A Bidirectional Converter for Battery Based Energy System for Residential Applications

By
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ABSTRACT

This Master thesis presents a bidirectional converter controlled by an energy management control system that is designed for a small scale residential application. The bidirectional converter is composed of four leg floating interleaved Buck-Boost converters to provide high power density and high DC-DC voltage gain for grid connection. The bidirectional converter is used to interface battery cells which are used to store excess solar energy and provide them to the load when needed. The energy management control system is composed of two levels: A high energy management control level and a low power conversion level. A new Energy management Algorithm is proposed that includes both load forecasting and solar energy forecasting into the control scheme of energy management.

The main goal of this project is to study and to implement the new energy management control system with the bidirectional converter. The objectives of the project are divided in two parts: evaluation of the bidirectional converter and evaluation of the energy management control system. The first part includes a mathematical analysis and modeling of the bidirectional converter as well as performance evaluation through simulation. The second part includes implementation of the new energy management control system and evaluating its performance through simulation. An overall simulation is performed to prove the effectiveness of the energy management control system with the bidirectional converter. The simulation is performed using PSIM software and shows a grid connected hybrid PV/Storage system.
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Figure 5.9 SOC of the battery (case 2)

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NOMENCLATURE

\begin{itemize}
  \item \( V_{bb} \) \quad \text{Battery voltage}
  \item \( V_{dc} \) \quad \text{DC link voltage}
  \item \( SOC \) \quad \text{State of charge}
  \item \( r_L \) \quad \text{Inductor resistance}
  \item \( r_C \) \quad \text{Capacitor resistance}
  \item \( Q \) \quad \text{Rated battery capacity}
  \item \( D \) \quad \text{Duty cycle}
  \item \( P_{bat} \) \quad \text{Power coming from battery}
  \item \( P_{Load} \) \quad \text{Load power}
  \item \( P_{pv} \) \quad \text{Power coming from PV panels}
  \item \( P_{grid} \) \quad \text{Power coming from grid}
  \item \( P_{pv,f} \) \quad \text{Forecasted Power from PV}
  \item \( P_{Load,f} \) \quad \text{Forecasted Load power}
  \item \( Tariff_n \) \quad \text{Current Electricity Price}
  \item \( Tariff_L \) \quad \text{Projected electricity price}
\end{itemize}
CHAPTER 1
INTRODUCTION

This chapter will present an introduction about this thesis. It will present the objectives, background and motivation, and a detailed literature review. In the literature review, battery modeling will be discussed. Then, the development of DC-DC converter topologies will be presented. Finally, background information about existing energy management systems will be presented. After the literature review, the proposed energy management system will be discussed and then the thesis scope and contribution will be explained.

1.1 Objective

The objective of this thesis is to design and simulate a high performance DC/DC converter for the purposes of interfacing a battery system with a PV system. The converter should provide a solid dynamic response and transfers power from and to the battery system with high efficiency and fast response to power demand. A battery model will be developed to simulate a real lead acid battery and a simulation of the model will be performed to verify its behavior compared to a real lead acid battery. A number of converters will be evaluated and compared through simulation and the converter with best performance will be selected for battery interface.

The performance criteria will be based on efficiency, ripple in current, voltage gain and cost. A smart energy management system will be developed to operate as a master controller to coordinate the power transfer between the battery bank, the PV panel, and the grid. The objective of the energy management system is to maximize the power coming from the PV panel, minimize grid power, and minimize the charging and discharging of the battery and protect the battery from overcharging and discharging. It should also coordinate the power flow when the system is grid connected or islanded.

1.2 Background and Motivation

Renewable energy systems have gained a lot of support from the government and in the past several years because they allow contributing for clean power minimizing fossil fuels consumption, and lowering the emissions greenhouse gases. Solar photovoltaic (PV) installations have been significantly installed all over United States in the past decade [1]. The intermittency of PV power generation is the challenging issue for widespread public acceptance [2]. In order to improve intermittency problem, energy storage systems can be placed to store excess energy and provide it at times of deficiency [3] and improve stability of the micro grid [4]. In order to properly integrate an energy storage system, such as a
battery bank, along with a PV installation, a bidirectional power converter must interface the connection to a DC link feeding an inverter. Such battery-based power converter must have high efficiency and provide smooth charging and discharging to extend the life-span of the battery bank. In addition to the power converter, a smart-energy management system is required to coordinate the power transfer from PV as well as the charging and discharging of the battery bank according to the demand and the grid state as well as energy cost. Energy storage systems have proven to be a vital part of any renewable energy system [3] and [4]. In fact, the deployment of more PV installations and wind turbines would require more energy storage systems to compensate the fluctuation in power generation and increase the stability of the system. Therefore, it is vital to have a high performance power converter to interface the storage system with the grid along with the PV system. In addition, a smart energy system is required to increase the system’s stability and reliability and provide coordination between different parts of the system.

The focus of this thesis is to design and simulate a Bidirectional DC/DC Converter to interface a battery-bank for a standard residential scale PV installation and develop a smart-energy management system to coordinate the operation of the battery bank along with the PV system, considering the utility grid connection.

1.3 Literature Review

This section details the background and literature on different bidirectional DC-DC converters, their types and application. It will also present background literature on energy management systems and their uses and applications.

1.3.1 Battery Modeling and Characteristics:

Lead acid batteries are the most used type of energy storage systems due to their reduced cost and high durability [5]. Due to their popularity, a large amount of research was performed to identify their properties and behavior for simulation purposes. Identifying the battery behavior is very important for the design of the converter. A large number of battery models were developed that include circuit based models such as [6]. It is important to identify a model for the battery that estimates the state of charge accurately to be able to assess the performance of the power converter operation. The battery model must be compatible with the charging and discharging profiles of typical lead acid batteries. The state of charge must be determined accurately for the purposes of converter control. A battery model is as found in [6] and can be summarized as follows:
The integrating loop provides an estimation of the actual charge of the battery. The voltage is then calculated and supplied to the controlled voltage source that converts the signal into a power signal. Even though this model has several simplifications, it still can provide an accurate response. The parameters are defined as follows:

Table 1: Battery Model Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E )</td>
<td>no-load voltage (V)</td>
</tr>
<tr>
<td>( E_0 )</td>
<td>battery constant voltage (V)</td>
</tr>
<tr>
<td>( K )</td>
<td>polarization voltage (V)</td>
</tr>
<tr>
<td>( Q )</td>
<td>battery capacity (Ah)</td>
</tr>
<tr>
<td>( I_{\text{integral}} )</td>
<td>actual battery charge (Ah)</td>
</tr>
<tr>
<td>( A )</td>
<td>exponential zone amplitude (V)</td>
</tr>
<tr>
<td>( B )</td>
<td>exponential zone time constant inverse (Ah)−1</td>
</tr>
<tr>
<td>( V_{\text{batt}} )</td>
<td>battery voltage (V)</td>
</tr>
<tr>
<td>( R )</td>
<td>internal resistance (Ω)</td>
</tr>
<tr>
<td>( i )</td>
<td>battery current (A)</td>
</tr>
</tbody>
</table>

In order to verify the model, a test simulation will be performed and the charging and discharging characteristics will be examined. A short circuit test will demonstrate the discharge characteristics and an open circuit test will demonstrate the charging characteristics of the model. This model should be useful in simulation and should give an idea about the expected behavior of a lead acid battery.

1.3.2 Bidirectional DC-DC Topologies

The literature shows two main types of bidirectional DC/DC converters: (i) the isolated converter and the (ii) non-isolated converter. The isolated converter consists of two bidirectional Bridge converters
that are separated by a transformer. The DC voltage and current are transformed into AC and then the ratio is Boosted/Bucked through an isolation transformer and then rectified back to a DC voltage. A typical isolated DC/DC converter can be seen in [7].

![Typical isolated bidirectional converter](image1)

**Fig 1.2: Typical isolated bidirectional converter.**

This topology provides a high gain because it utilizes the use of a transformer. It also provides a galvanic isolation for the energy storage system and the grid. However, this approach would require a very large transformer to produce high gain. A large transformer would consume space and weight and would result in a high cost and an increased losses. In addition, this approach would require two back to back converters which would result in an increased number of power switches and an increased number of controllers. Such converters should not be used unless the voltage gain could not be achieved through non-isolated converters. The other type is the non-isolated converter which also has many topologies. The simplest design is the synchronous buck converter which is still used with electric vehicles as mentioned in [8].

![Basic non-isolated bidirectional converter (synchronous buck)](image2)

**Fig 1.3: Basic non-isolated bidirectional converter (synchronous buck).**
In this design, the ideal, voltage-boost -gain is calculated as follows:

\[
\frac{V_o}{V_i} = \frac{1}{D}
\]  

(1)

The practical gain in this design cannot be more than 400% with reduced efficiency which in battery-grid interface connection is not suitable. In addition, this design has a high ripple in current that would require a large size capacitor to regulate the voltage and the stress on the switches will be high. High ripple currents could also affect the lifespan of a battery system (to be investigated). For high power density, efficiency is a key factor for designing the converter as well as size and cost. These criteria could be met by introducing the interleaved multi-phased converters. Multi-phased interleaved converters such as [9] have been used in power applications.

Fig 1.4: interleaved multiphase converter.

This configuration reduces the inductance size because the current is shared by the three phases. In addition, the current ripple can be reduced by shifting the switching signal by 360/N to achieve minimized total current ripple. The difference between input/output currents and inductor currents can be seen as follows:

Fig 1.5: ripple difference between input/output currents and inductor currents.
By reducing the current ripple, the capacitor size needed to regulate the voltage will also be reduced [9]. This configuration provides high power density sharing but does not offer a voltage gain more than a conventional boost converter which is at max 4 times the voltage. For grid connection applications, battery interface requires a converter with a high voltage gain. Several techniques have been reported to introduce high voltage gain such as interleaving the input and floating the output through two capacitors that will cumulatively produce the output voltage. Such technique is reported in [10]. This technique is reported to have high voltage gain, reduced element size and reduced stress on the switches [10]. A high density unidirectional power converter have been developed using this technique to interface fuel cells in [11] and [12]. A bidirectional version of this converter can be realized by substituting the diodes with IGBT switches yielding to a configuration that could be like the following:

![Fig 1.6: Four Phase Floating Interleaved Converter.](image)

This configuration provides high voltage gain, lower stress on the switches and reduced ripple in the input/output currents. Its transformerless design makes it a good candidate for high efficiency high power transfer and energy storage interface. Due to these potential features, this topology will be chosen for the power converter in this thesis. A detailed design, analysis and modeling will be performed in the next chapter and a comprehensive simulation will be conducted to evaluate the performance of the converter.
1.3.3 Energy management control systems

After deciding on which type of converter is best fit for a residential application, a management system must be designed to make the power flow more efficient and maximize the PV power dispatch. The energy management system coordinates between three parts of the system, the PV converter, the battery converter, and the grid connected inverter. In the literature, there are two main approaches to manage and optimize energy coming from renewable energy resources. The first approach employs the use of a model predictive control to manage the system. It utilizes generation and demand forecast as well as market price prediction through statistical models and neuro-fuzzy networks. Such management systems can be seen in [13], [14], [15], and [16]. These algorithms present many advantages for large scale integration of PV systems where optimization and response time are essential. However, these data may not be available for a small scale PV system. Therefore, the role of an energy management system in small scale PV systems is more concerned with maximizing PV power, minimizing grid power, extending the life of the energy storage system, providing backup using energy storage during islanded mode. The second approach is a direct approach that evaluates the state of the system instantaneously, decides the operation mode, and generates control signals to the converters in the system. Typical tasks of such a management system include maximum power tracking, state-of-charge (SOC) estimation, Battery dispatch optimization, and inverter control. Typical Systems can be seen in [17], [18], [19], and [20]. These systems share a common management structure which consists of a higher level controller that decides the mode of operation and generates reference signals to lower level controllers of power converters. The energy management structure is realized as follows:

![Energy Management Structure](image)

Fig 1.7: Energy Management Structure.
In [17], the control strategy consists of a higher level algorithm that decides the operation mode of the system, and a lower level control layer that generates the PWM signals for the converters. Operation modes are decided through measuring the system states, SOC, PV power, load demand, and system voltages. The operation modes can be: battery charging, battery discharging, and standby mode. PV generation is maximized through an MPPT algorithm and excess energy is injected to the grid. In [18], the control structure is similar to [17] but the operation modes are set through the value of the net power in the system and the state of the storage system which is:

\[
P_{\text{net}} = P_{\text{Wind}} + P_{\text{PV}} - P_{\text{Load}} - P_{\text{aux}}
\]  

(2)

Where \( P_{\text{aux}} \) represents auxiliary and losses power and the state of the storage system which in this case is the hydrogen level in the tank. After that, actuators are set through logical signals (1/0) that are generated by a simple management logic code. In [19], the control algorithm focuses on producing a fixed output power from PV and fuel cells. It generates variable power references for the fuel cells to maintain a fixed power output from the DC link. This technique could be useful to control the inverter to track the load demand and set the reference power according to it. The energy management algorithm in [20] prioritizes the power transfer according to: 1) Local load. 2) Battery SOC 3) Grid transaction. This algorithm covers all scenarios and maintains the objectives of an energy management system. Compared to other algorithms, this one provides simplicity as well as generality. However, the author did not provide any information about limitations and restrictions about the power transfer. By adding power limitations to this algorithm, we could find a very robust energy management algorithm that could be easily applied to a residential PV system with energy storage. In Addition, a simplified forecasting model could be included to the management system to improve battery dispatch and reduce energy consumption cost.

1.4 Proposed Energy Management Control System

The proposed management system is similar to the previously mentioned systems. However, they model predictive algorithms lack the simplicity that residential application require and the instantaneous algorithms lack the forecast focus. Therefore, the proposed algorithm will combine simplicity of application and apply forecasting that suits the residential application. The proposed system will not discuss island detection techniques and will assume the state of the point of common coupling (PCC) will be given by a binary integer (one/zero). The proposed energy management algorithm is similar to the one in [20] but power limitations and economic considerations are added. The proposed energy management algorithm is realized as follows in the next page:
The flowchart is similar to [20] which consider a grid-connected mode operation. However, in order to make economic decisions, load forecasting and PV forecasting must be included to make sure that the most economic state is chosen. Therefore, this algorithm will be modified to include conditions for the forecasted values and will be presented in chapter 4.

1.5 Thesis Scope and Contributions

The contributions of this thesis include:

1) Performing an expanded simulation for the Bidirectional floating interleaved converter along with the battery model and different charging and discharging scenarios,

2) Developing a, dual-loop, linear feedback controller for the converter,
3) Develop a C code to implement the proposed energy management system and test it on a PV system along with a battery system.

A detailed analysis of the bidirectional DC/DC converter along with the dynamic battery model will be performed. The battery model will be validated and tested before using it in the simulation. A dual-loop feedback controller will be designed using the K factor method or the Simulink tuning tool.

A C code will be written to implement the proposed energy management algorithm. After that, the energy management system will be tested through a comprehensive simulation that includes a PV system, a battery system, and a grid connected inverter. The system structure is realized as follows:

![Comprehensive simulation with energy management system](image)

Fig 1.9: Comprehensive simulation with energy management system

This simulation will evaluate the performance of both the bidirectional DC/DC converter and the energy management system. Both grid connected mode and islanded mode will be tested. The energy management system will decide the operation mode and generate the reference signals accordingly. The PV controller will perform an MPPT algorithm to extract maximum power. The battery controller will be consisted of two controllers (buck and boost). The inverter controller will have voltage control as well as active and reactive power control.
1.6 Organization

- Chapter 1:
  An introduction, introducing key motivation and background information, and highlighting the thesis goals.

- Chapter 2:
  Contains a detailed analysis of the bidirectional converter along with a detailed analysis of lead acid battery characteristics and modeling as well as testing and validation.

- Chapter 3:
  Describes the design of the controllers for the bidirectional converter for both buck and boost modes via K factor method as well as Simulink auto tuning tool.

- Chapter 4:
  Will discuss the implementation of the energy management system algorithm as a C code as well as power limitations and reference signals.

- Chapter 5:
  Contains a comprehensive simulation that includes the energy management system and a complete PV system with batteries. Different scenarios will be conducted to test the performance of both the energy management system and the bidirectional DC/DC converter. Results of the simulation will be presented and discussed.

- Chapter 6:
  Contains the final discussion, conclusion, and opportunities for future work.
This chapter will present the mathematical analysis of the bidirectional DC-DC converter. It will also present the details of the battery model that is used in this project. For the bidirectional converter, the differential equations, the state space equations and the transfer function will be presented. For the battery model, the chosen model will be explained and tested through simulation.

2.1 Battery Model

Lead acid batteries are the most popular form of energy storage systems due to their reduced cost and their high durability. Identifying the battery behavior is very important for the design of the converter. It is important to identify a model for the battery that estimates the state of charge accurately to be able to assess the performance of the power converter operation. The battery model must be compatible with the charging and discharging profiles of typical lead acid batteries. The state of charge must be determined accurately for the purposes of converter control. The chosen battery model is as follows [6]:

\[
E = E_0 - K \frac{Q}{Q_{\text{integral}}} + \Delta \exp(B_1 \text{integral})
\]

Fig 2.1: Battery Model

The integrating loop provides an estimation of the actual charge of the battery. The voltage is then calculated and supplied to the controlled voltage source that converts the signal into a power signal. In this model, there are a few approximations that simplify its implementation without effecting the charging and discharging characteristics. The approximations can be summarized as follows:

- The internal resistance is constant for both charging and discharging.
- The capacity of the battery is constant.
- The temperature effect is not included.
The battery model is implemented by PSIM. The parameters of the battery model are obtained using the manufacturer’s voltage and current discharge curves. From the discharge curve of the battery, there are three significant points that need to be taken, full charge voltage, exponential voltage, and nominal voltage. From these points all the other parameters can be estimated as proposed in [6]:

- The internal resistance: \[ R = V \frac{1 - \eta}{0.2Q} = 48 \frac{1 - 0.995}{0.2 \times 100} = 0.012 \Omega \] (3)

- \[ A = E_{full} - E_{exp} = 2.64 \text{ exponential voltage drop [V]} \] (4)

- \[ B = \frac{3}{Q_{exp}} = 37.5 \text{ exponential capacity [Ah]}^{-1} \]

- \[ K = \frac{(E_{full} - E_{nom} + A \exp(-BQ_{nom}) - 1).(Q - Q_{nom})}{Q_{nom}} = 1.32; \text{polarization voltage} \] (5)

- \[ E0 = E_{full} + K + Ri - A = 51.84; \text{full charge voltage [volts]} \] (6)

- \[ Q = 100 \text{ rated capacity [Ah]} \]

After finding these parameters the battery model can be simulated in PSIM using C code, and a controlled voltage source. The current value can be measured and integrated to find the actual state of charge using an externally resettable integrator:

\[
SOC = \frac{Q}{Q - \int_{t}^{t+T} i(t) \, dt}
\] (7)

The advantage of using an externally resettable integrator is that initial conditions can be placed. The model can now be built and tested using PSIM. The battery is charged using a current source and then the short circuited through a 2 ohm resistor. The expected behavior is that the voltage will increase during the charging and decrease during the discharge. Since we are using a current source (constant power), the current will be decreasing as the voltage increases during the charge and will follow the voltage during the discharge. From time=0 to 4, the battery is charging. From time=4 to time=6 to 8 the battery is discharging. The SOC was as follows:
And the Voltage and current were as follows:
The battery's behavior in the short circuit test is as expected. A voltage source of 50 volts will be used. When the battery’s voltage increases to equal 50 volts, the current will reach zero because voltages are equal. The battery will then be open circuited and the voltage should maintain at 50 volts. The voltage was as follows:

Fig 2.4: voltage during charging the battery with 50V.

And the current was as follows:

Fig 2.5: Current during charging the battery with 50V.
And the SOC was as follows:

![SOC of the battery during charging](image)

Fig 2.6: SOC of the battery during charging

The behavior of the model during the open circuit test was as expected. Even though this model has several simplifications, it still can provide an accurate response.

### 2.2 Bidirectional DC-DC Converter

The chosen topology combines the features of interleaving along with the features of the transformer-less topologies:

![Bidirectional interleaved buck boost inverter](image)

Fig 2.7: The Bidirectional interleaved buck boost inverter.
In this topology, there are two positive interleaved units and two negative interleaved units. In addition, there are two interconnected capacitors that help increase the voltage gain. Since the power is shared between the four units, the size of inductors and capacitors will reduce significantly. The circuit can operate in both directions (bucking and boosting). Transfer functions that relate the inductor current and the dc link voltage with the duty cycle can be achieved by finding the small AC signal model for:

- Boost mode
- Buck mode

### 2.2.1 State Space Equations

There are two sets of state space equations in this model based on the operation mode (Buck or Boost). In this analysis, we neglect the parasitic resistances and consider inductors and capacitors ideal. Equations of the boost mode at different switching states are presented and the first state is when the four switches are off:

![Fig 2.8: Switching state No. 1](image)
In this case, differential equations are as follows:

\[
L_1 \frac{di_1}{dt} = V_{bb} - v_{c1} \tag{7}
\]

\[
L_2 \frac{di_2}{dt} = V_{bb} - v_{c1} \tag{8}
\]

\[
L_3 \frac{di_3}{dt} = V_{bb} - v_{c2} \tag{9}
\]

\[
L_4 \frac{di_4}{dt} = V_{bb} - v_{c2} \tag{10}
\]

\[
C_1 \frac{dv_{c1}}{dt} = i_1 + i_2 - \frac{v_{DC}}{R_o} \tag{11}
\]

\[
C_2 \frac{dv_{c2}}{dt} = i_3 + i_4 - \frac{v_{DC}}{R_o} \tag{12}
\]

The second state that could happen is if one of the switches is on and the rest of the switched are off, i.e. switch 2 is on and the rest are off:

Fig 2.9: switching state No.2
And in this case, differential equations would be:

\[
L_1 \frac{di_1}{dt} = V_{bb} - v_{c1} \quad (13)
\]

\[
L_2 \frac{di_2}{dt} = V_{bb} \quad (14)
\]

\[
L_3 \frac{di_3}{dt} = V_{bb} - v_{c2} \quad (15)
\]

\[
L_4 \frac{di_4}{dt} = V_{bb} - v_{c2} \quad (16)
\]

\[
C_1 \frac{dv_{c1}}{dt} = i_1 - \frac{v_{DC}}{R_o} \quad (17)
\]

\[
C_2 \frac{dv_{c2}}{dt} = i_3 + i_4 - \frac{v_{DC}}{R_o} \quad (18)
\]

The third state that could happen is if two switches are on and the rest of the other switches are off:

![Diagram](image-url)
And in this case, differential equations would be:

\[ \frac{L_1}{dt} i_1 = V_{bb} \]  
\[ \frac{L_2}{dt} i_2 = V_{bb} \]  
\[ \frac{L_3}{dt} i_3 = V_{bb} - v_{c2} \]  
\[ \frac{L_4}{dt} i_4 = V_{bb} - v_{c2} \]  
\[ \frac{C_1}{dt} v_{c1} = -\frac{v_{DC}}{R_o} \]  
\[ \frac{C_2}{dt} v_{c2} = i_3 + i_4 - \frac{v_{DC}}{R_o} \]

The fourth state that could happen is if three switches are on and only one switch is off:

![Diagram of switching state No. 4](image_url)

Fig 2.11: switching state No. 4
And in this case, differential equations would be:

\[ L_1 \frac{di_1}{dt} = V_{bb} \]  
(25)

\[ L_2 \frac{di_2}{dt} = V_{bb} \]  
(26)

\[ L_3 \frac{di_3}{dt} = V_{bb} \]  
(27)

\[ L_4 \frac{di_4}{dt} = V_{bb} - v_{c2} \]  
(28)

\[ C_1 \frac{dv_{c1}}{dt} = -\frac{v_{dc}}{R_o} \]  
(29)

\[ C_2 \frac{dv_{c2}}{dt} = i_4 - \frac{v_{dc}}{R_o} \]  
(30)

It can be seen that different switching states provide different sets of differential equations and

For the boost mode the equations are presented in [13] and can be summarized as follows:

\[
\frac{dI_N}{dt} = \frac{1}{L_N} \left( V_{bb} - R_N I_N - V_{c1} \bar{U} \right) \quad \text{For } N=1\ldots N/2. 
\]  
(31)

\[
\frac{dI_N}{dt} = \frac{1}{L_N} \left( V_{bb} - R_N I_N - V_{c2} \bar{U} \right) \quad \text{For } N=N/2+1\ldots N
\]  
(32)

\[
\frac{dV_{c1}}{dt} = \frac{1}{C_1} \left[ \sum_{N=N/2}^{N/2} I_N \bar{U} \right] + \frac{V_{bb} - V_{c1} - V_{c2}}{R_o}
\]  
(33)

\[
\frac{dV_{c2}}{dt} = \frac{1}{C_2} \left[ \sum_{N=N/2}^{N} I_N \bar{U} \right] + \frac{V_{bb} - V_{c1} - V_{c2}}{R_o}
\]  
(34)

- \( N \) is the number of the units of the model which is in this case 4.

Since the previously mentioned reference was discussing the unidirectional version, state space equations for buck mode had to be derived using the same logic. Therefore, the buck mode equations are as follows:

\[
\frac{dI_N}{dt} = \frac{1}{L_N} \left( V_{dc} - R_N I_N - V_{c1} \bar{U} - V_{c2} \right) \quad \text{For } N=1\ldots N/2
\]  
(35)
\[
\frac{dI_N}{dt} = \frac{1}{L_N} \left( V_{dc} - R_N I_N - V_{c1} - V_{c2} \hat{U} \right) \quad \text{For } N = N/2 + 1 \ldots N
\]  
(36)

\[
\frac{dV_{c1}}{dt} = \frac{1}{C_1} \left[ \sum_{N=1}^{N/2} I_N \hat{U}_N + \frac{V_{dc} - V_{c1} - V_{c2}}{R_{bb}} \right]
\]  
(37)

\[
\frac{dV_{c2}}{dt} = \frac{1}{C_2} \left[ \sum_{N=N/2+1}^{N} I_N \hat{U}_N + \frac{V_{dc} - V_{c1} - V_{c2}}{R_{bb}} \right]
\]  
(38)

### 2.2.2 Small AC Signal Model

After finding the state space equations, the small AC signal Equations Can Be found for both the buck and boost mode. The following expansion of voltages and current must be presented to find the small AC signal model:

\[
v_x = (v_x + V_x)
\]  
(39)

\[
i_x = (i_x + I_x)
\]  
(40)

\[
d_x = (d_x + D_x)
\]  
(41)

Applying these expansions and neglecting the small values with small variations, the boost mode, and the equations will be as follows [12]:

\[
\hat{v}_{L1} - \hat{v}_{bb} + \hat{v}_{L1} - \hat{d}_1 \hat{V}_{c1} + \hat{D}_1 \cdot (\hat{v}_{c1} + \hat{v}_{c2}) = 0
\]  
(42)

\[
\hat{v}_{L2} - \hat{v}_{bb} + \hat{v}_{L2} - \hat{d}_2 \hat{V}_{c2} + \hat{D}_2 \cdot (\hat{v}_{c1} + \hat{v}_{c2}) = 0
\]  
(43)

\[
\hat{v}_{L3} - \hat{v}_{bb} + \hat{v}_{L3} - \hat{d}_2 \hat{V}_{c2} + \hat{D}_2 \cdot (\hat{v}_{c1} + \hat{v}_{c2}) = 0
\]  
(44)

\[
\hat{v}_{L4} - \hat{v}_{bb} + \hat{v}_{L4} - \hat{d}_2 \hat{V}_{c2} + \hat{D}_2 \cdot (\hat{v}_{c1} + \hat{v}_{c2}) = 0
\]  
(45)

\[
\hat{i}_{c1} - \hat{D}_1 (\hat{i}_{L1} + \hat{i}_{L2}) + \hat{d}_1 \cdot (\hat{I}_{L1} + \hat{I}_{L2}) + \hat{i}_{dc} = 0
\]  
(46)

\[
\hat{i}_{c2} - \hat{D}_2 (\hat{i}_{L3} + \hat{i}_{L4}) + \hat{d}_2 \cdot (\hat{I}_{L3} + \hat{I}_{L4}) + \hat{i}_{dc} = 0
\]  
(47)

And the equations For the Buck mode are found as well [12]:

22
After Finding the Small AC Signal Model, The Control Strategy Can Be established and the desired transfer functions can be found as well as the parameters of the controller which will be discussed in the next chapter.
This chapter aims to present the process and methodology of designing the closed loop control (power conversion level) for the Bidirectional DC-DC converter. There will be two control loops: one for the buck mode and one for the boost mode. In both cases, dual loop control will be used. Dual loop control uses an outer voltage control loop and an inner, faster current control loop and hence two PI compensators will be placed for each loop. The voltage control loop is used to maintain the dc link voltage and the battery voltage. Current control loop is used to control power from and to the battery.

3.1 Control structure and transfer functions

In the presented bidirectional converter, the current to be controlled is the inductors’ current and the voltage to controlled is the capacitors’ voltage as seen in the presented equations. The converter is governed by the following equation:

\[ V_{dc} = V_{C1} + V_{C2} - V_{bb} \]  

(54)

That equation is always valid for the bidirectional converter. After finding the small AC signal equations, the control strategy can be established. The inductor current and output voltage will be regulated by PI controllers. An internal current loop and an external voltage loop are established. The control scheme for both buck and boost is established. For Boost mode, the control scheme is as follows [4]:

![Control scheme for Boost mode](image)

Fig 3.1: Control scheme for Boost mode

The voltage on the DC link and the current of the inductors is regulated. Similarly, the same control scheme can be used for the buck mode as well [4]:
Fig 3.2: Control scheme for Buck mode.

It can be seen that the needed transfer function are \( \frac{i_L}{d} \) and \( \frac{V_{dc}}{d} \). The transfer functions are established for both buck and boost mode. For the boost mode, the transfer functions are as follows [14]:

\[
\frac{v_{dc-bus}(s)}{d(s)} = K_{boost} \frac{(1 - \frac{s}{w_{zr}})(1 + \frac{s}{w_{zd}})}{(1 + \frac{s}{w_o Q} + \frac{s^2}{w_o^2})} \tag{55}
\]

\[
\frac{i_L(s)}{d(s)} = K_{boost} \frac{(1 + \frac{s}{w_{zl}})}{(1 + \frac{s}{w_o Q} + \frac{s^2}{w_o^2})} \tag{56}
\]

\[
K_{boost} = \frac{V_{bb}(2R(1-D)^2 - R_L(1+D))}{(1-D)^2(R(1-D)^2 + R_L)} \tag{57}
\]

\[
w_{zr} = \frac{2R(1-D)^2 - R_L(1+D)}{L(1+D)} \tag{58}
\]

\[
w_{zl} = \frac{1}{R_c C} \tag{59}
\]

\[
K_{boost} = \frac{V_{bb}(D + 3)}{2(1-D) (R(1-D)^2 + R_L)} \tag{60}
\]

\[
w_{zr} = \frac{1}{R_C + R_c C} \tag{61}
\]
\[ w_o = \frac{1}{\sqrt{LC}} \sqrt{\frac{2R(1 - D)^2 + 2R_L}{R + 2R_C}} \]  
\[ Q = \frac{w_o(R + 2R_C)LC}{RC(R_L + 2R_C(1 - D)^2) + 2(L + R_C R_L C)} \]

The transfer functions can be derived for the buck mode except that the regulated voltage is the voltage across the battery terminals or the low side [14]:

\[ \frac{v_{bb}(s)}{d(s)} = K_{v_{buck}} \frac{(1 - \frac{s}{w_{zr}})(1 + \frac{s}{w_{zr}})}{(1 + \frac{s}{w_oQ} + \frac{s^2}{w_o^2})} \]  
\[ \frac{i_L(s)}{d(s)} = K_{i_{buck}} \frac{(1 + \frac{s}{w_{zr}})}{(1 + \frac{s}{w_oQ} + \frac{s^2}{w_o^2})} \]

Where:

\[ K_{v_{buck}} = \frac{V_{dc} (2RD^2 - R_L (2 - D))}{RD(2 - D)^2} \]  
\[ w_{zr} = \frac{8RD^2 - R_L (2 - D)}{L(2 - D)} \]  
\[ w_{zr} = \frac{1}{R_C C} \]  
\[ K_{i_{buck}} = \frac{V_{dc} (2 - D)}{RD(4D - 2D^2)} \]  
\[ w_{zr} = \frac{1}{2DRC} \frac{2DRC}{(4 - 2D)(2 - D)} + R_C C \]
\[ w_o' = \frac{1}{\sqrt{LC}} \sqrt{4D - 2D^2} \]  
(71)

\[ Q' = \frac{w_o L}{R_c (4D - 2D^2) + R_L} \]  
(72)

After finding the desired transfer functions, the Bode diagram frequency analysis can be used to find the values of the PI compensators.

### 3.1.1 Boost mode control

By replacing all the values in the previously presented equations, the K factor method did not present a PI compensator with good performance and Matlab auto tuning tool was used to find the compensator values. The transfer function of the compensator at boost mode is expressed as follows:

\[ C_i = \frac{0.01s + 0.0005}{S} \]  
(73)

The bode-plot of the compensated plant is shown in the next figure:

![Bode plot of the compensated control loop](image)

**Fig 3.3: Bode plot of the compensated control loop**

### 3.1.2 Buck mode Control

The same process can be done for the buck controller. However, it has been seen that the boost controller provides enough bandwidth to compensate for both buck and boost operations. A test of the operation modes has been performed and will be presented in the next section.
3.2 Controller testing

The controller has been tested for both buck and boost mode with the previously mentioned battery model. The controller showed ability to transfer energy from and to the battery. The next simulation case shows a discharge of 30 W and then a charge of 170 W:

![Fig 3.4: Charging the batter.](image)

Another case is also simulated that represents higher energy transfer levels and transition from buck to boost mode (charging to discharging):

![Fig 3.5: transition from charging to discharging](image)
In this case, it can be seen that the converter was able to successfully shift from charging the battery with 900W to discharging it with 700W and the voltage of the DC link in this case is as follows:

Fig 3.6: DC link Voltage from charging to discharging

It can be seen from this graph that the transient response time was 0.1 seconds and the ripple in the voltage does not exceed 1%. The second test case is the transition from boost to buck (discharging to charging):

Fig 3.7: transition from discharging to charging
It can be seen that the converter has successfully shifted from supplying 700W to receiving 400W and the DC link voltage in this case is:

![DC link voltage from discharging to charging](image)

IT can be seen that transient response time does not exceed 0.1 seconds and the ripple during high power transfer does not exceed 2%.

3.3 Cost Analysis and Comparison

After searching market prices and specifications for different companies, the following table illustrates some of the differences between isolated and non-isolated converters for a 5 KW system:

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
<th>Weight</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isolated converters</strong></td>
<td>91-95%</td>
<td>20-35 lbs.</td>
<td>500-1500$</td>
</tr>
<tr>
<td><strong>Non isolated converters</strong></td>
<td>97-99%</td>
<td>15-20 lbs.</td>
<td>&gt;1700$</td>
</tr>
</tbody>
</table>
CHAPTER 4
ENERGY MANAGEMENT CONTROL SYSTEM

In this chapter, the energy management algorithm and implementation will be presented. As explained in chapter one, most residential energy management control systems don’t include economic factors in their structure. Most energy management systems consider storage systems as backup or peak shaving tools. By including dynamic price scheduling, load forecast and PV forecast, the storage becomes more than just a backup. It becomes economically conscious and grid interactive. The energy management system’s capabilities can be extended to include electricity bill reduction and battery life extension. Therefore, the presented energy management algorithm will include load forecast, electricity tariff, and PV forecast to improve its capabilities. Each part will be explained individually along with the energy management control system.

4.1 Energy Management Structure and algorithm

The two main objectives of this energy management control system is to reduce the electricity bill and reduce number of charging / discharging cycles off the battery. In this system, charging and discharging decisions will be made every three hours based on averaged measurements for one hour. The energy function of this system is expressed as follows:

$$ E_{grid} (t) = E_{load} (t) - E_{pv} (t) - E_{bat} (t) $$

(74)

And the Price of electricity can be expressed as follows:

$$ price(t) = E_{grid} (t) c(t) $$

(75)

$$ price(t) = \left( E_{load} (t) - E_{pv} (t) - E_{bat} (t) \right) c(t) $$

(76)

And $c(t)$ is the cost for electricity function. From this equation it can be seen that load cannot be changed and the only way to control PV energy is to apply MPPT algorithm. Therefore, optimizing this function relies on optimizing the battery energy with respect to the cost. Since battery energy could be both positive and negative, price function should be reduced at charging the battery and increased at discharging the battery. Maximizing the battery life has many parameters but in this system only the number of charging and discharging cycles is included. Therefore, the load supply priority table can be seen as follows:
Table 3: Priority organization

<table>
<thead>
<tr>
<th>Priority 1</th>
<th>PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority 2</td>
<td>grid ( \equiv ) if (\text{tariff}<em>{\text{future}} \uparrow)) and ((P</em>{\text{PV}} &gt; P_{\text{Load}}))</td>
</tr>
<tr>
<td>Priority 3</td>
<td>battery ( \equiv ) if (\text{tariff}<em>{\text{future}} \downarrow)) and ((P</em>{\text{PV}} &lt; P_{\text{Load}}))</td>
</tr>
</tbody>
</table>

From these priorities, an energy management algorithm can be derived and the resultant algorithm is:

![Algorithm Diagram](image)

Figure 4.0: Modified Energy management algorithm
4.2 Load Forecast Model

There are many load forecast models in the literature. The simplest forecast models are linear regression models such as [23]. Linear regression models are simple to implement and have many forms. However, they are known to have consistent, over-estimating or under-estimating, errors. Nonetheless, the amplitude of error is considered acceptable in a residential energy management application especially when its main function is to determine the state of the battery. The chosen model for this system is a linear model that predicts a residential load based on its past history for the last four days. The model is expressed as [23]:

\[
d(t) = \begin{bmatrix} d(t-1) & d(t-2) & d(t-3) & d(t-4) \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}
\]

To find the (a) parameters, a set of at least 8 days of load data is needed and parameters a1 to a4 can be found as follows:

\[
\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \left( \begin{bmatrix} d(4) & d(3) & d(2) & d(1) \end{bmatrix} \right)^{-1} \begin{bmatrix} d(5) \\ d(6) \\ d(7) \\ d(8) \end{bmatrix}
\]

After finding these parameters, the load can be forecasted by simply providing load consumption for the last four days.

4.2.1 Testing the forecast model

After testing the forecast model for 8 days of data, the error was high. Therefore the number of test data was increased to reduce the error and the model was implemented using Matlab/Simulink toolbox. The forecast result was improved and the can be seen as follows:
Fig 4.1: Real load and forecasted load

It can be seen that the error shifts from positive to negative and does not consistently over estimate or under estimate which is the desired outcome from the forecast model.

4.3 PV Model

The output PV power is considered as MPPT output with a Gaussian function. The PV model is considered as a controlled current source that injects current at the DC link voltage:

Fig 4.2: PV power model.
However, the output PV Power is averaged for control and energy management purposes and the resulting PV power curve would be as follows:

![Fig 4.3: Averaged PV power model.](image)

In addition, the same curve will also be used in the actual simulation to behave as MPPT output.

### 4.4 Tariff Model

In this system, dynamic pricing is included in the energy management algorithm. Electricity price is changing through the day. The highest price corresponds to the highest demand or the peak of the demand. Including this type of pricing allows the energy management system to adapt to future technologies introduced by the utility. The price model can be seen as follows:

![Fig 4.4: Dynamic pricing chart](image)
In this chapter, the overall simulation of the converter and the energy management control system will be presented and discussed. The complete simulation will be performed in PSIM software and the energy management algorithm will be applied using C code. The performance of the energy management algorithm will be compared to another algorithm and four case studies will be presented. The first case study will be at high load and long daylight time. The second case study will be at light load and short daylight time. The third case study will be at light load and long daylight time. Finally, the fourth case will be at high load and short daylight time.

5.1 System Layout

The system is built in PSIM software using all the previously mentioned models for all the parts of the system. The grid connected inverter and all its control loops and design is explained in [14]. The system layout is as follows:

Fig 5.1: complete system simulation
The simulation will present 24 hours of data resized into 48 seconds. Which means that every hour will be represented by two seconds. The reason for that is to capture both the response of the low level controllers, which have very small timeframe, and capture the response of the high level energy management control, which takes place at a large timeframe. Every simulation case will be performed using lookup tables that send the wanted values to the load current source and the PV current source. The load forecast parameters are also performed using lookup tables. The simulation results will be explained individually in the next section.

5.2 High Load and Long Daylight Time

The first simulation case is to have a relatively high load and a long period of daylight. The peak of the PV power is right above 6000 W and higher than the peak of the load power at about 4500 W.

Fig 5.2: Power distribution in the system (case 1)
In this case, PV starts to produce power early in the morning (5 a.m.) at which the price of electricity is very low. The initial SOC of the battery is 0.2 which is lower than the critical limit. Therefore, based on forecasts and future price, the energy management control system decides to divert PV power that is available now to the battery because the price is low. Even though there will be excess PV power later, the current price is less than the future price and hence injecting power to the grid at high price is the better decision:

![Battery Power (case 1)](image)

Fig 5.3: Battery Power (case 1)

And the state of charge for the battery is as follows:

![SOC of the battery (case 1)](image)

Fig 5.4: SOC of the battery (case 1)
And the Voltage at the terminals of the battery is as follows:

![Voltage of the battery (case 1).](image)

And the price per hour along with the total daily electricity price is shown as follows:

![Daily cost per hour (case 1).](image)

Fig 5.5: Voltage of the battery (case 1).

Fig 5.6: daily cost per hour (case 1).
5.3 High Load and Short Daylight Time

The second case is a more interesting and critical case. During low electricity price, the battery charges. In peak time, PV does not cover the demand.

![Fig 5.7: Power distribution in the system (case 2)](image)

Fig 5.7: Power distribution in the system (case 2)

The battery discharges at a PV-peak time until low SOC protection activates and stops the discharge. The forecast indicates that the price is still going up in the next few hours. The battery at an unwanted time due to frequent change in PV to Load values:

![Fig 5.8: Battery power (case 2)](image)

Fig 5.8: Battery power (case 2)
And the SOC of the battery is as follows:

Fig 5.9: SOC of the battery (case 2).

And the voltage of the battery is as follows:

Fig 5.10: Voltage of the battery (case 2).
And the price per hour along with the total daily electricity price is shown as follows:

Fig 5.11: Daily cost per hour (case 2).

5.4 Low load and Long daylight time

Similar to the first case, PV starts to produce power early in the morning (5 a.m.) at which the price of electricity is very low.

Fig 5.12: Power distribution in the system (case 3).
The initial SOC of the battery is 0.2 which is lower than the critical limit. Therefore, based on forecasts and future price, the energy management control system decides to divert PV power that is available now to the battery because the price is low. Even though there will be excess PV power later, the current price is less than the future price and hence injecting power to the grid at high price is the better decision:

![Battery power (case 3).](image1)

Fig 5.13: Battery power (case 3).

And the SOC of the battery is as follows:

![SOC of the battery (case 3).](image2)

Fig 5.14: SOC of the battery (case 3).
And the voltage at the terminal of the battery is as follows:

![Graph showing battery voltage](image)

*Fig 5.15: Battery Voltage (case 3).*

And the price per hour along with the total daily electricity price is shown as follows:

![Price per hour graph](image)

*Fig 5.16: Daily price per hour (case 3).*
### 5.5 Low Load and Short Daylight Time

The last case presents a low load and a short daylight time. In this case, PV at peak is higher than the load and the battery needs to be charged.

![Power distribution in the system (case 4).](image)

The battery’s initial state of charge is 0.2 and needs to be charged. Therefore, it charges at the beginning of PV generation and continues. The PV generation increases and then the charging level of the battery increases. The Charging and discharging can be seen as follows:

![Battery power (case 4).](image)
And the SOC in this case is as follows:

Fig 5.19: SOC of the battery (case 4).

And the voltage at the terminal of the battery is as follows:

Fig 5.20: Voltage of the battery (case 4).
And the price per hour along with the total daily electricity price is shown as follows:

![CASE 4]

**Fig 5.21:** Daily price per hour (case 4).

### 5.6 Evaluation of Results

The management system has shown that it could provide decisions and the local controller has shown their ability to perform the commands. In addition, the management system has presented decisions that proven to reduce electrical cost and reduce the number of charging and discharging in one day. It has been noticed that changing the forecasted period gives different results which could presents an opportunity to improve the performance of the system.
CHAPTER 6
CONCLUSION AND FUTURE WORK

In this chapter, a summary of the collective work along with some of the conclusions about the results are presented. The opportunities for future work in continuation of the research are presented as well.

6.1 Conclusion

This Thesis presents a complete energy management system that includes analysis of a bidirectional DC-DC converter and a new energy management algorithm. The objectives for this MS Thesis have been successfully realized through simulation of multiple scenarios using PSIM software. As a part of this research activity, a C code was produced that could be easily uploaded into a microcontroller and interfaced with any PV/Storage system regardless of the topology and the layout. In addition, closed loop controls were designed using mathematical analysis as well as Matlab/Simulink tools which has shown ability to interface the converter successfully with the utility. The energy management algorithm has provided a very good performance under normal conditions. However, there were some extreme conditions that the algorithm did not produce maximum efficiency.

6.2 Future work

The performance of the bidirectional DC-DC converter and the cost analysis presented definitely supports experimental/hardware implementation of it in the future. In this energy management algorithm, a 3 hour forecast period is implemented which could be investigated in the future. In addition, variable forecast periods could be implemented to improve forecast decisions.

Future work of the present project includes:

- Experimental validation of the bidirectional DC-DC converter.
- Implementation of different forecast techniques for both load and PV
- Implementation of different forecast periods and evaluation of outcomes.
- Changing the prioritization in the energy management algorithm based on the type of storage.
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