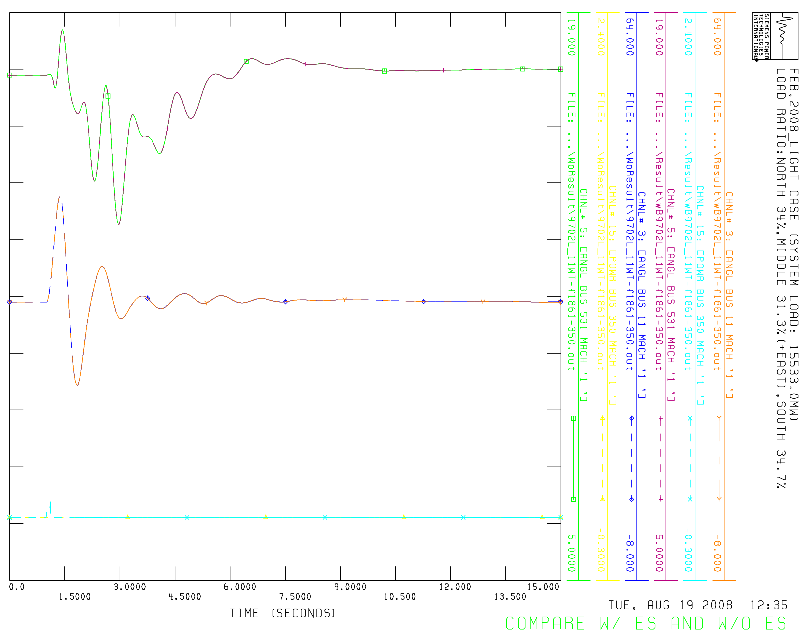

Figure 4.31 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 3)

Case 4: Fault at **Bus 1861** and trip one line between bus 3341 and 1861.

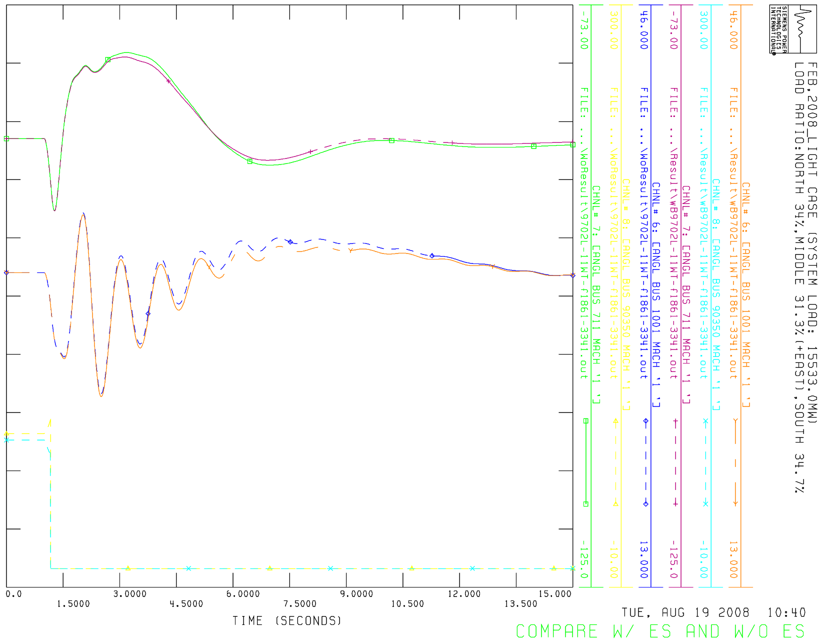

Figure 4.32 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 4)

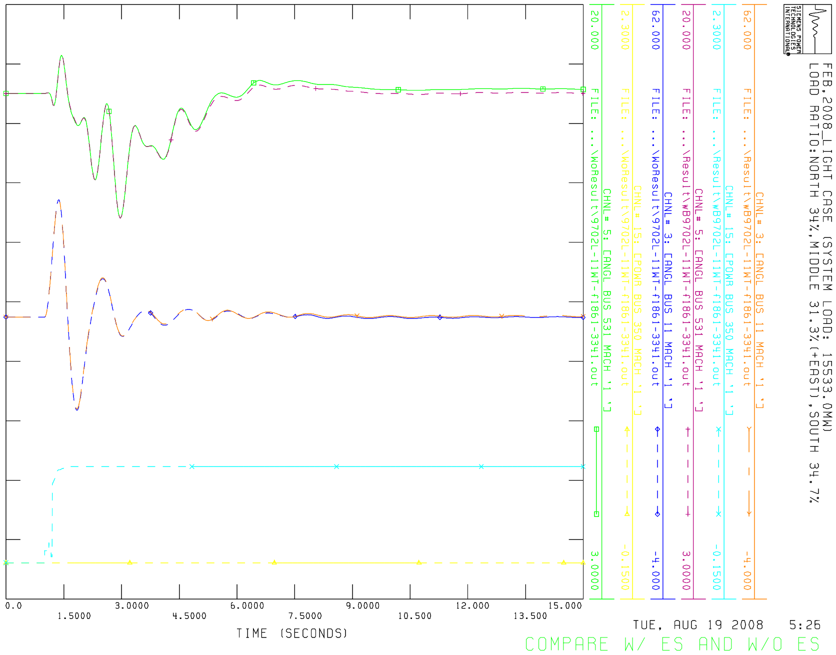

Figure 4.33 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 4)

Case 5: Fault at **Bus 1861** and trip one line between bus 4705 and 1861.

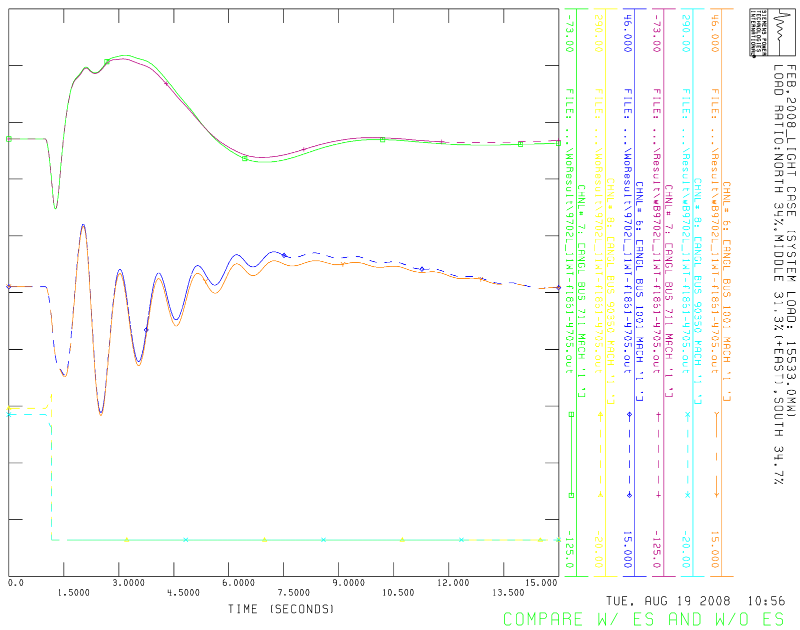

Figure 4.34 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 5)

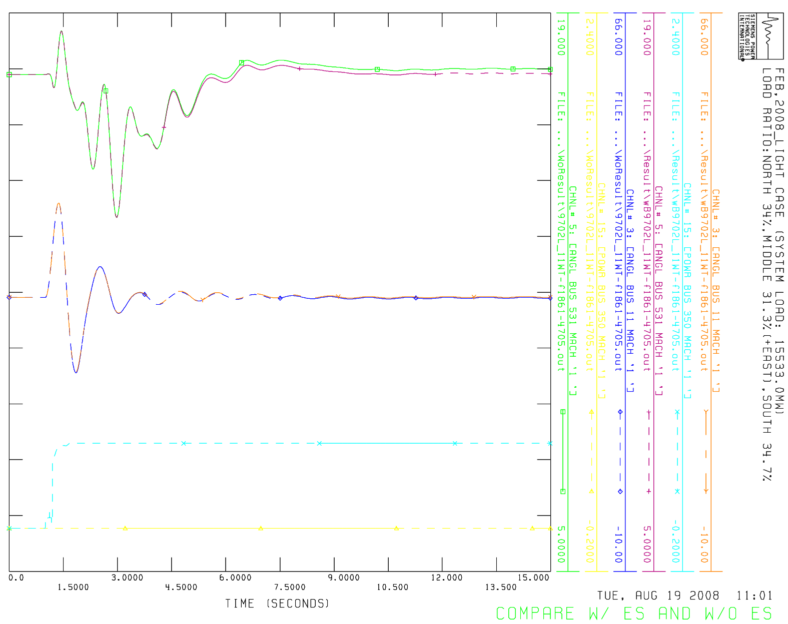

Figure 4.35 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 5)

Case 6: Fault at **Bus 3341** and trip one line between bus 1861 and 3341.

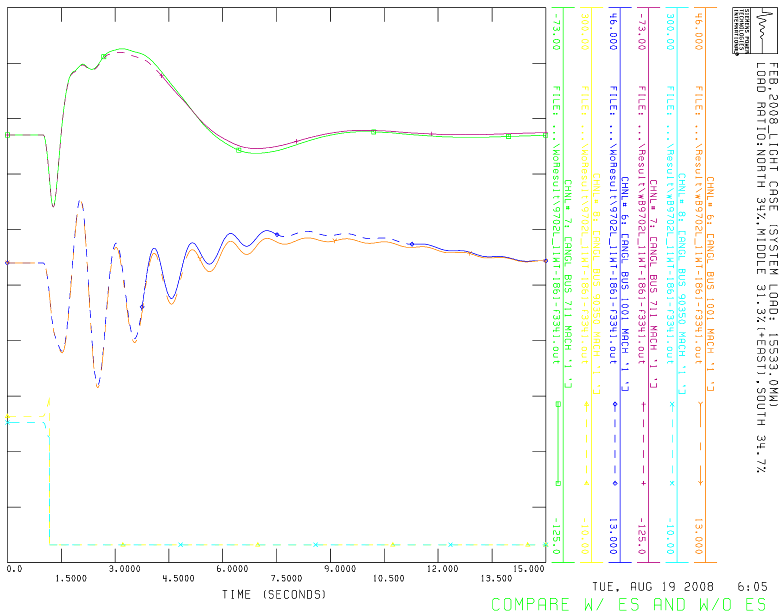

Figure 4.36 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 6)

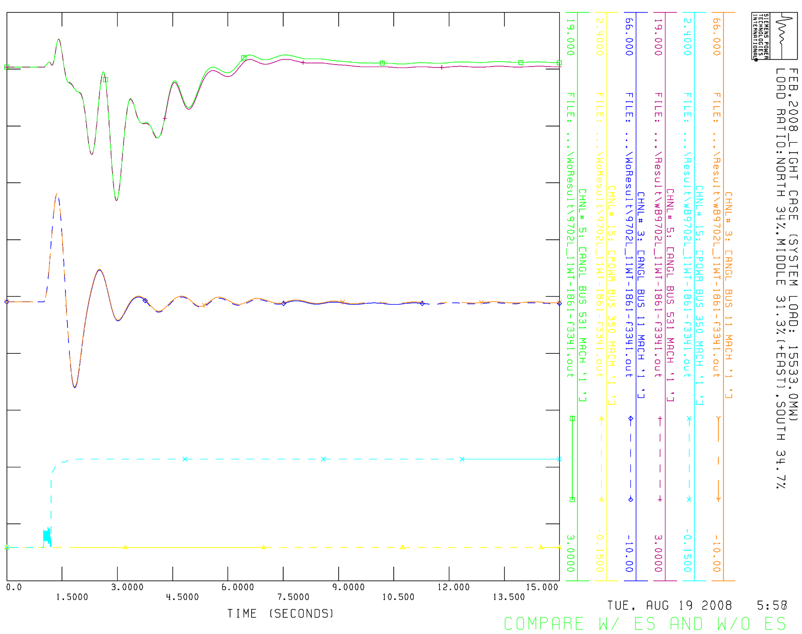

Figure 4.37 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 6)

Case 7: Fault at **Bus 4705** and trip one line between bus 1861 and 4705.

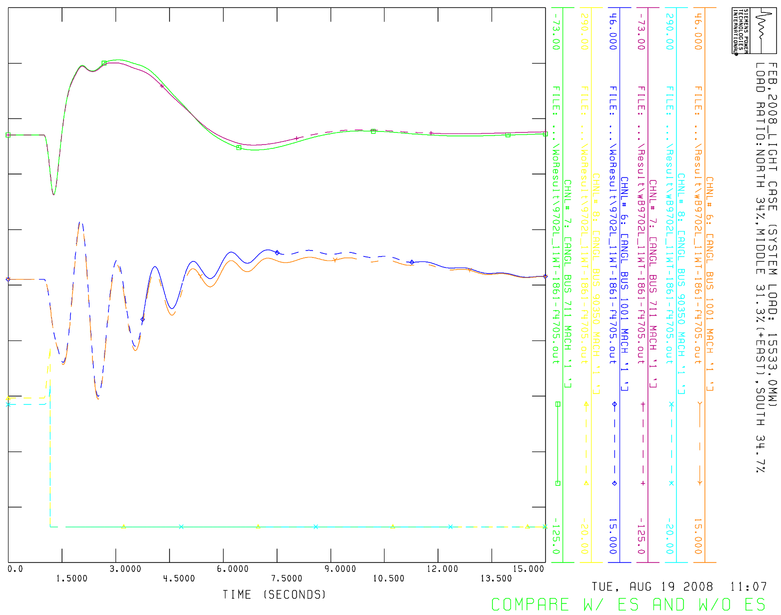

Figure 4.38 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 7)

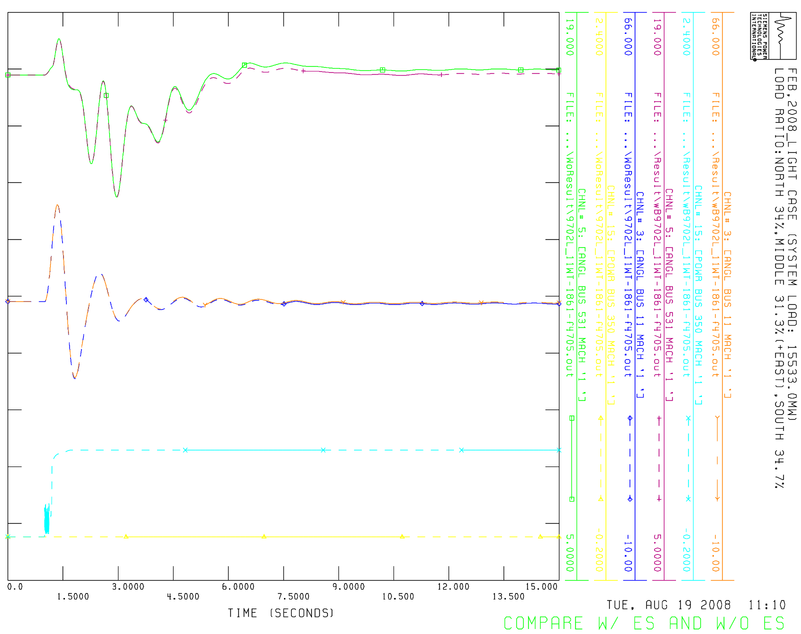

Figure 4.39 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 7)

Case 8: Fault at **Bus 1910** and trip two 345 kV line (N-2) between bus 2000 and 1910.

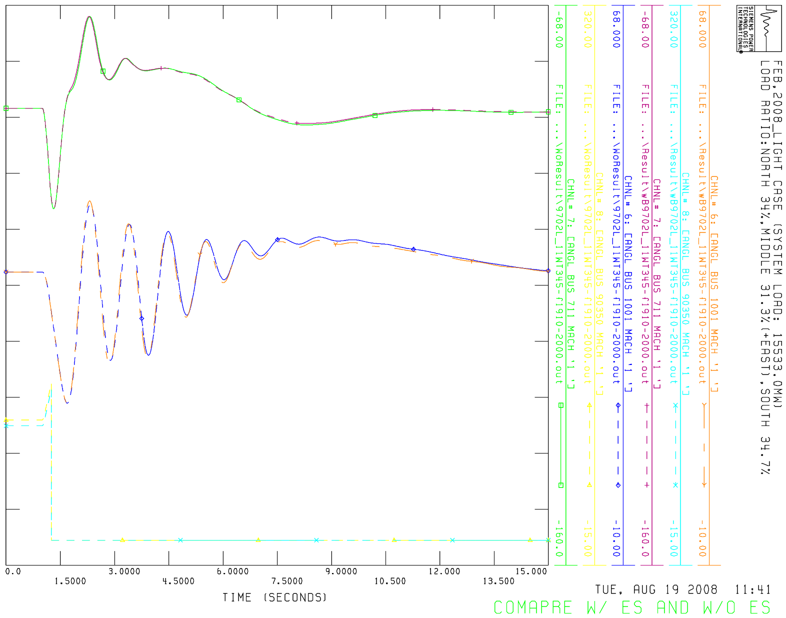

Figure 4.40 Green and red lines are Bus 711 generator angle, Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 8)

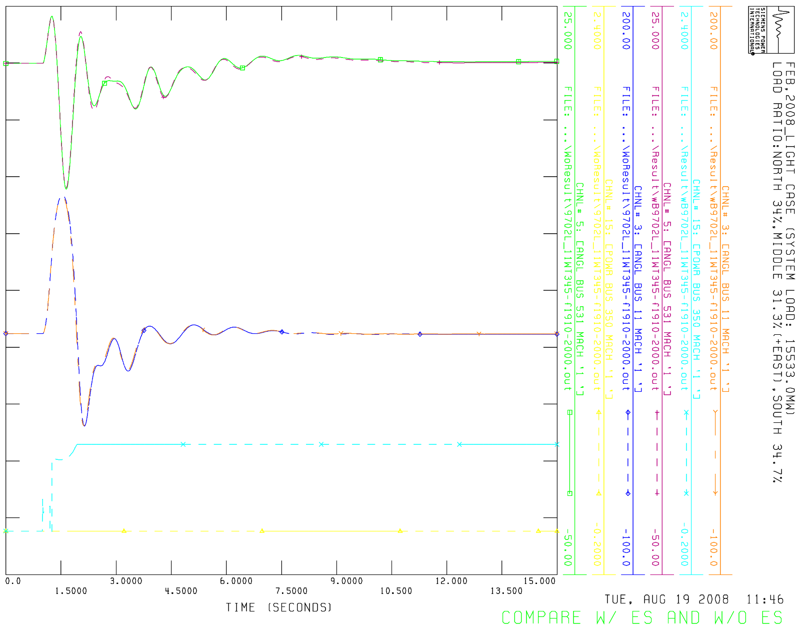

Figure 4.41 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 8)

Case 9: Fault at **Bus 1910** and trip two 345 kV line (N-2) between bus 1750 and 1910.

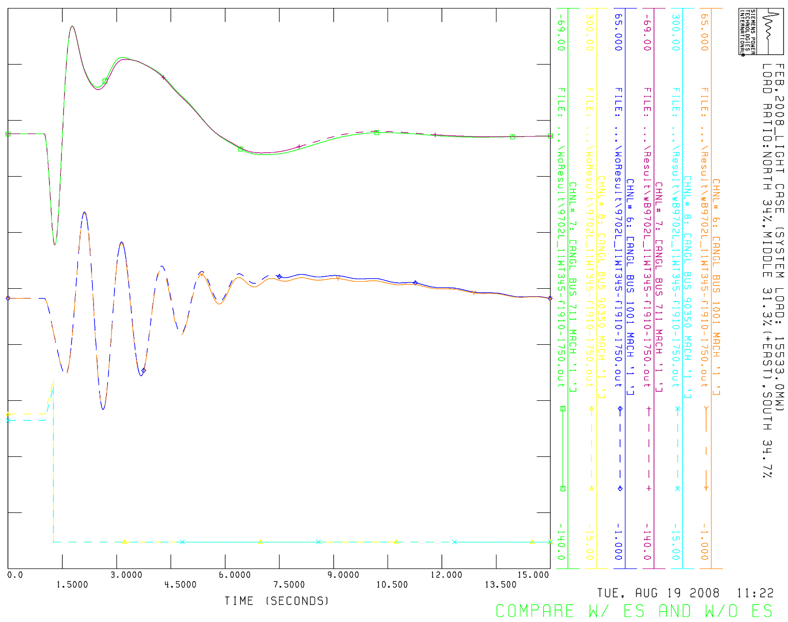

Figure 4.42 Green and red lines are Bus 711 generator angle. Orange and blue lines are Bus 1001 generator angle. Light blue and yellow are Bus 90350 generator angle (Case 9)

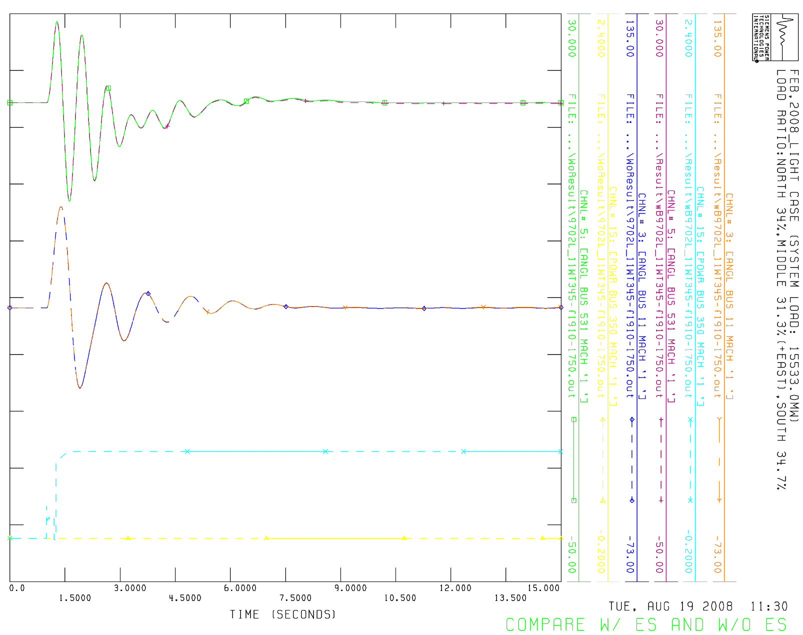

Figure 4.43 Green and red lines are Bus 531 generator Angle. Orange and blue lines are Bus 11 generator Angle. Light blue and yellow lines are Energy Storage Power Output (Case 9)

CHAPTER 5

CONCLUSION

Unlike coal, wind generation produces no air emission or solid wastes. Wind generation is the fastest growing renewable energy source all over the world with an average annual growth rate of more than 26 % since 1990 [22]. Annual wind generation markets have been increasing by an average of 24.7% over the last 5 years. Global Wind Energy Council (GWEC) predicts that the global wind market will reach 240 GW of total installed capacity by the year 2012 [23].

Based on information from studies and operational experience, the report of European Wind Energy Association (EWEA) concludes that it is perfectly feasible to integrate the targeted wind power capacity of 300GW in 2030 – corresponding to an average penetration level of up to 20% [24, 25]. For high penetration levels of wind power, optimization of the integrated system should be explored. One has to establish strategies to modify system configuration and operation practices to accommodate high level wind penetration.

For storage capacity option, our study reveals that more energy storage capacity and power rating are required if longer stable wind power output is desired. For simulation result during wind gust, combining the wind power generation system with proper energy storage equipments can reduce most of power system fluctuation. The ideal situation is making wind generation as dispatchable unit to reduce the operating cost and improve system reliability.

Since it needs significant capital investment for the energy storage devices, careful selection on the storage capacity and power ratings of the storage devices are needed. In the future, more and more new energy storage technologies will be available for better performance, higher reliability, and lower cost.

This study uses a proposed Datan wind farm in Taiwan Power System as sample system to illustrate the procedure to calculate required energy storage capacity and charging/discharging power ratings for different desired operation scenarios [19]. For the steady state study, after the new wind farm connects to grid, all power facilities and line power flows have no overloading conditions. And short-circuit current of all neighboring buses is under circuit breaker interrupted capacity. Therefore, it is determined that the new wind farm will have no adverse impact on the stable operation of the grid.

For the transient stability study, obviously, the benefits of energy storage devices not only to mitigate the most of power system fluctuations during wind gust but also to improve the dynamic stability during the severe fault.

5.1 Contribution

The idea of combining wind power generation system with energy storage equipments to balance wind power variation is not so new. However, published studies on capacity of energy storage systems are few. My contribution in this thesis to research community is in the following.

Wind power is intermittent and difficult to predict and control the output of the wind generation. At high penetration level, an extra fast response reserve capacity is needed to cover shortfall of generation when a sudden deficit of wind takes place. Combining wind generation with energy storage could reduce wind generation fluctuation uncertainty and provides operational benefits with moderate to high price variations and imbalance costs. It also shifts the generation pattern and smoothes the variation of wind power over a desired time horizon. It is also be used to mitigate possible price hikes or sags.

Since energy storage equipments need significant capital investment, careful selection on the storage capacity and power ratings of the storage devices are needed. It is important to perform cost benefit analysis to determine proper size of energy storage facilities for the desired operations.

The ideal scenario of combining wind generation with energy storage is making wind generation as dispatchable unit to reduce the operating cost and improve system reliability.

APPENDIX A

PROGRAMMING CODE

```
%=== Import the ANN (Artificial Neural Network) forcasting wind power file =====
%=== To estimate energy storage capacity by using Matlab programming =====
clc;
clear all;

%=== Users input the forcasting wind power data filename (File format ***.xls) ===
fprintf('\n\n Welcome to use "Estimate Energy Storage Capacity" program !! \n\n')
fprintf(' Please input desired wind power file name. (Only Excel Files)  \n')
input_filename=input(' The file name format is **.xls (Such as aaa.xls. Just input: aaa ):
','s');
[gen dates dategen]=xlsread(input_filename);
[raw,col]=size(gen);
MaxGen=max(max(gen));
axis_y_max=round(MaxGen*1.1);


%===== Calculate One Day Average Power =====
p_d_av=mean(gen,2);
for k=1:144
   p_day_av(:,k)=p_d_av;
end

%===== Calculate 1 Hour Average Power =====
shift_i=1;
for h=1:6:144
   hour=gen(:,h:(h+5));
   h_av=mean(hour,2);
   p_days_av(:,shift_i)=p_d_av;
   p_hours_av(:,shift_i)=h_av;
   for k=h:(h+5)
       p_1hour_av(:,k)=h_av;
   end
   shift_i=shift_i+1;
end

%===== Calculate 2 Hours Average Power =====
for h=1:12:144
   hour2=gen(:,h:(h+11));
   h2_av=mean(hour2,2);
   for k=h:(h+11)
       p_2hour_av(:,k)=h2_av;
   end
end
```

```
%===== Calculate 6 Hours Average Power =====
for h=1:36:144
    hour6=gen(:,h:(h+35));
    h6_av=mean(hour6,2);
    for k=h:(h+35)
        p_6hour_av(:,k)=h6_av;
    end
end

%===== Calculate 12 Hours Average Power =====
for h=1:72:144
    hour12=gen(:,h:(h+71));
    h12_av=mean(hour12,2);
    for k=h:(h+71)
        p_12hour_av(:,k)=h12_av;
    end
end


%===== Estimate 1 Hour Storage Capacity =====
h1av_minus_gen=p_1hour_av-gen;
col_s=1;
for h=1:6:144
    hour_s=h1av_minus_gen(:,h:(h+5));
    for i=1:raw
        h_stor(i,:)=0;
        for j=1:6
            if (hour_s(i,j) > 0)
                h_stor(i,:)=h_stor(i)+hour_s(i,j);
            end
        end
    end
    storage_hour1(:,col_s)=h_stor;
    col_s=col_s+1;
end
max_storage_hour1=(max(storage_hour1,[],2)/6);
%===== Calculate Maximum Charging/Discharging Power of 1 Hour =====
max_power=max(h1av_minus_gen,[],2);
min_power=abs(min(h1av_minus_gen,[],2));
for k=1:raw
    if (max_power(k) > min_power(k))
        max_power_hour1(k,:)=max_power(k);
    else
```

```
        max_power_hour1(k,:)=min_power(k);
    end
end
max_power_hour1;


%===== Estimate 2 Hours Storage Capacity =====
h2av_minus_gen=p_2hour_av-gen;
col_s=1;
for h=1:12:144
    hour_s=h2av_minus_gen(:,h:(h+11));
    for i=1:raw
        h2_stor(i,:)=0;
        for j=1:12
            if (hour_s(i,j) > 0)
                h2_stor(i,:)=h2_stor(i)+hour_s(i,j);
            end
        end
    end
    storage_hour2(:,col_s)=h2_stor;
    col_s=col_s+1;
end
max_storage_hour2=(max(storage_hour2,[],2)/6);
%===== Calculate Maximum Charging/Discharging Power of 2 Hours =====
max_power=max(h2av_minus_gen,[],2);
min_power=abs(min(h2av_minus_gen,[],2));
for k=1:raw
    if (max_power(k) > min_power(k))
        max_power_hour2(k,:)=max_power(k);
    else
        max_power_hour2(k,:)=min_power(k);
    end
end
max_power_hour2;


%===== Estimate 6 Hours Storage Capacity =====
h6av_minus_gen=p_6hour_av-gen;
col_s=1;
for h=1:36:144
    hour_s=h6av_minus_gen(:,h:(h+35));
    for i=1:raw
        h6_stor(i,:)=0;
        for j=1:36
```

```
        if (hour_s(i,j) > 0)
            h6_stor(i,:)=h6_stor(i)+hour_s(i,j);
        end
    end
  end
  storage_hour6(:,col_s)=h6_stor;
  col_s=col_s+1;
end
max_storage_hour6=(max(storage_hour6,[],2)/6);
%===== Calculate Maximum Charging/Discharging Power of 6 hours =====
max_power=max(h6av_minus_gen,[],2);
min_power=abs(min(h6av_minus_gen,[],2));
for k=1:raw
  if (max_power(k) > min_power(k))
    max_power_hour6(k,:)=max_power(k);
  else
    max_power_hour6(k,:)=min_power(k);
  end
end
max_power_hour6;


%===== Estimate One Day Storage Capacity =====
dayav_minus_hourav=p_days_av-p_hours_av;
col_s=1;
hour_s=dayav_minus_hourav;
for i=1:raw
  day_stor(i,:)=0;
  for j=1:24
    if (hour_s(i,j) > 0)
        day_stor(i,:)=day_stor(i)+hour_s(i,j);
    end
  end
end
storage_day(:,col_s)=day_stor;
max_storage_day=(max(storage_day,[],2));
%===== Calculate Maximum Charging/Discharging Power of One Day =====
dayav_minus_gen=p_day_av-gen;
max_power=max(dayav_minus_gen,[],2);
min_power=abs(min(dayav_minus_gen,[],2));
for k=1:raw
  if (max_power(k) > min_power(k))
    max_power_day(k,:)=max_power(k);
  else
```

```
        max_power_day(k,:)=min_power(k);
    end
end
max_power_day;


% date_char = char(date);
date_wanted_char=0;
min_date=datestr(dates{1},23);
max_date=datestr(dates{raw},23);
%===== Users indicate what day they want to see or Exit =====
fprintf('\n\n Please input what date would you like to see from %s to %s?
',min_date,max_date)
fprintf('\n Or "Q" and "Enter" for Exit ?  ')
date_wanted_char=input('\n The input date format is mm/dd/yyyy : ','s');
while ((date_wanted_char~='Q') & (date_wanted_char~='q'))
    close all;
    date_wanted_str=datestr(date_wanted_char,23);
    date_wanted_I=0;
    for k=1:raw
        date_temp=datestr(dates{k},23);
        if (date_wanted_str == date_temp)
            date_wanted_I=k;
            break
        else
            date_wanted_I=0;
        end
    end

%===== Figure all result of energy storage estimate
    figure('Name',date_wanted_str,'Numbertitle','off','position',[1 1 1024 700]);
%===== Plot result of energy storage estimate of one hour =====
    t=1:144;
    subplot(221),plot(t,p_1hour_av(date_wanted_I,:),'-');
    hold on;
    area(t,p_1hour_av(date_wanted_I,:));
    hold on;
    colormap summer;
    set(gca,'Layer','top');
    grid on;
    hold on;
    plot(t,p_1hour_av(date_wanted_I,:),':g');
    hold on;
    plot(t,gen(date_wanted_I,:),'-b','LineWidth',1.5);
```

```
   axis([1 144 0 axis_y_max])
   set(gca,'xtick',[1 12 24 36 48 60 72 84 96 108 120 132 144]);
   xlabel('Time (10 mins)');
   ylabel('Power (MW)');
   title({'Storage Capacity Estimate of One Hour';['Capacity and Max. Power :
',num2str(max_storage_hour1(date_wanted_I)),'MWh,
',num2str(max_power_hour1(date_wanted_I)),'MW']});

%===== Plot result of energy storage estimate of 2 hours =====
   subplot(222),plot(t,p_2hour_av(date_wanted_I,:),'-');
   hold on;
   area(t,p_2hour_av(date_wanted_I,:));
   hold on;
   colormap summer;
   set(gca,'Layer','top');
   grid on;
   hold on;
   plot(t,p_2hour_av(date_wanted_I,:),':g');
   hold on;
   plot(t,gen(date_wanted_I,:),'-b','LineWidth',1.5);
   axis([1 144 0 axis_y_max]);
   set(gca,'xtick',[1 12 24 36 48 60 72 84 96 108 120 132 144]);
   xlabel('Time (10 mins)');
   ylabel('Power (MW)');
   title({'Storage Capacity Estimate of 2 Hours';['Capacity and Max. Power :
',num2str(max_storage_hour2(date_wanted_I)),'MWh,
',num2str(max_power_hour2(date_wanted_I)),'MW']});

%===== Plot result of energy storage estimate of 6 hours =====
   subplot(223),plot(t,p_6hour_av(date_wanted_I,:),'-');
   hold on;
   area(t,p_6hour_av(date_wanted_I,:));
   hold on;
   colormap summer;
   set(gca,'Layer','top');
   grid on;
   hold on;
   plot(t,p_6hour_av(date_wanted_I,:),':g');
   hold on;
   plot(t,gen(date_wanted_I,:),'-b','LineWidth',1.5);
   axis([1 144 0 axis_y_max]);
   set(gca,'xtick',[1 12 24 36 48 60 72 84 96 108 120 132 144]);
   xlabel('Time (10 mins)');
   ylabel('Power (MW)');
```

```
   title({'Storage Capacity Estimate of 6 Hours';['Capacity and Max. Power :
',num2str(max_storage_hour6(date_wanted_I)),'MWh,
',num2str(max_power_hour6(date_wanted_I)),'MW']});

 %===== Plot result of energy storage estimate of one day =====
   subplot(224),plot(t,p_day_av(date_wanted_I,:),'-');
   hold on;
   area(t,p_day_av(date_wanted_I,:));
   hold on;
   colormap summer;
   set(gca,'Layer','top');
   grid on;
   hold on;
   plot(t,p_day_av(date_wanted_I,:),':g');
   hold on;
   plot(t,gen(date_wanted_I,:),'-b','LineWidth',1.5);
   axis([1 144 0 axis_y_max]);
   set(gca,'xtick',[1 12 24 36 48 60 72 84 96 108 120 132 144]);
   legend('Power w/o Storage','Power w/ Storage','Location','Best');
   xlabel('Time (10 mins)');
   ylabel('Power (MW)');
   title({'Storage Capacity Estimate of One Day';['Capacity and Max. Power :
',num2str(max_storage_day(date_wanted_I)),'MWh,
',num2str(max_power_day(date_wanted_I)),'MW']});

   fprintf('\n\n Please input any other dates you want to see from %s to %s?
',min_date,max_date)
   fprintf('\n Or "Q" and "Enter" for Exit ?  ')
   date_wanted_char=input('\n The input date format is mm/dd/yyyy : ','s');
end
fprintf('\n\n')
fprintf('Thank you for using "Estimate Energy Storage Capacity" program !! \n\n')

% End of the programming
```

REFERENCES

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