Design And Simulation Of A New Soft-Switching Buck-Boost Converter

Siddhartha Behera, Brijesh Kumar, Bibhu Prasad Panigrahi

Abstract : The dc-dc buck-boost converter is commonly used for transforming electrical power at different level because of their requirement starting from low power such as domestic application to reasonably high power like industrial application. The most important of this converter is its flexibility that it is able to operate in both stepping-down(buck) and stepping-up(boost) of the input voltage by varying its duty-ratio of the switch. A commonly buck-boost converters includes the combination of components such as boost inductor, boost capacitor, boost diode and switches etcand appear in different orientations in literature. But the switches in these circuit suffers from hard-switching and add switching loss thus reducing efficiency of circuit. As the demand of this converter is growing day by day because of its versatility of stepping up and stepping-down the input voltage, the aspect of better efficiency is a prime concern and obviously the soft-switching of devices is major issue that needs to be critically investigated. In literature there appears few papers as far as soft-switching of buck-boost converter is concerned. In most cases, the addition of more than one or two switches makes complexity for the soft-switching operation for which it lacks interest for the researchers. Many a times the inclusion of isolation in this circuit takes into consideration of coupling inductor that adds space and weight to the circuit. The proposed topology presents a non-isolated type of buck-boost converter which facilitates the soft-switching of the device. In this research work. a new simplified soft-switching buck-boost converter is proposed. The components of this converter are properly designed to enable soft-switching for the switch. The simulation of the proposed circuit is carried out with the help of MATLAB (Simulink) to validate the performance.

Index Terms: Buck-Boost converter, Ferrite core inductor, Polypropylene switched capacitors, Fast recovery diodes, Zero-Current Switching(ZCS), Zero-Voltage Switching(ZVS), MATLAB(Simulink).

1. INTRODUCTION

THE buck-boost converters transforms from fixed voltage level to higher voltage or lower voltage by dumping energy to the inductor temporarily and then feeding it to the output level. This converter is one of the family members of dc-dc converters that integrates the positive features of buck converter and boost converter into single circuit. All dc-dc converters (i.e.. buck, boost and buck-boost) have lot of utilities domestically, commercially and industrially, but buck-boost unit possesses special features as compared to other two. The first hand knowledge pertaining to various generalised dc-dc convertersand relevant steady-state equations are analysed [1].The conventional buck-boost converter is shown in Fig.1 and the relevant idealistic waveforms are shown in Fig.2. Though there are hundreds papers available in literature, but most of these experiences hard-switching and research papers associated with the soft-switching of these converters are few. In fact, the soft-switching converters overweigh the hard-switched converters in many aspects. The resonant principle is one of the prime technology responsible for facilitating the soft-switching of the converters. But the various soft-switching techniques using resonant principles like series resonant, parallel resonant, zero-voltage transition, zero-current transition, quasi-resonant etc are adopted and practiced based upon the compatibilities of the topologies. The principle of resonant technique using quasi-resonant principle for boost converter is demonstrated by Barreto et.al[2]. The quasi-resonant principle, which is one of the advanced technique under various resonant principles, deals with very small interval of a switching cycle and relieves device not only from over-voltage stress but also from switching loss. The ZVT (Zero-voltage transition) is an another principle in which the transition of switch from on-state to off-state or vice-versa is enabled for high step-up converter[3]. Similar concept is extended by H.L.Do[4] for increasing the gain of converter. W.Li et.al.[5] present the extension of ZVT principle for fuel-cell micro-grid system. The same author uses ZVT principle for a dual-stage boost converter using multifunctional inductor [6]. The soft-switching for bidirectional isolated dc-dc converter is analysed by A.K.Rathoreet.al[7] for fuel cell vehicle. Under soft-switching, the major issue is generation of current harmonics at input and the researchers[8] proposes a cancellation technique for elimination of current harmonics using a tapped inductor. Y.P.Siwakoti et.al proposes the new concept of quasi z-source for high voltage boost converter[9]. The simplest technique of soft-switching is load resonant principle for non-isolated bidirectional dc/dc converter is utilised by A.K.Rathore et.al [10]. The major drawback of this scheme, the resonant components involved in circuit carry the load current. As the load current increases, there will be increase in size and ratings of these components. M.Forouzesh et.al [11] propose the quasi-resonant operation using coupled inductor and switched capacitor for a high-step up converter , whereas S.S.Dobakhshri et.al [12] proposes the same quasi-resonant principle for current-fed converter along with minimisation of switching losses.

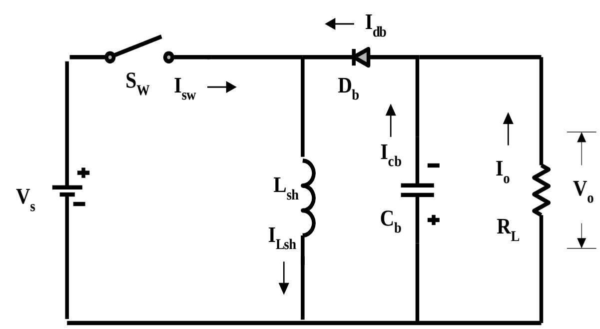

Fig.1. Conventional Buck-Boost Converter (dc-to-dc)

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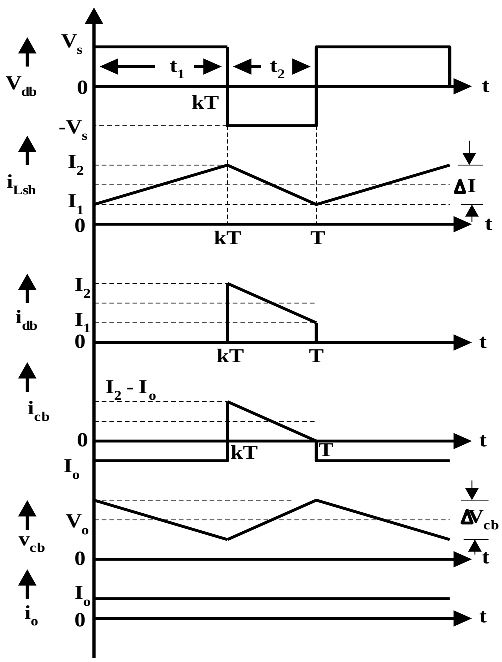


Fig.2. *Waveforms of conventional Buck-Boost Converter during turn-on, turn-off*

The papers relevant to soft-switching in case of buck-boost converters lack in literature. In this paper, a new buck-boost converter is proposed that comprises single switch and low value of resonant components. The circuit is analysed with MATLAB/Simulink to validate the justification.

2 PROPOSEDTOPOLOGY ANDMODES OF OPERATION

The proposed topology which is slightly different from the conventional one is shown in Fig.3. This topology facilitates soft-switching for the single switch in order to minimise switching loss. The different modes of operation for buck-boost converter are shown in Fig.4.

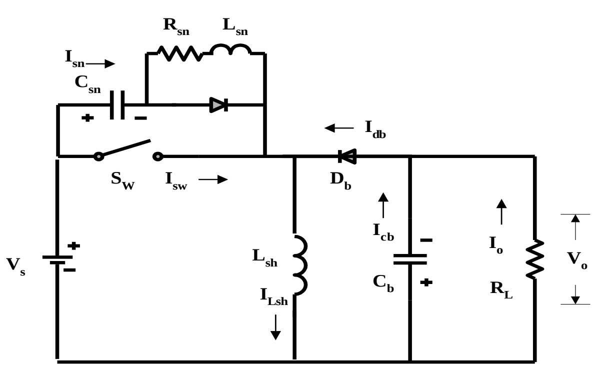


Fig.3. *Proposed Buck-Boost Converter*

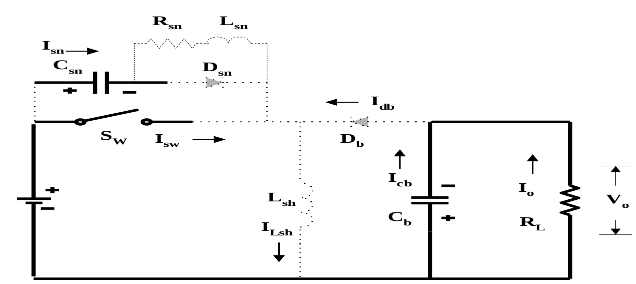
The operation of the proposed buck-boost converter is explained through various modes (I~ VI) shown in Fig.4. This is based upon steady-state application.

Mode-I: Initially the circuit is assumed to be off-state. The snubber capacitor attains the peak of source voltage and the load is disconnected from the source. The boost capacitor releases the power to the load.

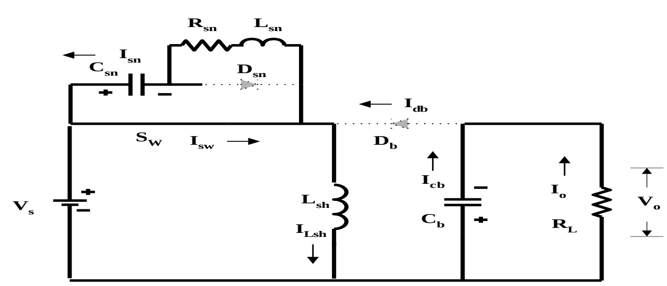
Mode-II: The initiation of Mode-II commences with turning-on the switch. The source voltageappears across the shunt inductor (boost inductor) and gradually current rises in it and simultaneously the snubber capacitor discharges through inductor and resistor to ensure the zero-current through switch during starting. The combined snubber capacitor, inductor and resistor is made to operated at close to critical damping.

Mode-III: Mode-II ends with the snubber capacitor discharges to zero and recharges to opposite direction. Now the oppositely charged snubber capacitor appears across the switch and keeps reverse-biased it even if the switch is on turned-on condition. The combined source and snubber capacitor voltage is acted upon the shunt inductor . This is continued till snubber capacitor is discharged to zero and switch is relieved from reverse-biased situation.

Mode-IV: In this mode, the current through the inductor goes on rising as switch is already on. This mode continues till the switch is turned-off.



(a)



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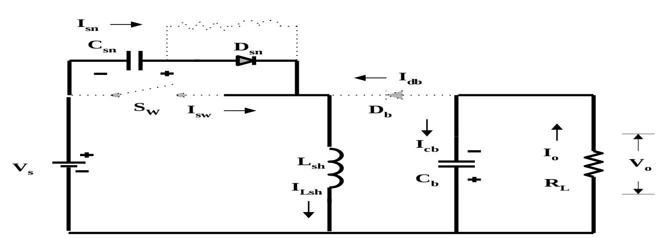
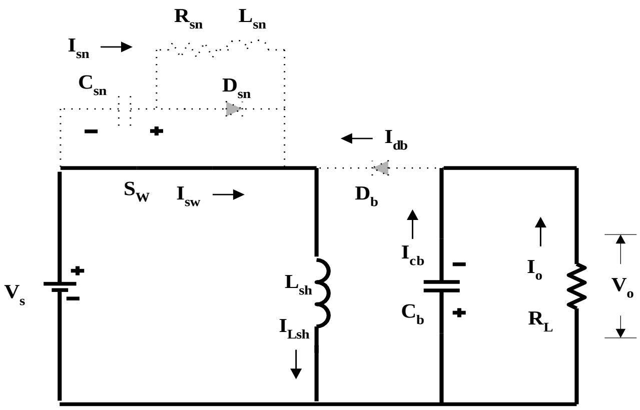
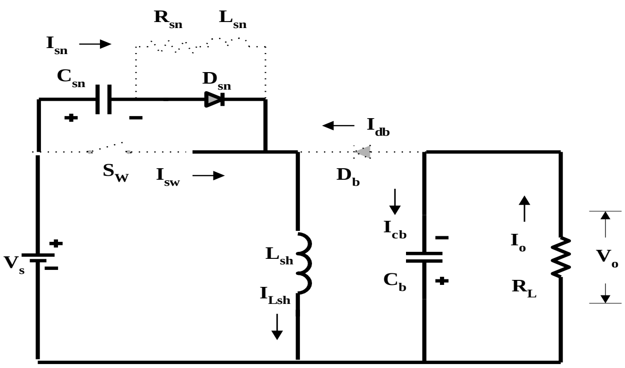


(c)

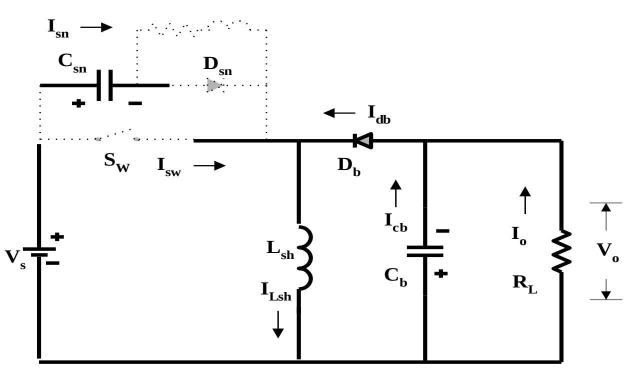
Fig.4.(a~c). *Modes of operation of proposed soft-switching topology from (a) to (c)*



(d)



(e)



(f)

Fig.4(d~f) *Modes of operation of proposed soft-switching topology from (d) to (f)*

Mode-V: This mode is initiated with the turned-off of the switch. The switch is operated on ZVS as the snubber capacitor appears across it. The current through switch is diverted through the capacitor and diode across it. This process is continued till the capacitor is charged to source voltage. At this stage, the secondary circuit after switch is disconnected from source.

Mode-VI: This mode starts when the shunt inductor delivers energy to Capacitor and load resistance via boost diode (Db). This process is continued when the current through shunt inductor falls to zero. So the boost capacitor delivers power to load resistance. Now the cycle is repeated with mode-I again.

3 ANALYSIS AND DESIGN OF CIRCUIT COMPONENTS

Under steady-state, a switching period is divided into two parts. (i.e., T= 1/f_s = t_1+t_2 ; t_1- on time and t_2 - off-time), whereas 'f_s' is the switching frequency. The steady-state analysis of the proposed converter isas follows.

3.1 During Switching-on process of device

Assuming that during time t_1, the inductor current rises linearly from I_1 to I_2.

$$V_s = L_{sh}\frac{I_2 - I_1}{t_1} = L_{sh}\frac{\Delta I}{t_1} \qquad (1)$$

$$\text{or}t_1 = \frac{\Delta I\, L_{sh}}{V_s} \qquad (2)$$

3.2 During Switching-off process of device

During switching-off period, the inductor current changes from I_2 to I_1 in time t_2. 'Vo' is the average output voltage across load. 'Vs' is the input dc supply.

$$V_o = -L_{sh}\frac{\Delta I}{t_2} \qquad (3)$$

$$\text{or}t_2 = \frac{-\Delta I\, L_{sh}}{V_o} \qquad (4)$$

where$\Delta I = I_2 - I_1$ is the peak-to-peak ripple current of inductor Lsh. From Eq. (1) and (3).

$$\Delta I = \frac{V_s t_1}{L_{sh}} = \frac{-V_o t_2}{L_{sh}} \qquad (5)$$

Substituting $t_1 = kT$and $t_2 = (1-k)T$ in eq.(5), the average output voltage is

$$V_o = -\frac{V_s\, k}{(1-k)} \qquad (6)$$

The negative voltage refers to reversal of polarity of output voltage. Eq.(6) can be simplified to

$$(1-k) = \frac{-V_s}{V_o - V_s} \qquad (7)$$

which simplifies to$k = \frac{V_o}{V_o - V_s}$

Substituting value of 'k' in $t_1 = kT$ yields

$$t_1 = \frac{V_o}{(V_o - V_s)f_{sw}} \qquad (8)$$

Assuming a lossless circuit, $V_s I_s = -V_o I_o = V_s I_o\, k/(1-k)$andthe average input current I_s is related to the average output current I_o by

$$I_s = \frac{I_o\, k}{1-k} \qquad (9)$$

The switching period T can be found from

$$T = \frac{1}{f_{sw}} = t_1 + t_2 = \frac{\Delta I\, L_{sh}}{V_s} + \frac{\Delta I\, L_{sh}}{V_o} \qquad (10)$$

$$\Delta I = \frac{V_s V_o}{f_{sw} L_{sh}(V_o - V_s)} \qquad (12)$$

$$\text{or}\Delta I = \frac{V_s\, k}{f_{sw} L_{sh}} \qquad (13)$$

3.3Design of Boost Capacitor

When switch is on, the boost capacitor supplies the load current for $t = t_1$. The average discharging current of the capacitor is $I_c = I_o$ and the ripple voltage (i.e., peak-to-peak) for the capacitor is given by

$$\Delta V_c = \frac{1}{C_b}\int_0^{t_1} I_{cb}\,dt = \frac{1}{C_b}\int_0^{t_1} I_o\,dt = \frac{I_o t_1}{C_b} \qquad (14)$$

Substituting $t_1 = V_o/(V_o - V_s)f_{sw}$ from Eq. (8) in eq.(14) becomes

$$\Delta V_c = \frac{I_o V_o}{(V_o - V_s) f_{sw} C_b} \qquad (15)$$

or$$\Delta V_c = \frac{I_o\,k}{f_{sw} C_b} \qquad (16)$$

For capacitor the voltage on the verge of continuous, the maximum ripple capacitor voltage$\Delta V_{cs} = 2V_{cs} = 2V_o$

Eq.(13) becomes

$$\Delta V_c = \frac{I_o\,k}{f_{sw} C_b} = 2V_o = 2I_o R_L \qquad (17)$$

So the critical value of capacitor is

$$C_b(\text{critical}) = \frac{k}{2 f_{sw} R_L} \qquad (18)$$

Where Cb (critical) is the capacitancevalue of boost capacitor above below which the capacitor voltage changes s from the discontinuous conduction mode to continuous mode. For minimization of the ripple content further, the values of Cb must be greater than those obtained in (18). So a ripple factor (%age) 'a' is incorporated in (18).

$$C_b = \frac{k}{2a\,R_L f_s} \quad \text{where } (0<a<1) \qquad (19)$$

3.4 Design of Boost Inductor(L_{sh})

The maximum ripple in input current of the boost inductor during continuous to discontinuous node of operation is

$\Delta I = 2\,I_{Lsh}$whereI_{Lsh} is the average current through inductor

Substituting above condition in (13), it gives

$$\Rightarrow \Delta I = 2\,I_{Lsh} \qquad (20)$$

$$\Rightarrow \frac{V_s\,k}{f_{sw} L_{sh}} = 2I_o = \frac{2V_o}{R_L}\frac{2kV_s}{(1-k)R_L} \qquad (21)$$

$$\Rightarrow L_{sh}(\text{critical}) = \frac{(1-k)R_L}{2\,f_{sw}} \qquad (22)$$

where Lsh (critical) is optimum value of L_{sh}above which there will be situation for the transition of input current from discontinuous tp continuous mode of operation. R_L=load resistance.

3.5 Design of Snubber Components

The snubber circuit comprises a inductor, a capacitor , a resistor and a diode. The snubber capacitor along with series diode assists in relieving stress of the switching device during turn-off. But during turn-on of the device, the charge of snubber capacitor is enrooted through resistance and inductance. The inductance is of very small value. The main objective of incorporating small snubber inductor to make zero current through switch.The combined snubber components (C_{sn}, L_{sn} and R_{sn}) are operated under either critical damped or over damped. The underdamped situationis forbidden to avoid frequent biasing of diode across switch. But under critical damped, there will be no oscillation of capacitor voltage. When this capacitor is fully reverse charged after the current falls to zero, the snubber diode is forward biased and snubber capacitor pumps its charge to the shunt inductor via source.

The maximum power loss due to snubber circuit that happens during time constant ($\tau = R_{sn}C_{sn}$)of turn-on period in absence of snubber inductor. The instantaneous current through snubber is given by

$$i_{sn} = \frac{V_s}{R_{sn}} e^{-\frac{t}{R_{sn}C_{sn}}} \quad \text{and} \quad P = \frac{1}{T}\int_0^T p\,dt = \frac{1}{T}\int_0^{\tau}(i_{sn}^2\,R_{sn})\,dt \qquad (25)$$

$$P = \frac{1}{2}\frac{C_{sn}V_s^2}{T}\left(1 - e^{-\frac{2\tau}{R_{sn}C_{sn}}}\right) \approx \frac{1}{2}\frac{C_{sn}V_s^2}{T} \approx \frac{1}{2}C_{sn}V_s^2 f_{sw} \qquad (26)$$

The snubber capacitor is designed as follows.

$$\frac{I_{psh}\,t_{off}}{C_{sn}} = V_s \qquad (27)$$

$$C_{sn} = \frac{I_{psh}\,t_{off}}{V_s} \left(t_{off} \approx 2 * t_q\right) \qquad (28)$$

where I_{psh} : Peak current through shunt inductor L_{sh}.

t_{off} : Charging time of snubber capacitor;

t_q : Turn-off time of the device specified by manufacturer

Snubber capacitor (C_{sn}) is obtained out from eq.(28). In order to limit the discharge current of snubber capacitor through switch, it requires a significant higher snubber resistance and complete charge is wasted through resistance. So an alternate solution is thought to connect a small inductor which will prevent the capacitor to discharge immediately and allows the device to start zero current.

The current during underdamped condition is

$$i \approx V_{co}\sqrt{\frac{C_{sn}}{L_{sn}}}\sin(w_d\,t) \quad \text{and} \quad I_{psn} = V_{co}\sqrt{\frac{C_{sn}}{L_{sn}}} \qquad (29)$$

wherew_d is damped frequency

The condition for critical damping/ overdamping

is$R_{sn} >= 2\sqrt{\frac{L_{sn}}{C_{sn}}}$ (30)

and for under damped$R_{sn} < 2\sqrt{\frac{L_{sn}}{C_{sn}}}$ (31)

This peak current I_{psn} in eq.(29) should be less than the current through L_{sh} from eq.(2). Since Vco is equal to source voltage (Vs), so L_{sn} is obtained and$R_{sn}$is decided at a value close to R_{sn} (critical) from eq.(30). For a switching device like practical device like high speed IGBT (ex Manufacturing part no STGFW40V60DF), the switching-on and switching-off time of the above IGBTare approximately 65 ns and 100ns respectively as per the data sheet of the manufacturer. So for smooth turning-off of the device, thecharging time of snubber capacitor must be higher than the turn-off time of the device which is available with the data sheet of by manufacturer.

With following data (sufficient toff =500ns= 0.5 μs, Ip= 20A, Vs=50V , fs =25 kHz, RL =20 ohm), if the then IGBT is taken into consideration, the designed value of snubber capacitor (Csn) is 0.02 μF from eq.(28). The snubber discharging current must be less than peak switch current. Assuming above facts in consideration, the value of snubber inductance (Lsn) is 1.25 μH and snubber resistance(Rsn) is 20 ohm which is for the condition of overdamping. With the prevailing snubber components, the maximum switching loss is less than 1 watt (i.e., eq(26)) without assuming effect of snubber inductor. So inclusion of snubber inductor will have no impact upon switching loss. The value of load capacitor (Cb) is determined from eq.(19) assuming very low ripple is 100 μF . In case of shunt inductor, it is considered below critical value (i.e., eq.(21)) so that the source current is discontinuous to enable soft-switching of the device. Though the designed components are ideal one, but in reality, all the passive components consists ohmic resistance. So comparing the passive components with reputed manufacturer, the final components considered in simulation is given in table-I.

Table-I : Specifications of components

Name of the item	Rating of the item	Part No of manufacturer
Boost inductor (L_{sh}), ferrite core type	50μH, DCR= 5.3mΩ, 35 A Ferrite core high frequency type (SCHURTER)	DLFL-0147-35C5
Load/ Boost capacitor (C_b)	5nos 20μF, 450V,ESR= 2.2mΩ electrolytic type	C4ATGBW5200A3MJ
Snubber inductor (L_{sn})	1.25 μH, Ferrite core(DigiKey)	B65661D1250K048
Snubber resistance (R_{sn})	20 ohm , 10 watt	71ALSR1020R00FE12
Snubber capacitor (C_{sn})	0.01μF, 630V dc; (Polypropylene)	R463I310050M1K
IGBT	600V,40A, freq range (50~100kHz)	STGFW40V60DF
Diode(D)	250V, 40A,V_D=0.97V	MBR40250T

4 SIMULATION RESULTS

In order to have a feeling of realistic feeling, the components are considered based upon availability in the market and those are close to designed value. The simulation is carried out with the help of MATLAB/ Simulink. The simulation results are shown in Figs 5 to 8 respectively. . The components which are considered for simulation are taken from the available components with manufactureras without sacrificing much with designed values. Fig.5 shows the current and voltage of diode (Db) and switch (Sw) respectively. It is observed from the Fig.5 that the switching device (SW) turns on under ZCS and turns off ZVS. Though the anti-parallel diode along with snubber capacitor connected across the switch facilitates the turn-off under ZVS, but on other hand the small ferrite inductor along with resistor across anti-parallel diode initiates the turn-on under ZCS. In Fig.6, it shows the voltage of boost capacitor(Cb), current through shunt inductor (Ilsh), current through load resistance(Irl), and current through boost capacitor (Icb) respectively. Fig. 7 shows the current and voltage across the snubber capacitor (Csn). The simulation results shown in Figs 5,6 and 7 are for the duty-ratio of 0.6 which is boost operation of buck-boost converter. Similarly in Fig.8, it shows the waveforms with duty-ratio of 0.4 which is buck operation of buck-boost converter. The Fig 8(a) shows the waveforms of current through and voltage across the switch, whereas it shows similar waveforms for boost diode (Db) in Fig,8(b). The observations ofthe simulation parameters at different duty-ratios are shown in Table-2.

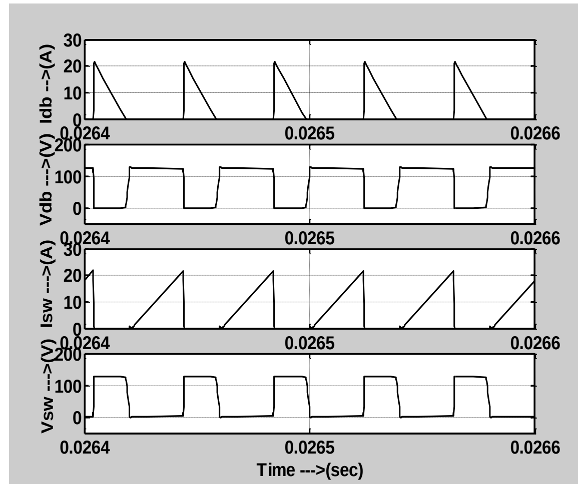


Fig. 5. Wave forms of current and voltage of boost diode (Db) and switch (Sw) respectively at duty-ratio pf 0.6

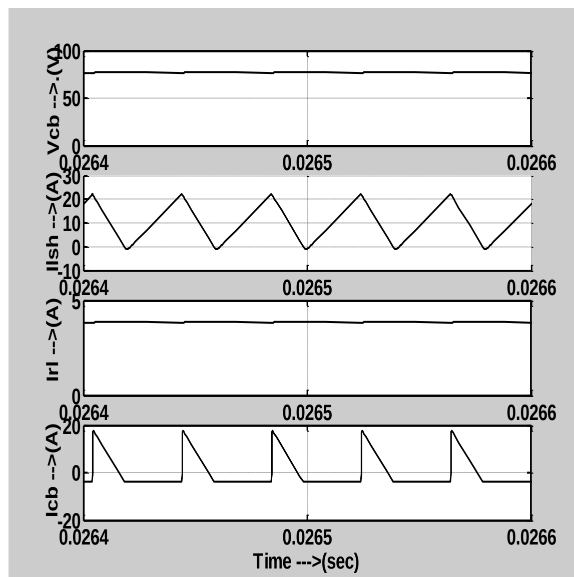


***Fig.6.** Waveforms of capacitor voltage (Vcb), current through shunt inductor (ILsh), losd resistance (Irl) and boost capacitor (Icb) respectively at duty-ratio of 0.6.*

TABLE- 2

SIMULATION PARAMETERS AT DIFFERENT DUTY-RATIOS

Duty_ ratio (k)	Load voltage (v)	Input Power (w)	Output Power (w)	Efficiency %	Switch-ing (Soft/ Hard)
0.2	27.38	41	37.23	91	soft
0.3	40.3	88.4	81.37	92	-do-
0.4	54.2	157	146	93	-do-
0.5	68.35	254	236	93	-do-
0.6	76.82	320	298	93.2	-do-
0.65	88	428	394	92.5	Hard
0.7	112	665	614	92.31	-do-
0.8	184	1857	1665	89.66	-do-

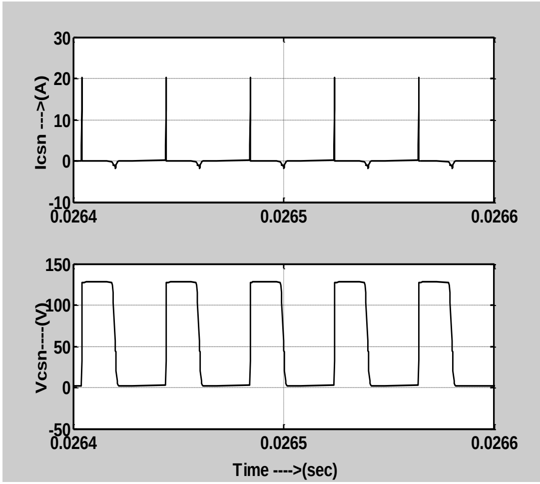
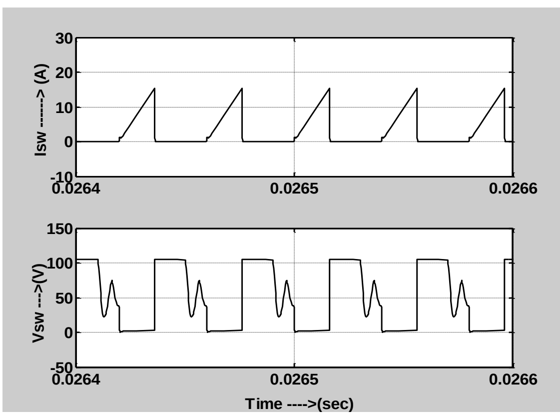
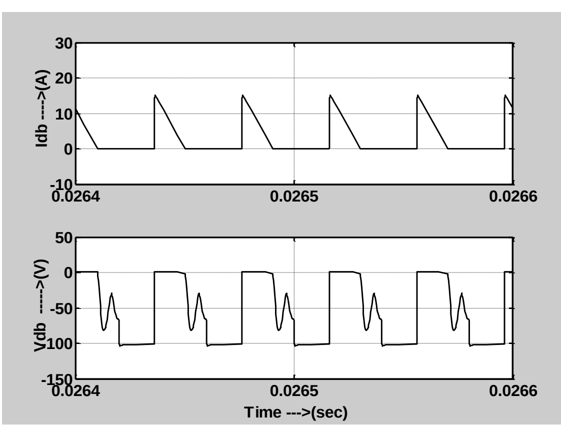


Fig. 7. Waveforms of current and voltage through snubber capacitor respectively.



(a)



(b)

Fig. 8. *Current and voltage wave form across (a) Switch (Sw) and (b) Boost diode (Db) at duty-ratio 0.4*

The limitation of the circuit is that for fixed values source voltage, duty-ratio and switching frequency, the major passive components (Lsh, Cb) designed are fixed which are operated at its optimum values. Here at higher value of duty-ratio of 0.6, the shunt inductance is designed below the critical value so that it can operate with soft-switching at lower duty-ratio. For boost capacitor (Cb), it is designed with lowest ripple factor (a <<1). So duty-ratio can be varied below the value of duty-ratio considered for designing components. Above this duty-ratio, the shunt inductor current becomes continuous and fails to turn on under ZCS.

5 CONCLUSION

The proposed topology is designed for soft-switching andsimulated by MATLAB(Simulink).During designing process, the shunt inductor, boost and snubber capacitor are designed for a given supply voltage, switching period, duty-ratio and load. The switching device is turned on under ZCS. Further thedevice is turned-off at the small forward-biased voltage of anti-parallel diode across it. So it is treated ZVS off. The physical components available with manufacturer,that are close to designed values, are considered in order to realise a practical type situation. At different duty-ratios, the designed values of shunt inductors are different, but in present case, a common shunt inductor is considered to make soft-switching at different duty-ratios. From the table of efficiency, it is observed that there is slightly change in efficiency upto duty-ratio 0.6 because of soft-switching, but after that there is gradual decrease in efficiency. This decrease in efficiency is due to the fact that as the device draws excessive current at inputdue to increase in level of output voltage. It means the need of higher rating of snubber capacitor. The duty-ratio of thecircuit is restricted upto limited value (i.e., 0.6) in order to avoid hard-switching. The ripple at the output voltage on load side is quite minimum, but on other hand there is significant increase in ripple content of input current. The need of higher value of snubber capacitor at higher duty-ratio adds more snubber loss. Though the topology contains a small value of ferrite inductor , but it successfully operate under soft-switching with limited range of duty-ratio. The inclusion of snubber inductor assists in recovering part of the energy of the snubber capacitor and that energy is transferred to shunt inductor for enhancement of efficiency.

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