A Fuzzy Controlled High Voltage Boosting Converter Based On Boost Inductors and Capacitors

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Abstract: A novel high voltage-boosting converter topology is explained in this paper. By changing the connection position of the anode of the diode two types of converters are obtained-Type1 and Type2. These converters are constructed based on boost inductors and capacitors and have different voltage conversion ratios. Furthermore, although there are three switches in each converter, only one half-bridge gate driver and one low-side gate driver are needed, but no isolated gate driver would be needed. In this paper, closed loop control of type2 converter using fuzzy logic controller is explained. Some simulated results are provided to verify the effectiveness of the proposed converter.

Keywords: Boost converter, fuzzy logic controller, voltage-boosting converter, voltage conversion ratio.

I. Introduction

As generally recognized, step-up converters have been widely used in many applications, such as battery powering device, uninterruptible power supply (UPS), photovoltaic (PV) system, etc. requiring some circuits transferring low voltages to high voltages used as input voltages for dc–ac converters[2],[3]. For the applications of the power supply using the low voltage battery, analog circuits, such as RF amplifier, audio amplifier, etc., often need high voltage to obtain enough output power and voltage amplitude. This is achieved by boosting the low voltage to the required high voltage. Therefore, in many 3C (consumer, communications, computer) electronics, some converters are needed to supply one boosted voltage or more under a given low voltage, especially for portable communications systems, such as MPEG-3 (MP3) players, Bluetooth devices, personal digital assistant, etc. For such applications, the output voltage ripple must be taken into account seriously. Regarding the conventional nonisolated voltage-boosting converter such as the boost converter and the buck–boost converter, their output currents are pulsating, thereby causing the corresponding output voltage ripples to tend to be large. As generally acknowledged, to overcome this problem, one way is to use the capacitor with large capacitance and low equivalent series resistance (ESR), another way is to add an inductance–capacitance (LC) filter, and the other way is to increase the switching frequency. Recently, some voltage-boosting converter topologies with low output voltage ripples have been derived. In some converters, the voltage-lift technique is utilized to boost the output voltage along with the small output voltage ripple taken into account [4], [5].

However, it is not easy for boost converter or the buck-boost converters to achieve high voltage ratio. In theory, the voltage ratios of these two converters can reach infinity, but in actuality about four or five, limited by parasitic component effect and controller capability. Consequently, if the voltage ratio of the converter is desired to be over five, then two-stage converter based on the boost converter or the buck-boost converter is utilized, or different converter topologies are created[6]-[8]. The boost converter is simple in structure, but the voltage conversion ratio is not so high, whereas the flyback converter possesses a high voltage conversion ratio but the corresponding leakage inductance is large. In certain converter topologies, a method of improving the voltage conversion ratio is proposed, which is based on the fact that the number of inductors is increased, and these inductors are connected in series during the demagnetizing period, thereby pumping the energy created by the input voltage and the energy stored in the inductors into the output terminal to obtain the high voltage conversion ratio [9], [10].
A new voltage-boosting converter, named as KY converter, provides low output voltage ripple and is very suitable for supplying power to devices that must operate under low-ripple conditions\[11\]-\[14\]. Unlike the conventional boost converter, it offers very fast load transient responses, similar to the behavior of the buck converter with synchronous rectification (SR). Besides, in order to enlarge the output voltages, additional proposed converters derived from the KY converter are proposed. KY converter always operates in continuous conduction mode (CCM). Besides, the output current is nonpulsating. However, its ratio of the output voltage to the input voltage is one plus D, where D is the duty cycle of the main switch. As a consequence, to further enlarge the output voltage under the same duty cycle, second-order-derived KY converters, 1-plus-2D and 2-plus-D converters, are used under the same structure but different control strategies.

Since the voltage conversion ratios can be upgraded by increasing the number of voltage-boosting cells, two high voltage-boosting circuits, based on two boost capacitors and two inductors, are presented here. The two inductors are connected in series during the demagnetizing period. In addition, based on different diode connections, two voltage-boosting converters with different voltage conversion ratios are generated under similar circuit structure. Under the same condition that two inductors and two capacitors are used except the input capacitor, any one of the proposed voltage conversion ratios is higher than all the other voltage conversion ratios in the conventional converters. On the other hand, under the condition where the same components are used, the proposed converters have higher voltage conversion ratios. In this paper, a brief illustration of the operation of one of the two converters is given along with some simulation results provided to demonstrate the effectiveness of such converters. Here, the closed loop control of the type2 converter, with same value for both inductors, is analyzed using fuzzy logic control \[15\] which ensures better performance of the converter than using other conventional control strategies.

II. Proposed converter topologies

Two converter topologies can be derived from the proposed high voltage-boosting converter. Each have individual voltage conversion ratios and individual control strategies. Hence, the type 1 converter is described in Fig. 3.1(a), whereas the type 2 converter is shown in Fig. 3.1(b).
addition, the input voltage is signified by $V_i$, the output voltage is represented by $V_o$, the voltages across $C_b$, $C_e$, $D_1$, and $D_2$ are shown by $V_{Cb}$, $V_{Ce}$, $V_{D1}$, and $V_{D2}$, respectively, and the currents flowing through $L_1$, $L_2$, and $D_b$ are denoted by $I_{L1}$, $I_{L2}$, and $I_{Db}$, respectively.

Here, the proposed converters are based on the charge pump of the KY converter and the series boost converter. By doing so, the conversion ratios can be upgraded further. Above all, if the anode of the diode $D_1$ is connected to the cathode of the diode $D_b$, the conversion voltage ratio in continuous conduction mode (CCM) is $(3 + D)/(1 - D)$, where $D$ is the duty cycle of the control signal created from the fuzzy logic controller, whereas if the anode of the diode $D_1$ is connected to the anode of the diode $D_b$ with switch turn-on types different from those of the former, the conversion ratio in CCM is $(3 - D)/(1 - D)$. Therefore, the proposed converters can be used according to industrial applications. In this paper, closed loop control of Type 2 converter using fuzzy logic controller is analyzed. Above all, the converter operated in the CCM under the condition that $L_1$ is equal to $L_2$ is analyzed here. The result is also verified by using MATLAB software.

### III. Basic operating principles

There are some assumptions about the operation of the proposed converter. They are:

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.
3) Since the boost 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 $T_s$, the values of $C_b$ and $C_e$ are large enough to keep the voltages across themselves constant at some values, and hence it is reasonable that the voltages across the capacitors $C_b$ and $C_e$ are both $V_1$ for type 2.

For these two converters to be considered, the turn on types for three switches and the voltages on the boost capacitors are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Type 2</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>$Q_3$</th>
<th>$V_{Cb}$</th>
<th>$V_{Ce}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1-D$</td>
<td>$D$</td>
<td>$D$</td>
<td>$V_o$</td>
<td>$V_{t1}$</td>
<td>$V_{t2}$</td>
</tr>
</tbody>
</table>

There are basically two operating modes for the proposed converter. They are:

a) Mode 1 [$t_0 < t_1$]:

As shown in Fig 3, $Q_2$ and $Q_3$ are turned on, but $Q_1$ is turned off. Due to $Q_2$ 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 $V_o$, whereas due to $Q_3$ being turned on, $D_b$ is forward biased, thereby causing $C_b$ to be abruptly charged to $V_o$. At the same time, the voltages across $L_1$ and $L_2$ both are $V_o$ thereby causing $L_1$ and $L_2$ to be magnetized. Also, $C_b$ releases energy to the output. In this mode, the voltages across $L_1$ and $L_2$, 663$V_{L1-on}$ and $V_{L2-on}$, can be written as:

$$V_{L1-on} = V_o$$
$$V_{L2-on} = V_o$$

b) Mode 2 [$t_1 < t_2$]:

**Table.1 Turn-on types for switches and voltages on capacitors**

![Fig.3 power flow of type 2 operated in CCM with $L_1$ equal to $L_2$ in mode 1.](image-url)
As shown in Fig. 4, Q2 and Q3 are turned off, but Q1 is turned on. At the same time, the input voltage plus the energy stored in Cb and Ce plus the energy stored in L1 and L2 supplies the load, thereby causing Co to be energized, Cb and Ce to be discharged, and L1 and L2 to be demagnetized. By doing so, the output voltage is boosted up, and is higher than the input voltage. According to the voltage-second balance, the voltages $V_{L1\text{-OFF}}$, $V_{L2\text{-OFF}}$, and $V_o$ can be expressed as:

$$V_{L1\text{-OFF}} = \frac{-D}{1-D} V_{L1\text{-ON}} \quad (3)$$

$$V_{L2\text{-OFF}} = \frac{-D}{1-D} V_{L2\text{-ON}} \quad (4)$$

$$V_o = -V_{L1\text{-OFF}} - V_{L2\text{-OFF}} + V_1 + V_{Cb} + V_{Ce} \quad (5)$$

Since $V_{Cb}$ and $V_{Ce}$ are equal to $V_1$, (1), (2), and (5) can be rewritten to be:

$$V_{L1\text{-ON}} = V_{L2\text{-ON}} = V_1 \quad (6)$$

$$V_o = -V_{L1\text{-OFF}} - V_{L2\text{-OFF}} + 3V_1 \quad (7)$$

By substituting (6) into (3) and (4), $V_{L1\text{-OFF}}$ and $V_{L2\text{-OFF}}$ can be rewritten to be:

$$V_{L1\text{-OFF}} = V_{L2\text{-OFF}} = \frac{-D}{1-D} * V_1 \quad (8)$$

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

$$\frac{V_o}{V_1} = \frac{3-D}{1-D} \quad (9)$$

Key waveforms for type 2 converter operated in CCM with L1 equal to L2 are shown in the figure below.
IV. Fuzzy logic control

Fuzzy Logic (FL) is a multivalued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. Here, Mamdani type Fuzzy Inference System (FIS) is used.

The two inputs error and deltaerror are fed to the FIS. Fuzzification, Application of rules, Implication, Aggregation and Defuzzification are the major process taking place in the fuzzy inference system. After these processes a crisp output is obtained. The membership functions used here are negative big (NB), negative medium (NM), negative small (NS), zero (Z), medium (M), positive small (PS), positive medium (PM) and positive big (PB).

Fig. 7 shows the membership functions of input variable error. Here, seven membership functions are used. They are NB, NM, NS, Z, PS, PM and PB.
The five membership functions used for the input variable \( \text{deltaerror} \) are shown in the fig.8. They are NB, NS, M, PS and PB.

\[
\text{Fig.8 membership functions of the variable deltaerror}
\]

For the output variable seven membership functions, NB, NM, NS, Z, PS, PM, PB, are used. They are shown in the fig.9.

\[
\text{Fig.9 membership functions of the output variable}
\]

In this paper, eleven rules are used to control the output variable. The weightage for all the rules are set to one. The rules are:

Rule 1: If error is (Z) then output1 is (Z).
Rule 2: If error is (PB) then output1 is (PB).
Rule 3: If error is (NB) then output1 is (NB).
Rule 4: If error is (NS) then output1 is (NS).
Rule 5: If error is (PS) then output1 is (PS).
Rule 6: If error is (NM) then output1 is (NM).
Rule 7: If error is (PM) then output1 is (PM).
Rule 8: If error is (PS) and \( \text{deltaerror} \) is (PS) then output1 is (PS).
Rule 9: If error is (PS) and \( \text{deltaerror} \) is (PB) then output1 is (PM).
Rule 10: If error is (NS) and \( \text{deltaerror} \) is (NS) then output1 is (NS).
Rule 11: If error is (NS) and \( \text{deltaerror} \) is (NB) then output1 is (NM).

V. Simulink model

In order to verify the performance of the proposed converter, simulations have been done using Matlab/Simulink software. The duty cycle of the converter is set as 50%. An input voltage of 12V is applied to the type2 high voltage boosting converter which boosts the input voltage. The simulation parameters are shown in Table 2.

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>SPECIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_i )</td>
<td>12V</td>
</tr>
<tr>
<td>( L_1, L_2 )</td>
<td>80mH</td>
</tr>
<tr>
<td>( C_b, C_e )</td>
<td>330( \mu )F</td>
</tr>
<tr>
<td>( C_o )</td>
<td>1000( \mu )F</td>
</tr>
<tr>
<td>( R_L )</td>
<td>470Ω</td>
</tr>
</tbody>
</table>
The simulink block diagram of the converter in closed loop is shown below. Here, fuzzy logic control is used. The terminal voltage of the converter is compared with the reference voltage, here, 60V. This error voltage along with the change in error serves as the two inputs of the fuzzy logic controller. The output of the fuzzy logic controller is compared with a repeating sequence having frequency 10 kHz to obtain the pulses. These pulses switch the multiinput multioutput dc-dc boost converter. So the converter switching frequency is 10 kHz.

![Simulink model of the proposed converter](image1)

Fig. 10 Simulink model of the proposed converter

A 12V DC is given to the input of the converter. It is shown in the figure below.

![Input voltage waveform](image2)

Fig. 11 Input voltage waveform

Gating signals for the switches Q₂ and Q₃ is shown below. Q₂ and Q₃ are operated together. The complement of this signal is fed to switch Q₁. The duty cycle of the switches is 50% of time period. The switching frequency is 10 kHz.

![Gating signals for switches Q₂ and Q₃](image3)

Fig. 12 Gating signals for switches Q₂ and Q₃

The figure below shows the current through the inductors L₁ and L₂.

![Current through inductors L₁ and L₂](image4)

The International Conference on Emerging Trends in Engineering & Management (ICETEM-2016)
Fig. 13 inductor current through L₁ and L₂

Fig. 14 shows the voltage across the capacitors Cₘ and Cₑ. The magnitude of voltages are same and equal to the input supply voltage, which is 12V.

The output voltage of the high voltage boosting converter with fuzzy logic control strategy is shown below. The output voltage is 60V DC. It is clear that the terminal voltage tracked the reference value well.

VI. Conclusion

In this paper, a fuzzy controlled high voltage-boosting converter is addressed, which is based on inductors connected in series with boost capacitors. It is noted that the proposed converter is based on the charge pump of the KY converter and the series boost converter. By doing so, the conversion ratios can be upgraded further. If the anode of the diode D₁ is connected to the anode of the diode Dₙ, the conversion ratio in continuous conduction mode is \((3 - D) / (1 - D)\) where \(D\) is the duty cycle of the control signal created from the fuzzy controller. The fuzzy logic controller provides fast response, better settling time and reduced overshoot than conventional controllers. From the simulation results, it is seen that such converter exhibit good performances and hence are suitable for industrial applications, such as the energy-recycling burn-in test of the buck-type converter, isolated or nonisolated.

References