

**Optimization of Sizing and Placement of Energy Storage
Systems on an Islanded Grid with High Penetration of
Renewables**

by

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Optimization of Sizing and Placement of Energy Storage Systems on an Islanded Grid with High
Penetration of Renewables

Thesis directed by Prof. Frank S. Barnes

This thesis seeks to find an optimized energy storage system (ESS) solution that reduces the effects of power variations and fluctuations from renewable energy sources like wind and solar. This study focuses on the effects of renewables at penetration levels larger than 20% for an isolated power grid. This optimized energy storage solution includes sizing the ESS appropriately while taking into account the economic cost of deploying the ESS. The ideal placement of the ESS on this grid seeks to reduce any impact on grid transmission congestion due to the ESS. Two configurations of the grid were modeled; the first is a simple load-frequency control model of the grid that only examines the effect of active power fluctuations from the renewables on the grid. The other model uses a one-line transmission line model of the isolated grid to model the transmission congestion in the grid. Modeling has shown that ESS systems are capable of reducing the frequency variations and reducing power fluctuations, however there is a trade off in economic cost.

Dedication

Look, if you had, one shot

Or one opportunity

To seize everything you ever wanted

In one moment

Would you capture it, or just let it slip?

Acknowledgements

This thesis would not be possible if not for the exceptional help and patience from the following people:

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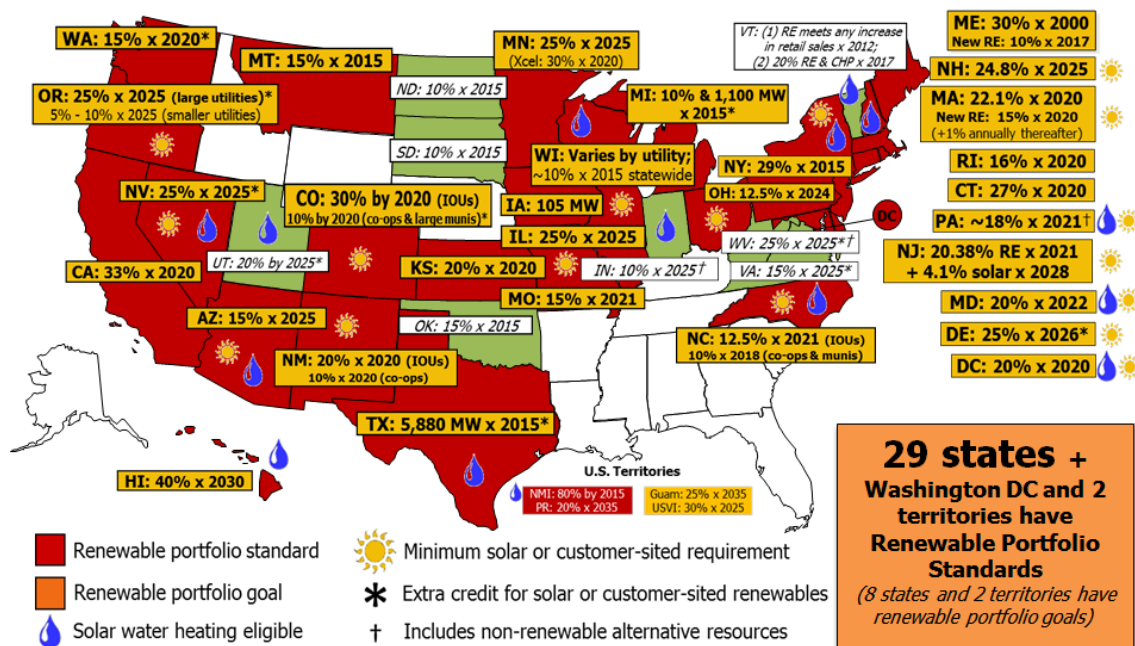
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Chapter 1

Introduction

The nature of the power grid is such that the energy demand (i.e. load) has to be met by energy generated (i.e. generation). As renewable forms of energy start to be more prominent, grid operators face increasing challenges in maintaining grid reliability and stability due to the variable nature of renewable source of energy. Figure 1.1 below shows the current mandates on renewable energy penetration goals by different states in the United States [1].

Figure 1.1: Renewable Portfolio Standards in the United States



Most states with a renewable portfolio standard (RPS) have at least a mandated standard of

having >20% of its energy generated from renewable sources by the year 2020. However, this study will concentrate on the RPS in the state of Colorado, which requires all investors owned utilities (IOUs) to generate 30% of its energy from renewable sources by the year 2020. The Energy Information Agency [2] in 2012, reported a 10% energy contribution from renewable sources in Colorado. This study assumes Colorado mandated values for 2020, which is the IOU level of 30% renewable penetration.

Studies have been done [3, 4, 5] on the negative impacts of the increasing renewable energy on the grid. This is mainly due to its variable and intermittent nature. The effect of these renewable sources specifically on the power grid frequency is also well documented [6] and this study seeks to minimize these frequency excursions due to increased levels of renewable energy by using energy storage systems (ESS).

This dissertation overall will be organized as follows:

(1) Introduction

(a) Objective 1.1

(b) Literature Review 1.2

(2) Methodology

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- (3) Results
 - (a) Base Cases 3.1
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 - (c) Placement of ESS 3.3
- (4) Conclusion

1.1 Objective

The main objective of this research is to find the optimal size and placement of an energy storage system (ESS) in an islanded power grid with high penetration of renewables. The sizing of the ESS is both in terms of the rated discharge power (e.g. kW or MW) or energy capacity (e.g. kWh and MWh). The function of the ESS is to reduce grid frequency fluctuations caused by renewable energy sources, i.e. the ESS will only provide active power compensation. ESS are also capable of performing reactive power compensation (VAR support) and voltage support. However, this research will only use the ESS for active power compensation. This is because there are a variety of other well-researched techniques [7] that provides reactive power compensation like capacitor banks, flexible AC transmission system (FACTS) devices and etc.

Power generation optimization problems typically utilize numerical methods, like dynamic programming methods, Lagrange relation methods and etc. [8] to solve the problems. However, this study uses a heuristic analytical approach that is more intuitive but unfortunately might not yield the optimal solution [7]. The entire sample set used in this study consists of a single 24-hour day for each month of a year, which means there are a total of 12 data sets.

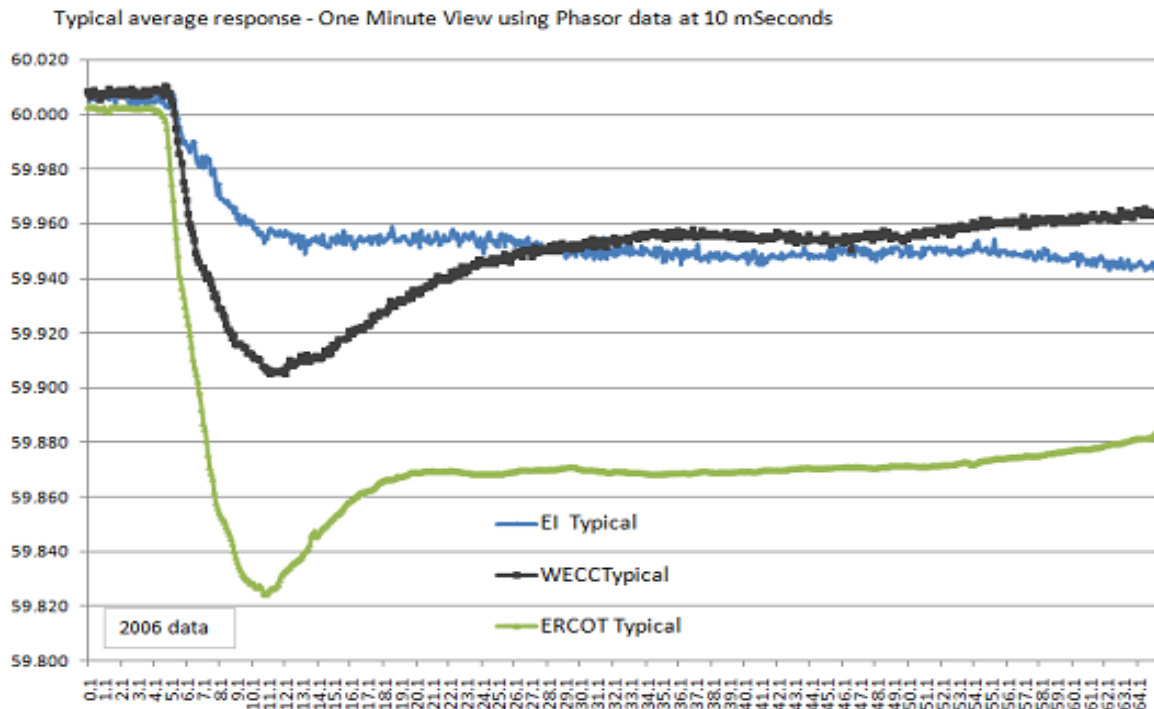
This study also uses Colorado’s 2020 penetration level of 30% renewable energy. The bulk of the renewable generation would be from wind energy, due to its lower capital cost. Photovoltaic (PV) capital cost in 2012 are still roughly twice that of wind: $\$3.10/W_{pk}$ for PV systems and $\sim \$1.50/W$ for wind systems [9, 10]. This study assumes a high penetration level of renewables at 25% wind and 5% solar levels.

Photovoltaic systems are assumed to be distributed generation, i.e. co-located at the load buses. The wind farm is located about ~ 35 miles away from the nearest load center. This grid configuration is based on a power grid of a utility in Northern Colorado. Although in reality this grid system is interconnected with other systems in Colorado and Wyoming, this research assumes that this grid is disconnected from neighbouring grids and operates in an islanded mode.

Islanded mode operation was selected for the model since larger interconnected systems have a better ability to withstand disturbances in the grid. This assumption is illustrated in Figure 1.2, which shows the frequency response from the three main grid interconnections in United States as done by a study in Lawrence Berkeley National Labs [6]. There are three electric grids in North America: the Eastern Interconnect that stretches from the Atlantic coast to the east of the Rockies, the Western Interconnect that includes west of the Rockies to the Pacific coast and the Texas Interconnect, also known as the Electric Reliability Council of Texas (ERCOT) that covers most of the state of Texas. Out of the three grids, ERCOT is the smallest in terms of both load demand (GWh) and geographical area.

Looking at Figure 1.2 around the 10ms mark, all three grids experience a sudden loss of generation, causing the grid frequency to fall. Out of the three responses, the ERCOT grid experiences the largest rate of frequency decline when compared to the larger Eastern and Western

Figure 1.2: Typical Frequency Response of the Three United States Interconnection



Interconnect. This is due to the fact that ERCOT has a much smaller system inertia (i.e. amount of traditional generation sources like steam and gas-fired plants) than that of the Eastern and Western Interconnect, and thus its ability to compensate for any sudden drops in generation is much worse than that of the Eastern and Western Interconnect. This illustrates the point that small island-like grids like ERCOT and also physical island systems like Hawaii will have a different experience in terms of maintaining grid reliability and stability when compared to large interconnected grids like that found in the Eastern Interconnect.

Another important point to make is that a larger geographical area has a smoothing effect on renewable energy sources. Using power spectral density analysis that will show power fluctuations from renewable sources as a function of frequency, leads to further examination of the characteristics of wind and solar fluctuations in a stochastic manner. This is illustrated by comparing the power spectral density of a single wind farm or a solar array and the power spectral density of the combined

power output from multiple wind farms or multiple solar farms that are situated at different points in a geographical area [11, 12]. The aggregate power output from multiple wind farms or multiple solar arrays will have lead to a smaller magnitude in fluctuations when compared to the single wind (or solar) site.

Four sites in Colorado with access to anemometers, that measures wind speed (m/s) and pyranometers, which measures solar irradiance (W/m^2), were used to estimate both wind and solar power output. Both these data are publicly available from NREL's measurement and instrumentation data center website (www.nrel.gov/midc).

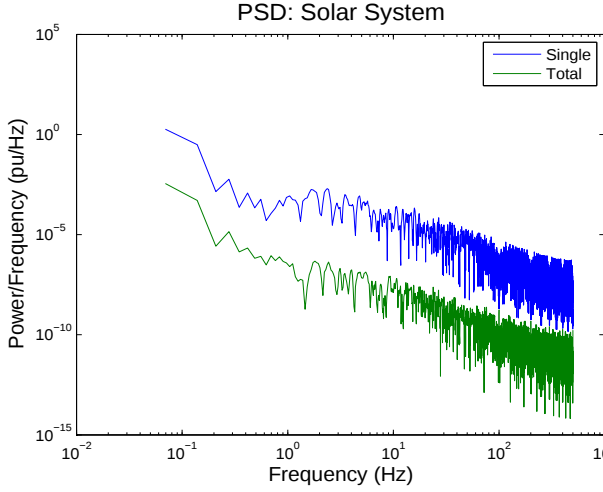


Figure 1.3: Solar Power Spectrum Density on 4/28/13 in Colorado

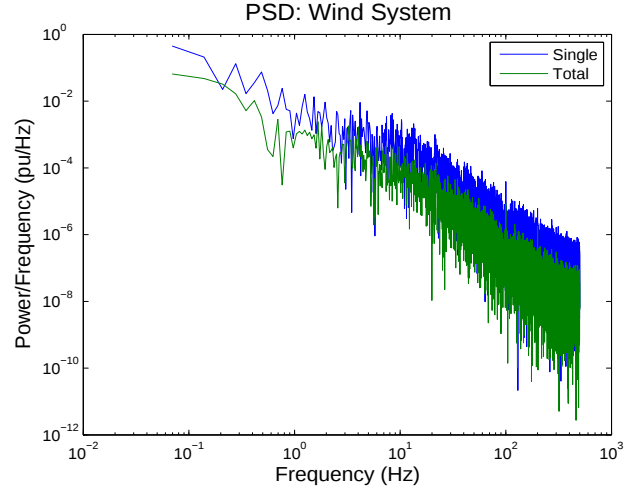


Figure 1.4: Wind Power Spectrum Density on 4/28/13 in Colorado

Figures 1.3 and 1.4 show the power spectrum density for a single site and four aggregated sites producing wind and solar power. As can be seen, the combined power outputs from four different sites produces smaller fluctuations when compared to the fluctuations from single sites.

This small example is to further show that small islanded systems will experience a more drastic impact towards grid reliability and stability at higher penetration of renewables. This is because of its smaller generation capacity, i.e. smaller system inertia and also with a smaller geographical area, there will less smoothing of renewable power fluctuations.

The wind speed and irradiance data is measured at a 1-minute resolution, which is acknowl-

edged to be inadequate for transient studies that are usually at the milliseconds range [3]. To accommodate this lack of data resolution, a linear extrapolation is performed between each 1-minute data sample. This is done for all analysis in this thesis. More on the linear extrapolation technique will explained in Section 2 on methodology. Even though the studies done here are not at the transient level but at the power frequency variation range (usually at the seconds to minute range [3]), initially extrapolation was done between each 1-minute data point.

With the knowledge that variable and intermittent renewable energy sources has a larger impact on a smaller grid and also understanding that the levels of renewable sources to be integrated into the grid will increase, it is important to study its detrimental effects on the grid and how to mitigate these effects effectively.

This study is done at the transmission level and the renewable sources are assumed to be concentrated at single locations on the grid (i.e. not distributed and spread out across a feeder), power balancing between generation and load is a more immediate problem, that is active power compensation is needed. There are various solutions on dealing with the fluctuating power output from wind and solar such as building new or expanding existing transmission lines, implenting smart inverter controls, increasing forecasting methods in methods of dispatching wind (as used in the Midcontinent Independent Service Operator operations) and other methods. Energy storage systems have an added advantage to the solutions mentioned and that is its rapid ramp up rates and also its flexibility in operation. However, ESS are costly and thus requires proper optimization to make it a cost effective solution.

Generally, energy storage systems can be divided into two main categories: long-term ESS that provides a long (usually > 4 hours of discharge duration at rated power output) discharge time and a short-term ESS. Depending on the application of the ESS, like for example the arbitrage service, which stores energy when electricity prices are cheap and discharges when electricity prices are high; this particular ESS requires a long-term type of ESS to store the large amounts of energy. A long-term ESS technology is usually a pumped hydro energy storage system or a compressed-air energy storage system. An example is Cabin Creek, a pumped hydro plant located in Colorado, that

was built to provide arbitrage services and so is not capable of fast ramp rates that are characteristic of wind and solar systems fluctuations, especially at higher penetration of renewables.

Since a high penetration of renewables on a smaller grid would be significantly more affected than a larger grid, this requires a change in how this smaller grid is to be operated, especially with a traditional grid that now requires a higher generation reserve (usually $> 20\%$ of total generation capacity) to compensate for the rapid renewable fluctuations. However, short-term ESS, which are usually electrochemical batteries and flywheels, have the ability to absorb and deliver power in a fraction of a second in order to compensate for very fast fluctuations.

Although ESS are technically capable of solving these problems, it is a cost-prohibitive solution, especially with larger ESS systems. At current renewable penetration level of a maximum of $\sim 10\%$ in Colorado, there is no immediate need for ESS technologies since there are much more affordable solutions like combustion turbines with rapid ramp rates exist. If and when the geography is suitable, pumped hydro plants perform well at lower levels of penetration of renewable energy, and performs load peak shaving or double s as a spinning reserve plant.

Hence, the sizing of the ESS, in terms of capacity (MWh) and rated power output (MW) is a function of both its ability to reduce frequency deviations and also its cost. This study seeks to find the range of ESS sizing and its ability to respond to disturbances in the grid due to variable renewable energy.

1.2 Literature Review

As mentioned in Section 1.1, only active power compensation by the ESS will be considered for this study. It is understood that other form of stability issues (e.g. voltage and rotor angle stability) is an important part, but only frequency stability will be considered in this study, as it has a more immediate impact on an isolated grid with higher penetration of renewables. Reactive power compensation can also be performed by ESS, but there are a number of competing technologies, like FACTS devices and more traditional capacitor banks that can provide the same reactive power compensation service.

The larger challenge in integrating more renewables in the power grid is its intermittency and variability. In terms of frequency stability, increased renewable sources like wind farms and photovoltaic (PV) plants will also reduce the inertia in the power grid [6, 13, 14]. This is because wind turbines are mostly based on induction generators, which have less inertial response than synchronous generators found in steam plants. PV plants have no electric machine component at all and thus cannot contribute to the system inertia, unless an artificial system inertia is integrated into its power output control algorithm. In its most basic form, artificial system inertia control derates the renewable energy plant, i.e. operates the plant away from its maximum power output and thus allows slack in supplemental generation.

The current literature surveyed has mainly been in the area of sizing energy storage systems in conjunction with a wind generating plant [15, 16]. Although the main bulk of renewable generation would come from wind, it is important to take into account PV generation. This study will take into account both types of generation, although it should be mentioned that PV generation would make up a smaller percentage of the total renewable energy portion.

Work on placement of energy storage systems on a grid has been studied [17, 18] but these studies assumed a fixed sizing and type of ESS. These studies have shown that ESS, specifically battery systems, are capable of improving the reliability of intermittency issues related to wind. Systems information on ESS technology was mainly found from [19, 20], although this literature placed a heavy emphasis on battery technology.

Much of the literature [21, 18] on optimal sizing and placement is based on using numerical programming methods, where objective functions that describe the parameters being optimized are solved to find its maximum (or minimum values) given a set of constraints that describe the system.

Chapter 2

Methodology

To reiterate, this study seeks to find:

- (1) Optimal capacity of system (MWh/ kWh)
- (2) Rated power output (MW/kW)
- (3) Location of the ESS on the grid
- (4) Ramp rate (MW/min, kW/min)

of an ESS system. The following Section 2.1 will explain the methods and models used in finding the above goals.

2.1 System Data

Both wind and insolation data was obtained from the National Renewable Energy Laboratory (NREL) measurement and instrumentation data center (www.nrel.org/midc). The load data however, was obtained from a power generation and transmission provider based in Northern Colorado, and henceforth will be called the Island Study Grid (ISG).

2.1.1 Load Data

The original load data in per unit (pu) was obtained in 5-minute increments. The island study grid has 11 load (or PQ) buses and so, the load data is then distributed as shown in Table 2.1. For each area, the load will be divided evenly into the number of buses in each of the respective area.

Table 2.1: Total Load Distribution

	Area I	Area II	Area III	Area IV
No. of Buses	4	2	3	4
% of Total Load	40%	10%	35%	15%

Table 2.2 shows some basic information about the nature of the load in the grid for a single 24 hour day of each month in the year. The grid system is assumed to have a system base of 100 MVA. The load factor is defined as the ratio of average load to the maximum load as shown in Equation 2.1:

$$\text{Load Factor} = \frac{\text{Average load (pu)}}{\text{Maximum load (pu)}} \quad (2.1)$$

The load factor is an indicator of how the grid facilities (e.g. transformers, lines, etc) are being utilized by the customer. An ideal load factor is 1.0, whereby the facilities are 100% utilized [22].

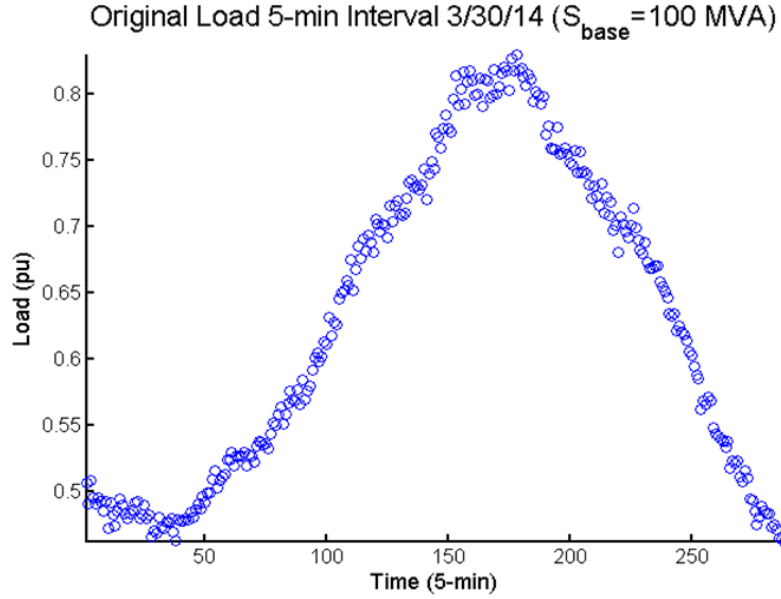
Table 2.2: Load Data for One Day in Each Month of Year 2013-2014

	Energy (pu.h)	Maximum Load (pu)	Average Load (pu.h)	Load Factor
01/01/2014	16.48	0.733	0.687	0.94
02/07/2014	15.73	0.870	0.655	0.75
03/30/2014	15.05	0.831	0.627	0.75
04/17/2013	12.47	0.676	0.520	0.77
05/01/2013	11.37	0.565	0.474	0.84
06/16/2013	11.85	0.590	0.494	0.84
07/04/2013	15.06	0.817	0.628	0.77
08/07/2013	15.60	0.877	0.650	0.74
09/03/2013	11.70	0.636	0.487	0.77
10/31/2013	11.28	0.600	0.470	0.78
11/29/2013	14.06	0.688	0.586	0.85
12/17/2013	9.06	0.446	0.377	0.85

The data used in the simulations require a finer resolution, i.e. at a 1-minute time intervals. This would then require extrapolating the wind speed data points between each 5-minute point. For this research, it assumes an initial linear extrapolation between each 5-minute data point. Figure 2.1 shows the original load data (in per unit values, with S_{base} of 100 MVA), on 07/04/2013, with linear extrapolation between each points. Originally, the data was extrapolated into a smaller

scale at 5-seconds but that meant there would be 17,280 data points for a 24-hour period day, which would increase simulation time. Hence, only the 1-minute resolution data would be used in the simulations.

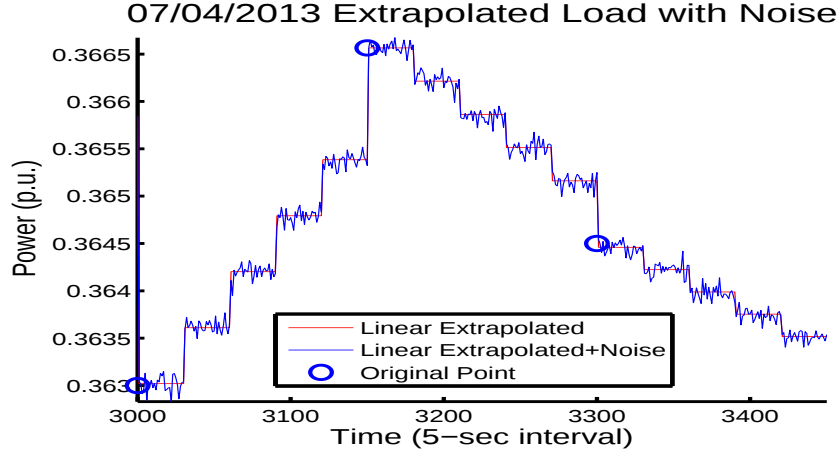
Figure 2.1: Load on 3/30/14 with Original 5-Minute Data Resolution



A linear constant extrapolation was done between each 5-minute data point such that there are now four intervals between each 5-minute data point, that constitutes 1-minute data. Acknowledging the fact that load probably does not stay constant between each 5-minute data point, a random white noise is added to the linear constant extrapolation. This is shown in Figure 2.1.1 shows a 15-minute snippet of load data on 07/04/2013 with the linear extrapolation and added white noise on top of the linear extrapolated data points. For this study, a signal-to-noise ratio (SNR) of 80 was used to generate the Gaussian white noise. This SNR value was approximated using the power spectrum plot (Figure 1.4), assuming a frequency of 0.2 Hz (i.e. 5 seconds - the original extrapolation).

The purpose of increasing the resolution of the data is because wind speed and photovoltaic power fluctuations were substantial at the sub 5-minute range, as seen from the power spectral

Figure 2.2: Load Snippet with Example of Extrapolation on 07/04/2013



density plots, hence requiring a finer resolution data.

2.1.2 Wind Speed Data

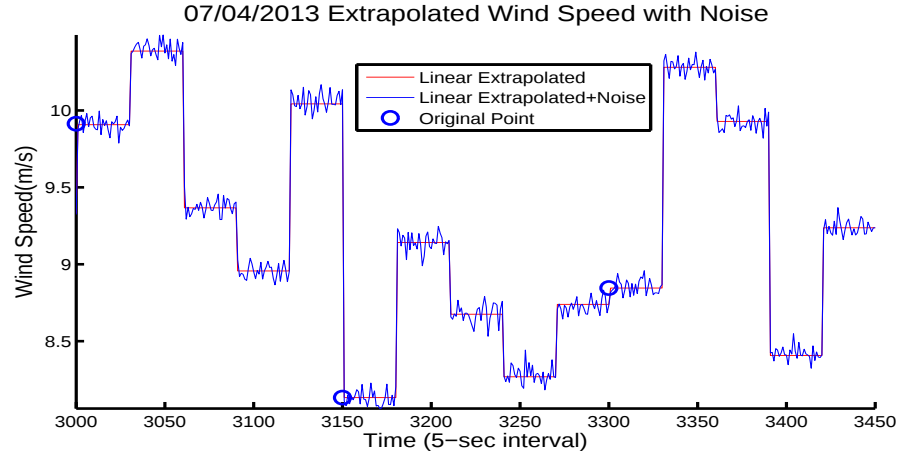
Wind speed data in m/s is taken at a 1-minute resolution for a 24-hour day of each month for a 12-month year. Table 2.3 illustrates this again. A wind farm comprising three 1.5MW doubly-fed induction generators (DFIG) with a total rated power of 4.5MW was used to find the power output (MW) from the wind speed data. More details on the wind farm model will be discussed in Section 2.2.1.

Similar to the load data, a linear constant extrapolation was done between each 1-minute data point, except this time it is extrapolated into 5-sec intervals. Again, a random white noise is added to the linear constant extrapolation. This is shown in Figure 2.1.2 with a 15-minute snippet of wind power data on 07/04/2013 with a linear extrapolation and the added white noise. For this study, a signal-to-noise ratio (SNR) of 60 was used to generate the white noise. The SNR was chosen to reflect the approximate magnitude of fluctuations as seen from the power density spectrum of a wind farm [12].

Table 2.3: Wind Power for One Day in Each Month of Year 2013-2014

	Average Wind (MW)	Maximum Wind (MW)	Standard Deviation (MW)
01/01/2014	0.599	4.394	0.950
02/07/2014	0.670	4.420	0.970
03/30/2014	1.136	4.541	1.477
04/17/2013	0.002	0.845	0.037
05/01/2013	0.232	1.087	0.265
06/16/2013	0.389	4.467	0.825
07/04/2013	0.346	2.592	0.517
08/07/2013	0.222	1.270	0.347
09/03/2013	0.267	1.333	0.366
10/31/2013	3.725	4.732	1.144
11/29/2013	1.528	4.410	1.230
12/17/2013	2.208	4.522	1.534

Figure 2.3: Wind Speed Snippet with Example of Extrapolation on 07/04/2013



2.1.3 Insolation Data

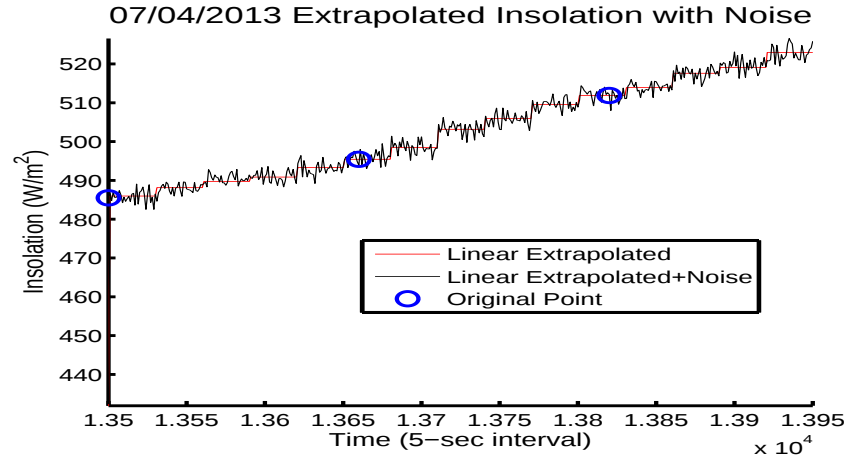
The insolation data (W/m^2) is also taken at a 1-minute resolution for a 24-hour day at each month for a 12-month year. Table 2.4 shows the results for the 12 data sets. The solar farm is rated at 100 kW. Using the insolation data, the power output (kW) can be obtained. Details on the solar farm model will be discussed more in Section 2.2.2.

Figure 2.1.3 shows a 15-minute snippet of solar power data on 07/04/2013 with the linear extrapolation and added Gaussian white noise. For this study, a signal-to-noise ratio of 50 was

Table 2.4: Solar Power for One Day in Each Month of Year 2013-2014

	Average Solar (kW)	Maximum Solar (kW)	Standard Deviation (kW)
01/01/2014	8.55	58.19	16.26
02/07/2014	14.28	81.75	22.36
03/30/2014	18.08	113.16	25.26
04/17/2013	29.90	98.63	35.70
05/01/2013	11.54	80.49	16.30
06/16/2013	22.53	115.30	30.66
07/04/2013	27.28	109.49	37.48
08/07/2013	7.94	74.94	13.60
09/03/2013	21.82	116.35	32.40
10/31/2013	13.26	68.66	20.42
11/29/2013	11.67	52.30	17.98
12/17/2013	10.37	47.84	16.56

Figure 2.4: Insolation Snippet with Example of Extrapolation on 07/04/2013



used to generate the white noise as it seems to capture the rapid fluctuations from solar systems without too much noise that will drown out the linear signal.

2.2 System Models

The main programs used in this research is Matlab and Simulink. The wind farm and solar array models are modeled in Simulink with the SimPowerSystems package.

A simulation of the grid 24-hour day operation follows the steps below:

(1) Both wind speed and insolation data is fed into the wind turbine and photovoltaic model respectively. The wind farm is rated at 4 MW and the solar array is at 100 kW. It should be emphasized that the rated power output of the plants can be scaled up (or down) depending on the amount of renewable penetration required in the grid. This is because the penetration levels is defined as percentages of the total load in the system as shown in Equation 2.2.

(2) With wind and PV power output (MW) obtained, it is scaled accordingly, together with load power, given a penetration level. The average penetration level is defined with Equation 2.2 below.

$$\text{Average Penetration} = \frac{\text{Energy from renewable source (MWh)}}{\text{Total energy delivered to Load (MWh)}} \quad (2.2)$$

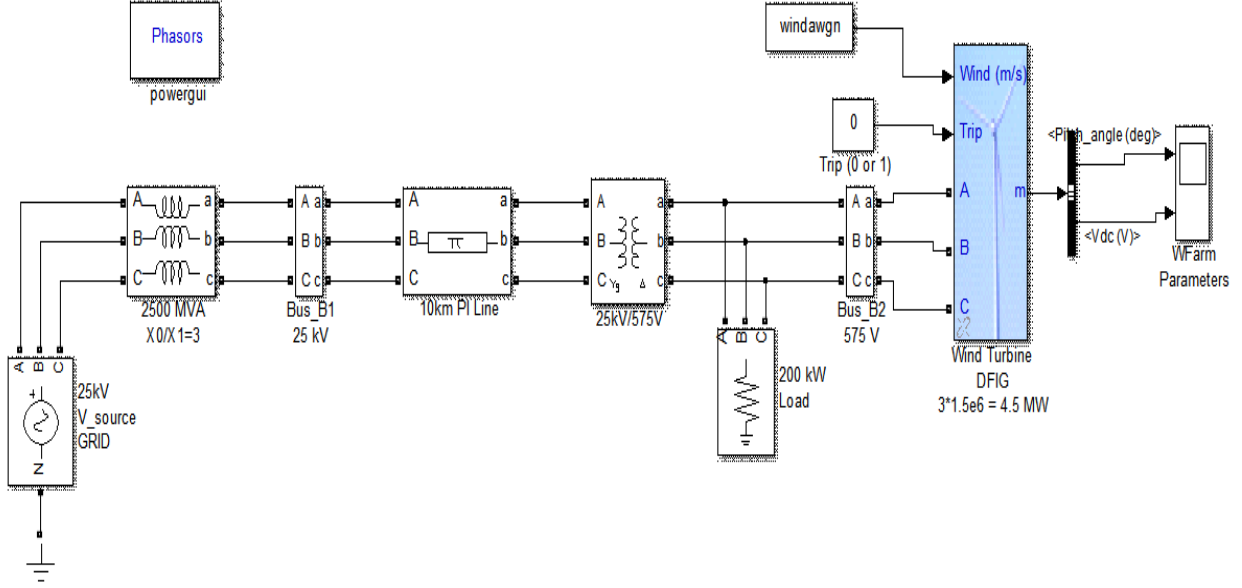
It should be noted that the simulation is done at a 1-minute resolution, even though the extrapolation was done at a 5-second resolution. This is because at the 5-second resolution the simulation took too long of a time to compile and the 1-minute resolution was considered adequate for this part of the simulation.

- (3) Using a system base of S_{base} of 100 MVA, all units are changed to per unit (pu) values.
- (4) In order to find the frequency deviations due to the fluctuating power of wind and solar, the load-frequency model of the grid is used. Section 2.2.6 describes in more detail about the load-frequency model.
- (5) Finally, an ESS is integrated into the system grid at increasing capacity and rated power output, to find its effectiveness in reducing the frequency deviations.
- (6) The power flow model is used to find the optimal placement of the ESS on the grid, based on the metric of transmission line usage.

2.2.1 Wind Turbine Model

The wind farm model comprises of three 1.5 MW DFIG wind turbine models. The Simulink model of the wind farm is shown in Figure 2.5 [23, 24].

Figure 2.5: Simulink Wind Farm Model 4.5 MW

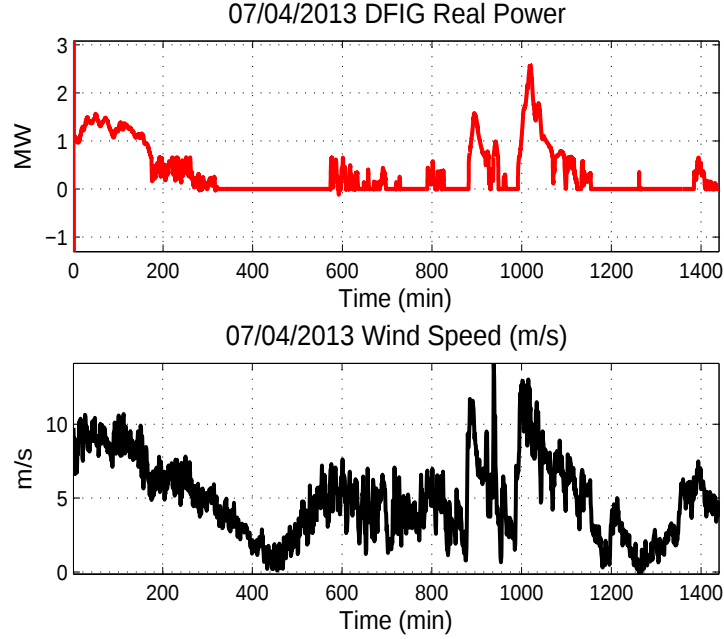


The point of interconnection to the grid is Bus B1 (see Figure 2.5) but the power output from the wind farm is collected at Bus B2 and this data is used in the simulations. The wind speed (m/s) is the input to the system and the output is the power output from the three wind turbines in MW. An example of the input and output of the wind farm is shown in Figure 2.6 below.

2.2.2 Photovoltaic System Model

The solar farm model is a single 100 kW solar array. The Simulink model of the system is shown in Figure 2.7. The PV array is controlled to have a fixed voltage at its point of interconnection (POC) to the grid, shown as Bus Bsvc in Figure 2.7. The PV array does not provide any reactive power support. There is an average boost converter model with a max power point tracking

Figure 2.6: Wind Power Real Power Output 07/04/2013



(MPPT) controller that controls the output voltage of the PV at 500 V. The output of the boost converter is then connected to a voltage-source converter (VSC) that converts the single-phase 500 V_{DC} into three-phase 260 V_{ac} . The PV power output data is collected at Bus Bsvc.

The insolation data (W/m^2) is the input to the system and the output is the power output from the PV array. An example of the input and output of the solar farm is shown in Figure 2.8 below.

2.2.3 Generic Generator Model

A simple generic electric generator can be described in terms of a governor block, an equivalent turbine (i.e. prime mover) block and total electric machines in the power grid, be it a generator or a load [8].

Equation 2.3 displays the relationship between mechanical power (be it powered from steam or natural gas or a hydro plant) and electrical power. Therefore, Equation 2.2 describes a generator

Figure 2.7: Simulink Solar Array Model 100 kW

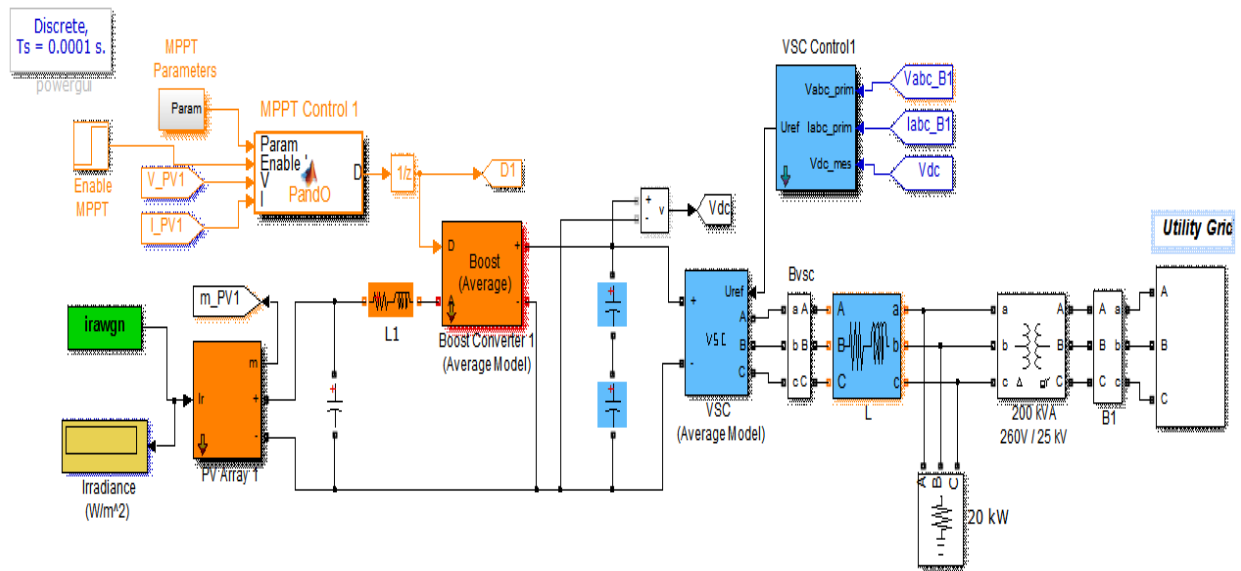
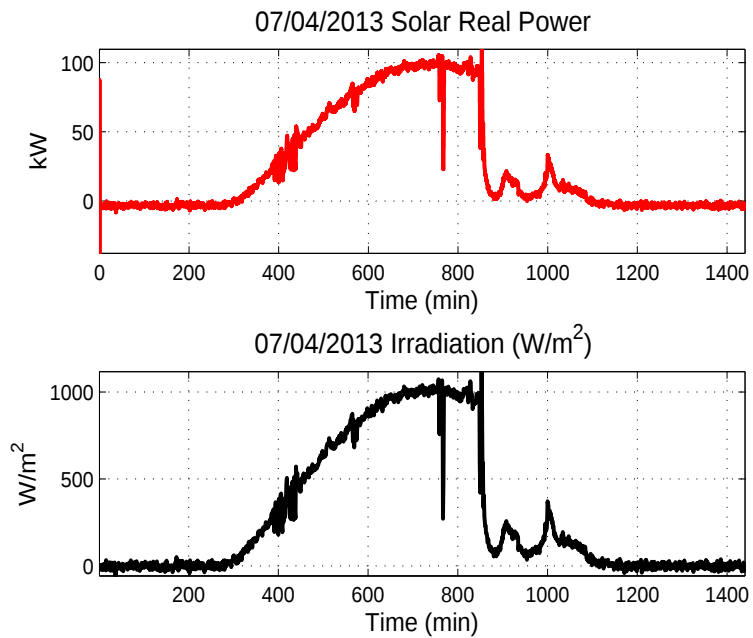


Figure 2.8: Solar Power Real Power Output 07/04/2013



model in a simple first order model.

$$\Delta P_{mechanical} - \Delta P_{electric} = M \frac{d}{dt}(\Delta \omega) \quad (2.3)$$

M is the angular momentum of the machine in W/rad/s².

ω refers to the rotational speed in the system (i.e. equivalent to grid frequency) (rad/s)

Equation 2.4 described the load in the system that is dependent on frequency.

$$\Delta P_{load_{freq}} = D(\Delta \omega) \quad (2.4)$$

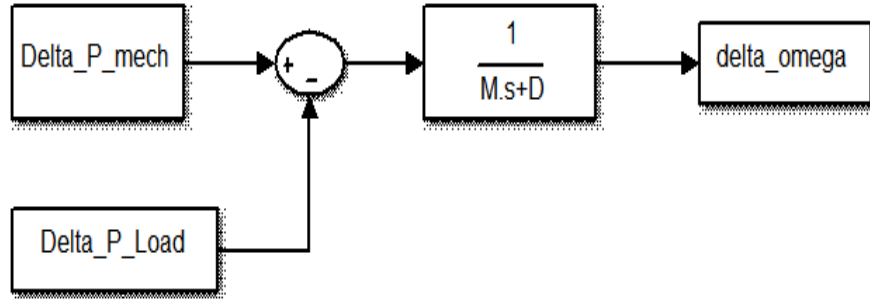
D is the net connected load that is dependent on grid frequency, usually expressed in % change in load over % change in frequency

And so, the net change in electric power can be expressed as below in Equation 2.5

$$\Delta P_{electric} = \Delta P_{load_{freq}} + D(\Delta \omega) \quad (2.5)$$

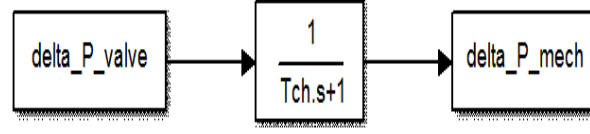
And Equation 2.5 can be expressed in a block diagram as shown in Figure 2.9.

Figure 2.9: Rotating Mass & Load Block Diagram for Generic Model



The simplest turbine or prime mover model can be modeled as a first-order system as shown in the block diagram of Figure 2.10. This model describes the relationship between the position of the steam valves (or in the case of a hydro turbine, the penstock gate position) to the power output of the turbine.

Figure 2.10: Prime Mover of Generic Model



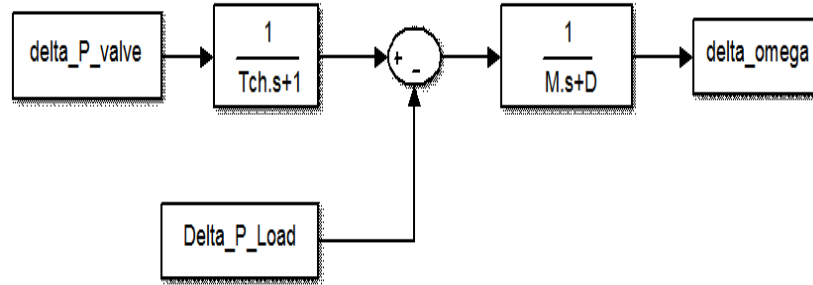
ΔP_{valve} is described as the per unit change in valve position from nominal.

τ_{ch} is the time constant that describes the response of the turbine to changes in valve position.

This is also known as the charging time constant.

The above two models can be combined into the prime-mover-generator and load model as shown in Figure 2.11

Figure 2.11: Prime-Mover-Generator-Load of Generic Model

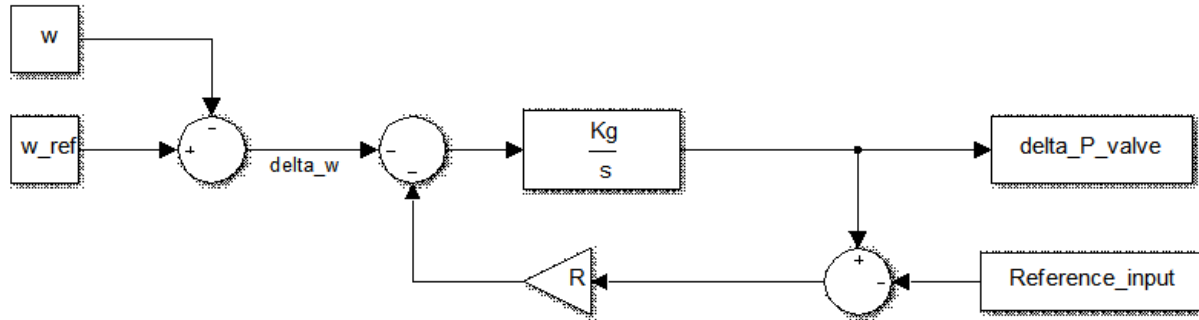


Finally, the governing mechanism that adjusts the valve position to compensate for any load or generation changes in the system is described below. In most steam, gas and hydro plants, the governor system incorporates a speed-droop controller in the feedback loop, which is a proportional-integrator type controller. The above two models can be combined into the prime-mover-generator and load model as shown in Figure 2.12

K_g is also known as an integrator gain that integrates the error signal $\Delta\omega$ to produce the control signal, ΔP_{valve} , which in turn, controls the power output from the turbine.

R is the droop constant, which determines the change in of the system's output for a given change

Figure 2.12: Governor with Droop of Generic Model

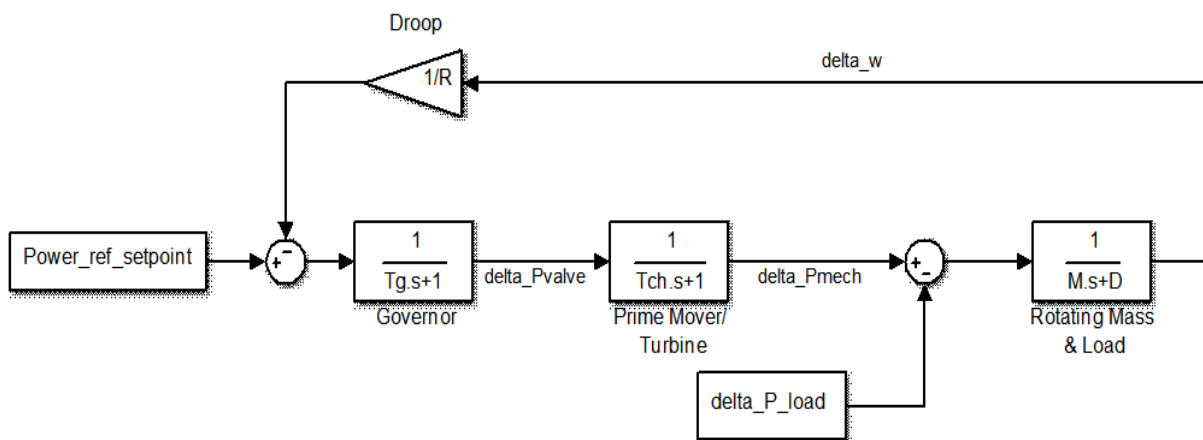


in frequency. An example is that a droop of 5% means a 100% change in valve position would require a 5% change from the nominal frequency. Equation 2.6 describes the droop characteristic in equation form.

$$R = \frac{\Delta\omega}{\Delta P} (pu) \quad (2.6)$$

Finally, all components of model can be combined into an equivalent power plant unit and is shown in Figure 2.13.

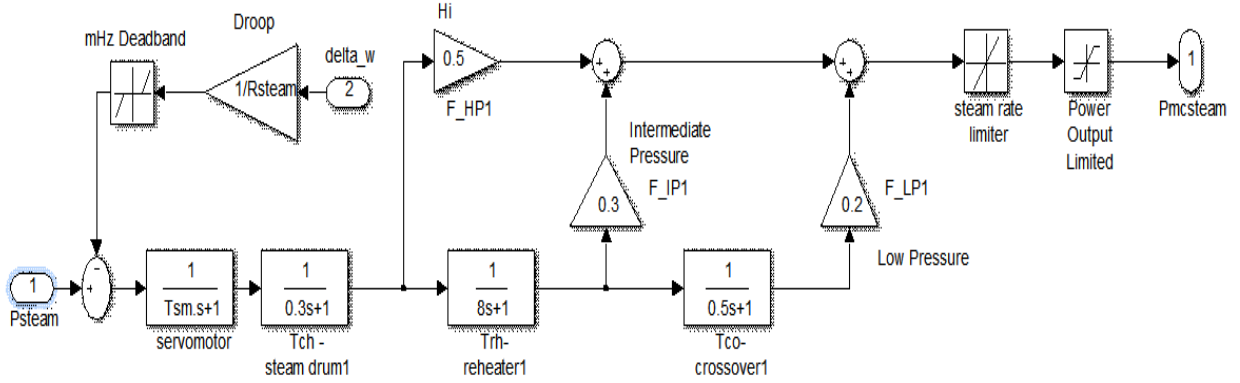
Figure 2.13: Load-frequency Model of Generic Power Plant



2.2.4 Steam Generator Model

The steam turbine used in the system is a fossil-fuelled (i.e. coal) single reheat tandem-compound turbine [25] and is shown in Figure 2.14 below:

Figure 2.14: Load-Frequency Model of Steam Turbine



From the steam drum section, described with the time constant τ_{ch} , the steam is then passed to three separate turbine sections: High Pressure (HP), Intermediate Pressure (IP) and Low Pressure (LP) sections. Each turbine section is given a fraction that contributes to the total power output of the system, i.e.

$$F_{HP} + F_{IP} + F_{LP} = 1 \quad (2.7)$$

F_{HP} is the fraction of power contributed by the high-pressure section

F_{IP} is the fraction of power contributed by the intermediate-pressure section

F_{LP} is the fraction of power contributed by the low-pressure section

The crossover piping is described the time constant, τ_{co} and is usually around 0.5s [25]. The reheater system uses the high-pressure steam and reroutes it back to the intermediate-pressure section. This is to increase the efficiency of the entire steam turbine, thereby reducing waste heat out of the system.

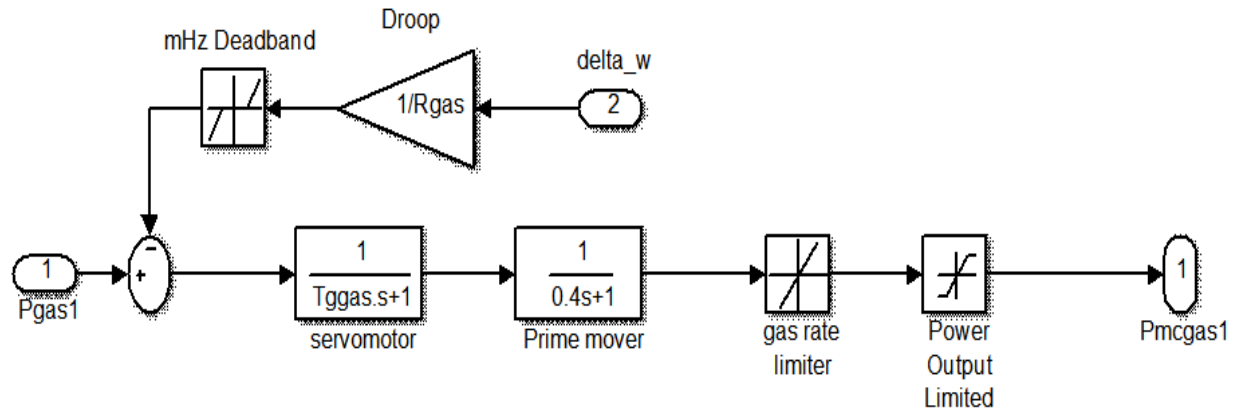
There are limiters in the steam turbine system and is the following:

- (1) Frequency Deadband - Limits changes to valve position at < 30 mHz frequency deviations
- (2) Rate Limiter - Steam turbine is limited to a ramp of $0.3 P_{rated}/\text{min}$
- (3) Power Output Limit - It is assumed that the steam turbine is running at 70% of rated power output and is only allowed to cycle up to 98% and down to 65% of power output during normal operations (i.e. at $< 5\%$ renewable penetration level)

2.2.5 Combustion Turbine Model

The combustion turbine used in the system is a very similar to the generic system model in section 2.2.3 in Figure 2.15 below:

Figure 2.15: Load-Frequency Model of Combustion Turbine



Just like the steam turbine, there are limiters in the CT system. However, the CT has less severe restrictions and is allowed to cycle at a higher frequency. The limiting parameters for the CT is described below:

- (1) Frequency Deadband - Limits changes to valve position at < 20 mHz frequency deviations

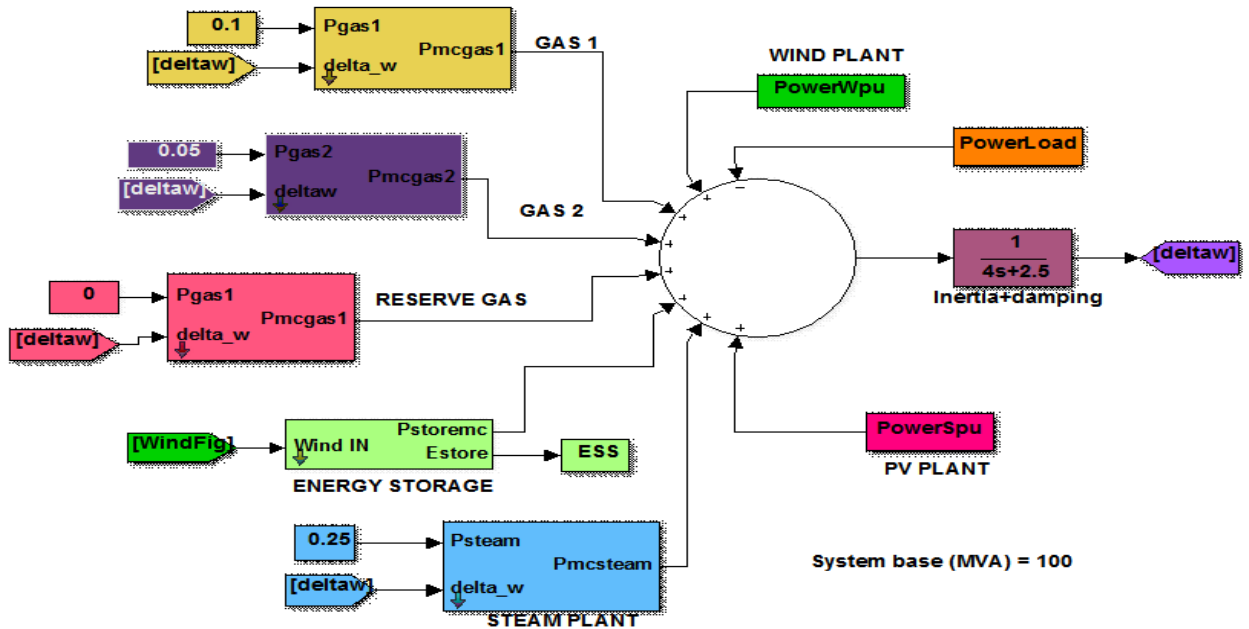
- (2) Rate Limiter - Combustion turbine is also limited to a ramp of $0.3 P_{rated}/\text{min}$
- (3) Power Output Limit - It is assumed that the CT is running at 50% of rated power output and is only allowed to cycle up to 98% and down to 30% of power output.

2.2.6 Load-Frequency Model of Islanded Grid

The load-frequency model of the entire islanded grid composes of a single steam turbine as described in Section 2.2.4 and two combustion turbines as described in section 2.2.5. There is a third CT plant that is a reserve plant and is assumed to require 30 minutes to start-up and synchronize to the grid.

Figure 2.16 incorporates the dynamic models of the steam plant, which serves as the baseload plant and three CT plants, that are the peaker plants [26]. The wind and PV systems are assumed to be operate without a droop-characteristic. This means that the power output from the renewables does not vary with load changes (i.e. frequency changes in the grid).

Figure 2.16: Load-Frequency Model of Isolated Grid



2.2.7 Power Flow Model of 16-bus System

This study uses a 16-bus power flow model of the isolated grid, that is based on the a Northern Colorado grid. The one-line diagram of this grid is shown in Figure 2.17.

Figure 2.17: One-Line Diagram of the 16-Bus Isolated Grid

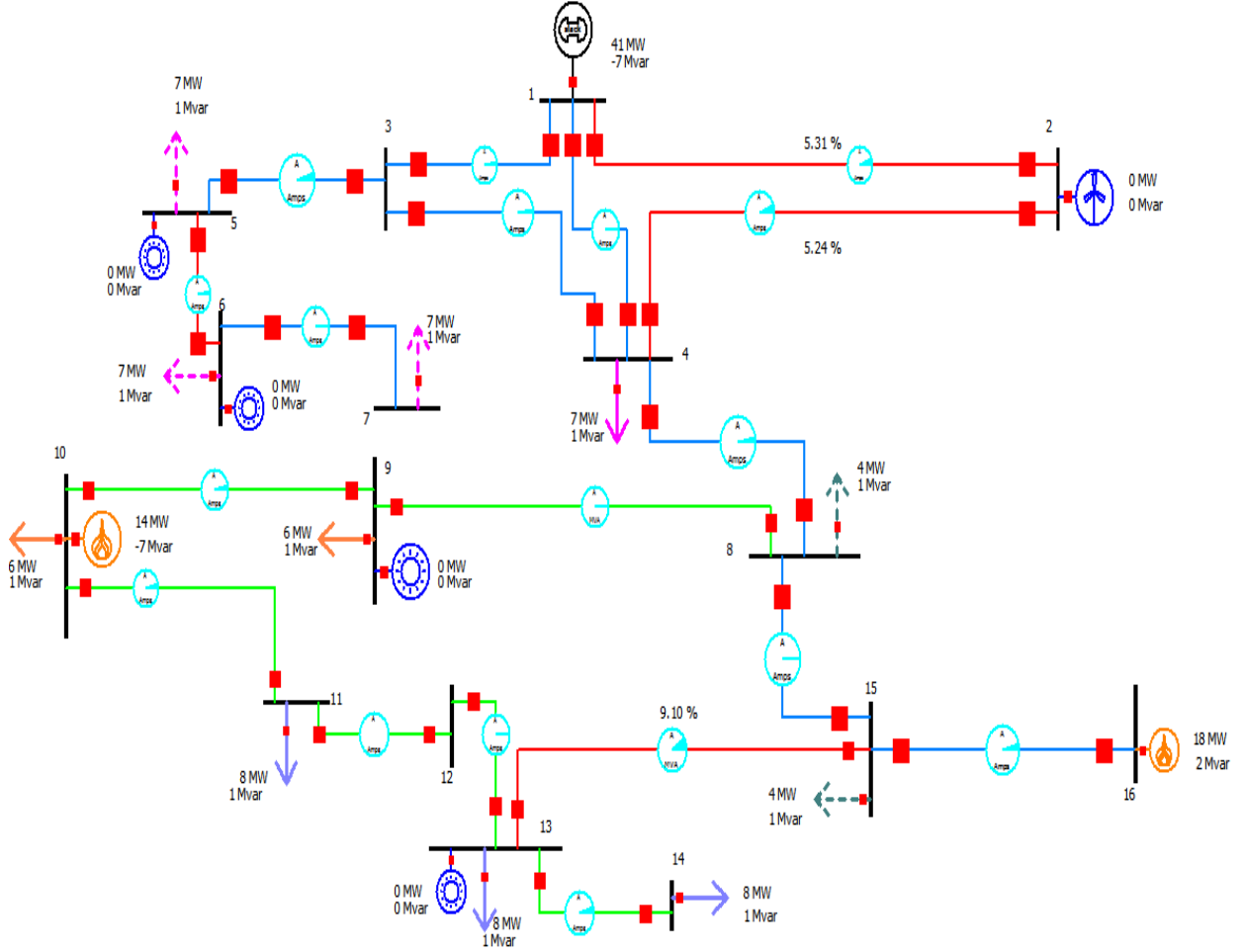


Table 2.5 summarizes the buses of the grid in Figure 2.17 into a specific type. The distributed photovoltaic (PV) plants are treated as negative load (with no ability to provide reactive power). The power flow simulation uses PowerWorld software and utilizes the Time Step Simulation capability. The Time Step Simulation is

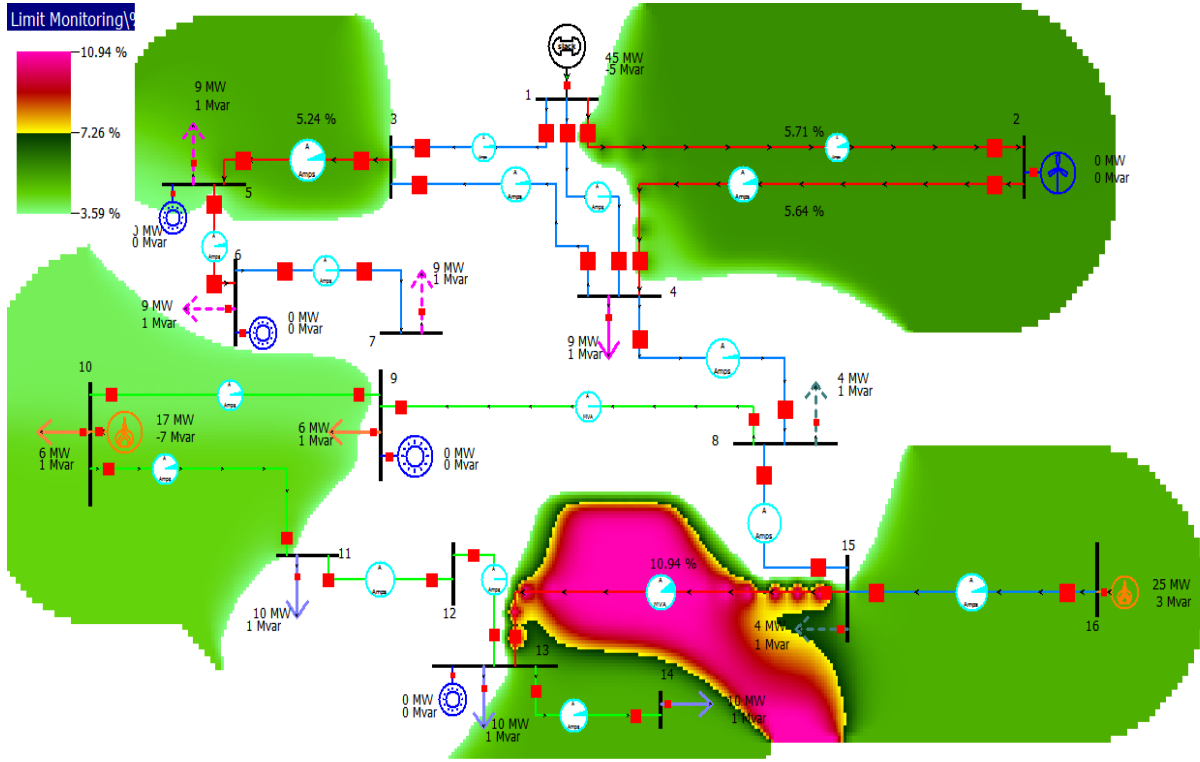
Using the base case scenario of a single day in August (08/07/2013): the following base case

Table 2.5: One-Line Diagram Buses Categorization

Area	Buses	Bus Types	Generation/Load
-	1	Swing	Baseload - Steam Plant
-	2	PV Bus	Wind Farm
Area I	3	Voltage-Controlled Bus	-
Area I	4, 5, 6, 7	PQ Buses (Load)	Load & Distributed PV
Area II	8, 15	PQ Buses (Load)	Load
Area III	9, 10	PQ Buses (Load)	Load & CT Plant & Distributed PV
Area IV	12, 16	Voltage-Controlled Buses	-
Area IV	13, 14, 15	PQ Buses	Load & CT Plant

of transmission line usage contour plot was obtained.

Figure 2.18: 08/07/2013 Power Flow Contour of Transmission Line Utilization



It should be noted that for the base case of no renewables at all in the system yields a fairly uncongested system: with the highest transmission line limit of $\sim 11\%$ of the transmission line limit at the line connecting buses 12-15. Note that lines 1-2 and 2-4 connect the rest of the grid to the wind farm.

2.3 Energy Storage Systems

The main purpose of the utilization of ESS in this research is to match the rapid power fluctuations from the renewables, which is a regulation service (i.e. part of the grid network ancillary services). Therefore, commercial bulk energy storage systems such as a pumped hydro energy storage (PHES) and compressed air energy storage (CAES) systems are not considered in this research. For applications that requires the energy storage systems to match fast variations in renewable generation, battery systems or flywheels are more suitable for those applications.

Table 2.6 shows the categorization of both long-term and short-term energy storage system in terms of duration of discharge, i.e. capacity of the ESS and is based on information from [27, 28]. Categorization information from this table is assumed throughout this research.

Table 2.6: Energy Storage System Categorization

Category	Duration	Type of ESS	Usual Applications
Long-term	≥ 4 hours	Pumped-Hydro Energy Storage Compressed Air Energy Storage Fuel Cells	Load Leveling, Load Smoothing, Peak Shaving Spinning Reserve, Arbitrage Services
Short-term	1-minute - 4 hours	Battery Technologies (e.g. Lead-Acid, Nickel-Cadmium Lithium-Ion, etc.) Supercapacitors, Flywheels	Frequency Regulation Renewable Compensation Power Quality

The modeling of the ESS is assumed such that all batteries modeled do not take into account the effect of temperature on battery efficiency (i.e. elevated temperature has an inverse relationship with battery efficiency).

Table 2.7 shows the various energy storage systems that are suitable for regulation applications and their individual characteristics [27, 19, 29]. The cost of each ESS will be discussed briefly in Section 2.3.1. The maturity of a technology is important as the characteristics of ESS still at the research and development (R&D) stage are based on conceptual engineering design analysis and therefore, its cost values are not fully developed.

Therefore, systems like the iron chromium, zinc air and zinc bromine (all of which are part

of the flow battery family) will not be taken into account in the overall analysis.

Table 2.7: Energy Storage Systems for Frequency and Renewables Regulation

Technology	Efficiency (%)	Cycles [†]	Lifetime (yr)	DoD* (%)	Maturity
Sodium Sulfur (NaS)	75	4,500	15	80	Mature
Advanced Lead-Acid (Pb-Acid)	75-90	>100,000	15	33-80	Field Demo.
Flywheel	85	>100,000	20	100	Mixture of Commercial and Demo.
Lithium-Ion (Li-Ion)	87-92	5,000	15	60-100	Mixture of Commercial and Demo.
Vanadium Redox (VaRedox)	65-75	10-30,000	10	100	Pre-commercial
Iron Chromium	75	>10,000	15	75	R&D
Zinc Air	75-80	>10,000	15	100	R&D
Zinc Bromine	75-80	>10,000	15	60-65	R&D

[†]Assumed system discharges at rated power output

*Depth of Discharge

2.3.1 Cost of ESS

As mentioned in the previous Section 2.3, only pre-commercial systems and beyond will be taken into account this analysis. Two sets of cost data are taken: the first from a 2013 DOE/EPRI/SANDIA report [30] and the other from an older 2010 EPRI report [29]. Each range of cost data set consist of a lower limit and an upper limit cost. Table 2.8 shows the range of the capital cost for each ESS based on the two reports mentioned.

The cost of the ESS given in both reports are in \$/kW, i.e. cost is a function of the rated discharge power output of the ESS. However logically speaking, the capital cost of an ESS should be a function of both its rated power output (i.e. kW/ MW) and its capacity (i.e. kWh/ MWh); instead of just a function of rated power output. This problem has been addressed in both reports by stressing the fact that the cost range is only applicable if the ESS is within the appropriate discharge duration range, e.g 5 minutes, 1 hour and etc.

Table 2.8: Capital Cost for Energy Storage Systems: Frequency and Renewables Regulation

Technology	2010 Cost (\$/kW)	2013 Cost (\$/kW)	Applicable Discharge Duration (hours)
Sodium Sulfur (NaS)	3,100-3,500	3,000-3,500	6 - 7.2
Advanced Lead Acid	1,590-4,600	1,200-1,500	0.25 - 1
Flywheel	1,100-2,500	2200	0.25
Li-Ion	1,100-1,800	1,100-2,600	0.25 - 1.5
Vanadium Redox	3,000-3,700	3,200-3,350	3- 5

2.4 Other Costs

As current renewable energy levels are still at around $\sim 10\%$, there are no incentives in installing costly ESS systems. However the balance of load and generation has to be maintained always to ensure reliability and efficiency of the power grid. This means that grid operators have to perform other measures to balance the load and generation.

One of these measures is the enabling rapid cycling and ramping of the current generation fleet, which are mainly made up of steam-powered plants and gas-fired combustion turbines. Traditionally, baseload systems like coal and nuclear plants typically do not cycle as peaker plants like gas-fired plants main function is to meet the load fluctuations. However, as wind and solar energy sources are increasingly integrated into the grid, power plants traditionally not required to cycle would now be required to cycle to compensate for the rapidly fluctuating renewables.

By cycling and ramping baseload plants that are designed to output constant power, this will incur a wear and tear cost [31] on the plant. On the flip side, the increased renewables present in the grid will displace traditional generators and this will lead to savings in fuel, such as coal and natural gas. Section 2.4.1 will briefly discuss the assumptions and costs involved in the cycling of power plants.

Another technique that wind farm operators do to aid in balancing load and generation is the allowing curtailment of excess wind energy (solar has yet to reach a level that requires curtailment). So, in the following Section 2.4.2, a short summary will be given on how the cost of curtailment is

calculated.

Also, it is important to note the alternative of an ESS, which is the construction of a combustion turbine power plant. Although a CT plant still emits CO₂, it is still a third of the CO₂ emission from a coal-plant[32]. Moreover, the cost of natural gas is falling in the United States due to the increase usage of hydraulic fracturing technology to retrieve shale gas and hence is an attractive alternative to ESS since an aeroderivative type of gas-fired power plant has quick starts and rapid ramp rates, like the GE Aeroderivative Gas Turbine LM 2500+ that claims to be able to have a 10-minute start capability [33]

In this study, the capital cost to install a CT plant is at \$650/kW, that are based on values found from the Energy Information Agency website.

2.4.1 Cycling of Power Plants

As mentioned in previous Sections 2.2.4 and 2.2.5 on steam plants and CT plants respectively, the steam plant runs at 70% of the rated power output and is allowed to cycle up to 98% and down to 65% of rated power output. However, at higher penetration of renewables, the baseload plant is allowed to ramp down to 40% of its rated power for increased flexibility in maintaining grid reliability.

According to the NREL study on power plant cycling cost [34], the wear-and-tear costs associated with cycling power plants can be categorized into several areas:

- (1) Hot, Warm and Cold Start Cost (\$/Cycle/MW)
- (2) Ramp Cost, i.e. Load Following Cost (\$/MW)
- (3) Noncyclic Operation Cost, e.g. baseload variable operations and maintenance (VOM) cost (\$/MWh)

This study assumes that noncyclic operation cost is not dependent upon the cycles of the system and hence will not be taken into account in this study.

Since both the steam and CT plants are already running and providing generation, cycling the plant does not incur hot/warm/cold start cost. A hot start cost is defined as starting up a generator that have been offline for less than 12 hours. Starting a plant from warm start requires 12-72 hours and a cold start is when the generator has been offline for more than 72 hours.

The third CT plant is assumed to be at hot start in this study grid, since it is assumed it would take 30 minutes to an hour to bring it online and synchronized to the grid. However, as will be shown in the results, the third CT plant will not be used since it will be displaced by the renewable generation.

The steam plant is assumed to be a large subcritical coal system and the combustion turbines are aeroderivative plants. A ramp as defined in the NREL report [35] is **an increase** of output of 30% from rated power in a minute.

It is also known that the heat rate of plants (BTU/kWh) deteriorates with increase of power plant cycling, however in this study it is assumed that the majority of wear-and-tear costs will be from the actual cycling and therefore heat rate is assumed to be constant.

Table 2.9 below show the related cycling and fuel cost used in this study (based on 2012 numbers, ignoring any increases due to inflation): [2, 34]

Table 2.9: Cycling and Fuel Cost

Cost or Characteristic	Large Subcritical Coal	Aeroderivative Combustion Turbine
Ramp or Load Following (\$/MW)	105	32
Fuel Rate (Btu/kWh)	10,128	11,499
Heat Content	20.63 MMBtu/short ton	1,027 Btu/ft ³
Fuel Cost	\$39.95/short ton	\$3.54/thousand ft ³
Equivalent Energy Cost	\$0.0196/kWh	\$0.0396/kWh

2.4.2 Curtailment of Wind

The curtailment of excess wind energy [35, 36] happens for several reasons as more wind energy is integrated in the grid system. One of the more common reasons as stated in [35] is to

minimize transmission congestion due to local line limitations. However, another main reason is the temporal mismatch between wind power output and load demand. This can be seen from Figure 2.19 below, for a day in January, assuming nominal constraints on operation of the steam plant (i.e. not allowed to cycle below 60% of capacity).

Figure 2.19: 01/01/2014 Dispatch Stack with 20% Wind and 5% Solar

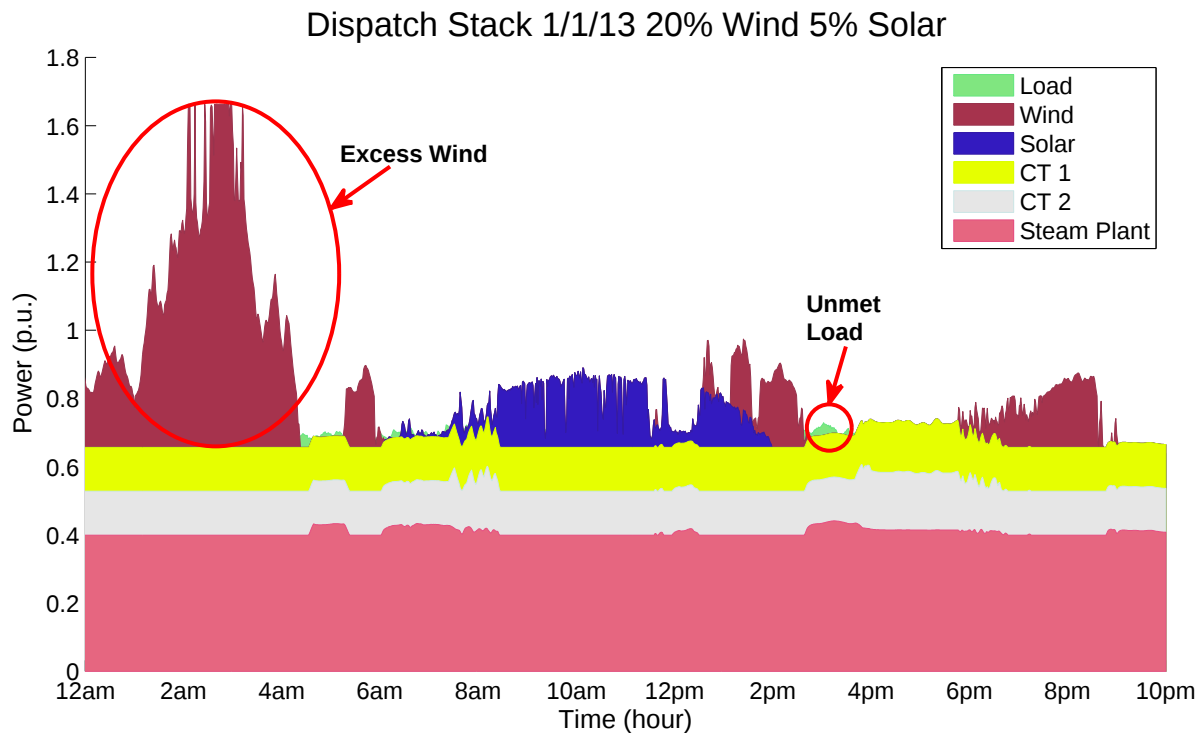


Figure 2.19 identifies the following:

- (1) Mismatch between wind energy producing around 2-4 am when the load demand is low.
- (2) Between 2-4 pm, both solar and wind power drops off rapidly such that the CT plants, which are running at full rated power output, are not able to ramp up in time to meet the increasing load.

In cases such as shown in Figure 2.19 illustrates the need for curtailment of wind, especially when there is a mismatch between wind power and load. Therefore, the cost of curtailing wind

should be taken into account when discussing the cost-benefits of installing ESS, especially if the cost of curtailing is far more attractive than investing in ESS technologies.

However, the exact cost of curtailment is a function of both market pricing and production tax credits [37, 35]. The cost also depends on where the wind farm is situated within a power market area, which would allow wind power producers to participate in a real-time power market, hence curtailing wind would lead to loss in revenue. However, this research is not about the economics of power market pricing and wind and thus for the sake of simplicity, the cost of curtailing wind is set as a function of amount of wind energy curtailed, i.e., \$/MWh wind energy curtailed.

There will be a lower limit cost, a middle limit cost and an upper limit cost for curtailing wind and is given below:

- (1) Low Limit Cost: \$30/MWh curtailed
- (2) Middle Limit Cost: \$60/MWh curtailed
- (3) High Limit Cost: \$90/MWh curtailed

These numbers are based on the report by BC Hydro in Canada [36] done in 2009. The numbers have been increased slightly to reflect changes in inflation.

There are two ways on which the power from the wind can be curtailed:

- (1) Curtailing at a constant power output (e.g. limiting maximum power output at 2 MW)
- (2) Limiting the ramp rate (MW/min) of the wind farm power output (usually with power converters)

Figure 2.20 shows the curtailed wind power output at increasing constant limit of power. Figure 2.21 shows the curtailed wind power by decreasing the ramp rates of the wind farm. Regardless of the method of curtailment, curtailing wind incurs a cost on the wind farm operators, which is undesirable.

Figure 2.20: Curtailment at Fixed Power Output 8/7/2013

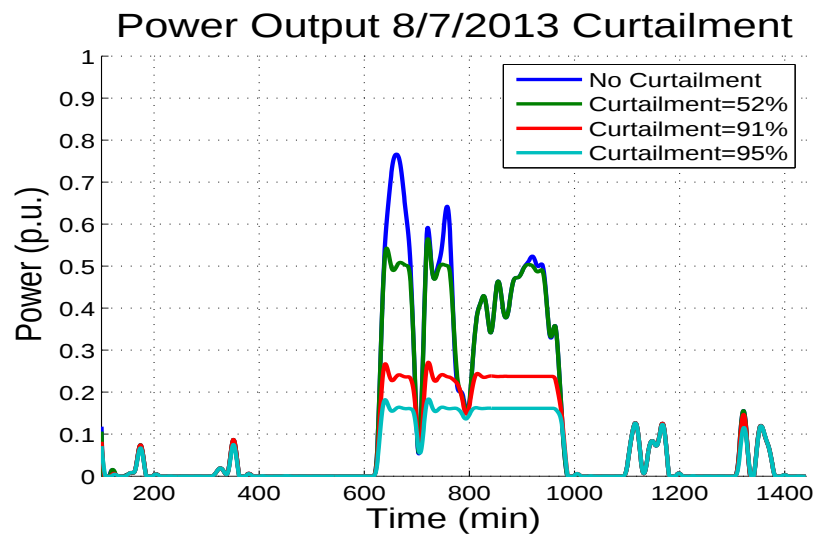
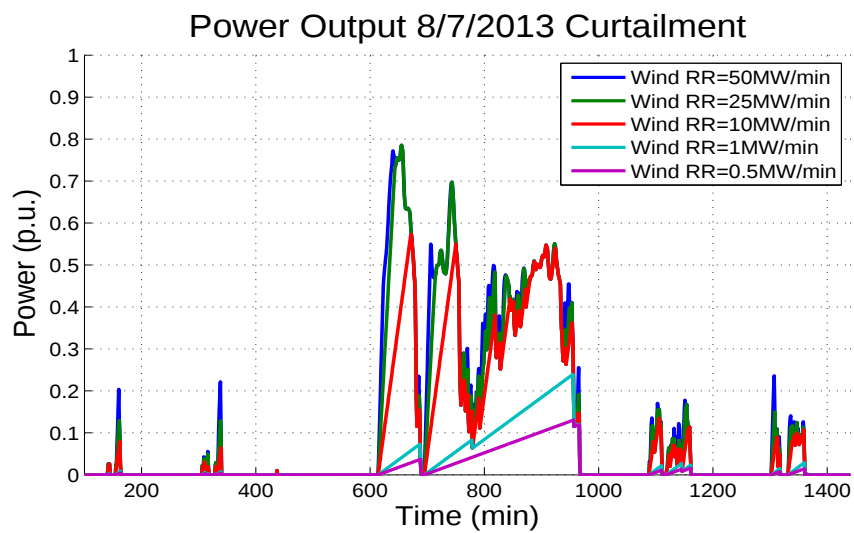


Figure 2.21: Curtailment with Decreasing Ramp Rates 8/7/2013



Chapter 3

Results

3.1 Base Cases

To start with, the simulation had no renewable sources of energy integrated into the power grid and this is used to establish a base line case. Then, 25% of wind and 5% of solar is introduced into the grid to reflect the power grid with high penetration of renewables.

3.1.1 25% Wind and 5% Solar - Curtailment

A limit of ± 2 Hz is imposed on the isolated grid, to ensure the reliability and stability of the grid. It is important to note that the grid frequency is usually regulated at $< 5\%$ deviation of the nominal value, i.e. 60 Hz in our case in Colorado and North America. Excessive grid frequency deviations from the nominal frequency leads to disruption of induction and synchronous motors in the grid as electric motor operation is dependent on the grid frequency. And the frequency of the grid is highly dependent on the active power injections and absorptions in the power grid [25]. Therefore with highly fluctuating power from wind, its curtailment is necessary to ensure that the grid frequency remains within the ± 2 Hz.

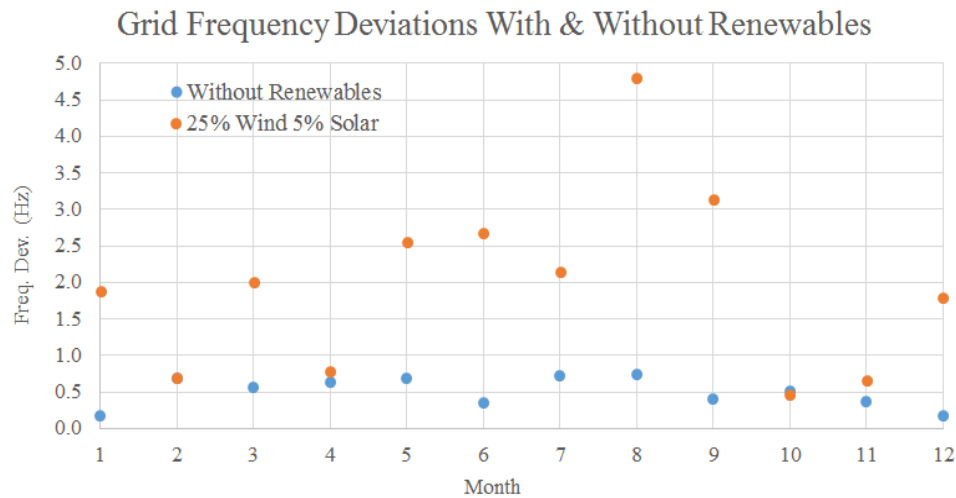
Table 3.1 below shows the daily energy contributions from the wind and solar, without any curtailment from wind. Figure 3.1 shows the maximum grid frequency deviations for the 12 data points:

It should be noted that with the grid at 25% wind and 5% solar, **both** curtailing of wind and deep cycling of the baseload plant is required such that the ± 2 Hz limit is not violated. However

Table 3.1: 25% Wind and 5% Solar Daily Energy Contributions

Day	Load (MWh)	Wind (MWh)	Solar (MWh)
01/01/2014	98,873	19,775	4,944
02/07/2014	94,361	18,872	4,718
03/30/2014	90,299	18,060	4,515
04/17/2013	74,847	14,969	3,742
05/01/2013	68,262	13,646	3,412
06/16/2013	71,086	14,217	3,554
07/04/2013	90,365	18,073	4,518
08/07/2013	93,579	18,716	4,679
09/03/2013	70,185	14,037	3,509
10/31/2013	67,654	13,531	3,383
11/29/2013	84,343	16,869	4,217
12/17/2013	54,346	10,869	2,717

Figure 3.1: Grid Frequency Deviations With & Without Renewables



even with those methods in place, the grid frequency do on occasion, exceed the ± 2 Hz limit as can be seen from the data sample from August (8/7/2013) shown in Figure 3.2. For this August case, curtailment of $\sim 90\%$ was required.

To reiterate, Figure 3.1 shows the effect of wind curtailment on the 12 data samples such that the grid frequency is limited to within ± 2 Hz. August is an exceptional case where only at almost 100% curtailment of wind would ensure the grid frequency remains within the ± 2 Hz limit.

Figure 3.2: 8/7/2013 Grid Frequency 25% Wind 5% Solar - No Curtail

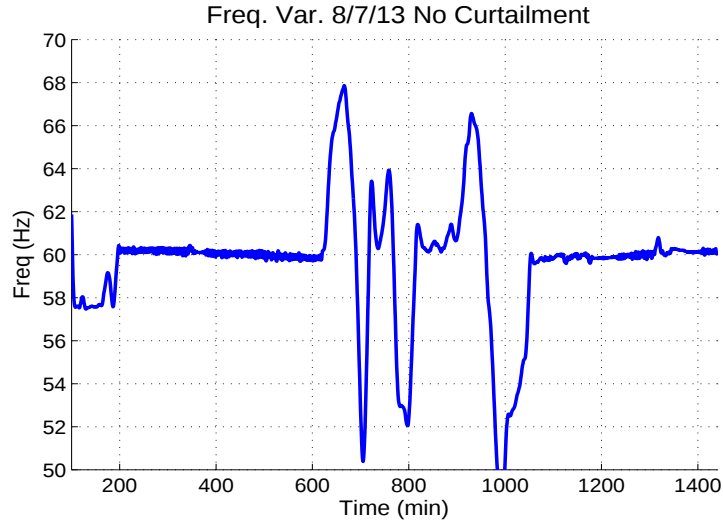


Figure 3.3 shows the grid frequency on 8/7/2013 with the curtailment of wind. Using the cost data from Section 2.4, the cost of cycling and curtailment can be found.

Figure 3.3: 8/7/2013 Grid Frequency 25% Wind 5% Solar - 92% Curtail

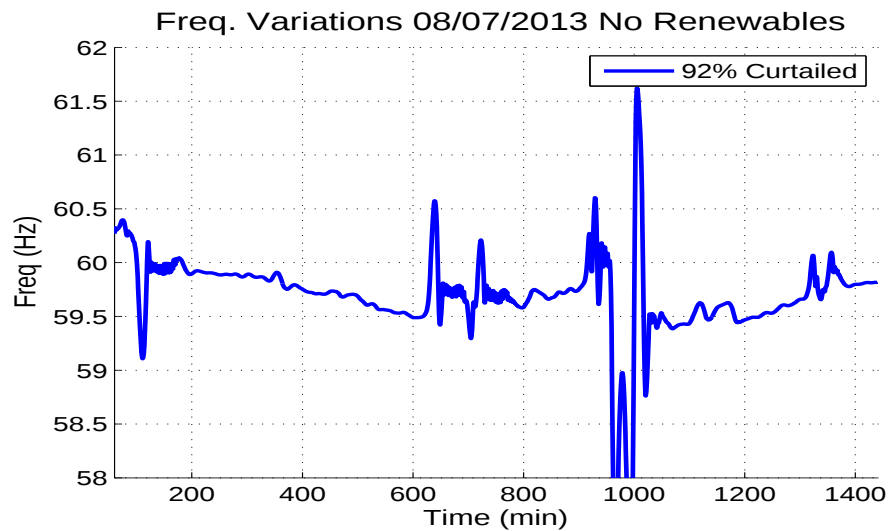


Table 3.2 shows the % curtailment for each data sample and the energy curtailed for that single day in MWh. There are three data samples (April, October and December) where wind curtailment was not necessary to ensure that the grid frequency was within the ± 2 Hz limit. Even

though curtailment of wind was not necessary, the generating units were still deep-cycled to ensure the grid frequency limits.

Table 3.2: Wind Curtailment for 25% Wind and 5% Solar

Day	% Curtailed	Energy Curtailed (MWh)
01/01/2014	68	282
02/07/2014	71	280
03/30/2014	77	290
04/17/2013	-	-
05/01/2013	78	223
06/16/2013	91	270
07/04/2013	88	332
08/07/2013	92	358
09/03/2013	91	267
10/31/2013	-	-
11/29/2013	39	137
12/17/2013	-	-

3.1.2 25% Wind and 5% Solar - Cost of Curtailment and Cycling

Figures 3.4, 3.5 and 3.6 show the differences in cycle cost per day between a grid with and without renewables for the individual power plants. The vertical axis is the cycling cost for the day in (\$/day) and the horizontal axis represents the month of the data sample set for each day.

Figures 3.7, 3.8 and 3.9 show the related **total cost** of all generating units for the following variables: fuel cost, cycle cost and cost of wind curtailment.

The next step is finding the total cost savings at each data sample as shown by Equation 3.1 below and Figure 3.10 shows the total cost of integrating 25% wind and 5% solar into the isolated grid of this study.

$$Total\ Cost = Curtailment\ Cost + Fuel\ Cost + Cycle\ Cost \quad (3.1)$$

Figure 3.10 shows that if there exists a high enough cost in curtailing wind, (roughly assumed as a \$/MWh amount in this study), the cost of integrating high levels of renewables especially wind, would be high in order to maintain the reliability of grid operations. An important note is that

Figure 3.4: Steam Plant Cycle Cost Differences

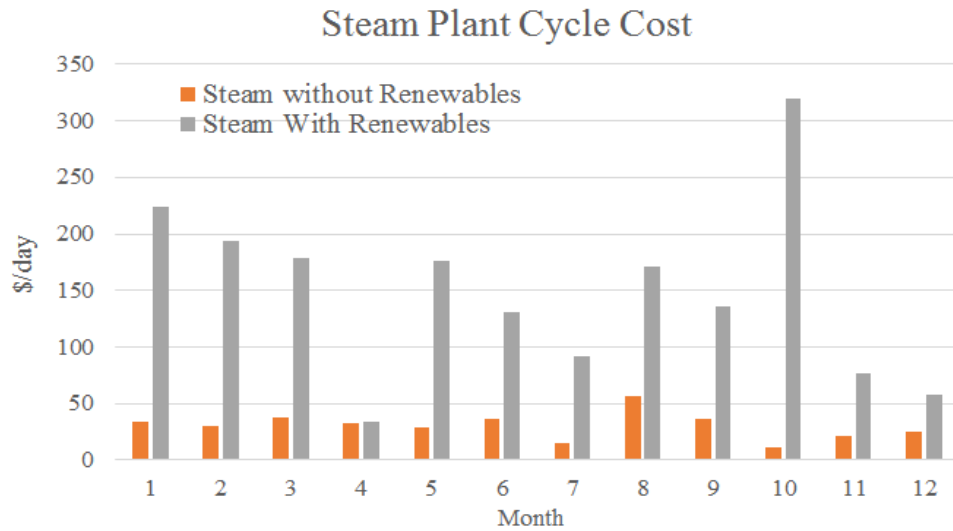
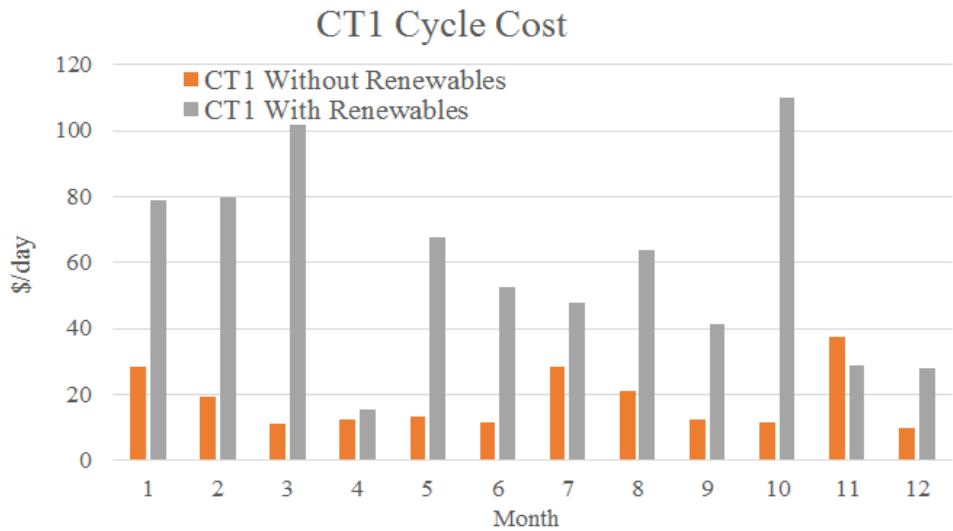


Figure 3.5: CT1 Plant Cycle Cost Differences



even though sometimes curtailment is not necessary (e.g. October data sample of 10/31/13), the baseload plant has to cycle as often as the CT plants to maintain the grid frequency within the ± 2 Hz limit, thereby incurring a cycle cost related to wear-and-tear of the baseload plant.

Table 3.3 shows the daily increased cost of cycling due to the high penetration of renewables

Figure 3.6: CT2 Plant Cycle Cost Differences

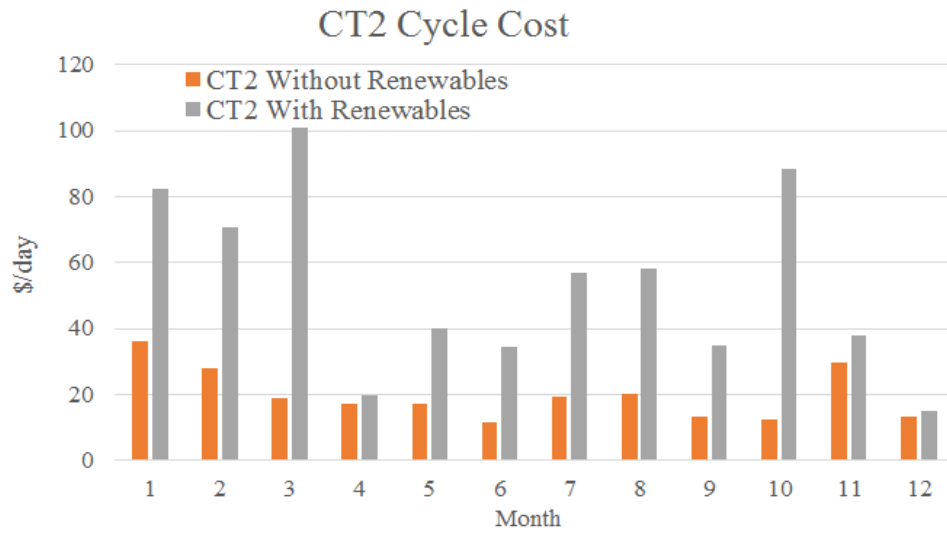
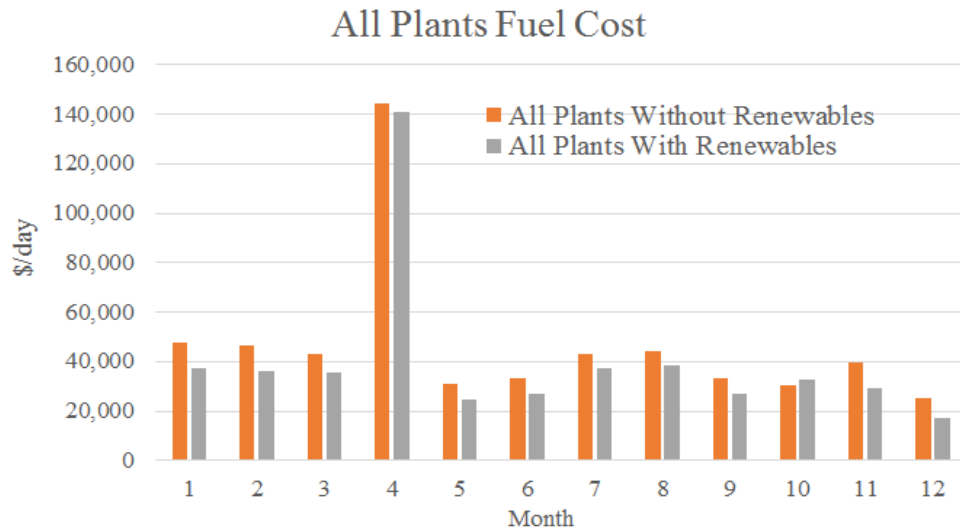


Figure 3.7: All Plants Fuel Cost Differences



and the cost savings related to reduced fuel (coal and natural gas) due to the displacement of traditional systems with the renewables.

The average daily cycling cost for the 12 data samples is \$193.63, although it should be noted that there is a significant difference between the largest cost (\$482 in October) and lowest

Figure 3.8: All Plants Cycle Cost Differences

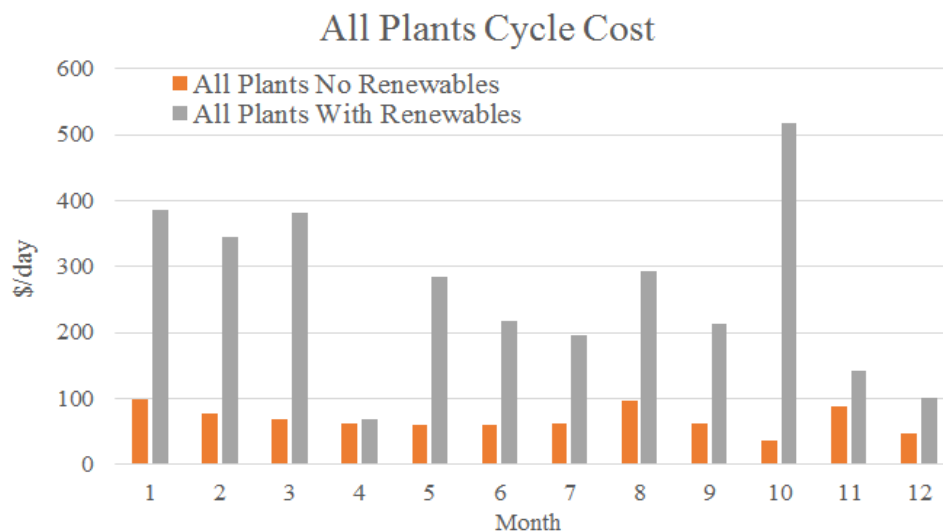
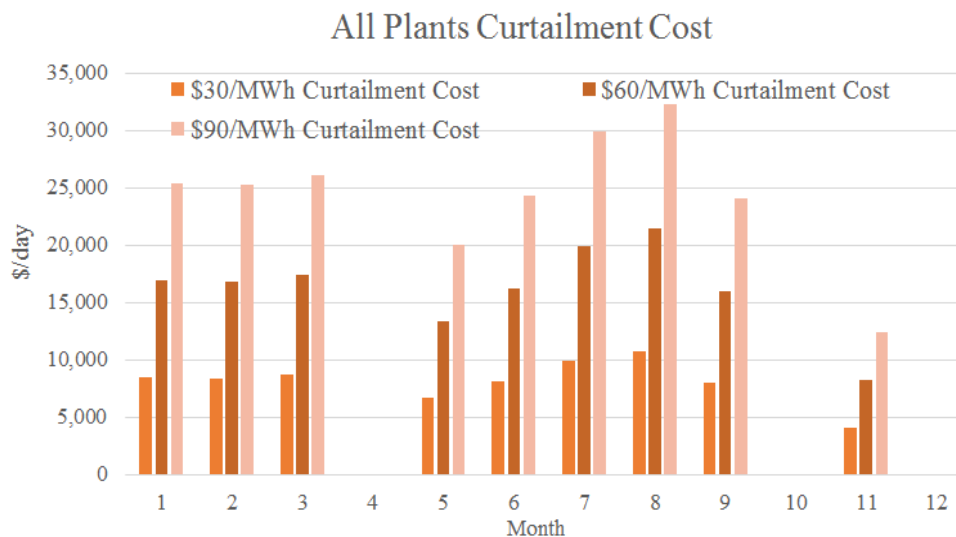


Figure 3.9: Wind Curtailment Cost for \$30/MWh, \$60/MWh \$/90/MWh



cost (\$6.66 in April). Using the average value of \$193.63, a rough estimate of an annual cycling cost due to high penetration of renewables is ~\$70,675.

Overall, the cost savings from fuel is a positive except for the day in October when extra fuel was used due to the fact that the wind speed was too low to produce power leading to more fuel

Figure 3.10: Cost of Integrating Renewables for 12 Data Samples

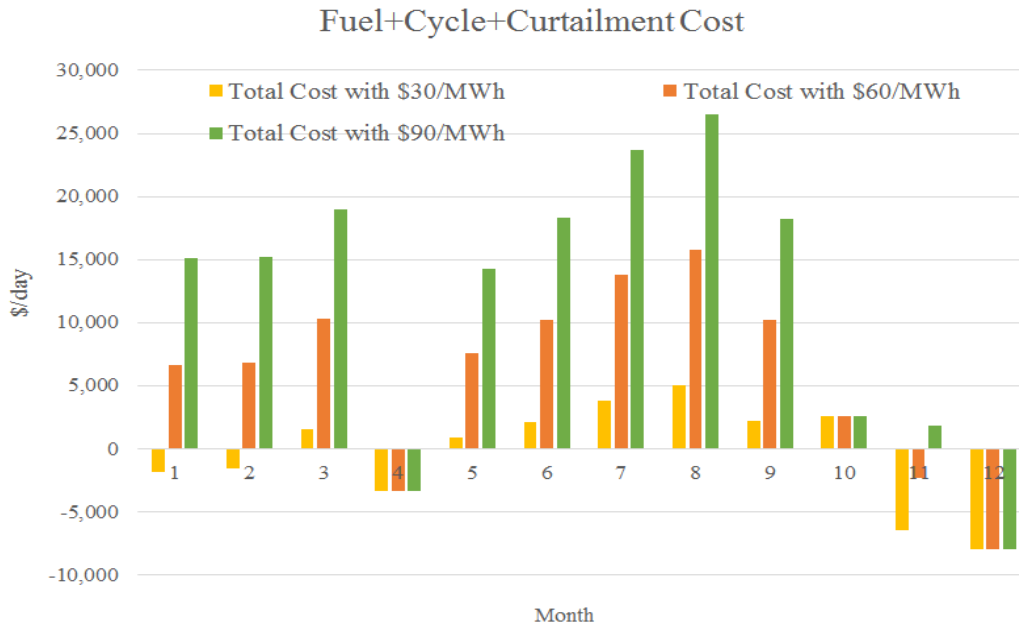


Table 3.3: Daily Increased Cost of Cycling and Fuel Savings at 25% Wind and 5% Solar

Day	Cost Increase (\$/day)	Fuel Savings (\$/day)
01/01/2014	285.87	10,570
02/07/2014	267.53	10,224
03/30/2014	313.36	7,413
04/17/2013	6.66	3,313
05/01/2013	223.82	6,029
06/16/2013	158.8	6,135
07/04/2013	133.97	6,269
08/07/2013	195.12	5,920
09/03/2013	149.62	5,944
10/31/2013	482.32	-2,127
11/29/2013	54.15	10,576
12/17/2013	52.34	8,029

being used to cycle the CT plant to compensate for the PV plant fluctuations. The average daily fuel savings is \$6,525/day, which roughly translates to an annual fuel savings of ~\$2.38 million.

The fuel savings far outweigh the cost of cycling the plants in this **particular** isolated grid case with 25% wind and 5% solar. As will shown later in the sizing of ESS section, the cost to

prevent cycling of plants is a more affordable option than installing ESS systems, if **operation cost is the only** variable involved in making transmission and generation investment decisions. However, it is not and the reliability of the grid (i.e. maintaining the grid frequency at proper limits) is an important priority, which would require additional measures put into place, like ESS integration.

3.1.3 25% Wind and 5% Solar - Transmission Congestion

The following section will briefly touch on the transmission line usage. Transmission line usage is defined as the fraction of the usage of the line from maximum line limit in MVA. A comparison between the transmission line usage of grid with and without 25% wind and 5% solar was done using the powerflow software PowerWorld. Due to the architecture of the study grid, there are no transmission lines with consistently high usage. With the introduction of solar power at the various buses and the wind farm at bus 2 (see Figure 2.17, different lines will encounter high usage at different times of the day. An important factor is also the time of day (i.e. when load demand is high or low) also affects the line congestion significantly. When the load is highest, usually around 4-7 pm, the transmission lines are most heavily used.

An example is shown below comparing the differences in transmission line congestion with and without the introduction of renewables in the grid. A 1-hour data snippet for the January data sample is used to run the power flow of the grid.

Looking at Figures 3.11 and 3.12, it can be seen that overall the line congestion increases with the introduction of renewables in the system. Therefore, the placement of the ESS on the grid must not significantly impact the line congestion when compared to the base case scenario (i.e. existing transmission congestion at 25% wind and 5% solar).

3.2 Sizing of ESS

The sizing of the ESS is done for capacity (MWh), rated power output (MW) and the ramp rate of the ESS (MW/min). In this study, the two out of the three variables mentioned are user-

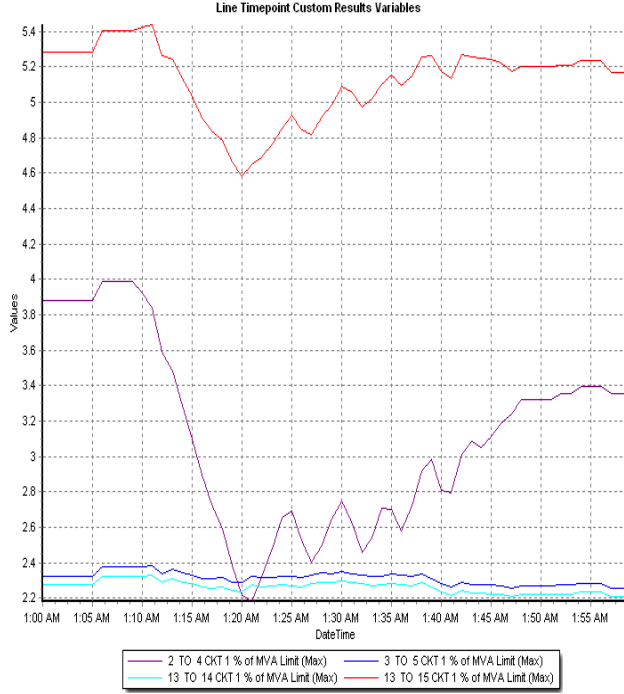


Figure 3.11: Transmission Line Congestion 1/1/14 at 1 am without Renewables

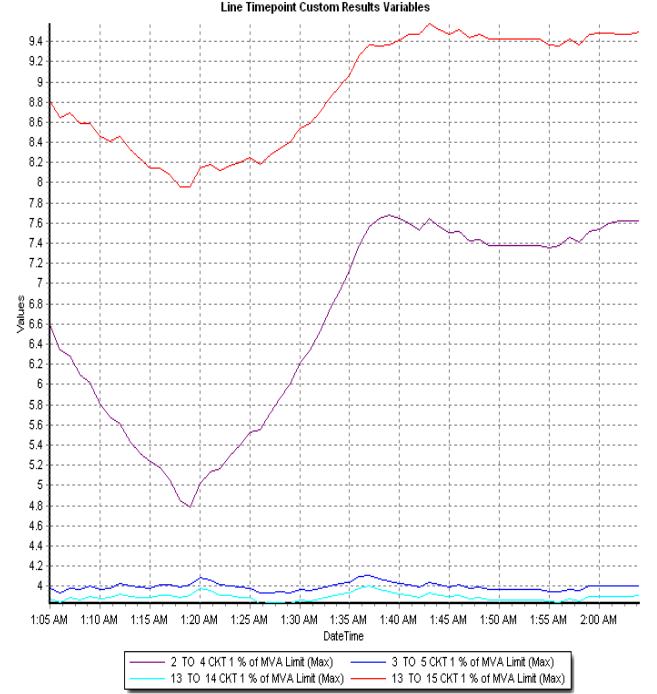


Figure 3.12: Transmission Line Congestion 1/1/14 at 1 am with Renewables

determined and the third variable is dependent on the first two. For example: if the capacity (MWh) and the ramp rate (MW/min) is chosen, then the optimized rated power output can be found from the ESS model such that the frequency deviation is minimized. In this study, the capacity and ramp rate is user-determined with a resulting optimum rated power output.

For all the simulation cases with ESS integrated into the grid, there is no curtailment of wind performed since ESS is to be the candidate in helping eliminate or reduce the curtailment of wind.

3.2.1 Sizing for a Moderate Day of Wind

An example is shown below for the day of October, where wind is relatively constant and does not require much curtailment of wind. Figure 3.13 shows the power output from generating plants with no curtailment needed since the frequency remains well within the ± 2 Hz range as seen with Figure 3.14.

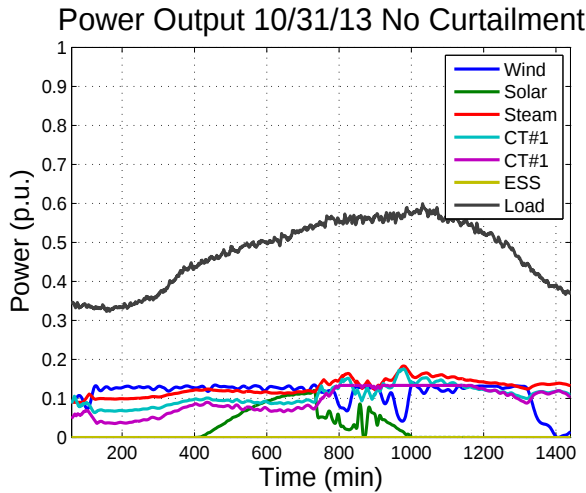


Figure 3.13: Power: October Day Sample with No Curtailment Needed

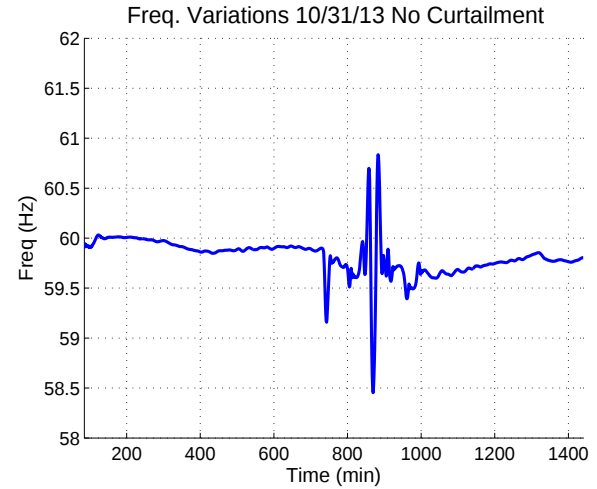


Figure 3.14: Frequency: October Day Sample with No Curtailment Needed

With the installation of ESS into the grid, the frequency deviations decrease. The following figures 3.15 and 3.16 show the difference between increasing capacity **and** ramp rates.

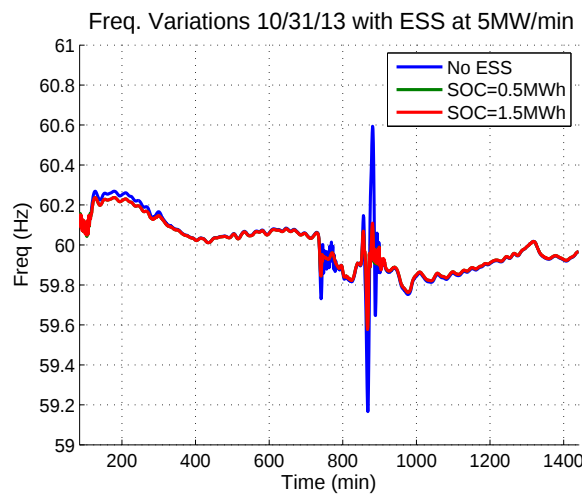


Figure 3.15: Frequency Variations with Increasing Capacity at 5MW/min

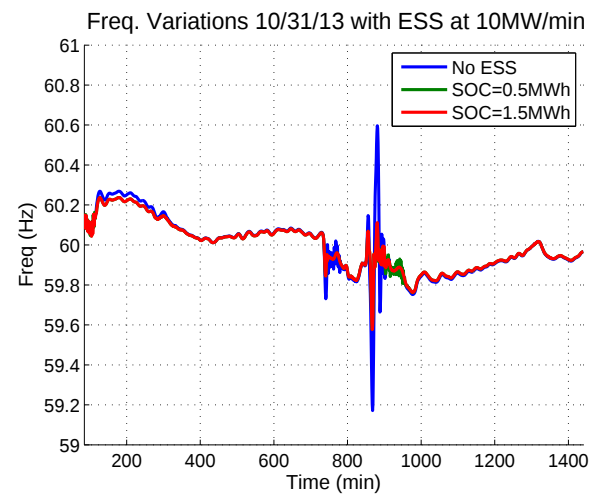


Figure 3.16: Frequency Variations with Increasing Capacity at 10MW/min

For this day in October, when the wind is relatively steady and the grid frequency remains stable except for the sudden drop in wind around the 900 minute mark (i.e. 3 pm), increasing both capacity and ramp rate does not significantly change the maximum frequency deviations as shown in Table 3.4 below:

Table 3.4: October with Increasing Capacity and Ramp Rate for ESS

Δfreq (Hz)	P_{rated} (MW)	Capacity (MWh)	Ramp Rate (MW/min)
1.425	0	0	0
0.661	8.02	0.5	5
0.661	8.02	1.5	5
0.661	8.02	0.5	10
0.661	9.38	1.5	10

As can be seen from Table 3.4, there is no significant difference in reduction of frequency deviations when both the capacity and ramp rate of the ESS is increased. However, what is certain from this data sample in October is that a higher ramp rate is a more desirable characteristic than a higher capacity (MWh) system.

3.2.2 Sizing for a Day of Volatile Wind

The data sample from August is used and it is a day with volatile wind as can be seen from the frequency plot of Figure 3.2. From the previous sample data, varying the capacity does not significantly affect the grid frequency deviations as much as changing the ramp rate does. Figures 3.17 and 3.18 below shows the grid frequency with an ESS system with a constant capacity of 0.5 MWh and varying ramp rates.

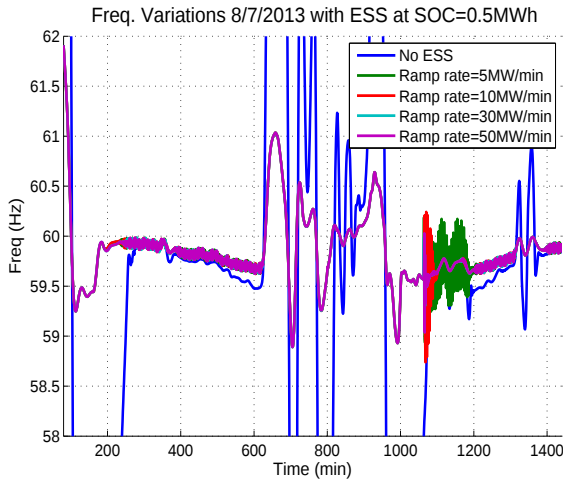


Figure 3.17: Frequency Variations with Increasing Ramp Rates at 0.5 MWh

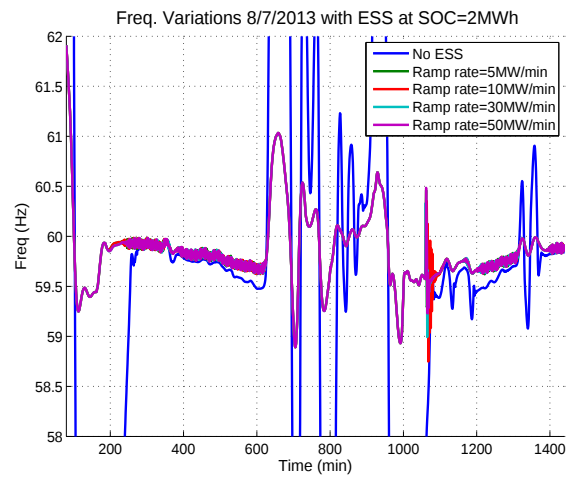


Figure 3.18: Frequency Variations with Increasing Ramp Rates at 2 MWh

Looking at Figures 3.17 and 3.18, it is noticed again there is no significance difference between an ESS with 0.5 MWh and an ESS with 2 MWh of capacity. However, by increasing the ramp rates of the ESS allows the ESS to respond in a timely manner to the fluctuations in renewables. For this case, the rated output of the ESS (assuming for now to be 100% efficient) is at ~ 60 MW.

Table 3.5: August with Increasing Capacity and Ramp Rate for ESS

Δfreq (Hz)	P_{rated} (MW)	Capacity (MWh)	Ramp Rate (MW/min)
30.77	0	0	0
3.33	30.76	0.5	5
3.52	30.76	10	5
3.48	30.77	0.5	10
3.36	30.78	10	10
3.33	30.74	0.5	50
3.33	30.75	10	50

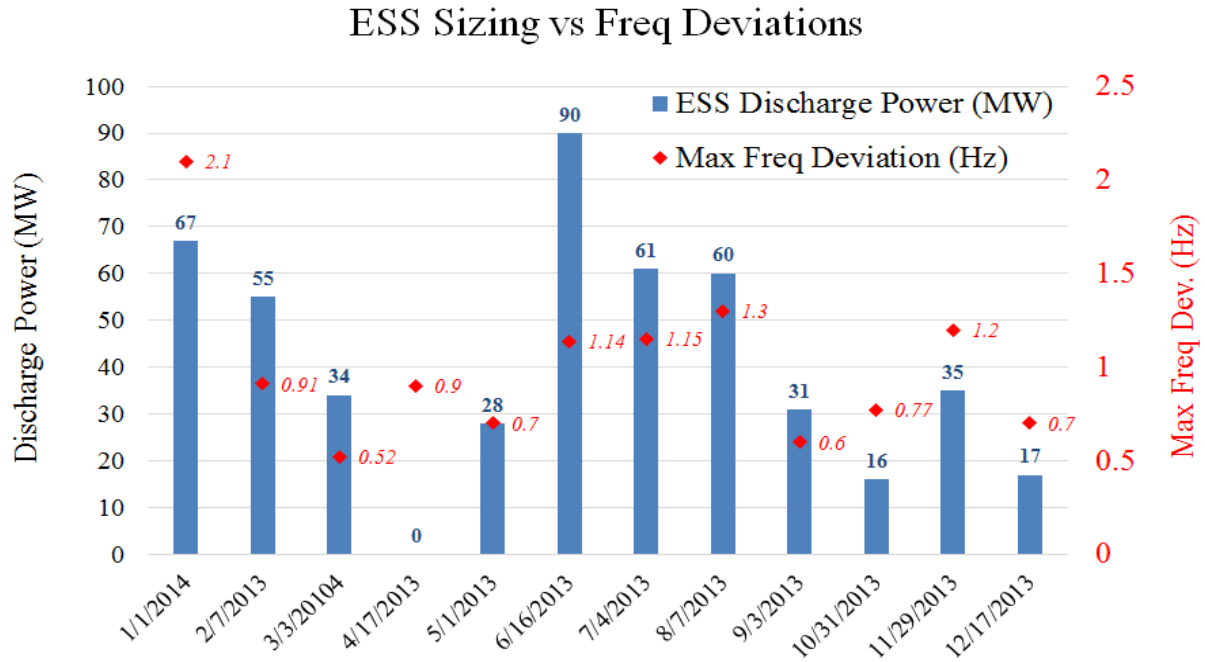
Table 3.5 shows the maximum frequency deviations for different capacity and ramp rate settings for the sample data set in August. Although the maximum frequency deviations did not change with varying ramp rates, a closer look at Figures 3.17 and 3.18 show that at higher ramp rates, the grid frequency does not oscillate as much when the ESS has lower ramp rates.

3.2.3 Sizing: Decision and Cost

Simulation was done for each 12 sampled in the set and the capacity is set at capacity of 20 MWh and ramp rate of 50 MW/min, which is the highest ramp rate encountered from the wind farm. The capacity value was found from simulations using the entire day (1440 data points) instead of the short time snippet shown in Sections 3.2.1 and 3.2.2. Figure 3.19 summarizes the optimal rated power output of an ESS with the equivalent maximum grid frequency deviation.

Looking at Figure 3.19, the highest rated power output value of the ESS is 90 MW, which is needed on the 6/16/2013 data sample set. The empty value on 4/7/2013 is due to the fact that there is no wind energy produced on that day, hence the ESS was not required as the rapid cycling of the CTs were adequate in minimizing the fluctuations from the PV alone. Hence, the desired optimum discharge power output from the ESS is capacity of 90 MW. Therefore, for the 12

Figure 3.19: ESS Sizing vs. Frequency Deviations



data sample set used in this study, the following summary of an optimized ESS can be found:

- (1) Low capacity ESS : 15-20 MWh
- (2) High discharge power output: 60-100 MW
- (3) Ramp rate of ESS: >50 MW/min

From the basic summary of the ESS and using the technologies and related capital cost described in Section 2.3.1, the capital cost of installing an ESS with the specifications shown above, the following Table 3.6 was found assuming a required P_{rated} of 90 MW. Since the capacity of the system is at 20 MWh, the discharge duration range at 15 min is within the limits of the cost assumptions as mentioned in Section 2.3.1.

Table 3.6: 35 MW ESS Capital Cost with CT Plant Comparison

Technology	Eff.	Range (hours)	Average Cost 2010 (\$/kW)	Average Cost 2013 (\$/kW)	2010 Cost (\$ millions)	2013 Cost (\$ millions)
NaS	0.75	6 - 7.2	3,550	3,250	426	390
Adv. Pb-Acid	0.83	0.25 - 1	3,095	1,850	336	201
Flywheel	0.85	0.25	1,800	2,200	191	233
Li-Ion	0.89	0.25 - 1.5	1,450	1,850	147	187
Va Redox	0.7	3 - 5	3,350	4,200	431	540

3.3 Placement of ESS

Since the ESS is designed for the worst data sample set (i.e. the August data set) and assuming a high ramp rate of 50 MW/min: an ESS is designed with the following characteristic:

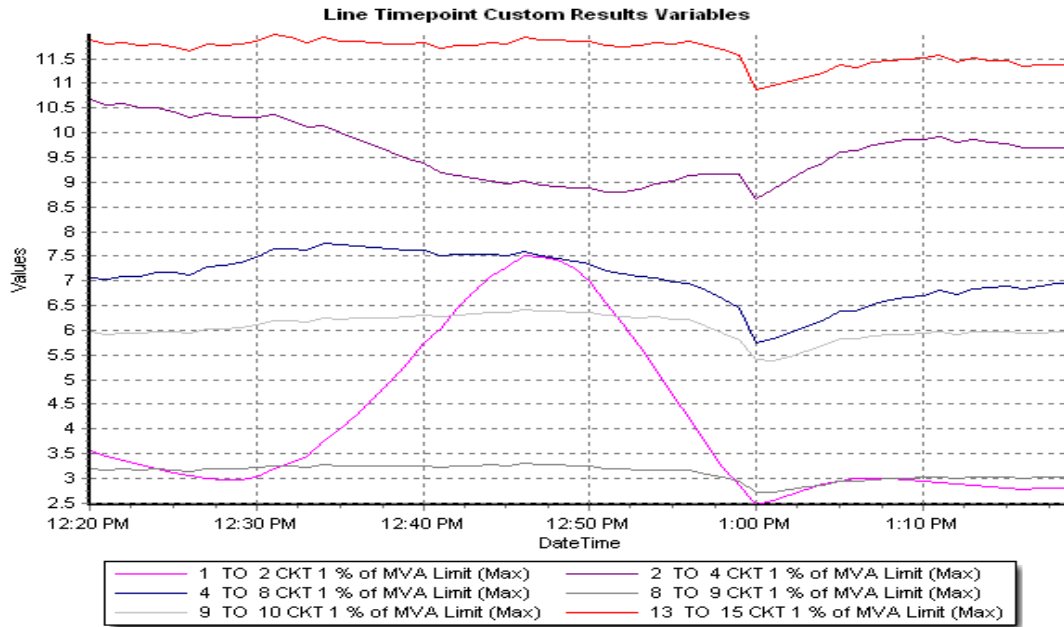
- (1) 20 MWh capacity
- (2) 90 MW rated power output
- (3) 50 MW/min ramp rate

The power flow for the August data set is used, as it contains the most volatile wind day from all 12 data sets. The ESS is modeled as a purely resistive (i.e. MW) load in the system for the time of day with the highest load, which correlates to the highest congestion in the existing transmission lines. Figure 3.20 below shows the base case at 25% wind and 5% solar with no curtailment and no energy storage system. The lines actually show reasonable usage (which is defined here as % of maximum line limit) as the lines are all well below <25% of the lines maximum limit. However, the load demand does not stay static over the next five, ten and even twenty years but is forecasted to increase over the years. The time snippet of Figure 3.20 starts at 2 pm, which is close to the load peak of the data sample.

The buses that connect the top six lines are (not including the slack bus #1) :

- (1) Bus 2 - Wind site located here

Figure 3.20: Top Six Transmission Lines with Highest Usage with No ESS



(2) Bus 4

(3) Bus 8

(4) Bus 9

(5) Bus 10 - Site located far from both the coal plant and wind

(6) Bus 13 - Site located far from both the coal plant and wind

(7) Bus 15 - Site located far from both the coal plant and wind

And the top six congested lines for the 25% wind and 5% solar for the 08/07/13 12:20 pm data set is:

(1) Line 1-2

(2) Line 2-4

(3) Line 4-8

(4) Line 9-10

(5) Line 13-15

The ESS is placed at all the buses listed above and then the power flow simulation is done again to find the new top congested lines. These lines are then compared with the base load case to verify if the ESS disrupts or assists in the base load congestion.

Figure 3.21 below shows the top five lines with highest usage when the ESS is placed as Bus 2, i.e. where the wind site is located. This plot is compared side-by-side with the base case of Figure 3.22. By placing the ESS at bus 2, the congestion on line 1-2 (which is line connecting the baseload and wind site) is reduced.

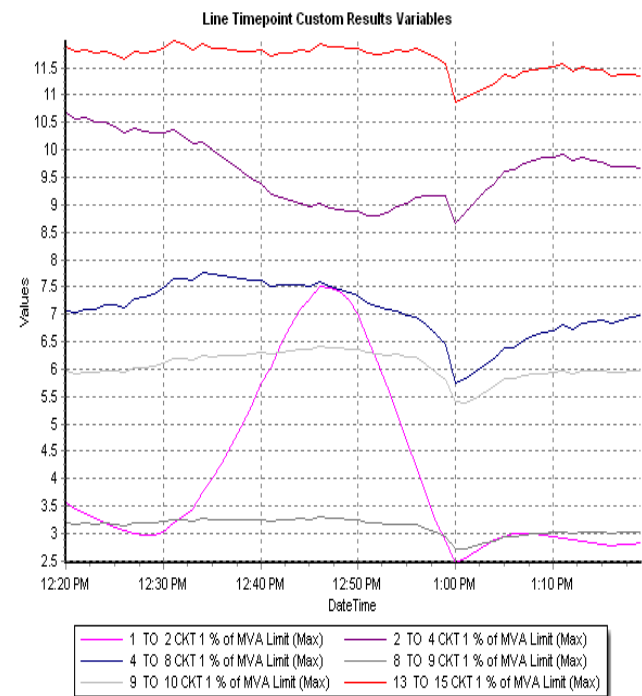
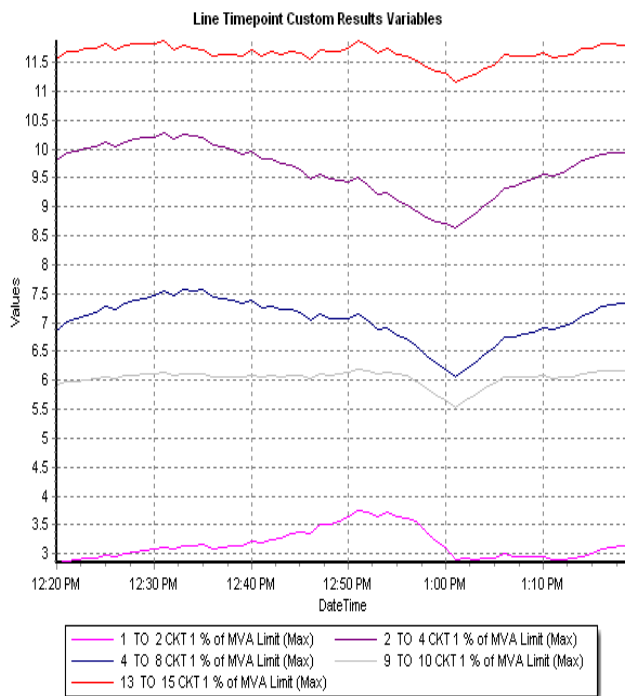


Figure 3.21: Top Five Transmission Lines with Highest Usage with ESS at Bus 2

Figure 3.22: Top Six Transmission Lines with Highest Usage with No ESS

Then, the ESS is placed at bus 4 and the comparison line congestion plots are shown in Figures 3.23 and 3.24. Lines 2-4 and 1-2 shows the most significant changes. Line 2-4 usage drops

off in the middle of the time snippet when the ESS is at Bus 4, where else for the base case its usage remains relatively constant but high. Again placing the ESS at Bus 4 leads to reduced congestion at line 1-2, similar to when the ESS is at Bus 2.

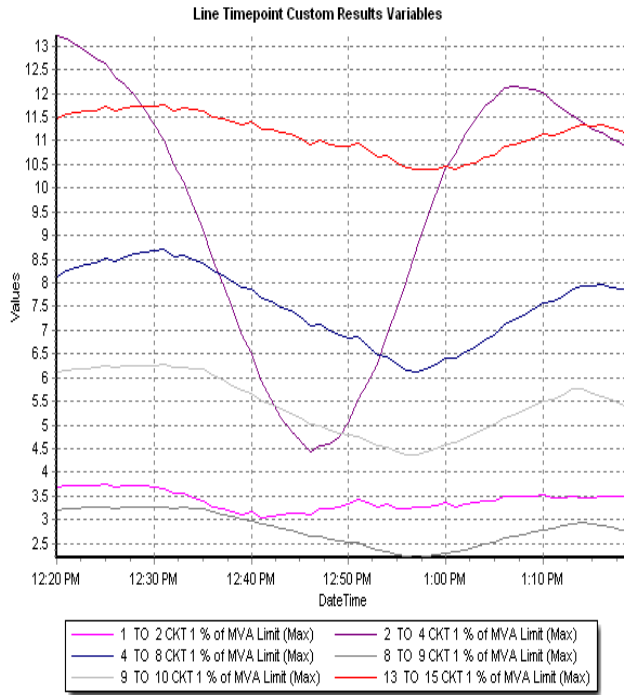


Figure 3.23: Top Six Transmission Lines with Highest Usage with ESS at Bus 4

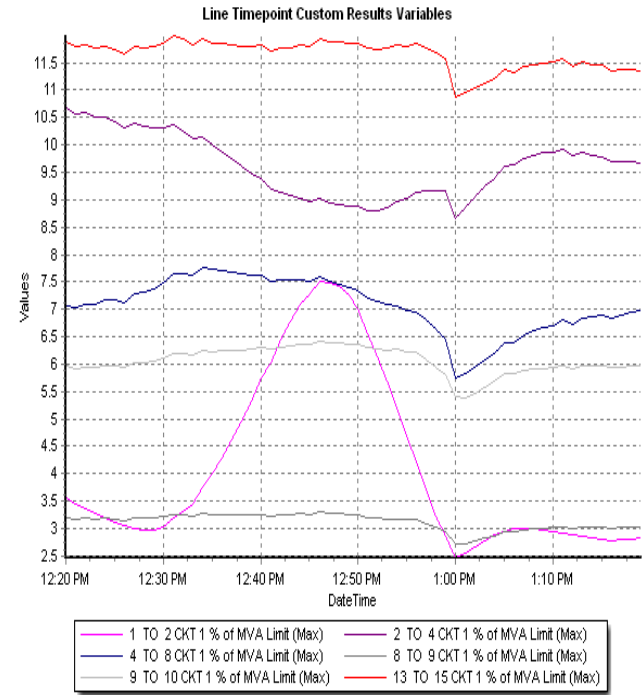


Figure 3.24: Top Six Transmission Lines with Highest Usage with No ESS

When the ESS is placed at Bus 8, there are now more lines with increased congestion as seen in Figures 3.25 and 3.25.

The trend of increased line congestion as the ESS is placed further away from the main fluctuating source (i.e. wind at Bus 2) can be seen from Figures 3.27 - 3.33 below:

Judging from the August data set, the optimal location for placing an ESS is Bus 2, which is where the wind site is located.

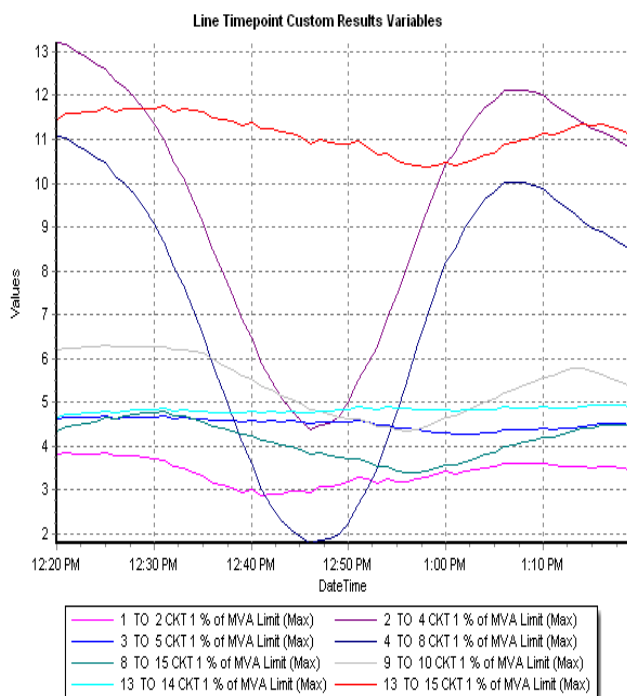


Figure 3.25: Top Eight Transmission Lines with Highest Usage with ESS at Bus 8

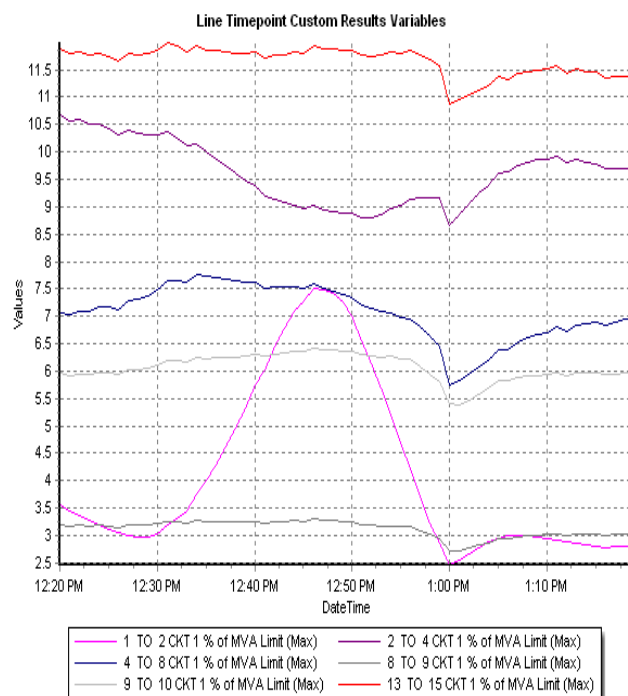


Figure 3.26: Top Six Transmission Lines with Highest Usage with No ESS

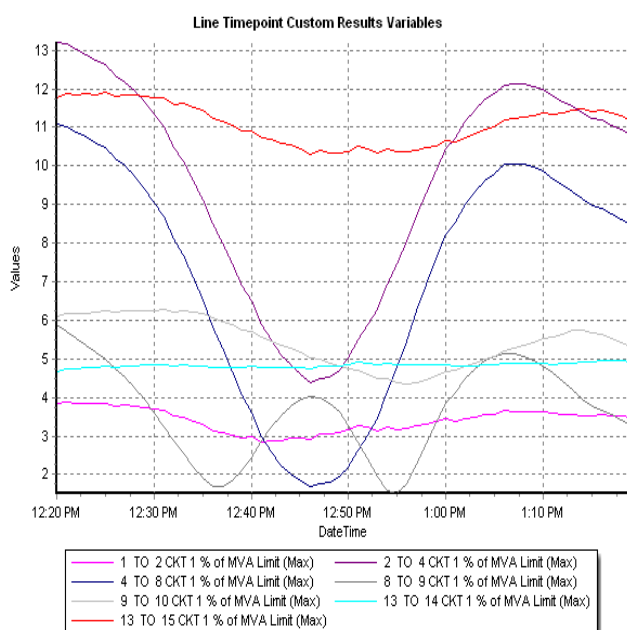


Figure 3.27: Top Seven Transmission Lines with Highest Usage with ESS at Bus 9

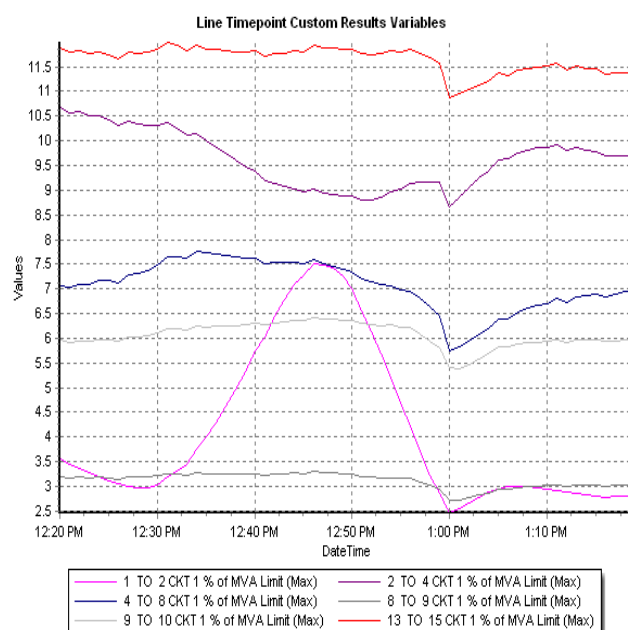


Figure 3.28: Top Six Transmission Lines with Highest Usage with No ESS

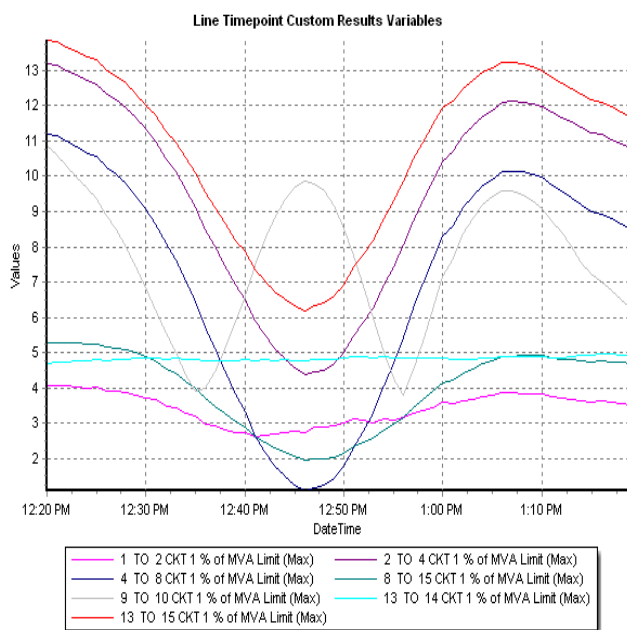


Figure 3.29: Top Seven Transmission Lines with Highest Usage with ESS at Bus 10

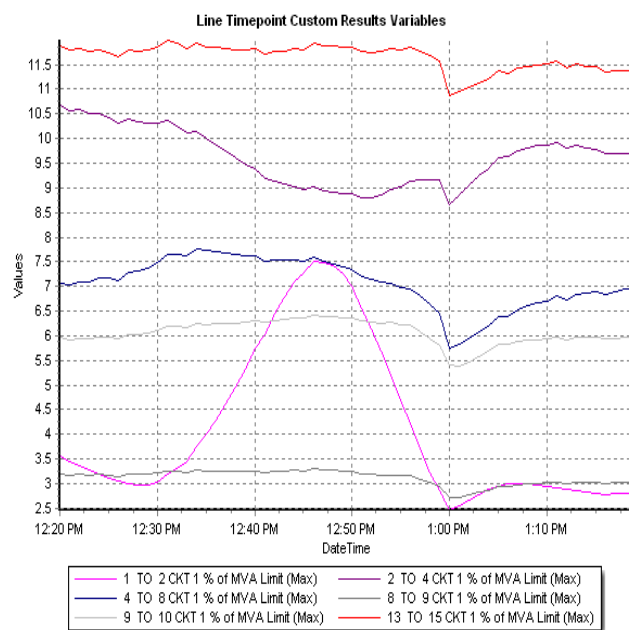


Figure 3.30: Top Six Transmission Lines with Highest Usage with No ESS

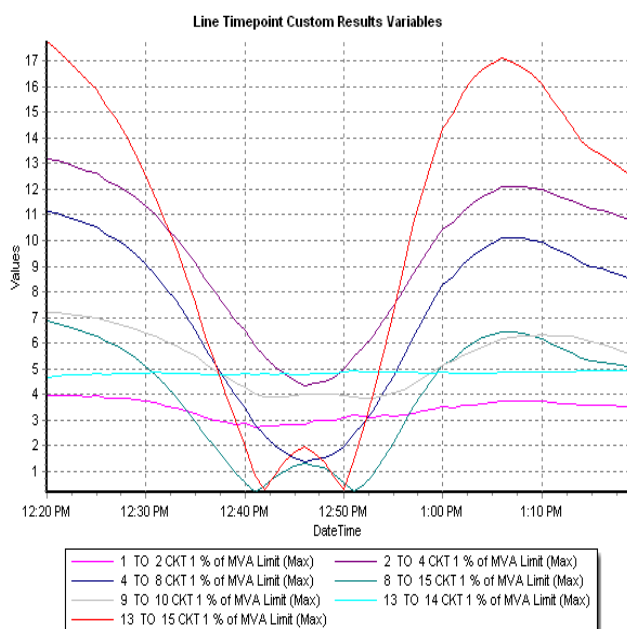


Figure 3.31: Top Seven Transmission Lines with Highest Usage with ESS at Bus 13

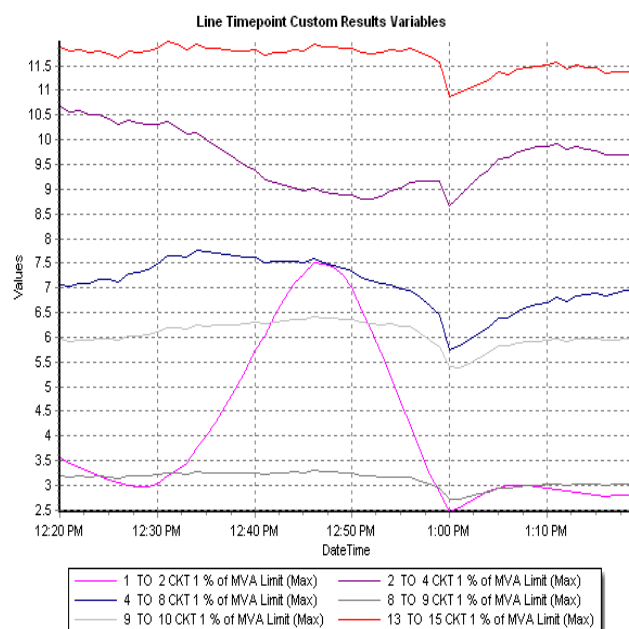


Figure 3.32: Top Six Transmission Lines with Highest Usage with No ESS

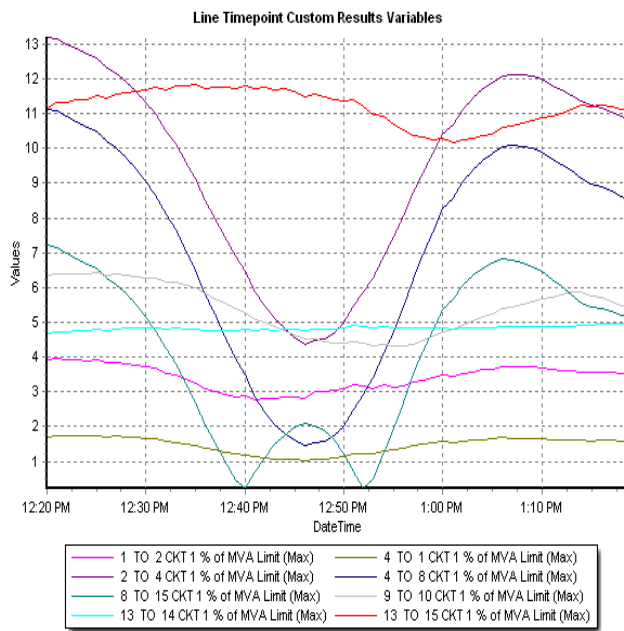


Figure 3.33: Top Seven Transmission Lines with Highest Usage with ESS at Bus 15

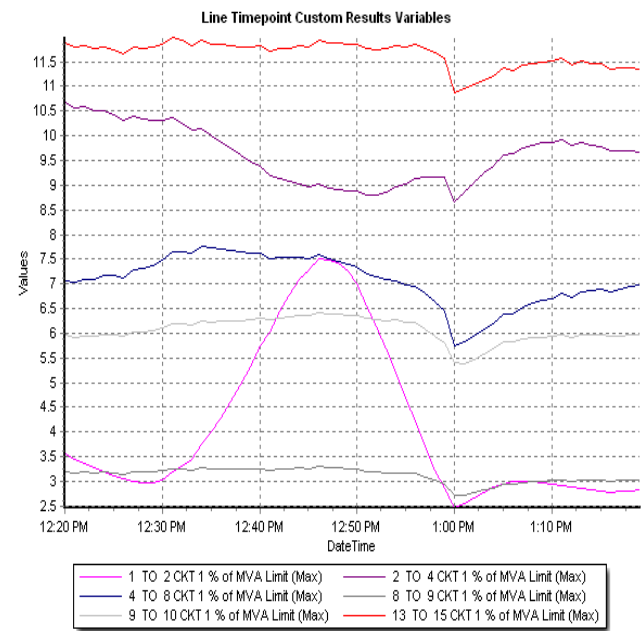


Figure 3.34: Top Six Transmission Lines with Highest Usage with No ESS

Chapter 4

Conclusion

To reiterate, this study seeks to find:

- (1) Optimal capacity of system (MWh/kWh)
- (2) Rated power output (MW/kW)
- (3) Location of the ESS on the grid
- (4) Ramp rate (MW/min, kW/min)

of an ESS system.

There are several conclusions to be drawn from this study and bearing in mind that the results shown here are optimized for a specific isolated grid that is based on a utility in Northern Colorado.

The study sought to determine whether ESS are suitable as a mitigation technique in reducing frequency deviations due to the rapid fluctuating power from renewables, i.e. wind and solar, and it can be safely concluded that energy storage system technologies are capable for frequency regulation and reducing fluctuations from renewable sources.

It was also shown that if the ESS is specifically used for regulations purposes, capacity (MWh) is not the important parameter when trying to minimize the frequency deviations but rather the ramp rate (MW/min) is a more important design criteria.

It is known that energy storage systems are very expensive, hence its limited deployment in the grid. The cost of curtailment and deep cycling baseload plants like coal plants at high

penetration of renewables (in this case 25% wind and 5% solar) is more affordable than installing an ESS; when comparing just the individual costs. Even with curtailment and deep cycling of the steam plant, the frequency deviation for some data sets barely met the ± 2 Hz limit, much less meet the standard grid operation limit of $\pm 5\%$ of nominal frequency of 60 Hz. The cost of avoiding cycling and curtailment may offset **some** of the capital cost of installing ESS but the reliability of the grid should be the foremost objective.

Installing a new combustion turbine plant would be cheaper than installing an ESS but it should be noted that a CT is not capable of the fast ramp rates and switching times that an ESS can provide, especially for regulation services.

The application of ESS here does not seek to reduce current transmission congestion or to be an alternative for future transmission investment but rather placing the ESS merely tries to limit the effect of increasing congestion on the existing system. This study found that the best place for the ESS is right at the fluctuating source, which is the wind site.

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