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The Management of A Utility-Scale Battery Storage System for Renewable Energy Applications

by

Feng Cheng

B.S., Tsinghua University, 2003
M.S., Beijing Jiaotong University, 2007

THESIS

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Dedication

To my LORD, Jesus Christ, for His encouragement and comfort in the process.

For the LORD giveth wisdom: out of His mouth cometh knowledge and understanding. (Proverbs 2:6)

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I would like to thank my advisors, Professor Andrea Alberto Mammoli and Professor Olga Lavrova for their support and encouragement in my study. Thanks for training me to be a graduate student with immeasurable time and efforts.

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To my parents, who gave me support over the years, their encouragement is greatly appreciated. And finally to my husband, his love is the greatest gift of all.

The Management of A Utility-Scale Battery Storage System for Renewable Energy Applications

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Abstract

Renewable resources are becoming more and more obtainable and affordable due to the development of technology and enactment of government policies. The output from solar power aligns reasonably well with daytime consumption on the electricity grid, reducing the need for new fossil power stations. Industry experts estimate about 5,000 MW of photovoltaic (PV) will connect to the power grid in only 10 years. However, the technical issue about PV is its variability due to weather conditions especially cloud cover. If the PV power is injected into a power system directly on a large scale, it may produce issues in power quality, reliability and stability. It is desirable to select a smoothing algorithm that would filter out the highest frequency intermittency, but would still be fast enough to avoid significant lag with respect to current power production. Usually a moving average algorithm was used. For the alternative methods, the author has tested two other algorithms: moving median algorithm and double moving average algorithm. The key parameters for these three algorithms are analysed. The results are compared, and show that the two alternate algorithms have merits in saving capacity and improving smoothness.

Meanwhile, in a power system, the production of electricity should match its consumption. Since the load is not constant for the whole day, many backup power plants only work at peak load times. If utility companies could store power for peak load times, they could eliminate a considerable investment for the backup and peaking plants. Using batteries can save investments through shifting stored energy from a time when the load is low to a peak load time. The shifting algorithm is introduced and the economic cost saving analysis is given.

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Chapter 1

Introduction

1.1 Motivation

Some researchers estimates the fossil fuel reserves can support the worlds demand for power for 50 years, while others say it will be 100 - 120 years. Though there is no accurate number about how many years the fuel reserves will deplete, at least it shows the current energy source is facing a serious shortage in the near future. The infrastructure for the current power grid is rapidly ageing. The radical changes of environment show the great negative effects brought by the consumption of fossil resources. Based on these factors, the concept of a “smart grids” has been advanced, requiring the modernization of the distribution and the transmission system. One of the priorities of the smart grid is to deploy and integrate the distributed resources, including renewable energy resources. Renewable resources are substantial for a long term and can be used to generate electricity with low or zero CO_2 emissions. For some European countries, there are more than 30 % of electricity comes from renewable energy including photovoltaic (PV) power, wind and other resources in 2010 [1].

Meanwhile, renewable resources become more and more obtainable and affordable due to the development of technologies and the enactment of government policies. In the renewable Portfolio Standard, California will generate 33 % of the total energy from renewable energy resources before 2020. Industry experts estimate that about 5,000 MW of PV will be connected to the power grid for the resource mix in only 10 years. The goal of New Mexico is to generate 20 % of the total energy from renewable energy resources till 2020. Considering this aggressive goal, a large amount of PV power needs to be installed in the next 10 years.

The PV power produces no CO_2 pollution to the environment. The output from the solar power aligns reasonably well with the daytime consumption on the electricity grid , which reduces the need for fossil power stations that cause serious pollution.

Renewable energy is penetrating into the power system more and more. A technical issue for the PV power is its great fluctuation due to the variation of weather. The output of a PV panel on a sunny day is relatively smooth. But on a cloudy day, a PV panel produces a variable power output due to the motion of clouds. The movement and the size of clouds can be random and irregular. Therefore, the output of a PV panel is also irregular. Such variations in a power system can bring issues on reliability in a power grid and high risks to electrical equipment. Another key characteristics of renewable energies (solar or wind) is their dependence on weather conditions. They are not controlled by people, but by natural factors.These two problems need to be addressed. One is called smoothing. It means how to make PV output smooth in order to bring less impact to the power system. Another is shifting; it is about how to shift consumer daily load profile to maximize use of PV output and minimize utility's peak load. Around these problems, energy storage showed great usages in these two aspects.

According to these needs, researchers design several kinds of storage systems working with PV system. Through storing and using PV power the variation of PV power is absorbed. Right now, there are several storage ways used to compensate the great variation of PV power, such as, batteries and diesel machines.For this project, we utilize a battery storage system with a large PV array to make PV farm output stable and reliable for the utility.

Since the advances in technology are beginning to make battery cost effective, there are huge demands for battery right now. In 2008, the demand for batteries is around \$ 36 billion on the world market. For 2013, there is an estimate about \$ 51 billion for batteries [2].

Smoothing is to adjust a battery to charge or discharge to compensate rapidly varying PV output. A battery is connected with a PV power in parallel. In this way, the power penetrating into the grid is controlled. There are a lot of parameters influencing the results of smoothing and shifting. The capacity, the charging and discharging rates, and the ramping rate of the battery power output need to be studied and optimized in order to have good results. A moving average algorithm is used to address the smoothing problem.It is designed to calculate the rate of charging and discharging based on the real time PV output. The battery makes the output smooth through fast charging and discharging the feeder every second. A moving median algorithm is also tested. It can save the capacity of battery better than moving average algorithm. A double sliding window algorithm is proposed to further improve the smoothness. A series of simulation are done with the GridLAB-D and Matlab software for these three algorithms.

Since the load is not constant for the whole day, many backup power plants only work at peak load times. Many facilities are only used for hundreds hours a year for the peak hour of the power demand.If utility companies could store PV power for peak load times, they could eliminate a considerable investment for the backup and peaking plants.It's a practical way to reduce the equipment cost and the deferral of system upgrades by using battery. Shifting means moving the PV output from the low-demand time period into another high-demand time period through storing the power with battery and discharging it later. Peak shaving management needs to be designed so that batteries can provide power directly to the load in the peak-load time. The times to charge and discharge the battery need to be addressed in the shifting.

The focus of this thesis is how to make the battery effectively and safely conduct smoothing and shifting in the power system. Both smoothing and shifting algorithms are introduced. The GridLAB-D software is used to model the battery and the PV power.Different discharging rates means different battery capacities. In this thesis, we assume the capacity is a constant.

The following sections in this chapter will give some basic concepts of PV, VRLA batteries which are used in this project's energy storage system.

1.2 Introduction to PV

Photovoltaic (PV) cell is a technology that transforms solar irradiation into direct current electricity. PV power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. The solar spectrum consists of different wavelengths which correspond to the different amounts of energy (photons). When photons strike a PV cell, they may be reflected or absorbed, or they may pass right through. The absorbed photons excite electron hole pairs inside a PV cell into a higher state of energy. A flow of electrons act as charge carriers for an electric current [3].

The PV output power will reduce greatly if solar insolation is reduced by clouds. It is hard to forecast the PV output power accurately, hence energy management and operation is a challenging due to uncertainty of PV output forecast.

1.3 Introduction to Lead Acid Battery

Valve-regulated lead acid (VRLA) battery is one type of lead acid batteries. The lead acid battery was invented about 150 years ago. It is the oldest rechargeable battery. It has low energy-to-weight and energy-to-volume ratios, but it has a relatively large power-to-weight ratio hence it can provide a high surge current. Considering these features and its low cost, it is a good choice for energy storage in renewable energy systems.

When the battery is in discharged state, a chemical reaction occurs between the sulphate acid and the lead in the plates immersed in the acid. This reaction generates electricity through a flow of electrons from the plates. The sulphuric acid is consumed and produces water in this reaction. When the battery is recharged, the reaction is reversed. The electrons go back to the plates, and the water becomes acidic again [4].

If the battery is overcharged, some hydrogen gas is released. This gas can accelerate the reaction and bring the battery to a fuller charge. The gassing can boil the water in the battery, and then lead to overheat of the battery. It will shorten the life time of the battery [5].

Chapter 2

The energy system

2.1 Introduction to the VRLA

The storage system is composed of four parts: a PV solar array, a smoothing battery, a shifting battery and an inverter. Figure 2.1 shows the structure of this system. When the PV solar array connects with the smoothing battery directly, the great variation of the battery output causes the life time of the battery shortened. In this system the battery and the PV plant are paralleled and connected with the inverter which is connected with the feeder.

2.2 The introduction of PV power

The solar PV array is rated at 0.5 MW as its peak power output. The output of the PV array depends on the temperature, the solar flux and the cloud conditions. There are five sensors to collect solar flux information in different positions of the array. The PV output is connected with the feeder through the inverter.

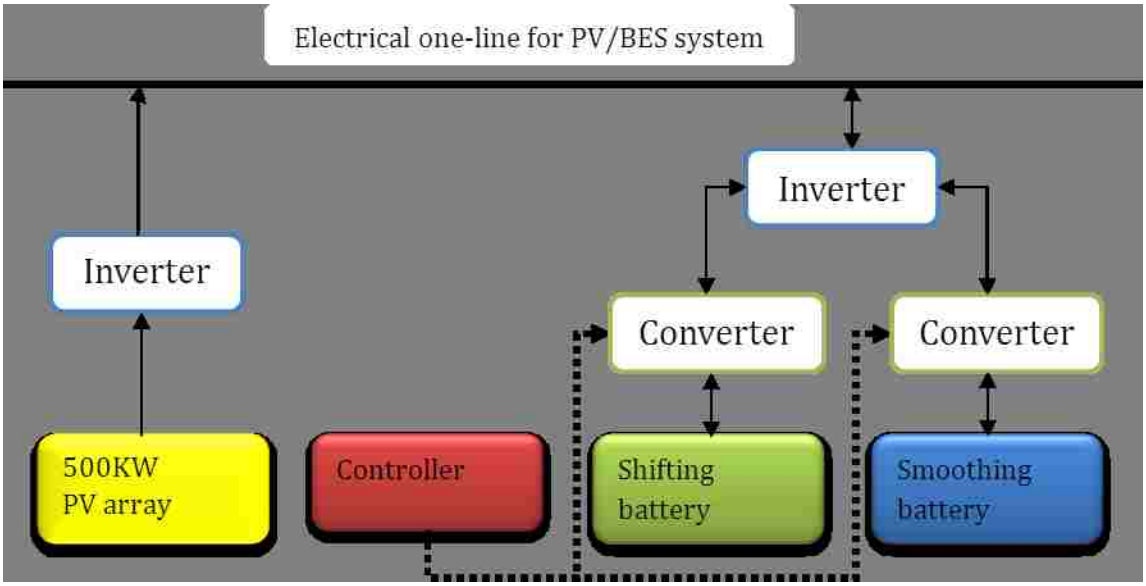

Figure 2.1: Energy Storage system

2.3 The introduction of battery system

The rating of the smoothing battery is 0.5 MW. The rating of the shifting battery is 0.25 MW/ 0.99 MWhr. To smooth variations in the output of a solar power, the smoothing battery in the storage system needs to change the charging rate and discharging rate frequently. Standard VRLA battery can't meet the need in such situation. The negative plate will accumulate a large quantity of lead sulfate, and then less surface of negative plate can deliver and acquire the power. A new battery named "ultrabattery" can address this problem. It has merits of both an ultra-capacity and a VRLA battery. The Ultrabattery is a VRLA battery exhibiting ultra-capacitor features for rapid discharge applications. The second shifting battery is the Advanced Carbon Battery, which is a VRLA battery exhibiting a significantly longer cycle-life than those batteries with the standard VRLA technology. The combination of these two battery technologies enables long-life VRLA batteries to be deployed with Solar PV power plants. Such batteries can smooth power generation that is interrupted by variable clouds, and shift power to a later time of a high power demand.

2.4 Power conversion system (PCS)

The PCS concludes two converters and one inverter. The two converters are connected with the shifting battery and the smoothing battery separately to convert the DC of the battery into a certain DC voltage. Then the two converters are connected with one inverter which inverts DC into AC. A 0.5-MW bi-directional DC Converter works for the Smoothing Battery System. A 0.25-MW bi-directional DC Converter works for the Shifting Battery System. The converter collects the information of DC voltage and DC current of both batteries. The inverter is one 0.75-MW bi-directional DC-AC and AC-DC inverters in this system. An AC filter filters the inverter output and there are two DC filters for each battery input. The inverter is controlled and protected by a digital processing unit, a master controller. The inverter collects the information of AC current, AC voltage and DC voltage of the battery system.

2.5 Introduction to the controller

There are two controllers in this battery energy system (BES)(see Figure 2.2). One is called the application controller which is dedicated to derive the active and reactive power references for the battery systems. Another controller is the BESS Master Controller which is used to collect all of the information of the battery systems, and sends the control signal to the power conversion system (PCS).

A battery monitor in the system is composed of a digital processing unit, propri-

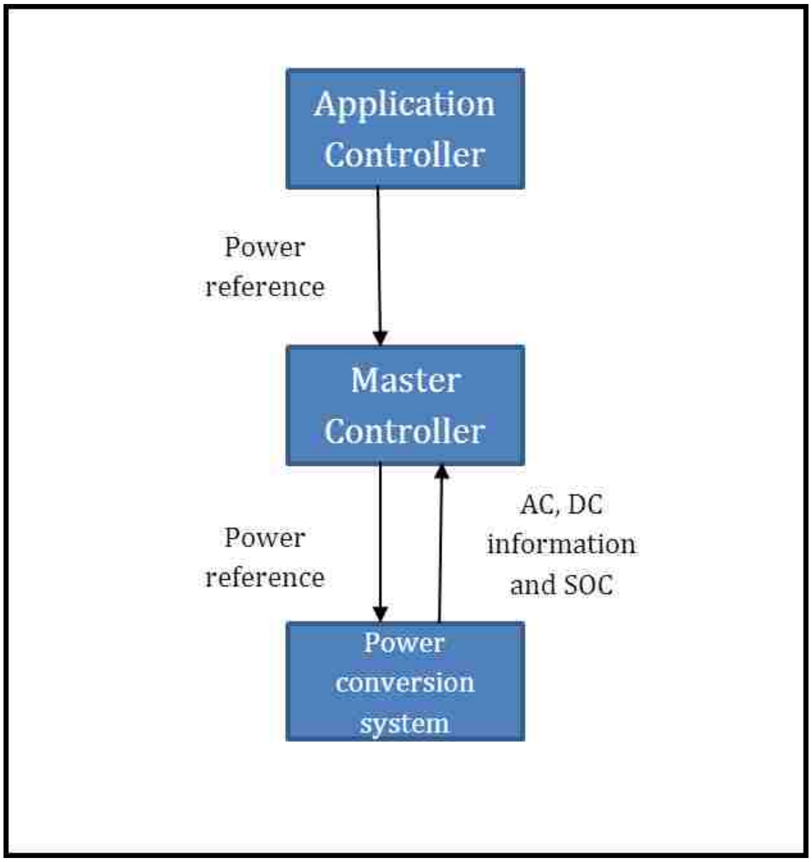

Figure 2.2: Controller

etary cell sensors and a fused DC isolation switch to protect and isolate the output of the battery. The monitoring system can pass the Master Controller the charging status of the battery. The master Controller get the information from the PCS and the battery monitor. The information includes the following for both the shifting battery and the smoothing battery:

- DC Power
- DC Voltage
- DC Current per String

- Battery State of Charge

The power reference derived from the application controller goes to the PCS through the Master Controller. The converters of the PCS use the active power(P) reference to regulate the power output of the battery. The inverter of the PCS uses the reactive power(Q) reference to regulate the reactive power output.

Chapter 3

Introduction to the modelling of the battery

3.1 Introduction to GridLAB-D

GridLAB-D ^{TM} was developed by the U.S. Department of Energy (DOE) at Pacific Northwest National Laboratory (PNNL). It is a new power distribution system simulation and analysis tool. An amount of advanced end user models are developed in this software. It makes it possible for researchers to study distribution system installed with latest technologies. It's agent-based and information-based modelling tools. Researchers can create detailed models of each house level. The simulation can give valuable information about how new end-use technologies, distributed energy resources (DER), distribution automation, and retail markets interact and evolve over time.

3.2 Introduction to modelling

Here is an example of battery model in GridLAB-D.

```
object battery {
  parent battery_meter;
  name battery_central;
  generator_mode CONSTANT_PQ;
  V_Max 8000;[V]
  I_Max 250; [A]
  P_Max 250000;[W]
  E_Max 500000;[Whr]
  base_efficiency 0.86;
  parasitic_power_draw 190 W;
  power_type DC;
  generator_status ONLINE;
  Energy 1000000;[Whr]
  scheduled_power 250000;[W]
  }
```

In the battery model, some rules are as following:

- The battery must be connected with a meter, a triplex meter or an inverter.
- Parent means the meter that the battery is connected with.
- Parameter Name gives every battery a specific name.
- Generator_mode consist of three types: CONSTANT_PQ, Power_drive and Hybrid power and voltage control.

Discharge Power	Usable Energy	Discharge Time
250 kW	990 kWhr	3.9 hrs
200 kW	1060 kWhr	5.3 hrs
150 kW	1155 kWhr	7.7 hrs
100 kW	1280 kWhr	12.8 hrs

Table 3.1: The discharge power and useable energy of the shifting battery

- The Following four parameters define the maximum voltage, current, power and energy when the battery is running in the system.

Here are our battery specifications:

- Smoothing Battery System:

  Charge: 500 kW within a voltage range from 660 to 775 VDC

  Discharge: 500 kW within a voltage range from 700 to 580 VDC

- Shifting Battery System:

  Charge: 250 kW within a voltage range from 660 to 775 VDC

  Discharge: 250 kW within a voltage range from 700 to 580 VDC

From Table 3.1 we can see the capacity of the shifting battery changes with the discharging rate. There is more usable energy when the discharging rate is small. For example, there are 30 % less usable energy for a 250-kW charging rate than a 100-kW charging rate. The battery can't tolerate deep discharge or deep charge. Otherwise it is overused. The battery need to maintain the state of charge between 40 % to 80 % of the maximum capacity.

According to the manufacture specification, the battery is modelled as below.

```
object battery {
     name battery_1;
     parent batterymeter_1;
     generator_mode CONSTANT_PQ;
     V_Max 775;   DC
     I_Max 758;   DC
     P_Max 500;   500kW
     E_Max 100;   100kWhr
     base_efficiency 0.9;
     parasitic_power_draw 50 W;
     power_type DC;
     generator_status ONLINE;
     Energy 50;   50kWhr
     scheduled_power ;
    }
```

A runtime class is used to control scheduled_power, the value showed in the battery model above. The runtime class has the following characters:

- Defined by user
- Override the build-in object behavior
- Creates a new class
- Both private C/C++ and public GridLAB-D properties allowed
- Requires procedure definitions

re A runtime class named smoothing class controls the battery behaviours. A smoothing algorithm is defined in this class. The smoothing class controls the battery to charge or discharge according to the calculation results of smoothing algorithm.

Chapter 4

The smoothing algorithm

4.1 The PV variability

The total PV production can be split into two components: one relatively smooth signal that corresponds to daily irradiation pattern in a clear sky ? , and another high-frequency intermittent component, which is due to clouds and is much less predictable. On a sunny day, the irradiation is mostly composed of the first component. In a cloudy day, the irradiation is composed of both components as shown in Figure 4.1.

Figure 4.2 shows the irradiance varies greatly. The resolution of data is 1 second. In this figure the variation can be up to 15 % of peak irradiance every second. But it may be even higher for an ever more intermittent PV irradiance day. The severity of variance depends not only on the weather, but also on the size of system. A small system will have greater variance in the output than a multi-MW PV farm.

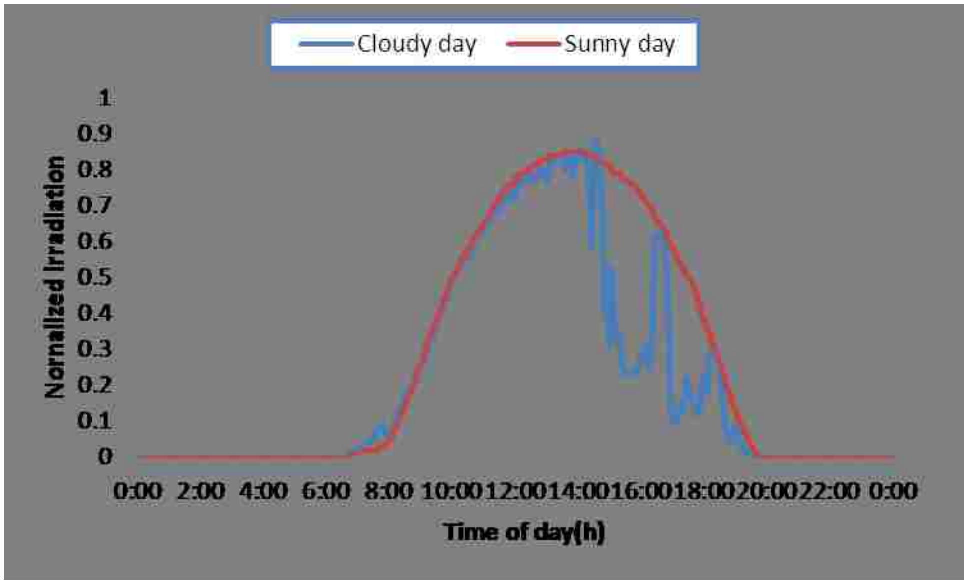

Figure 4.1: Solar normalized irradiation

4.2 Moving average algorithm

Given a series of numbers and a fixed subset size, the moving average can be obtained by first taking the average of the first subset. The fixed subset size is then shifted forward, creating a new subset of numbers, which is averaged. This process is repeated over the entire data series. The moving average can be obtained by making the average of a fixed sized subset. The subset moves forward, and a new average can be obtained through the subset. This process removes high-frequency variability from the PV power. It is repeated over the entire data series [6]. Figure 4.3shows this process.The blue line is the smoothed result.

In Figure 4.4, the blue line represents the irradiation for a very typical cloudy day. The irradiation is collected at one second. From the diagram, the PV output drops from 300 kW to less than 100 kW in seconds. That's about 30 % of the prior PV output. Also, in the diagram the PV output can jump to 3 times larger than the

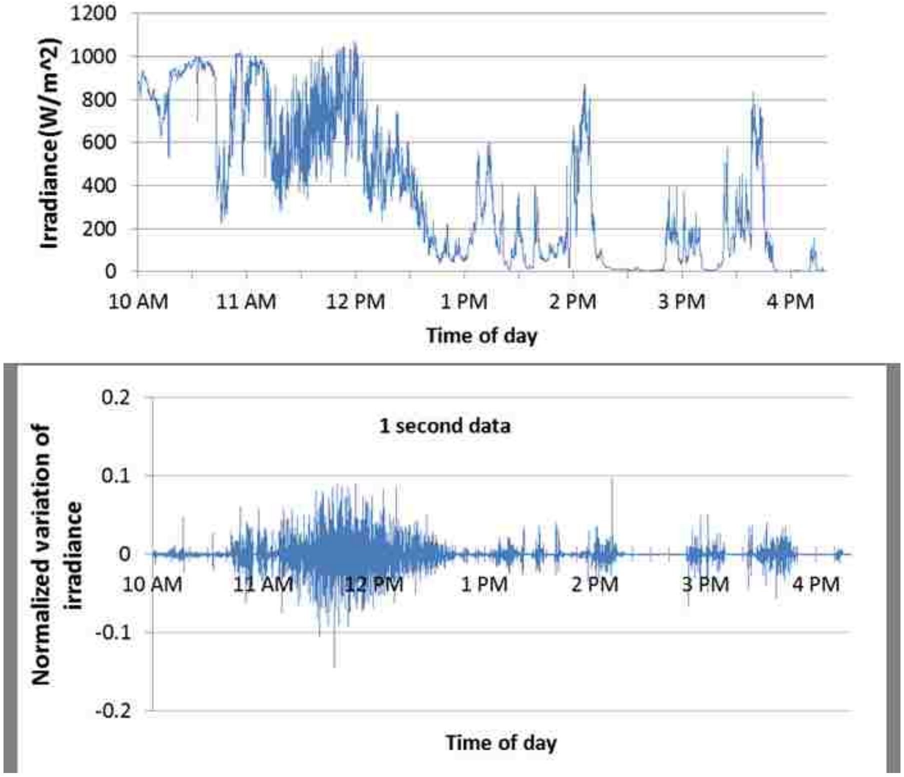

Figure 4.2: Irradiance of a cloudy day and normalized irradiance variance

prior PV output. The green line represents the PV output after the smoothing with the moving average algorithm. The transient fluctuations are removed.

The next issue is how to design the window size. Different window sizes can produce different smoothing results. The bigger the window size is, the smoother the result will be for certain weather.But the smoothed curve will lag the real signal accordingly. For the different window sizes, the requirements of the charging rate and the discharge rate of the battery are different also. Usually larger window sizes need relatively larger charging rates and discharging rates. But the requirements for the charging rate and the discharging rate don't solely depend on the window size. Meanwhile, the battery has a ramping rate limit. The ramping rate alters

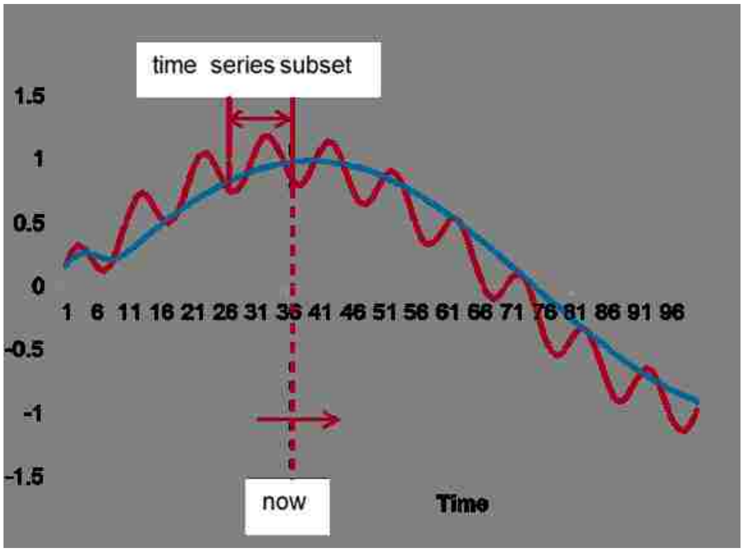

Figure 4.3: Moving average

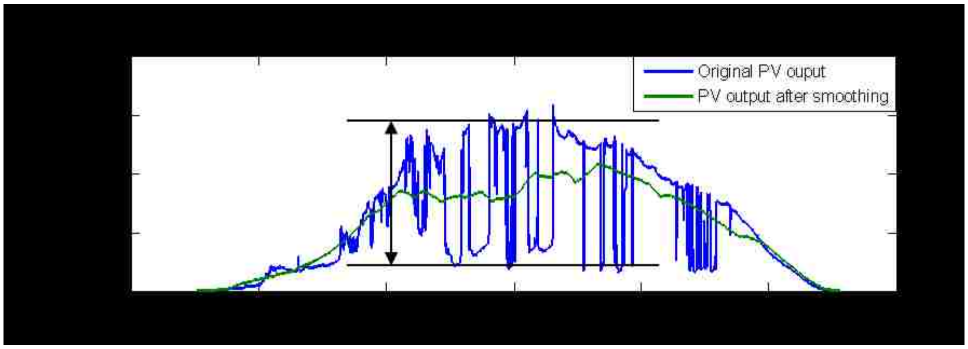

Figure 4.4: Irradiation of a cloudy day

with different window sizes . In the following sections, the relationship between the charging rate, the discharging rate, the ramping rate, the capacity and window sizes has been studied. This study will help us to find out how we can design the smoothing algorithm.

4.3 Parameters study

4.3.1 Maximum charging rate and discharging rate

In this section, the relationship among the charging rate, the discharging rate and the window size is studied. Decisions on the charging and discharging rates will depend heavily on the weather conditions during a particular day.Note that this simulation, a day with a significant cloud covering in the afternoon was intentionally selected to illustrate our findings, resulting in a very non-uniform PV power curve. The smoothing battery is keeping rapid power variations to within less than 10 % of the target value. The day is shown in Figure 4.2.

Next, we study how big the charging rate and discharging rate will be. The following equations show the the upper limits of the charging rate and the discharging rate.$Power_{refer}$ represents the reference value of PV output power, and the PV_{output} represents the real PV output power. The difference between these two values is the power the battery system need to provide.This value also means the charging rate or discharging rate of the battery system. We use $Power_{need}$ to represent it.

$$Power_{need} = Power_{refer} - PV_{output}; \tag{4.1}$$

If $Power_{refer} \geq PV_{output}$, the system begins to discharge the battery. since $Power_{refer} \leq Max(Power_{output})$ and $PV_{output} \geq 0$,

$$Power_{need} = Power_{refer} - PV_{output} \leq Max(Power_{output}) - 0 = Max(Power_{output}) \tag{4.2}$$

Here, the positive $Power_{need}$ means discharging rate of battery. Its value is smaller than the maximum output of PV.

If $Power_{refer} \leq PV_{output}$, the system begins to charge the battery. Since $Power_{refer} \geq 0$

$$Power_{need} = Power_{refer} - PV_{output} \geq 0 - max(PV_{output}) = -max(PV_{output}) \tag{4.3}$$

Here, the negative $Power_{need}$ means charging rate of battery. Its absolute value is smaller than the maximum ouput of PV.

So, $max(PV_{output}) \geq Power_{need} \geq -max(PV_{output})$

$$|Power_{need}| \leq max(PV_{out}) \tag{4.4}$$

The equation above means the absolute value of power needed from the battery is equal and less than the maximum generated PV power, which means the charge rate or discharge rate won't beyond the rating of PV power. In this system, the PV farm capacity is 500 kW. So the 500kW battery is big enough for this system.

Figure 4.5 shows the battery system charges or discharges the battery according to the $Power_{need}$.

Next, we study how much power is needed in reality. In the simulation, we don't set the limit to the power output. The battery will output power according to how much power is needed in order to get the best smoothing result.

The battery power needed in a certain weather is showed in Figure 4.6 for different window sizes. The maximum power ranges around from 50 % to 70 % of the rated power when the window sizes are from 10 minutes to 120 minutes. The maximum power happens when the window size equals to 80 minutes. The smallest power happens when the window size equals to 10 minutes. The ratio of these two power value is 1.33, and the difference is about 18 % of the rated power. In general the power will not increase with the window sizes linearly. However, the average of the

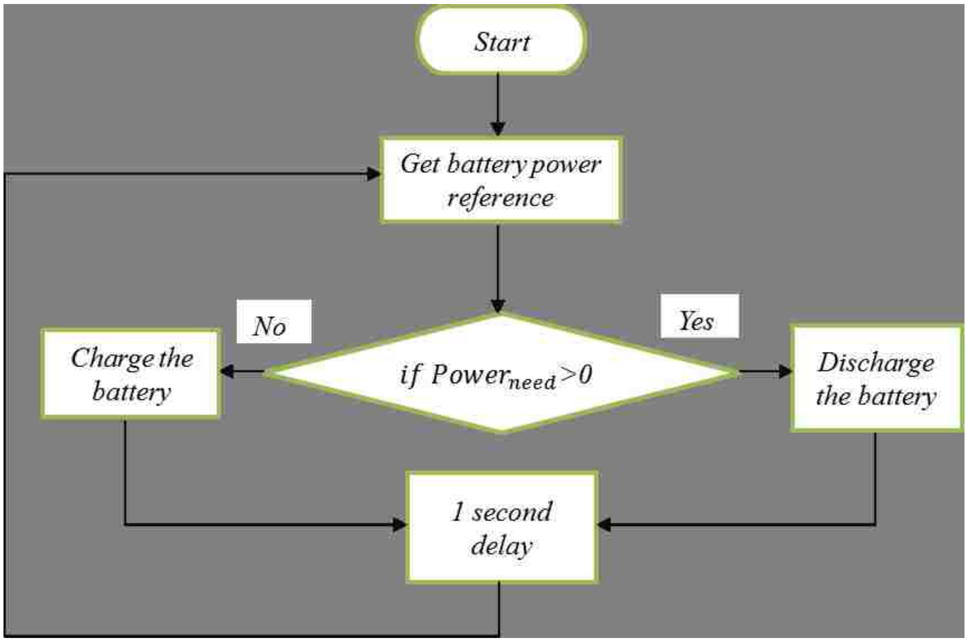

Figure 4.5: Flow Chart

maximum power for the window size between 70 minutes to 120 minutes is larger than the average of maximum power needed for the window size between 10 minutes to 60 minutes.

We can learn that the maximum power needed is dependent not only on the window size, but on the weather conditions.

4.3.2 Average discharging rate and charging rate

The average discharge rate and charge rate are related to the usage of the battery. Higher average charge rate indicates that the battery is used deeper. Since the average discharge rate is usually the same as the average charge rate. In this section, the absolute values of these two parameters are used to observe the changes of these two rates.

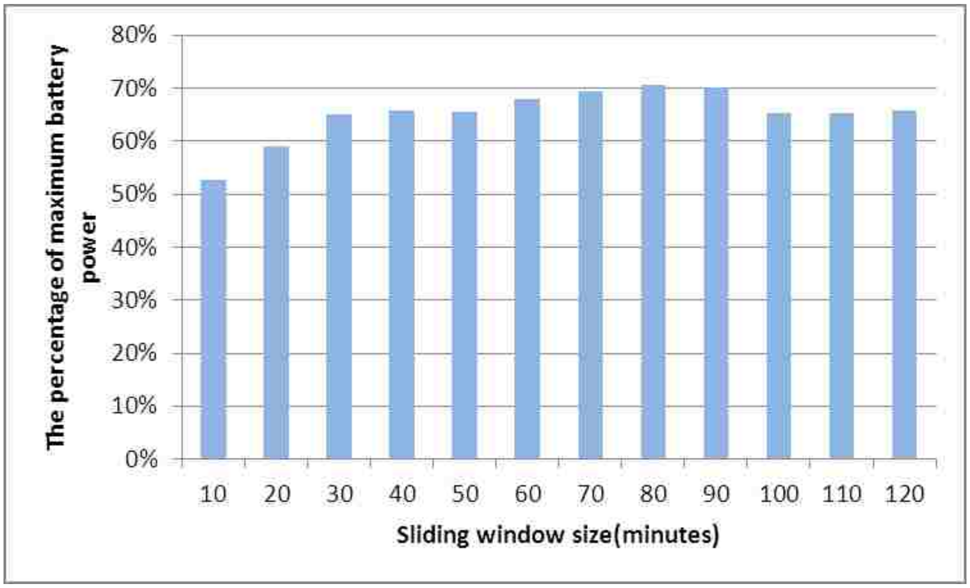

Figure 4.6: Charging rate and discharging rate needed for different window sizes

A 6-hour solar irradiance data is put into the solar model. The time of the solar irradiance data is from 10 am to 4 pm. The following diagram shows the irradiance for every hour from 12:00 pm to 4:00 pm and the corresponding average charging rate and discharge rate. The time period between 12 pm to 4 pm is divided into four time slots, 12:00 pm to 1:00 pm, 1:00 pm to 2:00 pm, 2:00 pm to 3:00 pm and 3:00 pm to 4:00 pm.

Four each time slot, the rates change with the window size, and have a trend of increase. But it doesn't always increase with the window size. The average rate of the battery not only depends on the window sizes, but also depends on the weather.

When window size is 10 minutes, the average rate is about 10 % of rated rates for these four different cases. When window size is 120 minutes, the average rate ranges from around 15 % to 33 % of rated rates.

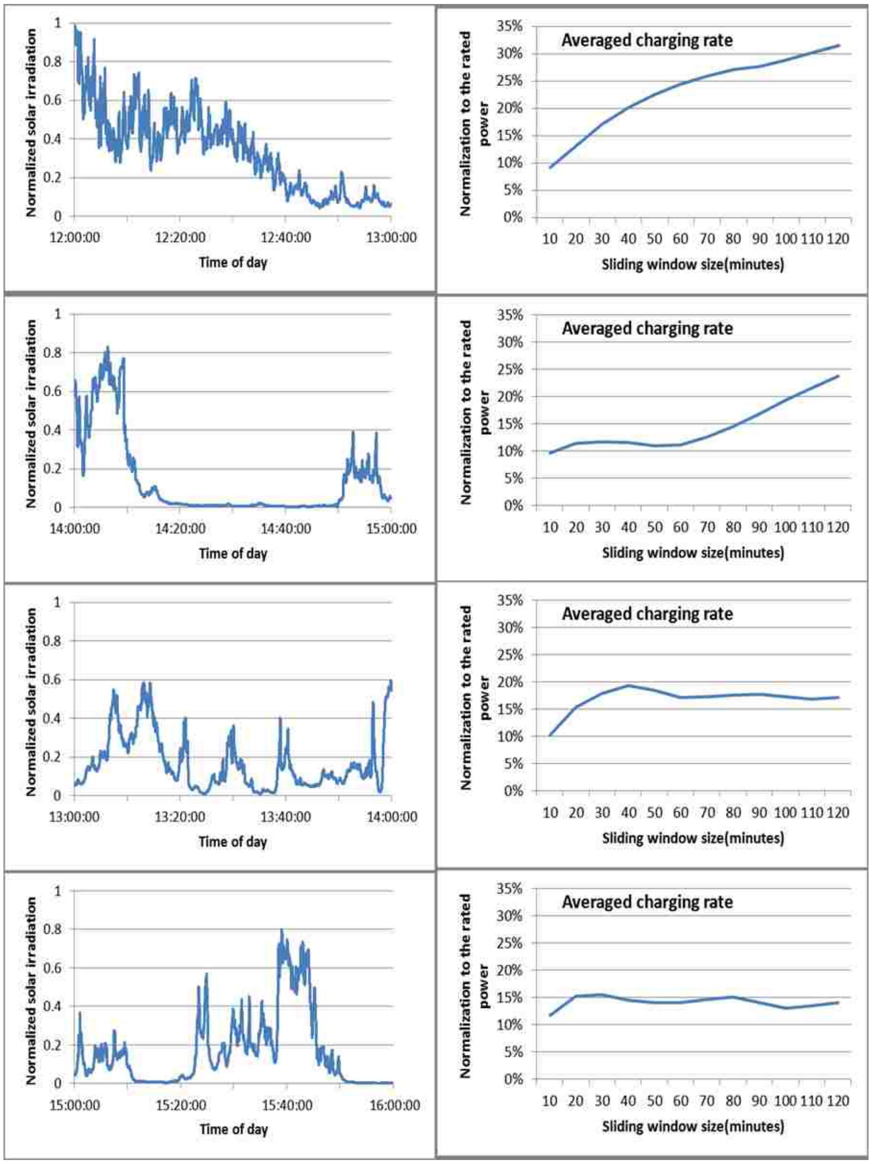

Figure 4.7: Average charging rate

4.3.3 Smoothness

The standard deviation of the PV output is used to measure the smoothness of the figure. A lower standard deviation means a smaller PV irradiance variation. From

Figure 4.8: Standard deviation of smoothed results

Figure 4.8, we can see that the standard deviation decreases with the increasing window size.

No matter what the weather is, a larger window size leads to a smoother battery output(see Figure 4.9). The more data involved in the calculation, the more smooth the result is. So the window size can determine how smooth the output is. The size can be chosen based on the requirement of the smoothness. For example, if the system require the normalized standard deviation to be lower than 0.27, the window size can be set as 1200 minutes (see Figure 4.8).

4.3.4 Capacity

Figure 4.10 reveals that the capacity varies with the window sizes evidently. For this battery storage system project, the battery need to maintain the SoC within a band of ± 100 kWhrs (total bandwidth of 200 kWhrs) while maintaining an average

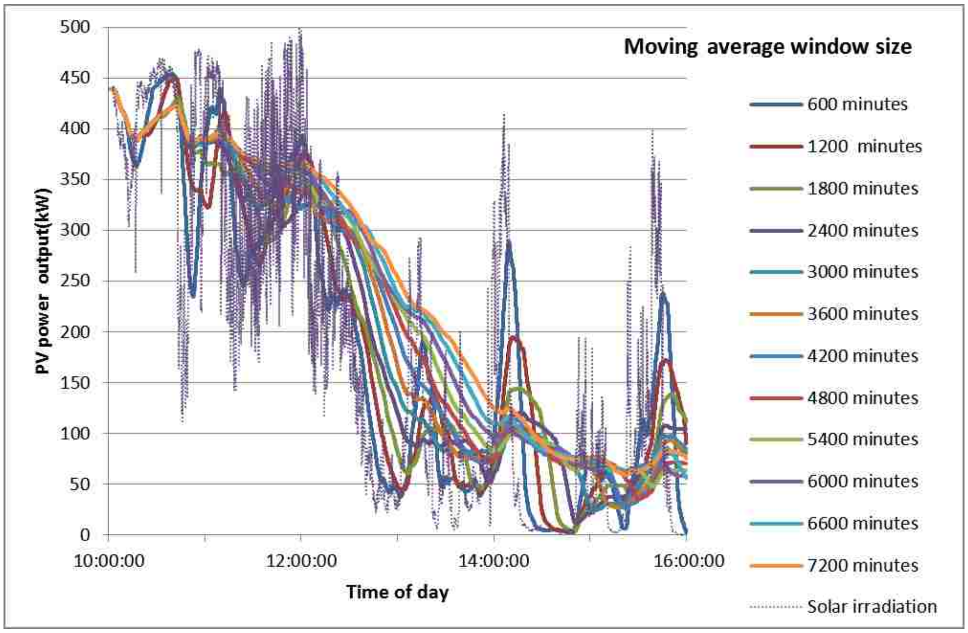

Figure 4.9: Smoothing results for different window sizes

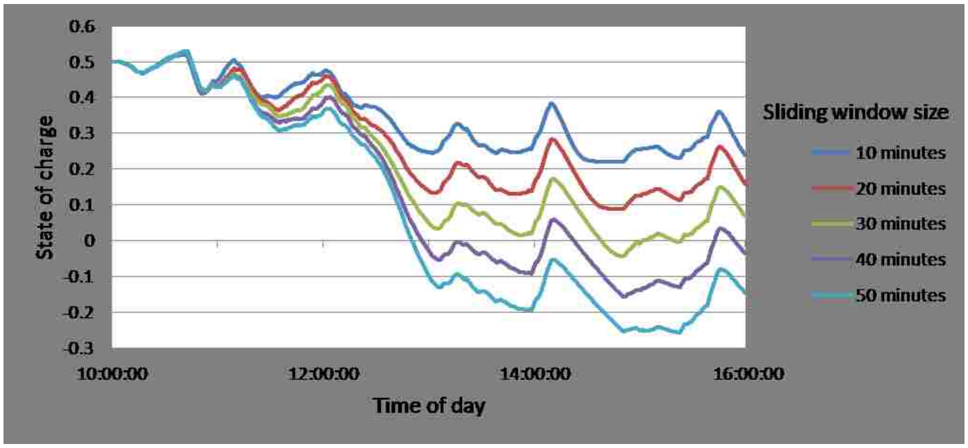

Figure 4.10: Capacity

SoC over a 1 hour period equal to the nominal SoC. According to this constraint, the status of charging(SOC) needs to to maintain between 10 % to 90 % of the rating 250 kWhrs. When the window size is 30 minutes, the SOC drops below 10%. Therefore a storing power is needed in addition to the smoothing to offset the battery losses.

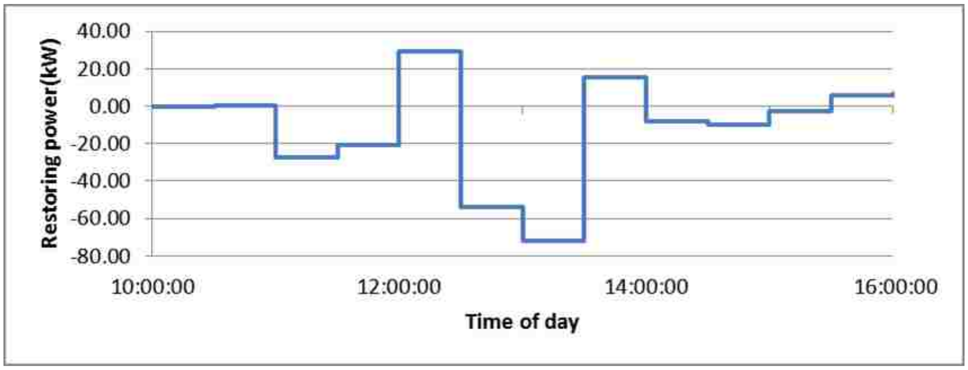

Figure 4.11: Restoring power

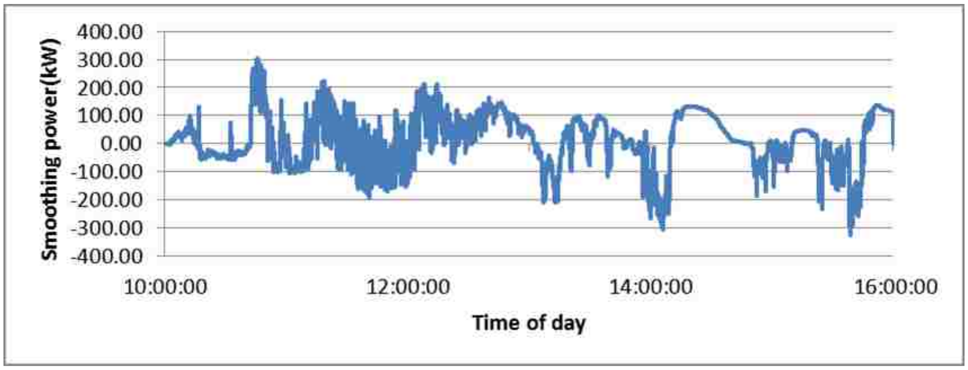

Figure 4.12: Smoothing power

In order to make the SOC is consistently close to 50% of rating, the restoring power needs to be proportional to the difference between the current SOC and 50% of the rating. Usually the reference power for every second is determined by the sum of the weighted smoothing power and weighted restoring power. The restoring power is set based on the difference between the current SOC and 50% of the rating for every second. The restoring power works against the smoothing to some extent . If the smoothing power plays a leading role in the reference power, the SOC of the battery

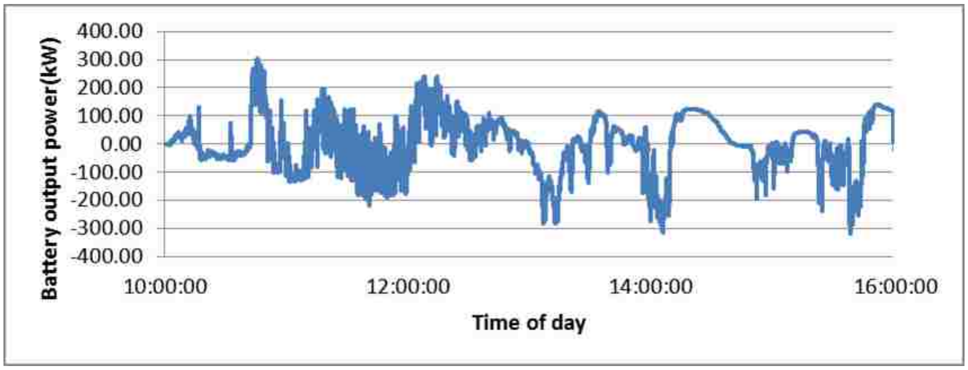

Figure 4.13: The battery output

may reach the set limit. If tracking the SOC is overemphasized, the smoothness of the results will be affected. So this method's drawback is that it's hard to get the perfect smoothing results and keep the SOC close to the nominal SOC at the same time. In this thesis, a new method is proposed to address this problem. The restoring power is set same value for each half hour instead of changing the value according to the SOC every second. It won't affect the smoothing results since the restoring power is kept evenly for each half hour.

Figure 4.11 shows the restoring power used to restore the battery's capacity; Figure 4.12 is the smoothing power used to smooth the PV output; Figure 4.13 shows the sum of restoring power and smoothing power. Figure 4.14 shows the smoothing results are almost same smooth for both cases, but the capacity of battery using restoring power is much closer to 50% of rating than not using restoring power. In summary, the restoring power can help restore the capacity of battery, but doesn't affect the smoothness of PV output.

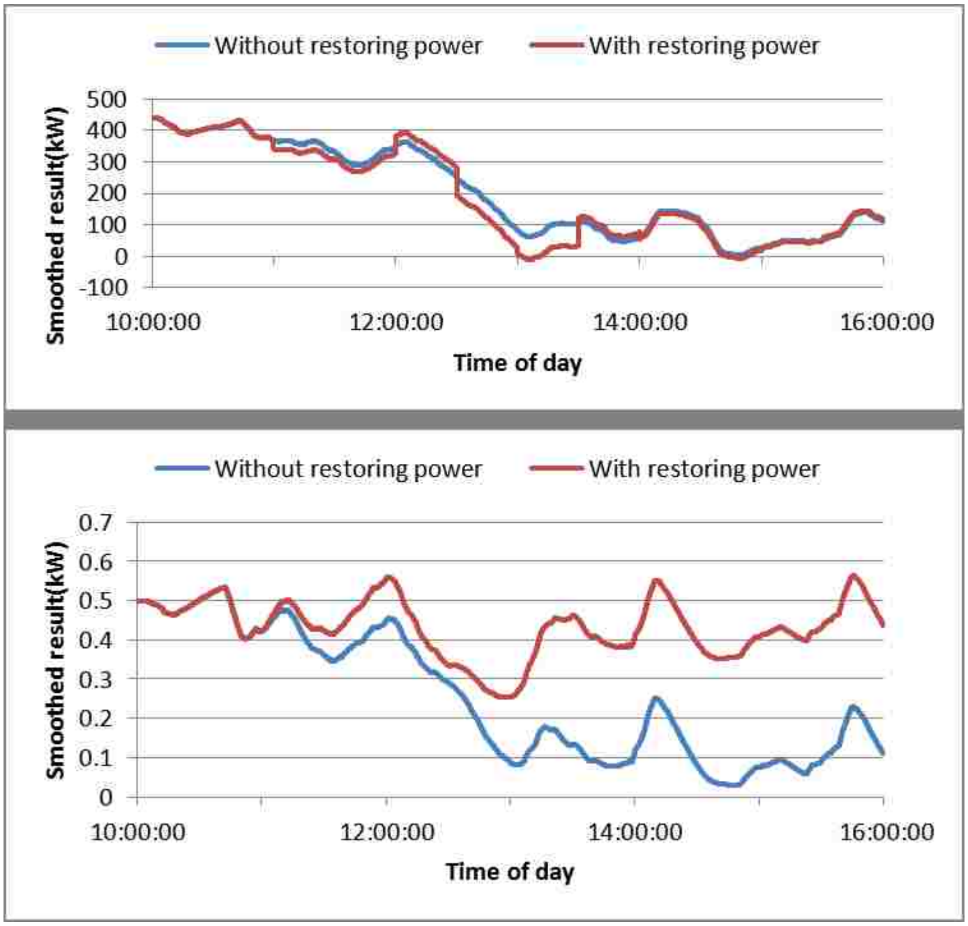

Figure 4.14: The comparison between tracking SOC and not tracking SOC

4.3.5 Ramping rate

Another important concern with the control of battery system is the change of charge/discharge rates (or "ramping" rates), which needs to be kept under the manufacturer's specified values. It is the rate of change in the instantaneous output from a battery. It is established to prevent undesirable damaging due to rapid changes in charging or discharge of a battery.

The ramping rate limit of battery is 60 kW/s. The ramping rate doesn't increase as the window size increases. The Figure 4.15 shows the ramping rate needed in the smoothing algorithm if we don't set a limit to it. In the figure the ramping rates for the window size 600 s and 7200 s are almost the same. The ramping rates are in the range of 60 kW except for one point. Most of ramping rates vary between +40 kW/s and -40 kW/s.

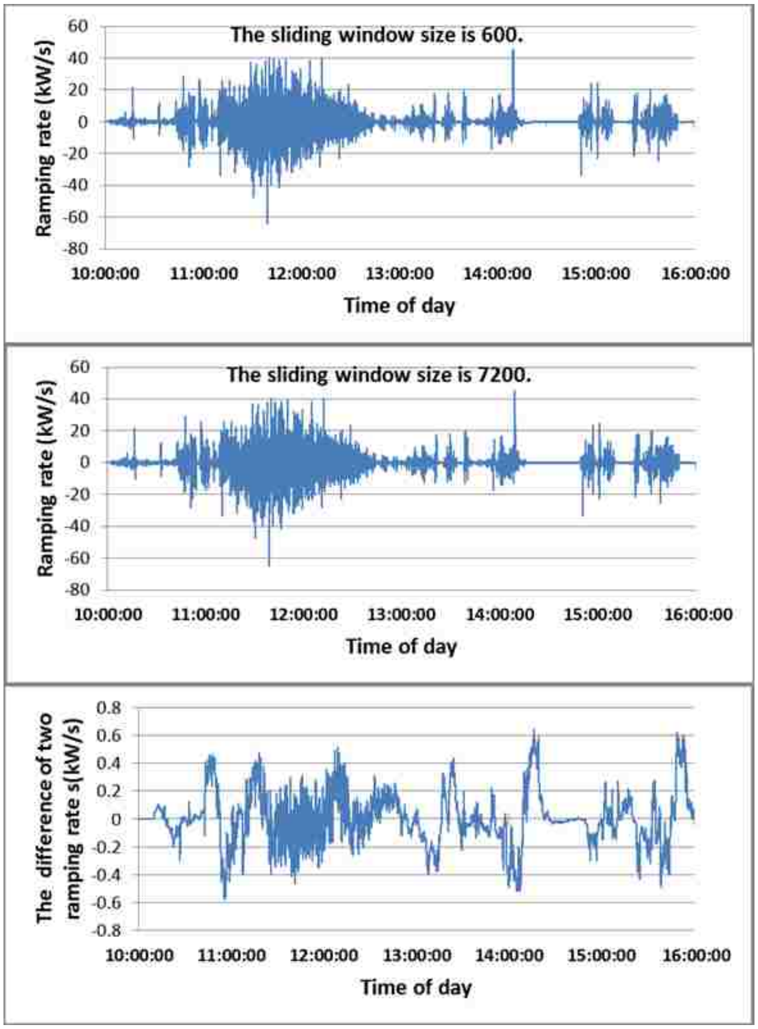

Figure 4.15: Ramping rates of two different window sizes

The difference between these two ramping rates is less than 1 kW/s. Comparing to the rating of 60 kW/s, this difference can be ignored. Therefore, the ramping rate changes minimally with the window sizes.

Next, we limit the the ramping rate to a smaller value. Some spikes appear in the output. The ramping rate is set as 24 kW/s, 30 kW/s, 36 kW/s, and 42 kW/s to observe the ramping rates' effects on the smoothing result.

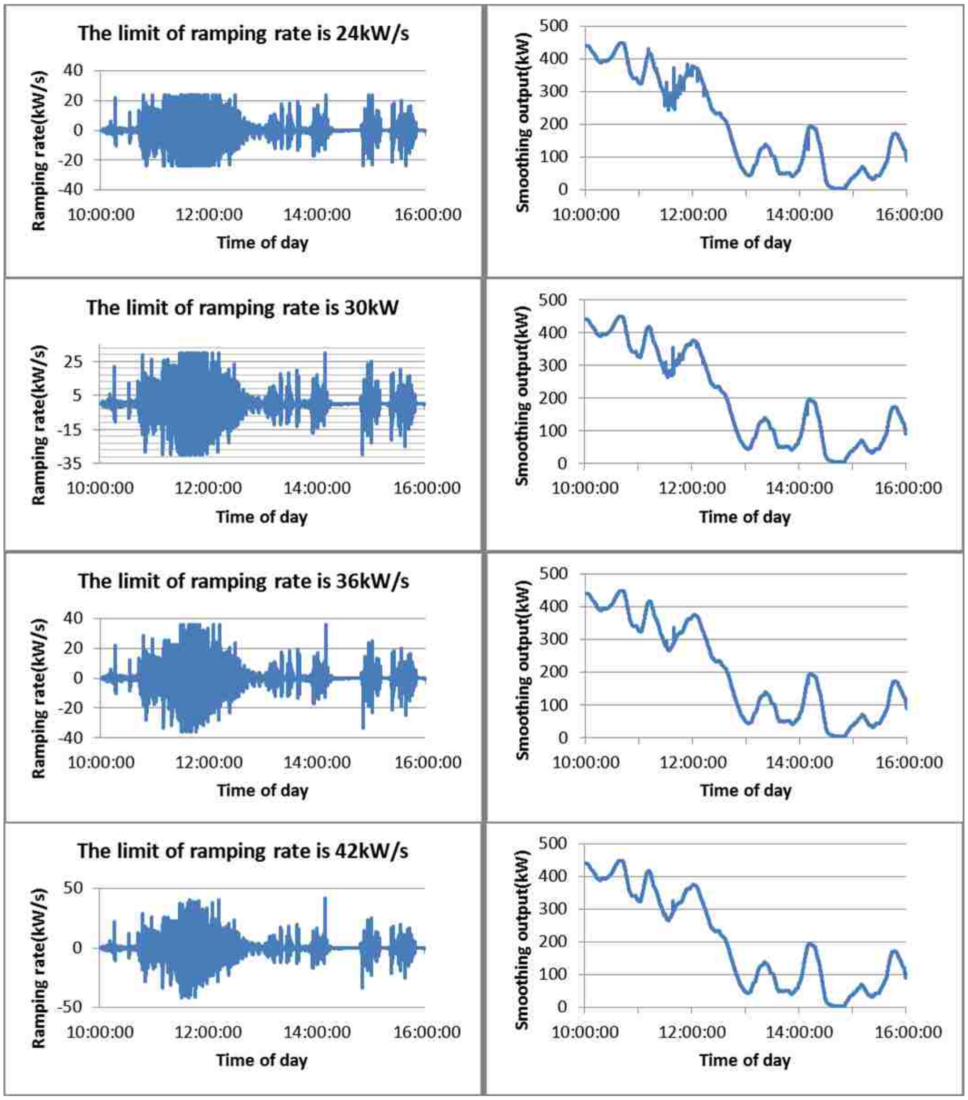

Figure 4.16: The smoothing results for different Ramping rate limits

Figure 4.16 shows smaller ramping rate can bring the smoothed PV output a lot of spikes. Especially spikes appear where the weather changes intensely. According to the requirement of this project, the rapid power variations need to be kept within less than 10 % of the target value (50 kW). The Figure 4.16 shows the power variations for these four ramping rates. Though the limited ramping rate will bring a lot of spikes to the smoothed PV output, the rapid power variations is still kept within 50 kW. In summary, ramping rate limit won't affect the smoothing results greatly for this weather.

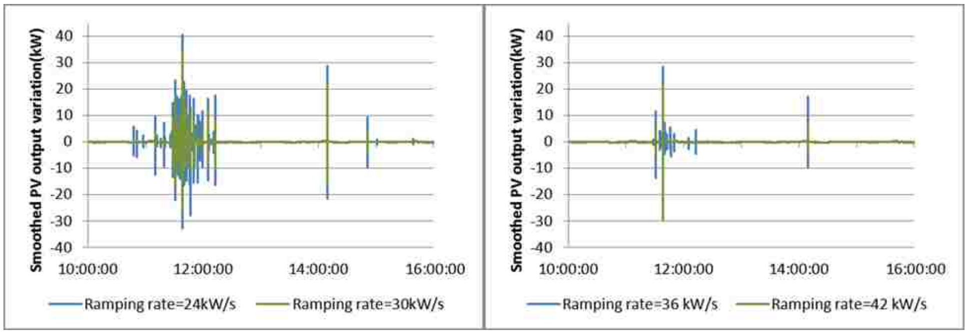

Figure 4.17: Smoothed pV output variation

How much is the ramping rate needed in reality is an issue we need to consider.In the weather we studied in this thesis, the solar variation is about 10%. The 10% of variation indicates the ramping rate of the battery won't beyond the 10% of the rating of PV output power. That will be 50 kW/s for this case. From the diagram 4.16, we know ramping rate of 50kW/s can meet the requirement of smoothing.

4.4 Moving median algorithm

From a statistical point of view, the moving median can track the trend of the PV outputs better than moving average since it underplayed a lot of rapid shocks or other

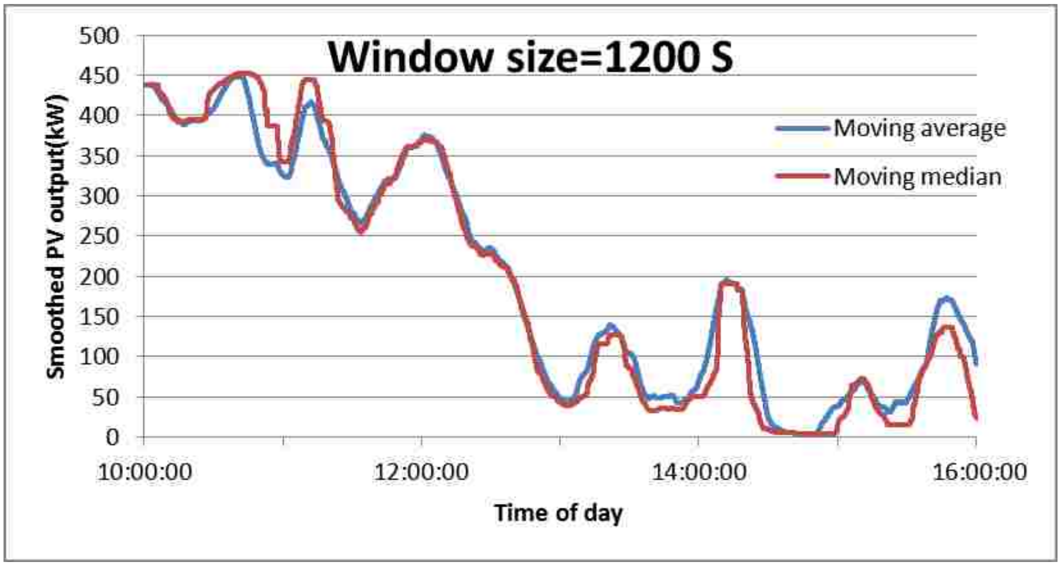

Figure 4.18: Comparison of smoothing result between moving average and moving median

anomalies. Moving average calculates the average of a subset. If the subset includes a lot of anomalies, the amount of rapid changes which isn't representative for the trend is counted with the good data. But moving median tracks the median for a time series of results, and the rapid shocks is ignored by it. It's more robust to the variations brought by the clouds. Figure 4.18 presents the different results generated by these two algorithms. Apparently, the result from moving average algorithm is more smooth than the result from moving median algorithm.

Since the trend of PV can be tracked better than the moving average, the less charging rate and discharging rate is needed. The battery use less capacity than the moving average.

Different window sizes are used in the moving median algorithm as the moving average algorithm. The window sizes 600 s, 1200 s are chose to make a comparison with moving average. In Figure 4.19, we can see in the moving median SOC is closer

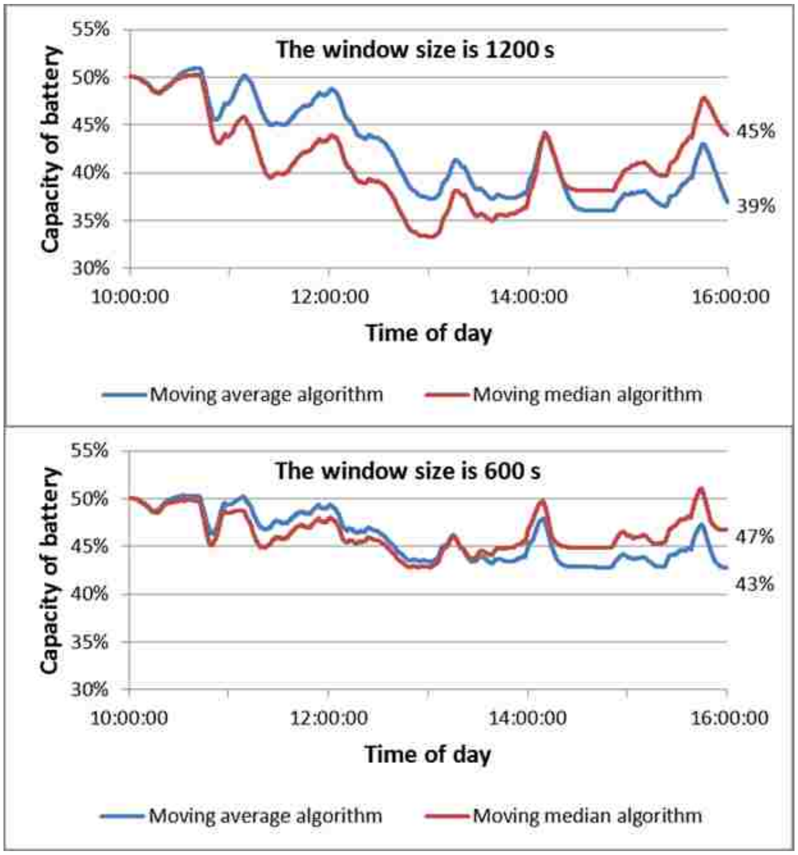

Figure 4.19: Comparison of capacity beteen moving average and moving median

to 50 % of rated capacity than moving average.

4.5 Double moving average algorithm

In order to make the output smoother, window algorithm can be used twice. The result will be smoother than that from using window algorithm once, but the ramping rate and SOC keeps the same. From Figure 4.20, we can see the result from double moving average algorithm is smoother than moving average algorithm. Next, we will compare the charging and discharging rate, ramping rate and SOC for these two algorithms.

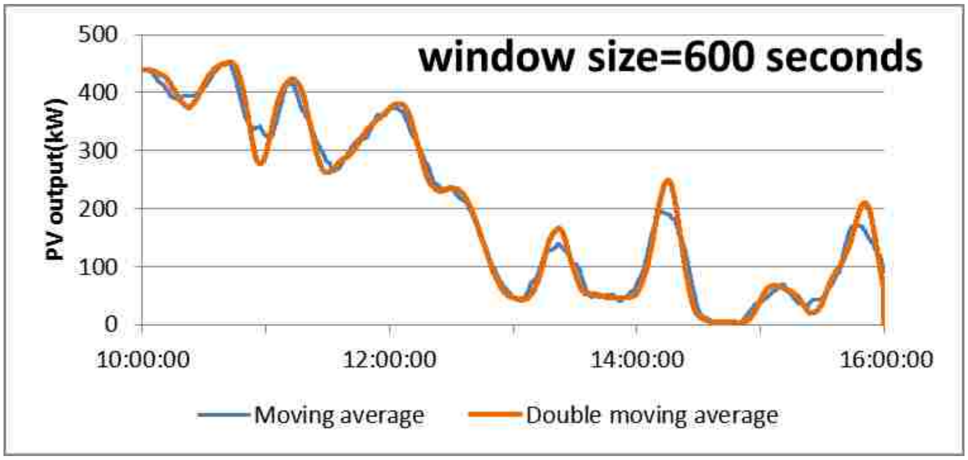

Figure 4.20: The comparison of smoothness

From Table 4.1, we can see the double moving average algorithm need slightly higher charging and discharging rate than moving average.

window size	Moving average	Double moving average
600	54 %	58 %
1200	60 %	66 %
1800	65 %	67 %

Table 4.1: The comparison of charging and discharging rate

The ramping rates are almost same for these two algorithms. 60kW/s is enough for both algorithms (see Figure 4.21). Both of ramping rates vary between 40kW/s and -40kW/s mainly.

From Figure 4.22, we can see the change in SOC is almost same for double moving average algorithm and moving average algorithm.

The different window sizes lead to the result with different smoothness. There are apparent changes between the results using the algorithm once and twice.

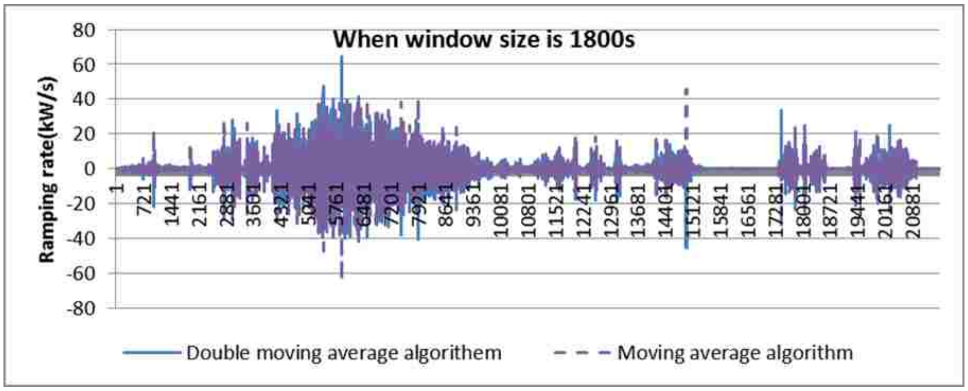

Figure 4.21: The comparison of ramping rates

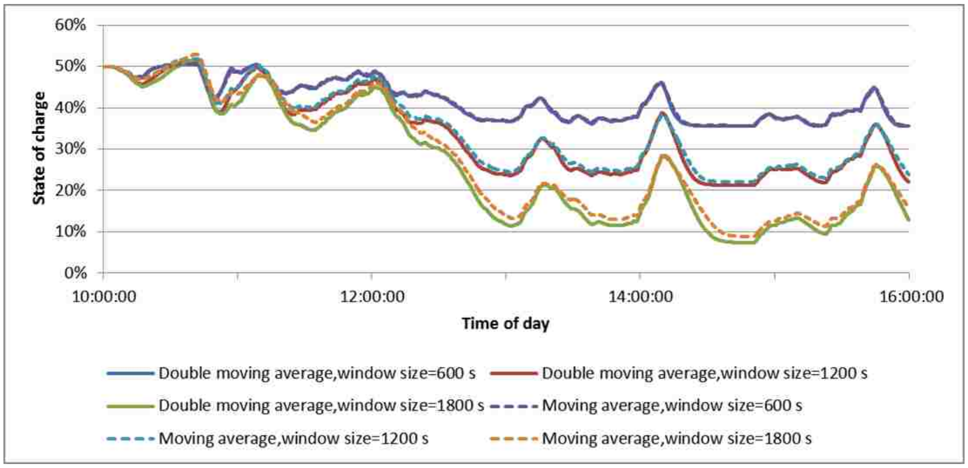

Figure 4.22: The comparison of capacities

4.6 Comparison of three algorithms

For the charging rate and discharging rate, the 500kW is big enough for any algorithms and any window sizes. For the ramping rate, there is almost no difference among the three algorithms.

The only two aspects differentiate the three algorithms are the degree of smooth-

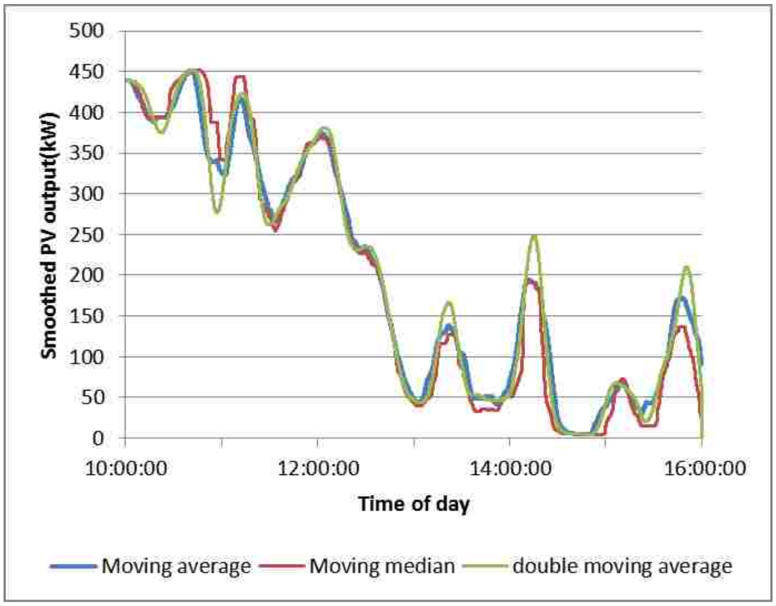

Figure 4.23: Comparison of smoothness for three algorithms

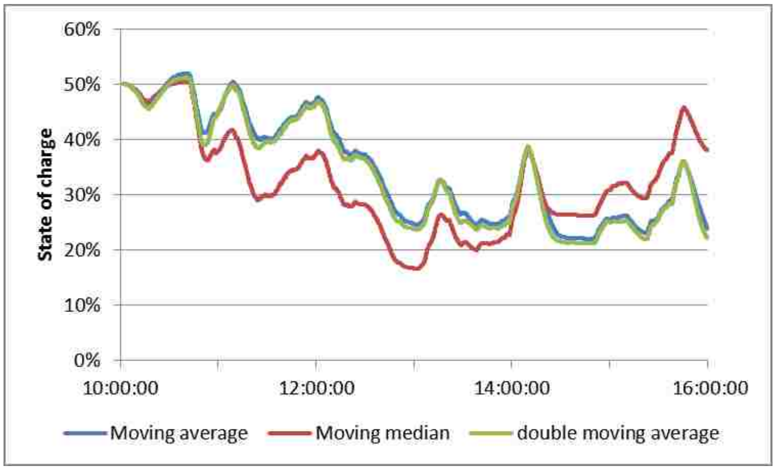

Figure 4.24: Comparison of SOC for three algorithms

ness and the value of SOC. Figure 4.23 and 4.24 show that the comparisons of smoothness and SOC for three algorithms.Obviously the double smoothing algorithm generates the smoothest result among the three algorithms. The result from moving median algorithm is a little coarser than the result from moving average in some time, but almost same.

For the SOC of battery system, the SOC of moving average and double moving average are almost same most time. The SOC of moving median are closer with 50% than two other algorithms.

In summary, the double moving algorithm can generate most smooth results, and the moving median can use less capacity of battery to do smoothing.

4.7 Delay

All of former smoothing results are based on an assumption: there is no delay in the digital controller and battery can delivery power as the controller commands instantly. However, it takes time for controller to calculate the battery reference, and battery needs time to response the system also. If delay exists in the smoothing, the battery system will compensate the PV output according to outdated and inaccurate battery reference. There will be a lot of power spikes in the PV output. The Delay is an important issue needed to consider. Here is the result when the system has delay (see Figure 4.25).

When the delay is one second, the power output variation is still under 50 kW. When the delay increases to two seconds, the power output variation is beyond 50 kW at 3 points. Once the delay reaches one second delay for this weather condition.

Meanwhile, the clouds take time to pass over plant and changes of PV output become slower as plant size increase [7]. PV power output is not only related with solar irradiance, but also related with spatial-temporal effect. When the clouds pass over the PV farm, the PV panels at different positions produce different value of electricity [8].

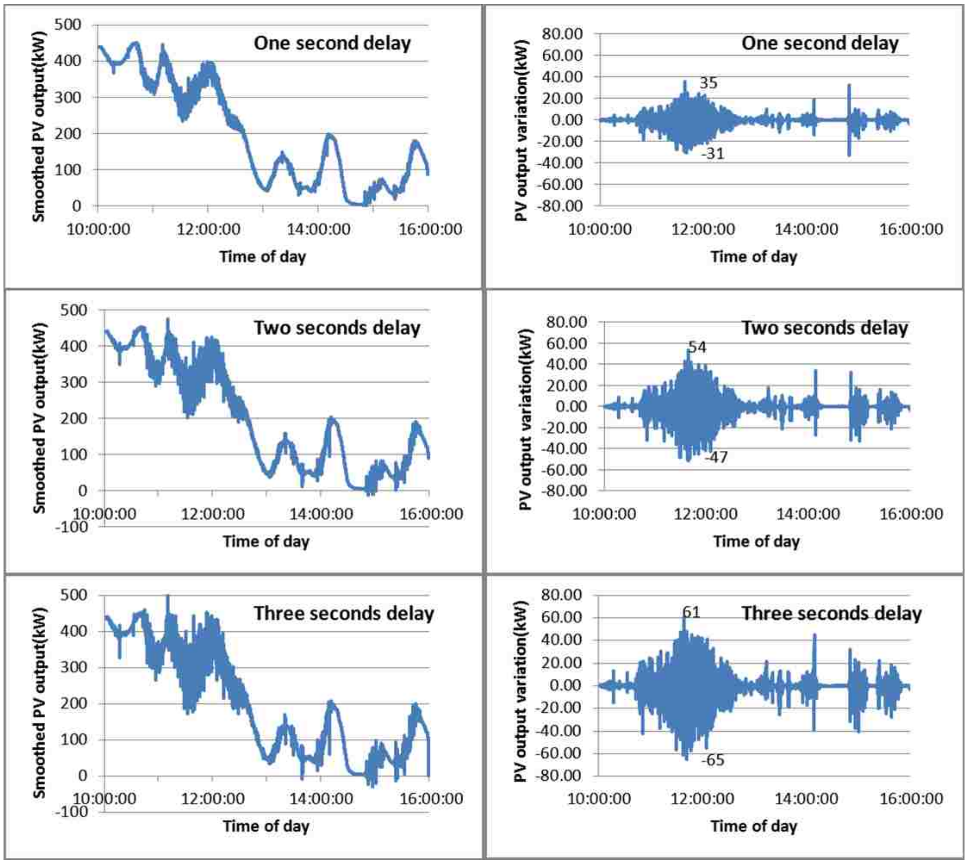

Figure 4.25: The consequence of Delay

When these different electricity add together, it becomes less variable as shown in Figure 4.26. The variability of output of a PV plant will not directly correspond to the variability of irradiance measurement observed by a point . In [8], the author find that Large 1-s, 10-s, and 1-min ramps in the multimega watt PV plant are approximately 60 %, 40 %, and > 10 % less severe, respectively, than those observed at a point. And the power change at the inverter is slower than a single solar panel. For a multimega watt PV farm a cloud usually passes through the farm in minutes rather than seconds. The battery system delay is in the order of seconds. So this delay can be ignored. But this needs to be verified with more data. At the same time, considering the spatial-temporal effect of big PV farm, the spatial average of irradiance should be used to calculate the battery reference instead of one point irradiance [7].

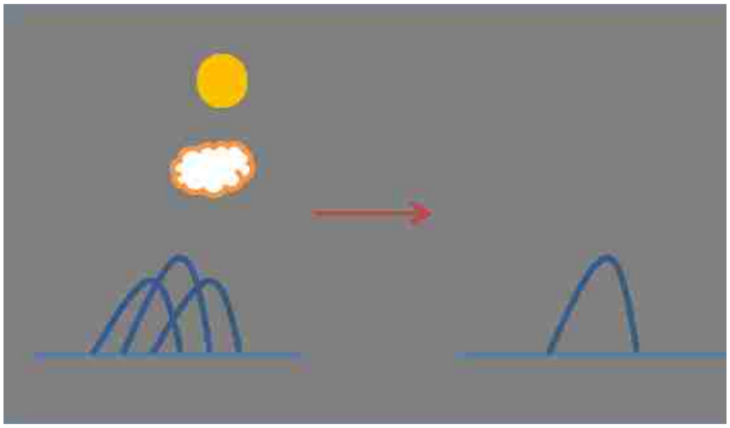

Figure 4.26: The power variation for a PV farm

Chapter 5

The shifting algorithm

5.1 Introduction

The goal of shifting algorithms is to identify a combination of start/stop times for both charging and discharging of the shifting battery, along with the optimal charge / discharge rates for a given feeder configuration. Figure 5.1 illustrates the peak shaving of the peak power by scheduled controlled discharge of the power from the battery over a course of several hours.

During morning hours, when there may not be enough power produced by the PV system alone, controlled discharge from the battery reduces the demand to a required level. When PV power exceeds the load, the excess power is used to re-charge the battery.

In Figure 5.1 black electrons means the battery gets charged from the power grid.The electricity are generated mostly from coal, natural gas and nuclear plant. The green electrons means the battery gets charged only from PV output. The battery discharged at 7pm. Noticeable peak load reduction can be observed from the figure below.

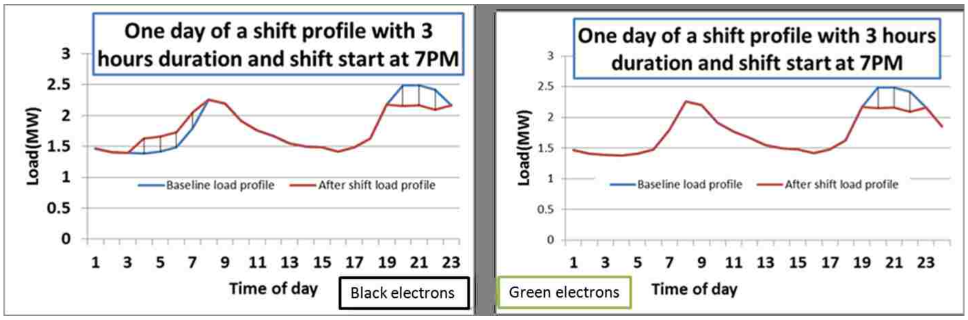

Figure 5.1: Shift profile

5.2 How is the benefit calculated?

There are 70 different cases in Figure 5.2and 5.3 . Each point represents a case. For example, the first point from the left in the lowest line represents the benefit if the battery starts to discharge from 11:00 am for 1 hour.

As the battery system has three years warranted performance,we calculate the benefits it could bring in 3 years. The unit, \$/kW, means how much cost savings each kW battery operation will bring in 3 years. For example, 400 \$/kW means a 100 kW battery will bring 400 × 100= \$40000 benefits to the power system for the ideal shift scenario. (Here the 100 kW means the charging rate of the battery, not the capacity.)

The Load Shifting algorithms, as described before, is to identify a combination of start / stop times for both charging and discharging of the shifting battery, along with the optimal charge/discharge rates for a given feeder configuration.

Because the different prices for different hours, the benefit of one typical day is calculated. Then it is multiplied by 1000 to represent 3 years. This estimation is based on the many assumptions: the weather is same for every day of summer or winter. The price information for 2005, 2006, half year of 2007 is used. The average of price in summer is used for the day. The average and the load data for 4 days in different seasons are used.

Right now the result is only a rough estimate since it's assumed that the capacity of the battery isn't changing with the discharging rate. The discharging rate is assumed to be constant for each case. The battery system is designed for a warranted battery life of three years based on one cycle per day, a cycle being defined as a full charge and discharge of usable energy.

Since the purpose of this study is to investigate cost-effectiveness of battery storage solutions for different parameters, one of the main economic criteria which can be used as a common denominator for comparison, is the avoided costs benefit. For the purpose of this study, the avoided cost benefits include electrical energy, losses, ancillary services, system (generation) capacity, transmission and distribution capacity, environmental costs, avoided additional renewable energy purchases, as battery system life-cycle cost. A detailed financial model will be adopted to make these economic evaluations in-depth and accurate in future work.

From Figure 5.2 and 5.3, some optimal points can be found. For summer, the most optimal point is a battery starts to shift the load from 12:00 am for 7 hours. For winter, the most optimal point is a battery starts to shift the load from 2 pm or 3 pm for 7 hours. Then 1 kW charging rate can bring the power company \$ 600 benefit in summer, \$ 400 benefit in winter for its whole lifetime. If we assume half year is summer, half year is winter. Then a battery with the size of 1000 kW can save the cost about $1000 \times (600+400) \div 2 =$ \$ 500,000 for its whole lifetime if we don't count the cost of battery system.

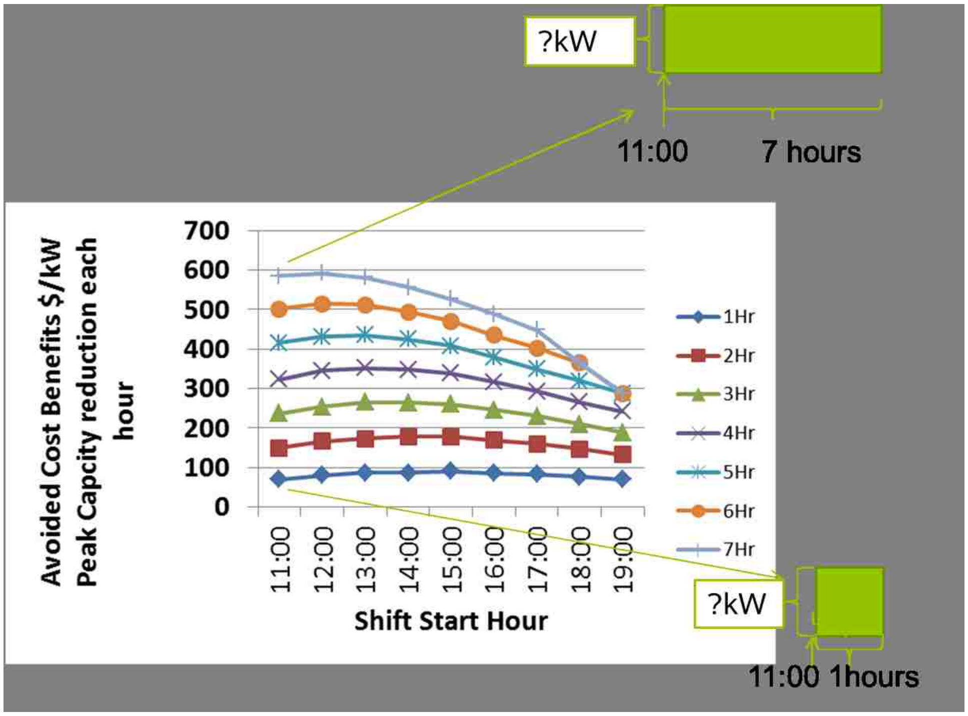

Figure 5.2: Shifting in the summer

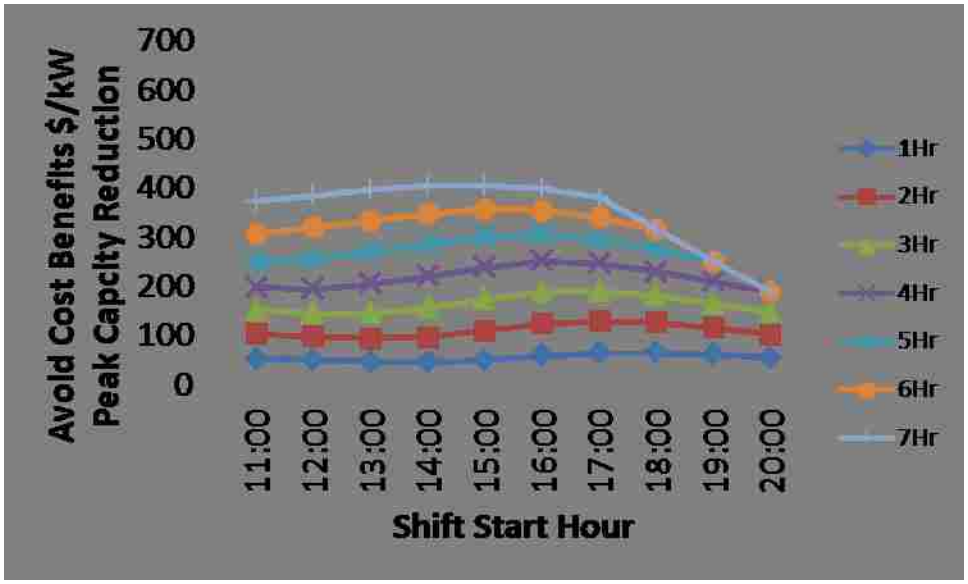

Figure 5.3: Shifting in the winter

Chapter 6

Conclusions and future work

A brief description of the battery storage system is presented in this thesis, along with the description of detailed parameters analysis. Modelling results are presented showing the result of load shifting, smoothing, and the algorithms configurations.

Multiple benefits can be quantified throughout smoothing and shifting. The benefits include: economic (lower renewable electricity cost, firming of the dispatchable resource, lower peak fossil fuel from traditional peaking resources, lower total energy consumption, lower distribution system losses from optimized T & D network, generation closer to load, and lower O & M cost), reliability and power quality (smoothing of PV intermittence, fewer severe sags and swells), environmental (increased value of PV and battery acting as a dispatchable resource), as well as financial value proposition to electrical customers of the utility (which may include incentives) [9].

Future work encompasses complete models for more of shifting control strategies, comparing the economic and energy benefits metrics, and comparing these results with the actual test results from the site. And the relations between the characteristic of battery output and the solar irradiation in utility scale will be observed and analysed furthermore. The weather forecast will be added into the model.

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