

SOFT SWITCHING OF BOOST CONVERTER USING H-I BRIDGE RESONANT CIRCUIT

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Abstract—A innovative soft-switching boost converter is proposed in this paper. The conventional boost converter produces switching losses at turn ON and OFF, and this causes a reduction in the whole system's efficiency. The proposed boost converter employs a soft switching method using an auxiliary circuit with a resonant inductor and capacitor, auxiliary switch, and diodes. Therefore, the proposed soft-switching boost converter diminishes switching losses more than the conventional hard-switching converter. The efficiency, which is about 91% in hard switching, rises to about 96% in the proposed soft-switching converter. In this paper, the performance of the proposed soft-switching boost converter is confirmed through the theoretical analysis, simulation, and experimental results.

1. INTRODUCTION

In conventional dc-ac power conversion, the input to three-phase PWM inverters is a firm dc voltage supply and the power switches operate in a switch mode. Therefore, the power devices are subjected to high switching strains and switching power losses that increase linearly with the switching frequency of pulse-width modulation. High switching power losses not only restrict switching frequency, but also diminish the system efficiency and produce tremendous heat inside the inverter. This compels the industrial personnel to use greater heat sinks, which result in increased volume and weight of the system. In addition to these restrictions, the system suffers from other shortcomings such as EMI and acoustic noise.

The increased demand for high power density converters in aerospace, defense and communications has provoked to design Soft-switching converters.

To decrease the switching losses and improve the system's efficiency.

These converters realize power supplies that are highly dynamic, high performance with negligible noise.

Switch-mode power supplies have become lesser and lighter due to higher switching frequency. However, higher switching frequency causes lots of intermittent losses at turn ON and turn OFF, resulting in increasing losses of the whole system. Therefore, many converters have been presented that use resonance to diminish switching losses. Many do research using resonance have presented a zero-voltage and zero-current switching (ZVZCS) converter that performs zero-voltage switching (ZVS) and zero-current switching (ZCS) simultaneously. However, the auxiliary circuit for resonance rises the complexity of the circuit, as well as its cost. For some resonant converters with an auxiliary switch, the main switch allows soft switching, while the auxiliary switch makes hard switching. These converters cannot advance the whole

system's efficiency owing to the switching losses of the auxiliary switch.

DC-DC CONVERTERS

For high effectiveness, the SMPS switch must turn on and off quickly and have low losses. The arrival of a commercial semiconductor switch in the 1950's implied a major milestone that made SMPSs such as the boost converter likely. Semiconductor switches turned on and off more fast and lasted longer than other switches such as vacuum tubes and electromechanical relays. Middlebrook averaged the circuit configurations for each switch state in a method called state-space averaging. This simplification reduced two systems into one. The new model led to perceptive design equations which helped SMPS growth.

2. BOOST CONVERTERS

A boost converter (step-up converter) is a power converter with an output DC voltage larger than its input DC voltage. It is a session of switched-mode power supply (SMPS) containing minimum two semiconductor switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to decrease output voltage ripple. A boost converter may also be referred to as a 'Joule thief'. This term is usually used only with very low power battery applications, and is aimed at the capability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be missed since a normal load wouldn't be able to handle the battery's low voltage.

3. EXISTING SYSTEM

Power can also come from DC sources like batteries, solar panels, rectifiers and DC generators. A process that variations one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage larger than the source

voltage. A boost converter is sometimes called a step-up converter since it “steps up” the source voltage. Since power ($P = VI$) must be conserved, the output current is lesser than the source current.

4. HARD SWITCHING BOOST CONVERTER

Boost converter is a DC-DC converter whose output voltage is larger than the input voltage. In PV fed system, this acts as a maximum power point tracker. It consists of a switch, a diode, a capacitor and an inductor. The switch used here is MOSFET. Capacitor is typically added in output side to reduce the ripples. The input to the boost converter is fed from PV system. The switching losses are high in hard switching converter since there is overlapping of voltage and current during switching.

A. CHARACTERISTICS OF HARD SWITCHING SIMPLER SWITCHING CIRCUIT

Hard switching requires less power for inductors and capacitors in the circuit at all operating conditions. This means that it avoids the cost complexity and power loss from at least one power component. The total energy stored in the resonant circuit will discharge completely in the spark. This gives the spark more energy than it otherwise would get and make the spark cause more damage.

B. OUTPUT ENERGY IN THE EVENT OF PARKS

Often in a high voltage SMPS it is unavoidable that, in the event of sparks the total energy stored in the resonant circuit will discharge completely in the spark. This gives the spark more energy than it otherwise would get, and make the spark cause more damage.

C. LOAD INDEPENDENT OUTPUT VOLTAGE

By moving switching frequency far-off off the resonant frequency and using a simple buck type converter we have been able to make a switching converter with very low output impedance. The buck converter’s output voltage is accurately controlled by PWM of the switching transistors. To control the output voltage by a forward regulated load independent converter is especially important in the events of load transients, because even a fast, advanced controller, will not by itself manage to compensate for rapid transients.

D. CHALLENGES OF HARD SWITCHING LOSS

By accepting relatively high switching powers we are left with only one means to reduce the average power loss in transistors namely switching time. It is the time relation between switching phases, and ON or OFF phases, on each transistors determines it’s average switching loss. Smaller the switching phases are, compared to the ON or OFF phases, the better. When we take into account the unavoidable higher conduction loss and additional loss in a larger number of reactive components, there would probably be the same amount of loss in a real “soft switching” regulator.

E. PROBLEMS IN HARD SWITCHING

- Losses occur during switching
- Device stress, thermal management
- EMI due to high di/dt and dv/dt
- Energy loss in stray L and C
- Switching of high voltage transformer

F. POSSIBLE SOLUTIONS

- Snubbers to decrease di/dt and dv/dt usually no change in losses (unless loss recovery)
- Circuit layout to reduce stray inductances
- Gate drive
 - 1) Circuit layout
 - 2) Turn on / off speed

Soft switching to achieve ZV Sand/or ZCS

The above mentioned problems can be overcome by the above solutions and we are approaching the soft switching technique which utilizes the resonant circuit.

5. SIMULATION OF EXISTING SYSTEM

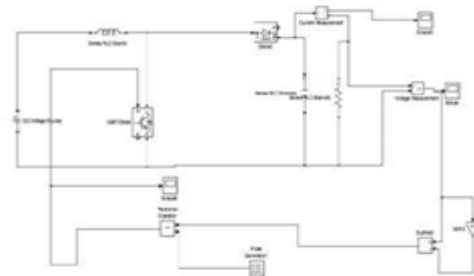


Fig.1 simulation model

SPECIFICATIONS

PARAMETERS	VALUES
Input voltage	130 V
Switching frequency	30 kHz
Output voltage	330 V
Output current	0.35 A

OUTPUT VOLTAGE WAVEFORM

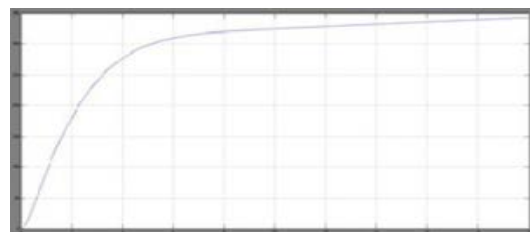


Fig.2 output voltage

OUTPUT CURRENT WAVEFORM

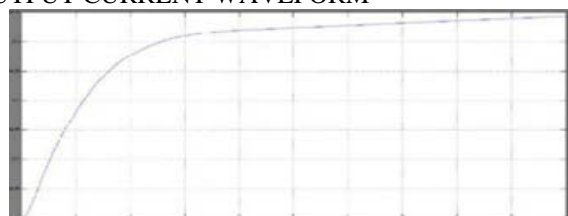


Fig.3 output current

In order to get the regulated output voltage we are proposing the “soft switching boost converter with an HI Bridge resonant circuit”.

6. PROPOSED SYSTEM SOFT SWITCHING

- Switching transitions occur under satisfactory conditions – device voltage or current is zero.
- Reduced switching losses, switch stress, possibly low EMI, easier thermal management.
- A must for very high frequency operation.
- Usually involves compromises in conduction loss, switch rating, passive components etc.

Advances in soft switching converters have set new benchmarks in performance and cost in power converter technology, and have shown potential in overcoming the limits of conventional hard switching technology. Resonant dc link inverters have been understood at power ratings of 200 kVA in single modules. The use of zero voltage switching with MOSFET power devices demonstrates of some aggressive benchmarks when compared with conventional technology. These include: 100% power device utilization

- Low EMI which meet Mil-specs
- Enhanced robustness.
- High power densities
- High switching frequencies
- High efficiencies
- Power factor improvements
- Isolated input and output
- Reduced number of components
- Lower peak currents
- Low Cost

APPLICATIONS

- Traction motors
- Industrial SMPS systems
- Aircraft Power supplies
- Industrial Oven Controls
- High frequency applications.

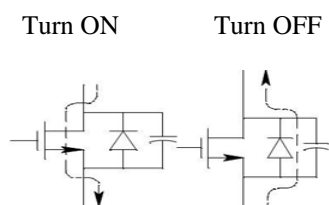
SWITCHING

- ZVS (Zero Voltage Switching)
- ZCS (Zero Current Switching)

ADVANTAGES

- Lower losses
- Low EMI
- Allows high frequency operation

ZERO VOLTAGE SWITCHING



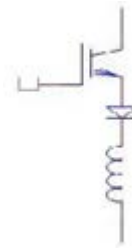
TURN ON

- Switch voltage brought to zero before gate voltage is applied.
- Ideal zero loss transition
- Preferred scheme for very high frequency applications using MOSFETs

TURN OFF

- Low loss transition
- Parallel capacitor as a loss less snubber

ZERO CURRENT SWITCHING



TURN ON

- Low-loss transition
- Series inductor as a loss-less snubber
- Energy in junction capacitor is lost

TURN OFF

- Switch current brought to zero before gate voltage is removed
- Ideal, zero-loss transition

7. SOFT SWITCHING BOOST CONVERTER

A new soft-switching boost converter with an auxiliary switch and resonant circuit is planned in this paper. The resonant circuit consists of a resonant inductor, two resonant capacitors, two diodes, and an auxiliary switch. The resonant capacitor is discharged beforehand the main switch is turned ON and the current flows through the body diode. Compared with other soft-switching converters, the planned converter increases the whole system’s efficiency by reducing switching losses better than other converters at the same frequency. In this paper, some simulation results are obtainable for a 600- W, 30-kHz prototype boost converter by means of insulated-gate bipolar transistor (IGBT). Then, experimental results are presented to verify the steady-state operational principle of the proposed circuit.

A. ADVANTAGES OF SOFT SWITCHING BOOST CONVERTER

An active snubber, which consists an active switch and a capacitor, has to switch at twice the switching frequency and at the full power of the main dc/dc converter. In order to eliminate the snubber circuit, Reimannetal precharge the leakage inductance current by vigorously turning on the inverter switch at the voltage-fed side to a level that matches the boost inductor current.

However, the commutation time has to be precisely controlled by a feedback loop, and the complexity of this loop significantly limits practical applications. The system outlined in short-circuits the two upper or lower switches at the voltage-fed inverter side for a short interval and permits the leakage inductance current to charge up via the clamped voltage at the current-fed side. Technique employs a fixed commutation time and is adaptable to a wide load and voltage operation range. In both active commutating methods, the switches at voltage-fed side inverter are hard switching. This paper proposes a “soft-commutating” method for an isolated boost full bridge converter in high power –application. In boost operation isolated boost converter. The boost converter topology has been extensively used in various ac/dc and dc/dc applications. In fact, the front end of today’s ac/dc power supplies with power-factor correction (PFC) is almost entirely implemented with boost topology. Also, the boost topology is used in numerous applications with battery-powered input to generate a high output voltage from a moderately low battery voltage. At higher power levels, the continuous-conduction-mode (CCM) boost converter is the preferred mode of operation for the implementation of a front end with PFC. As a result, in recent years, important effort has been made to improve the performance of High-power boost converters. The majority of these development efforts have been focused on dropping the adverse effects of the reverse-recovery characteristic of the boost rectifier, especially for the conversion efficiency and electromagnetic compatibility (EMC). Generally, the lessening of reverse-recovery-related losses and EMC problems require that the boost rectifier is soft switched off, which is attained by prevailing the turn-off rate of its current. So far, a number of soft-switched boost converters and their variations have been proposed. All of them use additional components to procedure passive snubber or active snubber circuits that control the turn-off di/dt rate of the boost rectifier. The passive snubber approaches in use only passive components such as resistors, capacitors, inductors, and rectifiers,

although active snubber approaches employ one or more active switches. The majority of them offer the soft turn off of the boost rectifier, ZVS of the boost switch, and “hard” switching of the active-snubber switch. However, a number of active-snubber implementations feature soft switching of all semiconductor components, i.e., in addition to the soft turn off of the boost rectifier, the boost switch and the active-snubber switch operate with ZVS or ZCS. In this paper, a novel implementation of the soft-switched boost converter with active snubber is described. The major feature of these circuits is the soft switching of all semiconductor components. Exactly, the boost rectifier is switched off with a controlled turn-off di/dt rate, the boost switch is turned on with ZVS, and the auxiliary button in the active snubber is turned off with ZCS. As a result, switching losses are reduced, which has beneficial effects on the conversion efficiency and EMC performance.

B. SOFT-COMMUTATING METHOD

Not like the voltage-fed dc/dc converter, the input power in a current-fed dc/dc converter is continuous and cannot be interrupted in operation. It either goes into the boost inductor in energy storing mode or goes to the load in energy transferring mode. But, in an isolated boost converter, commutation from energy storing mode to energy transferring mode cannot take place instantly due to the existence of the leakage inductance of the isolation transformer. The mismatched current between the current-fed inductor and the transformer leakage inductance has to flow backward into a snubber circuit during commutation, resulting in a disallowed power back into the clamping switch and the capacitor. Moreover, the energy (the reactive power) “rejected” by the leakage inductance also increases switch conduction loss and current rating due to energy circulation in the current-fed side of the converter. As a matter of fact, in boost converter that connects between a 12-V battery and a near 300-V high voltage bus in a fuel cell/hybrid vehicle, the rejected power in a isolated boost converter could be substantial due to hundreds of amperes current draw from the battery. The present soft-commutating way breaks through the barriers uniquely existing in the current-fed isolated dc/dc converter through the following approaches.

- 1) Separating the commutating mode from the energy transferring mode to prevent load power from flowing into the snubber circuit (unlike the active clamped approaches which mix these two modes together).
- 2) Minimizing the incongruity current when commutation takes place by presetting the transformer winding current through a resonant tank in the voltage-fed side full bridge inverter during energy storing mode (soft-commutating mode).
- 3) Reducing the commutating time by short-circuiting the transformer winding through the voltage-fed side full bridge inverter during commutating mode (accelerated commutating mode).
- 4) Maintaining soft-switching structures for the switches of the voltage-fed side full bridge inverter by utilizing a similar soft-switching mechanism in the well-known full bridge soft-switching buck converter. With the current soft-commutating method and control scheme, the isolated boost full bridge dc/dc converter can be implemented as a dual operation of the conventional ZVS-PWM full bridge buck converter together with soft-switching feature.

8. CIRCUITDIAGRAM

- 1) Switching devices and passive elements are constant.
- 2) Constant input voltage.
- 3) Constant output voltage (V_o) is constant.
- 4) The recovery time of all diodes is ignored.

9. BLOCK DIAGRAM



Schematic of the proposed soft-switching boost converter.

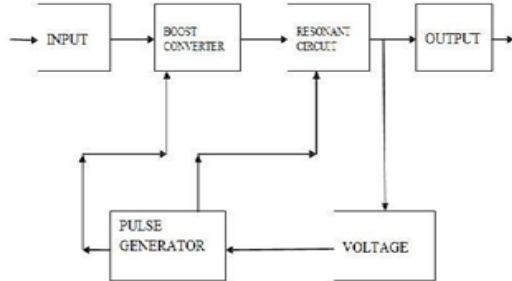


Fig. 6 block diagram

10. CONFIGURATION

A. MODE 1

The main switch (S1) and the auxiliary switch (S2) of the proposed circuit qualify soft switching through an auxiliary switching block, consisting of an auxiliary switch, two resonant capacitors (Cr and Cr2), a resonant inductor (Lr), and two diodes (D1 and D2). The HI-Bridge auxiliary resonant circuit in the circuit diagram composes the major operating region of our soft switching method. The auxiliary circuit for resonance increases the complexity of the circuit, as well as its cost. For some resonant converters with an auxiliary switch, the main switch enables soft switching, while the auxiliary switch performs hard switching.

TABLE: RATING OF COMPONENTS

Symbol	Part number	V [V]	I [A]	tr [ns]	tf [ns]	trr [ns]
S ₁	IRG4PC30	600	17	20	350	-
S ₂	IRG4PC30	600	17	20	350	-
D ₁ , D ₂	DSEI 23-120A	1200	17	-	-	40
D ₀	DSEI 12-06A	600	14	-	-	35

OPERATIONAL ANALYSIS

The operational principle of the planned converter can be divided into nine modes. For simple analysis of each mode of the proposed converter, the following assumptions are made, Mode 1 operates between (t0 ≤ t < t1). All of the switches are turned OFF. The accumulated energy of the main inductor (L) transfers the load through the main diode

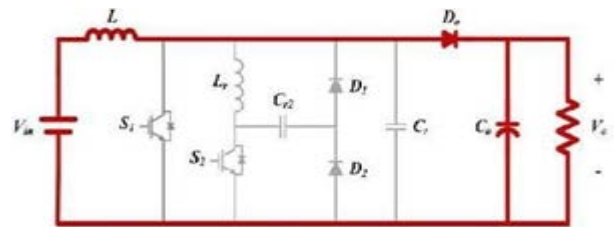
(D0). In this mode, the main inductor voltage and current are signified by (1) and (2), and using these equations, the inductor current can be expressed as (3). During this time, the resonant inductor current is zero, and the resonant capacitor (Cr) has been charged to the output voltage and the resonant

$$V_L(t) = V_{in} - V_o \tag{1}$$

$$i_L(t) = -1/L \int V_L dt \tag{2}$$

$$i_L(t) = (V_{in} - V_o)/L (t - t_0) + I(t_{g_1}) - I(t_{g_2}) - [(V_o - V_{in})/L](t - t_0) \tag{3}$$

$$i_{Lr}(t_r) = 0, V_{Cr}(t) = V_o, V_{Cr2}(t) = 0 \tag{4}$$



Mode 1 - (t₀ ~ t₁)

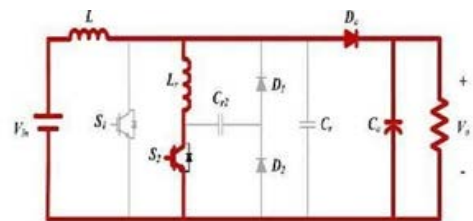
Fig.4.5.1 mode

B. MODE 2

Mode 2 operates between (t1 ≤ t < t2). When the auxiliary switch turns ON, mode 2 begins. After turning ON the auxiliary switch, the resonant inductor current begins to increase linearly from zero. When the resonant inductor current (iLr) is equivalent to the main inductor current at t2, mode 2 completes and the resonant inductor voltage equals the output voltage. Thus, the resonant inductor current is expressed by (5). The main inductor current drops and, at the end of this mode, the main inductor current is equal to the minimum, as defined by (6)

$$i_{Lr}(t) = V_o / L_r (t - t_1) \tag{5}$$

$$i_L(t_2) \approx I_{min} \tag{6}$$



Mode 2 - (t₁ ~ t₂)

Fig. 4.5.2 mode

C. MODE 3

Mode 3 operates between (t2 ≤ t < t3). Immediately after the resonant inductor current and main inductor current have equalized, the main diode is turned OFF. The resonant capacitor Cr and the resonant inductor start their resonance, then the resonant capacitor Cr is decreases through resonant path Cr and Lr. After final the resonance, the resonant capacitor voltage is equal to zero. Mode 3 completes at t3. At t2, the resonant inductor voltage is equal to the output voltage. Thus, the time interval for the two currents to match after t1 is determined

by (7). The resonant inductor current is the sum of the main inductor and resonant current, and is expressed by MODE 4.5.5 (8). The resonant capacitor Cr voltage is charged, as said by (9). During this mode, the resonant impedance and angular frequency are given by Zr and ωr

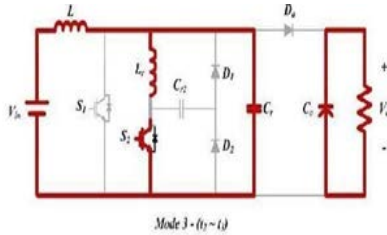


Fig.4.5.3 mode 3

D. MODE 4

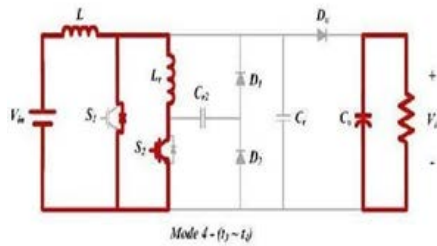


Fig 4.5.4 mode 4

Mode 4 operates between (t3 ≤ t < t4): As soon as the resonant capacitor (Cr) voltage has reached zero, the body diode of main switch is turned ON naturally. In this case, the main switch voltage is equivalent to zero and the turn-ON signal is given to the main switch under the zero-voltage condition. In this mode, the main inductor voltage is equal to the input voltage. Thus, the main inductor current is spoken by (11). After the resonance in mode 3, the resonant inductor current is constant. The resonant capacitor (Cr) voltage has been strongly discharged in mode 3. Therefore, the resonant capacitor voltage is zero.

E. MODE 5

Mode 5 operates between (t4 ≤ t < t5). In mode 4, the main switch turns ON under the zero-voltage condition. When the auxiliary switch is turned OFF for the same condition, mode 5 begins. In this period, the resonant inductor and resonant capacitor (Cr2) start the resonance. After the quarter-wave resonance of Lr and Cr2, the current of Lr is zero. Mode 5 is complete and Cr2 has been fully charged by the resonance. In this manner, the resonant inductor current can be expressed as (13). In addition, the resonant impedance and angular frequency are given by Za and ωa. turned OFF, this mode is complete. In this interval, the magnitude of the resonant inductor current is equivalent at t3. However, the current flow is reversed. In this mode, the main and auxiliary inductor currents are as follows:

$$t_1 = IL (V_d/L_r) \tag{7}$$

$$i_{Lr}(t) = i_{min}(t) + V_d/Z_r \sin \omega_r (t - t_2) \tag{8}$$

$$v_{Cr}(t) = V_s \cos \omega_r (t - t_2) \tag{9}$$

$$Z_r = L/C_r, \omega_r = 1/\sqrt{L_r C_r} \tag{10}$$

$$i_{Lr}(t) = i_{Lr}(t_3) \cos \omega_a (t - t_4) \tag{13}$$

$$\omega_a = 1/\sqrt{L_r C_{r2}}, Z_a = L_r/C_{r2} \tag{14}$$

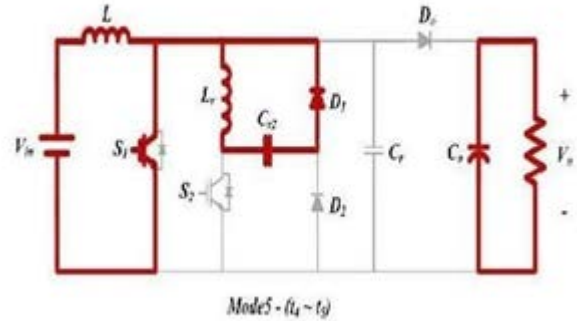


Fig 4.5.5 mode 5

F. MODE 6

Mode 6 operates between (t5 ≤ t < t6). After mode 5 completes, the current flow of the resonant inductor Lr reverses and the next stage starts. In mode 6, a reverse resonance of L and Cr2 through the main switch and D2 occurs. When the Cr2 voltage has touched zero by

$$v_{Cr2}(t) = Z_a i_{Lr}(t_5) \sin \omega_a (t - t_4) \tag{15}$$

$$v_{Cr2}(t_6) = Z_a i_{Lr}(t_6) = 0 \tag{16}$$

$$i_L(t) = I_{min} + V_d/L (t - t_3) \tag{17}$$

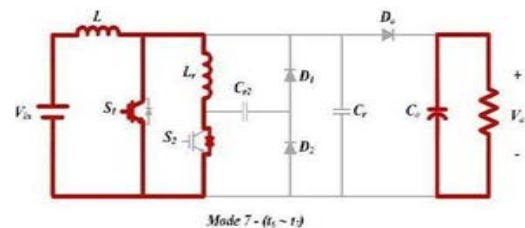
$$i_{Lr}(t_7) = -i_{Lr}(t_5) \tag{18}$$

G. MODE 7

Mode 7 operates between (t6 ≤ t < t7). After the Cr2 voltage has reached zero, the body diode of the auxiliary switch is turned ON. The current flows through the freewheeling path of the frame diode the resonant MODE 4.5.9

$$i_{Lr}(t) = i_L(t_7) - \{i_L(t_7) + i_{Lr}(t_5)\} \cos \omega_{r1} \tag{19}$$

$$Z_r \{i_L(t_7) + i_{Lr}(t_5)\} > V_{co} \tag{20}$$

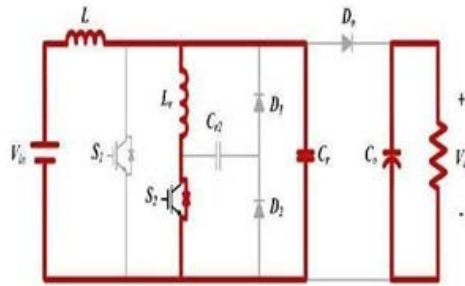


Mode 7 - (t6 - t7)

H. MODE 8

resonance, the resonance of Lr and Cr2 is complete and the Cr2 voltage is zero. During manners 5 and 6, the resonant capacitor voltage is charged and discharged, according to (15). Thus, the resonant capacitor

voltage (v_{Cr2}) for each point of time is expressed by (16).



Mode 8 - ($t_7 \sim t_8$)
fig 4.5.8 mode 8

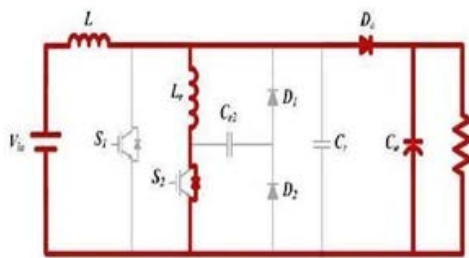
inductor the main switch. By the pulse width modulation (PWM) algorithm, when the main switch is

I. MODE 9

Mode 9 operates between ($t_8 \leq t < t_9$). At t_8 , the resonant capacitor C_r has been charged and the main diode voltage is zero. Therefore, the main diode turns ON under the zero-voltage condition and the resonant inductor current reductions linearly toward zero. After the current has reached zero, mode 9 completes and the next switching cycle starts. In this mode, the main inductor current and resonant inductor current are given by the following:

$$i_L(t) = i_L(t_7) - (V_o - V_{in})/L_r t \quad (21)$$

$$i_{Lr}(t) = -i_{Lr}(t_3) + (V_o/L_r)t \quad (22)$$



Mode 9 - ($t_8 \sim t_9$)
Fig 4.5.9 mode 9

11. OUTPUT CHARACTERISTICS

To achieve zero-voltage switching, a delay time (T_{Delay}) is required in the main switch PWM. The minimum delay time must satisfy the following equation:

$$T_{Delay} \geq (I_{Lr} L_r) / V_{in} + \pi/2 \sqrt{L_r C_r} \quad (23)$$

The time consisted of the resonant time amongst L_r and C_r , and the time that the resonant inductor current takes to become equal to the input current. During the delay time, the auxiliary switch is turned ON. The PWM signals of the main and auxiliary switch are shown in the Fig. 4.6

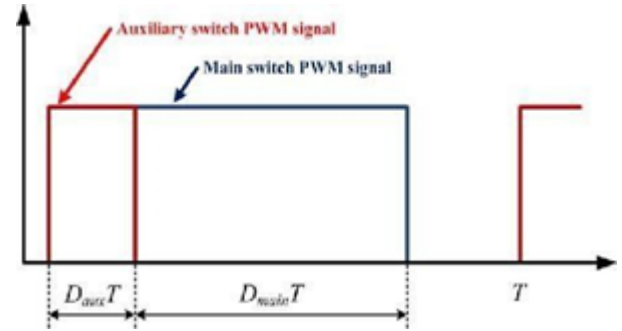


Fig 4.6 In a steady-state operation, the main inductor voltage $v_L(t)$ is specified by

Where T_r is the resonant time among the resonant inductor (L_r) and resonant capacitor (C_r). D_{main} is the main-switch duty percentage and D_{aux} is the auxiliary-switch duty ratio. After the delay time, the energy has accumulated in the main inductor. The switch is turned ON like a conventional boost converter. Thus, when the auxiliary switch is turned ON, the result on the total duty is larger. From the volt-second balance for the main inductor, the voltage-conversion ratio is defined by the following equation:

$$v_L(t) = V_{in} (D_{aux} - T_r/T) + V_{in} (D_{main} + T_r/T) + (V_{in} - V_o)(1 - D_{aux} - D_{main}) \quad (24)$$

$$V_o/V_{in} \approx 1/[1 - (D_{aux} + D_{main})] \quad (25)$$

12. SIMULATION RESULTS CIRCUITDIAGRAM

The simulation circuit for the proposed system is

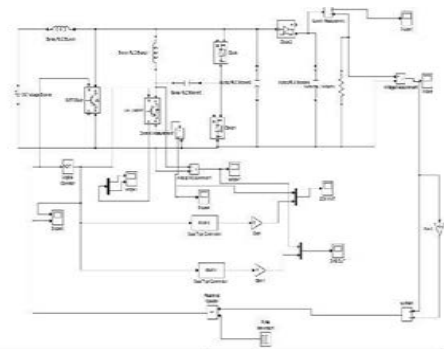


Fig 5.1.1

A. OUTPUT VOLTAGE WAVEFORM:

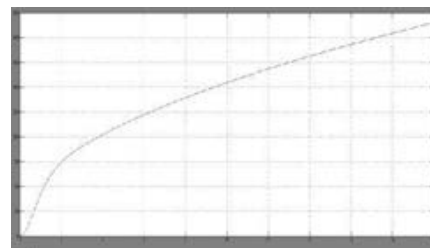


Fig 5.1.2

B. OUTPUT CURRENT WAVEFORM:

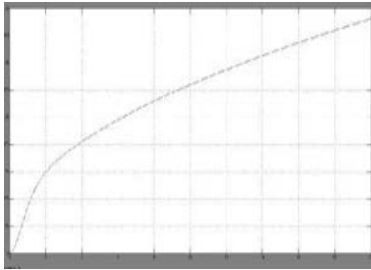


Fig 5.1.3

13. CONCLUSION

In this paper, a innovative soft-switching boost converter has been proposed that uses an auxiliary switch and resonant circuit. The main switch performs soft switching under the zero-voltage condition by means of a resonant capacitor and inductor, as does the auxiliary switch. The proposed converter has been analyzed in detail. The operation principles and theoretical analysis of the proposed converter have been confirmed by simulation and a prototype of 600 W and 30 kHz. The proposed converter is suitable for applications such as high-efficiency converters, photovoltaic dc/dc converters, a power-factor-correction circuit, and battery chargers.

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