DESIGN OF A COST EFFECTIVE BATTERY-SUPERCAPACITOR HYBRID ENERGY
STORAGE SYSTEM FOR HOURLY DISPATCHING SOLAR PV POWER

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ABSTRACT

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This study aims to develop a low cost energy storage system for hourly dispatching solar photovoltaic (PV) power for 1MW grid connected PV array. To fulfill this objective, the optimum (most economical) scaling of a battery and supercapacitor (SC) hybrid storage is developed based on the time constant of a low pass filter (LPF) that is used to allocate the power between a battery and SC. Based on the battery state of charge (SOC), rule based algorithms are developed to estimate the perfect grid reference power for each one-hour dispatching period. Another rule-based algorithm is implemented to keep the battery SOC within a certain limit that helps to increase the battery lifetime. An economic comparison of different kinds of battery and SC combination in hybrid energy storage system (HESS) is presented in this research. This study also considers the relationship between the actual PV cell temperature and the ambient temperature and presents their effects on energy storage price calculations. This study uses actual solar data of four different days recorded at Oak Ridge National Laboratory (ORNL) in MATLAB/Simulink environment simulations to get the better picture about annual energy storage cost for hourly dispatching solar power. According to the results, the HESS combination of li-ion battery and SC, outperforms a battery only or lead acid and SC combination in HESS operation regardless of temperature framework.

# CHAPTER 1: INTRODUCTION

## 1.1     Key Terms

*State of Charge (SOC):* The state of charge (SOC) of a battery is defined as the capability of a battery to hold a specific amount of charge in reference to its original capacity, and it is represented as a percentage.

*Depth of Discharge (DOD):* The lowest depletion state of charge of a battery is defined as a depth of discharge (DOD).

*Dispatchable:* capability of providing power at a constant level for a time interval acceptable by the utility.

*High energy density property:* capability of slow charge and discharge rates at higher energy levels, e.g., Battery.

*High power density property:* capability of fast charge and discharge rates at lower energy levels, e.g., Supercapacitor.

*Battery Bank:* multiple batteries that are connected to provide a greater combined capacity.

*Supercapacitor Bank:* multiple supercapacitors that are connected to provide a greater combined capacity.

## 1.2     Problem Statement

Solar energy is one of the most important renewable energy sources that has the potential to solve the shortage of power supply around the world. Solar energy also has the potential to significantly decrease greenhouse gas emissions and increase the earth's longevity by reducing the demand for fossil fuels. One problem with solar energy as a renewable energy source is its intermittent nature for various reasons such as cloud cover and time of the day. Eliminating the intermittency of the

solar energy is important because it has the potential economic advantages as well as environmental benefits. The output of the photovoltaic array mainly depends on solar irradiation and solar cell temperature. Due to these natural and meteorological conditions, a solar panel can provide varying power levels. The electric power grid is not designed or suitable for varying power levels supplied by the power source. Because of this, the intermittent solar power poses a great challenge of integration when it is connected directly to the utility grid. Therefore, there is a strong need for developing low cost, high capacity storage systems to provide solar power at a constant level for a time interval acceptable by the utility.

The battery and the supercapacitor have high energy density property and high-power density property respectively. Because of this, the battery is capable of slow charge and discharge rates at higher energy levels. On the other hand, the supercapacitor is capable of fast charge and discharge rates at lower energy levels. If the fast changing (high frequency) components of the power are passing through the battery during its charging / discharging cycle, it decreases the lifetime of a battery. If a supercapacitor is a part of storage framework along with the battery, it can help reduce fast changing components of the power passing through the battery bank and accordingly increases the lifetime of the battery. Moreover, the longevity of battery significantly depends on its undergoing beyond the DOD. To increase the battery lifetime, it is also advisable that battery should not discharge beyond of its DOD.

To develop a cost-effective energy storage system, it is important to figure out the most optimum scaling of a battery and SC in HESS for:

- utility scale photovoltaic (PV) arrays (such as 1MW rated)

- one-hour dispatching period

- an entire day.

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It is also advisable to implement a control technique for perfect grid reference power ($P_{Grid,ref}$)

estimation so that energy storage able to finish each dispatching period with the same SOC as it

started. It is also required to use actual cell temperature in the experiment to get a better picture of

energy storage price calculation.

The outline of this thesis is organized as follows: Chapter 2 describes the literature review,

research on related topics is analyzed to choose the best technique for size optimization and

evaluation of reference generation algorithm of HESS for 1 MW grid connected PV array. Chapter

3 describes the methodology and control methods are used to develop a cost-effective energy

storage system for hourly dispatching solar power. Chapter 4 verifies the effectiveness of the

methodology and control methods through simulations. Finally, conclusions and future works are

described in Chapter 5.

# CHAPTER 2: LITERATURE REVIEW

## 2.1    Current Techniques

Teleke et al. proposed a mechanism for dispatching solar power on an hourly basis through an effective and responsive energy storage system [1]. However, this control technique was not cost effective to design a storage system for hourly dispatching solar power. This control strategy only used lead acid battery energy storage system (BESS) and due to this the fast changing components of the power pass through, and reduce the life time of the lead acid battery significantly.

Due to high energy density property of the battery, it has the capability of slow charge and discharge rates at higher energy levels. However, SC has the capability of fast charge and discharge rates at lower energy levels due to high power density property [2-3]. For this reason, when SC is a part of energy storage framework with battery, it helps to increase the battery lifetime by reducing the high frequency components of power passing through it. Therefore, a hybrid energy storage system (HESS) that consists of a battery bank and SC bank can be potentially used to develop an economical energy storage system. When a hybrid energy storage system is incorporated in a solar framework, it is also able to absorb and supply the necessary levels of power to provide a constant output power to the power grid from this solar farm.

A hybrid energy storage system comprised of a lead acid battery and SC with 100 kW PV array was used for dispatching solar power to the grid on an hourly basis [4]. However, the size optimization of the energy storage bank was not possible by Chaires et al.'s method due to the overestimation of the output power from PV array. Because of this, there is also a possibility to fully deplete or overcharge the battery bank leading to severe damage to the system and increase the associated battery bank cost. It is also advisable to increase the PV array capacity and improve

the accuracy of the grid power estimation from PV array while ensuring to successfully dispatching solar power.

In [5], the authors studied another HESS framework for developing a low cost energy storage system. However, the authors made some simplifying assumptions such as the total charged and discharged energy over the period was same and their objective was to dispatchable wind power rather than solar power.

In [6], the authors studied one HESS framework aim to develop a cost-effective energy storage system for hourly dispatching solar power. However, the authors used one specific day solar input data in their simulation experiment and assumed that the PV output power was the same for all the days of the year during annual energy storage cost calculation. In this paper, the minimum required capacity of the HESS was calculated by finding the maximum energy demand through the integration of power transferred in/out of HESS. But the power transferred in/out of HESS depends on PV output power, and it significantly varies from season to season of the year. Consequently, the approximation of annual energy storage cost based on one specific day solar input data may be overestimated or underestimated. In addition, the authors assumed that the ambient temperature and solar cell temperature was the same for the sake of simplicity.

### 2.2    Chosen Techniques

The 1 MW grid connected PV array will be developed to study different kinds of HESS framework for successfully dispatched solar power in one-hour increments for an entire day. A low pass filter will be used to allocate power between battery and SC. The most economical scaling of a battery and SC combination for 1 MW PV arrays will be developed based on the time constant of the low pass filter. The four diverse days' solar input data as a representation of each season will be used

in our experiment to get a better idea of the annual energy storage cost for hourly dispatching solar power. An economic comparison of two hybrid energy storage system (lead acid battery+SC, and lithium ion battery+SC) will be presented to find the most economical hybrid energy storage system for dispatching solar power. Rule based algorithms will be implemented to keep the state of charge of the energy storage bank within a specified range that will help increase the longevity of energy storage bank. Another rule based algorithms as a function of battery SOC will be developed to achieve perfect $P_{Grid,ref}$ estimation that will reduce the risk of overestimating or underestimating the annual energy storage cost by ensuring the battery bank to finish each dispatching period with the same SOC as it started. The relationship between the ambient temperature and solar cell temperature and its effects on the price calculation of the energy storage system for a solar framework will be demonstrated. In this research, an economic comparison between (i) rule-based algorithm vs. linearized rule-based algorithm (ii) ambient temperature vs. solar cell temperature will be presented to develop an economical energy storage system for dispatching solar PV power. The effects of SC on battery longevity when it is a part of storage framework will be investigated.

# CHAPTER 3: METHODOLOGY

## 3.1     System Topology

The photovoltaic energy system (PVES) is comprised of 1 MW solar PV arrays that output power through a unidirectional DC/DC boost converter. The energy storage system (ESS) in consideration is either battery only or HESS, a combination of Battery and SC, and a bi-directional DC/DC converters associated with each bank. The PVES and ESS are connected in parallel to the DC-link capacitor that acts as the DC bus. A DC/AC inverter or grid-connected converter (GCC) is used to control the voltage level at the DC-link. Since the PVES and ESS are connected to the DC bus as a current source, and the GCC controls the DC bus voltage, controllable power flow is possible by changing current flow through the DC/DC converters [7].

## 3.2     Control of PVES

The number of series and parallel strings of the solar photovoltaic (PV) arrays depends on the set of the DC bus voltage. When DC bus voltage set to 2500V, the solar photovoltaic (PV) arrays contain 132 parallel strings and 25 series connections of SunPower SPR-305-WHT solar cells. On the other hand, when DC bus voltage set to 1700V, the solar photovoltaic (PV) arrays contain 193 parallel strings and 17 series connections of SunPower SPR-305-WHT solar cells. The output of the photovoltaic array depends on two weather conditions (i) Solar Irradiation (W/m²) (ii) Solar Cell Temperature (˚C). In this experiment, the actual data recorded at Oak Ridge National Laboratory (ORNL) is used. The photovoltaic (PV) array is connected to a unidirectional boost converter which is controlled by a maximum power point tracking algorithm (MPPT) algorithm called incremental conductance (IC). The IC MPPT algorithm is commonly used in present

photovoltaic systems because it is highly efficient producing the maximum power from intermittent solar irradiation [8].

### 3.3    PV Cell Temperature Estimation

Since the ambient temperature and solar cell temperature is not same, it is very important to figure out the difference between these two temperatures and determine the effects on solar energy efficiency and energy storage price calculation. To do this, an effective approach for estimating PV cell temperature, which is adopted in our study, was formulated in [9]. This approach uses a simple formula to derive the PV cell temperature from the environmental variables such as ambient temperature, irradiance and wind speed. By using this method, the PV cell temperature can be predicted with an error of less than 3%. Another advantage of using this method, it is very simple and does not need any complicated calculations to predict the PV cell temperature successfully. The following relationship shown in (3.1) was used to determine the PV cell temperature.

$$(T_{module} °C) = a \times T_{ambient} + b \times Irradiance - c \times WindSpeed + d \qquad (3.1)$$

where, a, b, c, and d are system-specific regression coefficients, $T_{ambient}$ is given in (°C), irradiance in (W/m$^2$) and wind speed in m/s. By using a curve fitting tool, the regression coefficients a, b, c, and d were calculated using one year PV data [9]. Therefore, the formula for prediction of the PV cell temperature became

$$(T_{module} °C) = 0.943 \times T_{ambient} + 0.0195 \times Irradiance - 1.528 \times WindSpeed + 0.3529 \qquad (3.2)$$

### 3.4    Dispatchable Power Level Estimation

An estimate as to how much power can be efficiently dispatched on an hourly basis is predicted by using the actual solar irradiance, wind speed and temperature data recorded at Oak Ridge National Laboratory (ORNL). This estimated dispatched power for each hour is referred to as the

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grid reference power ($P_{Grid,ref}$) and the solar farm (PVES and ESS) is responsible for providing this reference power to the utility grid. The four different data sets with diverse PV output regimes, recorded at ORNL on 9th January 2017, 9th April 2017, 9th June 2017 and 9th September 2017 are collected to use in the experiment.

The average output power of the PV array over each dispatching period is estimated by using the average irradiation and temperature of the ORNL solar data, and it is used to calculate the grid reference power. The PV array module in Matlab/Simulink provides power-voltage characteristic curves based on user-input parameters such as solar cell type, the number of cells in parallel, and the number of cells in series under various weather conditions. The power-voltage characteristic curves for 1MW PV array are found as shown in Fig. 3.1 and Fig. 3.2. At maximum power point operation, the PV arrays' output power is indicated as a circle of their respective curves. To create a set of solar irradiation and temperature data and map a value other than the four given maximum power points shown on Figs. 3.1 and 3.2, cubic spline interpolation technique is used. The mean operation technique is performed to calculate the average irradiation and temperature for each dispatching period. The power level estimation from the average irradiation is referred to as $P_{PVES,est}$ and the efficiency estimated and provided by the average temperature is referred to as $\eta_{PVES,est}$. Due to the compensation for the inefficiency of IncCond MPPT, a constant factor of 0.95 is multiplied with final estimated power dispatched by PVES and the formula is used to estimate the power dispatch by PVES is shown in (3.3).

$$P_{Grid,est} = 0.95 \times P_{PVES,est}(kW) \times \eta_{PVES,est}(\%) \tag{3.3}$$
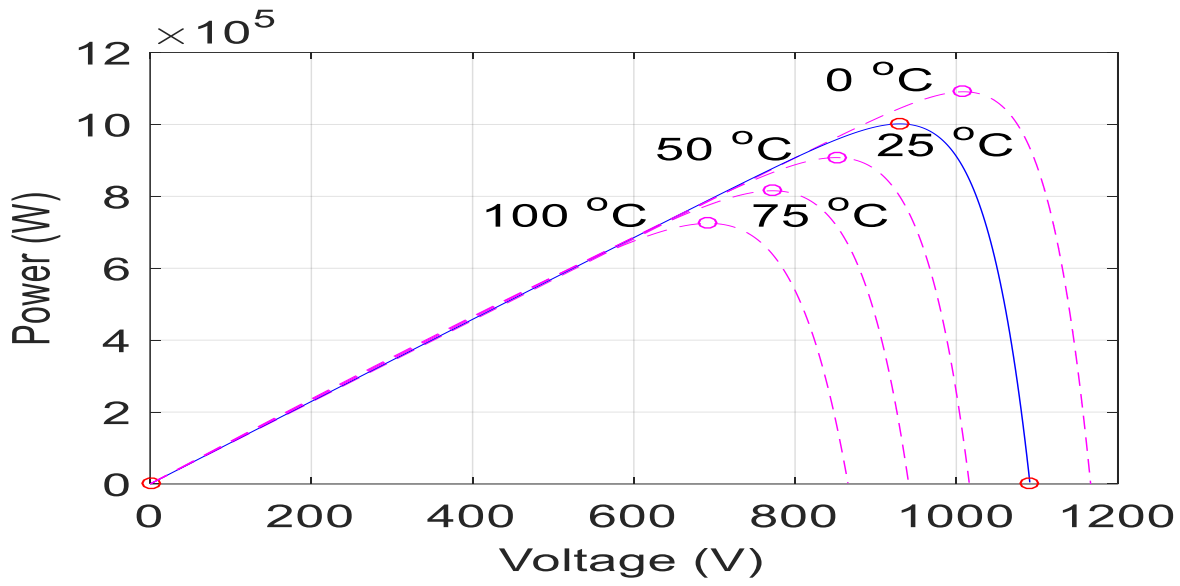
Figure 3.1: P-V array characteristics at various temperature (solid blue is at 25 °C)
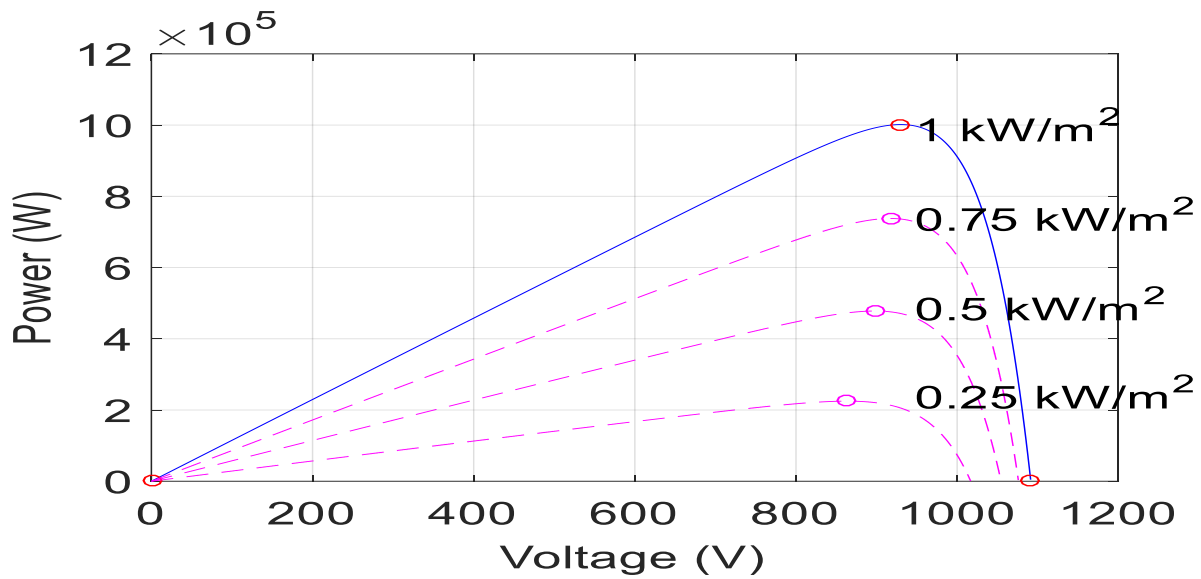


Figure 3.2: P-V array characteristics at various irradiance (solid blue is at 1 kW/m$^2$)

It is necessary to adjust the $P_{Grid,est}$ at the start of each dispatching period to mitigate errors that could propagate through a longer simulation and could lead to the ESS bank's SOC to be too high or too low. The multiplication factor to $P_{Grid,est}$ directly corresponds to the state of charge

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(SOC) of the BESS at the end of each dispatching period, and the resulting adjusted power level is referred as the grid reference power ($P_{Grid,ref}$). The grid reference power ($P_{Grid,ref}$) is used as a power expected to be dispatched for the entire system to the utility grid for each dispatching period. The block diagram used for $P_{Grid,ref.}$ calculation is shown in Fig. 3.3.

```
            ┌─────────────────┐
            │   P_Grid,est    │────────┐
            └─────────────────┘        │
                                       ▼
┌───────────┐   ┌─────────────────┐  ┌───┐   ┌─────────────┐
│ BESS SOC  │──▶│Rule based Algorithm│─▶│ X │──▶│  P_Grid,ref  │
└───────────┘   └─────────────────┘  └───┘   └─────────────┘
                                       ▲
            ┌─────────────────────┐    │
            │Multiplication Factor│◀───┘
            └─────────────────────┘
```
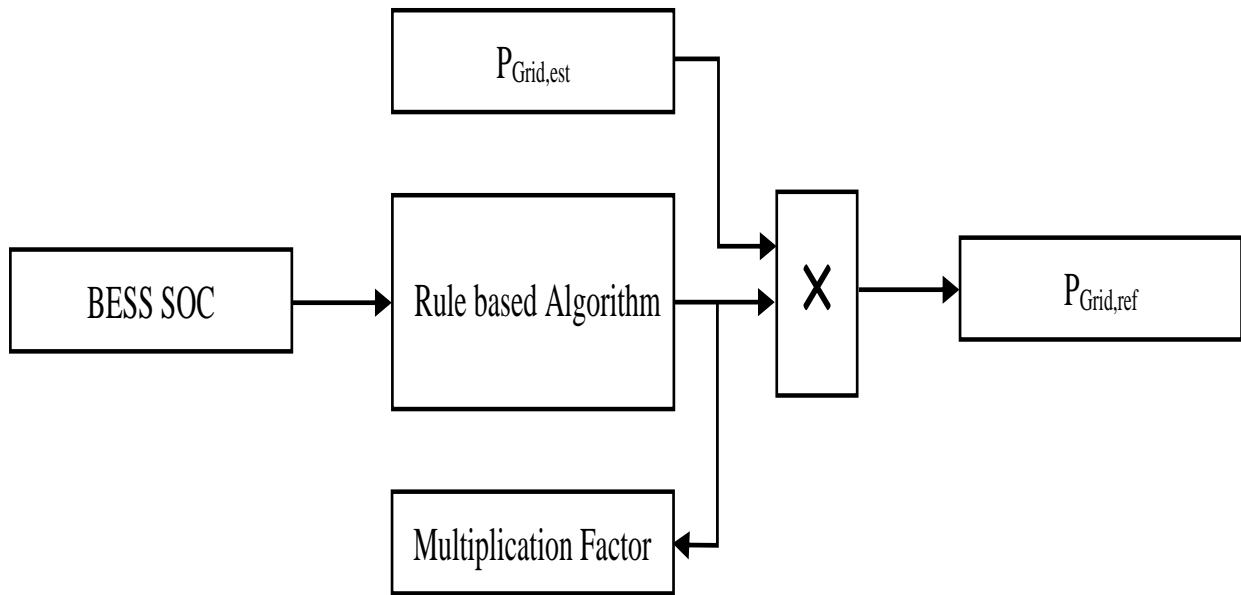
Figure 3.3: Grid reference power calculation for simulation

It is very important for the ESS to finish each dispatching period with the same SOC as it started in order to minimize the energy storage cost. For this reason, it is necessary to achieve near perfect $P_{Grid,est}$ estimation. The multiplication factor that is used to adjust $P_{Grid,est}$ plays a significant role in developing the most effective energy storage cost for hourly dispatching solar power. In this research, rule-based control algorithm and linearized rule-based algorithm are used to find the optimum multiplication factor to $P_{Grid,est.}$

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Table 3.1 shows the rule-based control algorithm that is used to calculate $P_{Grid,ref.}$ from adjusting $P_{Grid,est}$ with BESS SOC [4]. The formula shown in (3.4) is used to linearize the rule-based algorithm through regression analysis for calculating $P_{Grid,ref.}$ from adjusting $P_{Grid,est}$ with BESS SOC. Figure 3.4 shows the linearization of the battery SOC, which is given in %.

Table 3.1: $P_{Grid,ref}$ calculated from adjusting $P_{Grid,est}$ with BESS SOC

| BESS | Multiplication factor |
|---|---|
| 100 % ≥ SOC > 92 % | 1.10 |
| 92 % ≥ SOC > 84 % | 1.05 |
| 84 % ≥ SOC > 76% | 1.00 |
| 76 % ≥ SOC > 68% | 0.95 |
| 68 % ≥ SOC ≥ 60% | 0.90 |

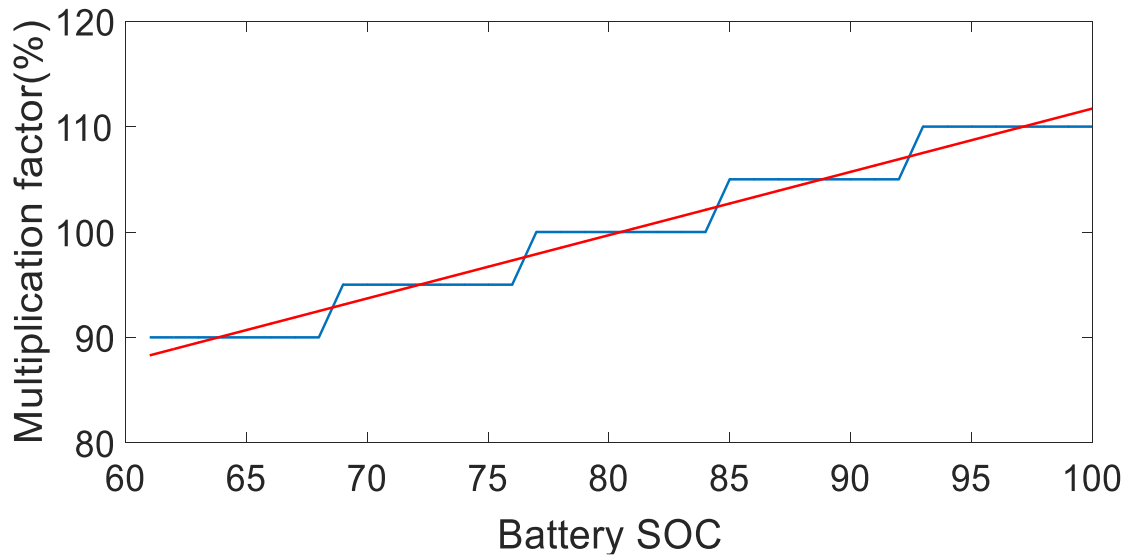$$\text{Multiplication factor} = \frac{(0.60 \times SOC + 51.7)}{100} \tag{3.4}$$



Figure 3.4: Linearization of rule based algorithm

## 3.5    Control of HESS

According to the control framework proposed by Zheng et al. [7], the HESS is responsible for maintaining the system's power injected into the utility grid and the grid side inverter is responsible for maintaining a constant DC bus voltage. Due to its superior performance, this control framework was adopted in this study. The reference power for the HESS is the difference between PVES output power and the grid reference power that is calculated using (3.5).

$$P_{HESS,ref} = P_{Grid,ref} - P_{PVES} \tag{3.5}$$

The reference power of the HESS, $P_{HESS,ref}$ is sent through a low pass filter to provide the BESS with a power reference referred to as $P_{BESS,ref}$ . The low pass filter helps reduce the high frequency components of power passing through the battery, corresponding to an increase in the battery lifetime. The power reference for the supercapacitor energy storage system (SESS), referred to as $P_{SESS,ref}$ is the difference between the HESS and the BESS reference power that is comprised of the high frequency components of $P_{HESS,ref}$ . The block diagram of the rule-based algorithm that is shown in Fig. 3.5 is implemented to prevent the battery bank SOC from going above 100 % SOC or below its SOC of 60%. This eventually helps increase the lifetime of the battery, correspondingly decreasing the energy storage cost. Fig. 3.6 shows the power transfer mechanisms for the BESS and SESS in the HESS scheme.
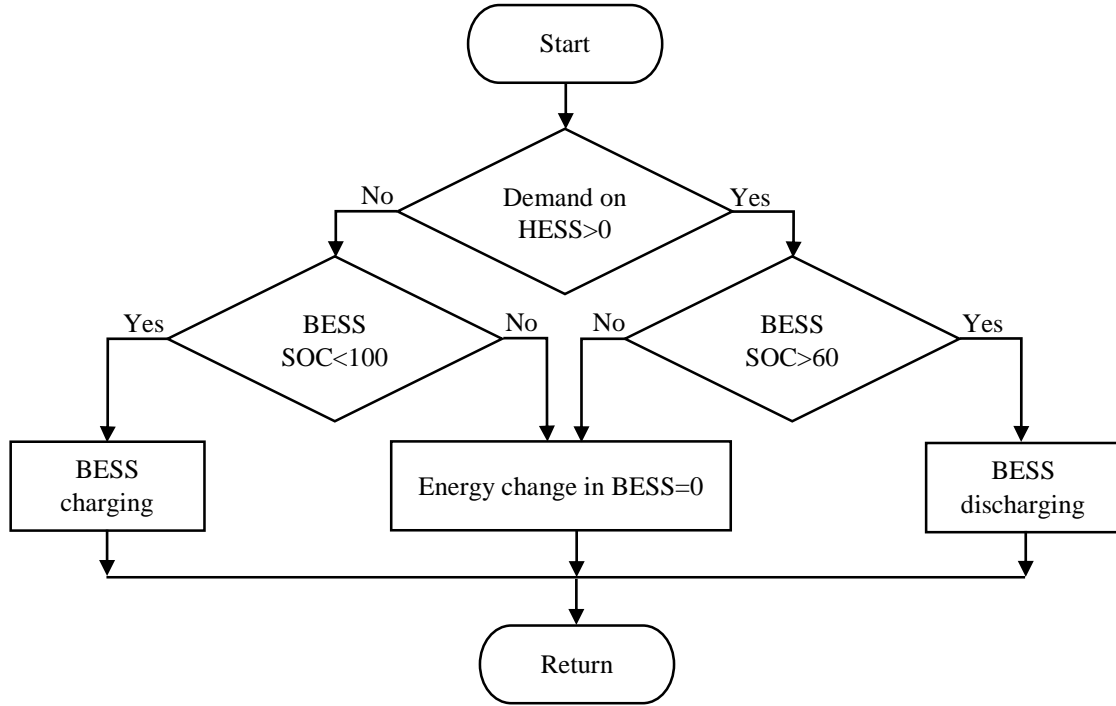
Figure 3.5: Rule-based algorithm for Battery SOC control

Duty ratio for DC/DC converters controls the ratio of output to the input voltage that helps mitigate the proportional and integral error of the system. The change in duty ratio is determined by comparing the reference signals for the BESS and SESS with their current output powers. In this study, a pair of PI controllers is used to determine the duty ratio for the DC/DC converters in the BESS and the SESS.

The PI calculation formula is shown in (3.6)

$$PI(t) = K_p \times e(t) + K_i \times \int_0^t e(t)dt \qquad (3.6)$$

where, e(t) is the error signal that is calculated using the difference between the reference power ($P_{ref}$)and the current power of the BESS or SESS ($P_{actual}$).

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For a larger value of the proportional gain constant $K_p$ that generally controls the overshoot response of the system, the system becomes more sensitive to oscillatory response. The integral gain constant $K_i$ generally controls the settling time response of the system. For a larger value of the integral gain constant $K_i$, the system response settles down faster resulting in a smaller residual steady state error, but it can also become unstable. So, it is important to find the optimum value of $K_p$ and $K_i$ for both BESS and SESS converters where the system shows small overshoot and quick settling time. Through numerous trial and error attempts, a near optimum performance of the BESS converter was found using a $K_p$ to be $6 \times 10^{-4}$ and a $K_i$ to be $5 \times 10^{-3}$. Similarly, the optimum performance of the SESS converter is found using a $K_p$ to be $1 \times 10^{-3}$ and a $K_i$ to be $5 \times 10^{-1}$ [4].

As mentioned earlier in section 3.1, a bi-directional buck/boost converter is being used to control power flow into the energy storage system. A positive error signal for PI controller indicates that the ESS is in a discharge mode and, a negative error signal indicates that the ESS is in charge mode. When ESS is in discharge mode, the DC/DC converters operate in boost mode. Conversely, when ESS is in charge mode, the DC/DC converters operate in buck mode. The DC bus voltage is approximately twice as much as the storage (BESS/SESS) voltage. This mechanism will help avoid the discontinuity in input current in ESS caused by buck converter operation. In order to mitigate initial transients from the converter's response caused by a drastic change in duty ratio, the PI control signal is adjusted by an initial value $D_{init}$ that plays an important role for such a large scale energy storage system.

As the voltage of the energy storage bank is a function of its SOC at the start of the dispatching period, it can be varied. Through a trial and error method, an ideal initial duty ratio for BESS SOCs of 100%, 75%, 50%, and 25% are found to be 0.535, 0.51, 0.485, and 0.46,

respectively. The same initial duty ratio is selected for the SESS as well. In order to prevent the energy storage system from being damaged by an extreme PI control signal, a limiter module is placed at the end of the PI controller model. The upper limit and lower limit of the PI controller for the BESS are selected to be 0.65 and 0.35, respectively. On the other hand, the upper limit and lower limit of the PI controller for the SESS are selected to be 0.55 and 0.25, respectively [4].
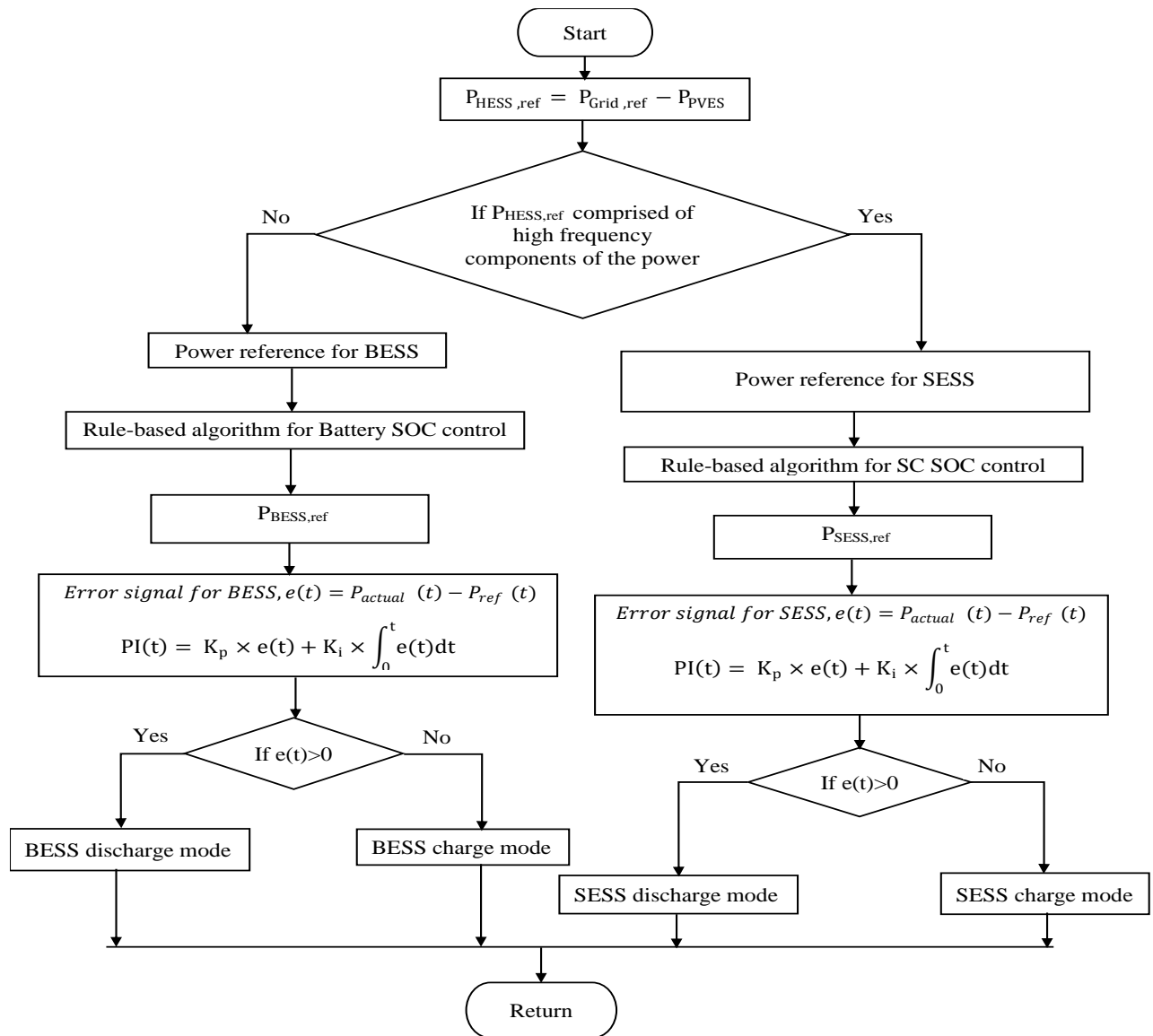


Figure 3.6: Bidirectional BESS and SESS power transfer tuning mechanisms
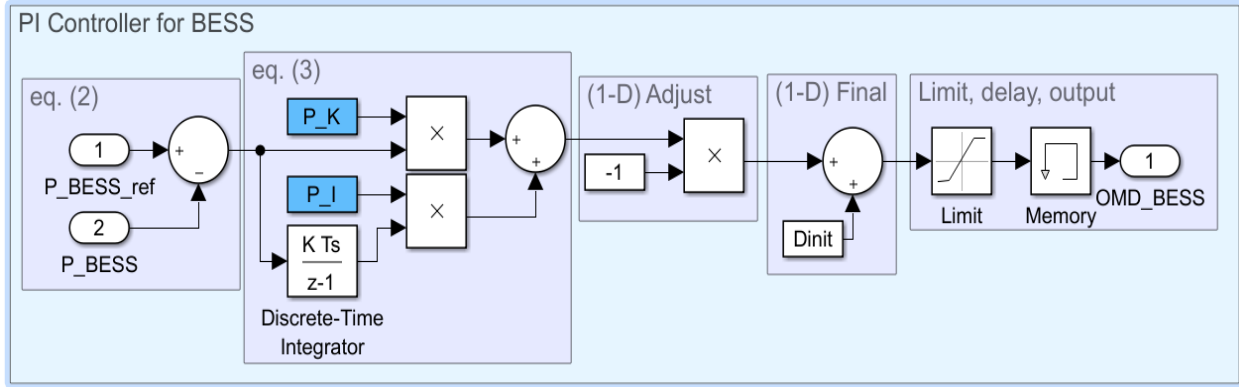
Figure 3.7:  PI Controller for BESS [4]

## 3.6　Minimum Capacity Calculation for BESS and SESS

The minimum capacity needed for BESS and SESS is calculated through integrating the power profile of the battery bank and supercapacitor over each dispatching period respectively. The absolute maximum amount of energy used by the BESS is calculated through integrating the BESS power curve over each dispatching period and then compared to other dispatching period's maximum energy needed for the BESS. The maximum of these maximums is used to determine the minimum capacity required for the battery bank to successfully dispatch solar power to the grid at one-hour increments for an entire day.

In a similar way, the maximum energy used by the SESS is calculated. After that, the required size for the supercapacitor is calculated by using (3.7) [10].

$$E = \frac{1}{2} CV^2 \qquad (3.7)$$

### 3.7 Size Optimization for BESS and SESS

In HESS, a low pass filter is used to allocate the power between the battery and the SC. With the increasing time constant of the low-pass filter, the minimum capacity required for the battery and SC are decreasing and increasing respectively. Since SC is more expensive than the battery, it is important to find the optimum value of the filter time constant for developing a most economical energy storage system. In this research, first, the simulations are run with different time constants using solar input data on 9$^{th}$ June,2015 and chose the time constant that exhibits the least cost ($/kWh) HESS for dispatching solar power. After that, this optimum time constant filter is used in HESS when the simulations are run using four diverse days from 2017 to get a better idea about energy storage system utilization.

### 3.8 Price Calculation for Energy Storage System

The lifetime of the energy storage depends on the usage of depth of discharge (DOD) and rate of change of the charging/discharging power. The energy storage manufacturers provide cycle life data as a function of DOD, and the deeper discharge of energy storage can reduce its lifetime significantly. Solar energy is an intermittent power source, and due to this, the charging-discharging cycles of the energy storage is not necessarily regular in an HESS scheme. In this research, the charging and discharging characteristics of the energy storage over a period is used to estimate its lifetime. The total energy discharged and charged is calculated through integrating the power over all discharging intervals and charging intervals throughout the period. If SOC is the same at the beginning and at the end of each dispatching periods, then total energy charged and discharged is theoretically equal. However, this cannot be guaranteed in a setting where potential PV output power needs to be estimated. Therefore, due to the possibility of total energy

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discharged and charged over the dispatching period being different, higher of the two (total charged or discharged energy) is used in price calculation of the energy storage system in order to get the worst possible figure about the storage cost.

The equivalent service cycle life ($C_{B,T}$) of the battery over the period $T_S$ is calculated by using (3.8) [6].

$$C_{B,T} = \sum_{j \in T_s} \frac{E_{sj}}{E_{sr}}$$

(3.8)

where $E_{sr}$ is battery's rated energy capacity multiplied by DOD and a correction factor to derate the manufacturer's data (a correction factor of 0.8 is assumed in this research), and $E_{sj}$ is the total energy discharged or charged (whichever is bigger) over the period $T_S$.

Equation (3.9) is used to calculate the expected life $E|L_B|$ of the battery.

$$E|L_B| = \left(\frac{C_{B,n}}{C_{B,T}}\right) \times T_s$$

(3.9)

where $C_{B,n}$ is the cycle life of the battery provided by the manufacturers.

In a similar way, the expected life $E|L_S|$ of the SC is determined in this research. It is important to mention that; the maximum lifetime of the solar PV scheme is assumed in this research to be 25 years. Therefore, the expected life of the BESS or SESS cannot exceed this time limit. Equations (3.10) and (3.11) are used to calculate the annual HESS cost. After calculating the HESS cost per kWh, the HESS cost is increased by 10% to account for operation & maintenance as well as power converter costs.

$$\text{Annual HESS cost (\$)} = \left(\frac{E_B \times C_B}{E|L_B|} + \frac{E_S \times C_S}{E|L_s|}\right)$$

(3.10)

$$\text{Normalized HESS cost} \left(\frac{\$}{\text{kWh}}\right) = \frac{\text{Annual HESS cost}}{P_B \times CF \times T}$$

(3.11)

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where $E_B$ is the battery capacity (kWh), $C_B$ is the battery cost ($/kWh), $E_S$ is the SC capacity (kWh), $C_S$ is the SC cost ($/kWh), $P_B$ is the PV array capacity (kW), CF is the capacity factor, and T is the number of hours in a year.

The PV array capacity factor directly depends on the output power of the solar panel. When the cell temperature increases, it is responsible for decreasing the PV output power, and correspondingly this decreases the PV array capacity factor. In this study, the simulations are run in two ways (i) assume that ambient temperature and cell temperature are the same (ii) estimate the solar cell temperature using the method that is described in section 3.3 to demonstrate the solar cell temperature effects on price calculation of the energy storage system. The capacity factor of PV array is 20 percent considered if the ambient temperature and cell temperature are the same. By comparing the output power of PV array with ambient temperature input vs. the estimated cell temperature input, the capacity factor of the PV array with the estimated cell temperature is recalculated.

In this study, the following assumptions are made for price calculation of the energy storage system. The unit price and cycle life of lead acid battery are $100/kWh and 1435 (at 40% DOD) respectively. The unit price and cycle life of Li-ion battery are $400/kWh and 7000 (at 40% DOD) respectively. The unit price and cycle life of SC are $2500/kWh and 500000 respectively [5].

### 3.9 Effects of Battery Lifetime on Energy Storage Cost Calculation

For developing a cost-effective energy storage system for dispatching solar PV power, it is important to increase the battery lifetime. In this research, SC is used with the battery in HESS framework, and a rule-based algorithm is employed in order to increase the battery lifetime, correspondingly to decrease the energy storage cost. SC helps mitigate the fast-changing

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components of the power passing through the battery bank and rule based algorithms ensures to keep the state of charge of the battery between 60 % to 100 %. For these reasons, SC and this control algorithm would help increase the battery lifetime. The battery lifetime comparison with and without SC in energy storage system is presented in this study.

# CHAPTER 4: RESULTS

The 1 MW grid connected PV array is designed and simulated using Simulink™ software to develop a low-cost energy storage system for hourly dispatching solar power. The hourly dispatching solar farm Matlab/Simulink model shown in Fig. 4.1 is used to validate the ability of the system to dispatch solar power for one-hour dispatching for an entire day. First, the 100kW grid-connected PV array example is from Giroux et al. [11] was selected and then we changed the properties of PVES, DC link, GCC, and utility grid models to design 1MW grid connected PV array. In addition, bidirectional power converters and rule-based algorithms are designed and employed to develop the most cost effective energy storage system. Cell temperature estimation algorithm is also incorporated in this study to account for realistic temperature constraints for PV modules.
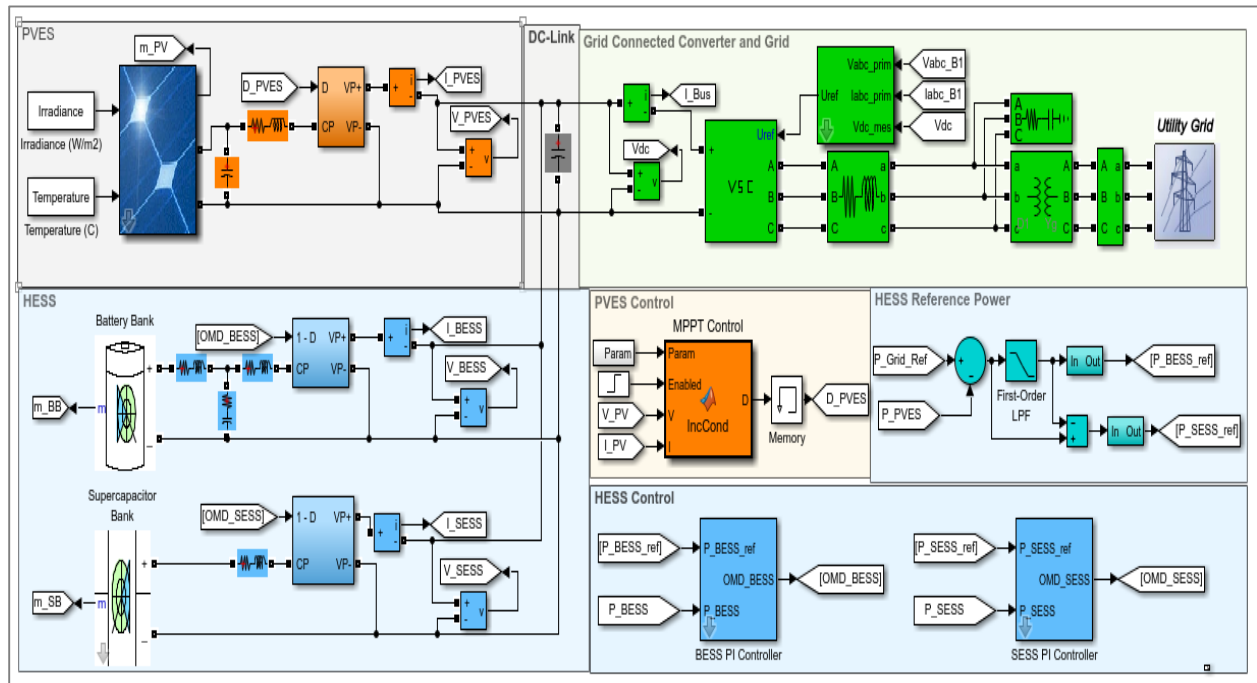


Figure 4.1: Solar Farm Simulink Model

The power profiles of PVES, BESS, SESS, $P_{Grid}$, and $P_{Grid,ref}$ are shown in Fig. 4.2. In this case, 1MW PV array and energy storage system (lithium-ion battery+SC) are used to provide power to the utility grid. $P_{Grid,ref}$ is used as a target power level for the PVES and HESS to provide to the utility grid. $P_{Grid}$ is the combination of the power of PVES, BESS, and SESS and the GCC injects this combined power into the utility grid. Fig. 4.2 shows that the $P_{Grid}$ remains constant in each dispatching period and successfully follows the grid reference power ($P_{Grid,ref}$). Further investigation into the simulation results shows that the high frequency components of the power are charged and discharged through the SESS, and low frequency components of the power are charged and discharged through the BESS. Fig. 4.3 and 4.4 show the simulation results of BESS and SESS SOC variations that highlight this fact.
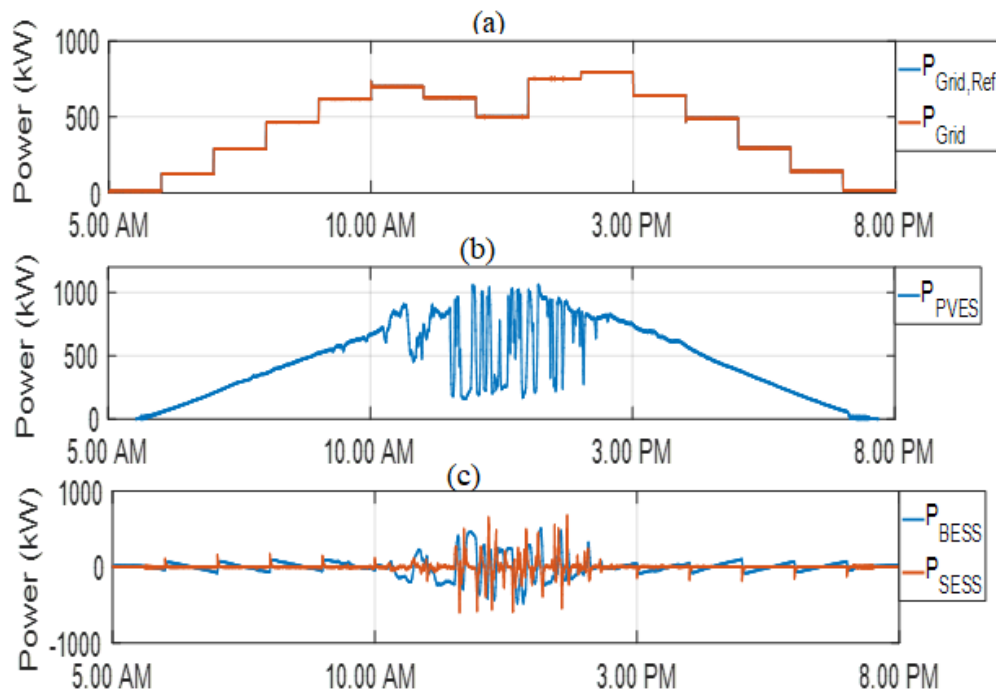


Figure 4.2: Simulation results for one-hour dispatching with 2500V dc bus. In (a), the target power profile ($P_{Grid,ref}$) and injected power profile ($P_{Grid}$) into the utility by the PVES and HESS combined are shown. In (b) and (c), the power profiles of PVES, and the power profiles of BESS and SESS are shown respectively.
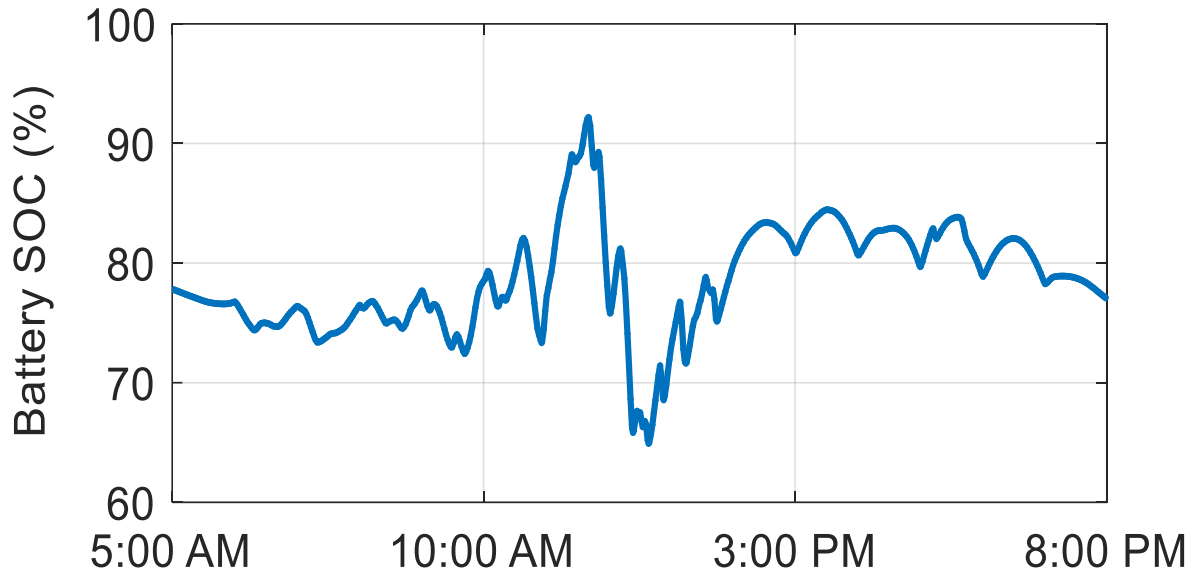
Figure 4.3: Simulation results of battery bank SOC
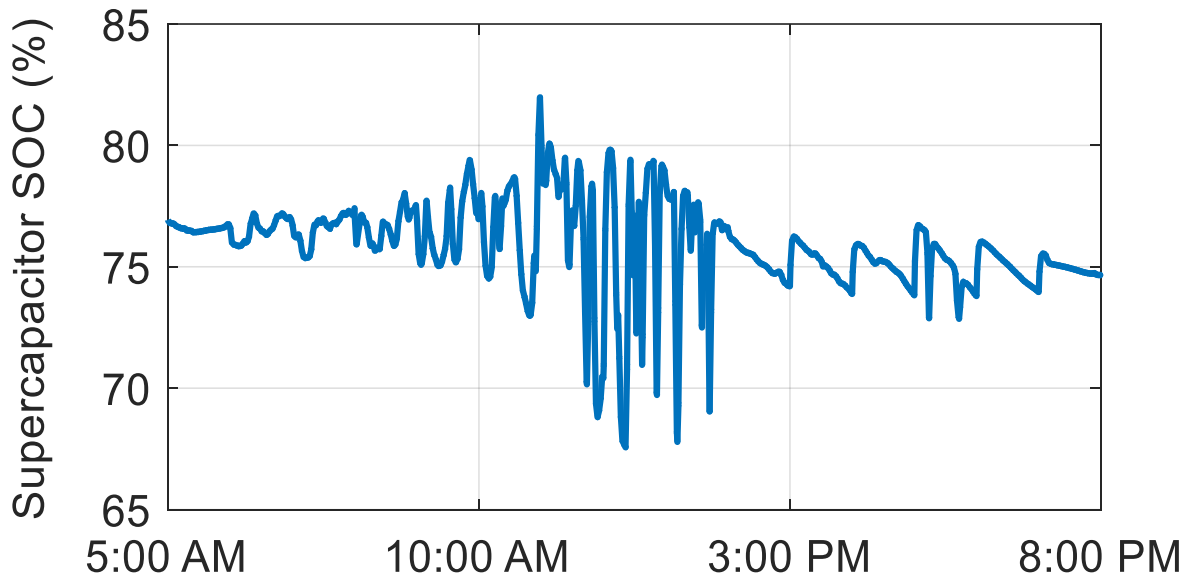


Figure 4.4: Simulation results of supercapacitor bank SOC

Equation (4.1) is used to calculate the percentage of error between the estimated grid power ($P_{Grid,ref}$) and the actual dispatched grid power ($P_{Grid}$) and that is shown in Fig. 4.5. It is found that the percentage of error is nearly 1% during peak hours and less than 0.5% during non-peak hours of the day.

$$Error(\%) = \frac{|P_{Grid,ref} - P_{Grid}|}{P_{Grid,ref}} \times 100 \qquad (4.1)$$
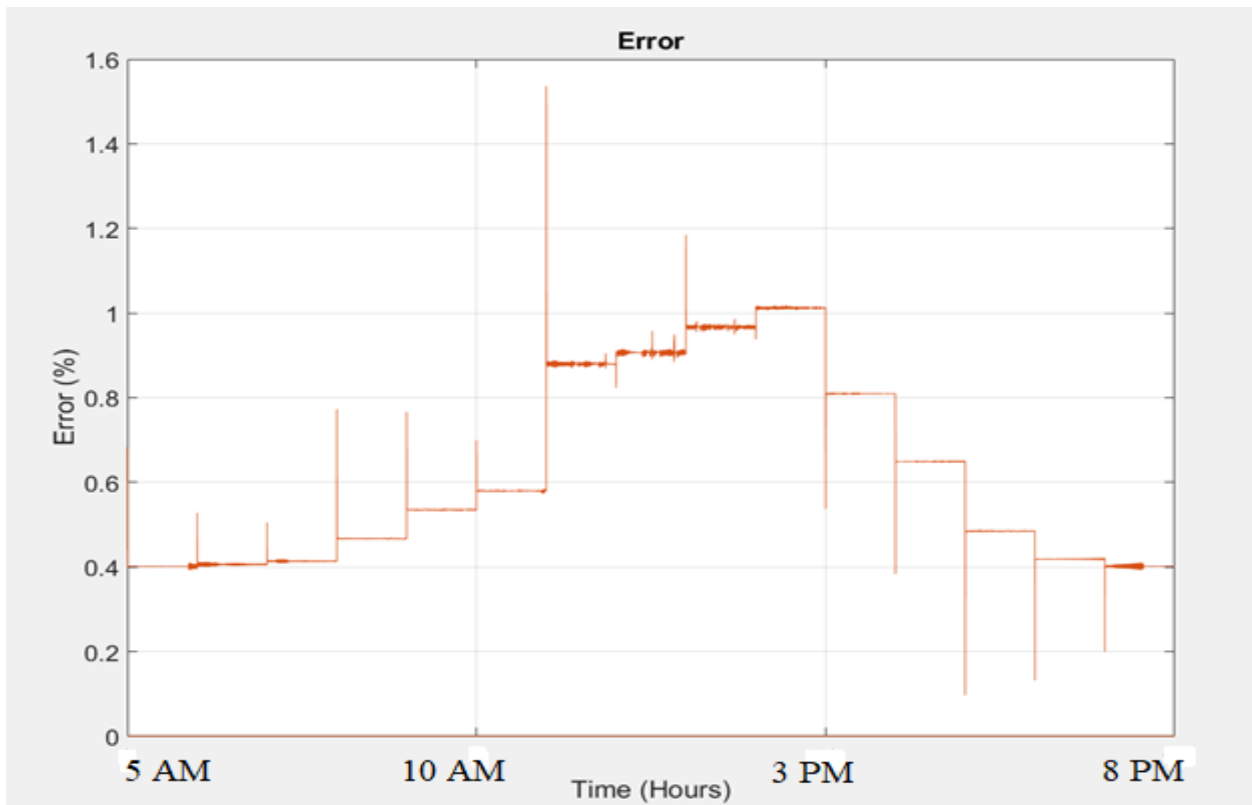


Figure 4.5: Error of dispatched power for June 9th,2017 (15 hour's simulation results)

Rule based algorithm is employed to successfully keep the state of charge (SOC) of the battery bank and SC bank between 60 % to 100 % that is shown in Figs 4.3 and 4.4 . To maintain

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the SOC of battery bank within a specified range helps increase the battery longevity. However, the SC SOC range can be flexible since SC does not have strict DOD requirements.

In this study, it is assumed that there are no transmission losses within the system and BESS finishes each dispatching period with the same SOC (80 percent) as it started due to near perfect $P_{Grid,ref}$ estimation. Because of this, it is found that the absolute value of maximum energy used by battery bank on 9th June, 2015 (total simulation time) is approximately 60 kWhr then the minimum capacity required for the battery bank is found approximately 300 kWhr (5×60 for 60% battery DOD limiting).

In a similar way, the minimum capacity needed for SESS is also calculated. Let the absolute value of maximum energy used by SC bank on 9th June, 2015 (total simulation time) is approximately 20 kWhr then the minimum capacity required for the battery bank is found approximately 100 kWhr (5×20). Then the minimum capacitance can be calculated for SC by using following formulas.

$$Energy \ (Joules) = Energy \ (kWh) \times 3.6 \times 10^6 \tag{4.2}$$

$$Capacity \ (Farads) = \frac{2 \times Energy \ (Joules)}{V^2} \tag{4.3}$$

Using solar input data on 9th June, 2015 alone in the simulation, an economic comparison is made between different kinds of battery (Lead acid and Li-ion) and SC combination in HESS that are shown on Table 4.1. From Table 4.1, it is found that the hybrid energy storage system is the most cost-effective scheme compared with using only battery (0 seconds time constant) or SC ($\infty$ seconds time constant) for dispatching solar power. It is also noticeable that the HESS gives the best competitive cost per kWh at 60 seconds filter time constant. From Table 4.1, it is found that the utilization of the lithium ion battery in HESS is more economical than using the lead acid battery. The most economical scaling of lithium ion battery and SC combination is found to be

474 and 44 kWh respectively. It is important to mention that a correction factor of 1.0 is used to derate the manufacturer's data here and it is assumed that the cell temperature and ambient temperature are the same for this price comparison study. In this case, the DC bus voltage is set to 1700 V in Matlab/Simulink solar farm model.

Table 4.1: Hybrid energy storage system cost comparison

| Low pass filter time constant | 0s | 60s | 120s | 3600s | Infinity |
|---|---|---|---|---|---|
| HESS (lead-acid+SC) cost ¢/kWh | 2.53 | 2.18 | 2.27 | 2.39 | 3.04 |
| HESS (Li-ion+SC) cost ¢/kWh | 2.17 | 1.91 | 2.09 | 2.33 | 3.04 |

The aim is to get a better picture of the annual storage cost, therefore, the solar irradiance and temperature data from four diverse days from 2017 are used in this simulation. Due to the fact that seasonal solar irradiation is relatively smaller during the early morning and late afternoon hours, which correspond to lower temperatures data, these hours are ignored in overall energy storage cost calculations. Because of this simplifying assumption in this study, simulations are run by using 15 hours of solar irradiance and temperature data on 9th June and 9th April, 13 hours of solar irradiance and temperature data on 9th September, and 7 hours of solar irradiance and temperature data on 9th January. The annual energy storage cost is calculated by averaging of four different days' energy storage cost. The price comparison between two kinds of energy storage system (i) Battery only (ii) HESS, Li-ion battery and SC combination shown in Table 4.2. It is important to mention that during this price calculation; the DC bus voltage is set to 2500 V in the

Matlab/Simulink solar farm model and a more realistic correction factor of 0.8 is used to derate the manufacturer's data [5].

Table 4.2: Energy storage cost comparison

| Date of selected PV data | | ESS cost (¢/kWh) | | | |
|---|---|---|---|---|---|
| | | Ambient Temperature | | Cell Temperature | |
| | | Rule based algorithm | Linearized rule based algorithm | Rule based algorithm | Linearized rule based algorithm |
| 9th Jun. | Battery | 3.4 | 3.3 | 3.4 | 3.4 |
| | Battery +SC | 2.9 | 2.7 | 2.7 | 2.7 |
| 9th Apr. | Battery | 2.0 | 2.0 | 1.9 | 1.9 |
| | Battery+ SC | 1.4 | 1.4 | 1.4 | 1.4 |
| 9th Sept. | Battery | 1.9 | 1.9 | 1.7 | 1.8 |
| | Battery+ SC | 1.5 | 1.5 | 1.4 | 1.4 |
| 9th Jan. | Battery | 0.8 | 0.6 | 0.9 | 0.9 |
| | Battery+ SC | 0.6 | 0.5 | 0.6 | 0.6 |
| Annual | Battery | 2.0 | 2.0 | 2.0 | 2.0 |
| | Battery+ SC | 1.6 | 1.5 | 1.5 | 1.5 |

In order to estimate $P_{Grid,ref}$ perfectly , it is required for energy storage system to finish each dispatching period with the same SOC as it started. Rule-based control algorithm and linearized rule-based algorithm are implemented to find an appropriate multiplication factor to calculate $P_{Grid,est}$. To observe the effect of rule-based control algorithm and linearized rule-based algorithm on price calculation of various energy storage systems, the simulations are run using four diverse days' solar input data, representative of each season. The effects of those algorithms on annual energy storage cost are also presented in Table 4.2. On average energy storage price calculations,

the performances of those algorithms are almost the same, but linearized rule-based algorithm performs slightly better.

To predict the worst possible figure of annual energy storage cost, solar cell temperature is estimated using a method that is described in section 3.3. In Table 4.2, the energy storage comparative price calculation is presented while considering the ambient temperature and estimated cell temperature input into the PV array. The estimated cell temperature is generally higher than the ambient temperature and it is responsible for reducing the PV array output and capacity factor. By comparing the output power of PV array with ambient temperature input vs. estimated cell temperature input, the PV array capacity factor for estimated cell temperature input is calculated. The capacity factors of PV array with estimated call temperature input are found to be 19.1% on 9th June, 18.8% on 9th April, 18.9% on 9th September, and 19.5% on 9th January.

From Table 4.2, it is important to notice that the PV cell temperature case does not really increase the annual energy storage cost (¢/kWh). The reason can be explained as follows. Equation (3.11) is used to calculate the annual energy storage costs (¢/kWh) and it shows that the annual energy storage cost (¢/kWh) is directly proportional to the annual HESS cost, and is inversely proportional to the PV capacity factor. As this study mentioned earlier, the estimated cell temperature is generally higher than ambient temperature and it is responsible for reducing PV capacity factor. But, at the same time, it is also responsible for reducing the power transferred in/out of HESS. Since the HESS cost depends on power transferred in/out of HESS, the ratio of annual HESS cost to PV capacity factor remains nearly the same in (3.11) with estimated cell temperature case input to PV array in comparison with the ambient temperature case.

The ESS cost and PV capacity factor comparison between the effects of ambient temperature and estimated cell temperature inputs are presented in Table 4.3. From Table 4.3, it

can be concluded that the power transferred in/out of HESS has occurred the highest on 9th June and the lowest on 9th January, corresponding to highest and lowest ESS costs respectively.

Table 4.3: ESS cost and PV capacity factor

| Date of selected PV data | | ESS cost | | | |
|---|---|---|---|---|---|
| | | ESS cost ($) | | PV capacity factor (%) | |
| | | Ambient Temp. | Cell Temp. | Ambient Temp. | Cell Temp. |
| 9th Jun. | Battery | 60,006 | 56,039 | 20 | 19.1 |
| | Battery+ SC | 50,523 | 45,379 | 20 | 19.1 |
| 9th Apr. | Battery | 35,017 | 30,975 | 20 | 18.8 |
| | Battery+ SC | 24,297 | 23,372 | 20 | 18.8 |
| 9th Sept. | Battery | 33,315 | 28,865 | 20 | 18.9 |
| | Battery+ SC | 26,088 | 23,912 | 20 | 18.9 |
| 9th Jan. | Battery | 14,747 | 14,973 | 20 | 19.5 |
| | Battery+ SC | 9,598 | 10,501 | 20 | 19.5 |

When SC is a part of the HESS, it helps decrease the fast-changing components of the power passing through the battery. Consequently, the battery lifetime significantly increases, and it helps develop a cost-effective storage system for this scheme. The estimated battery lifetime with or without SC in the energy storage framework is shown in Table 4.4. Since the cost associated with energy storage system is inversely proportional to energy storage lifetime, the HESS (combination of battery and SC) can be the most economical energy storage scheme in comparison to using only battery or SC for dispatching solar power to the grid. Note that in Table 4.4, the SC is expected to work for 25 years. Once the battery is no longer usable, it will be

replaced, and the HESS still functions. The cost calculation in this thesis is compared in each day using the same irradiance data between different schemes. In the long run, the costs are accumulative from all days. Now that the average cost of HESS (Battery+SC) is lower than ESS (Battery only) on the four days that are experimented representing the four seasons, the accumulative cost of HESS (Battery+SC) is expected to be lower than ESS (Battery only) in the long run.

Table 4.4: Battery lifetime comparison (in years)

| Date of selected PV data | | ESS life (years) | | | |
| --- | --- | --- | --- | --- | --- |
| | | Ambient Temperature | | Cell Temperature | |
| | | Rule based algorithm | Linearized rule based algorithm | Rule based algorithm | Linearized rule based algorithm |
| 9th Jun. | Battery | 4.6 | 5.0 | 3.3 | 3.5 |
| | Battery+SC | 6.4 | 7.0 | 4.4 | 4.6 |
| 9th Apr. | Battery | 4.4 | 4.5 | 4.3 | 5.2 |
| | Battery+SC | 6.8 | 7.3 | 6.1 | 7.4 |
| 9th Sept. | Battery | 3.9 | 5.0 | 6.4 | 6.0 |
| | Battery+SC | 5.7 | 7.2 | 8.8 | 8.4 |
| 9th Jan. | Battery | 5.7 | 4.7 | 8.1 | 7.3 |
| | Battery+SC | 10.4 | 7.0 | 13.0 | 12.3 |

## CHAPTER 5: CONCLUSION AND FUTURE WORK

In conclusion, a cost-effective energy storage system has been investigated through (i) figuring out the optimum (most economical) scaling of battery and supercapacitor combination, and (ii) evaluating reference generation algorithms for hourly dispatching solar power for 1 MW photovoltaic (PV) arrays. The size optimization of battery and SC was made based on time constant of low pass filter. By comparing different kinds of battery and SC combination in HESS, it was found that the HESS consists of lithium ion battery and SC was most cost effective at 60s filter time constant in comparison to lead acid battery and SC combination. To find the appropriate multiplication factor for near perfect grid reference power estimation for each dispatching period, rule-based algorithms and linearized rule-based algorithms were used. The relationship between ambient temperature and cell temperature was looked up and its effect on annual ESS cost also presented.

The HESS that consists of battery and SC was used to provide constant power to the utility grid by absorbing or supplying necessary power from intermittent solar power source. From simulation results it was shown that, the solar farm successfully provided the target power to the utility grid for one-hour dispatching for one day at an error of nearly 1% during peak hours and less than 0.5% during non-peak hour's of the day. Due to the high-power density property of SC, it provided a relief to battery bank by absorbing high frequency components of HESS reference power. The effects of SC on battery longevity when it was integrated to HESS also presented. To increase the battery lifetime that helps develop cost effective energy storage cost, another rule-based algorithm was implemented to prevent the battery bank from operating out of their state of charge (SOC) window. Based on simulation results, it was found that the cell temperature

framework had negligible impact on annual energy storage cost calculation regardless of the rule-based algorithms and linearized rule-based algorithms were used for near perfect grid reference power estimation for each dispatching period, and the hybrid energy storage system (HESS) was the most economical (1.5 ¢/kWh) energy storage system for hourly dispatching solar power.

Due to the significant amount of time (approximately 15 to 20 hours) being required to complete the computer simulation for one-day solar input data, four diverse days' solar input data was used for calculating the annual energy storage. However, a more comprehensive study about annual energy storage should be done in the future by selecting more days for solar input data and using higher processing power for simulations. Future work may also include implementing a fuzzy logic controller rather than using rule-based algorithms for estimation of perfect grid reference power.

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```matlab
%% Pre-Simulation Code (ambient temperature=cell temperature assumed)


% Ts_Power=50e-6
% Ts_Control=100e-6
% Dec_Power=40000
% Dec_Control=20000

clc; clear all;
STH = 15; % SimTime in hours
ST = 3600*STH; % 3600s = 60mins = 1hr, 15hrs = 54000

% Step 1:  Input Actual Irradiance and Temperature Data
% Step 2:  Interpolate Data
% Step 3:  Find Average Irradiance and Temperature
% Step 4:  Plot Irradiation and Temperature
% Step 5:  Estimate Average PV Output Power
% Step 6:  Clear Unnecessary Variables


%% Step 1: Input Actual Irradiance and Temperature

% Irradiance (Ir) measured in W/m^2 was sampled every minute
load('Irradiance_data.mat')
Ir=Ir';
% Time axis of Ir (Irt) is converted from mins to secs
Irt = 0:60:ST;
% Irradiance data and time saved as structure
Irradiance.signals.values = Ir';
Irradiance.time = Irt';

% Temperature (Temp) measured in degrees C was sampled every minute
load('Temperature_data.mat')
Temp=Temp';
% Time axis of Temp (Tempt) is converted from 30mins to 1800secs
Tempt = 0:60:ST;

% Temperature data and time saved as structure
Temperature.signals.values = Temp';
Temperature.time = Tempt';
save('Irradiance.mat','Irradiance');
save('Temperature.mat','Temperature');
```

```matlab
%% Step 2: Interpolate Data
t2 = 0:0.5:ST;
SpHr = (1/(0.5))*60*60;

% Interpolate (Connect missing data points) of original Ir data to new time axis
Ir2 = interp1(Irt,Ir,t2,'cubic');
% Interpolate (Connect missing data points) of original Temp data to new time axis
Temp2 = interp1(Tempt,Temp,t2,'cubic');


Irradiance_Interp.signals.values = Ir2';
Irradiance_Interp.time = t2';

Temperature_Interp.signals.values = Temp2';
Temperature_Interp.time = t2';

save('Irradiance_Interp.mat','Irradiance_Interp');
save('Temperature_Interp.mat','Temperature_Interp');
clear('SPM','t2','SimTime','SPM','ST','Irt','Ir','Temp','Tempt');

%% Step 3: Find Average Irradiance and Temperature

% Irradiation
Ir_Avg(1) = mean(Ir2(1:SpHr+1));
for i = 2:STH
    Ir_Avg(i) = mean(Ir2((i-1)*SpHr+2:i*SpHr+1));
end

% Temperature
Temp_Avg(1) = mean(Temp2(1:SpHr+1));
for i = 2:STH
    Temp_Avg(i) = mean(Temp2((i-1)*SpHr+2:i*SpHr+1));
end

save('Solar_avgs','Temp_Avg');


%% Step 4: Estimate Average PV Output Power
% Based on Solar Cell Characteristics in Matlab Simulink

% Irradation versus Power Model
Irr_Model = [0 250 500 750 1000];        % x = Irr_Model
Irr_Power_Model = [0 22.68 48.75 74.25 100.73]*10;   % y = Irr_Power_Model
Irr_Model_interp = 0:0.01:1000;    % xx = Irr_Model_interp
Irr_Power_Model_interp = spline(Irr_Model,Irr_Power_Model,Irr_Model_interp);  % yy = Irr_Pow_Model_interp
```

```matlab
% Temperature versus Efficiency Model
Temp_Model = [0 25 50 75 100];        % x = Temp_Model
Temp_Power_Model = [1.1 1.0 0.85 0.75 0.65];   % y = Temp_Power_Model
Temp_Model_interp = 0:0.01:100;    % xx = Temp_Model_interp
Temp_Power_Model_interp = spline(Temp_Model,Temp_Power_Model,Temp_Model_interp);

% Estimate Average PV Output Power
for i = 1:STH
    P(i)                                                                    =
Irr_Power_Model_interp(round(length(Irr_Power_Model_interp)*Ir_Avg(i)/Irr_Model_interp(en
d)));
    T(i)                                                                    =
Temp_Power_Model_interp(round(length(Temp_Power_Model_interp)*Temp_Avg(i)/Temp_M
odel_interp(end)));
    P_Grid_ref(i) = 0.95*P(i)*T(i);
end

save('P_Grid_ref.mat','P_Grid_ref');
P_Grid_ref_array.time=Irradiance_Interp.time(1:end-1);
P_Grid_ref_array.signals.values=ones(SpHr,1)*P_Grid_ref(1);


for i=2:STH
    P_Grid_ref_array.signals.values=[P_Grid_ref_array.signals.values;
ones(SpHr,1)*P_Grid_ref(i)];
end
save('P_Grid_ref_array.mat','P_Grid_ref_array');


%% Step 6: Clear Unnecessary Variables
clc;  clear all;

load('P_Grid_ref.mat');
load('Irradiance.mat');
load('Temperature.mat');
load('P_Grid_ref_array.mat')
```

```matlab
%% Pre-Simulation Code (actual cell temperature considered)

% Ts_Power=50e-6
% Ts_Control=100e-6
% Dec_Power=40000
% Dec_Control=20000

clc; clear all;
STH = 15; % SimTime in hours
ST = 3600*STH; % 3600s = 60mins = 1hr, 15hrs = 54000

% Step 1:  Input Actual Irradiance and Temperature Data
% Step 2:  Interpolate Data
% Step 3:  Find Average Irradiance and Temperature
% Step 4:  Plot Irradiation and Temperature
% Step 5:  Estimate Average PV Output Power
% Step 6:  Clear Unnecessary Variables


%% Step 1: Input Actual Irradiance and Temperature

% Irradiance (Ir) measured in W/m^2 was sampled every minute
load('Irradiance_data.mat')
Ir=Ir';
% Time axis of Ir (Irt) is converted from mins to secs
Irt = 0:60:ST;
% Irradiance data and time saved as structure
Irradiance.signals.values = Ir';
Irradiance.time = Irt';

% Temperature (Temp) measured in degrees C was sampled every minute
load('Temperature_data.mat')
Temp=Temperature_data(301:1201);
Temp=Temp';
load('Wind_speed_data.mat')
Wind_speed_ms=Wind_speed_data(301:1201);
Wind_speed_ms=Wind_speed_ms';
Cell_Temp=(0.943*Temp+0.0195*Ir-1.528*Wind_speed_ms+0.3529);

%%
% Time axis of Temp (Tempt) is converted from 30mins to 1800secs
Tempt = 0:60:ST;

% Temperature data and time saved as structure
% Temperature.signals.values = Cell_Temp';
Temperature.signals.values = Cell_Temp';
```

```
Temperature.time = Tempt';


save('Irradiance.mat','Irradiance');
save('Temperature.mat','Temperature');

%% Step 2: Interpolate Data
t2 = 0:0.5:ST;
SpHr = (1/(0.5))*60*60;

% Interpolate (Connect missing data points) of original Ir data to new time axis
Ir2 = interp1(Irt,Ir,t2,'cubic');
% Interpolate (Connect missing data points) of original Temp data to new time axis
Temp2 = interp1(Tempt,Temp,t2,'cubic');


Irradiance_Interp.signals.values = Ir2';
Irradiance_Interp.time = t2';

Temperature_Interp.signals.values = Temp2';
Temperature_Interp.time = t2';

save('Irradiance_Interp.mat','Irradiance_Interp');
save('Temperature_Interp.mat','Temperature_Interp');
clear('SPM','t2','SimTime','SPM','ST','Irt','Ir','Temp','Tempt');

%% Step 3: Find Average Irradiance and Temperature

% Irradiation
Ir_Avg(1) = mean(Ir2(1:SpHr+1));
for i = 2:STH
   Ir_Avg(i) = mean(Ir2((i-1)*SpHr+2:i*SpHr+1));
end

% Temperature
Temp_Avg(1) = mean(Temp2(1:SpHr+1));
for i = 2:STH
   Temp_Avg(i) = mean(Temp2((i-1)*SpHr+2:i*SpHr+1));
end

save('Solar_avgs','Temp_Avg');


%% Step 4: Estimate Average PV Output Power
% Based on Solar Cell Characteristics in Matlab Simulink
```

```matlab
% Irradation versus Power Model
Irr_Model = [0 250 500 750 1000];        % x = Irr_Model
Irr_Power_Model = [0 22.68 48.75 74.25 100.73]*10;   % y = Irr_Power_Model
Irr_Model_interp = 0:0.01:1000;    % xx = Irr_Model_interp
Irr_Power_Model_interp  =  spline(Irr_Model,Irr_Power_Model,Irr_Model_interp);  %  yy =
Irr_Pow_Model_interp

% Temperature versus Efficiency Model
Temp_Model = [0 25 50 75 100];        % x = Temp_Model
Temp_Power_Model = [1.1 1.0 0.85 0.75 0.65];   % y = Temp_Power_Model
Temp_Model_interp = 0:0.01:100;    % xx = Temp_Model_interp
Temp_Power_Model_interp = spline(Temp_Model,Temp_Power_Model,Temp_Model_interp);
% Estimate Average PV Output Power
for i = 1:STH
   P(i)                                                                         =
Irr_Power_Model_interp(round(length(Irr_Power_Model_interp)*Ir_Avg(i)/Irr_Model_interp(en
d)));
   T(i)                                                                         =
Temp_Power_Model_interp(round(length(Temp_Power_Model_interp)*Temp_Avg(i)/Temp_M
odel_interp(end)));
   P_Grid_ref(i) = 0.95*P(i)*T(i);
end

save('P_Grid_ref.mat','P_Grid_ref');
P_Grid_ref_array.time=Irradiance_Interp.time(1:end-1);
P_Grid_ref_array.signals.values=ones(SpHr,1)*P_Grid_ref(1);
for i=2:STH
   P_Grid_ref_array.signals.values=[P_Grid_ref_array.signals.values;
ones(SpHr,1)*P_Grid_ref(i)];
end
save('P_Grid_ref_array.mat','P_Grid_ref_array');


%% Step 6: Clear Unnecessary Variables
clc;  clear all;

load('P_Grid_ref.mat');
load('Irradiance.mat');
load('Temperature.mat');
load('P_Grid_ref_array.mat')
```

```matlab
%% Plot and Save total Simulation Results:

% % Step 1:  Plot Output Power for PV, Battery, SC, and Grid
% % Step 2:  Plot Battery Characteristics (Voltage, Current, and SOC)
% % Step 3:  Plot SC Characteristics (Voltage, Current, and SOC)
% % Step 4:  Plot Error
% % Step 5:  Plot one-min-D
% % Step 6:  Plot Irradiance and Temperature


Simulation_time=15;
Time2 = 0:2:Simulation_time*3600;
TM = 0:Simulation_time/(length(Time)-1):Simulation_time;
save('Time.mat','Time','TM');


%% Step 1: Plot Output Power
figure(1)
subplot(311)
plot(TM,P_Grid_Ref,TM,P_Out_1,'LineWidth',2)
xlabel('Time (Hours)','FontSize',18); ylabel('Power (kW)','FontSize',18);
legend('P_{Grid,Ref}','P_{Grid}');
set(gca,'fontsize',18)
grid on;

subplot(312)
plot(TM,P_PVES,'LineWidth',2)
xlabel('Time (Hours)','FontSize',18); ylabel('Power (kW)','FontSize',18);
legend('P_{PVES}');
set(gca,'fontsize',18)
grid on;

subplot(313)
plot(TM,P_BESS,TM,P_SESS,'LineWidth',2)
xlabel('Time (Hours)','FontSize',18); ylabel('Power (kW)','FontSize',18);
legend('P_{BESS}','P_{SESS}');
set(gca,'fontsize',18)
grid on;

%% Step 2:  Plot Battery Characteristics (Voltage, Current, and SOC)
figure(2)
subplot(311);
plot(TM,Bat_V);
title('Battery: Voltage');
xlabel('Time (Hours)','FontSize',24); ylabel('Voltage (V)','FontSize',26);
set(gca,'fontsize',18)
```

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```matlab
grid on;

subplot(312);
plot(TM,Bat_I);
title('Battery: Current');
xlabel('Time (Hours)','FontSize',24); ylabel('Current (A)','FontSize',26);
set(gca,'fontsize',18)
grid on;


subplot(313);
plot(TM,Bat_SOC,'linewidth',2);
title('Battery: SOC');
xlabel('Time (Hours)','FontSize',34); ylabel('SOC (%)','FontSize',34);
set(gca,'fontsize',30)
grid on;


%% Step 3:  Plot SC Characteristics (Voltage, Current, and SOC)
figure(3)
subplot(311);
plot(TM,SC_V);
title('SC: Voltage');
xlabel('Time (Hours)','FontSize',24); ylabel('Voltage (V)','FontSize',26);
set(gca,'fontsize',18)
grid on;

subplot(312);
plot(TM,SC_I);
title('SC: Current');
xlabel('Time (Hours)','FontSize',24); ylabel('Current (A)','FontSize',26);
set(gca,'fontsize',18)
grid on;

subplot(313);
plot(TM,SC_SOC,'linewidth',2);
title('SC: SOC');
xlabel('Time (Hours)','FontSize',34); ylabel('SOC (%)','FontSize',34);
set(gca,'fontsize',30)
grid on;


%% Step 4: Plot Error
figure(4)
plot(TM,((P_Grid_Ref-P_Out)./P_Grid_Ref)*100);
title('Error');
```

```matlab
xlabel('Time (Hours)','FontSize',24); ylabel('Error (%)','FontSize',26);
set(gca,'fontsize',18)
grid on;




% Step 5: Plot one_min_D
figure(5)
subplot(211)
plot(TM,OMD_BESS);
title('Battery Duty Ratio');
xlabel('Time (Hours)','FontSize',24); ylabel('1-D','FontSize',24);
set(gca,'fontsize',18)
grid on;

subplot(212)
plot(TM,OMD_SESS);
title('SC Duty Ratio');
xlabel('Time (Hours)','FontSize',24); ylabel('1-D','FontSize',26);
set(gca,'fontsize',18)
grid on;


%% Step 6: Plot Grid Reference Power
figure(6)
plot(TM,P_Grid_Est,'*-',TM,P_Grid_Ref,'LineWidth',2);
title('Grid Reference Power');
xlabel('Time (Hours)','FontSize',24); ylabel('Power (kW)','FontSize',26);
legend('P_{Grid,Est}','P_{Grid,Ref}');
set(gca,'fontsize',18)
grid on;


%% Step 7: Plot Irradiation and Temperature
TM2 = 0:Simulation_time/(Simulation_time*60):Simulation_time;
figure(7)
[ax,p1,p2]  =  plotyy(TM2,Irradiance.signals.values,TM2,Temperature.signals.values,'plot');   %
Plot Ir2 and Temp2 on same graph
xlabel(ax(2),'Time (Hours)','FontSize',30); % x-axis = time
ylabel(ax(1),'Irradiance (W/m^2)','FontSize',30); % y1-axis = Irradiance
ylabel(ax(2),'Temperature (C)','FontSize',30);    % y2-axis = Temperature

p1.LineWidth = 2; % Irradiance line is width = 2
p2.LineWidth = 2; % Temperature line is width = 2
p2.LineStyle = '--'; % Temperature line is made of dashes
```

```matlab
legend('Irradiance (W/m^2)','Temperature (C)');
set(gca,'fontsize',30)
grid on;
title('Irradiation and Temperature');
%% step 8: plot PV voltage and current
figure(8)
plot(TM,P_Va1,TM,P_Ia1,'LineWidth',2);
title('PV voltage and current');
xlabel('Time (Hours)','FontSize',24); ylabel('PV voltage & current','FontSize',26);
legend('P Va','P Ia');
set(gca,'fontsize',18)
grid on;

%% step 9 : plot battery and SC reference power
figure(9)
plot(TM,P_BESS_ref,TM,P_SESS_ref,'LineWidth',1);
title('Battery: and SC  Ref Power');
xlabel('Time (Hours)','FontSize',24); ylabel('Ref Power (%)','FontSize',26);
legend('P BESS ref','P SESS ref')
set(gca,'fontsize',18)
grid on;
```

```matlab
%%%% integrate the battery power curve

N=length(P_BESS)-1;
E_BESS=zeros(N,1);
for k=2:N
    E_BESS(k)=E_BESS(k-1)+trapz(Time(k:k+1),P_BESS(k:k+1));
end
Simulation_time=15;
Time2 = 0:2:Simulation_time*3600;
TM = 0:Simulation_time/(length(Time)-1):Simulation_time;
save('Time.mat','Time','TM');
plot(TM(1:end-1),E_BESS/3600,'LineWidth',2);
xlabel('Time (Hours)','FontSize',24);
ylabel('BESS capacity (kW/Hour)','FontSize',26);
title('BESS capacity ');
set(gca,'fontsize',18)
grid on;
BESS_Capacity=max(abs(E_BESS(1:end)))/3600;
fprintf('If BESS starts at an SOC of 80%,\n');
fprintf('then the minimum required capacity is: %g kW/hr ...\n',5*max(BESS_Capacity));
```

```matlab
%%%% integrate the SC power curve

N=length(P_SESS)-1;
E_SESS=zeros(N,1);
for k=2:N
    E_SESS(k)=E_SESS(k-1)+trapz(Time(k:k+1),P_SESS(k:k+1));
end
Simulation_time=15;
Time2 = 0:2:Simulation_time*3600;
TM = 0:Simulation_time/(length(Time)-1):Simulation_time;
save('Time.mat','Time','TM');
plot(TM(1:end-1),E_SESS/3600,'LineWidth',2);
xlabel('Time (Hours)','FontSize',24);
 ylabel('SESS capacity (kW/Hour)','FontSize',26);
title('SESS capacity ');
set(gca,'fontsize',18)
grid on;
SESS_Capacity=max(abs(E_SESS(1:end))/3600);
fprintf('If SESS starts at an SOC of 80%,\n');
fprintf('then the minimum required capacity is: %g kW/hr ...\n',5*max(SESS_Capacity));
```

```matlab
%%%% integrate the PV power curve

N=length(P_PVES)-1;
E_PVES=zeros(N,1);
for k=2:N
    E_PVES(k)=E_PVES(k-1)+trapz(Time(k:k+1),P_PVES(k:k+1));
end
Simulation_time=15;
Time2 = 0:2:Simulation_time*3600;
TM = 0:Simulation_time/(length(Time)-1):Simulation_time;
save('Time.mat','Time','TM');
plot(TM(1:end-1),E_PVES/3600,'LineWidth',2);
xlabel('Time (Hours)','FontSize',24);
ylabel('PVES output(kWh)','FontSize',26);
title('PVES output');
set(gca,'fontsize',18)
grid on;
PVES_Output=(E_PVES(1:end))/3600;
fprintf('The total PV array output: %g MWh ...\n',PVES_Output(end)/1000);
```

%%% Battery lifetime estimation

Battery_rated_capacity=375.484*0.4*1; %%%% 40% DOD, derate factor=1
Battery_cycle_life=7000;

%%%%Battery life estimation code%%%%%
sum_of_battery_discharge_energy=0;
simulation_time=24/24;   %%% hours to day conversion

np=find(P_BESS>0);
Total_discharge_battery_energy=trapz(Time(np),P_BESS(np))/3600; %Esj in kWh
nn=find(P_BESS<0);
Total_charge_battery_energy=trapz(Time(nn),P_BESS(nn))/3600; %Esj in kWh
Battery_equivalent_service_life=max(Total_discharge_battery_energy,abs(Total_charge_battery_energy))/Battery_rated_capacity; %C_B,T
Battery_survival_days=(Battery_cycle_life/Battery_equivalent_service_life)*simulation_time;
Battery_survival_years=Battery_survival_days/365;

%%%%%%%%%%%Results%%%%%%%%
fprintf('The number of years Battery survival : %8.6f\n',Battery_survival_years)

```matlab
%% SC lifetime estimation

%%%%%% input%%%%%%%
SC_rated_capacity=15.5121*0.4; %kWh
SC_cycle_life=500000;

%%%SC life estimation code%%%%%
sum_of_SC_discharge_energy=0;
simulation_time=24/24;   %%% hours to day conversion

np=find(P_SESS>0);
Total_discharge_SC_energy=trapz(Time(np),P_SESS(np))/3600; %Esj in kWh
nn=find(P_SESS<0);
Total_charge_SC_energy=trapz(Time(nn),P_SESS(nn))/3600; %Esj in kWh
SC_equivalent_service_life=max(Total_discharge_SC_energy,abs(Total_charge_SC_energy))/SC_rated_capacity; %C_B,T
SC_survival_days=(SC_cycle_life/SC_equivalent_service_life)*simulation_time; %E|L_B|
SC_survival_years=min(25,SC_survival_days/365);

%%%%%%%%%%%%Results%%%%%%%%%
fprintf('The number of years SC survival : %8.6f\n',SC_survival_years)
```

%% Price calculation for energy storage system


%%%%%%%% Input%%%%%%%%
Battery_capacity_without_SC=476.116;
only_SC_capacity=414.078 ;
Battery_capacity_with_SC=466.88; %%%from Integrate_battery_power.m file
SC_capacity=89.6191;    %%%from Integrate_SC_power.m file
Battery_price=400;
SC_price=2500;
EBL1=4.421197;  %%%% estimate battery life time in years without SC.This is comes from Battery_life_estimation.m file
EBL2=6.141886;  %%%% estimate battery life time in years with SC.This is comes from Battery_life_estimation.m file
ESL=25;  %%%% estimate SC life time in years.This is comes from SC_life_estimation.m file

Battery_survive_days_without_SC=EBL1*365;
Battery_survive_days_with_SC=EBL2*365;
only_SC_survive_days=ESL*365;
SC_survive_days=ESL*365;
 PV_array_output=(1000000*0.2*24*365)/1000; %%PV array capacity=1MW, Capacity factor=20%, 15 hours energy harvested from sun per day.
%% Battery only
Yearly_storage_cost_without_SC_1=(Battery_capacity_without_SC*Battery_price*365)/Battery_survive_days_without_SC;
Yearly_storage_cost_without_SC=Yearly_storage_cost_without_SC_1+(0.1*Yearly_storage_cost_without_SC_1);
Yearly_added_cost_per_kWh_for_storage_without_SC=(Yearly_storage_cost_without_SC/PV_array_output);


%%%  SC only %%%%
Yearly_storage_cost_only_SC_1=(only_SC_capacity*SC_price*365)/only_SC_survive_days;
Yearly_storage_cost_only_SC=Yearly_storage_cost_only_SC_1+(0.1*Yearly_storage_cost_only_SC_1);
Yearly_added_cost_per_kWh_for_storage_only_SC=(Yearly_storage_cost_only_SC/PV_array_output);
 %% HESS
Yearly_storage_cost_with_SC_1=(((Battery_capacity_with_SC*Battery_price)/Battery_survive_days_with_SC)+((SC_capacity*SC_price)/SC_survive_days))*365;
Yearly_storage_cost_with_SC=Yearly_storage_cost_with_SC_1+(0.1*Yearly_storage_cost_with_SC_1);
Yearly_added_cost_per_kWh_for_storage_with_SC=(Yearly_storage_cost_with_SC/PV_array_output);
Yearly_Saving=(Yearly_storage_cost_without_SC-Yearly_storage_cost_with_SC);

%%%%%%%%% output%%%%%%%%%%%%%%%
fprintf('The yearly storage cost without SC: %8.2f\n',Yearly_storage_cost_without_SC)

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```
fprintf(' The yearly added cost per kWh for storage without SC:
%8.4f\n',Yearly_added_cost_per_kWh_for_storage_without_SC)

fprintf('The yearly storage cost only SC: %8.2f\n',Yearly_storage_cost_only_SC)
fprintf(' The yearly added cost per kWh for storage only SC:
%8.4f\n',Yearly_added_cost_per_kWh_for_storage_only_SC)

fprintf('The yearly storage cost with SC: %8.2f\n',Yearly_storage_cost_with_SC)
fprintf(' The yearly added cost per kWh for storage with SC:
%8.4f\n',Yearly_added_cost_per_kWh_for_storage_with_SC)
fprintf(' The yearly saving with SC reference 1: %8.2f\n',Yearly_Saving)
```