CHAPTER 5

DESIGN, MODELLING AND IMPLEMENTATION
OF INTERLEAVED BOOST CONVERTER WITH
OBSERVER CONTROLLER

5.1 OVERVIEW

This chapter discusses in detail about the design and modelling of the Interleaved Boost converter with the Observer controller. The derivation of the state feedback gain matrix using pole placement method and Linear quadratic optimal regulator method are explained. The derivation of the full order state observer and the observer controller are also explained in detail. The simulation results are presented and discussed. The first section explains the design and state space modelling of the Interleaved Boost converter.

5.2 DESIGN AND MODELLING OF INTERLEAVED BOOST CONVERTER

The Interleaved Boost converter consists of two single Boost converters connected in parallel. The schematic diagram of Interleaved Boost Converter is shown in Figure 5.1.

![Figure 5.1 Schematic diagram of interleaved Boost converter](image-url)
Here $V_s$ is the input voltage, $L_1$ and $L_2$ are the magnetizing inductances, $S_1$ and $S_2$ are semiconductor switches, $D_1$ and $D_2$ are diodes, $C$ is an output capacitor and $R$ is a load resistance respectively. The design involves the selection of inductors and output capacitor. In interleaved design both the inductors must be identical. In particular, the design assumes the room temperature operation over the entire input voltage without the air flow requirement. Major design of the converter involves the selection of inductor which is discussed now.

Inductor value can be calculated by assuming peak to peak inductor ripple to a certain percentage of about 20% of the output current corresponding to the individual phase. The average inductor current is determined as,

$$I_L(\text{avg}) = \frac{0.5 \times I_{\text{out}}}{1 - D_{\text{max}}} \tag{5.1}$$

where $I_{\text{out}}$ is the load current and $D_{\text{max}}$ is the maximum duty cycle ratio and it is defined as,

$$D_{\text{max}} = \frac{V_{\text{out}} + V_d - V_{\text{on}}}{V_{\text{out}} + V_d - V_{\\text{in}}} \tag{5.2}$$

where $V_{\text{out}}$ is the output voltage, $V_d$ is the forward diode voltage drop, $V_{\text{on}}$ is the on stage voltage of the MOSFET and $V_{\\text{in}}$ is the minimum input voltage.

Assuming peak inductor ripple current per phase ($\Delta I_L$) as 20% of the average inductor current, the peak inductor current is determined as follows,

$$I_{\text{peak}} = I_L(\text{avg}) + \frac{\Delta I_L}{2} \tag{5.3}$$
Assuming appropriate switching frequency, the inductor value is selected using the following equation,

\[
L = \frac{(V_{\text{in(min)}} - V_{\text{on}}) \cdot D_{\text{max}} \cdot (1 - D_{\text{max}})}{f_s \cdot I_{\text{out}}}
\]  

(5.4)

Knowing the minimum load current, \( L \) value can be designed which gives the critical value to maintain the converter in continuous mode of operation.

By assuming appropriate peak to peak capacitor ripple, the output capacitor value can be obtained using the following equation,

\[
\Delta V_{\text{out}} = \frac{I_{\text{out(max)}} \cdot (1 - D_{\text{min}})}{f_s \cdot C_{\text{out}}}
\]  

(5.5)

where \( D_{\text{min}} \) is the minimum duty cycle defined as,

\[
D_{\text{min}} = \frac{V_{\text{out}} + V_{\text{d}} - V_{\text{in(min)}}}{V_{\text{out}} + V_{\text{d}} - V_{\text{on}}}
\]  

(5.6)

Based on the above discussion the parameters designed for Interleaved Boost Converter is shown in Table 5.1.

**Table 5.1 Design values of interleaved Boost converter**

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Parameters</th>
<th>Design Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input Voltage</td>
<td>24 V</td>
</tr>
<tr>
<td>2</td>
<td>Output Voltage</td>
<td>50 V</td>
</tr>
<tr>
<td>3</td>
<td>Inductance, ( L_1=L_2 )</td>
<td>72 ( \mu )H</td>
</tr>
<tr>
<td>4</td>
<td>Capacitance, ( C )</td>
<td>216.9X10(^{-6}) F</td>
</tr>
<tr>
<td>5</td>
<td>Load Resistance, ( R )</td>
<td>23 ( \Omega )</td>
</tr>
<tr>
<td>6</td>
<td>Switching frequency, ( f_s )</td>
<td>20 kHz</td>
</tr>
</tbody>
</table>
The design details of Interleaved Buck converter are explained above and using the designed values the open loop response of the Interleaved Buck converter is obtained and shown in the Figure 5.2, where the peak overshoot and steady error are found to be maximum. The voltage ripples are also observed which requires the design of closed loop control.

![Figure 5.2](image)

**Figure 5.2  Open loop response of interleaved Boost converter**

Now the state space modeling of the Interleaved Boost converter is discussed in detail as follows.

The state variables are assumed as inductor currents \(i_{L1}\) and \(i_{L2}\) and the capacitor voltage \(V_o\). This converter comprises of four modes of operation similar to the case of Interleaved Buck Converter. The state equations are derived as follows:

During mode 1 both the switches \(S_1\) and \(S_2\) are on and the diodes \(D_1\) and \(D_2\) are in the off condition. The equivalent circuit for this mode is shown in Figure 5.3.
Applying Kirchoff's laws to the above circuit, the equations describing this converter for mode 1 can be obtained as follows,

\[
\frac{di_{u1}}{dt} = \frac{V_S}{L_1} \quad (5.7)
\]

\[
\frac{di_{u2}}{dt} = \frac{V_S}{L_2} \quad (5.8)
\]

\[
\frac{dV_Q}{dt} = -\frac{V_Q}{RC} \quad (5.9)
\]

The coefficient matrices for this mode can be written as,

\[
A_1 = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -\frac{1}{RC}
\end{bmatrix} \quad (5.10)
\]

and

\[
B_1 = \begin{bmatrix}
\frac{1}{L_1} \\
\frac{1}{L_2} \\
0
\end{bmatrix} \quad (5.11)
\]
During mode 2, the switch $S_1$ is in on condition and switch $S_2$ is in off condition and the corresponding diodes are in the complementary switching states, (i.e.) $D_1$ is in off condition and $D_2$ is in on condition respectively. The equivalent circuit for this mode is shown in Figure 5.4.

![Equivalent circuit of interleaved Boost converter for mode 2](image)

**Figure 5.4 Equivalent circuit of interleaved Boost converter for mode 2**

Applying Kirchoff’s laws to the above circuit, the equations describing this converter for mode 2 can be obtained as follows,

\[
\frac{di_{L1}}{dt} = \frac{V_S}{L_1} \tag{5.12}
\]

\[
\frac{di_{L2}}{dt} = \frac{V_S}{L_2} - \frac{V_O}{L_2} \tag{5.13}
\]

\[
\frac{dV_O}{dt} = \frac{i_{L2}}{C} - \frac{V_O}{RC} \tag{5.14}
\]

The coefficient matrices for this mode can be written as,

\[
A_2 = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & \frac{1}{L_2} \\
0 & \frac{1}{C} & \frac{1}{RC}
\end{bmatrix} \tag{5.15}
\]
and

\[
B_2 = \begin{bmatrix}
1 \\
-\frac{1}{L_1} \\
\frac{1}{L_2} \\
0
\end{bmatrix}
\]  \hspace{1cm} (5.16)

In mode 3, the switch \( S_1 \) is in off condition and the switch \( S_2 \) is in on condition and the corresponding diodes such as \( D_1 \) and \( D_2 \) are in on and off conditions respectively. The equivalent circuit for this mode is shown in Figure 5.5.

![Figure 5.5 Equivalent circuit of interleaved Boost converter for mode 3](image)

Applying Kirchoff's laws to the above circuit, the equations describing this converter for mode 3 can be obtained as follows,

\[
\frac{di_{L1}}{dt} = \frac{V_S}{L_1} - \frac{V_O}{L_1} \tag{5.17}
\]

\[
\frac{di_{L2}}{dt} = \frac{V_S}{L_2} \tag{5.18}
\]

\[
\frac{dV_O}{dt} = \frac{i_{L1}}{C} - \frac{V_O}{RC} \tag{5.19}
\]
The coefficient matrices for this mode can be written as,

\[
A_3 = \begin{bmatrix}
0 & 0 & -\frac{1}{L_1} \\
0 & 0 & 0 \\
\frac{1}{C} & 0 & -\frac{1}{RC}
\end{bmatrix}
\] (5.20)

and

\[
B_3 = \begin{bmatrix}
\frac{1}{L_1} \\
\frac{1}{L_2} \\
0
\end{bmatrix}
\] (5.21)

During mode 4 the semiconductor switches \( S1 \) and \( S_2 \) are in off condition and the diodes \( D_1 \) and \( D_2 \) are in on condition, and the corresponding equivalent circuit for this mode is shown in Figure 5.6.

![Figure 5.6 Equivalent circuit of interleaved Boost converter for mode 4](image)

Applying Kirchoff’s laws to the above circuit, the equations describing this converter for mode 4 can be obtained as follows,

\[
\frac{di_{L1}}{dt} = \frac{V_S}{L_1} - \frac{V_0}{L_1} \] (5.22)

\[
\frac{di_{L2}}{dt} = \frac{V_S}{L_2} - \frac{V_0}{L_2} \] (5.23)
The coefficient matrices for this mode can be written as,

\[
A_4 = \begin{bmatrix}
0 & 0 & \frac{-1}{L_1} \\
0 & 0 & \frac{-1}{L_2} \\
\frac{1}{c} & \frac{1}{c} & \frac{-1}{RC}
\end{bmatrix}
\]  

(5.25)

and

\[
B_4 = \begin{bmatrix}
\frac{1}{L_1} \\
\frac{1}{L_2} \\
0
\end{bmatrix}
\]

(5.26)

The coefficient matrix for the interleaved converter is defined as,

\[
[A] = A_1d_1 + A_2d_2 + A_3d_3 + A_4d_4 \quad \text{and} \quad [B] = B_1d_1 + B_2d_2 + B_3d_3 + B_4d_4, \quad [U] = V_s \quad \text{and the duty cycle ratio is given by} \quad d_1 + d_2 + d_3 + d_4 = 1. \quad \text{The output equation is defined as follows},
\]

\[
y(t) = [0 \quad 0 \quad 1] \begin{bmatrix} i_{L_1} \\ i_{L_2} \\ V_o \end{bmatrix}
\]

(5.27)

By substituting the values of \( L \) and \( C \) thus designed, the state coefficient matrices for the Interleaved Boost converter is obtained as follows:

\[
A = \begin{bmatrix}
0 & 0 & -13.88859 \times 10^3 \\
0 & 0 & -13.88859 \times 10^3 \\
4.60878 \times 10^3 & 4.60878 \times 10^3 & -400.7638
\end{bmatrix}
\]

(5.28)
Thus the design and the state space modelling of the Interleaved Boost converter is explained above section and the detailed discussion about the derivation of the Observer controller for this converter is explained in the following section. Similar to the Interleaved Buck converter, the state feedback matrix for this converter is also derived using both the pole placement method and Linear Quadratic optimal regulator method. Finally the above matrix derived using both the methods are combined together with the observer gain matrix using Separation principle to obtain two different transfer functions which are explained in detail in the following sections.

5.3 DERIVATION OF STATE FEEDBACK MATRIX FOR INTERLEAVED BOOST CONVERTER

5.3.1 Pole Placement Method

In this section the state feedback matrix for the Interleaved Boost converter using pole placement method is derived. The procedure for the design is same as that used for the other converters which have already been explained in the previous chapters. The root locus of the Interleaved Boost converter is drawn as shown in the Figure 5.7. The desired poles are arbitrarily placed in order to obtain the state feedback matrix.
Figure 5.7 Root locus of interleaved Boost converter

The state feedback matrix can be obtained by substitution method and is explained as follows:

**Step 1:** The characteristic polynomial to find the unknown values of state feedback matrices, $[k_1 \ k_2 \ k_3]$ is formed as follows,

$$|sI - (A - Bk)| = s^3 + (222.22 \times 10^6 k_1 + 222.22 \times 10^6 k_2 \cdot 400.76)s^2 + (11.1319 \times 10^6 k_1 + 11.1319 \times 10^6 k_2 + 255.992 \times 10^6 k_3 + 127.9918 \times 10^6)s + 3.09211 \times 10^{11} k_1 k_2 = 0$$ (5.31)

**Step 2:** The desired characteristic equation is formed by arbitrarily placing the poles as follows,

$$s^3 + 28.17 \times 10^3 s^2 + 121.9723 \times 10^6 s + 7.7303 \times 10^{10} = 0$$ (5.32)
By equating the like powers of $s$ in the Equations (5.31) and (5.32), the state feedback matrices are obtained as $k_1 = 0.5$, $k_2 = 0.5$ and $k_3 = -0.067$.

In order to check the robustness of the control law, the step input is used and the output response has been demonstrated in the Figure 5.8. It is very well understood that the system settles down faster and the state feedback matrix is efficient enough to realize the stability of the Interleaved Boost converter.

![Step Response](image)

**Figure 5.8  Step response of interleaved Boost converter**

### 5.3.2 Linear Quadratic Optimal Regulator Method

Linear quadratic optimal regulator method which has been already discussed in the chapter 4 is applied for the Interleaved Boost converter and corresponding matrices are obtained as follows,

The positive definite matrices $Q$ and $R$ for this converter are determined as,
\[ Q = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \] (5.33)

\[ R = [2] \] (5.34)

and

\[ P = \begin{bmatrix} 2.2683 \times 10^3 & 2.2683 \times 10^3 & 0 \\ -2.2683 \times 10^3 & 2.2683 \times 10^3 & 0 \\ 0 & 0 & 0 \end{bmatrix} \] (5.35)

The \( k \) values are obtained for this converter by substituting the above matrices in Equation (4.48). The value of the state feedback matrix is obtained as, \( k = [0.5365 \quad 0.4498 \quad -0.0410] \). Thus the state feedback matrix for the Interleaved Boost converter is derived by using both the methods. Now, the derivation of the Observer controller is explained in the following section.

5.4 DERIVATION OF OBSERVER GAIN MATRIX FOR INTERLEAVED BOOST CONVERTER

The derivation of full order state observer gain matrix has already been explained in the second chapter. Now, for the Interleaved Boost converter this matrix can be derived by the substitution method by assuming appropriate natural frequency of oscillation and damping ratio as per the thumb rule. By assuming the damping ratio, \( \zeta = 0.5 \) and the natural frequency of oscillation, \( \omega_n = 195.959 \times 10^3 \) rad/sec, the desired characteristic equation can be obtained as follows,

\[ \lambda^3 + (400.764 + g_3)\lambda^2 + (4.6088 \times 10^3 g_1 + 4.60878 \times 10^6 g_2 + 128.0189 \times 10^6)\lambda = 0 \] (5.36)
The polynomial equation with unknown values of observer poles is given by,

$$\lambda^3 + 1.7575 \times 10^6 \lambda^2 + 2.304 \times 10^{11} \lambda + 3.7624 \times 10^{16} = 0$$

(5.37)

Comparing the Equations (5.36) and (5.37), the observer gain matrix is obtained. The values are $$g_1 = g_2 = 24.9819 \times 10^6$$ and $$g_3 = 1.1754 \times 10^6$$.

By combining this observer gain matrix and the state feedback matrix which is already derived using both the pole placement and Linear quadratic optimal regulator methods, the transfer function for the Observer controller can be determined as follows.

The Observer transfer function can be obtained by substituting the appropriate values in the Equation (2.76) using the pole placement method as follows,

$$\mathcal{T}(s) = \frac{2.496 \times 10^7 s^2 - 2.174 \times 10^{10}s + 632}{s^3 + 1.204 \times 10^6 s^2 + 2.63 \times 10^{11}s - 6657}$$

(5.38)

Similarly the Observer transfer function can be obtained using the linear quadratic optimal regulator method by substituting the necessary values in the Equation (2.76) and is given by,

$$\mathcal{T}(s) = \frac{2.459 \times 10^7 s^2 - 1.567 \times 10^{10}s + 2556}{s^3 + 1.203 \times 10^6 s^2 + 2.626 \times 10^{11}s + 265}$$

(5.39)

Thus the Observer Controller for the Interleaved Boost converter is derived by using pole placement method and Linear quadratic optimal regulator method in this section. Extensive simulation has been carried out and is presented in the following section.
5.5 RESULTS AND DISCUSSION

This section clearly discusses the simulation results obtained for the Interleaved Boost converter with the Observer controller obtained using both pole placement method and Linear quadratic optimal regulator method. The results thus obtained for both the methods are shown compared against each other. The converter specifications under consideration are rise time, settling time, maximum peak overshoot and steady state error which are shown in Table 5.2. The system settles down fast at about 0.15 s and 0.005 s for the pole placement and Linear quadratic optimal regulator methods respectively. The steady state error, peak overshoots and output voltage ripples are not evident in both the methods. The results thus obtained are in concurrence with the mathematical calculations. The simulation is also carried out by varying the load not limiting to $R$ load and it is illustrated in Table 5.3. The simulation is also carried out by varying the input voltage and the corresponding output voltage, inductor currents and load currents are shown in Figures 5.9 and 5.10 for pole placement method and linear quadratic optimal regulator method respectively.

The input voltage is changed as $\pm 2$ V with respect to the input 24 V DC supply. From time 0 s to 0.2 s input voltage is maintained at 24 V and at 0.2 s it has been changed to 22 V and the input voltage remains at 22 V till 0.3 s. Further the voltage is changed to 24 V and 26 V at 0.3 s and 0.4 s respectively. Simultaneously the load resistances are also changed as 28 $\Omega$, 23 $\Omega$ and 18 $\Omega$ respectively. Inspite of such variations, the controller is robust and efficient enough to track the reference of 60 V. The overshoots and undershoots are seen which is very minimum of the order of 2%. The inductors $L_1$ and $L_2$ have good current sharing among them. The current shows very much reduced ripples.
Table 5.2 Comparison of the performance parameters of interleaved Boost converter

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Controller</th>
<th>Settling Time (s)</th>
<th>Peak Overshoot (%)</th>
<th>Steady State Error (V)</th>
<th>Rise Time (s)</th>
<th>Output Ripple Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Observer Controller(Pole Placement method)</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>0.075</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Linear Quadratic Optimal Regulator</td>
<td>0.005</td>
<td>0</td>
<td>0</td>
<td>0.001</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.3 Output response of interleaved Boost converter for load variations

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>R (Ω)</th>
<th>L (mH)</th>
<th>E (V)</th>
<th>Reference Voltage (V)</th>
<th>Output Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>50</td>
<td>-</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>100</td>
<td>-</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>100</td>
<td>-</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>50</td>
<td>5</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>100</td>
<td>10</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>100</td>
<td>15</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>100</td>
<td>20</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>
Figure 5.9  Output response of interleaved Boost converter for Pole Placement method

\(V_s\) - input voltage, \(V_o\) - Output voltage, \(IL1\) - inductor current1, \(IL2\) - inductor current2, \(Io\) - Load current)
In order that the dynamic performance has to be ensured both methods show tight output regulation with much lesser settling time, no steady state error without any undershoots or overshoots which is evident from the Figure 5.11. In this figure the output voltage obtained for both the methods are shown compared against each other for one particular value of input voltage, 24 V. It is evident that the optimal solution for control law thus obtained shows improved results when compared with pole placement method in terms of the performance specifications as listed in Table 5.2.
Simulation has also been carried out in two modes. In mode 1 the inductances are chosen as $L_1 = L_2$ and in mode 2 inductances are chosen as $L_2 = 2L_1$. The efficiency of this converter is determined for these two modes and are tabulated in the Table 5.4. The added advantage is that the efficiency is higher even with high input to output ratios. It is very well understood that the control scheme offers a robust control and good current sharing among the converters. It is palpable that the efficiency thus obtained for both the modes are more or less same. Also the current sharing among the converters is excellent. Figure 5.12 shows the efficiency as a function of output load current and it is seen that the state feedback control method achieves higher efficiency for a wide range of load variations and the maximum efficiency achieved is 95.63% at a 176 W load condition.
Table 5.4  Performance calculations for the interleaved Boost converter

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Mode</th>
<th>Vref (V)</th>
<th>Vout (V)</th>
<th>$I_L$ (A)</th>
<th>$I_{in}$ (A)</th>
<th>$V_{in}$ (V)</th>
<th>$P_{in}$ (W)</th>
<th>$P_{out}$ (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>60</td>
<td>60</td>
<td>2.5</td>
<td>6.5360</td>
<td>24</td>
<td>156.8640</td>
<td>150</td>
<td>95.62</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>2.499</td>
<td>6.5360</td>
<td>24</td>
<td>156.8640</td>
<td>149.94</td>
<td>95.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>65</td>
<td>65</td>
<td>2.708</td>
<td>7.6700</td>
<td>24</td>
<td>184.08</td>
<td>176.024</td>
<td>95.62</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>2.708</td>
<td>7.6735</td>
<td>24</td>
<td>184.164</td>
<td>176.112</td>
<td>95.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>70</td>
<td>70</td>
<td>2.916</td>
<td>8.9034</td>
<td>24</td>
<td>213.616</td>
<td>204.115</td>
<td>95.52</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>2.916</td>
<td>8.9050</td>
<td>24</td>
<td>213.7200</td>
<td>204.129</td>
<td>95.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>I</td>
<td>75</td>
<td>75</td>
<td>3.124</td>
<td>10.23</td>
<td>24</td>
<td>245.52</td>
<td>234.83</td>
<td>95.44</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.124</td>
<td>10.229</td>
<td>24</td>
<td>245.5008</td>
<td>234.345</td>
<td>95.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>I</td>
<td>80</td>
<td>80</td>
<td>3.28</td>
<td>11.652</td>
<td>24</td>
<td>279.648</td>
<td>258.202</td>
<td>92.33</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.332</td>
<td>11.651</td>
<td>24</td>
<td>279.622</td>
<td>266.373</td>
<td>95.26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.12  Efficiency of the interleaved Boost converter
The inductor currents and corresponding duty cycle ratios are shown in the Figures 5.13 and 5.14 for mode 1 and mode 2 respectively. It is evident from the current waveforms that the controller provides an effective current sharing among the converter modules irrespective of the values of the inductances.

**Figure 5.13 Inductor currents and duty ratio for mode 1**

**Figure 5.14 Inductor currents and duty ratio for mode 2**

The Interleaved Boost converter with observer controller is efficient enough in such a way that it is capable of tracking the reference...
voltages of 50 V and 60 V inspite of the input voltage variations. The input voltage is varied as 24 V till 0.2 s and at 0.2 s it is varied as 22 V till 0.3 s. Again it is varied as 24 V, 26 V and 24 V at 0.3 s, 0.4 s and 0.5 s respectively. The reference values are varied as 50 V and 60 V and it is illustrated in the Figure 5.15. The overshoots and undershoots that are evident lie within the allowable range.

![Figure 5.15](image)

**Figure 5.15** Output response of interleaved Boost converter for variation in the reference voltage

Thus the simulation results obtained for the Interleaved Boost converter has been discussed in detail and this particular chapter is concluded as follows.

### 5.6 CONCLUSION

A state feedback control approach has been designed for the Interleaved Boost converter in continuous time domain using pole placement technique and Linear Quadratic Optimal Regulator method. The load estimator has been designed by deriving full order state observer to ensure
robust and optimal control for the converter. The Separation Principle allows designing a dynamic compensator which very much looks like a classical compensator since the design is carried out using simple root locus technique. The mathematical analysis and the simulation study show that the controller thus designed achieves good current sharing among the converters, tight output voltage regulation and good dynamic performances and higher efficiency.

In the next chapter the hardware implementation for the Buck converter has been carried out.