Bidirectional Isolated DC-DC Power Supply

A Project Report
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Abstract

The energy storage is of critical importance in the application such as hybrid electric vehicle, space vehicle etc. A bidirectional converter is necessary between the energy storage battery and the supply to match the voltage level. For medium to low power range application bidirectional double switch forward converter is proposed.

This project deals mainly with building the hardware for bidirectional power flow between battery and source or load.

In this work, Bidirectional Isolated DC-DC converter is designed to operate with a battery.

Overall, the project work involves the building of the converter hardware, the filters, transformer and design and implementation of closed loop control for the converter.
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<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_b$</td>
<td>Battery voltage</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Switching period</td>
</tr>
<tr>
<td>$d$</td>
<td>Duty ratio</td>
</tr>
<tr>
<td>$n$</td>
<td>Turns ratio of transformer</td>
</tr>
<tr>
<td>$e(n)$</td>
<td>Error signal to PI controller</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Area of core</td>
</tr>
<tr>
<td>$A_w$</td>
<td>Area of winding</td>
</tr>
<tr>
<td>$a_w$</td>
<td>Area of wire</td>
</tr>
<tr>
<td>$k_w$</td>
<td>Winding factor</td>
</tr>
<tr>
<td>$J$</td>
<td>Operating current density for copper</td>
</tr>
<tr>
<td>$B_m$</td>
<td>Peak flux density of inductor core</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The bidirectional dc-dc converter along with energy storage has become a promising option for many power related systems, including hybrid vehicle, fuel cell vehicle, renewable energy system and so forth. It not only reduces the cost and improves efficiency, but also improves the performance of the system.

In the electric vehicle applications, an auxiliary energy storage battery absorbs the regenerated energy fed back by the electric machine. In addition, bidirectional dc-dc converter is also required to draw power from the auxiliary battery to boost the high-voltage bus during vehicle starting, accelerate and hill climbing. With its ability to reverse the direction of the current flow, and thereby power, the bidirectional dc-dc converters are being increasingly used to achieve power transfer between two dc power sources in either direction.

Recently, clean energy resources such as photovoltaic arrays and wind turbines have been exploited for developing renewable electric power generation systems. The bidirectional dc-dc converter is often used to transfer the solar energy to the capacitive energy source during the sunny time, while to deliver energy to the load when the dc bus voltage is low. The bidirectional dc-dc converter is regulated by the solar array photovoltaic level, thus to maintain a stable load bus voltage and make fully usage of the solar array and the storage battery.

Numerous topology for possible implementation as bidirectional DC-DC converters have been reported so far. Basically they are divided into two type, non-isolated and isolated converters meetind different application requirements.

In isolated DC-DC bidirectional converter, isolation is normally provided by a transformer. The added transformer cause additional cost and losses. However, since transformer can isolate the two side of the converter and provide the impedance matching between them.
Also for high voltage ratio between two sides of converter, efficiency of non-isolated DC-DC bidirectional converter is very poor. So Isolated idirectional DC-DC converter is an alternative in those kinds of applications.

1.1 Project Work

This project deals with the complete design of Bidirectional DD-DC converter and control of a power converter to use with battery. The block diagram of converter with battery is shown in Figure 1.1.

![Figure 1.1: Block Diagram of DC-DC Bidirectional Converter with Battery](image)

The DC-DC bidirectional converter is designed and built for 200/24 V at a power level of 100W. Apart from the hardware development, the project work involves the closed loop control of the power converter for application with battery.

1.2 Organization of the Thesis

In chapter 2, the topology selected for Power and its advantage is discussed, and the specification are given for corresponding stage.

Chapter 3 discusses the hardware design of power converter in detail. The selection of switches, capacitors, design of filters, transformers and the development of main circuit board is discussed. This chapter also presents the loss calculations and the overall system efficiency at the rated power.

Chapter 4 includes the details of the control system design for closed loop control and implementation of the same in digital domain.

In chapter 5, simulation and experimental results with the pertinent waveforms are discussed in different mode power circuit. Conclusion and Future work are discussed in chapter 7.

The schematics of main circuit board is provided in Appendix ??.
Chapter 2

Topology Selection and Specification

In this chapter, Non-isolated topology and topology for isolated bidirectional DC-DC converter is selected among the available topologies and their specification in terms of power, voltage and switching frequency are specified.

2.1 Non-isolated Bidirectional DC-DC Converter

![Circuit Diagram of Non-isolated DC-DC Bidirectional Converter](image)

Figure 2.1: Circuit Diagram of Non-isolated DC-DC Bidirectional Converter

The circuit diagram of basic non-isolated bidirectional converter is shown in Figure 2.1. The function of circuit is as follows,
**Buck Mode:** In this mode of operation only Switch $S_1$ is switched corresponding to required voltage. When $S_1$ is off, inductor current freewheels through antiparallel diode of switch $S_2$. For duty ratio $d$,

$$V_b = V_i d$$  \hspace{1cm} (2.1)

**Boost Mode:** In this mode of operation only Switch $S_2$ is switched corresponding to required voltage. When $S_2$ is off, inductor current flow through antiparallel diode of switch $S_1$. For duty ratio $d$,

$$V_i = \frac{V_b}{1 - d}$$  \hspace{1cm} (2.2)

For high voltage turns ratio between two sides of converter, the duty ratio has to be high, so the efficiency will be poor.

### 2.2 Isolated Bidirectional DC-DC Converter

For isolated bidirectional DC-DC converter, Double switch forward converter topology is chosen and the secondary diode is changed to switch for bidirectional power flow. Figure 2.2 shows the circuit diagram of the topology.

![Figure 2.2: Circuit Diagram of Isolated DC-DC Bidirectional Converter](image-url)
Advantage of this topology compared to other isolated topology are the following

- As there is no reset winding, transformer design is simple
- Device voltage rating in the primary side is same as the DC bus voltage
- Clamp diodes recover magnetising energy in the core and it is fed back to supply

In the forward direction of power flow, both switches $S_1$ and $S_2$ gets the same PWM and secondary switches is not given PWM. During the ON time of $S_1$ and $S_2$ antiparallel diode of switch $S_3$ will be forward biased, during OFF time inductor current freewheels through the antiparallel diode of switch $S_4$. For duty ratio $d$ and turns ratio $n$,

$$V_b = V_i \cdot n \cdot d \quad (2.3)$$

In the reverse direction of power flow, the switches $S_3$ and $S_4$ are given complementary PWM signals. The voltage at the load side is given by

$$V_i = \frac{V_b}{n(1-d)} \quad (2.4)$$

The limitation of the circuit is that two power switches are needed with the associated drive circuits and unidirectional flux swing in the core which limits the maximum duty cycle of switch $S_1$ and $S_2$ to 50% during forward power flow direction to avoid core saturation. Similarly minimum duty ratio of $S_4$ is limited to 50% during reverse power flow direction.

Bidirectional double switch forward converter is designed for 100W output power and 200/24 V. Switching frequency of switches $S1$ and $S2$ are chosen to be 100 kHz to reduce the sizes of transformer and filter components.
Chapter 3

Hardware Design

The hardware design of the double Switch bidirectional converter power circuit is explained in this chapter. It includes the selection of switches, design and construction of filter inductor and transformer, and design of snubber circuit. The efficiency and loss calculations are presented. The development of the complete circuit board is also discussed.

3.1 System Ratings

Figure 3.1: Power Circuit Topology for the Bidirectional Double Switch Forward Converter

The power circuit topology is shown in Figure 3.1 which is meant to be used for charging the battery from a DC source of different voltage level and giving power from battery to a load of different voltage level. The rating of the power circuit is given in the Table 3.1. The switching frequency is chosen as 100kHz.
### Component

<table>
<thead>
<tr>
<th>Component</th>
<th>Rated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>200V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>24V</td>
</tr>
<tr>
<td>Power</td>
<td>100W</td>
</tr>
</tbody>
</table>

Table 3.1: Ratings of Power Converter

3.2 Power Circuit Design

First, a double switch forward converter (as shown in the Figure 3.2) is designed for system rating and then modified the circuit for bidirectional power supply. It include transformer design, filter component design and switch selection.

![Circuit Diagram of Double Switch Forward Converter](image)

Figure 3.2: Circuit Diagram of Double Switch Forward Converter

3.2.1 Design of Transformer

For an input voltage, \( V_i = 24V \) and output voltage, \( V_o = 200V \) at a power level, \( P = 100W \) and duty ratio \( d = 0.35 \) turns ratio of transformer is given by

\[
\frac{N_1}{N_2} = \frac{V_i d}{V_o}
\]

(3.1)

which gives \( \frac{N_1}{N_2} = 3 \).
Using area product approach \[2\] we can find that

\[ A_c A_w = \frac{2V_i d_{\text{max}} i_{s1\text{rms}}}{\Delta B K_w J_f s} \quad (3.2) \]

where \( A_c \) and \( A_w \) are cross sectional area of core and window area respectively, \( d_{\text{max}} \) is maximum duty ratio possible, \( i_{s1\text{rms}} \) is rms current of primary winding, \( \Delta B \) is change in magnetic field, \( K_w \) is window space factor of core, \( J \) is current density of wire and \( f_s \) is switching frequency. With \( V_i = 200V, d_{\text{max}} = 0.5, i_{s1\text{rms}} = \frac{100}{2\pi} \sqrt{0.5} = 0.982A, \Delta B = 0.25T, K_w = 0.3, J = 3A/mm^2 \) and \( f_s = 100kHz \)

\[ A_c A_w = 0.872cm^4 \]

ETD39 [8] with \( A_c = 1.25mm^2 \) and \( A_w = 1.78mm^2 \) is chosen. Now

\[ N_1 = \frac{V_i d_{\text{max}}}{\Delta B f_s A_c} \quad (3.3) \]

gives \( N_1 = 33 \), so \( N_2 = 11 \).

The size of winding wire is chosen by using

\[ a_w = \frac{I_{\text{rms}}}{J} \quad (3.4) \]

which gives \( a_{w1} = 0.33mm^2 \) and \( a_{w2} = 0.98mm^2 \), where \( a_{w1} \) and \( a_{w2} \) are the cross sectional area of primary and secondary windings. SWG21 with \( a_w = 0.5189mm^2 \) and \( R = 33.23\Omega/km \) for primary winding and SWG15 with \( a_w = 2.627mm^2 \) and \( R = 6.564\Omega/km \) for secondary winding are selected.

The used core material is N87 which is having \( \mu_r \simeq 2000 \), and mean length of flux path, \( l_m = 92.2mm \). Therfore it is obtained that \( L_{m-p} \simeq 3.72mH \) and \( i_{m-p} = 0.19A \) using

\[ L_{m-p} = \frac{\mu_0 \mu_r A_c N_1^2}{l_m} \quad (3.5) \]

and

\[ i_{m-p} = \frac{V_i}{L_{m-p}} dT_s \quad (3.6) \]

respectively. Also mean length of turn, \( l_m \simeq 69mm \), so \( R_p = 33.23 \times 69 \times 10^{-6} \times 33 = 75m\Omega \), similarly \( R_s = 4.98m\Omega \). Therfore copper loss is obtained as 0.116W by using
\[ Cu_{\text{loss}} = i_{p\text{-rms}}^2 R_p + i_{s\text{-rms}}^2 R_s \] (3.7)

Core loss in transformer is given as

\[ \text{Core loss} = V_c (cm^3) k B_{ac} (mT)^a f_s (kHz)^b \text{ mW} \] (3.8)

At 100kHz, for N87, \( k = 3 : 34 \times 10^{-6} \), \( a = 2.7 \), \( b = 1 \) and core volume of ETD39, \( V_c = 11.5 cm \).

For \( B_{ac} = 100 mT \). So, core loss = 0.965 W, therefore total loss = 1.08W. \( R_{th} \) of core is 23.7°C/W, so temperature rise of core is 25°C.

Leakage inductance of transformer is obtained using

\[ L_\sigma = \frac{\mu_0 N_1^2 l_w b_w}{3 p^2 h_w} \] (3.9)

as \( L_{\sigma1} = 9.14 \mu H \) and \( L_{\sigma2} = 1.02 \mu H \).

The summary of transformer design is given in Table 3.2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage ( V_i )</td>
<td>200V</td>
</tr>
<tr>
<td>Duty cycle ( d )</td>
<td>0.35</td>
</tr>
<tr>
<td>Power ( P )</td>
<td>100W</td>
</tr>
<tr>
<td>Frequency ( f_s )</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Core Selected</td>
<td>ETD39</td>
</tr>
<tr>
<td>No. of turns</td>
<td>( N_1 = 33 ), ( N_2 = 11 )</td>
</tr>
<tr>
<td>Wire Sizes</td>
<td>SWG21 (primary), SWG15 (secondary)</td>
</tr>
<tr>
<td>Leakage inductance ( L_{m-p} )</td>
<td>9 mH</td>
</tr>
<tr>
<td>Resistance</td>
<td>( R_p = 0.075 \Omega ), ( R_s = 4.98 m\Omega )</td>
</tr>
<tr>
<td>Loss</td>
<td>1.08W</td>
</tr>
</tbody>
</table>

Table 3.2: Transformer Design Summary

### 3.2.2 Design of Output Filter

For the output filter component, using

\[ \delta i_{L_{a-p}} = \frac{(1 - d)V_o}{L_o f_s} \] (3.10)

During forward direction of power flow \( i_o = 1A \), for \( \delta i_{L_{a-p}} = 40 \% \) of \( i_o = 0.4A \) and \( d = 0.35 \), \( L_o = 400 \mu H \). But in the reverse power flow direction \( i_o = 4.16A \) and \( L_o \) is found 100 \( \mu H \).

So an inductor of 400\( \mu H \) with current rating 4A is designed.
3.2.2.1 Inductor Design

To design inductor using area product approach

$$A_c A_w = \frac{L_o i_{p, rms}}{K_w \Delta BJ}$$

which gives $A_c A_w = 4.44cm^4$. ETD49 with $A_c = 2.11cm^2$ and $A_w = 2.69cm^2$ is chosen. Now

$$N = \frac{L_o i_p}{B_m A_c}$$

which gives $N = 38$. From Eq. 3.4 $a_w = 1.33mm^2$. Air gap $l_g$ is found by

$$l_g = \frac{\mu_o N i_p}{B_m}$$

which gives $l_g = 0.955mm$. Total loss of (copper loss and core loss) of inductor is estimated as 2.204W.

The summary of transformer design is given in Table 3.3:

<table>
<thead>
<tr>
<th>Specification</th>
<th>$i_{L_o (peak)} = 5.82A$, $i_{L_o (rms)} = 4.27A$, $L_b = 400 \mu H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Selected</td>
<td>ETD49</td>
</tr>
<tr>
<td>No. of turns</td>
<td>38</td>
</tr>
<tr>
<td>Wire Sizes</td>
<td>SWG15</td>
</tr>
<tr>
<td>Air gap in core</td>
<td>0.955mm</td>
</tr>
<tr>
<td>Resistance of inductor</td>
<td>$R_L = 21 m\Omega$</td>
</tr>
<tr>
<td>Loss</td>
<td>2.204W</td>
</tr>
</tbody>
</table>

Table 3.3: Inductor Design Summary

3.2.2.2 Selection of Capacitors

Output capacitor $[6]$ is selected for 1 % voltage ripple in $V_o$

$$C_o > \frac{(1 - d)V_o}{8 L_o f_s^2 \delta V_{o-p}}$$

and

$$E_{SR C_o} < \frac{\delta V_{o-p}}{\delta i_{cap}}$$
give \( C_o > 2 \mu F \) and \( E_{SRC_0} < 0.12 \Omega \). A capacitor of 1000 \( \mu F \) with 0.1 \( \Omega \) is chosen. Similarly for the reverse direction of power flow input capacitor is selected as

\[
C_i > \frac{i_i(1 - d)}{\delta V_i f_s}
\]

(3.16)
give \( C_i = 63 \mu F \) and \( E_{SR_{C_0}} < 0.85 \Omega \). A capacitor of 100 \( \mu F \) with 0.75 \( \Omega \) is chosen.

### 3.2.3 Selection of Power Device

Primary switches \( S_1 \) and \( S_2 \) need to have blocking voltage capability of more than \( V_i \) and \( i_{rms} \) rating more than \( i_{s1_{rms}} (max) \), clamp diodes \( D_{C1} \) and \( D_{C2} \) need to have blocking voltage of more than \( V_i \) and \( i_{rms} \) rating more than maximum rms of magnetizing current. Secondary switches \( S_3 \) and \( S_4 \) need to have blocking voltage of more than \( \frac{V_i}{n} \) and \( i_{rms} \) rating more than \( i_{L_{rms}} \sqrt{1 - d} \) for \( S_3 \) and \( i_{L_{rms}} \sqrt{d} \) for \( S_4 \).

Table 3.4 lists the selected devices for Bidirectional DSFC along with their voltage and current rating. Total loss in the switch is found as 10.691W

<table>
<thead>
<tr>
<th>Device</th>
<th>Selected Device</th>
<th>Blocking Voltage Rating</th>
<th>Current Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Switches ( S_1, S_2 )</td>
<td>IRF840</td>
<td>500V</td>
<td>8A</td>
</tr>
<tr>
<td>Clamp Diode</td>
<td>MUR460</td>
<td>600V</td>
<td>4A</td>
</tr>
<tr>
<td>Secondary Switches ( S_3, S_4 )</td>
<td>IRF3710</td>
<td>100V</td>
<td>43A</td>
</tr>
</tbody>
</table>

Table 3.4: Device Voltage and Current Rating

Total loss in DSFC at rated power 100W and 200V input voltage = 12.346W. Therefore, expected efficiency \( \eta = 92 \% \).

### 3.2.4 Design of Snubber

Snubber is used to reduce the loss in switch in primary side and to remove the spike voltage in the secondary side. MUR160 is used as snubber diode which has a voltage rating of 600V and current rating of 1A. Snubber capacitor and resistor is selected as

\[
C_{snub} = \frac{i_{s_{max}} f}{2V_o}
\]  

(3.17)

\[
R_{snub} = \frac{t_{on_{min}}}{5C_{snub}}
\]  

(3.18)
which gives $C_{snub} = 200\,\text{pF}$ and $R_{snub} = 100\,\Omega$ in primary side and $C_{snub} = 2\,\text{nF}$ and $R_{snub} = 10\,\Omega$ in secondary side. Figure 3.3 shows the RCD snubber circuit.

### 3.2.5 Gate Drive Circuit

The existing gate drive card is used without modification. It consist of an optocoupler IC HCPL3101 to isolate the control circuit from power circuit and MIC44258 driver IC for driving MOSFET. The driver is powered through a flyback converter for isolation.

### 3.3 Controller Platform

The controller is implemented digitally by using dsPIC30F2023. The existing board is used without modification. The schematic is given in Appendix A.1.

### 3.4 Current and Voltage Sensing Circuit

To perform the controller action, all the voltages and currents should be converted into the processor’s voltage range, for dsPIC30F2023 this being 5V. The existing voltage and current sensors are used with gain modification. The output of these cards are fed to the ADC pins of the dsPIC30F2023 through an anti-aliasing filter circuit with a cut off frequency less than 1kHz.
3.5 Conclusion

The bidirectional double switch forward converter was designed and built for 100W power level. Snubber circuit was designed to reduce the voltage stress across the secondary switch. For the implementation of PWM signal and controller dsPIC30F2023 was used.
Chapter 4

Controller Design

This chapter discusses the design of current and voltage controllers for the power circuit, their transformation to the z-domain and finally digital implementation of these controllers in dsPIC30F2023 microcontroller through C programming.

4.1 Closed Loop Control

The closed loop control is done to prevent variations in the output voltage or output current, due to any disturbances, by introducing a control variable in the form of duty ratio. This control variable $d$, is used to turn on the active devices in the switching circuits for a duration corresponding to its value. Closed loop control varies the duty ratio, in case of any deviation in output parameter, from its present steady state value to a new steady state value and thereby correcting the variation in the output.

4.1.1 Control Objective

The main objective of closed loop controller are the following

1. **Steady state accuracy**: The steady state error should be less than 1%. For that DC gain of the system is set to be very high.

2. **Settling time in response to disturbance**: Any disturbance in the input affect the output of system. The time to respond to this variation should be small. ie is bandwidth is to be set as high.
For the above objectives, controller for inner current loop is designed first at a high bandwidth and then controller for outer voltage loop is designed by assuming gain of inner current loop is unity [7]. Bandwidth of outer voltage loop is kept at one-tenth of inner current controller bandwidth. The outer voltage loop sets the inner current reference.

The block diagram of closed loop control is shown in Figure 4.1 and Figure 4.2.

4.2 Forward Direction Control with Resistive Load

The power converter was first tested with a resistive load, before charging the battery. The control involved both current control and voltage control. The bandwidth of the both control is kept high, but less than switching frequency. In the following section, the control transfer function, the controller equations, open loop bode plot and their implementation in z-domain is discussed. Controller transfer function is obtained using small signal model.

4.2.1 Current Control

The small signal transfer function of current to control is given by
Chapter 4. Controller Design

\[ \hat{g}(s) = \frac{\hat{i}_i(s)}{d(s)} = \frac{V_i}{nR} \frac{(1 + sC_oR)}{(1 + sL + s^2LC_o)} \]  

(4.1)

The bode plot of this transfer function with the experimental values of \( V_i = 200 \) V, \( n = 3 \), \( R = 24 \) Ω, \( C_o = 1000 \) μF, \( L = 300 \) μ is shown in Figure 4.3 and

\[ \hat{g}(s) = \frac{\hat{i}_i(s)}{d(s)} = 2.78 \frac{(1 + \frac{s}{41.67})}{(1 + \frac{s}{60000} + \frac{s^2}{2500000})} \]

PI controller is designed for a bandwidth of 10000 rad/sec. The transfer function of the PI controller used is

\[ \hat{h}(s) = \frac{1 + \frac{s}{1580}}{\frac{s}{100}} \]  

(4.2)

The bode plot of the loop gain \( GH \) is given in Figure 4.4. The digital implementation of the above PI controller is done using bilinear transformation. The controller implemented with a sampling frequency of 10kHz is

\[ k_p[n] = 0.0625 * error[n] \]  

(4.3)

\[ k_i[n] = k_i[n - 1] + 0.005 * error[n] + 0.005 * error[n - 1] \]  

(4.4)

\[ d[n] = k_p[n] + k_i[n] \]  

(4.5)

4.2.2 Voltage Control

The small signal transfer function of voltage to current is given by

\[ \hat{g}(s) = \frac{\hat{v}_o(s)}{\hat{i}_i(s)} = \frac{R}{1 + sRC_o} \]  

(4.6)

\[ \hat{g}(s) = \frac{\hat{v}_o(s)}{\hat{i}_i(s)} = \frac{24}{1 + \frac{s}{41.67}} \]

The bode plot of this transfer function with the experimental values is shown in Figure 4.5. The transfer function of the controller used is

\[ \hat{h}(s) = \frac{1 + \frac{s}{41.67}}{\frac{s}{50}} \]  

(4.7)
Chapter 4. Controller Design

Figure 4.3: Current to Duty Ratio Transfer Function $\frac{i_l(s)}{d(s)}$

Figure 4.4: Current Control Loop Gain Transfer Function
Figure 4.5: Voltage to Current Transfer Function $\frac{\hat{v}_o(s)}{\hat{i}_l(s)}$

Figure 4.6: Voltage Control Loop Gain Transfer Function
Chapter 4. Controller Design

The bode plot of the loop gain GH is given in Figure 4.6. The above controller in digital domain is

\[ k_p[n] = 1.2 \times \text{error}[n] \]  
\[ (4.8) \]

\[ k_i[n] = k_i[n - 1] + 0.0025 \times \text{error}[n] + 0.0025 \times \text{error}[n - 1] \]  
\[ (4.9) \]

\[ i_{\text{ref}}[n] = k_p[n] + k_i[n] \]  
\[ (4.10) \]

4.3 Reverse Direction Control

4.3.1 Current Control

The small signal transfer function of current to control is given by

\[ \hat{g}(s) = \hat{i}(s) = \frac{n^2V_i}{R(1 - D)^3 \left(1 + s \tau C_i R + s^2 \frac{n^2}{(1 - D)^2} \right)} \]  
\[ (4.11) \]

The bode plot of this transfer function with the experimental values of \( V_i = 24 \text{ V}, n = 3, R = 400 \Omega, C_i = 100 \mu\text{F}, L = 300 \mu\text{ is shown in Figure 4.7 and} \]

\[ \hat{g}(s) = \frac{\hat{i}_i(s)}{\hat{d}(s)} = 12.6 \frac{(2 + \frac{s}{25})}{(1 + \frac{s}{13611} + \frac{s^2}{340278})} \]

PI controller is designed for a bandwidth of 10000 rad/sec. The transfer function of the PI controller used is

\[ \hat{h}(s) = \frac{1 + \frac{s}{50}}{50} \]  
\[ (4.12) \]

The bode plot of the loop gain GH is given in Figure 4.4. The above controller in digital domain is

\[ k_p[n] = 0.0833 \times \text{error}[n] \]  
\[ (4.13) \]

\[ k_i[n] = k_i[n - 1] + 0.0025 \times \text{error}[n] + 0.0025 \times \text{error}[n - 1] \]  
\[ (4.14) \]

\[ d[n] = k_p[n] + k_i[n] \]  
\[ (4.15) \]
Chapter 4. Controller Design

Figure 4.7: Current to Duty Ratio Transfer Function $\frac{\hat{i}(s)}{d(s)}$

Figure 4.8: Current Control Loop Gain Transfer Function
4.3.2 Voltage Control

The small signal transfer function of voltage to current is given by

\[
\hat{g}(s) = \frac{\hat{v}_o(s)}{\hat{i}_l(s)} = \frac{nR(1 - D)}{1 + sC_iR}
\]  
(4.16)

\[
\hat{g}(s) = \frac{\hat{v}_o(s)}{\hat{i}_l(s)} = \frac{46.67}{1 + \frac{s}{25}}
\]

The bode plot of this transfer function with the experimental values is shown in Figure 4.9. The transfer function of the controller used is

\[
\hat{h}(s) = \frac{1 + \frac{s}{25}}{\frac{s}{25}}
\]  
(4.17)

The bode plot of the loop gain GH is given in Figure 4.10. The above controller in digital domain is

\[
k_p[n] = 1 \ast \text{error}[n]
\]  
(4.18)

\[
k_i[n] = k_i[n - 1] + 0.00125 \ast \text{error}[n] + 0.00125 \ast \text{error}[n - 1]
\]  
(4.19)

\[
i_{ref}[n] = k_p[n] + k_i[n]
\]  
(4.20)
Figure 4.9: Voltage to Current Transfer Function $\hat{v}(s) / \hat{i}(s)$

Figure 4.10: Voltage Control Loop Gain Transfer Function
4.4 Implementation of PI Control in Digital Domain

The digital implementation of PI control is shown in Figure 4.11. A limiter is included in the output of PI controller.

![Digital Implementation of PI Controller](image)

Figure 4.11: Digital Implementation of PI Controller

4.5 Conclusion

The bidirectional double switch forward converter was modelled using small signal analysis for different mode of operation. Current controller and voltage controller were designed to achieve control objectives. PI controller was implemented in digital domain.
Chapter 5

Simulation and Experimental Results

In this chapter, simulation and experimental results of the Bidirectional Double Switch Converter are presented. It includes open loop, closed loop current and voltage controller results for both directions of power flow.

5.1 Simulation Results

All the simulation has been done in the simulation software PSIM

5.1.1 Open Loop Results

![Waveform during Forward Power Flow Direction](image)

Figure 5.1: Waveform during Forward Power Flow Direction
Figure 5.2: Waveform during Reverse Power Flow Direction

The output voltage waveform with switching signal is shown in Figure 5.1 and Figure 5.2 for forward and reverse power flow direction respectively.

5.1.2 Closed Loop Results

Figure 5.3: Step Response of Controller during Forward Power Flow Direction

Figure 5.3 and Figure 5.4 shows the response of current and voltage controllers for a step change in corresponding references in forward and reverse direction respectively.
5.2 Experimental Results

5.2.1 Open Loop Result

Figure 5.5 and Figure 5.6 show the experimental waveform of output voltage and gate signal in the forward power flow direction and reverse power flow direction respectively in open loop.
5.2.2 Closed Loop Results

Figure 5.7: Step Change in Current during Forward Power Flow Direction

Figure 5.7 shows the response of current controller mode to a step change of current reference from 0.5A to 1A in forward direction of power flow with resistive load.
Figure 5.8: Step Change in Voltage during Forward Power Flow Direction

Figure 5.8 shows the response of voltage controller mode to a step change of voltage reference from 20V to 24V in forward direction of power flow with resistive load.

Figure 5.9: Current controller during Reverse Power Flow Direction

Figure 5.9 shows the response of current controller mode to a current reference of 4A in reverse direction of power flow with resistive load.
5.2.3 Efficiency of Converter

Table 5.1 and Table 5.2 show the efficiency of the double switch bidirectional forward converter during forward and reverse direction of power flow at different power level.

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>96.25</td>
</tr>
<tr>
<td>50</td>
<td>92.92</td>
</tr>
<tr>
<td>75</td>
<td>89.56</td>
</tr>
<tr>
<td>100</td>
<td>86.95</td>
</tr>
</tbody>
</table>

Table 5.1: Efficiency During Forward Power Flow at Different Power Level

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>91.83</td>
</tr>
<tr>
<td>75</td>
<td>88.41</td>
</tr>
<tr>
<td>100</td>
<td>86.72</td>
</tr>
</tbody>
</table>

Table 5.2: Efficiency During Reverse Power Flow at Different Power Level

5.3 Conclusion

The bidirectional double switch forward converter is tested in PSIM simulation software and experimentally. Both the results were found to be matching.
Chapter 6

Conclusions

The project was aimed at developing the hardware for Isolated Bidirectional DC-DC converter and close loop control for battery charging and discharging. The hardware built for the project consists of:

1. Power circuit board.

2. The magnetic components - inductors and transformer

First the bidirectional double switch forward converter was designed and validated in simulation software PSIM. By using the bidirectional switch and appropriate switching the power flow in the bidirectional double switch forward converter can be controlled. The direction of power flow is decided by current flow direction. The controller is designed for controlling both current and voltage and experimentally validated for forward direction of power flow.
Appendix A

A.1 Controller Platform

Figure A.1: dsPIC30F2023 Schematic Diagram
A.2 Schematic of Power Circuit

Figure A.2: Power Circuit Board Schematic Diagram - Primary Side

Figure A.3: Power Circuit Board Schematic Diagram - Secondary Side
References


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