Simulation of ZVS H-Bridge Inverter Using Soft Switching Boost Converter

K. Sreekanth Reddy

ABSTRACT: This paper presents a two stage zero-voltage-switching H-Bridge inverter using soft switching boost converter. The conventional H-Bridge inverter generates switching losses at turn on and off. So that, the efficiency is reduced. The proposed inverter operates ZVS using an auxiliary switch and resonant circuit to improve the efficiency of inverter. DC-DC converter stages reduce not only switching loss but also the capacity and size of the passive device. DC-AC inverter stage supplies load with energy through the ZVS operation of 4 switches. The operating mode analysis is presented in detail. We present the inverter topology, principle of operation and simulation results obtained from the MATLAB Software.

Keywords- Boost converter, Soft switching, Resonant converter, H-Bridge inverter.

I. INTRODUCTION

Nowadays, trends of the power electronics system are toward smaller size, lighter weight and higher efficiency. So, it is necessary to evaluate their switching frequency of operation. However, as known, the switching losses of semiconductor devices are proportional to switching frequency [1]. In this way to minimize or even to eliminate the switching losses, the soft commutation techniques are needed for improving the efficiency of the converters. When the switching devices like MOSFET or IGBT perform hard switching, during turn on and off process, the power device has to withstand high voltage and current simultaneously resulting in high switching loss and stress. Also according to that, the whole system efficiency goes down. So, to solve this problem, soft switching converters provide an effective solution to suppress electromagnetic interference and have been applied to DC-DC, AC-DC and DC-AC [2]. The disadvantages of hard switching are; expensive, heavy weight and low efficiency. Therefore in this, the soft Switching is performing in both converter stage and inverter stage.

However in applications with high voltage (above 500v) and high values of rms currents through the Semiconductor devices, Insulated-Gate Bipolar Transistors (IGBTs) are preferred as the power switches, because they present lower conduction losses than MOSFETs[3]. Nevertheless, the turn- off losses compose the major part of the total switching losses in IGBTs. This fact makes the zero-current-transition (ZCT) the most effective one for IGBTs. In order to verify validity of proposed inverter, it is simulated using MATLAB software.

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II. BASIC BLOCK DIAGRAM

Fig. 1 shows the basic block diagram of ZVS H-Bridge inverter. This is a two stage converter that is DC-DC converter stage and DC-AC stage. In this the resonant network consists of a resonant inductor, two resonant capacitors, two diodes and an auxiliary switch. It makes partial resonant path for main switch perform soft switching at zero voltage. Moreover, the auxiliary switch also achieves soft switching by resonant circuit. In the H-Bridge inverter, the inverter is capable of ZVS switching and that can reduce switching loss and size of the passive device.

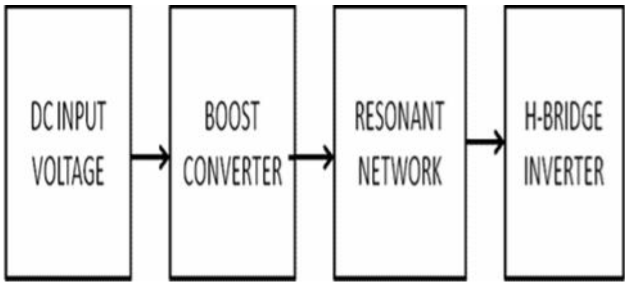

Fig. 1 Basic Block Diagram

III. SOFT SWITCHING BOOST CONVERTER

Fig. 2 shows the proposed soft switching inverter capable of ZVS switching and that can reduce switching loss and size of passive device. Soft switching boost converter with resonance as an inverter in order to gain high stable density and high efficiency. Resonance type soft switching DC-DC converter can reduce switching loss than hard switching DC-DC converter, and can reduce scale of the passive elements (inductor, capacitor).

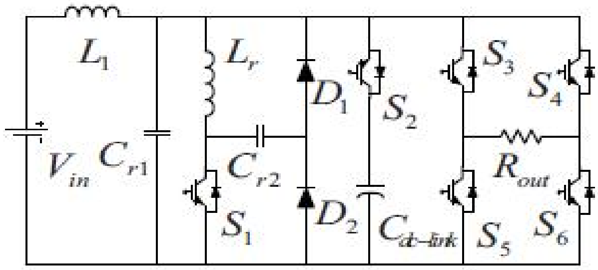

Fig. 2 proposed ZVS H-bridge inverter

. First stage is soft switching boost converter and in second stage, there is conventional H-bridge inverter. The switching loss can be reduced switching at zero current and zero voltage made by the resonance between inductor L_r and capacitors C_{r1}, C_{r2}.

IV. EQUIVALENT CIRCUIT ANALYSIS

Mode 1 $(t_0 \le t < t_1)$

In this mode the main switch S_1 is turned on with zero-current switching (ZCS) and Only S_3, S_6 are turned off among 4 switches of inverter.

$$From\,the\,equivalent\,circuit$$

$$V_{in} - V_{out} = V_{L1} = L_1 \frac{di_{L1}}{dt}$$

$$di_{L1} = \frac{V_{in} - V_{out}}{L_1}.dt$$

$$Integrating\,on\,both\,sides,$$

$$i_{L1} = i_{L1}(t_0) - \frac{1}{L_1}(V_{out} - V_{in}).t \tag{1}$$

$$L_r.\frac{di_{Lr}}{dt} = V_{out}$$

$$i_{Lr} = \frac{1}{Lr}.V_{out}.t \tag{2}$$

$$\mathrm{v}_{cr1}(t) = V_{out} \tag{3}$$

$$\mathrm{v}_{cr2} = 0 \tag{4}$$

The main inductor current decreases linearly and when the resonant inductor current i_{Lr} is equal to the main inductor current, the switch S_2 is turned off, at that time mode1 is finished. The main and resonant inductor Currents of this mode are presented as (1) and (2). The voltages of resonant capacitor C_{r1}andC_{r2} are given by (3) and (4).

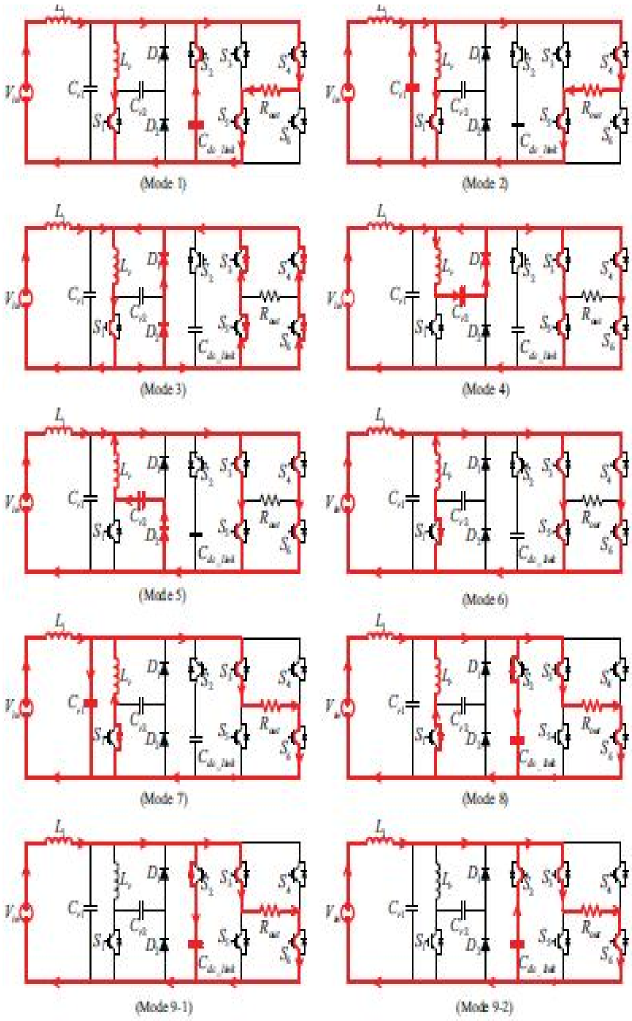

Fig. 3 Equivalent circuits of half switching mode

Mode 2 $(t_1 \le t < t_2)$ This mode starts at the time that resonant switch S_2 is turned off.

$$V_{cr1} + V_{Lr} = 0$$

$$V_{cr1} + L_r \frac{di_{Lr}}{dt} = 0$$

$$V_{cr1} + L_r.\frac{d}{dt}\left(c_{r1}.\frac{dv_{cr1}}{dt}\right) = 0$$

$$V_{cr1} + L_r c_{r1}\frac{d^2 v_{cr1}}{dt} = 0$$

$$\left(\frac{d^2 v_{cr1}}{dt^2} + \frac{1}{L_r c_{r1}} v_{cr1}\right) = 0$$

$$\left(D^2 + \frac{1}{L_r c_{r1}}\right) v_{cr1} = 0$$

$$D_{12}^2 = -\frac{1}{L_r c_{r1}}$$

$$D_{12} = \pm j\frac{1}{\sqrt{L_r c_{r1}}}$$

$$V_{cr1} = A\cos\frac{1}{\sqrt{L_r c_{r1}}}t + B\frac{1}{\sqrt{L_r c_{r1}}}t \qquad \left\{\because \omega_{r1} = \frac{1}{\sqrt{L_r c_{r1}}}\right\}$$

$$V_{cr1} = A\cos\omega_{r1}t + B\sin\omega_{r1}t$$

By applying initial conditions

$$t = 0;\ V_{cr1} = V_{out} = A$$

$$V_{cr1}^1 = B\cos\omega_{r1}t.\omega_{r1}$$

$$\mathrm{i}_{cr1(0^+)} = c_{r1}\frac{dv_{cr1}}{dt}$$

$$\frac{i_{out}}{c_r} = V^1_{cr1(0^+)} \quad then$$

$$\frac{i_{out}}{c_r} = B\omega_{r1}$$

$$B = \frac{i_{out}}{c_r\omega_{r1}} = i_{out}\sqrt{\frac{L_r}{c_{r1}}}$$

By substituting these values in V_{cr1}

$$\mathrm{v}_{cr1}(t) = V_{out}\cos\omega_{r1}t - I_{out}Z_{r1}\sin\omega_{r1}t \tag{5}$$

$$i_{Lr}(t) = (I_{L\min} - I_{Lout}) - I_{out}\cos\omega_{r1}t + \frac{V_{out}}{Z_{r1}}\sin\omega_{r1}t \tag{6}$$

$$\mathrm{i}_{L1}(t) = I_{L1\min} \tag{7}$$

$$\mathrm{v}_{cr2}(t) = 0 \tag{8}$$

The resonant period is

$$t_{r1} = \frac{\pi}{2}\sqrt{L_r C_{r1}} \tag{9}$$

The resonant impedance is

$$Z_{r1} = \sqrt{\frac{Lr}{Cr1}} \tag{10}$$

resonant capacitor C_{r1} is discharged through the resonant path $C_{r1} - L_r$. At the end of this mode the resonant capacitor C_{r1} is equal to zero. The corresponding equations are given by (5)-(8)

Mode 3 $(t_2 \le t < t_3)$

At the beginning of this mode, the resonant capacitor C_{r1} has been discharged fully; the resonant capacitor voltage becomes zero. Then the diodes D_1 and D_2 are turned on, also the anti-parallel-diodes of the H-Bridge inverter's switches S_3, S_4, S_5 and S_6 are turned on. At that time the PWM signal of main switch is removed with zero-voltage-condition. In this interval, the main inductor current is shown as (11).

$$\mathrm{V_L} = \mathrm{V_{in}}$$

$$\mathrm{L_1}.\frac{\mathrm{di_{L1}}}{\mathrm{dt}} = \mathrm{V_{in}}$$

$$\frac{\mathrm{di_{L1}}}{\mathrm{dt}} = \frac{1}{\mathrm{L_1}}\mathrm{V_{in}}$$

Integrating on both side

$$i_{L1}(t) = I_{L1}(t_2) + \frac{V_{in}}{L_1}t \tag{11}$$

$$i_{Lr}(t) \approx I_{Lr\max} \tag{12}$$

$$\mathrm{v}_{cr1}(t) = 0 \tag{13}$$

$$\mathrm{v}_{cr2}(t) = 0 \tag{14}$$

Mode 4 $(t_3 \le t < t_4)$

At mode 3, the current flow into the anti-parallel-diodes of switches S_3, S_4, S_5 and S_6 under zero voltage. At that time, the turn-on signal is given to the two switches S_3, S_6 of H-bridge inverter. Needless to say, the two switches S_4, S_5 are turned on already in advance for the currents flow through the 4 switches in this mode.

$$i_{Lr}(t) = I_{Lr(t3)}\cos\omega_{r2}t \tag{15}$$

$$\mathrm{v}_{cr2}(t) = Z_{r2}.I_{Lr(t3)}.\sin\omega_{r2}t \tag{16}$$

$$i_{L1}(t) = I_{L1(t3)} + \frac{V_{in}}{L_1}.t \tag{17}$$

$$\mathrm{v}_{cr1}(t) = 0 \tag{18}$$

The resonant period is

$$t_{r2} = \frac{\pi}{2}\sqrt{L_r C_{r2}} \tag{19}$$

The resonant impedance is

$$Z_{r2} = \sqrt{\frac{L_r}{C_{r2}}} \tag{20}$$

Therefore the 4 switches of H-bridge inverter can be turned on in zero-voltage-condition. Also due to the on state of the all inverter switches, freewheeling current flows through the inverter stage. In this section, resonant inductor L_r and resonant capacitor C_{r2} start resonance. When the current of L_r is equal to zero, the resonant inductor L_r has no energy and this mode is finished. The corresponding equations are given by (15)-(18)

Mode 5 $(t_4 \le t < t_5)$

In mode 4, the freewheeling current flows via inverter stage and the current of L_r becomes zero. This means the total energy of resonant inductor L_r is transferred to resonant capacitor C_{r2}.

$$i_{L1}(t)=I_{L1}(t_4)+\frac{V_{in}}{L_1}.t \quad (21)$$

$$\mathrm{v}_{cr2}(t)=Z_{r2}.I_{Lr(t3)}.\cos\omega_{r2}t \quad (22)$$

$$\mathrm{i}_{Lr}(t)=-I_{Lr(t3)}.\sin\omega_{r2}t \quad (23)$$

$$\mathrm{v}_{cr1}(t)=0 \quad (24)$$

$$t_{r2}=\frac{\pi}{2}\sqrt{L_r C_{r2}} \quad (25)$$

$$Z_{r2}=\sqrt{\frac{L_r}{C_{r2}}} \quad (26)$$

At the same time C_{r2} has been fully charged by the energy transferred from L_r. After that, the resonant capacitor C_{r2} supplies the energy to the L_r oppositely in mode 5. The resonant path is Composed of D_2-C_{r2}-L_r. When the capacitor voltage V_{cr2} is equal to zero, this mode is finished. The related equations are represented as (21) ~ (24), the resonant period and impedance equations are same to (19) and (20).

Mode 6 $(t_5 \le t < t_6)$

In mode 6, the inductor current i_{Lr} flows continuously through the anti-parallel-diode of switch S_1. The switches of H-bridge inverter have zero-voltage condition, therefore the switches S_4, S_5 can be turned off in zero-voltage-condition (ZVC). At the end of mode 6, the freewheeling current is stopped due to the turn off signals of inverter switches. The corresponding equations are given by (27)-(30).

$$i_{L1}(t)=I_{L1}(t_5)+\frac{V_{in}}{L_1}.t \quad (27)$$

$$\mathrm{i}_{Lr}(t)\approx I_{Lr\min} \quad (28)$$

$$v_{cr1}(t)=0 \quad (29)$$

$$v_{cr2}(t)=0 \quad (30)$$

Mode 7 $(t_6 \le t < t_7)$

When the PWM signal of H-bridge inverter switches S_4, S_5 are stopped, this mode begins. The main inductor transfers the energy to the load during mode 7. The resonant capacitor C_{r1} is charged by resonance with resonant inductor L_r. When the resonant capacitor C_{r1} is charged fully, this mode is finished. The equations related with mode 7 are as following.

$$i_{Lr}(t)=(I_{L1\max}-I_{out})-(I_{out}-I_{L1\max}+I_{Lr\min}).\cos\omega_{r1}t \quad (31)$$

$$v_{cr1}(t)=-(I_{out}-I_{L1\max}+I_{Lr\min})Z_{r1}.\sin\omega_{r1}t \quad (32)$$

$$i_{L1}(t)=I_{L1\max} \quad (33)$$

$$v_{cr2}(t)=0 \quad (34)$$

Mode 8 $(t_7 \le t < t_8)$

After the resonant capacitor C_{r1} is charged fully, this mode starts. In this mode, the DC-link capacitor is charged and the resonant inductor L_r is completely discharged. Then the resonant Inductor current i_{Lr} becomes zero at the end of this section. Also, the load is supplied the energy from input source, main inductor and resonant inductor. The main and resonant inductor current equations are given by (35) and (36).

$$i_{L1}(t)=I_{L1\max}-\frac{1}{L_1}(\mathrm{V}_{out}-\mathrm{V}_{in}).\mathrm{t} \quad (35)$$

$$i_{Lr}(t)=I_{Lr(t7)}+\frac{1}{L_r}V_{out}.t \quad (36)$$

$$v_{cr1}(t)=V_{out} \quad (37)$$

$$v_{cr2}(t)=0 \quad (38)$$

Mode 9 $(t_8 \le t < t_9)$

This mode begins after the resonant inductor L_r discharged the energy totally. On the first half of the mode 9, the main inductor current i_{L1} is decreased linearly and transferred the energy to the DC-link capacitor and the load. But on the second half of the mode 9, the DC-link capacitor is discharged. Because of that, the load current i_{out} can be constant despite decreasing of the main inductor current. The corresponding equations are

$$i_{L1}(t) = I_{L1(t8)}-\frac{1}{L_1}(\mathrm{V}_{out}-\mathrm{V}_{in}).\mathrm{t} \quad (39)$$

$$i_{Lr}(t) = 0 \quad (40)$$

$$v_{cr1}(t)=V_{out} \quad (41)$$

$$v_{cr2}(t)=0 \quad (42)$$

Among of the 18 modes in one cycle, we have analyzed only 9 modes in half cycle.

V. SIMULATION RESULTS

For this, the input voltage is 200V, the converter switching frequency is 30 kHz and the inverter switching frequency is 15 kHz

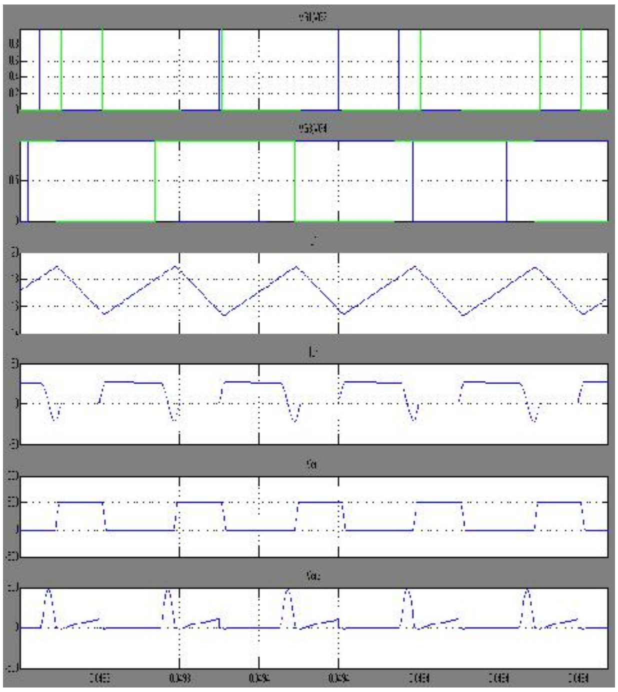

Fig. 4 PWM signals and waveforms of the capacitors voltage, currents of resonant inductor and main inductor.

In order to verify the validity of proposed system, it is simulated using the MATLAB / SIMULINK Software.V_{g1},V_{g2},V_{g3} and V_{g4} are the switch PWM signals, i_{L1} *and* i_{Lr} are main inductor current and resonant inductor current and V_{cr1}, *and* V_{cr2} are the voltages of resonant capacitors respectively in figure 4

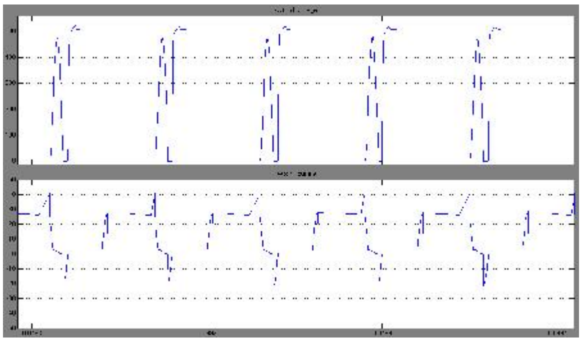

Fig. 5 The voltage and the current waveforms of switch S1

and voltage waveforms at the switching points. Before the resonant switch S_2 and H-Bridge inverter switches S_3, S_4, S_5 and S_6 turns on, the anti-parallel diodes are turned on. Therefore, the switches S_3, S_4, S_5 and S_6 are capable of ZVS. Furthermore, when the resonant switch S_2 is turned off, the resonant capacitor C_r make the switch S_2 can be turned off in ZVS. .

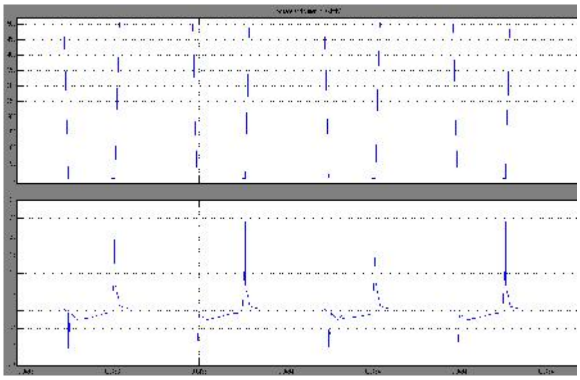

Fig. 6 The voltage and the current waveforms of switch S2

The Fig. 6 shows waveforms of auxiliary switch current and voltage when the switch is turned on and off. The Fig. 7 shows the voltage and current waveforms of the H-bridge inverter switch S_3 adapted to the proposed boost converter at turns on and off.

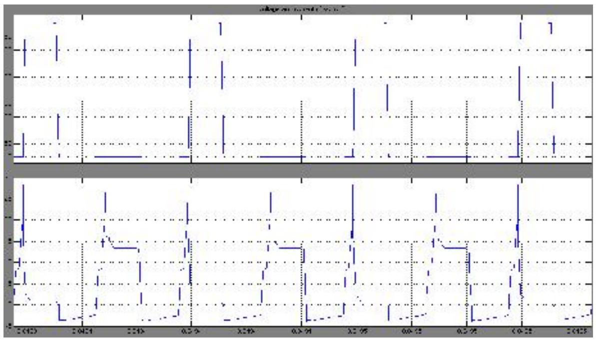

Fig. 7 The voltage and the current waveforms of switch S3

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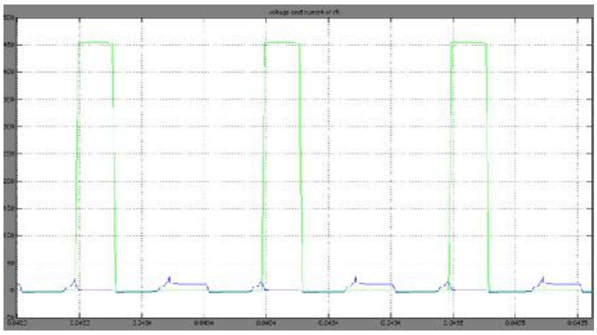

Fig. 8 The voltage and the current waveforms of switch S5

The Fig.8 shows the voltage and current waveforms of the H-bridge inverter switch S_5 adapted to the proposed boost converter at turns on and off.

The switching loss of the power semiconductor devices can be calculated by using the equation

$$Switching\ loss = \frac{1}{2}.V_0.I_0.F_s.\left(t_{c(on)} + t_{c(off)}\right)$$

$t_{c(on)}$ $-$ *circuit turn on time*,

$t_{c(off)}$ $-$ *circuit turn off time*,

F_s $-$ *switching frequency*,

V_0 $-$ *output voltage*,

I_0 $-$ *output current*

The switching loss of the main switch is 0.82W and the auxiliary switch is 0.21W.

IV. CONCLUSION

In this paper, a new soft switching boost converter is proposed using auxiliary switch and resonant circuit. Auxiliary switch performs soft switching in zero voltage by resonant capacitor and inductor, and the Switches of the H-Bridge inverter are capable of ZVS using resonant inductor or capacitor or anti-parallel-diodes of the switches. The proposed system is analyzed in detail mathematically, the switching losses are very less and its validity has been confirmed through the simulation.

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