IFERP

ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

A High Efficient Fully Soft Switched Isolated DC-DC Boost Converter

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Abstract: **This paper proposes a fully soft switched isolated DC-DC boost converter, which consists of only one switch and this switch is turned-on at zero current switching and turned-off at zero voltage switching. All the diodes in this proposed converter is turned-off at zero current condition, regardless of voltage and load variations. This converter consists of a lossless snubber and an isolation transformer. Leakage inductance of this isolation transformer is used for zero voltage switching (ZVS). All these features make this particular boost converter high efficient and low cost. Simulation results are given in order to validate the proposed concept and these results are compared with simulation results of conventional converters**

Index Terms- **Isolated step-up DC-DC converter, single switch, lossless snubber, fully soft switched.**

I. INTRODUCTION

The scarcity of conventional energy sources has become one of the most discussed global problems. Therefore we are looking for renewable energy sources such as Sun, wind, tides etc, instead of conventional energy sources. As the terminal voltage of such renewable energy sources are very low, a DC-DC converter is essential for the useful utilization of electrical energy. The existing methods of DCDC converter have its specific advantageous and disadvantageous based on its specifications and operating conditions [1], [4], [7]. The voltage conversion ratio range, maximal output power, number of components, power densities are the examples of such specifications. Many conventional DC-DC converters are available, but isolated DC-DC converters are commonly used to get the requirement of isolation standards. The electrical isolation in switching DC power supplies are provided by high frequency transformers [3]. The voltage stress on transformer windings and rectifier diodes are very high in conventional isolated DC-DC converters such as fly back converters, push-pull converters and full bridge converters etc. This will increase the components ratings and cost of the converter. Snubber circuits are used to reduce the voltage stress across the switch, but it reduces the efficiency of converter by dissipating some amount of power [1]-[4].

In step-up applications current fed isolated converters are more common due to its lower transformer turn ratio, lower diode rating and reduced ripples at input. There are two types of current- fed isolated converters; those are passive clamped current-fed converter and active clamped current fed converter [3], [5]. Structure and design of passive clamped current-fed converter is simple, but it suffers excessive power loss due to RCD snubber circuit and hard switching. In active clamped current-fed converter the voltage spikes due to leakage inductance of isolation transformer is clamped without any loss and also the main switch of this converter is turned-on in Zero Voltage Switching (ZVS). However these converters are not suited for low power applications, because they require at least four switches and its gate driver circuits that increase the cost and reduce the efficiency of converter [8]-[11]. Isolated converters with reduced number of switches have been developed for low power applications. Isolated converter with single switch can be turned-on in ZVS, but the switch is turned-off with hard switching. In Z-source converters a coupled inductor is used to increase the step-up ratio, but here switches are turned-on and turned-off with hard switching [6]. In PWM resonant single switch converter the voltage stress across the output diodes and leakage current are less than that of fly back converter, but the PWM single switch isolated resonant converter require a transformer with high turn ratio for step-up applications[3], [4], [12].

The proposed isolated DC-DC boost converter consist only one switch and this switch is turned-on in Zero Current Switching (ZCS) and turned-off in Zero Voltage Switching (ZVS). All the diodes used in this converter are turned-off in

Zero Current Switching and this reduce the voltage surge across the diodes due to diode reverse recovery. These

ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

fully soft switched conditions make a considerable reduction in switching losses in proposed converter from that of conventional isolated converters. A low rated lossless snubber is used here in order to makes the proposed converter high efficient and low cost.

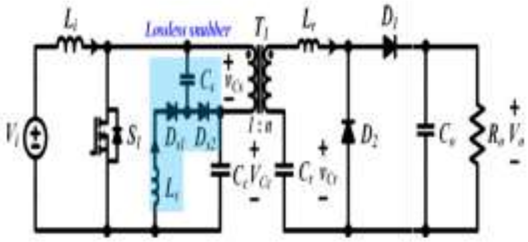


Fig.1. Proposed Circuit Configuration

II. PROPOSED CONVERTER

Fig.1 shows the circuit configuration of proposed converter. The circuit consists of a input filter inductor L_i, input DC source V_i, the main MOSFET switch S_1, a clamp capacitor C_C and a lossless snubber circuit at the primary side of isolation transformer T_1. Capacitor Cs, inductor Ls, diodes Ds1 and Ds2 are the components of snubber circuit. Lr-Cr is the series resonant circuit. D1 and D2 are the output diodes and C0 is the output diodes. The lossless snubber clamp the voltage spikes of the switch due to leakage inductance and turn-off the switch in ZVS. Zero current turn-off of diodes are achieved by Lr-Cr resonant circuit. Three resonance operations according to the variation of resonance frequency fr1 are shown in Fig. 2. Which are above resonance operation ($DT_S < 0.5T_{r1}$), below resonance operation ($DT_S > 0.5T_{r1}$), and resonance operation ($DT_S = 0.5T_{r1}$), where resonance frequency can be expressed as in (1).

$$f_{r1} = \frac{1}{T_{r1}} = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad (1)$$

From Fig. 2, it is clear that the switch turn-off current and rate of change of current of diode (di/dt) in below resonance operation are less than that of above resonance operation, so that the total switching losses are smaller for below resonance operation. Therefore the proposed converter is operated under below resonance condition.

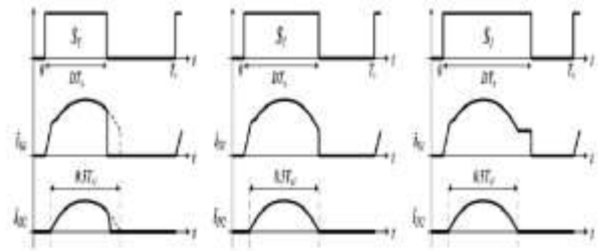
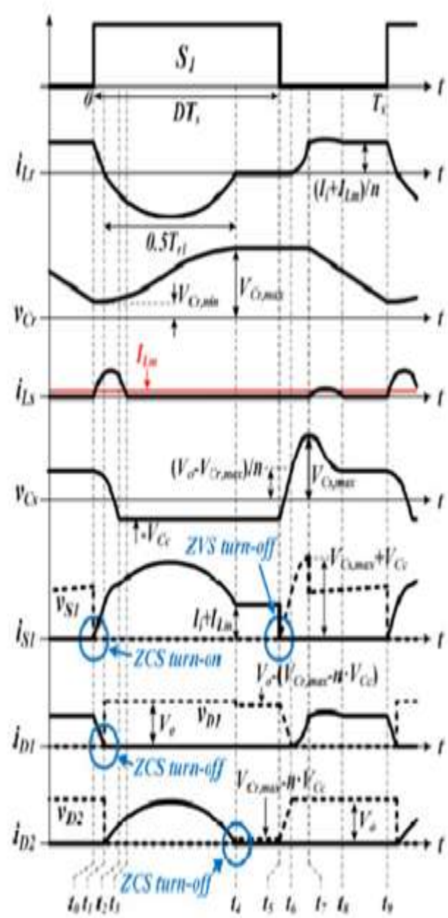


Fig. 3. Comparison of current through switch and diodes according to the variation of f_{r1}: (a) above resonance operation (DT_S>0.5Tr1), (b) Resonance Operation ($DT_S=0.5T_{r1}$), and below resonance operation ($DT_S<0.5T_{r1}$)

A. Operating Principles

Key waveform of proposed converter during below resonance operation is shown in Fig. 3. It is assumed that the input filter and magnetizing inductances are constant current source during the switching period that means these inductances are large values. It is also assumed that clamp and output capacitances are constant voltage sources during switching period. These assumptions make the analysis of circuit simple. In this circuit voltage across the clamp capacitor Vcc same as that of input voltage Vi. In below resonance operation each switching periods consists of nine modes of operations and these nine modes are shown in fig 4.



Modes of operations

IFERP

ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
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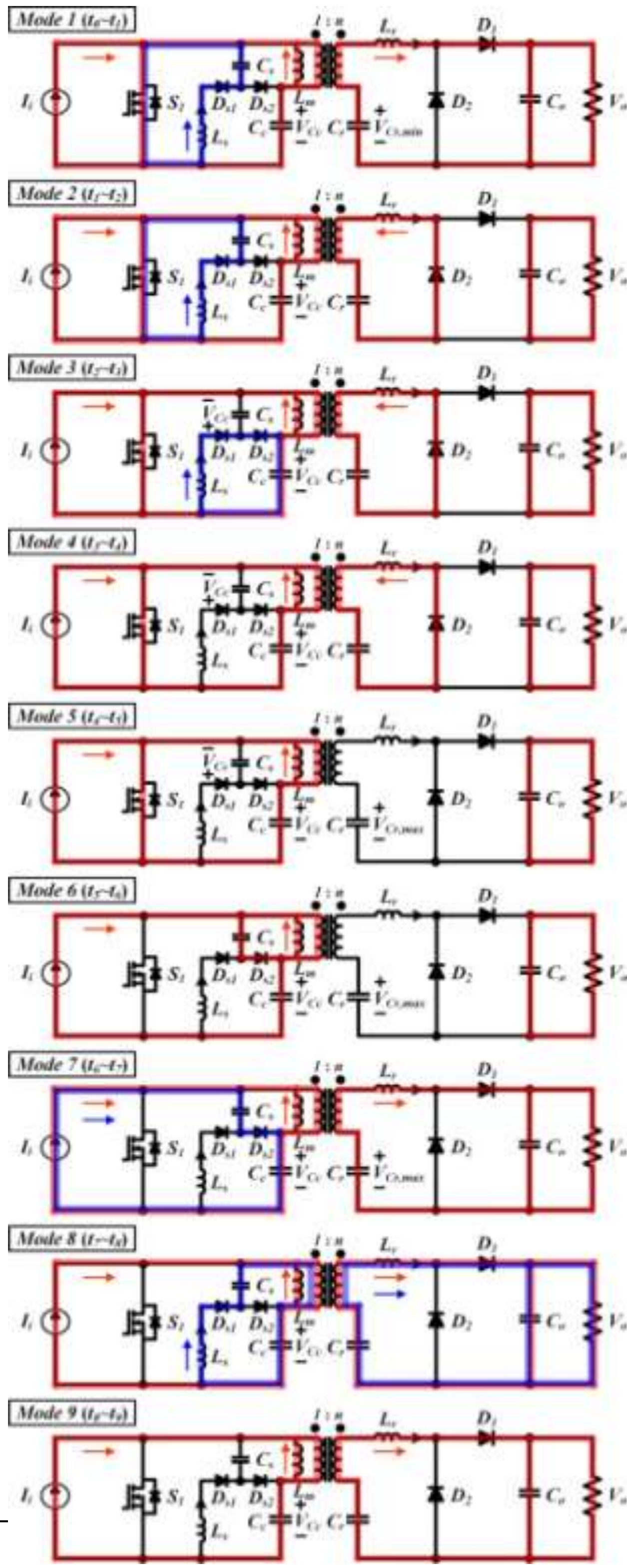

Fig. 4. Operation Modes in Below Resonance Operation

Mode 1 ($t_0 - t_1$)

This mode begins when switch S1 is turned ON, then the source current and snubber capacitor (Cs) current will flow through the switch S_1. The resonating current of resonant inductor (L_r) will flow through the switch (S_1) in opposite direction of source current, so at the moment of turn-on current through the switch will be zero and it will increases with the slop of i_{Lr}, resulting in ZCS turn-on of switch S1. This mode ends when current i_{Lr} reaches 0A and then the diode D1 is turned Off under ZCS condition.

Mode 2 ($t_1 - t_2$)

In this mode V_{CC} will come across the primary winding of the isolation transformer, then the diode D_2 will be turned-on and the direction of current through the resonant inductor (L_r) will change. At the same time the snubber capacitor (C_S) will discharge completely, and then the snubber inductor Ls will reverse its polarity and capacitor (C_S) charges in the negative direction. When the voltage across the capacitor C_S reaches V_{CC}, then this mode will end.

Mode 3 **($t_2 - t_3$)**

In this mode diode D_{S2} become forward biased condition and turned-On, then the remaining energy stored in the inductor L_S will dissipate through D_{S1}, D_{S2} and C_C. Current through the diodes D_{S1} and D_{S2} become zero, when the inductor L_S dissipates completely. Then the snubber diodes turned-Off at zero current condition.

Mode 4 **($t_3 - t_4$)**

Duration of this mode is comparatively more than that of other modes, in this mode V_{CC} discharge completely and then i_{Lr} reaches its negative peak. Now The L_r dissipates stored energy till current i_{Lr} reaches 0 A and then the diode D_2 is turned OFF under ZCS condition.

Mode 5 **($t_4 - t_5$)**

In this mode, sum of the input current I_i and the magnetizing current I_{Lm} flow through the switch S_1. Secondary of the isolation transformer opens at this mode, because D_1 and D_2 are turned-off at this mode. Whatever may be the conditions at the end of mode-4 are continuing at this mode.

Mode 6 **($t_5 - t_6$)**

This mode begins when S_1 is turned OFF. Now, the current through the switch in mode-5 is flowing through the snubber capacitor (C_S), Now the snubber capacitor(C_S) is charging from $-V_{CC}$ to zero and then a positive value equal to $(V_0 - V_{crmax}) / n$. When the capacitor C_S voltage equals to this particular positive value, then this mode ends.

***Mode 7* ($t_6 – t_7$)**

When the V_{CS} increases further the value $(V_o - V_{Crmax}) / n$, then the anode of D_1 is more positive than that of cathode and then D1 turns on. The L_r and C_S start resonating and resonant current I_{Lr} follows through C_S, D_{S2}, L_r, D_1 and C_r and also this mode ends when the V_{CS} becomes equal to maximum value. At this condition no more current will follow through the snubber diode D_{S2}, so D_{S2} will turn-off at zero current condition.

***Mode 8* ($t_7 – t_8$)**

During this mode the snubber capacitor will discharge through the primary winding, up to which V_{CS} equal to $(V_o - V_{Cr;max}) / n$. After that capacitor will not discharge, then the snubber inductor L_S will reverse its polarity and dissipates energy stored in it through D_{S1}, C_S, primary winding and V_{CC}. After the complete dissipation of energy stored in L_S, current through the D_{S2} will be zero and zero current turn-off of diode D_{S2} is achieved at that moment.

***Mode 9* ($t_8 – t_9$)**

Switch S1 is in the turn-off state, and now the primary current of transformer is the sum of input current (I_i and magnetizing current (I_{lm}). This primary current is being transferred to secondary, now the current through the diode D_1 is equal to $(I_i + I_{Lm})/n$. This mode ends when switch S_1 is turned ON.

B. Design Procedure

In this section, components of the proposed converter are designed. A design example is given below with the following specifications: Output power P_0=250W, output voltage V_0=380V, input voltage V_i=38V and switching frequency f_s=100kHz. In order to reduce the conduction loss of snubber components, the average value of snubber inductor current $I_{Ls,avg}$ should be very small. This current $I_{Ls,avg}$ is proportional to the snubber capacitance C_S, but trying to reduce the snubber capacitance C_S leads to increase the voltage rating of the switch. Therefore, considering a trade off between conduction losses of switch and snubber components, that is average value of snubber inductor current I_{Lsavg} is chosen to be 3% of average input current $I_{i,avg}$ [1].

$$I_{Ls,avg} = 0.03 I_{i,avg} = 0.27A \qquad (2)$$

The minimum value of duty ratio (D_{min}), in order to keep the proposed converter in below resonance operation can be obtained from (3).

$$D_{min} = \pi f_s \sqrt{L_r C_r} \qquad (3)$$

The resonant inductor (Lr) should be designed to reduce the reverse recovery effect of diode D_1, in order to reduce reverse recovery effect of the diode, the resonant inductor should keep the duration of mode-1 ($t_1 - t_0$) at least equal to 3 times that of reverse recovery time (t_{rr}). The duration of mode-1 can be expressed by following equation

$$t_1 - t_0 = 3t_{rr} = \frac{(I_i + I_{lm})L_r}{nV_0(1 + 1/2C_rF_sR_s)} \qquad (4)$$

By substituting the values I_i = 9A, I_{lm} = 0.27A, n = 5, V_0 =380v, f_s = 100kHz, R_0 = 640, t_{rr} = 10ns and D_{min} = 0.5 in (3) and (4), and the resonant values L_r and C_r can be determined by 5µH and 560nF respectively. Value of the snubber capacitance can be obtained from solving (5).

$$V_{Cs,max} = \frac{I_i - I_{Lm}}{n}\sqrt{\frac{L_r}{C_s}} + \frac{V_c - V_{cr,max}}{n} \qquad (5)$$

V_{csmax} is the maximum value of voltage that come across the snubber capacitor, so the equation for V_{csmax} can be formed from the key waveform for the proposed converter, that is given in the Fig. 2.

$$V_{cs}(t_0) = 2\left(V_{cc} + \frac{V_0 - V_{cr,max}}{n}\right) - V_{Cs,max} \qquad (6)$$

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Where V_{cc}, is the voltage across the coupling capacitor C_c, which is equal to input voltage V_i and $V_{cr,max}$ is given by (7)

$$V_{cr,max} = nV_{cc} + \frac{V_0}{2C_r f_s R_0} \quad (7)$$

$V_{cs,max}$ and $V_{cr,max}$ can be obtained from solving (6) and (7).

Substitution of these values in (5) determines the snubber capacitance (C_s), which is equal to 16nF.

Snubber inductance L_s should be designed to minimize the reverse recovery effect of snubber diodes D_{s1} and D_{s2}. The reverse recovery effect can be reduced by keeping the time interval t_2 to t_3 greater than that of reverse recovery time (t_{rr}) of snubber diodes. Duration of mode-3 (t_3 - t_2) can be obtained from the key wave form of proposed converter in Fig.2. Then, the duration of mode-3 is given by (8).

$$t_3 - t_2 = 3t_{rr2} = \frac{V_{Cs}(t_0) L_s \sin(\cos^{-1} {}^{-V_i}/_{V_{cs}(t_0)})}{V_i} \sqrt{\frac{C_s}{L_s}} \quad (8)$$

Where t_{rr1} is the reverse recovery time of snubber diode, which is taken as 10ns. The snubber inductance (L_s) 5μH

can be obtained from solving (8), which is equal to

TABLE 1 COMPONENT RATING

COMPONENTS	RATING
Filter inductor L_i	100μ H
Snubber inductor L_s	5μ H
Snubber capacitor C_s	16nF
Clamp capacitor C_c	82μ F
Transformer Leakage inductance Magnetizing inductance Turn ratio VA	 5μ H 93μ H 1:5 273VA
Resonant capacitor C_r	560nF
Output capacitor C_0	1μ H

III. SMULATION RESULT

Simulation of the proposed converter is done in MATLAB with designed values of components as in Table-1. Fig. 5 and 6 show the output voltage and current of proposed converter. The duty ratio (D) of the main switch and switching frequency is taken as 0.62 and 100kHz respectively.

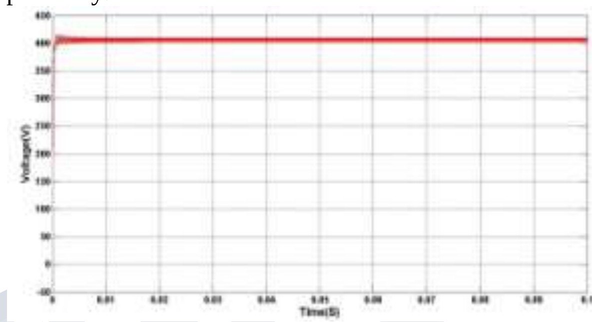

Fig. 5. Output Voltage of proposed converter in open loop simulation V_0=409.4V, under V_i=38V, R_0=577Ω

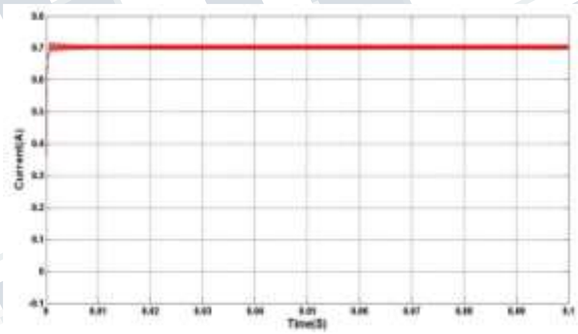

Fig. 6. Output current of proposed converter in open loop simulation I_0=0.7088A, under V_i=38V, R_0=577Ω

Input voltage of proposed DC-DC converter (V_{in}) is 38V and input current (I_{in}) is 7.37A, so the input power (P_{in}) is 280.06W. Output voltage of proposed DC-DC converter (V_o) is 391.21V and output current (I_o) is 0.68A, so the output power (Po) is 266.02W. So the efficiency of the proposed DC-DC converter can be calculated from the following equation

$$efficiency = \frac{P_0}{P_{in}} \times 100 = \frac{290.18}{301.68} \times 100 = 96.18\% \quad (9)$$

Fig. 9. shows the current and voltage of the main switch

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S1. Here the voltage across the switch (S1) is zero at the moment of turn-off. The current through the switch (S1) is zero at the moment of turn-on. So the switch is turned-on in zero current switching and turned-off in Zero voltage switching.

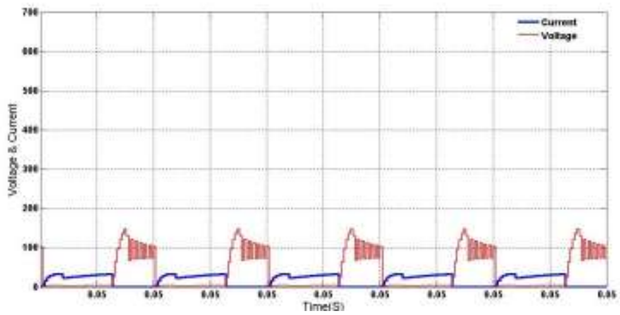

Fig. 7. Voltage and Current of Switch S1 with snubber circuit

Fig. 10. shows the current and voltage of the main switch S1 of the proposed DC-DC boost converter, without snubber circuit.

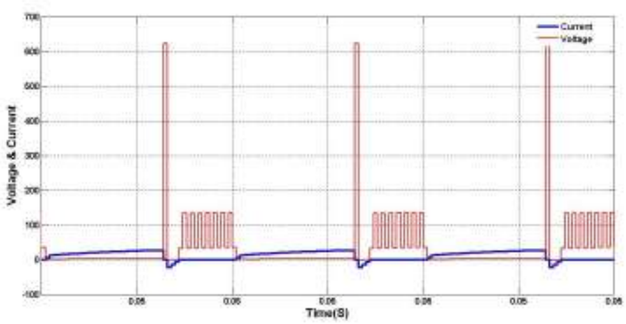

Fig. 8. Voltage and Current of Switch S1 Without snubber Circuit

Here the simulation results of proposed converter are compared with conventional converters such as Integrated Boost Resonant converter (IBR) [7], conventional flyback converter, and conventional DC-DC boost converter [13]. For these converters the simulation results are taken under input voltage Vi=38V, duty ratio D =0.62, output resistance R0=577_, and switching frequency fs=100kHz. A comparison of output voltages of proposed converter and conventional converters are shown in Fig.9, and the values are tabulated in Table-2.

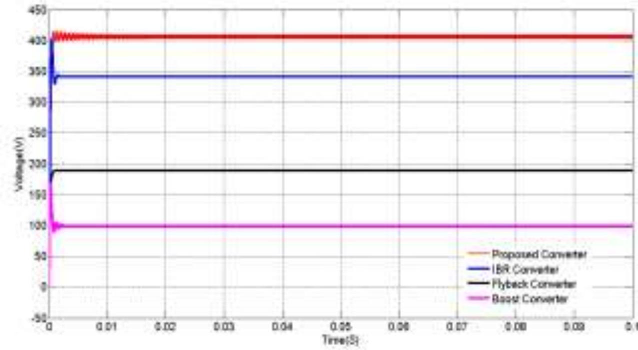

Fig. 9. Comparison of Output Voltage of Proposed Converter with Conventional Converters under V_i=38V, R_0=577Ω

Table-2
Comparison of Output Voltages

Converters	Output Voltages V_0 (V)
Conventional DC-DC Boost Converter	99.76
Conventional Flyback Converter	188.4
IBR Converter	344.3
Proposed Converter	409.4

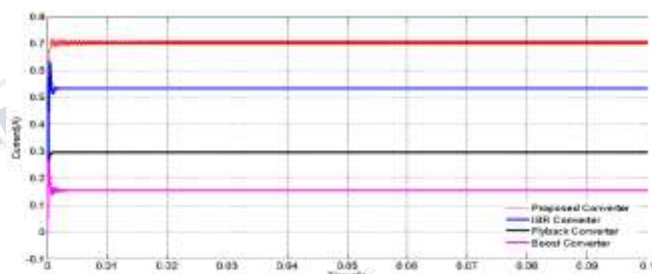

Fig. 10. Comparison of Output Current of Proposed Converter with Conventional Converters under V_i=38V, R_0=577Ω

Table-3
Comparison of Output Current

Converters	Output Current I_0 (A)
Conventional DC-DC Boost Converter	0.1559
Conventional Flyback Converter	0.2944
IBR Converter	0.54
Proposed Converter	0.7088

ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

The values of input current of converters are tabulated in Table-4

Table-4
Comparison of Input Current

Converters	Input Current I_0 (A)
Conventional DC-DC Boost Converter	0.453
Conventional Flyback Converter	1.598
IBR Converter	5.3
Proposed Converter	7.939

Efficiency of proposed converter is calculated in (9) which is equal to 96.16%. Efficiency of other converters also can be calculated using (9), which are tabulated in Table-5.

Table5
Comparison of Efficiencies

Converters	Efficiency (%)
Conventional DC-DC Boost Converter	90.30
Conventional Flyback Converter	91.34
IBR Converter	92.34
Proposed Converter	96.18

From Table-5 it is clear that the efficiency of proposed isolated DC-DC converter is higher than that of conventional converters. From Fig.9, it is also clear that the step-up ratio of proposed converter is very high. Proposed DC-DC converter provides an output voltage of 409.4V for an input voltage of 38V, but the output voltage of latest IBR converter is only 344.4V for the same input voltage under same conditions.

IV. CONCLUSION

In this paper, a high efficient fully soft switched isolated DC-DC boost converter was proposed for step-up applications. This converter consists only one switch which is fully switched and the snubber circuit for this switch is lossless. All the diodes used in this converter are turned –off at zero voltage condition. The proposed converter has a high efficiency of 96.16 %, this is 4% greater than that of latest IBR converter. The proposed converter also has a high step-up ratio and a well stabilized output voltage.

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