Closed Loop Control of High Voltage Gain IBC with Voltage Multiplier Module

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Abstract—This paper presents the closed loop control of a high voltage gain IBC. A high voltage gain Interleaved Boost Converter (IBC) with Voltage Multiplier module is suitable for renewable energy system, which requires high step up conversion ratio. In order to obtain high gain, a built-in transformer and a voltage multiplier module inserted into each phase of conventional interleaved boost converter. The voltage multiplier cell is composed of built-in transformer windings, diodes and small capacitors. The Voltage multiplier module is efficient, low cost and simple topology composed of switched capacitors and diodes to obtain high DC output voltage. In order to obtain the controlled output voltage from a DC – DC converter under varying input conditions, it is necessary to regulate the output voltage which is achieved through closed loop control. A PI controller is implemented to improve its performance of the proposed IBC during the disturbances due to renewable energy sources. The closed loop control of the proposed IBC with multiplier module is analyzed and simulated for high voltage gain using MATLAB Simulink.

Keywords—Interleaved Boost Converter (IBC), High Voltage Gain, Voltage Multiplier, PI controller.

I. INTRODUCTION

The dc-dc converters with high step up voltage gain is widely used in many applications such as lasers, fuel cell energy conversion systems, X-ray systems, solar cell energy conversion systems, and high intensity-discharge lamp for automobile headlamps. Theoretically, a dc–dc boost converter can achieve a high step up voltage gain with an extremely high duty ratio [1–3]. However, in practice, the step-up voltage gain is limited due to the effect of power switches, rectifier diodes, and the equivalent series resistance (ESR) of inductors and capacitors.

The conventional boost converter is used to provide a voltage conversion ratio with low voltage gain. It is hard to provide a large voltage conversion ratio, due to a large duty cycle that brings high conduction loss, and the large peak current may impact the capacitors seriously. Various topologies have been developed to provide a high step up voltage gain without a large duty ratio [4]. The isolated converters will boost the voltage by increasing the turn’s ratio of the high frequency transformer [5-6].

When compared with non-isolated converters for isolated converters it is easy to achieve high voltage gain. It is done by selecting the transformer turns ratio properly; high voltage conversion ratio can be obtained by optimal duty cycle [7]. The switch duty cycle and the transformer turns ratio are controlled to lift the voltage ratio. The main advantage of this converter is switch voltage stress reduction; switch turn-off voltage spikes suppression and diode reverse recovery problem alleviation.

IBC splits the input current based on each phase. Equal current is shared among two converters to minimize the ripple. To overcome the problem of ripples and losses in boost converter, interleaved topology is used [8]. Paper [9] discusses the closed-loop control of interleaved high step up converter to obtain high reliability. The switch voltage stress and the diode peak current are minimized due to the built-in transformer multiplier cells to improve the conversion efficiency [10-12]. Furthermore there is no reverse-recovery problem for the clamp diodes.

In the proposed paper, a closed loop control is implemented to the IBC with built-in transformer and voltage multiplier module. In order to obtain the controlled output voltage from a DC – DC converter under varying input conditions, it is necessary to regulate the output voltage which is achieved through closed loop control. The closed loop control of the proposed converter is simulated and the results are compared with the open loop control system.

II. IBC WITH VOLTAGE MULTIPLIER MODULE

The circuit configuration of interleaved boost converter with Voltage Multiplier Module for high voltage gain is shown in Fig.1. In the circuit, L1 and L2 are the energy storage inductors, S1 and S2 are the power switches, C1, C2 and C3, C4 are the clamp capacitors, Cois the output capacitor, D1, D2 and D3, D4 are the clamp diodes, and D5 and D6 are the rectified diodes. A primary winding Np, a secondary winding Ns1, a third winding Ns2, and a leakage inductor Lk constitutes the built in transformer. The gate-driving signals of the two power switches are interleaved with a 180° phase shift.

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The inductor currents \( i_L \) at \( V_i \) are respectively, given by

\[
L_i = \frac{V_i}{R_i} \quad (1)
\]

\[
L_2 = \frac{V_i}{R_2} \quad (2)
\]

III. CIRCUIT OPERATION

There are totally 10 modes of operation. The analysis and operating principle of the proposed converter modes 1–5 are discussed. Due to the completely symmetrical interleaved topology, operating modes 6–10 of the proposed converter in second phase are similar to the operating modes 1–5.

Stage 1 \([t_0, t_1]\): In this interval, at \( t = t_0 \), both main power switches \( S_1 \) and \( S_3 \) turn ON. All the diodes \( D_1, D_2, D_3, D_4, D_5, \) and \( D_6 \) are reverse-biased. The path of current flow in mode 1 is shown in Fig. 2. Inductors \( L_1 \) and \( L_2 \) are charged by input voltage \( V_{in} \), and currents through inductions \( L_1 \) and \( L_2 \) linearly increase. The inductor currents \( i_L_1 \) and \( i_L_2 \) are respectively, given by

\[
i_{L_1}(t) = i_{L_1}(t_0) + \frac{V_{in}}{L_1} t \quad (1)
\]

\[
i_{L_2}(t) = i_{L_2}(t_0) + \frac{V_{in}}{L_2} t \quad (2)
\]

Stage 2 \([t_1, t_2]\): In this interval, at \( t = t_1 \), main power switch \( S_1 \) turns OFF, and its parasitic capacitor is charged by inductor current \( i_L_2 \). The path of current flow in mode 2 operation is shown in Fig. 3. The voltage of the parasitic capacitor is given by

\[
V_{DS2}(t) = \frac{i_{L_2}(t_1)}{C_{ds2}} \quad (3)
\]

Stage 3 \([t_2, t_3]\): In this interval, at \( t = t_2 \), power switch \( S_2 \) remains OFF. The voltages of clamp diode \( D_2, D_4 \) and rectified diode \( D_6 \) decrease; then, \( D_2, D_4 \) and \( D_6 \) begin to turn ON at \( t = t_2 \). The path of current flow in mode 3 is shown in Fig. 4. The input voltage \( V_{in} \) and the inductor \( L_2 \) provide energy to leakage inductor \( L_1 \) and primary winding \( N_p \) through switch \( S_1 \). The voltage of clamp capacitor \( C_1 \) through \( S_1 \) and \( L_2 \). The rectified diode current \( i_{D_2} \) is charged by inductor \( L_1 \) and primary winding \( N_p \).

\[
\begin{align*}
i_{L_2}(t) &= i_{D_2}(t) + i_{D_4}(t) + (n + 1)i_{D_6} \quad (4) \\
i_{L_2}(t) &= n \cdot i_{D_6}(t) \quad (5) \\
i_{L_2}(t) &= i_{L_1} + i_{D_2}(t) + i_{D_4}(t) + i_{D_6} \quad (6)
\end{align*}
\]

Stage 4 \([t_3, t_4]\): In this interval, at \( t = t_3 \), power switch \( S_2 \) is still OFF. The diode current \( i_{D_2}, i_{D_4} \) decreases to zero, and the clamp capacitor voltage \( V_{C_1} \) and \( V_{C_3} \) is equal to the drain–source voltage of power switch \( S_2 \). The path of current flow in mode 4 is shown in Fig. 5. The rectified diode current \( i_{D_6} \) is proportional to leakage-inductor current \( i_L_4 \). The currents through \( L_2, L_4, \) and \( S_1 \) are, respectively, given by

\[
i_{L_2}(t) = (n + 1) \cdot i_{D_6} \quad (7)
\]
\[ i_{Lk}(t) = n \ast i_{D6}(t) \] \[ i_{DS1}(t) = i_{L1} + n \ast i_{D6}(t) \]

Stage 4 \([t_3, t_4]\): In this interval, at \( t_4 \), the power switch \( S_2 \) turns ON. The rectified diode \( D_6 \) remains forward-biased, because leakage inductor current \( i_{Lk} \) still exists. The path of current flow in mode 5 is shown in Fig.6. The leakage inductor current \( i_{Lk} \) decreases to zero at \( t = t_5 \), and rectified diode \( D_6 \) begins to be reverse-biased. The current through \( L_2 \) is given by

\[ i_{L2}(t) = i_{DS2} + (n + 1) \ast i_{D6} \] \[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (10) \]

Fig.7: voltage-mode control

IV. CLOSED LOOP CONTROL OF PROPOSED IBC

In order to obtain the controlled output voltage from a DC–DC converter under varying input and output conditions, it is necessary to regulate the output voltage which is achieved with the help of concept of negative feedback that is carried out in a closed loop method. The control of the output voltage should be performed in a closed-loop manner through two common closed-loop control methods for PWM dc-dc converters, namely,

- The voltage-mode control.
- The current-mode control.

In the voltage-mode control system shown in Fig 7, the converter output voltage is sensed and subtracted from an external reference voltage in an error amplifier. The error amplifier produces a control voltage that is compared to a constant-amplitude saw tooth waveform. The comparator produces a PWM signal to the main switches of the proposed converter. The duty ratio of the PWM signal depends on the value of the control voltage.

The Error amplifier shown in Fig.7 reacts fast to changes in the converter output voltage. Thus, the voltage-mode control provides good load regulation. Line regulation (regulation against variations in the input voltage) is, however, delayed because changes in the input voltage must first manifest themselves in the converter output before they can be corrected. To alleviate this problem, the voltage-mode control scheme is sometimes augmented by a so-called voltage-feed forward path. The feed forward path affects directly the PWM duty ratio according to variations in the input voltage.

B. PI CONTROLLER

A Proportional and Integral controller block diagram shown in Fig.8. PI controller continuously calculates an error value as the difference between a desired set point (SP) and a measured process variable (PV) and applies a correction based on proportional and integral is given by.

\[ e(t) = SP - PV \] \[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (11) \]
The overall control function can be expressed mathematically as

\[ u(t) = K_p e(t) + K_i \int_0^t e(t)dt \] ........................ (12)

Where, \( K_p \) and \( K_i \) all non-negative, denote the coefficients for the proportional and integral terms respectively.

A PI controller gives the control signal based on the error value by comparing the obtained output voltage (Vo) and reference voltage. The major advantage of PI controller is its feasibility and it can be easily implemented. The PI controller based closed loop operations for the IBC with built in transformer and voltage multiplier module is shown in Fig. 9.

The Simulink model of the closed loop control of high voltage gain IBC with the Voltage multiplier module is shown in Fig.10. And the simulation results are compared with closed loop system, which are as follows.

Fig. 10: Simulink Model of closed loop control of high voltage gain IBC with the Voltage multiplier module

Table I: Parameters used for simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (Vin)</td>
<td>48V</td>
</tr>
<tr>
<td>Output voltage (Vo)</td>
<td>505V</td>
</tr>
<tr>
<td>Switch frequency (fs)</td>
<td>50kHz</td>
</tr>
<tr>
<td>Duty ratio</td>
<td>0.62</td>
</tr>
<tr>
<td>C1, C2</td>
<td>10μF</td>
</tr>
<tr>
<td>Output capacitor (C0)</td>
<td>120μF</td>
</tr>
<tr>
<td>Filter inductor (L1, L2)</td>
<td>110μH</td>
</tr>
</tbody>
</table>

Fig. 11: Input voltage and output voltage waveform of the proposed IBC with open loop system

Figure 11 shows input and output voltage waveform of the proposed IBC with open loop model. The simulated input and output voltage waveform of the
The proposed IBC converter with open loop control system is \( V_{in} = 40 \text{V} \) and \( V_{Out} = 400 \text{V} \). Fig. 12 shows the simulated input and output voltage waveform of the proposed IBC converter with closed loop control system is \( V_{in} = 40 \text{V} \) and \( V_{Out} = 505 \text{V} \).

Figure 15 shows input and output voltage waveform of proposed IBC with open loop system. The simulated input and output voltage waveform of proposed IBC with open loop control system \( V_{in} = 60 \text{V} \) and \( V_{Out} = 600 \text{V} \). And Fig. 16 shows the simulated input voltage and output voltage waveform of the closed loop control system with voltage multiplier \( V_{in} = 60 \text{V} \) and \( V_{Out} = 505 \text{V} \).

Table II shows the performance comparison of the IBC with built in transformer and voltage multiplier for open loop and closed loop control system. From the table it is observed that output voltages are maintained at constant values for the Variation of input voltages in the case of closed loop system compared to open loop system.

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**Table II: Comparison of open loop and closed loop system output voltages of the proposed IBC**

<table>
<thead>
<tr>
<th>Input Voltage in Volts</th>
<th>Open Loop system</th>
<th>Closed Loop system</th>
</tr>
</thead>
<tbody>
<tr>
<td>40V</td>
<td>400V</td>
<td>505 V</td>
</tr>
<tr>
<td>48V</td>
<td>505 V</td>
<td>505 V</td>
</tr>
<tr>
<td>60 V</td>
<td>600 V</td>
<td>505 V</td>
</tr>
</tbody>
</table>

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The simulated input and output voltage waveform of the proposed IBC with open loop model. The simulated input and output voltage waveform of the proposed converter with open loop control system is \( V_{in} = 48 \text{V} \) and \( V_{Out} = 505 \text{V} \). And Fig. 14 The simulated input and output voltage waveform of the proposed converter with closed loop control system is \( V_{in} = 48 \text{V} \) and \( V_{Out} = 505 \text{V} \).

Table II shows the performance comparison of the IBC with built in transformer and voltage multiplier for open loop and closed loop control system. From the table it is observed that output voltages are maintained at constant values for the Variation of input voltages in the case of closed loop system compared to open loop system. The
closed loop system output voltages remain constant and robust for the variation of input voltages.

VIICONCLUSION

An Interleaved Boost Converter with voltage multiplier module along with closed loop control system has been proposed for high voltage gain conversion for renewable energy system. The Closed loop control system of high voltage gain IBC with the Voltage multiplier module is implemented and simulated using MATLAB Simulink. For variation in input voltages, the closed loop control system maintains the constant output voltage and improves the converter performance.

REFERENCES


