PWM Controlled High Voltage Boosting converters based on Charge pump and Boost Inductors

1Jessy Thomas, 2Betsy Baby, 3Jobin Rochey & 4Athira Thomas
1,2,3Dept of EEE Vimal Jyoti Engineering College
4Dept of EEE Nehru Engineering College, Thrissur

Abstract - Step up converters are widely used in electric vehicles, Uninterrupted Power Supplies (UPS) and photovoltaic systems etc. High voltage gain can be obtained mainly through charge pump principle. This work presents high voltage boosting converters. These converters are constructed based on bootstrap capacitors and boost inductors. By changing the connection position of the anode of the diode and by using different pulse-width-modulation control strategies, different voltage conversion ratios can be obtained. Above all, two boost inductors with different values, connected in series, can still make this converters work appropriately. Furthermore, for these converters only one half-bridge gate driver and one low-side gate driver are needed, but no isolated gate driver would be needed. These high voltage-boosting converters have individual pulse width modulation control strategies and individual voltage conversion ratios.

Keywords - Boost converter, bootstrap capacitor, pulse-width-modulation (PWM), voltage-boosting converter, voltage conversion ratio.

I. INTRODUCTION

The step-up power conversion is continuously increasing its applications and power capability demands. Some examples are electric vehicles, Uninterrupted Power Supplies (UPS) and photovoltaic systems etc. For the solar cell system to be considered, it needs the high voltage-boosting converter to transfer the low voltage to the high voltage which will be transferred to the ac output voltage via the dc-ac converter. The photovoltaic (PV) grid-connected power system in the residential applications is becoming a fast growing segment in the PV market due to the shortage of the fossil fuel. How to find renewable energy sources is becoming urgent. Photovoltaic (PV) source is one of the significant players in the world’s energy portfolio, and it will make one of the biggest contributions to electricity generation among all the renewable energy candidates by 2040, because it is a clean, emission-free, and renewable electrical generation source with high reliability. In particular, high voltage gain can be obtained through a voltage-boosting converter consists of the traditional boost or fly back converter. The boost converter is simple in structure, but the voltage conversion ratio is not so high, whereas the fly back converter possesses a high voltage conversion ratio but the corresponding leakage inductance is large.

This paper presents high voltage-boosting converters, based on two bootstrap capacitors and two inductors. Above all, although two inductors are connected in series during the demagnetizing period, variations in values of these inductors allow such converters to work appropriately.

II. BASIC OPERATING PRINCIPLES

In order to improve the voltage conversion ratios, voltage boosting converters based on bootstrap capacitors and boost inductors has been developed. These converters have individual voltage conversion ratios and individual pulse-width modulation (PWM) control strategies. Hence, the type 1 converter is described in Fig.1.

For type 1 anode of diode D1 is connected to the cathode of the diode D0, the conversion voltage ratio in continuous conduction mode (CCM) is (3+D)/(1-D), where D is the duty cycle of the PWM control signal created from the controller. This converter contains three MOSFET switches S1, S2, and S3, two bootstrap capacitors Cb and Ce, three bootstrap diodes Dp0, D1, and D2, one output diode D0, two inductors L1 and L2, one output capacitor Co, and one output resistor Ro. Type 1 converter with a voltage conversion ratio (4+2D)/(1-D) in continuous conduction mode (CCM) is given in Fig.2. This contains five MOSFET switches with two bootstrapping capacitors and two boost inductors.
Before this section is taken there are some assumptions are given as follows: 1) the blanking times between the switches are omitted; 2) the voltage drops across the switches and diodes during the turn-on period are negligible; and 3) since the bootstrap capacitors \( C_b \) and \( C_e \) operating based on the charge pump principle, are abruptly charged to some voltage within a very short time, which is much less than the switching period \( T_s \).

A. Type 1 with \( L_1 \) Equal to \( L_2 \) in CCM Operation

The illustrated key waveform is shown in Fig. 3. \( V_{g1}, V_{g2}, V_{g3}, V_{L1}, V_{L2}, L_{1}, \) and \( L_{2} \) for type 1 operated in CCM with \( L_1 \) equal to \( L_2 \), where \( T_s \) is the switching period and \( V_{g1}, V_{g2} \) and \( V_{g3} \) are the gate driving signals for \( S_1, S_2 \) and \( S_3 \), respectively.

Fig.2 High Voltage Boosting Converters

1) Mode 1 \([t_0-t_2]\): As shown in Fig.4, \( S_1 \) and \( S_3 \) are turned on and \( S_2 \) is turned off. Due to \( S_1 \) being turned on, \( D_b \) is reverse biased, but \( D_1 \) and \( D_2 \) are forward biased, thereby causing \( C_e \) to be abruptly charged to \( V_i \) plus \( V_{Cb} \), whereas due to \( S_1 \) being turned on \( D_b \) is reverse biased, thereby causing \( C_b \) to be discharged. At the same time, the voltages across \( L_1 \) and \( L_2 \) are \( V_{L1} \) plus \( V_{Cb} \) thereby causing \( L_1 \) and \( L_2 \) to be magnetized. Also, \( C_b \) releases energy to the output. In this mode the voltage across \( L_1 \) and \( L_2 \) are \( V_{L1-ON} \) and \( V_{L2-ON} \) can be written as

\[
V_{L1-ON} = V_i + V_{Cb} \quad (1)
\]

\[
V_{L2-ON} = V_i + V_{Cb} \quad (2)
\]

2) Mode 2 \([t_1-t_3]\): As shown in Fig.5, \( S_1 \) and \( S_3 \) are turned off, but \( S_2 \) is turned on. Due to \( S_2 \) being turned on, \( D_b \) is forward biased, thereby causing \( C_b \) to be abruptly charged to \( V_i \). At the same time, the input voltage plus the energy stored in \( C_e \) plus the energy stored in \( L_1 \) and \( L_2 \) supplies the load, thereby causing \( C_e \) to be energized, \( C_b \) to be discharged, and \( L_1 \) and \( L_2 \) to be demagnetized. By doing so, the output voltage is boosted up, and is much higher than the input voltage. According to the voltage-second balance, the voltages \( V_{L1-ON}, V_{L2-ON}, \) and \( V_0 \) in this mode can be expressed to be

\[
V_{L2-OFF} = \frac{D}{1-D} V_{L2-ON} \quad (3)
\]

\[
V_{L1-OFF} = \frac{D}{1-D} V_{L1-ON} \quad (4)
\]

\[
V_0 = -V_{L1-OFF} - V_{L2-OFF} + V_i + V_{Ce} \quad (5)
\]

Fig.4 Power Flow of Type 1 Operated in CCM with \( L_1 \) Equal to \( L_2 \) in Mode 1

Since \( V_{Cb} \) and \( V_{Ce} \) are equal to \( V_i \) and \( 2V_i \) respectively, (1), (2) and (5) can be rewritten to be

\[
V_{L1-ON} = V_{L2-ON} = 2V_i \quad (6)
\]

Fig.5 Power Flow of Type 1 Operated in CCM with \( L_1 \) Equal to \( L_2 \) in Mode 2
V0 = -VL1-OFF - VL2-OFF + 3Vi (7)

By substituting (6) into (3) and (4), VL1-OFF and VL2-OFF can be rewritten as

VL1-OFF = VL2-OFF = \frac{D}{1-D} \times 2Vi (8)

Substituting (8) into (7) yields the following CCM voltage conversion ratios:

\frac{V0}{V_i} = \frac{3 + D}{1-D} (9)

B. High voltage Boosting Converters in CCM

Fig.6 Illustrated Key Waveforms for L1 Equal to L2

The illustrated key waveform is shown in Fig.6. Vgs, Vgs2, Vgs3, Vgs4, Vgs5, VL1, VL2, iL1 and iL2 for high voltage boosting converters operated in CCM with L1 equal to L2, where Ti is the switching period.

1) Mode 1 [t0-t1]: Principle of operation is same as that of the type 1 converter. Power flow of this is given in Fig.7.

Fig.7 Power Flow of high voltage boosting converters
Operated in CCM with L1 Equal to L2 in Mode 1

VL1-ON = Vi + Vcb + Vca (11)

2) Mode 2 [t1-t2]: As shown in Fig.8, S1, S3 and S are turned off, but S2, S1 is turned on. Due to S2, Sa being turned on, D0 and D4 is forward biased, thereby causing Cb, Cc to be abruptly charged to Vi. At the same time, the input voltage plus the energy stored in Cc plus the energy stored in L1 and L2 supplies the load, thereby causing Cc to be energized, Cb to be discharged, and L1 and L2 to be demagnetized. By doing so, the output voltage is boosted up, and is much higher than the input voltage.

VL2-OFF = -\frac{D}{1-D} VL2-ON (12)

VL1-OFF = -\frac{D}{1-D} VL1-ON (13)

V0 = -VL1-OFF - VL2-OFF + Vi + Vcb + Vcc (14)

Vcb and Vcc are equal to Vi and 3Vi respectively, (14) can be rewritten to be

VL1-ON = VL2-ON = 3Vi (15)

V0 = -VL1-OFF - VL2-OFF + 4Vi (16)

By substituting (15) into (12) and (13), VL1-OFF and VL2-OFF can be rewritten as

VL1-OFF = VL2-OFF = -\frac{D}{1-D} \times 3Vi (17)

Substituting (17) into (16) yields the following CCM voltage conversion ratios:

\frac{V0}{V_i} = \frac{4 + 2D}{1-D} (18)
III. DESIGN PROCEDURES

The specifications of the converters are given as follows:
The rated dc input voltage \( V_i \) is set to 24V; The rated dc output voltage \( V_{os} \) is set to 200 V; The rated output power is set to 100 W; The switching frequency \( F_s \) is chosen to be 200 kHz. One 680\( \mu \)F Rubycon capacitor is selected for \( C_o \).

A. Design of Two Inductors

The values of two inductors can be figured out according to the following equation:

\[
L = \frac{V_i}{\left( \frac{di}{dt} \right)}
\]

(19)

The values of \( L_1 \) and \( L_2 \) are identical and are set to \( L \) with the current slew rate \( \frac{di}{dt} \) being 0.140 A/\( \mu \)s for type 1 during the magnetization period. Therefore, the value of \( L \) can be calculated to be 170\( \mu \)H under the rated input voltage.

B. Design of Capacitors

The value of the charge pump capacitors can be worked out based on the following equation:

\[
C = \frac{V_i DT_s}{\Delta V} (1 - D) T_s
\]

(20)

The converter operates in the rated condition with the voltage sag \( \Delta V \) being 0.4% of the voltage during discharging period for type 1. Therefore, the value of \( C_b \) and \( C_c \) can be calculated to be 100\( \mu \)F and 220\( \mu \)F.

<table>
<thead>
<tr>
<th>TABLE I SIMULATION PARAMETERS OF CONVERTERS</th>
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<tbody>
<tr>
<td>( L_1 = L_2 ) for type 1</td>
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<tr>
<td>( L_1 &gt; L_2 ) for type 1</td>
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<tr>
<td>( L_1 &lt; L_2 ) for type 1</td>
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<tr>
<td>( C_b, C_c ) and ( C_o )</td>
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<tr>
<td>( 170\mu )H</td>
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<tr>
<td>( 240\mu )H</td>
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<tr>
<td>( 170\mu )H</td>
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<tr>
<td>( 220\mu )F and ( 680\mu )F</td>
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IV. SIMULATION AND RESULTS

The high voltage-boosting converters based on Bootstrap capacitors and boost inductors, converters model is developed using MATLAB-Simulink version 2011a to feed the load. Closed loop PWM control is used here. The high voltage boosting converters was simulated using MATLAB/SIMULINK and the resulting waveforms are as shown below.

![Fig. 9 Simulation Model of Type 1 converter](image)
![Fig. 10 Simulation Model of High Voltage Boosting converter](image)

![Fig. 11 Input Voltage Waveform](image)

Above all, the converters are operated in the CCM. However, actually, \( L_1 \) is different from \( L_2 \). Consequently, for analysis convenience, converters are operated only in CCM under the condition that \( L_1 \) equal to \( L_2 \). When analyzing with \( L_1 \) greater than \( L_2 \) or \( L_1 \) is smaller than \( L_2 \), the same voltage conversion ratios of the type converter and high voltage boosting converters is obtained.
based on inductors connected in series with bootstrap capacitors. Two inductors are connected in series during the demagnetizing period, so that variations in values of these inductors allow such converters to work appropriately. In addition, based on different switch turn-on types and different diode connections, voltage-boosting converters with different voltage conversion ratios are generated under similar circuit structure. Converters with only one half-bridge gate driver and one low side gate driver are needed, but no isolated gate driver would be needed. These converters exhibit good performance even with different inductance.

VI. REFERENCES


