A PI-CONTROLLER ASSISTED SARC BASED HIGH FREQUENCY BOOST CONVERTER USING SOFT SWITCHING TECHNIQUE

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Abstract

In this paper, A simple auxiliary resonant circuit (SARC) is a new topology of DC-DC converter which is found to provide improved efficiency compared to the conventional DC converters. The improved efficiency is achieved by using soft switching techniques for turning on and off of the devices connected in the converter circuit. Soft switching techniques like ZCS and ZVS combined with a suitable controller results in the operation of the converter with less switching loss and less strain on the devices. The DC converter used in this circuit is basically a boost converter with a closed loop control through a PI controller. The PI controller used here is an Electronic PI controller for better performance especially during transient conditions.

Keywords Soft switching, ZCS, ZVS, Boost converter, SARC, Electronic PI-controller.

I. INTRODUCTION

Recently, switch-mode power supplies has become smaller and lighter, because the switching frequency has increased. However, as the switching frequency has increased, the periodic losses at turn-ON/OFF have also increased. As a result, this loss brings increasing loss of whole system. Therefore, to reduce these switching losses, a soft-switching method is proposed, which involves an added auxiliary circuit, instead of a conventional hard-switching converter. However, the auxiliary circuit for resonance increases the complexity and cost. For some resonant converter with auxiliary switch, main switch achieves soft-switching but auxiliary switch performs hard switching. Thus, these converters cannot improve the whole system efficiency owing to switching loss of auxiliary switch.

On the other hand, in cases of converters doing hard switching at a high frequency, the switching loss increases in proportion to the switching frequency. Thus, in order to reduce switching losses, the soft switching technology, which uses resonance by inductor and capacitor, has been actively researched. The proposed converter has better efficiency than a conventional boost converter. Through this circuit, all of the switching devices perform soft-switching under zero-voltage and zero-current conditions. Therefore, the periodic losses generated at turn-on and turn-off can be decreased. The adopted soft switching boost converter is simulated by PowerSIM (PSIM) software.

II. PROPOSED SOFT SWITCHING BOOST CONVERTER

The auxiliary circuit is composed of main switch (S_1), an auxiliary switch (S_2), a resonant capacitor (C_r), a resonant inductor (L_r), and two diodes (D_1 and D_2), as shown in Fig.1. The operational principle of this converter can be divided into six intervals.

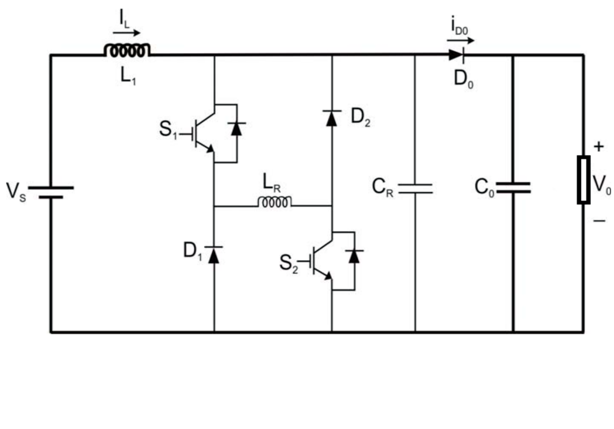

Fig. 1. Proposed Boost Converter.

A. *Interval-1* ($t_0 \le t < t_1$)

Switches S_1 and S_2 are both in the OFF state, the current cannot flow through switches S_1 and S_2, and the accumulated energy of the main inductor is transferred to the load. In this interval, the main inductor current decreases linearly. During this time, the current does not flow to the resonant inductor, and the resonant capacitor has charged as output voltage.

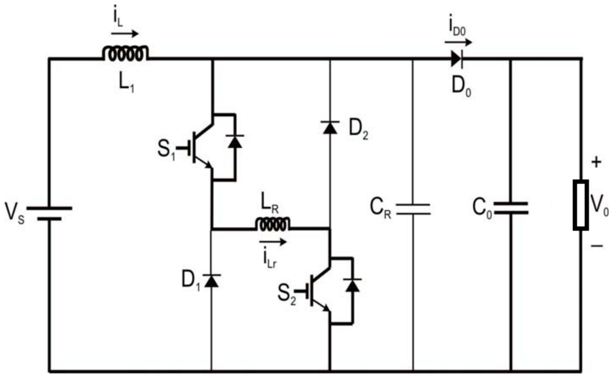

Fig. 2. Operating Mode-1.

After two of the switches have been turned-ON, interval-1 is over. These conditions are as follows:

$$v_L(t) = V_s - V_o \tag{1}$$

$$i_L(t) = i_L(t_o) - \frac{V_o - V_s}{L_1} \tag{2}$$

$$i_D(t) = i_L(t) \tag{3}$$

$$i_L(t) = 0 \tag{4}$$

$$V_c(t) = v_o \tag{5}$$

$$i_L(t_1 = 0 \tag{6}$$

$$V_{Lr}(t) = V_o \tag{7}$$

B. *Interval-2* ($t_1 \le t < t_2$)

After turning on switches S_1 and S_2, the current flows to the resonant inductor. At that time, two of the switches are turned- ON under zero-current condition. This is known as Zero-Current Switching (ZCS).

Because the main and auxiliary switches implement ZCS, this converter has lower switch loss than the conventional hard switching converter.

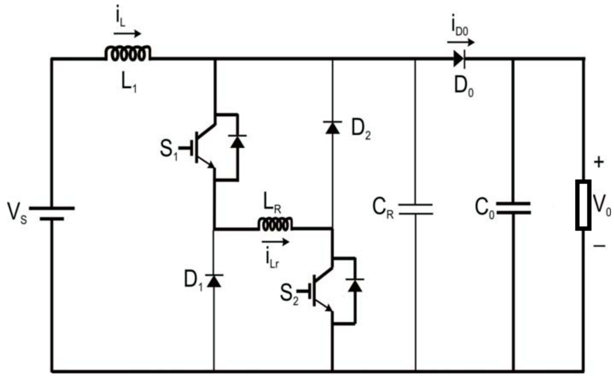

Fig. 3 Operating Mode-2.

As the resonant current rises linearly, the load current gradually decreases. At t_2, the main inductor current equals the resonant inductor current, and the output diode current is zero. When the resonant capacitor voltage equals V_O, the output diode is turned-off, and interval- 2 is over.

D. *Interval- 4* ($t_3 \le t < t_4$)

$$i_{Lr}(t) = \frac{V_o}{L_r} t \tag{8}$$

$$i_L = i_{L_r}(t_2) \tag{9}$$

$$i_{D_o}(t_2) = 0 \tag{10}$$

C. *Interval-3* ($t_2 \le t < t_3$)

The current that flowed to the load through output diode D_O no longer flows, since t_2 and the resonant capacitor C_r, and the resonant inductor L_r start a resonance. The current flowing to the resonant inductor

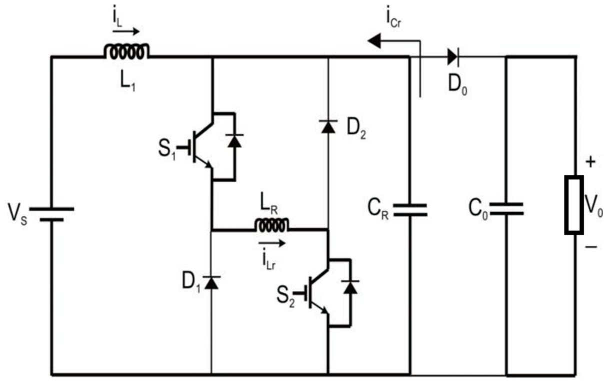

Fig. 4. Operating Mode-3.

is a combination of the main inductor current and the resonant capacitor current.

$$i(t) \equiv I_{min} \quad (11)$$

During this resonant period, the resonant capacitor C_r is discharged from V_o to zero. Resonant frequency and impedance are given by equations (14) and (15). When the voltage of the resonant capacitor equals zero, the interval-3 is over.

$$V_{C_r}(t_2) = V_o \quad (12)$$

$$V_{C_r}(t_3) = 0 \quad (13)$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \quad (14)$$

$$Z_r = \sqrt{\frac{L_r}{C_r}} \quad (15)$$

After the resonant period in interval-3, when the voltage of the resonant capacitor equals zero, interval-4 begins.

In this interval, the freewheeling diodes of D_1 and D_2 are turned-ON, and the current of the resonant inductor is the maximum value. The resonant inductor current flows to the freewheeling diodes S_1-L_r-D_2 and S_2-L_r-D_1 along the Free wheeling path.

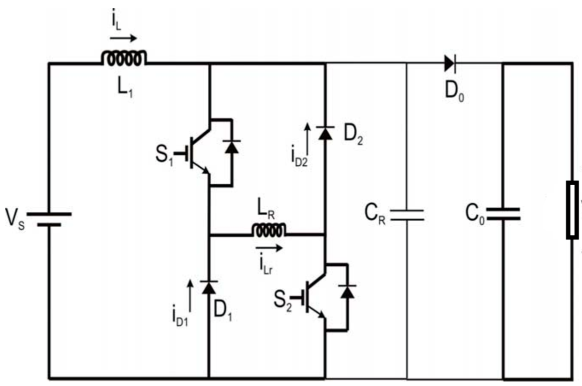

Fig. 5. Operating Mode-4.

$$i_{Lr}(t) = i_L(t) + i_{D1}(t)\, i_{D2}(t) \quad (16)$$

$$i_L(t_3) = i_{Lr}(t_4) = i_L \quad (17)$$

During this time, the main inductor voltage equals the input voltage, and the current accumulating energy increases linearly.

$$V_L(t) = V_s \quad (18)$$

$$i_L(t) = I_{min} + \frac{V_s}{L} t \quad (19)$$

E. Interval- 5 $(t_4 \le t < 15)$

In interval-5, all of switches are turned-OFF under the zero transferred to the load. Then, the interval-6 is over.

voltage condition by the resonant capacitor. During this interval, the initial conditions of the resonant inductor current and resonant capacitor voltage are as follows:

$$i_{Lr}(t_4) = i_{L,\,max} \quad (20)$$

$$V_{Cr}(t_4) = 0 \quad (21)$$

$$i_L \equiv I \quad (22)$$

$$V_{Cr}(t_5) \equiv V_o \quad (23)$$

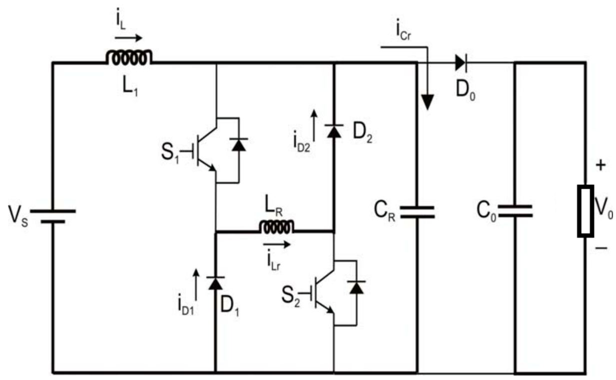

Fig. 6 Operating Mode-5

When all of the switches are turned-OFF, the resonant capacitor C_r is charged to the output voltage by two of the inductor currents. Until the resonant capacitor has been charged to V_o, the output diode is in the OFF state.

F. Interval-6 $(t_5 \le t < t_6)$

Interval-6 begins when the resonant capacitor equals the output voltage, and the output diode is turned-ON under the zero voltage condition. During this interval, the main inductor current i_L and the resonant inductor current i_{Lr} flow to the output through the output diode D_o.

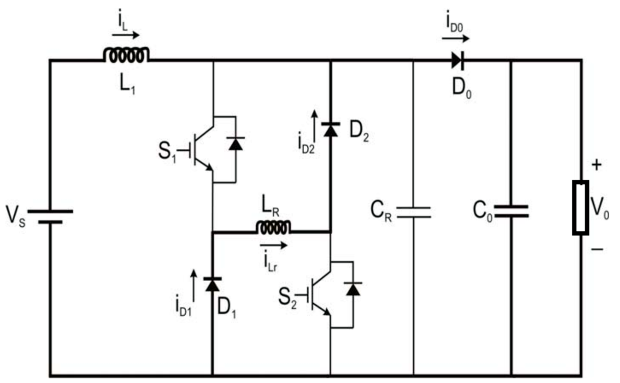

Fig. 7. Operating Mode-6.

$$i_{Do}(t) = i_L(t) + i_L(t) \quad (24)$$

$$V_{Cr}(t) = V_o \quad (25)$$

At that time, two of the inductor currents are linearly decreased, and the energy of the resonant inductor is completely transferred to the load. Then, the interval-6 is over.

$$i_L(t) = I_{max} - \frac{V_o - V_s}{t} \quad (26)$$

$$i_{Lr}(t) = i_{Lr}(t_6) - \frac{V_o}{L_r} t \quad (27)$$

$$i_{Lr}(t_6) = 0 \quad (28)$$

III. DESIGN PROCEDURE OF RESONANT INDUCTOR AND CAPACITOR

To satisfy the Zero-Voltage Switching (ZVS) condition, the resonant inductor current must exceed the main inductor current during the freewheeling interval of interval-4.

In Fig. 8, the time of interval-2, which is the rising time of the resonant inductor current, is expressed by equation (29). For the maximum resonant current, the time of interval-3, which is the resonant time of the resonant inductor and capacitor, is defined as one-fourth of the resonant period. As a rule of thumb, the rising time of the resonant inductor current

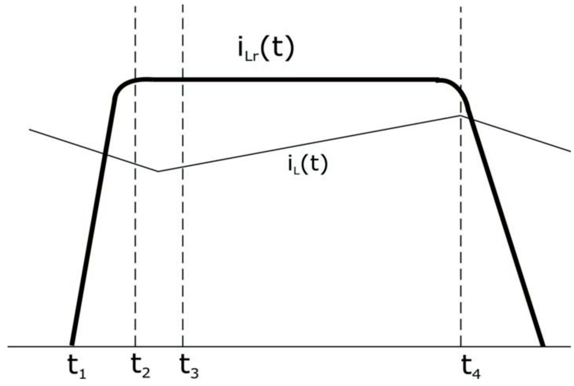

Fig. 8. ZVS Condition.

(intervals 2–3) can be set to 10% of the minimum ON time. This is expressed as (31).

$$t_2 - t_1 = \frac{L_r}{V_o} I_{min} \quad (29)$$

$$t_3 - t_2 = \frac{T_r}{4} \quad (30)$$

$$\frac{L_r}{L_o} I_{min} + \frac{T_r}{4} = 0.1DT \quad (31)$$

$$\frac{V_O}{Z_r} > \Delta i_L \quad (32)$$

TABLE I. CONVERTER SPECIFICATIONS

Parameters	Symbol	Range in units
Input Voltage	V_{in}	200 V
Switching Frequency	F	30 KHz
Main Inductor	L	560 mH
Resonant Inductor	L_r	40 μ H
Resonant Capacitor	C_r	20 nF
Output Capacitor	C_o	1000 μ F
Resistances	R	1k ohm
	R1	2k ohm
	R2	1 k ohm
capacitance	C	1000 μ F

IV. SIMULATION RESULTS

A. Open- Loop Circuit Of Proposed Boost Converter

The adopted Soft-switching Boost Converter for input voltage of 200V and switching frequency of 30KHz is simulated using the PSIM software.

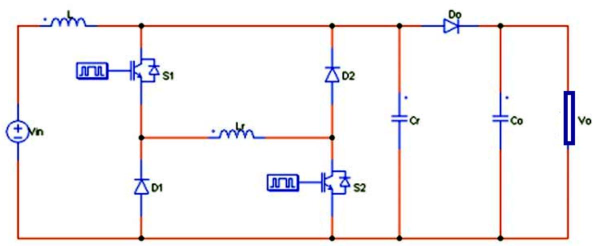

Fig. 9. Open- loop circuit of proposed boost converter in PSIM.

Fig. 10 shows the current and voltage waveforms of the switch. Via resonance of the resonant inductor and capacitor, ZVS and ZCS are achieved at turn-ON and turn-OFF.

Fig. 11 shows the main inductor current and the gate signal of the main switch. When the main switch is turned-ON, the energy of inductor is accumulated. When it is turned-OFF, this energy is transferred to the output.

B. Closed-Loop Circuit Of Proposed Boost Converter

Electronic PI-controller with the use of op-amps is adopted here to control the output voltage for any change in the input voltage and the corresponding reference voltage. The Fig. 13 shows the schematic diagram of the closed-loop control for the proposed boost converter.

The Proportional gain (K_P) and the Integral gain (K_I) are calculated by using equations (33) and (34).

$$K_p = \frac{R_2}{R_1} \tag{33}$$

$$K_1 = \frac{1}{R_2\, C} \tag{34}$$

The Fig. 14. to Fig. 16. shows the simulation results of the proposed booset converter in closed-loop

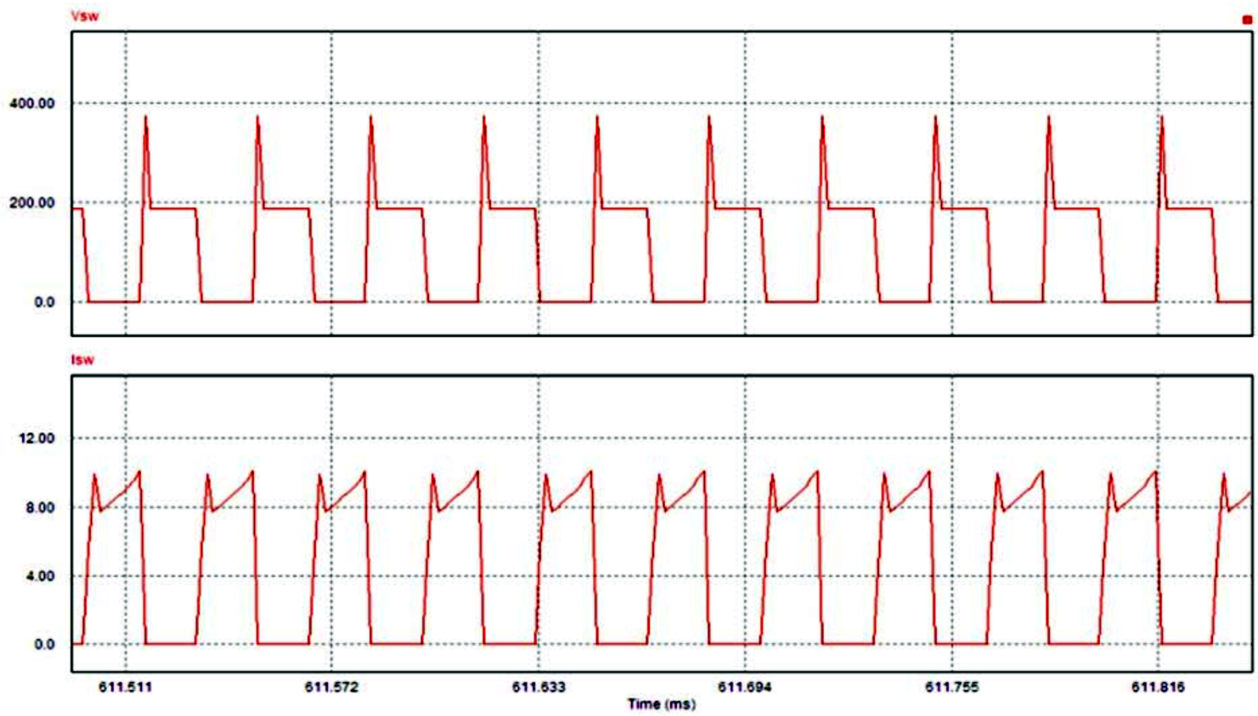

Fig. 10. Simulated waveforms of main switch voltage and current in open-loop

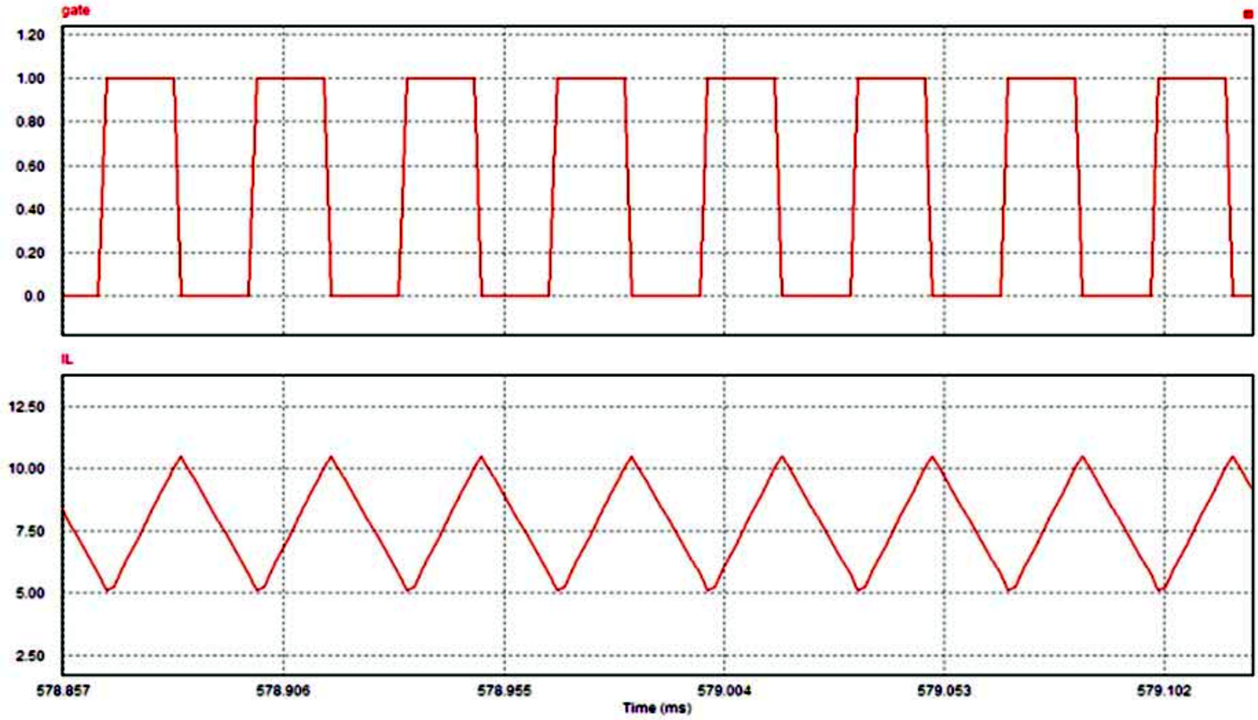

Fig. 11. Simulated waveforms of the gate pulse and main inductor current in open-loop.

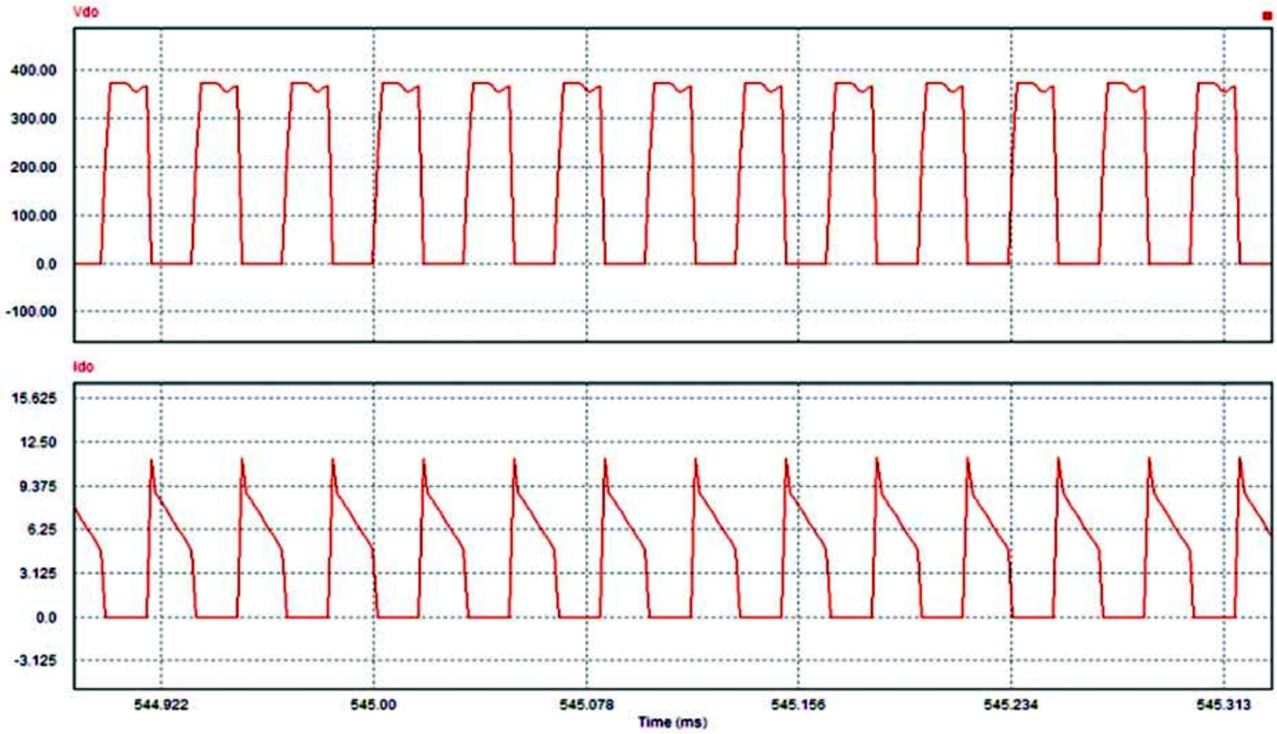

Fig. 12. Simulated waveforms of output diode voltage and current in open-loop.

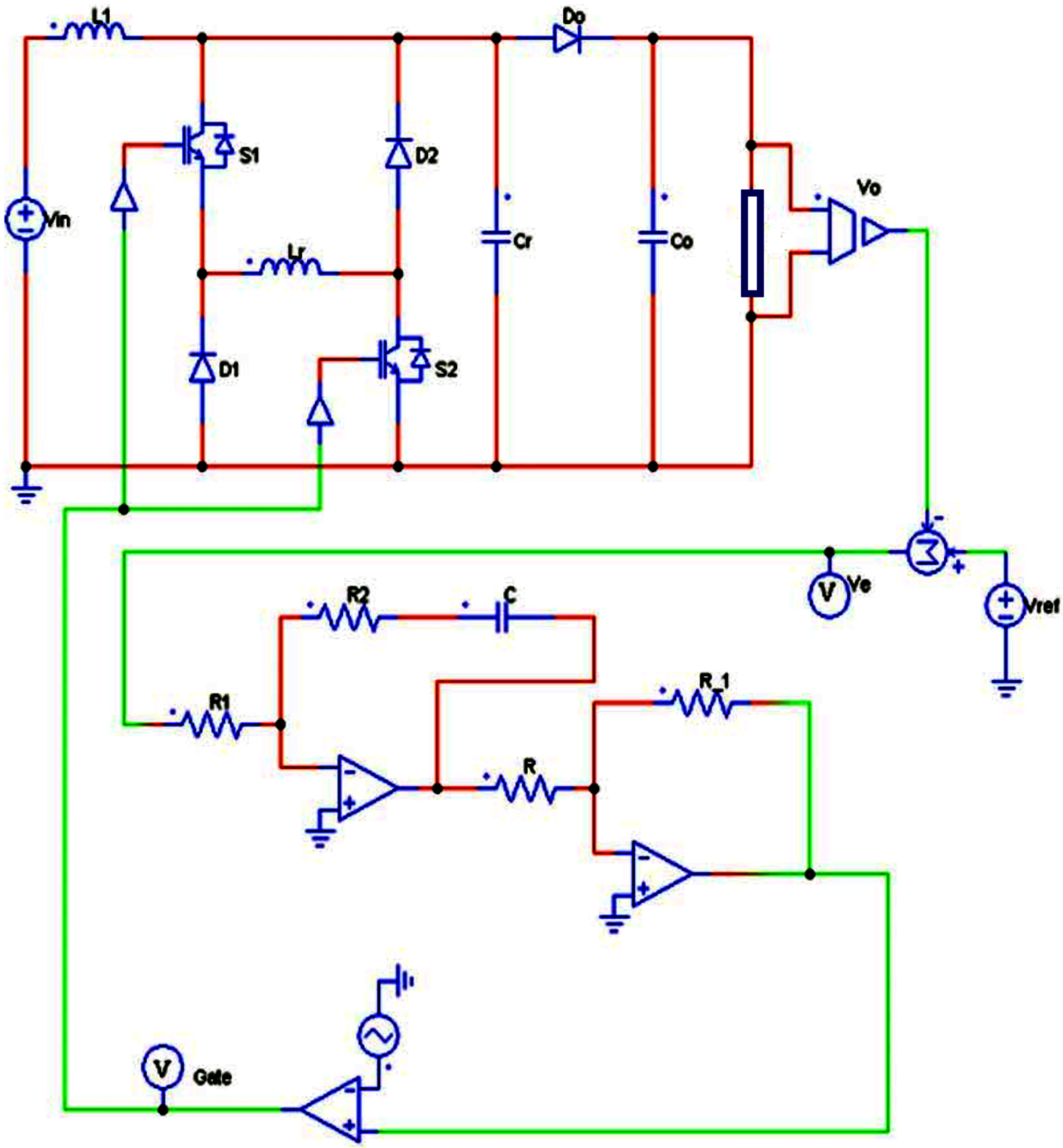

Fig. 13. Closed-loop circuit of proposed boost converter in PSIM.

C. Comparison Between Open-Loop and Closed-Loop Response

For the input voltage of 200 V and switching frequency of 30 KHz, the output voltage is compared with open-loop and closed-loop.

From the simulated waveform of output voltage in open- loop as shown in Fig. 17 and simulated waveform of output voltage in closed-loop as shown in Fig. 18, it is clearly noticed that the closed-loop has greatly improved the voltage profile, when compared with open-loop.

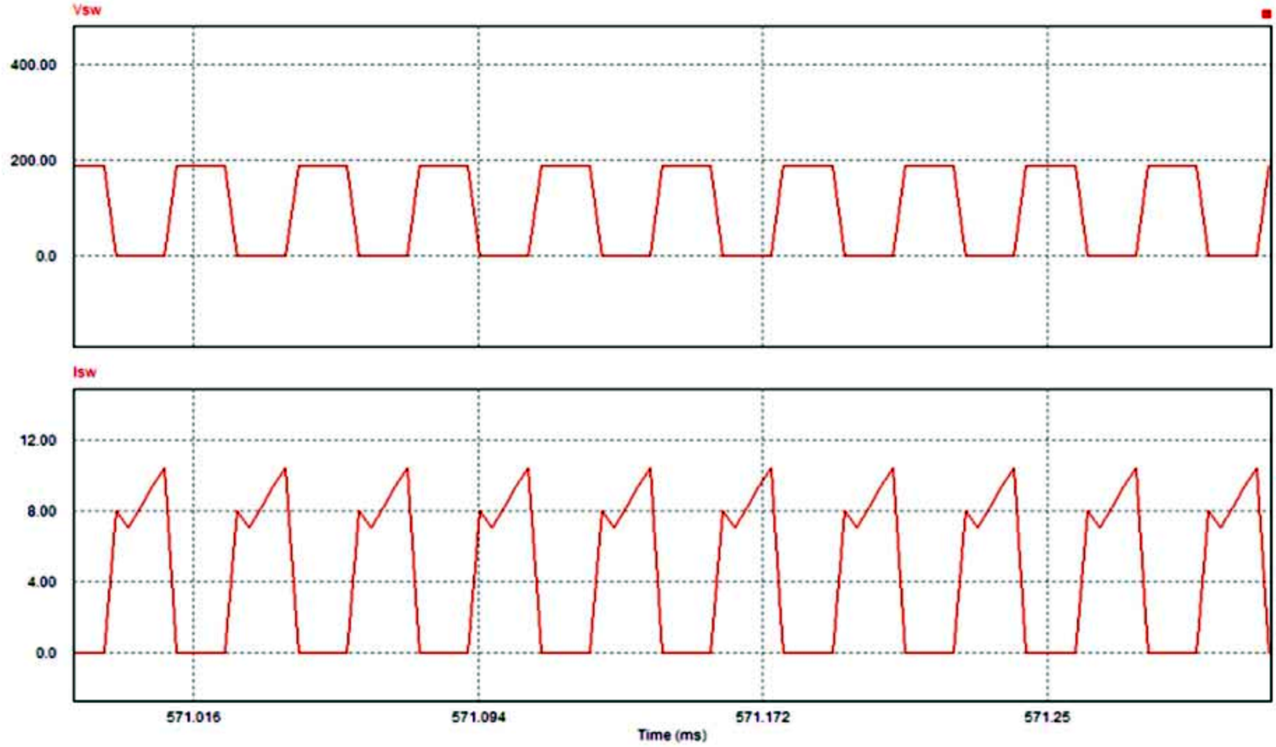

Fig. 14. Simulated waveforms of main switch voltage and current in closed-loop

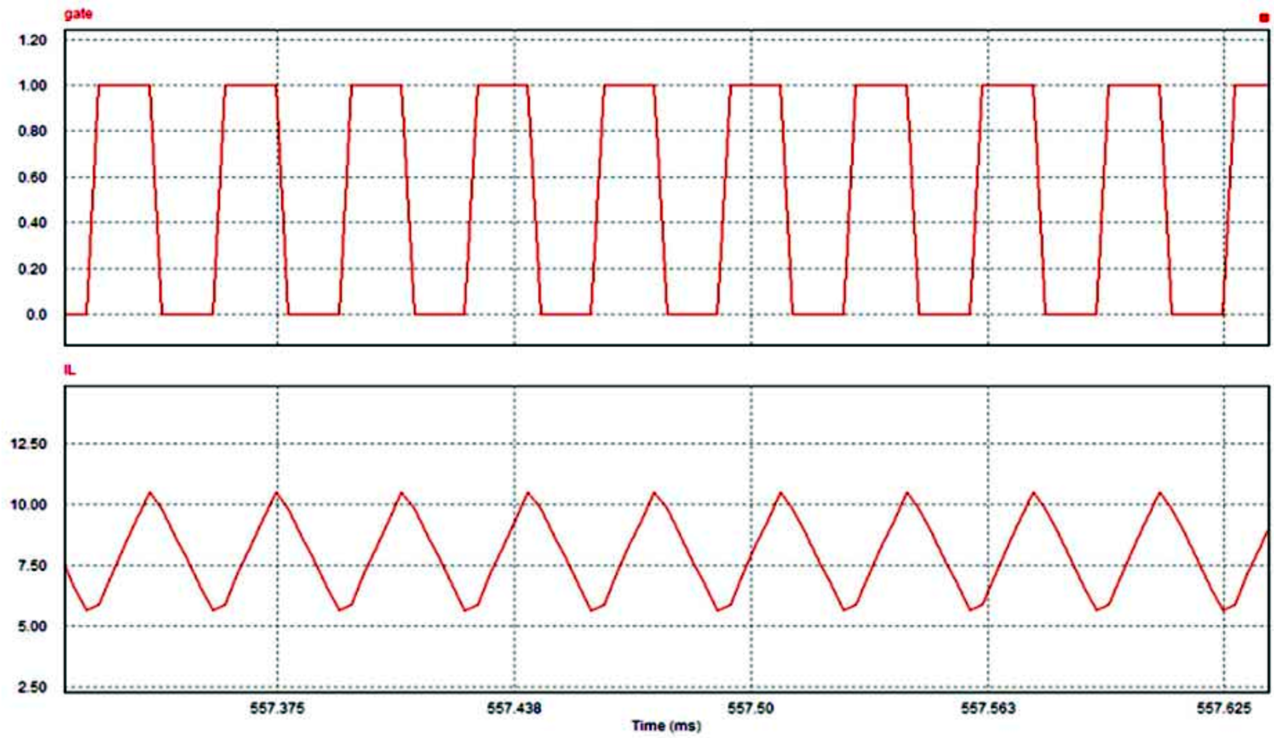

Fig. 15. Simulated waveforms of the gate pulse and main inductor current in closed-loop.

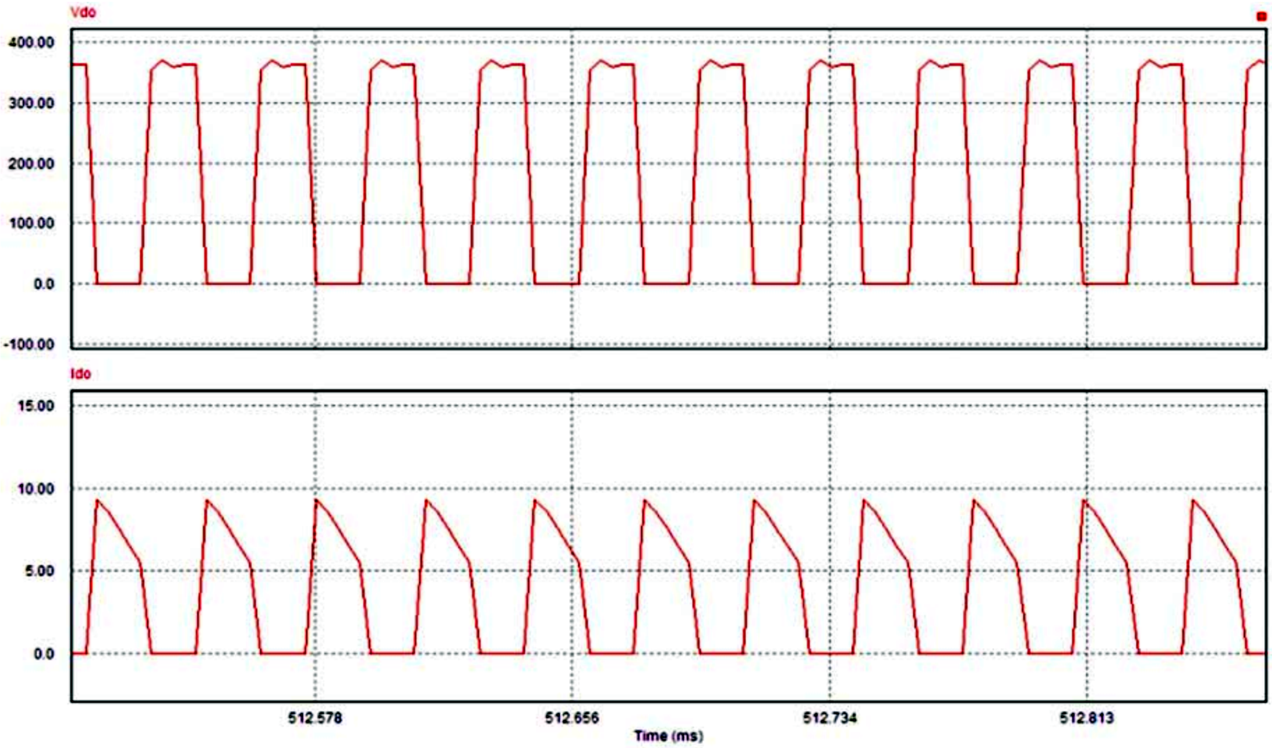

Fig. 16. Simulated waveforms of output diode voltage and current in closed-loop

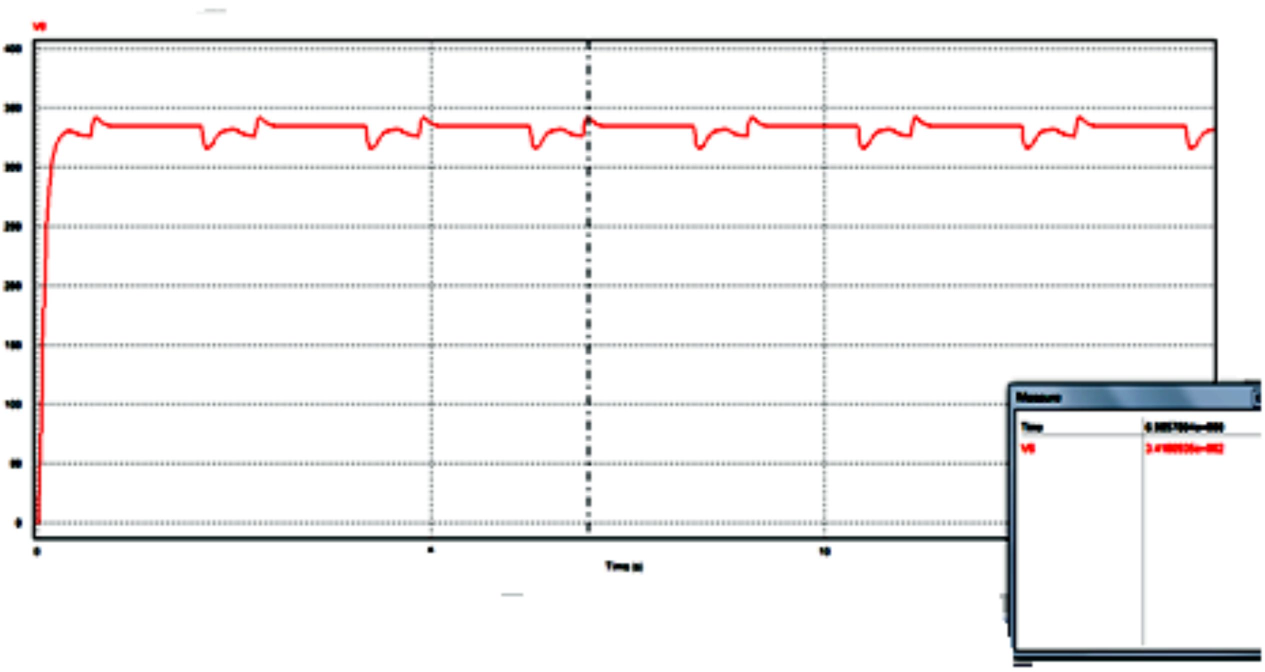

Fig. 17. Simulated waveform of output voltage in open- loop.

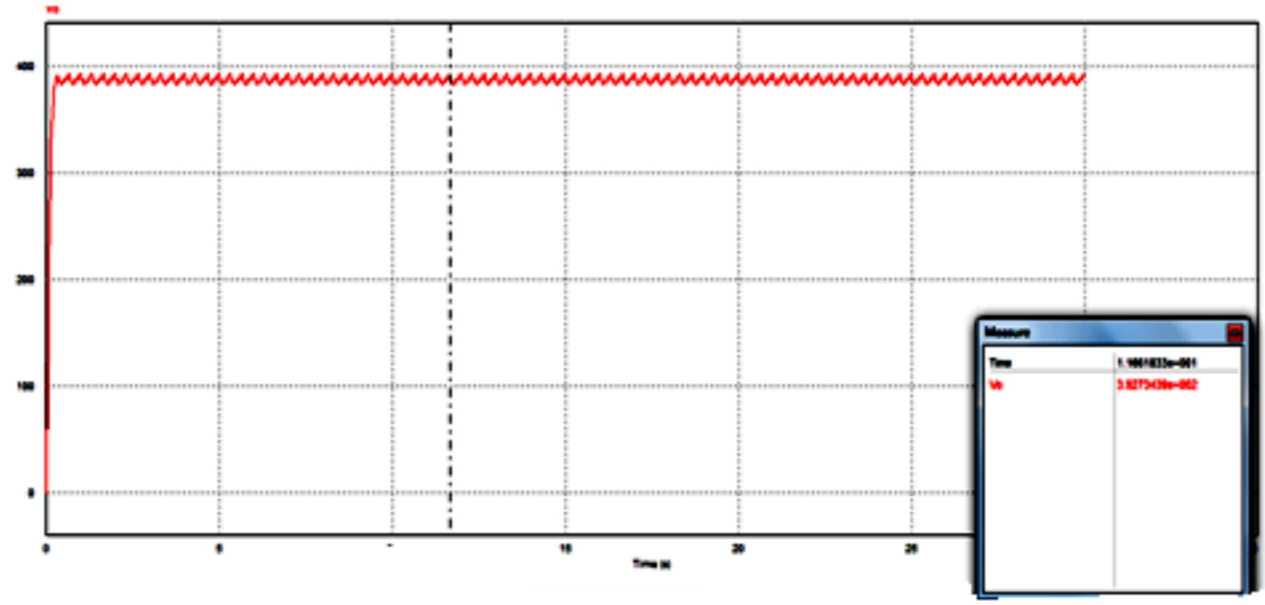

Fig. 18. Simulated waveform of output voltage in closed- loop.

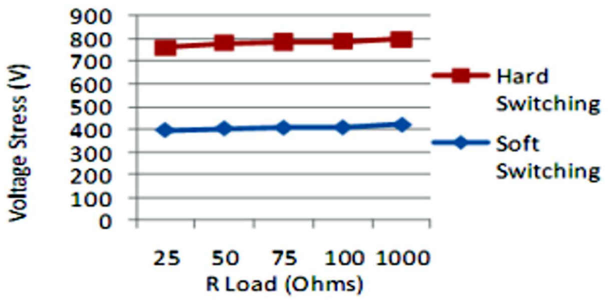

Fig. 19. Voltage Stress across the switch under various load conditions.

V. CONCLUSION

In this proposed work, we have designed and analyzed the operational modes of the adopted high frequency Soft- switching Boost Converter, which involved an added Simple Auxiliary Resonant Circuit (SARC) in the conventional boost converter with closed-loop control mode using Electronic PI- controller. This soft-switching boost converter is easy to control because the two switches are controlled by the same gating signal. Moreover all the switching devices in this converter have achieved ZCS and ZVS conditions by the resonant inductor and capacitor at turn-ON/OFF. As a result, the switching losses were reduced dramatically. This Soft- switching Boost Converter can be applied to a stand-alone and a grid-connected PV system using power conditioning system.

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