EFFECTIVE PV OUTPUT FLUCTUATION SMOOTHING BASED ON FREQUENCY ANALYSIS AND DIFFERENT WEATHER PATTERNS

by

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A Thesis Submitted in
Partial Fulfillment of the
Requirements for the Degree of

Master of Science
in Engineering

at

The University of Wisconsin-Milwaukee

May 2017

ABSTRACT

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The University of Wisconsin-Milwaukee, 2017
Under the Supervision of Professor David Yu

As the Hybrid Energy Storage System (HESS) has the advantages of both power-based and energy-based energy storage devices. It is suitable for a microgrid to smooth the power fluctuation. Analyze the power data of a grid-connected photovoltaic (PV) power station. This research considers grid-connected PV requirements to join the HESS and take advantage of the HESS charge and discharge characteristics to reduce the problems caused by light intensity and temperature change of grid-connected PV power output fluctuations. Using battery optimization control strategies to reduce power and capacity of the HESS configuration. This paper Analyze the effect evaluation when HESS rated power and capacity changed. In addition, proposed a strategy that using methods to decide the most representative day among a year. Fast Fourier Transform (FFT) is applied to transform the solar radiation to the frequency domain. The simulation results verify the feasibility of this strategy and method.

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Introduction

1.1 General Background Information

In recent times, global warming is a burning issue as the CO2 density increased highly in the atmosphere due to the massive usage of energy, there is a rapid depletion of energy resources. Because of the urgent need for energy, clean and renewable energy sources must be introduced to reduce the CO2 density. Therefore, many countries are moving in the direction of developing and introducing new sources of energy, especially renewable energy. Among various renewable energy systems, one of the most abundant and infinitely renewable energy sources is solar energy. Photovoltaic (PV) systems are expected to play a promising role as a clean power electricity source in meeting future electricity demands. Their uses are widespread in industrial, farming, and transportation system area. This research will focus on the solar radiation absorb by the solar panel and the optimization of the storage system.

In the future, when a significant number of PV systems will be connected to the grids of power utilities, power output fluctuation may cause problems like voltage fluctuation and large frequency deviation in electric power system operations [1]-[3]. The issue of smoothing out power fluctuations in PV generation are to be smoothed has attracted widespread interest and attention. However, the power output of PV systems fluctuates depending on weather conditions, season, and geographic location. Therefore, for the penetration of large PV system’s output power in the utility without reducing of the reliability of utility power systems, suitable measures must be applied to the PV systems side. Several control strategies and configurations for hybrid energy storage systems such as Battery Energy Storage System (BESS) [4]–[8], superconducting magnetic energy system (SMES) [9], a flywheel energy system (FES) [10], an energy capacitor system (ECS) [11]–[15], and a fuel cell hybrid system [16], have been proposed to smooth solar power fluctuation or enhance power quality. There are many kinds of batteries which have different characteristics such as energy storage density, charge/ discharge rate, life cycle, cost, etc. When using BESS to control PV power fluctuations, which can provide flexible energy management solutions that can improve the power quality of renewable-energy hybrid power generation systems, there is a trade-off between battery effort and the degree of smoothness. That is, if one is willing to accept a less smooth output, the battery can be spared some effort. However, energy storage devices increase capital cost, as they needs maintenance. The maintenance cost mainly depends on charge/discharge action of batteries. Thanks to the rapid development of batteries, battery energy storage systems recently have recently begun to be utilized for multiple applications such as frequency regulation, grid stabilization, transmission loss reduction, diminished congestion, increased reliability, wind and solar energy smoothing, spinning reserve, peak-shaving, load-shifting, uninterruptible power sources, grid services, electric vehicle (EV) charging stations, and others.

Logically, the installation of an ESS has a major impact on the energy/economic balance of the PV system, playing a key role in the viability of the future PV systems due to their high costs and reduced shelf life. There have been investigations aimed at improving the performance of PV systems equipped with batteries. As a result, parameters such as energy capacity, losses and the cycling degradation of the ESS, take on particular importance. Any reduction in both the ESS capacity required and charge/discharge cycles will have a positive impact on reducing the investment required to install and maintain the ESS. Consequently, the control strategy selected in order to smooth the fluctuations will be a crucial decision. Nevertheless, given the maximum fluctuation limitation, there is a range of control strategies to reduce the fluctuations to under this limit. At present, the two most often proposed strategies in the literature are ramp-rate control [17] and the moving-average (MA) [18]. The main advantage of MA is that, if the system is equipped with an ideal converter and battery, by definition of the mean value, the value of the energy in the ESS at the beginning and end of any given day should be the same. In real practice, at the end of the day, the battery is discharged to a value equal to the energy lost in the charging/discharging processes. On the other hand, the key point of the ramp-rate control is that only acts when the fluctuation exceeds the lower degradation. There are also other strategies available such as the constant production strategy [19]. However, this goes beyond smoothing out the fluctuations in short periods of time and requires a much larger ESS.

1.2 Research Purpose

Solar power has several factors to affect the radiation, including air quality, geographic location, season and weather conditions, these factors are essential when installing solar panel. In the other hand, collecting data of solar condition is important such as solar radiation, weather, and temperature. According to those factors, we can find the best combination of components' angle and location.

Solar power fluctuates a lot which will influence no matter the power grid or the size of the storage system. In order to use HESS, it might not be appropriate according to the data of a day. This research focuses on the data analyzing which provide different ways to find the most representative periods among a year. For example, finding a day to represent a month, or furthermore representing a season. The following optimization of energy storage system will be carried out.

After that, deciding the cut-off frequency in order to size different storage device based on different response speed. Furthermore, do the optimization and find out which is the best combination to carry out the lowest cost.

1.3 Research Questions

This research will process the optimizing of the storage system, based on the characteristic of storage technology, take the technology apart into:

1. High power density and massive storage amount:
    a. Conventional Batteries
    b. Such as Compressed air energy storage (CAES)
    c. Pumped hydroelectric storage (PHS)
2. High energy density, fast response timing, capable to charge and discharge frequently:
    a. Flywheel energy storage
    b. Superconducting magnetic energy storage (SMES)
    c. Supercapacitor

Concluding, based on the previous research [20], selecting the combination of electric double layer capacitor (EDLC) and lead-acid battery will be the best option. For lead-acid battery, the advantages are massive storage amount, mature technology, simple and inexpensive to manufacture, easily to maintain which also means self-discharge rate is among the lowest of rechargeable battery systems when using it properly, the greatest energy density per pound, and the most mature recycling infrastructure of similarly priced batteries, also one of the most useful batteries with the longest life cycle. On the other hand, the disadvantages are that the lead acid battery cannot be stored in a discharged condition. With low energy density, poor weight-to-energy density limits its use to stationary and wheeled applications. They allow only a limited number of full discharge cycles well suited for standby applications that require only occasional deep discharges. The electrolyte and the lead content can cause environmental damage, which is environmentally unfriendly. There are environmental concerns regarding spillage in case of an accident when transporting flooded lead acid. For electric double layer capacitor, the manufacturing perspective, supercapacitor is a mix between batteries. The advantages and disadvantages will be list on the following. Furthermore, the Ragone plot of characteristic is shown in figure 1.

Advantages:

a. Supercapacitor has high energy storage, compared to conventional capacitor EDLC has higher power density.
b. Unlimited cycle life
c. Short charge/discharge time, high current charging and discharging is achievable without any damage to the parts.

Disadvantages:

a. Low per cell voltage, EDLC cells have a typical voltage of 2.7V. Since for most applications a higher voltage is needed, the cells have to be connected in series.
b. Low energy density; usually holds 1/5-1/10 of a battery.
c. High self-discharge as compared to electrochemical batteries

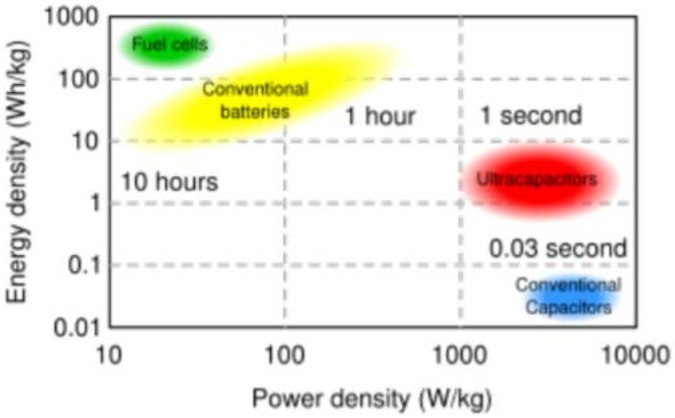


Figure 1. Batteries Ragone Plot

Considering intermittent, randomly, and the continuous changing of solar power, installing storage system play an important role of discipline fluctuation, enhance the reliability of electricity. On account of lead-acid batteries and supercapacitors has a complementary characteristic, there are two benefits to applicate hybrid energy storage system, firstly by adjusting the state of charge (SOC) to control the output power. Secondly, considering supercapacitor as the supplement to support the lead-acid batteries in the benefits to reduce the amount of charge/discharge. To be more precisely, extend the lifetime of batteries, moreover, cut down on the funds of replacement and maintenance. By observing solar output power and grid-acceptable power separately, simulating the characteristic within the environment of Matlab, in order to find the best combination of storage system and likewise verifying the methods introduce at section 2.

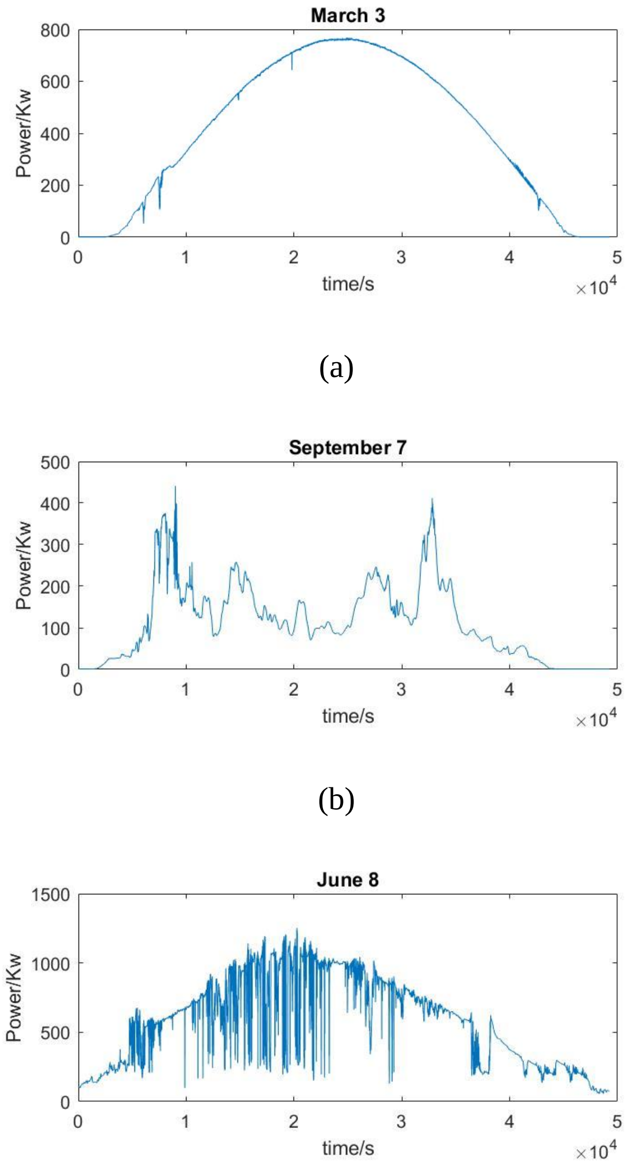
1.4 Value of Research

To find a representative period among a year has important benefits of the further constructing, knowing the peak value and considering the other elements comprehensively could be capable of deciding the mass of storage system. Besides, optimal capacity and minimum capital cost of the ESS needed to reduce the PV output power fluctuations should also be investigated.

Methods

2.1 Data Collection Procedure

Using the data of the year 2015 in Milwaukee, the information including wind speed, temperature, wind direction, and the most important solar radiation. Due to the solar power only generate during the daytime, this research excludes the solar radiation of photovoltaic at the night time, choosing the time from 6:10 a.m. to 7:50 p.m. for the afterward use. For example, figure 2 and figure 3 is the weather consideration shows that power magnitude variety and fluctuate differently day by day.

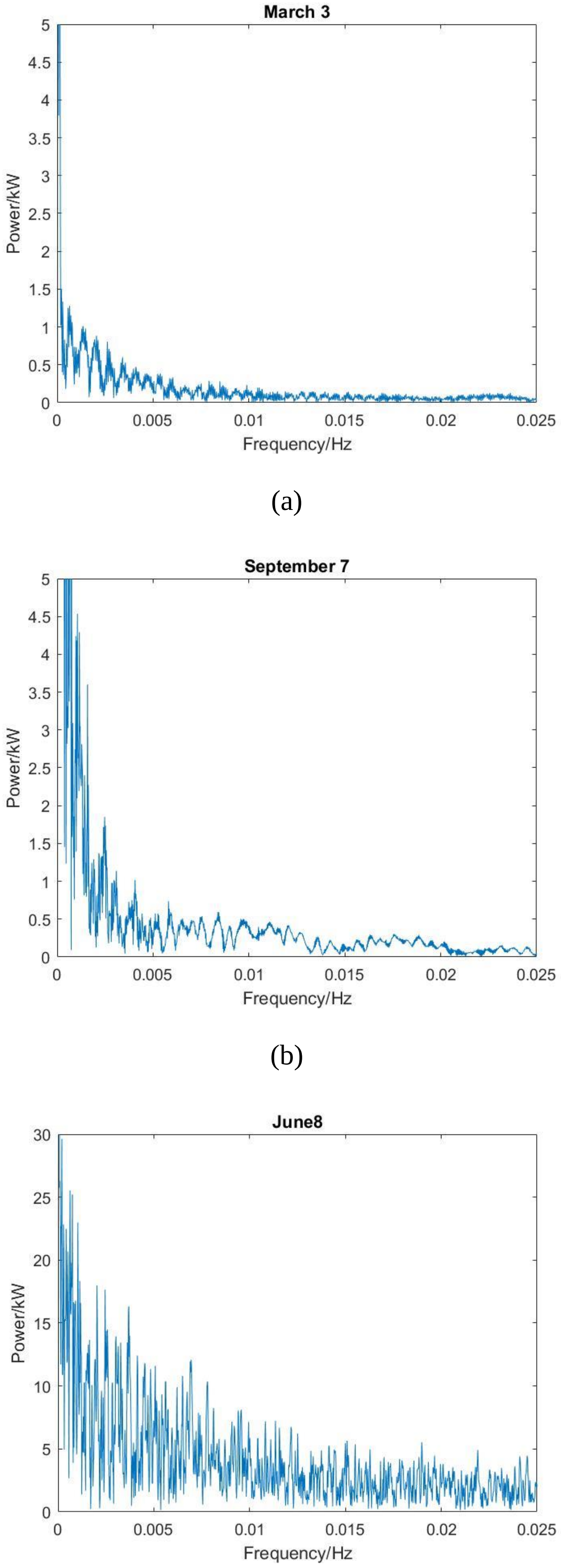


(a)

(b)

(c)

Figure 2. Weather consideration in time domain
(a) March3 (b) September 7 (c) June 8.



(a)

(b)

Figure 3. Weather consideration in frequency domain

(a) March3 (b) September 7 (c) June 8.

2.2 FFT Method

Due to the different storage systems have the different response time which means capable of operating at different frequency section. When it comes to the methods, this research using Fast Fourier Transform (FFT) to switch the data from time domain to frequency domain in the favor of observing the data such as the frequency of certain radiation level occurs the most. Then the Fast Fourier Transform is taken to give the power spectrum and the spectrum is smoothed over adjacent point.

Discrete Fourier Transform (DFT) method to decompose the required balancing power into different time-varying periodic components. The transforming rule is based on the non-infinite time domain signal or non-infinite sequence, to sampling the signal from frequency domain and not to lose any signal. As a consequence, if the time sequence is long enough, as long as sampling frequency reaches the level. Frequency sampling is capable of reflecting the trend of the signal in the frequency domain. In the other word, FFT is able to analyzing continuous signal. Of course, it has to reach two conditions:

1. Using discrete sampling signal Fourier Transform to replace continuous signal in the frequency domain. Otherwise, the signal will only approximately to the real signal and containing distortion

2. Using non-infinite sequence to replace infinite discrete sampling signal

In summary, emphasizing again that the simulation of frequency deviation is computed by Fourier transformation and Inverse Fourier transformation. Considering that Fourier transformation can be implemented by Fast Fourier transformation, a very fast and mature algorithm, it, therefore, ensures fast computation even when the duration curves require numerous samples for risk assessment.

It can be seen that the balancing power fluctuates at variable speeds and contains different frequencies. The balancing power can be transformed into frequency domain by using FFT. Each component of the periodic signal, the FFT analysis equation is:

$$X[f] = \sum_{t=0}^{N-1} x[t] W_N^{tf}, f = 0, \ldots, N-1 \tag{2}$$

Inverse Fourier transform (IFFT) synthesis equation is:

$$x[t] = \frac{1}{N} \sum_{f=0}^{N-1} X[f] W_N^{-tf}, f = 0, \ldots, N-1 \tag{3}$$

Where N is the number of the data points in the sequence:

$$(x[0], x[1], \ldots, x[N-1]) \tag{4}$$

$$W_N^{tf} = e^{-j(2\pi/N)tf} \tag{5}$$

For example, the FFT conversion of data in Figure 2(a) are shown in Figure 3(a).

It can be seen in Figure 3(a) that the higher power magnitude components were located in the lower frequency range. Since in the lower frequency range, the corresponding time parameter was greater, this resulted in higher energy density in the lower frequency range.

Therefore, it was proven that a battery with slower response speed could be considered as a high energy density energy storage device.

2.3 Research Design

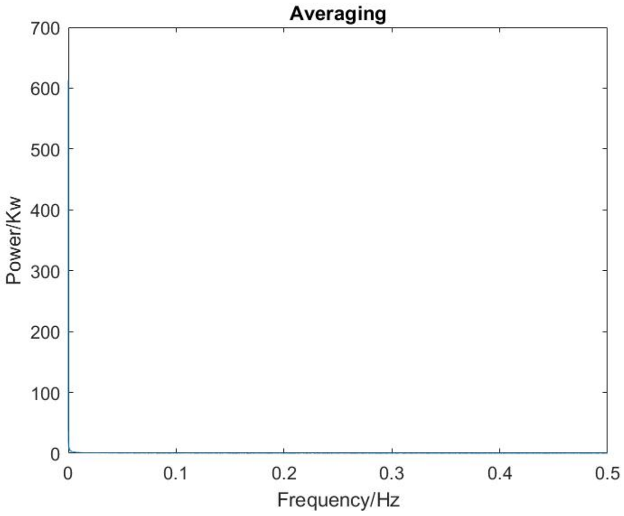
In order not to oversize the energy storage system to prevent extra cost and to find the most economical way, the methods to decide the value from the numerous data is important. First of all, according to the variety of daytime, extract 5 most iconic months which is March, June, August, September, and November. This research provides 4 ways to find the representative day. Data in the frequency domain has 49 days and 49261 frequencies, showing part of them in the table I. In this research, generally doing adjustment between the value of each day under same frequency, after that, apply that pattern to the rest of frequencies.

Table 1. Data

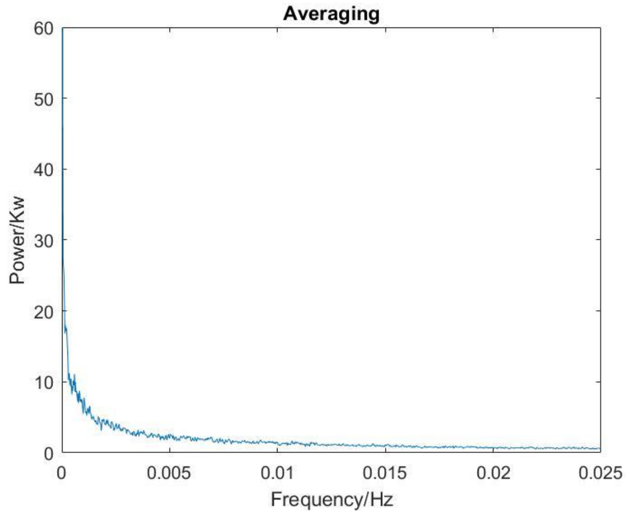
Frequency	1-Mar	2-Mar	3-Mar	4-Mar	5-Mar	6-Mar
0.0000203	295.8054	178.6298	387.1124	337.734	154.2093	296.8332
0.0000406	26.14337	86.93893	37.24017	50.103	61.1274	40.6673
0.0000609	1.279081	45.8642	5.606758	25.78543	28.88589	47.52599
0.0000812	10.62566	53.07801	3.794084	17.83723	29.48579	37.31305
0.000102	24.19556	40.24768	6.718259	24.72385	18.42726	34.39059
0.000122	30.35425	5.020492	7.764173	21.9566	22.75989	19.78283
0.000142	29.82889	8.262996	6.116041	23.18603	12.9691	38.1816
0.000162	23.71149	10.57824	3.122931	5.27562	2.680841	35.95143

Method 1 Averaging:

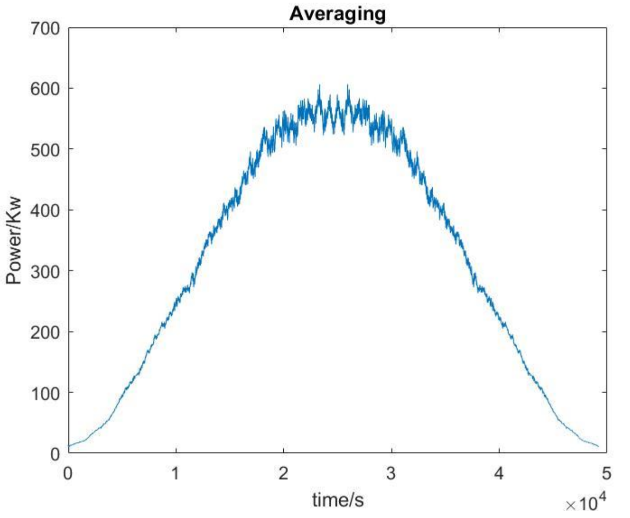
The first method makes a new data by averaging the value of solar power of 5 months after transforming the solar power into frequency domain by using Fast Fourier Transform. Among the past research, they tend to choose the worst day representing the whole year. On account of that the hybrid energy storage system capable of covering the worst day which is mean the most fluctuation day, it will also fulfill the other day of rest of the days. On the other hand, it means for the reason to settle for the only worst day, the storage system must cost more than the most part of cases. As a consequence, using average will be more suitable than to use the worst day for representing whole year even though some of the cases solar power input might not generate a good result or to accept by the grid. Which is mean, some percentage of the days will not be covered by the designed storage system.



(a)



(b)



(c)

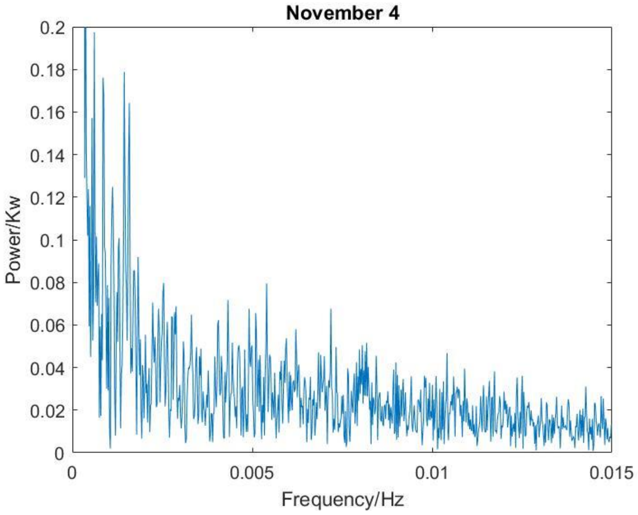
Figure 4. Results of Method 1 (a) Result (b) Zoom in the overshoot (c) Inverse FFT

Method 2 Peak:

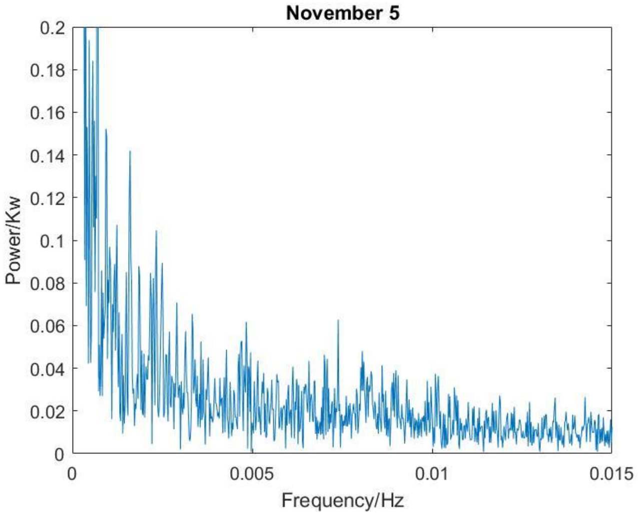
According to the method 1, sometimes the data will occur distortion and lose some characteristic while doing averaging. Generally, the method 1 averaging will make the power curve more smoothly. As a consequence, the method 2 will not use averaging but select the peak value of all time and plot to a new figure. Due to choosing the peak value

For example:

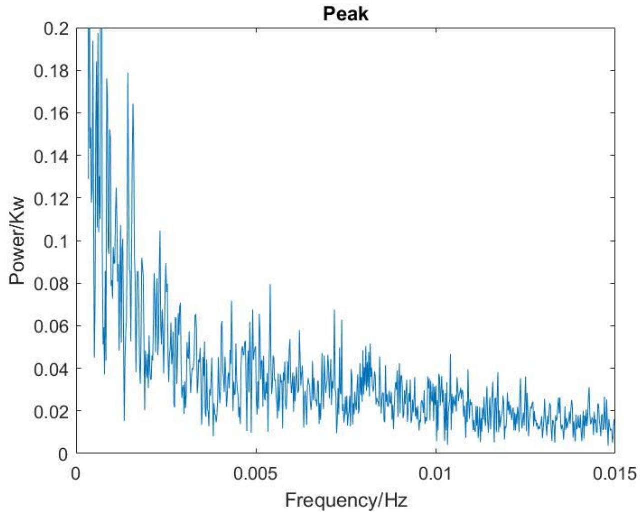
Randomly select two days and generate the frequency domain to show the trend of solar power. The bigger value will be the representative value of that frequency.



(a)



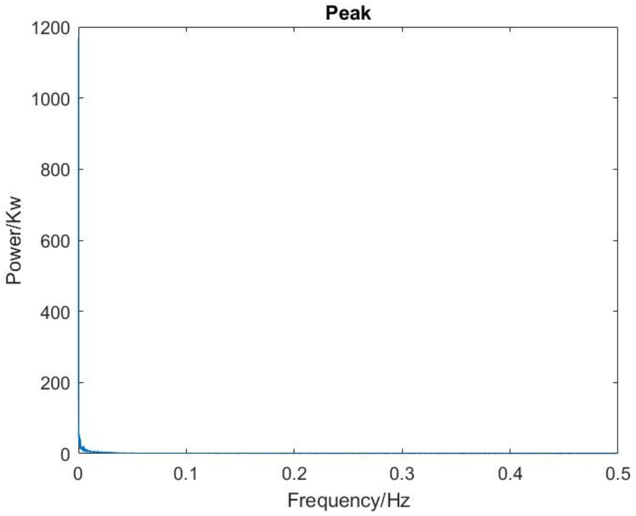
(b)



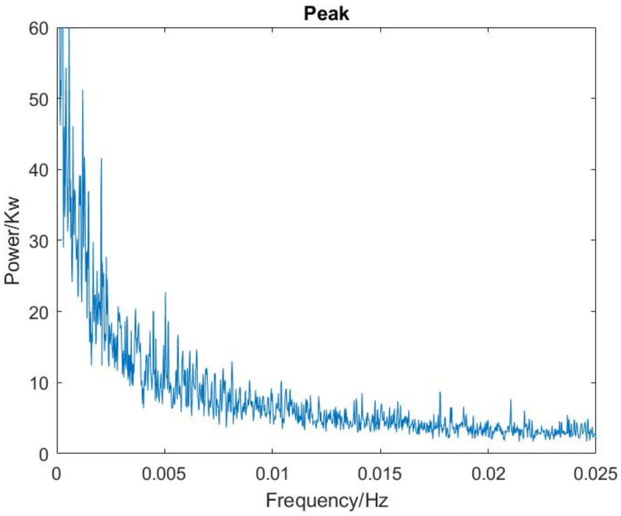
(c)

Figure 5. Demonstration of Method 2 (a) November 4 (b) November 5 (c) peak value

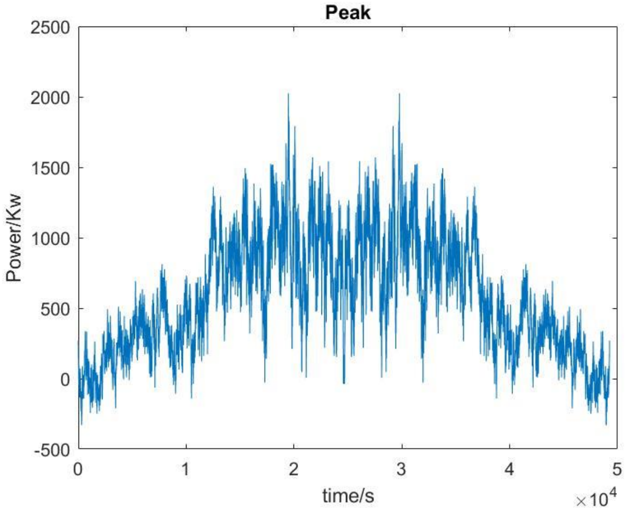
The results of method 2 applying the pattern of the example to 49261 frequency data points shown in the following figures.



(a)



(b)



(c)

Figure 6. Results of Method 2 (a) Result (b) Zoom in the overshoot (c) Inverse FFT

Method 3 Probability:

The method in this research has to process several procedures. In the beginning, evaluating if the solar radiation has any specific trend at the same frequency. Instead of using the value at the head or tail, due to where the overshoot appears, dividing the data by 6 section evenly and extract 5 point at the middle. There are several advantages:

1. Not to affect the result by the extreme value occur on the both side, furthermore appraise the posture clearly.
2. Get to evaluate the circumstances from high frequency to low frequency.

In order to prevent that the trend of the solar power will not appear because of the high power only occur at the low-frequency part, this method also extracts a few frequency at the low frequency.

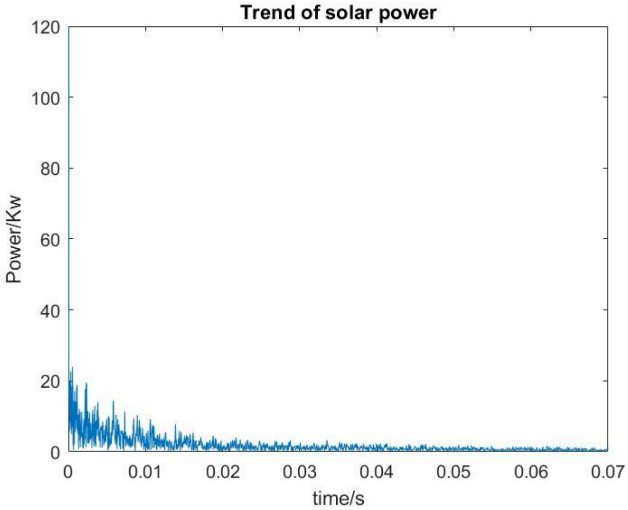


Figure 7. The trend of solar power in frequency domain

As the figure shows, it clearly shows that the trend of the altitude from 0.01 gradually decrease as long as the frequency goes higher. The following figure shows the value of power at frequency 0.01, 0.02, 0.03, 0.04, 0.166, 0.333, 0.5 where x-axis represent the 50 data point.

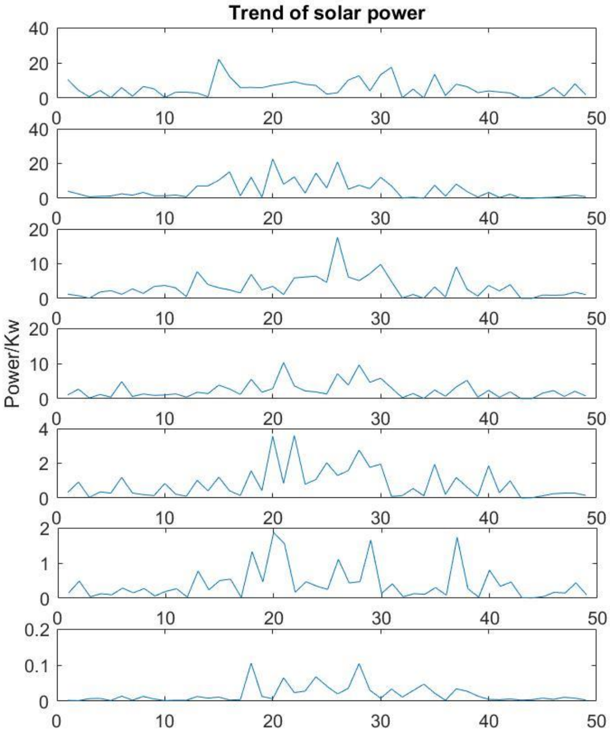
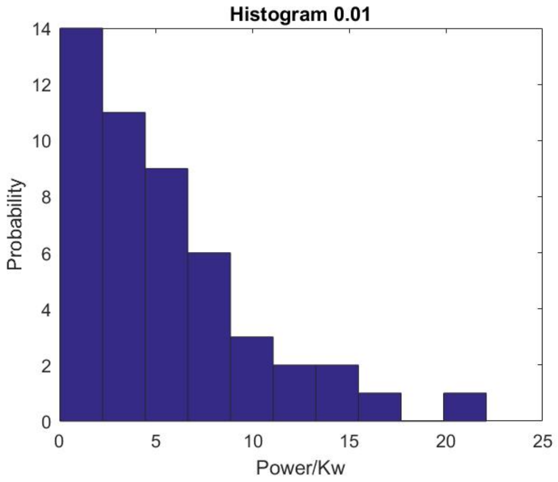
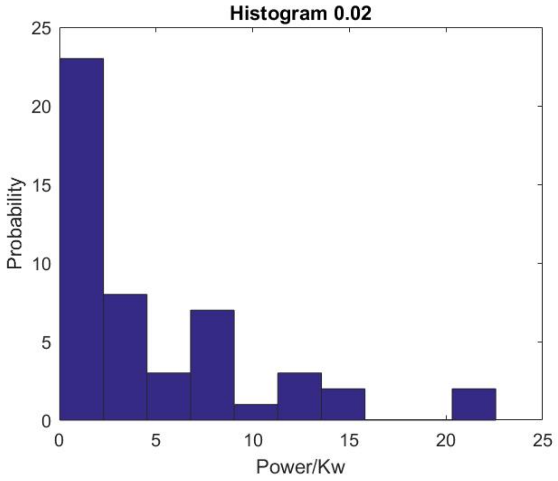


Figure 8. Trend of the solar power in different data point

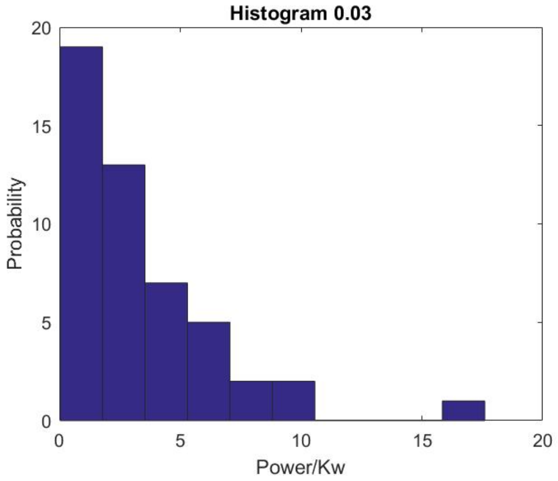
According to the Figure 8, there is no specific trend that we can easily observe among the solar radiation at the common frequency. For the next step, this method will check the distribution of probability of the power value and observe if the value follows the pattern that probability of high power among the lower frequency should be higher than the higher frequency. Due to the values of each day are variable, it is essential to combine by averaging the value which is approximately the same. The standard to combine different value is 2% of the average under the condition of the same frequency. After that, select the group which appears the most and do averaging to represent value of the frequency. The following charts are the histogram of 7 selected point which frequencies are 0.01, 0.02, 0.03, 0.04, 0.166, 0.333, 0.5.


Histogram 0.01
Probability
Power/Kw
0
2
4
6
8
10
12
14
0
5
10
15
20
25

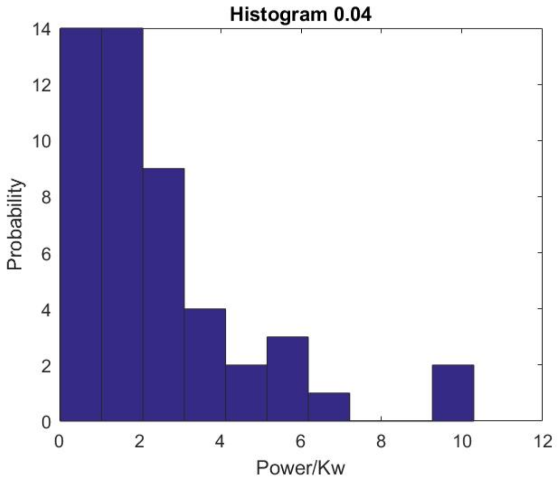
(a)


Histogram 0.02
Probability
Power/Kw
0
5
10
15
20
25
0
5
10
15
20
25

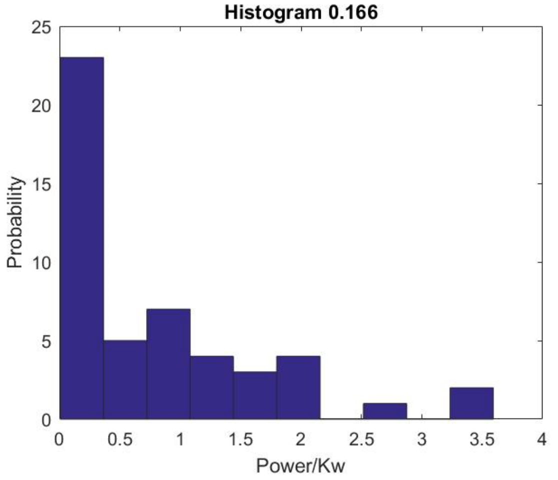
(b)


Histogram 0.03
Probability
Power/Kw
0
5
10
15
20
0
5
10
15
20

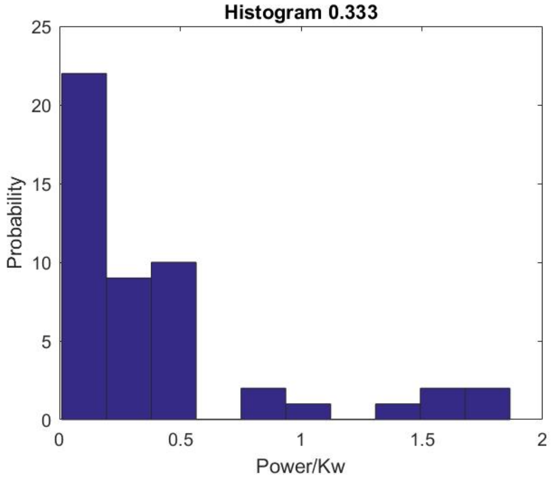
(c)


Histogram 0.04
Probability
Power/Kw
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12

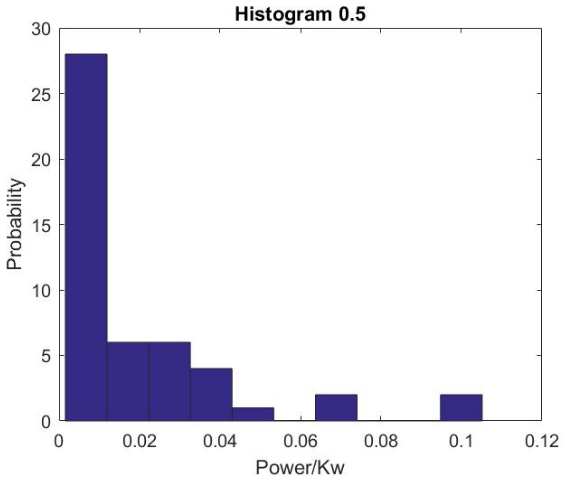
(d)


Histogram 0.166
Probability
Power/Kw
0
5
10
15
20
25
0
0.5
1
1.5
2
2.5
3
3.5
4

(e)


Histogram 0.333
Probability
Power/Kw
0
5
10
15
20
25
0
0.5
1
1.5
2

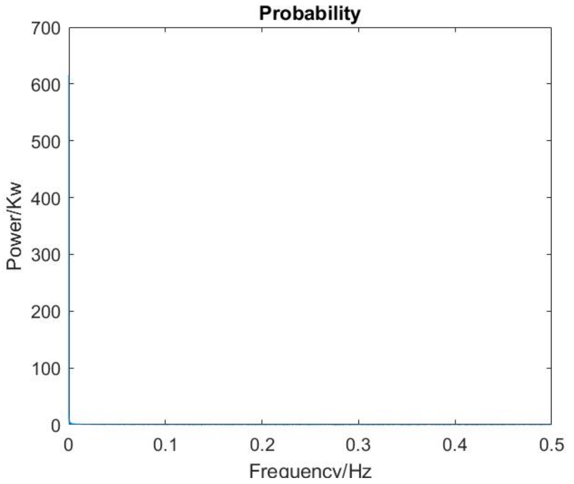
(f)



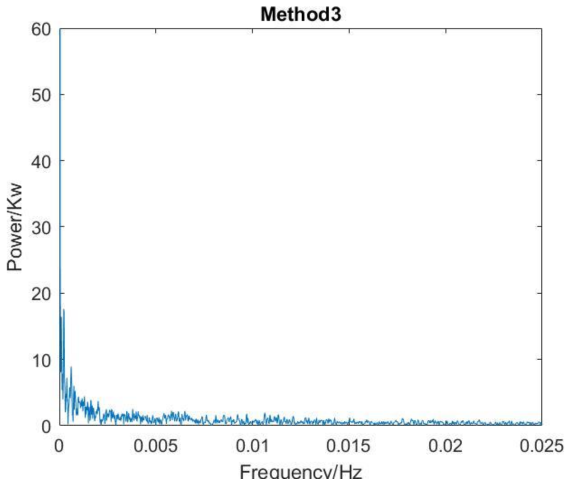
(g)

Figure 9. Probability of power in 7 frequencies (a) 0.01 (b) 0.02 (c) 0.03 (d) 0.04 (e) 0.166 (f) 0.333 (g) 0.5 Hz.

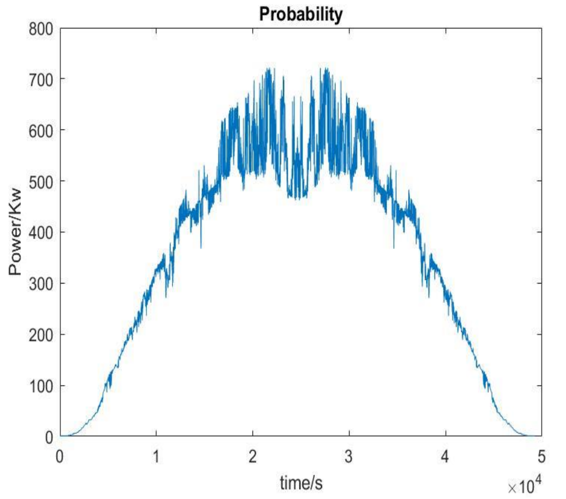
It is apparently that the value decreases as long as the frequency shifting to the right side. After showing the probability, method 3 is to select the value to appear the most to represent the solar power of the frequency, furthermore, apply this pattern to the rest of the data point and generate a new data.



(a)



(b)



(c)

Figure 10. Results of Method 3 (a) Result (b) Zoom in the overshoot (c) Inverse FFT

Method 4 Worst Case:

In the method 4, this research tends to discuss what the worst cast will be, and by applying the worst case storage system is capable of covering the entire solar power of whole year. At the beginning, select the cut-off frequency which is shown in figure 11. To separate apart the frequency and defining over the cut-off point belongs to high frequency, lower will be the low frequency, this part will be mentioned more specific in the design of storage system. Secondly, using the cut-off frequency at 0.0083 as an example, sum up the value of solar power lower than the cut-off point and sum up the value higher than 0.0083. After that, make the ratio which is low/high.

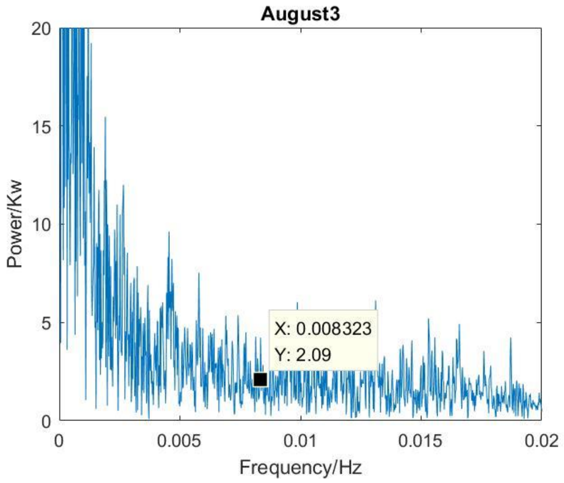


Figure 11. Cut-off frequency

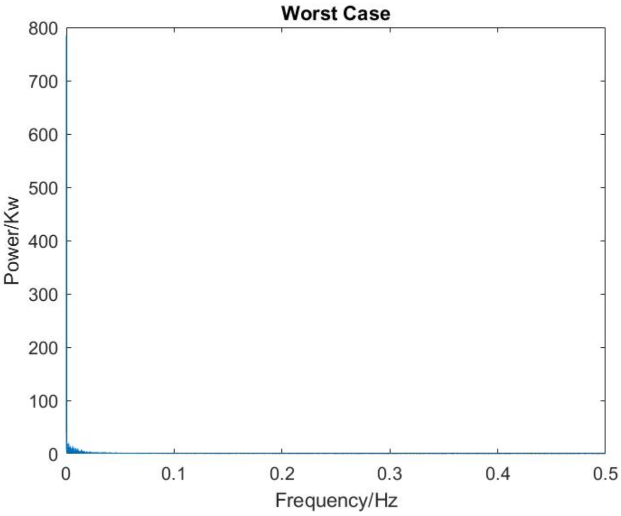
According to the principle, that the higher the denominator is, represents the greater the high-frequency part influence, which also means that the higher the ratio will be. On the other hand, less proportion of high-frequency value and makes the day more stable and fewer fluctuations. As the table 2 shows that the maximum value occurs at Nov5 which is the most stable day, the minimum ratio occurs at Aug9 which is the worst case. To make sure this method works by choosing the cut-off frequency at 0.0083, 0.0016, 0.00034 for verification, which also related to the sizing energy storage system, table 3 shows that Aug 9 is the worst case especially when the cut-off frequency 0.00034 where the smallest ratio equals to 0.11 approximately near 0.14.

Table 2. Ratio of data

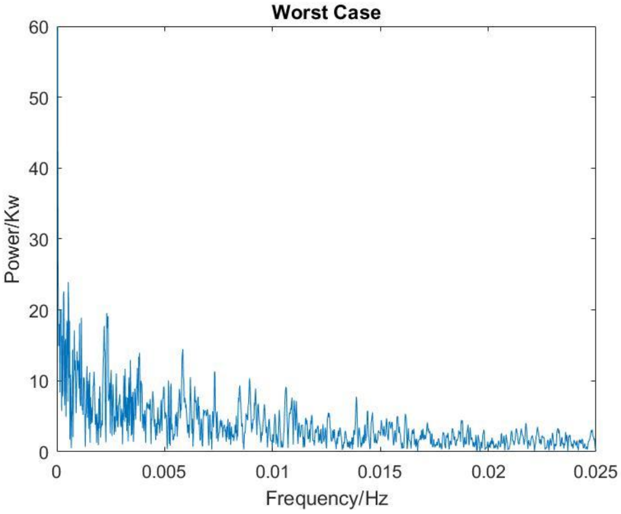
March1	2.484319	Aug6	0.622137
March2	1.192202	Aug7	0.756157
March3	5.05257	Aug8	1.130818
March4	2.638689	Aug9	0.549069
March5	2.056357	Aug10	0.634431
March6	0.77398	Sep1	0.909561
March7	1.243122	Sep2	0.910729
March8	0.918611	Sep3	1.177331
March9	4.181474	Sep4	1.208392
March10	1.493828	Sep5	1.010255
June1	2.252139	Sep6	0.600197
June2	4.863465	Sep7	2.05752
June3	0.675133	Sep8	0.560223
June4	2.008839	Sep9	0.923316
June5	1.088018	Sep10	2.138295
June6	1.18719	Nov1	0.637471
June7	3.287107	Nov2	0.649476
June8	0.576793	Nov3	0.587574
June9	1.032525	Nov4	7.31196
Aug1	0.665554	Nov5	7.895647
Aug2	0.719624	Nov6	2.101739
Aug3	0.866396	Nov7	0.978469
Aug4	0.969521	Nov8	0.835176
Aug5	0.87548	Nov9	0.681636

Table 3. Ratio of August 9

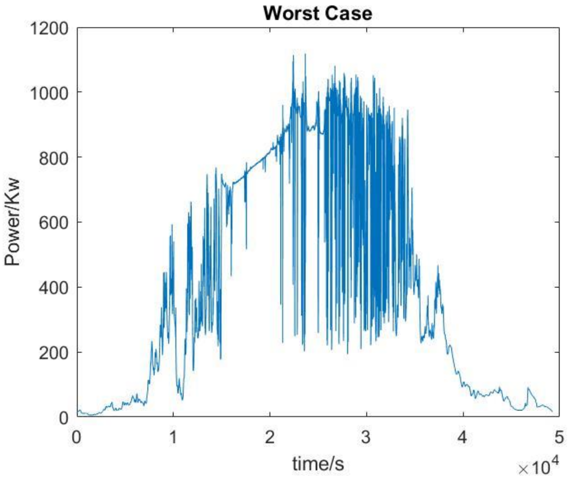
Cut-off frequency	Ratio	Rank
0.0083	0.634431	Minimum
0.0016	0.289678	Minimum
0.00034	0.145855	3rd smallest


Worst Case
Power/Kw
800
700
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
Frequency/Hz

(a)


Worst Case
Power/Kw
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
Frequency/Hz

(b)


Worst Case
Power/Kw
1200
1000
800
600
400
200
0
0
1
2
3
4
5
time/s
×10^4

(c)

Figure 12. Results of Method 4 (a) Result (b) Zoom in the overshoot (c) Inverse FFT

Design of Hybrid ESS

3.1 Balancing Power

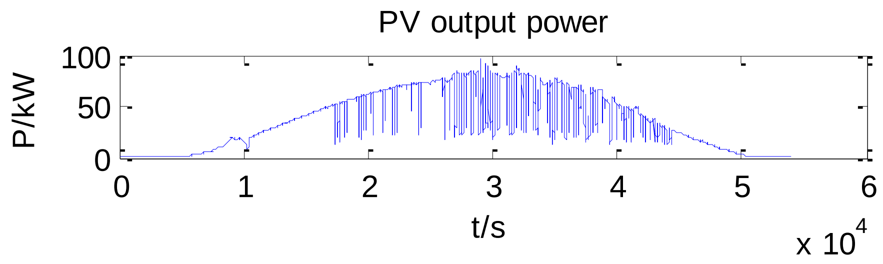
Due to the random changes in solar radiation, the fluctuation of the output power of solar power output is large, which also affect the stability of power system when a solar panel is connected to a grid. A method for balancing fluctuation which is based on a hybrid energy storage system will be proposed to solve this problem. Firstly, the fluctuation power of solar power output will be separated, the grid-acceptable power P_a, the output power will be P_o, and the balancing power P_b. The relationship among three of them express as follow:

$$P_b = P_o - P_a \tag{1}$$

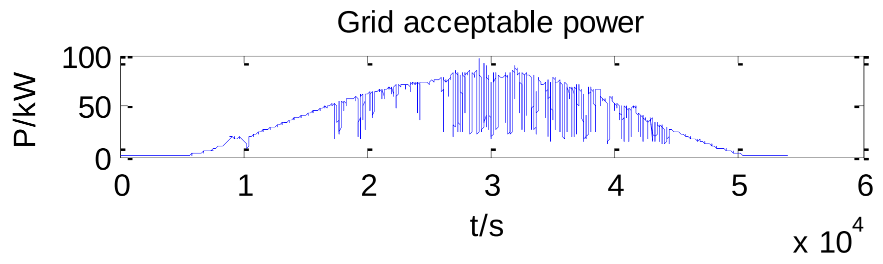
Where:

$P_b > 0$: PV generates excess available power which needs to be absorbed by ES. ES is charging.

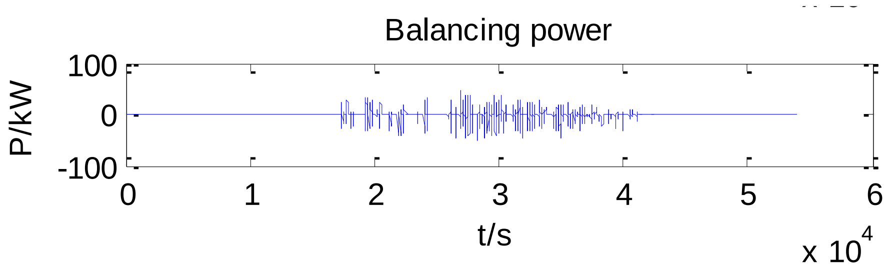
$P_b < 0$: PV generates insufficient available power which needs to be supplied by ES. ES is discharging.



(a)



(b)



(c)

Figure 13. Balancing power calculation (a) The original PV output power under a worst case scenario (b) Grid acceptable power (c) Balancing power

The complete frequency spectrum of the balancing power can be similarly divided into separate sections based on frequency ranges which will be called cut-off frequency in the upcoming paragraph. Since different batteries have different response speeds, by properly determining frequency range of each section, a corresponding energy storage system can be determined to handle the balancing power in that range.

Apart from this, according to the characteristics, the variety of batteries and electric double layer capacitor will be considered as the energy storage system to smooth out the fluctuation. Here are many types of batteries, e.g., lead-acid, nickel-cadmium, nickel metal hydride, nickel zinc, zebra batteries of sodium chloride, vanadium redox, lithium-ion, and lithium polymer. In order to correctly choose the right technology for each application, it is essential to characterize them properly; basically, one needs to know, for each competing technology, energy density, cycle life and operating temperature. According to the other research, they commonly use lead-acid, lithium-ion, and supercapacitor the most. The following table is the characteristic of three kinds of energy storage.

Table 4. ESS type and information

ESS	Type	Shortest response time	Maximum response frequency
lead-acid battery	long-term	2 min	8.33×10^{-3} Hz
lithium-ion battery	long-term	1 min	0.0167 Hz
EDLC	short-term	1 s	1.00 Hz

Lead-acid and lithium-ion batteries have relatively low response speed comparing to the supercapacitor, thus they are suitable for tracking power variations of the frequency lower than 8.33×10-3 Hz and 0.0167 Hz respectively. The response rate of EDLC is very fast and is well suitable for the compensation of the high-frequency components. Utilizing the different energy storage response, a hybrid integrated energy storage system can be developed. For example, an energy storage system combination made of lead-acid and EDLC can have a cut-off frequency 8.33×10-3 Hz, and the cut-off frequency of a lithium-ion and EDLC combination can be 0.0167 Hz.

3.2 Optimization

Based on the techniques mentioned in the paragraph3.1, the combination of lead-acid battery, lithium-ion battery, and EDLC can be optimized to smooth out the balancing power and to meet the requirement of power grid. The cycle life of energy system and capacity loss were also taken into consideration.

A. System Cost

For any given ES, its rated energy cost should be equal to the rated power cost as shown in equations (6) and (7). Equation (8) determines the cost ratio of an energy storage.

$$\text{ES rated energy cost (\$)} = \text{ES rated power cost (\$)} \tag{6}$$

$$\text{Unit Cost } (\$/kWh) \times E(kWh) = \text{Unit Cost } (\$/kW) \times P(kW) \tag{7}$$

$$\frac{E(kWh)}{P(kW)} = \frac{\text{Unit Cost}(\$/kW)}{\text{Unit Cost}(\$/kWh)} = \text{Cost Ratio} \tag{8}$$

E(kWh) is the rated energy capacity and P(kW) is the rated power capacity in the ES. The ratio between E(kWh) and P(kW) is the fixed unit cost ratio. The unit costs of power, energy, cycle lives, and cost ratios used in this paper are listed in Table 5.

Table 5. ESS parameters

Battery type	Unit cost		Cycle life	Cost ratio
	P $/kW	E $/kWh		
Lead-acid	200	100	1000	2
Lithium-ion	500	300	2000	5/3
EDLC	150	4000	90000	3/80

B. Capacity Lost

Capacity loss or capacity fading is the phenomenon observed in rechargeable battery usage where the amount of charge a battery can deliver at the rated voltage decreases use.

When taking the capacity loss into consideration, the total energy that ES can provide in its cycle life is the summation of geometric progression formula as shown in equation (11). The geometric progression ratio m equals to the average capacity loss percentage per cycle of the ES. N presents the PV's life span in years.

$$Total\ energy\ ES\ can\ provide = E(kWh)/2 \times (1 + m + m^2 + \cdots + m^{N-1}) \qquad (11)$$

In this paper, we assume that each ES will lose 40% capacity when reaches its cycle life [14]. Using data from Table III, the average capacity loss percentage per cycle m of different ES can be calculated as follow:

1. Lead-acid battery: 4×10-2 %
2. Lithium-ion battery: 2×10-2 %
3. EDLC: 4×10-4 %

C. Cycle Life

Cycle life is used to specify a battery's expected lifespan. In general, number of cycles for a rechargeable battery indicates how many times it can undergo the process of complete charging and discharging until failure.

Assuming the example PV station will operate for 15 years, thus the ES practical replacement times k after rounding up can be calculated by equation (12).

$$k = ceil\left(\frac{PV\ required\ energy\ from\ an\ ES\ in\ 15\ years}{Total\ energy\ an\ ES\ can\ provide}\right) \tag{12}$$

Taking capacity loss into consideration, the total energy of a particular ES can provide can be obtained in equation (11). The PV required energy from an ES in 15 years can be calculated by using the ES daily maximum charging or discharging energy multiplying by number of days in 15 years.

To obtain the daily maximum charging or discharging energy, positive and negative balancing power corresponding to the ES were integrated separately. The maximum absolute value of positive and negative integration represented ESS largest discharging and charging energies. The higher value of these two integration results was selected as the total possible daily maximum charging or discharging energy for this ES as shown in equation (13).

$$Daily\ maximum\ charging\ or\ discharging\ energy =$$

$$\max(\sum positive\ balancing\ power, \sum |negative\ balancing\ power|) \tag{13}$$

D. Decision

The simulation is carried out from under the environment of Matlab/Simulink, the simulation shows that the method effectively stabilized the fluctuating output power of solar panel. The lead-acid batteries and the supercapacitors into play their own advantages, most of the time supercapacitors are on the duty of smooth out the fluctuations that decrease the chance of consuming lead-acid batteries’ cycle life, therefore extending the service life of storage system.

Results

4.1 Research and Findings

Method1 : Averaging

Due to the averaging of method 1, the characteristics are smooth out, there is no more peak value cause that the result of optimization no need to have balancing power, which means unnecessary to have energy storage system.

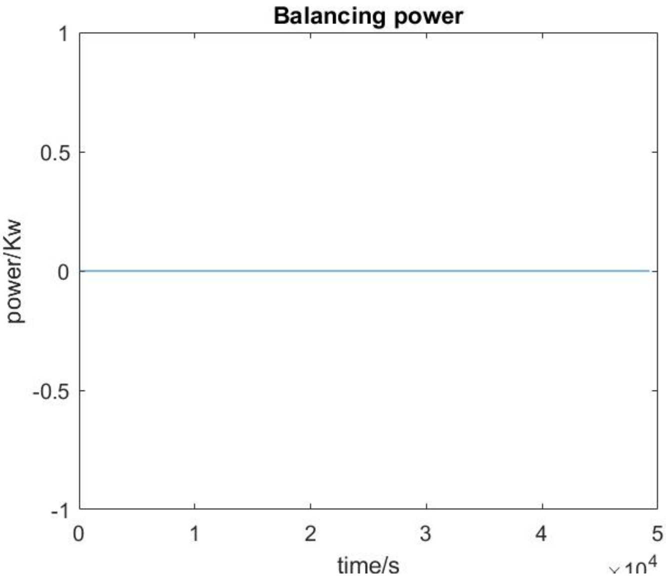
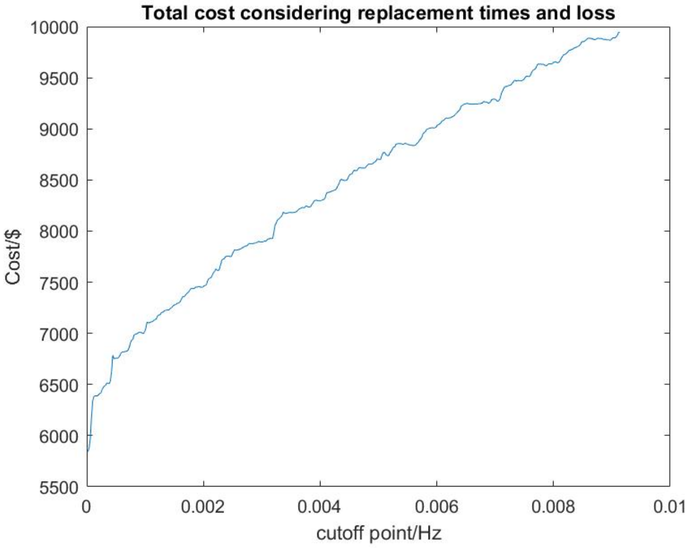


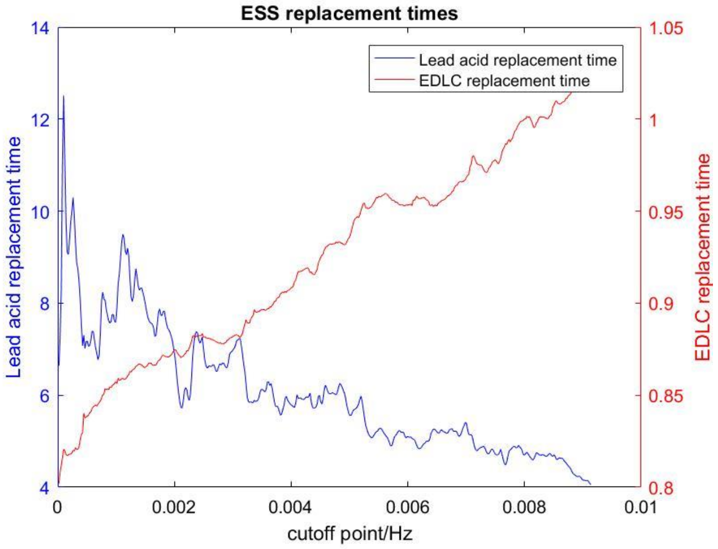
Figure 14. Balancing power of Method 1

Method2 : Peak value

According to the balancing power, it shows that power fluctuate all time and need to be balanced because choosing the peak value of all time.



(a)



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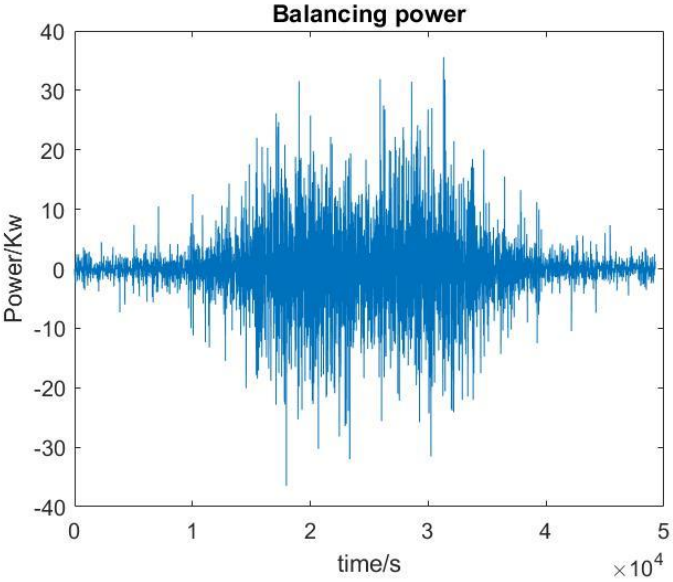
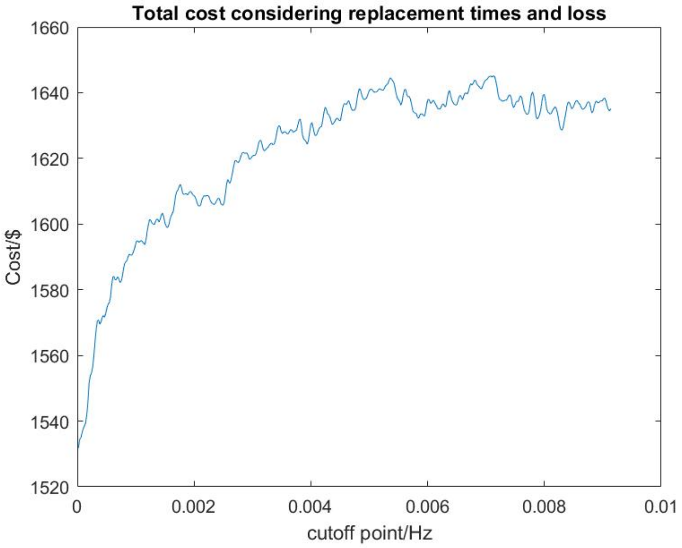


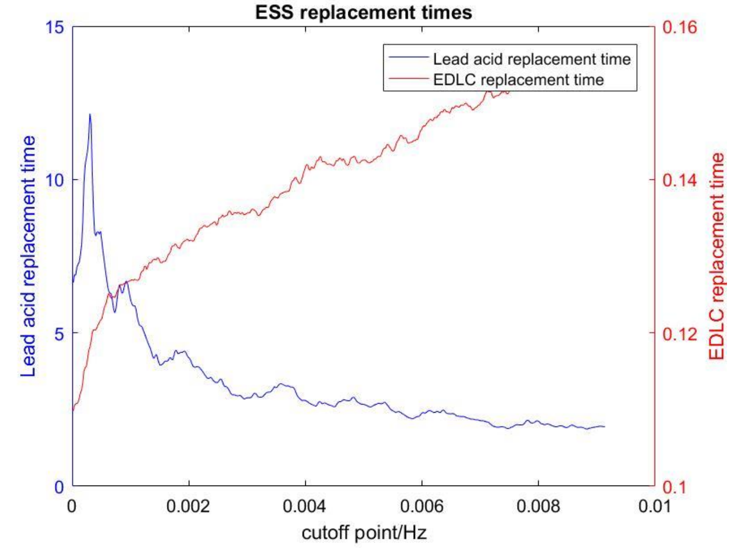
(c)

Figure 15. Results of Method2 (a) Costs in different Cut-off frequencies (b) ESS replacement time (c) Balancing power

Method3 : Probability



(a)



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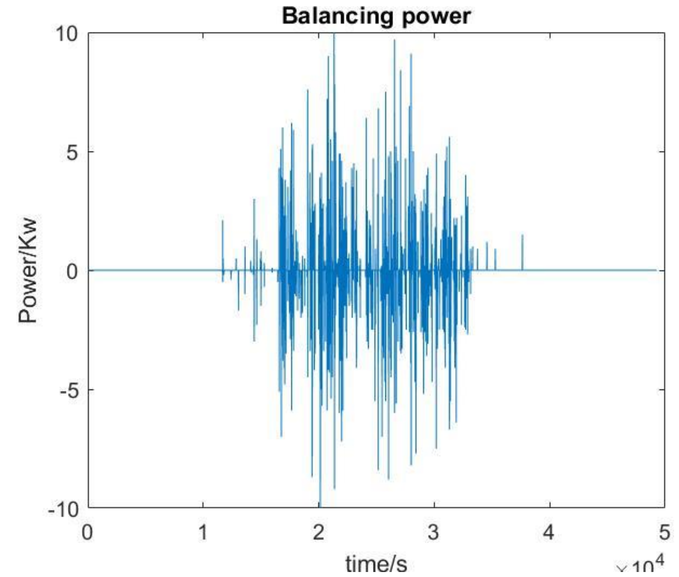


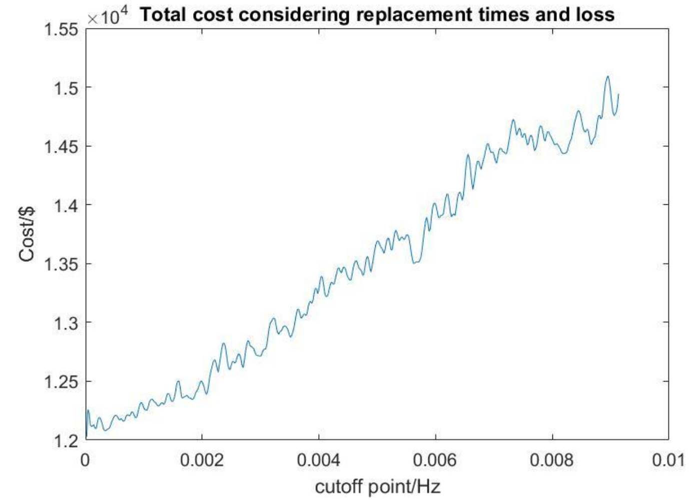
(c)

Figure 16. Results of Method 3 (a) Costs in different Cut-off frequencies (b) ESS replacement time (c) Balancing power

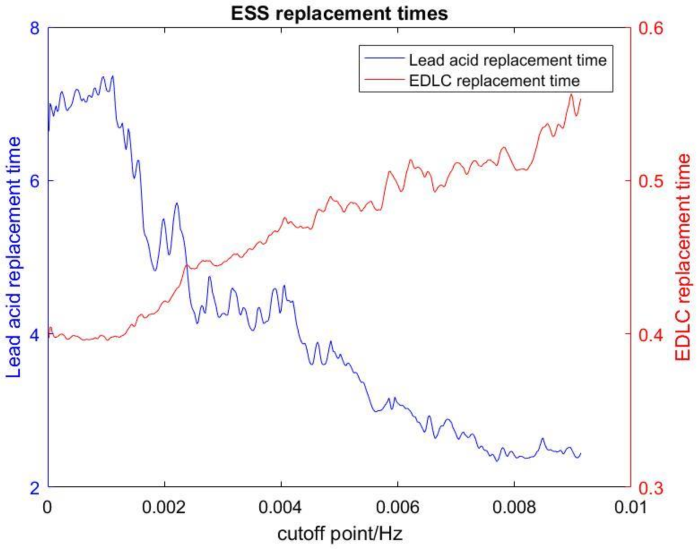
Method4 : Worst case

In comparison, figure 17 show that the magnitude of balancing power is the biggest.

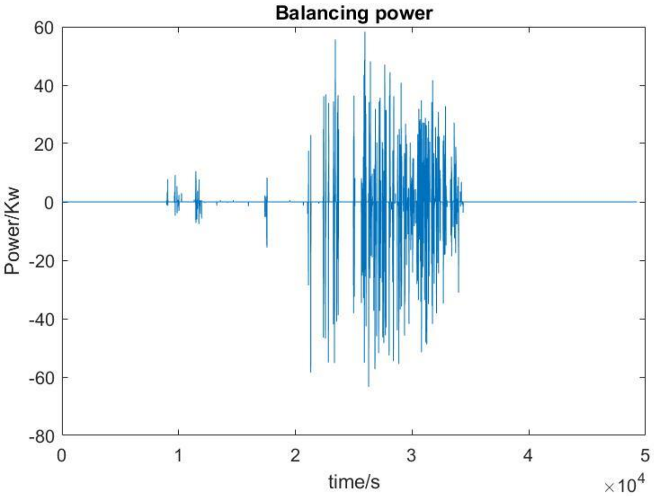
As a result, sizing will be bigger, which might cost higher.



(a)



(b)



(c)

Figure 17. Results of Method 4 (a) Costs in different Cut-off frequencies (b) ESS replacement time (c)Balancing power

4.2 Locations of Results

Table 6 is the sizing of each method, showing that method 1 no need to have any energy storage system. Method 3, probability, is the most economical way. Method 4,the worst case, which is the worst case, definitely has the most needed to be balanced by energy storage system.

Table 6. Optimum capacity combination

Methods	Cut-off point/Hz	Lead acid		EDLC		Cost/$h
		P/kW	E/kWh	P/kW	E/kWh	
Method1	0	0	0	0	0	0
Method2	0.0000203	0.038	0.563	36.459	1.367	5843
Method3	0.0000203	0.003	0.047	10.002	0.375	1531
Method4	0.0003451	1.277	3.890	62.597	2.347	12078

Table 7 is the replacement time of each storage device under operation in 15 years. It is worth to be mentioned that due to the balancing power in method 2 shows that always needs to be balanced. The EDLC cycle life consumes the fastest.

Table 7. Replacement time

Methods	Lead acid	EDLC
Method1	0	0
Method2	6.641	0.801
Method3	6.641	0.109
Method4	6.911	0.396

Conclusion

5.1 Conclusion

This research presented an FFT based methodology for the design of the methods analyzing for the different pattern of weather according to solar power. Furthermore, for the design of an optimal hybrid ESS to smooth out photovoltaic power fluctuation under 4 methods scenario. By using FFT method, resolving the solar power and plot into the frequency domain to observe the frequency, secondly, according to the response characteristics of different energy storage equipment including lead-acid battery, lithium-ion battery, and EDLC, an optimum sizing method was developed based on frequency analysis. In the methods to reframe the data of solar power, by combining the power at the same frequency and construct a new power data in order to observe the power trend at different frequency contribute to the use of cut-off point in the optimization. Then, transform the data back into time domain through inverse FFT. In the optimization, the best hybrid ESS was obtained to satisfy energy smoothing requirements of the power grid. The FFT method was applied for analyzing the spectrum of balancing power. The optimization process also considered ES cycle life, capacity loss during charging and discharging, and ES capacity ratios. The results indicated that the selected ESS can provide effective PV output power smoothing and satisfy the grid requirement. In conclusion, method 1 is not suitable for this research. Method 2 and method 4 may cause oversize problem though people might have the different consideration to use them. Method3 is the most economical way to represent the data.

5.2 Recommendations for Future Research

In this research, running optimization by comparing combination of energy storage system composed of lead-acid battery with EDLC, or lithium-ion battery with EDLC. The energy storage system can include multiple types of storage device as shown in Figure 345 for the future work suggestion. Due to the improper use of doing averaging, the method 1, it can be a better way to present averaging without smoothing out the characteristic in power curve.

References

1. S. Yanagawa, T. Kato, K. Wu, A. Tabata, and Y. Suzuoki, “Evaluation of LFC capacity for output fluctuation of photovoltaic generation systems based on multi-point observation of insolation,” in Proc. IEEE Power Engineering Society Summer Meeting, 2001, pp. 1652-1657.
2. A. Woyte, V.V. Thong, R. Belmans, and J. Nijs, “Voltage fluctuations on distribution level introduced by photovoltaic systems,” IEEE Trans. Energy Convers., vol. 21, no. 1, pp. 202-209, March 2006.
3. Y.T. Tan, D.S. Kirschen, and N. Jenkins, “A model of PV generation suitable for stability analysis,” IEEE Trans. Energy Convers., vol. 19, no. 4, pp. 748-755, Dec 2004.
4. W. Li and J. Géza, “Comparison of energy storage system technologies and configurations in a wind farm,” in Proc. Power Electronics Specialists Conf. (PESC 2007), Jun. 2007, pp. 1280–1285.
5. M. E. Baran, S. Teleke, L. Anderson, A. Q. Huang, S. Bhattacharya, and S. Atcitty, “STATCOM with energy storage for smoothing intermittent wind farm power,” in Proc. Power and Energy Soc. General Meeting—Conv. and Delivery of Elect. Energy in the 21st Century, Jul. 2008, pp. 1–6.
6. C. Abbey, K. Strunz, and G. Joós, “A knowledge-based approach for control of two-level energy storage for wind energy systems,” IEEE Trans. Energy Convers., vol. 24, no. 2, pp. 539–547, Jun. 2009
7. G. Koshimizu, T. Nanahara, K. Yoshimoto, H. Hasuike, and T. Shibata, “Subaru project: Application of energy storage for stabilizaion of wind power in power systems,” in Proc. EAS 2005 Annu. Meeting Conf. Energy Storage Assoc., Toronto, Canada, 2005.
8. K. Yoshimoto, T. Nanahara, and G. Koshimizu, “New control method for regulating state-of-charge of a battery in hybrid wind power/battery energy storage system,” in Proc. IEEE Power Syst. Conf. and Exposition, 2006, pp. 1244–1251.
9. F. Zhou, G. Joos, C. Abbey, L. Jiao, and B. T. Ooi, “Use of large capacity SMES to improve the power quality and stability of wind farms,” in Proc. IEEE Power Eng. Soc. General Meeting, Jun. 2004, pp. 2025–2030.
10. R. Cardenas, R. Pena, G. Asher, and J. Clare, “Power smoothing in wind generation systems using a sensorless vector controlled induction machine driving a flywheel,” IEEE Trans. Energy Convers., vol. 19, no. 1, pp. 206–216, Mar. 2004.

11. S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura, “Integration of an energy capacitor system with a variable-speed wind generator,” IEEE Trans. Energy Convers., vol. 24, no. 3, pp. 740–749, Sep. 2009.
12. S. M. Muyeen, R. Takahashi, M. H. Ali, T. Murata, and J. Tamura, “Transient stability augmentation of power system including wind farms by using ECS,” IEEE Trans. Power Syst., vol. 23, no. 3, pp. 1179–1187, Aug. 2008.
13. H. Fakham and D. L. B. Francois, “Power control design of a battery charger in a hybrid active PV generator for load-following applications,” IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 85–94, Jan. 2011.
14. R. Kamel, A. Chaouachi, and K. Nagasaka, “Wind power smoothing using fuzzy logic pitch controller and energy capacitor system for improvement micro-grid performance in islanding mode,” Energy, vol. 35, pp. 2119–2129, 2010.
15. T. Kinjo, T. Senjyu, N. Urasaki, and H. Fujita, “Output levelling of renewable energy by Electric double-layer capacitor applied for energy storage system,” IEEE Trans. Energy Convers., vol. 21, no. 1, pp. 221–227, Mar. 2006.
16. X. Li, S. Yu-Jin, and H. Soo-Bin, “Study on power quality control in multiple renewable energy hybrid micro grid system,” in Proc. IEEE Power Tech 2007, pp. 2000–2005, Jul. 2007.
17. Kakimoto, N.; Satoh, H.; Takayama, S.; Nakamura, K. “Ramp-rate control of photovoltaic generator with electric double-layer capacitor,” IEEE Trans. Energy Convers, pp. 465–473, 2009.
18. Datta, M.; Senjyu, T.; Yona, A.; Funabashi, T.; Kim, C.-H. “Photovoltaic output power fluctuations smoothing methods for single and multiple PV generators,” Curr. Appl. Phys. 10, S265–S270, 2013.
19. Beltran, H.; Bilbao, E.; Belenguer, E.; Etxeberria-Otadui, I.; Rodriguez, P. “Evaluation of storage energy requirements for constant production in PV power plants. IEEE Trans. Ind. Electron,” 60, pp. 1225–1234, 2013.
20. Ruirui Yang, David C. Yu, Member, IEEE, Qiang Fu, Student Member, IEEE, and Deyang Qu. “An Optimum Design of Hybrid Energy Storage for Photovoltaic Power Fluctuation Smoothing Based on Frequency Analysis,” 2016. Theses and Dissertations. 1230.