DESIGN, ANALYSIS AND SIMULATION OF INTERLEAVED TWO PHASE INDUCTOR COUPLED DC-DC BUCK CONVERTER

P.Pratima¹, K.P.Guruswamy²

¹ME, Power Electronics, Department of Electrical Engineering, University Visvesvaraya college of engineering, Bangalore-560001, Karnataka, India
²Associate Professor ME, Power Electronics, Department of Electrical and Electronics, University Visvesvaraya college of engineering, Bangalore-560001, Karnataka, India

Abstract

A coupled inductor is a gadget principally utilized for vitality stockpiling during a power converter exchanging cycle, and the power entering the coupled-inductor isn’t equivalent to the power leaving it in a given moment. Transformers are utilized for voltage and current scaling, for dc confinement, and to get different yields from a solitary converter. Interleaved buck converter is utilized to change over the unregulated DC contribution to a controlled DC yield at an ideal voltage level. IBC topologies have gotten expanding consideration as of late for high power applications. The advantages of interleaving incorporate high power ability, particularity and improved dependability. The accompanying favorable circumstances when contrasted with traditional buck converter are:

1. Low input current ripple
2. Low output voltage ripple
3. High efficiency
4. Reduces the size of filter components

Keyword: Coupled inductor, Multiphase converter, Non coupled converter.

1. INTRODUCTION

A coupled inductor is a gadget fundamentally utilized for vitality stockpiling during a power converter exchanging cycle, and the power entering the coupled-inductor isn’t equivalent to the power leaving it in a given moment. Transformers are utilized for voltage and current scaling, for dc confinement, and to acquire different yields from a solitary converter[1].

The coupled inductor buck Converter Operates along these lines to the conventional buck converter. The activity of the converter is decreased to two sub circuits. At the point when the switch is on and off. The high buck capacity is on the grounds that the releasing procedure of the attractive component is made with a higher inductance esteem.

The connection somewhere in the range of L1 and L2 is controlled by the turns proportion of the attractive component that is:

L1/L2 = [N2/N1]^2

The inductance is Proportional to the turn square of the inductor.

L1 = k(N1)^2

At that point comparable inductance of L1 and L2 is:

Leq = k(N1 + N2/2)

Taking into account that N2 = NN1, and utilizing (2) and (3):

Leq = ((N+1)/N)^2 L2

Fig.1. Single phase Buck converter with coupled inductor
From fig1 single stage Buck converter with coupled inductor creates more yield wave contrast with multiphase dc-dc converters. The interleaved buck converter is only Multi staging. The primary favorable position of interleaved parallel associated changes over expands the power handling capacity and to improve the unwavering quality of the power electronic framework. What’s more, multiphase parallel associations of intensity converters diminish support, increment dependability and adaptation to non-critical failure.

2. TWO STAGE NON COUPLED INDUCTOR

From the waveform $T_1 = D \cdot \frac{\Delta I_L}{V_O}$ is changing time of the converter

3. TWO STAGE COUPLED INDUCTOR

The expanded inductor current wave diminishes the converter proficiency. To accomplish both inductor current wave and yield current wave the two inductors ought to be coupled somehow or another. From a study the yield current wave and inductor current wave will be relies upon the benefit of coupling coefficient ($k$). The estimation of coupling coefficient increments so as to get an ideal exhibition of the coupled inductor and the power converter.
The figure 4 shows Two stage interleaved buck converter with coupled inductor. The Ideal transformer is utilized.

\[ i_{Lm} = i_{L1} - i_{L2} \]

There are 4 modes in buck converter with coupled inductor. The accompanying articulation is gotten from the circuit outline.

\[ V_{L1} = V_{Lk1} + V_{Lm} \]
\[ V_{L2} = V_{Lk2} - V_{Lm} \]
\[ V_{Lm} = L_m \frac{d}{dt}(i_{L1} - i_{L2}) \]

The methods of activity of Two stage buck converter with coupled inductor as pursues.

### 3.1. Mode 1 \([0 – DTs]\)

In Mode 1 the switch S1 and S4 are turned on. The voltage over the inductor and current over the inductor as pursues

\[ V_{L1} = V_{in} - V_o \]
\[ V_{L2} = -V_o \]

From above equations the leakage voltages across the inductors \(V_{Lk1}\) and \(V_{Lk2}\) are expressed as

\[ V_{Lk1} = L_{k1} \frac{di_{L1}}{dt} = V_{L1} - V_{Lm} = (V_{in} - V_o) - V_{Lm} \]
\[ V_{Lk2} = L_{k2} \frac{di_{L2}}{dt} = V_{L2} + V_{Lm} = (-V_o) + V_{Lm} \]

\( L_{k1} = L_{k2} = L_k \), and substitute in the above equation then the equation for magnetizing inductance is

\[ V_{Lm} = \frac{L_m}{L_{Lk} + L_{Lm}} V_{in} \]

All in all coupled inductor hypothesis the spillage inductors and Magnetizing inductor \(L_k\) and \(L_m\) are communicated as pursues

\[ L_k = (1-k)L_s \]
\[ L_m = kL_s \]

Where \(L_s\) and \(k\) speak to self inductance and the coupling coefficient of the coupled inductor, individually.

Substituting spillage inductor and charging inductor in condition of

\[ V_{Lm} = \frac{k}{1+k} V_{in} \]

Substituting \(V_{Lm}\) in Inductor current conditions and utilizing the connection \(V_o = D V_{in}\), the inductor flows in mode 1 will be communicated as.

\[ \frac{di_{L1}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{1-D-Dk}{1+k}D\right] \]
\[ \frac{di_{L2}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{k-D-Dk}{1+k}D\right] \]

\(k\) speaks to the coupling coefficient and the estimation of \(k\) ought to be under 1. In the buck converter the obligation proportion ought to be under half. So the estimation of inductor current of \(L1\) is more prominent than inductor current of \(L2\).

The yield inductor current is aggregate of two inductor current and is communicated as

\[ \frac{di_{Lo}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{1-2D}{0.5-D}\right] \]

### 3.2. Mode 2 \([DTs - Ts/2]\)

In mode 2 \(V_{L1} = V_{L2} = -V_o\), along these lines

\(VLk1 = Lk1 \) \[ \frac{di_{L1}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{1-D-Dk}{1+k}D\right] \]
\(VLk2 = Lk2 \) \[ \frac{di_{L2}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{k-D-Dk}{1+k}D\right] \]

Substitute spillage inductor voltages in \(VL1\) and \(VL2\) and the polarizing voltage \(V_{Lm}\) is equivalent to zero, so the inductor flows are communicated as pursues

\[ \frac{di_{L1}}{dt} = \frac{V_o}{L_{Lk}} \]
\[ \frac{di_{L2}}{dt} = -V_o/L_{Lk} \]

The yield inductor current is communicated as pursues

\[ \frac{di_{Lo}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{1-2D}{0.5-D}\right] \]

### 3.3. Mode 3 \([Ts/2 – (Ts/2+DTs)]\)

In the Mode 3 The main distinction is that \(V_{L1} = -V_o\) and \(V_{L2} = V_{in} - V_o\) rest all equivalent as mode 1. The inductor and yield current is communicated as pursues.

\[ \frac{di_{L1}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{k-D-Dk}{1+k}D\right] \]
\[ \frac{di_{L2}}{dt} = \frac{V_o}{L_{Lk}} \left[\frac{1-D-Dk}{1+k}D\right] \]

\(k\) speaks to the coupling coefficient and the estimation of \(k\) ought to be under 1. In the buck converter the obligation proportion ought to be under half. So the estimation of inductor current of \(L2\) is more prominent than inductor current of \(L1\).

### 3.4. Mode 4 \([Ts/2 + DTs) ~ Ts]\)

The Mode 4 is same as mode 2. Voltage over the inductors are same.
In the mode 1 the dt is equivalent to the DTs the inductor current and yield current is communicated as
\[ \Delta i_L = V_o/L_{lk} [(1-D-kD)/((1+k))]TS \]
\[ \Delta i_{Lo} = V_o/L_{lk} [1-2DT]TS \]

4. ENDURING STATE QUALITIES

Enduring state activity necessitates that the inductor current toward the finish of the switching cycle be equivalent to that toward the start, implying that the net change in inductor current more than one period is zero.

This requires
\[ \Delta i_{L1} \text{ (close)} + \Delta i_{L1} \text{ (open)} = 0 \]

Here using Eqs. 9 and 12,
\[ (V_S - V_o) - \frac{V_I}{L_{lk}} DT - \frac{-V_o + V_I}{L_{lk}} (1 - D)T = 0 \]

Since the above equation
\[ (V_S - V_o) - \frac{V_I}{L_{lk}} T_1 \text{, } T + \frac{-V_o + V_I}{L_{lk}} T_2 \text{, } T = 0 \]

Where \( T_1 \) is D and \( T_2 \) is 1 - D
equation for \( V_o \),
\[ V_o = (D+K(1-D))/(1+k) \]

The all out normal inductor current must be equivalent to the normal current in the heap resistor, since the normal capacitor current must be zero for unaltering state activity:
\[ I_L = I_o \]

Here
\[ I_L = I_{L1} + I_{L2} \]
dequation for I_L max is known from Eqs. 9 and 12 the greatest and least estimations of the inductor current are can be composed as
\[ I_{L1, \text{max}} = \frac{V_o}{2R_o} - \frac{-V_o (1 - D)T}{L_{lk} 2} \]

\[ I_{L1, \text{max}} = \frac{V_o}{2R_o} - \frac{(1 - D)}{(k^2 - 1)D}L_{L1f} \]

Similarly
\[ I_{L2, \text{max}} = \frac{V_o}{2R_o} - \frac{(1 - D)}{(k^2 - 1)D}L_{L2f} \]

\[ I_{L1, \text{min}} = \frac{V_o}{2R_o} - \frac{(1 - D)}{(k^2 - 1)D}L_{L1f} \]

Similarly
\[ I_{L2, \text{min}} = \frac{V_o}{2R_o} - \frac{(1 - D)}{(k^2 - 1)D}L_{L2f} \]

Eqs. 34 can be utilized to decide the mix of L1 and f that will bring about nonstop current. Since \( I_{L1} \text{ min} = 0 \) is the limit among constant and intermittent current,
\[ (L1f)_{\text{min}} = \frac{(1 - D)R_o}{(k^2 - 1)D} \]

Similarly
\[ L_{1, \text{min}} = \frac{(1 - D)R_o}{((k^2 - 1)D)} \]

By and by, the yield voltage can’t be kept impeccably steady with a limited capacitance. The variety in yield voltage, or wave, is processed from the voltage-current relationship of the capacitor. The current in the capacitor is
\[ i_c = i_{L1} + i_{L2} - i_0 \]

While the capacitor current is certain, the capacitor is charging. From the meaning of capacitance,
\[ Q = C_o \times V_o \]
\[ \Delta Q = C_o \times [\Delta V]_o \]
\[ \Delta V_o = \Delta Q/C_o \]

The adjustment in control \( \Delta Q \) is the region of the triangle over the time pivot
\[ \Delta Q = \frac{1}{2} \frac{T}{4} \left( \frac{\Delta i_{L1}}{2} \right) \]
\[ \Delta Q = \left( \frac{1}{16} \frac{T}{6} \Delta i_{L1} \right) \]
\[ \Delta V_o = \left( \frac{T}{16C_oL_{lk}} \right) \]

From eqs 44 eqs 45 can be written as
\[ \Delta V_o = \frac{T}{16C_oL_{lk}} \left( \frac{-V_o}{(1 - D)} \right) \]

In this condition, \( \Delta V_o \) is the top to-to wave voltage at the yield, as appeared in

Figure 12. It is likewise valuable to express the wave as a small amount of the yield voltage,
\[ \Delta V_o = \frac{(1 - D) \frac{1}{16C_oL_{lk}}}{(1 - (k - 1)L_1)} \]
\[ C_o = \frac{16 \Delta V_o L_{lk}}{V_o (1 - k)L_1} \]
5. THE COMPARISON BETWEEN COUPLED AND NON COUPLED CONVERTERS

Table 1. Comparison between Coupled and Non-coupled Converters

<table>
<thead>
<tr>
<th>Duty ratio</th>
<th>Output Ripple Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coupled</td>
</tr>
<tr>
<td>0.1</td>
<td>0.015</td>
</tr>
<tr>
<td>0.2</td>
<td>0.016</td>
</tr>
<tr>
<td>0.3</td>
<td>0.0164</td>
</tr>
<tr>
<td>0.4</td>
<td>0.011</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

![Fig 6 Efficiency versus Power](image)

6. SPECIFICATION OF TWO PHASE INTERLEAVED BUCK CONVERTER WITH COUPLED INDUCTOR

Table 2 Specification of the Converter

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>48</td>
</tr>
<tr>
<td>Output voltage</td>
<td>12</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100KHZ</td>
</tr>
<tr>
<td>Current ripple</td>
<td>Less than 5% of output current</td>
</tr>
<tr>
<td>Output voltage ripple</td>
<td>Less than 1%</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>0.9</td>
</tr>
<tr>
<td>Output power</td>
<td>250W</td>
</tr>
</tbody>
</table>

7. SIMULATION RESULT

7.1. Open loop Simulation of Interleaved buck converter with coupled inductor

From figure 7 it is seen that exchanging beats Vgs1 and Vgs2 are 180° stage moved and obligation proportion is 0.25 individual inductor current are additionally stage moved and consequently both inductor flows get dropped each other so all out inductor wave will be diminished to zero. This case will happen in two stage IBC for just obligation proportion of 0.5.

![Fig 7 Open loop simulation of IBC with coupled inductor](image)

Fig 8 simulated voltage and current waveforms of IBC with coupled inductor for open loop operation
7.2. Closed loop simulation of interleaved buck converter with coupled inductor

Fig 9 closed loop simulation of IBC with coupled inductor

Fig 10 simulated voltage and current waveforms of IBC with coupled inductor for Closed loop operation

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