PEAK SHAVING AND ENERGY MANAGEMENT FOR GRID-CONNECTED PV SYSTEMS INTEGRATED WITH BATTERY STORAGE

A Project

Presented to the faculty of the Department of Electrical and Electronic Engineering

California State University, Sacramento

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Electrical and Electronic Engineering

by

Bingjie Wang

FALL
2015
PEAK SHAVING AND ENERGY MANAGEMENT FOR GRID-CONNECTED PV SYSTEMS INTEGRATED WITH BATTERY STORAGE

A Project

by

Bingjie Wang

Approved by:

______________________________, Committee Chair
Mahyar Zarghami, Ph.D.

______________________________, Second Reader
Mohammad Vaziri, Ph.D.

________________________________
Date
Student: Bingjie Wang

I certify that this student has met the requirements for format contained in the University format manual, and that this project is suitable for shelving in the Library and credit is to be awarded for the project.

__________________________, Graduate Coordinator
Preetham Kumar, Ph.D.  

date

Department of Electrical and Electronic Engineering
Abstract

of

PEAK SHAVING AND ENERGY MANAGEMENT FOR GRID-CONNECTED PV SYSTEMS INTEGRATED WITH BATTERY STORAGE

by

Bingjie Wang

Statement of Problem

Reducing CO₂ emissions is a necessary subject due to the existing ecological problems. Many alternative energy sources can be used instead of fossil fuels. It is widely believed that solar energy can sustainably replace fossil fuel sources without harming the environment.

These days, commercial and residential photovoltaic (PV) systems are extensively coming into the market due to the following advantages: (1) More affordable costs with respect to homeowners’ economic situations and (2) Utilizing the roof of the buildings as the supporting structure, thereby eliminating land and direct structure expenses [1]. However, proper interfaces will need to be provided between these systems and the utility in order to maximize the benefits associated with them.
Small battery energy storage systems (BESS) have demonstrated to be effective devices for proper interfacing between residential/commercial/industrial PV systems and utilities in order to provide uninterrupted and reliable power to the loads.

This project focuses on the application of BESS in PV systems as the continuation of previous works based on 1) a state-space based battery energy storage system; [2], and 2) a simple and effective approach for peak load shaving using battery energy storage systems.[3]

The grid-connected PV system with batteries (PV+BESS) containing DC/DC converter, AC/DC inverter, AC loads and BESS, is capable of simultaneous control of active power, reactive power, and DC link voltage. Continuing on the previous work, this project has proposed and verified a control strategy based on state-space model(s) of PV+BESS by utilizing an energy management strategy with the goal of peak-shaving, while considering batteries’ degradation and ageing limits. Simulations have been performed in different battery capacity cases and the results have been compared with the simple approach described in [3].

Sources of Data

The simulation is performed using Simulink/SimPowerSystems toolbox under Matlab, and the models are created based on several published research papers.
Conclusions Reached

PV+BESS control strategy was analyzed, and the results were simulated and verified in two different examples.

_______________________, Committee Chair
Mahyar Zarghami, Ph.D.

_______________________
Date
ACKNOWLEDGEMENTS

I have taken efforts in this project. However, it would not have been possible without the kind support and help of my advisor, family and friends. I would like to extend my sincere thanks to all of them.

I wish to express my sincere gratitude to Dr. Zarghami, who provided me guidance and constant supervision as well as necessary information regarding the project.

My thanks and appreciation also goes to Dr. Vaziri and Dr. Kumar for spending time on reading my report and providing me with guidance.

Finally, I would like to express my special gratitude to my family and friends, who provided me support at any time. The accomplishment of the project would not have been possible without them.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>viii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xi</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. Background of the Project</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Goal of the Project</td>
<td>1</td>
</tr>
<tr>
<td>1.3. Layout of the Project</td>
<td>2</td>
</tr>
<tr>
<td>2. MODEL OF THE GRID-CONNECTED PV SYSTEM INTEGRATED WITH BATTERY ENERGY STORAGE</td>
<td>3</td>
</tr>
<tr>
<td>2.1 Overview</td>
<td>3</td>
</tr>
<tr>
<td>2.1.1 System Architecture</td>
<td>3</td>
</tr>
<tr>
<td>2.1.2 Power Management</td>
<td>4</td>
</tr>
<tr>
<td>2.2. State-space Modeling of PV+BESS</td>
<td>5</td>
</tr>
<tr>
<td>2.2.1. Battery Model</td>
<td>5</td>
</tr>
<tr>
<td>2.2.2. DC/DC Converter</td>
<td>6</td>
</tr>
<tr>
<td>2.2.3. AC/DC Rectifier</td>
<td>6</td>
</tr>
<tr>
<td>2.2.4. PV+BESS State-space Model</td>
<td>8</td>
</tr>
</tbody>
</table>
3. CONTROL METHODS OF THE PROJECT ................................................................. 10
  3.1. Control of Reactive Power and DC-Link Voltage Control .......................... 10
  3.2. Control of Active Power with Peak Load Shaving ................................. 11
      3.2.1. Battery Charging/Discharging......................................................... 11
      3.2.2. Active Power Flow Peak Shaving Strategy ....................................... 12
      3.2.3. BESS Control Strategy .................................................................... 15
4. SIMULATION APPLICATIONS AND RESULTS ............................................... 17
  4.1 Data Source and Desired Result ................................................................. 17
  4.2 Simulation Result and Analysis ................................................................. 20
      4.2.1 Sufficient Battery Capacity ............................................................... 20
      4.2.2. Insufficient Battery Capacity ............................................................ 22
5. CONCLUSIONS AND FUTURE WORK ..................................................... 27
References............................................................................................................. 28
LIST OF TABLES

<table>
<thead>
<tr>
<th>Tables</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PV Generation and Load Consumption in One Day</td>
<td>17</td>
</tr>
<tr>
<td>2. Aggregated Power Demand in a Node ($P_d$) in One Day</td>
<td>17</td>
</tr>
<tr>
<td>3. $P_{dshaved}$ (desired $P_d$) and the Amount of Power to be Charged or Discharged in One Day</td>
<td>19</td>
</tr>
<tr>
<td>4. Values of System Parameters</td>
<td>20</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figures</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System Schematic Diagram (One Unit Included)</td>
<td>4</td>
</tr>
<tr>
<td>2. Different Power Flow Modes</td>
<td>5</td>
</tr>
<tr>
<td>3. Thevenin Battery Model</td>
<td>6</td>
</tr>
<tr>
<td>4. Schematic Diagram of Voltage Oriented Control</td>
<td>10</td>
</tr>
<tr>
<td>5. Schematic Description of the Peak Shaving Algorithm</td>
<td>13</td>
</tr>
<tr>
<td>6. BESS Charge/Discharge Control Algorithm</td>
<td>16</td>
</tr>
<tr>
<td>7. Average NSW (Sydney) Household in Summer – Electricity Consumption versus Generation</td>
<td>18</td>
</tr>
<tr>
<td>8. ( P_d ) and its Average which Calculated using Proposed Strategy</td>
<td>18</td>
</tr>
<tr>
<td>9. Area (energy) to be Shaved</td>
<td>19</td>
</tr>
<tr>
<td>10. Reactive Power Provided by the Grid</td>
<td>21</td>
</tr>
<tr>
<td>11. Voltage of DC link</td>
<td>21</td>
</tr>
<tr>
<td>12. Amount of Power Charged(&gt;0) or Discharged(&lt;0) by BESS in One Day</td>
<td>22</td>
</tr>
<tr>
<td>13. Aggregated Power Flow Profile of Interconnection Point with Sufficient Battery Capacity</td>
<td>22</td>
</tr>
<tr>
<td>14. Aggregated Power Flow Profile of Interconnection Point with Insufficient Battery Capacity (I)</td>
<td>23</td>
</tr>
<tr>
<td>15. Batteries’ SOC Operation in One Day (I)</td>
<td>23</td>
</tr>
<tr>
<td>16. Aggregated Power Flow Profile of Interconnection Point with Insufficient Battery</td>
<td></td>
</tr>
</tbody>
</table>
17. Batteries’ Real Power Operation in One Day (II) ................................................................. 24

18. Aggregated Power Flow Profile of Interconnection Point with Insufficient Battery Capacity (III) ........................................................................................................................................... 25

19. Batteries’ Real Power Operation in One Day (III) ........................................................................ 26

20. Batteries’ SOC Operation in One Day (III) .................................................................................. 26
CHAPTER 1
INTRODUCTION

1.1. Background of the Project
Due to ecological problems caused by utilization of fossil fuels, it is required to reduce CO\textsubscript{2} emissions associated with these sources. As a result, applications of grid connected renewable power generation systems have gained outstanding interest. Generation of electricity by PV (Photovoltaic) systems is rapidly increasing in the buildings in recent years due to their advantages. However, highly penetrated PV causes frequency fluctuation, voltage fluctuation and complicated economic scheduling of the generation in power systems, because PV generation is highly dependent on weather and sun irradiation. Furthermore, surplus of the generation and problems associated with the backflow of power during peak generation periods is a matter of concern to electric utilities. Many researchers have addressed these technical problems using approaches such as battery energy storage systems (BESS) or other controllable loads for demand response. With increased penetration of PV systems, more research and development projects related to energy management strategies are necessary for grid connected PV systems equipped with storage.

1.2. Goal of the Project
Previous work has presented simulation and control of a state-space based battery energy storage system with bidirectional AC/DC and DC/DC converters \cite{2}. This project intends
to extend the previous work to include PV generation, AC load, and BESS control strategy and power management mechanisms, to represent a fully controllable PV+BESS system. With the provided state-space model, PV+BESS have been simulated using Matlab/Simulink/SimPowerSystems. Power management for peak-load shaving has been implemented based on the method obtained from previous work \cite{3}. Additionally, control schemes for charging/discharging of the BESS in this project have considered the batteries’ degradation and ageing limits into account.

1.3. Layout of the Project

In this project, first a simple system configuration was designed to represent a grid connected PV+BESS system. Then possible power flow modes between the grid, load and PV+BESS were discussed. Next modeling of the PV+BESS based on state-space was accomplished \cite{3}. VOC (Voltage Oriented Control) \cite{4} was used in this project and a BESS control strategy was proposed to perform peak-shaving in the aggregated load at the interconnection with the grid considering SOC (State of charge) constraints. Simulation and analysis was performed to validate the control and peak shaving methods. The project description is organized as follows: PV+BESS overview and their operation modes have been introduced and then detailed modeling of the system based on state-space is presented in Chapter 2. In Chapter 3, control methods for active and reactive powers and DC-link voltage and power management are presented. Simulation results of the sample system are presented in Chapter 4, and lastly concluding remarks are brought in Chapter 5.
CHAPTER 2
MODEL OF THE GRID-CONNECTED PV SYSTEM INTEGRATED WITH BATTERY ENERGY STORAGE

2.1 Overview
Massive penetration of distributed grid-connected PV can compete with large-scale utility power generation technologies such as nuclear and fossil plants and at the same time can avoid environmental impacts on the planet. As a result, a growing trend to employ building-integrated photovoltaic (BIPV) systems has occurred in which PV power is generated at the point of consumption. These systems may be incorporated into roof or facade of the buildings without needing additional ground area. “Residential and commercial Sacramento Municipal Utility District (SMUD) customers currently provide roof space for over 1.5MWp of installed BIPV capacity, paying an additional four dollars per month to do so [SMUD, 1998]” [5].

2.1.1 System Architecture
In this project, the PV+BESS system includes four major parts: AC grid side and AC load, AC/DC active rectifier, DC/DC converter, and PV generation and batteries. AC/DC rectifier is connected through $L_{ac}$ which represents the combined inductance of the transformer and line on the grid side. The DC/DC converter is directly connected to the battery. The AC/DC rectifier is connected to the DC/DC converter through a DC-link capacitor $C_{dc}$. It is assumed that the grid side resistance and the loss of the DC link are
negligible. The DC-link capacitor also works as part of the bidirectional DC/DC converter which can charge and discharge the battery. Detailed explanation will be presented in the coming sections.

Figure 1. System Schematic Diagram (One Unit Included)

2.1.2 Power Management

For the system above, several operation modes can be assumed as shown in Figure 2. Some of these modes are enumerated below:

(1) All power sources (grid, battery, PV) provide power to the load;

(2) PV generation and the grid provide power to the load and charge the battery at the same time.

(3) PV generation solely supports the load and charges the battery. No power is needed from the grid.
(4) PV generation and batteries support the load together. No power is needed from the grid.

(5) PV generation and batteries support the load and their extra power flows back to the grid.

(6) The grid and the battery together support the load and the power generated from PV is negligible.

Instead of analyzing these operational modes individually, this project proposes a simpler method to control and manage the flow of power, which will be discussed in the coming chapters.

![Diagram of PV+BEES system](image.png)

Figure 2. Different Power Flow Modes

2.2. State-space Modeling of PV+BESS

2.2.1. Battery Model

Different types of batteries have different characteristics: some of them might be designed for small applications, and their energy cannot last for a long time; while some of them may be used for higher energy levels and bigger size. Three types of the batteries
that are commonly used in PV applications are Nickel Cadmium, Lead Acid and Lithium Ion \[^3\].

For electrical modeling, Thevenin battery model, which is shown in Figure.3 has been selected and simulated previous work \[^2\]. This model has a voltage source $E_0$, internal battery resistance $R_0$ and another resistance $R_t$ in parallel with a capacitance $C_t$.

![Thevenin Battery Model](image)

**Figure.3.** Thevenin Battery Model

### 2.2.2. DC/DC Converter

Assuming the DC/DC converter to be lossless, we can express the relation between $i_{dc}$ and $i_{bat}$ in steady-state as:

$$i_{dc} = (1 - d).i_{bat} \quad \quad v_{bat} = (1 - d).v_{dc}$$

(1)

### 2.2.3. AC/DC Rectifier

On the grid and AC/DC converter side, through KVL we get:

$$-v_{abc} + L_{ac} \frac{d_{abc}}{dt} + e_{abc} = 0$$

(2)
Assuming the AC/DC converter to be lossless, and equalizing the power on the two sides, we can get:

\[-v_aid - \nu_{bi}b - \nu_{ci}c - P_l = -P_{pv} + C_{dc} \cdot \nu_{dc} \cdot \frac{dv_{dc}}{dt} + \nu_{dc}idc\]  (3)

Assuming the DC/DC converter to be lossless, power will be the same on both sides, which leads to:

\[i_{dc} = \nu_{bat} \cdot \nu_{bat} / \nu_{dc}\]  (4)

Using the following transformation, equations in the abc stationary reference frame can be transformed into the dq reference frame rotating at synchronous speed [4]:

\[x_{dq0} = \left(\frac{2}{3}\right) \begin{bmatrix} \cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ -\sin \theta & -\sin(\theta - 120^\circ) & -\sin(\theta + 120^\circ) \end{bmatrix} x_{abc}\]  (5)

where \(\theta = \omega t + \theta_0\).

Equation (2) can be written in the dq reference frame as:

\[\frac{d}{dt}i_d = \omega i_q + \frac{1}{L_{ac}} (\nu_d - e_d)\]  (6)

\[\frac{d}{dt}i_q = -\omega i_d + \frac{1}{L_{ac}} (\nu_q - e_q)\]  (7)

Neglecting the harmonics and assuming a sinusoidal pulse width modulation for the AC/DC converter, \(\nu_d\) and \(\nu_q\) can be written as:

\[\nu_d = 0.5k \cdot \nu_{dc} \cos(\theta_0 + \alpha)\]  (8)

\[\nu_q = 0.5k \cdot \nu_{dc} \sin(\theta_0 + \alpha)\]  (9)

where \(k\) and \(\alpha\) are modulation amplitude and angle, respectively.

By substituting (8) and (9) into (6) and (7), we get:
\[
\frac{d}{dt} i_d = \omega i_q + \frac{1}{L_{ac}} (0.5k.v_{dc} \cos(\theta_0 + \alpha) - V_m \cos \theta_0 ) \quad (10)
\]

\[
\frac{d}{dt} i_q = -\omega i_d + \frac{1}{L_{ac}} (0.5k.v_{dc} \sin(\theta_0 + \alpha) - V_m \sin \theta_0 ) \quad (11)
\]

We can also rewrite equation (3) by transforming the stationary abc reference frame to the rotating dq frame, which becomes:

\[
\frac{d}{dt} v_{dc} = -\frac{1}{C_{dc}} \left[ \frac{3}{4} k \cos(\theta_0 + \alpha) i_d + \frac{3}{4} k \sin(\theta_0 + \alpha) i_q + i_{dc} - \frac{P_{pv}-P_t}{v_{dc}} \right] \quad (12)
\]

2.2.4. PV+BESS State-space Model

In this project, by using the Thevenin battery model, five state variables are found for the PV+BESS, including \( i_d, i_q, v_{dc}, i_{bat} \) and the voltage of the capacitor inside the Thevenin battery model \( v_t \), which is related to the battery’s current through the following differential equation:

\[
\frac{d}{dt} i_{bat} = \frac{1}{L_{dc}} ((1 - d) v_{dc} - v_t - R_0 \cdot i_{bat} - E_0) \quad (13)
\]

In the above equation, \( E_0 \) is the voltage of the voltage source inside the Thevenin battery model. The differential equation for \( v_t \) is written as:

\[
\dot{v}_t = \frac{1}{C_t} (i_{bat} - \frac{v_t}{R_t}) \quad (14)
\]

In summary, we can express equations (10) - (14) in a state-space form as follows:

\[
\dot{X} = F(X) + G(X)U \quad (15)
\]

where:

\[
X = \begin{bmatrix}
    i_{bat} \\
    v_{dc} \\
    i_d \\
    i_q \\
    v_t
\end{bmatrix}^T \quad (16)
\]
\[ F(X) = \begin{bmatrix} -\nu_t - R_0 i_{bat} - E_0 \\ \frac{L_{dc}}{P_{pu} - P_t} \\ \frac{P_{pu} - P_t}{c_{dc} v_{dc}} \\ + \omega i_q - \frac{e_d}{L_{ac}} \\ - \omega i_d - \frac{e_q}{L_{ac}} \\ \frac{1}{C_t} (i_{bat} - \frac{\nu_t}{R_t}) \end{bmatrix} \] (17)

\[ G(X) = \begin{bmatrix} \frac{v_{dc}}{L_{dc}} & 0 & 0 \\ \frac{i_{bat}}{c_{dc}} & -\frac{3}{2} \frac{i_d}{C_{dc}} & -\frac{3}{2} \frac{i_q}{C_{dc}} \\ 0 & \frac{v_{dc}}{L_{ac}} & 0 \\ 0 & 0 & \frac{v_{dc}}{L_{ac}} \\ 0 & 0 & 0 \end{bmatrix} \] (18)

\[ U = \begin{bmatrix} (1 - d) & u_d & u_q \end{bmatrix}^T \] (19)

\[ u_d = 0.5 k \cos(\theta_0 + \alpha) \] (20)

\[ u_q = 0.5 k \sin(\theta_0 + \alpha) \] (21)
3.1. Control of Reactive Power and DC-Link Voltage Control

In this project, Voltage Oriented Control (VOC) method based on [4] has been used to control the reactive power $Q$ and the DC-link voltage $v_{dc}$. Figure 4 shows the schematic diagram of the VOC method.

![Schematic Diagram of the Voltage Oriented Control](image)

Figure 4. Schematic Diagram of the Voltage Oriented Control [4]
By assuming $\theta_0 = 0$ in the dq reference frame (taking the angle of grid voltage as the reference), we get $e_q = 0$. Then using the following equations we can find the active and reactive powers on the AC side as:

$$P_{ac} = -1.5e_d \cdot i_d$$ \hspace{1cm} (22)

$$Q = +1.5e_d \cdot i_q$$ \hspace{1cm} (23)

Assuming $e_d$ (the max value of grid voltage) to remain constant, we can see from equations (22) and (23) that the changes in active and reactive powers can be related to the changes of $i_d$ and $i_q$, respectively. Based on VOC, PI controllers have been applied to control $v_{dc}$ (through control of $P_{ac}$) and $Q$ \cite{3}.

3.2. Control of Active Power and Peak Load Shaving

3.2.1. Battery Charging/Discharging

Sliding mode control method can be used to control the duty ratio $d$ of the DC/DC converter in the system. Assuming the DC/DC converter to be lossless, the desired active power to be injected into PV+BESS can be related to other terms by:

$$P_{ac}^* - P_I \approx -P_{pv} + v_{bat}^* \cdot i_{bat}^*$$ \hspace{1cm} (24)

where $i_{bat}^*$ is the desired current of the battery, $v_{bat}^*$ is the desired voltage of the battery, $P_{ac}^*$ is the desired active power from the grid, $P_I$ is the AC load, and $P_{pv}$ is the active power generation of the PV array.

In the sliding mode control method \cite{6}, the convergence factor $\lambda$ is used to control the value of a variable $x$ to be close to its desired value $x^*$, as the below equation shows:

$$\dot{x} = -\lambda(x - x^*)$$ \hspace{1cm} (25)
The value of battery current can be controlled using the following equation:

\[ i_{bat}^* = \frac{P_{dc}^* + P_{pv} - P_l}{v_{bat}} \]  

(26)

By applying equation (4) in chapter 3 to the above equation, the duty ratio can be found as:

\[ d = \frac{\lambda L_{dc} (i_{bat} - i_{bat}) + v_{dc} - v_{bat}}{v_{dc}^*} \]  

(27)

3.2.2. Active Power Flow Peak Shaving Strategy

The interconnection point power flow at unit number \( n \) \( (P_d^n) \) is calculated as follows:

\[ P_d^n = -P_{pv}^n + P_l^n + P_{bat}^n \]  

(28)

\( P_{bat}^n < 0 \) when discharging battery;

\( P_{bat}^n > 0 \) when charging battery

in which, \( P_{pv}^n \) is the PV output, \( P_l^n \) is demand power and \( P_{bat}^n \) is the battery charge/discharge power of unit number \( n \).

This project chose to use the definition of the interconnection point power flow because it takes the effect of aggregated generation of PV and BESS into consideration. As a result, during peak-shaving, we do not need to consider the power flow modes (as explained in 2.1.2) in detail. Based on the definition of \( P_d^n \), when \( P_d^n > 0 \), the grid provides active power to the system. On the contrary, \( P_d^n < 0 \) means that the system sends the power back to the grid. The aggregated power flow profile at the interconnection point, which needs to be peak-shaved, does not include charge/discharge of the battery. The proposed strategy in [3] uses the power demand at the point of interconnection to perform peak-
shaving based on the following: assuming a sliding window, the method re-calculates the average of the interconnection point power ($P^n_{dav}$) after each time interval ($\tau$) for the next utilization period (up). This calculation estimates the charging/discharging of the batteries for the next eligible time interval ($\tau$) determined by the utilization factor ($uf$). Utilization factor ($uf$) is defined as the area designated by energy bars (which is the area to be shaved) over the total area above (or below) the average power line, as shown in Figure 5.

![Figure 5 Schematic Description of the Peak Shaving Algorithm](image)

The desired amount of charged or discharged energy for BESS is found by:

$$|E^n_{bat}| = \sum_{i \in S} |E_i|$$  \hspace{1cm} (29)
where $S$ is the set of all energy bars determined by $uf$. Based on (29), the desired absolute charged or discharged power of BESS $n$ is:

$$|P_{bat}^n| = |E_{bat}^n|/(S \cdot \tau)$$  

(30)

The power value in (30) needs to be constrained based on two conditions. The first condition limits the power of the BESS to its maximum rate of charge/discharge:

$$\eta_m|E_{bat}^n|/\tau \leq P_{max,bat}^n$$  

(31)

in which $\eta_m$ is the efficiency of the BESS. If $\eta_m|E_{bat}^n|/\tau \geq P_{max,bat}^n$, then $\eta_m|E_{bat}^n|/\tau$ is kept at $P_{max,bat}^n$.

The second condition, as shown in (32), limits the state of charge of the BESS to its minimum (during discharge) or maximum (during charge) intervals, respectively.

$$SOC_{min}^n \leq SOC^n \leq SOC_{max}^n$$  

(32)

To fulfill the purpose of peak shaving within proper state of charge of the BESS, the following two methods are proposed:

(1) The actual absolute charged or discharged power of BESS $n$ during each interval time is:

$$|P_{bat,\tau}^n| = uf \cdot |E_{bat,\tau}^n|/\tau$$  

(33)

This method has been demonstrated in 4.2.2 (1), which will not result in a smooth profile when SOC limitations are reached.

(2) In order to improve the method described in (1), the actual absolute charged or discharged power of BESS $n$ during each interval time can be calculated as:

$$|P_{bat,\tau}^n| = (SOC_{max}^n-SOC_{min}^n)P_{max,bat}^n \cdot uf \cdot |E_{bat,\tau}^n|/\tau \cdot \Sigma_{i=t+u}^{t+u} |E_i|$$  

(34)
in which $\sum_{t=t+up}^{t+u} |E_t|$ is the total desired amount of energy to be charged or discharged in the next utilization period.

This method, contrary to (1) takes the batteries’ capacity into consideration with a futuristic view to the next utilization period. As a result, it provides a smoother profile while charging/discharging the batteries at a lower rate which can potentially result in a longer life for the batteries.

3.2.3. BESS Control Strategy

Based on the constraints in (31) and (32), and taking the power flow peak shaving into consideration, the following BESS control strategies have been applied in this project:

1) When $SOC_{\min}^n \leq SOC^n \leq SOC_{\max}^n$, BESS is charged or discharged as commanded by the setting.

2) If $SOC^n < SOC_{\min}^n$, BESS should be charged and the amount of energy decided by:

   (1) If $P_d^n \geq P_{dav}^n$, the battery is charged to $SOC_{\min}^n$ in order to protect it against over discharge.

   (2) If $P_d^n < P_{dav}^n$, the battery is charged up to a maximum of $SOC_{\max}^n$.

3) If $SOC^n > SOC_{\max}^n$, BESS should be discharged and the amount of energy is decided by:

   (1) If $P_d^n \geq P_{dav}^n$, the battery is discharged up to a minimum of $SOC_{\min}^n$.

   (2) If $P_d^n < P_{dav}^n$, the battery is discharged to $SOC_{\max}^n$ in order to protect it against overcharge.
The BESS charge/discharge control algorithm based on the above rules is shown in Figure 6.

Figure 6. BESS Charge/Discharge Control Algorithm
CHAPTER 4
SIMULATION APPLICATIONS AND RESULTS

4.1 Data Source and Desired Result

Table 1 is the amount of power being used by 10 average residential units, and the generated power by 10 average solar PV systems (3kW system) during an average summer’s day. The average production of a solar PV system in Sydney has been calculated using the online performance calculator for a grid connected system. The electricity consumption data has been calculated from grid wide electricity consumption data for NSW from the Australian Electricity Market Operator (AEMO) [7] and is also shown in Figure. 7.

<table>
<thead>
<tr>
<th>Hours(h)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd(kW)</td>
<td>9.7</td>
<td>8.8</td>
<td>6.7</td>
<td>5.3</td>
<td>4.7</td>
<td>5.0</td>
<td>6.7</td>
<td>7.3</td>
<td>8.0</td>
<td>8.3</td>
<td>9.0</td>
<td>9.3</td>
</tr>
<tr>
<td>Ppv(3kW)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
<td>3.0</td>
<td>6.0</td>
<td>10.0</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>Hours(h)</td>
<td>12.0</td>
<td>13.0</td>
<td>14.0</td>
<td>15.0</td>
<td>16.0</td>
<td>17.0</td>
<td>18.0</td>
<td>19.0</td>
<td>20.0</td>
<td>21.0</td>
<td>22.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Pd(kW)</td>
<td>9.7</td>
<td>10.3</td>
<td>10.7</td>
<td>11.1</td>
<td>12.0</td>
<td>12.3</td>
<td>12.3</td>
<td>12.3</td>
<td>11.3</td>
<td>11.0</td>
<td>10.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Ppv(3kW)</td>
<td>2.00</td>
<td>2.07</td>
<td>2.03</td>
<td>1.90</td>
<td>1.50</td>
<td>1.00</td>
<td>0.07</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 1. PV Generation and Load Consumption in One Day

Based on the data, \( P_d \) is found by calculation, and is shown in Table. 2 using (28).

<table>
<thead>
<tr>
<th>Hours(h)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd(kW)</td>
<td>9.7</td>
<td>8.8</td>
<td>6.7</td>
<td>5.3</td>
<td>4.7</td>
<td>5.0</td>
<td>6.7</td>
<td>7.3</td>
<td>8.0</td>
<td>8.3</td>
<td>9.0</td>
<td>9.3</td>
</tr>
<tr>
<td>Hours(h)</td>
<td>12.0</td>
<td>13.0</td>
<td>14.0</td>
<td>15.0</td>
<td>16.0</td>
<td>17.0</td>
<td>18.0</td>
<td>19.0</td>
<td>20.0</td>
<td>21.0</td>
<td>22.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Pd(kW)</td>
<td>-10.3</td>
<td>-10.4</td>
<td>-9.6</td>
<td>-8.0</td>
<td>-3.0</td>
<td>2.3</td>
<td>8.3</td>
<td>11.3</td>
<td>11.3</td>
<td>11.0</td>
<td>10.0</td>
<td>9.7</td>
</tr>
</tbody>
</table>

Table 2. Aggregated Power Demand in a Node (\( P_d \)) in One Day

The data of Tables 1 and 2 are shown in Figure.7.
For peak load shaving in this project, up (utilization period) and $\tau$ (interval time) have been considered at 24 hours and 1 hour, respectively. Using these values, the aggregated $P_d$ and its average have been plotted in Figure.8. If batteries have enough capacity to charge/discharge, $P_d$ and $P_{dav}$ can be practically overlapped using the proposed peak shaving algorithm. In practice, however, this is not the case and additionally, a utilization factor is considered for the batteries in order to prolong their useful age. Taking a utilization factor of $uf=0.6$, $P_{dshaved}$ (desired $P_d$) has been listed and plotted in Table.3.
and Figure.9, respectively. In Figure.9, the shadowed area shown in black represents the area that will need to be charged or discharged by BESS, if enough capacity exists. Since \( u_f = 0.6 \), only 60\% of the amount of the shadowed area should be charged or discharged by BESS. If enough capacity exists, the peak shaving algorithm will bring the aggregated power demand as close as possible to the \( P_{\text{dshaved}} \) plot in Figure. 9.

![Figure 9 Area (energy) to be Shaved](image)

<table>
<thead>
<tr>
<th>Hours(h)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{dshaved}} ) (Kw)</td>
<td>6.00</td>
<td>5.27</td>
<td>4.72</td>
<td>4.13</td>
<td>3.87</td>
<td>4.00</td>
<td>4.72</td>
<td>4.68</td>
<td>4.00</td>
<td>2.85</td>
<td>1.45</td>
<td>-0.98</td>
</tr>
<tr>
<td>( P_{\text{bat}} ) (Kw)</td>
<td>-3.71</td>
<td>-2.73</td>
<td>-1.98</td>
<td>-1.18</td>
<td>-0.83</td>
<td>-1.00</td>
<td>-1.98</td>
<td>-1.92</td>
<td>-1.00</td>
<td>0.55</td>
<td>2.45</td>
<td>5.73</td>
</tr>
<tr>
<td>Hours(h)</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
</tr>
<tr>
<td>( P_{\text{dshaved}} ) (Kw)</td>
<td>-2.51</td>
<td>-2.55</td>
<td>-2.21</td>
<td>-1.53</td>
<td>0.60</td>
<td>2.85</td>
<td>5.40</td>
<td>6.68</td>
<td>6.68</td>
<td>6.55</td>
<td>6.12</td>
<td>6.00</td>
</tr>
<tr>
<td>( P_{\text{bat}} ) (Kw)</td>
<td>7.80</td>
<td>7.85</td>
<td>7.39</td>
<td>6.47</td>
<td>3.60</td>
<td>0.55</td>
<td>-2.90</td>
<td>-4.63</td>
<td>-4.63</td>
<td>-4.45</td>
<td>-3.88</td>
<td>-3.71</td>
</tr>
</tbody>
</table>

Table.3 \( P_{\text{dshaved}} \) (desired \( P_d \)) and the Amount of Power to be Charged or Discharged in One Day
4.2 Simulation Result and Analysis

Parameters of the PV+BESS are shown in Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$E_0$(V)</th>
<th>$L_{ac}$(mH)</th>
<th>$R_t$(Ω)</th>
<th>$C_{dc}$(F)</th>
<th>$f$(Hz)</th>
<th>$L_{dc}$(mH)</th>
<th>$C_t$(F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>40</td>
<td>0.1098</td>
<td>0.007</td>
<td>0.05</td>
<td>60</td>
<td>0.755</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$e_d$(V)</th>
<th>$e_q$(V)</th>
<th>$R_b$(Ω)</th>
<th>$V_{dc}$(V)</th>
<th>$\lambda$</th>
<th>maxSOC</th>
<th>minSOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>32.6599</td>
<td>0</td>
<td>0.0207</td>
<td>800</td>
<td>180000</td>
<td>80</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4. Simulation System Parameters

In the simulations, DC-link voltage is set at 800 V from 0 to 12:00 hr and at 800.1 V from 12:00 hr to 24:00 hr. The setting for reactive power injection by the grid is at 20000 VAr from 0 to 12:00 hr and changes to -20000 VAr from 12:00 hr to 24:00. Despite these settings, the peak-shaving algorithm will need to charge/discharge the batteries as close as possible to the desired $P_{dshaved}$ plot in Figure. 9.

4.2.1 Sufficient Battery Capacity ($E_{max,bat}^n = 150kWh$) Results

In this case, a sufficient battery capacity of 150 kWh has been considered in the simulations. Operations of the VOC control are shown in Figure.10 and Figure.11. It can be seen from the results that VOC has provided a good control over the DC-link voltage and reactive power. Based on an initial SOC of 50%, charge/discharge of the BESS and results of the peak-shaving algorithm are shown in Figure.12 and Figure.13, respectively. Comparing the actual $P_{dshaved}$ plot in Figure.13 with the ideal $P_{dshaved}$ plot in Figure.9,
it can be seen that the peak shaving algorithm has successfully met the required expectations.

Figure. 10 Reactive Power Provided by the Grid

Figure. 11 Voltage of DC link
4.2.2. Insufficient Battery Capacity

In this section, the peak-shaving algorithm has been tested in three different cases to keep the SOC of the batteries within the required boundaries, when the capacity of the BESS is insufficient to result in the ideal aggregated $P_{dshaved}$ plot shown in Figure. 9.

(1) An initial SOC of 50% with a maximum capacity of 50kWh has been considered in the first case using equation (33). The actual and desired shaved power demand
profiles have been plotted and compared in Figure.14. As can be seen from this figure, due to the SOC constraints, the actual and desired profiles have not been completely overlapped. The actual demand profile, however, is considerably smoother compared with the case when no BESS exists. The corresponding SOC profile in this case has been shown in Figure.15. As seen, the power management algorithm has successfully kept the SOC constraints within the allowed boundaries.

Figure.14 Aggregated Power Flow Profile of Interconnection Point with Insufficient Battery Capacity (I)

Figure.15 Batteries’ SOC Operation in One Day (I)
(2) An initial SOC of 50% with a maximum capacity of 50kWh has been considered in this circumstance using equation (34). The actual and desired shaved power demand profiles have been plotted and compared in Figure 16.

Figure 16 Aggregated Power Flow Profile of Interconnection Point with Insufficient Battery Capacity (II)

As can be seen from this figure, due to SOC constraints, the actual and projected charged/discharged powers have not been completely overlapped. However, variations of the desired profile are consistently followed by the actual profile.

From Figure 17 we can see that, although the capacity of the BESS is not sufficient, but the strategy based on equation (34) will result in less charged/discharged power in the BESS. As a result, the BESS will not go into an idle mode, or in other words SOC limitations are not reached. In order to test the performance of the control strategy when SOC constraints are reached, another test case has been performed in the following.
(3) An initial SOC of 25% with a maximum capacity of 35kWh has been considered using equation (34).

As can be verified in the following figures, the control strategy has taken the battery into an idle mode (stopping discharge) between hours 3 and 9, since the BESS hits its minimum SOC.

Figure.17 Batteries’ Real Power Operation in One Day (II)

Figure.18 Aggregated Power Flow Profile of Interconnection Point with Insufficient Battery Capacity (III)
Figure 19 Batteries’ Real Power Operation in One Day (III)

Figure 20 Batteries’ SOC Operation in One Day (III)
CHAPTER 5
CONCLUSIONS AND FUTURE WORK

As the continuation of previous works \cite{2,3}, this project has presented a detailed PV+BESS system which includes models of the batteries, PV, bidirectional AC/DC and DC/DC converters, AC load and the grid. By applying state-space modeling, the project has successfully simulated the control of the battery storage system to accomplish peak-shaving while protecting batteries’ life. Compared to the previous work \cite{3}, models of PV generation and AC load have been added in the simulations, and at the same time, limits of SOC have been considered in the peak-shaving algorithm.

Future project can focus on applying efficient energy management methods such as peak-shaving in a group of houses/commercial/industrial units. Also, instead of using PV generation data, models of PV arrays and MPPT control can be used to take the weather and sun irradiation conditions into account.
REFERENCES


