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Research Article

A DC-DC Non-Isolated Step-up Converter Based on Three State Switching Cell for High Voltage Applications

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Keywords

Boost converter,
step-up dc-dc converters,
state switching cell(SSC),
double half bridge
inverter.

Abstract

This paper introduces a dc-dc boost converter based on three state switching cell and double half bridge resonant inverter. The proposed converter comprises of two active switches, two diodes and coupled inductor. The converter can be applied for operation of high gain applications supplying renewable energy systems and uninterruptible power supplies. The important advantages over other classical converters are low conduction and commutation losses and low input and output current ripple. For high voltage applications the converter is made to operate at overlapping mode which corresponds to duty cycle higher than 0.5 with continuous conduction in operation. The output voltage can be increased by increasing the turns ratio of the transformer without affecting the voltage stress in the switches. Thus they supply power to double half bridge, resonant inverter. In addition to the mathematical calculations an experimental prototype of 1kw validates the theoretical analysis of the converter performance.

Introduction

Step-up converters are widely used in modern technologies as sources to many industrial drives. In industrial drives to supply the source of a dc drive systems which require high voltage. When a high voltage is demanded at industries, it is useful when the demand can be met by a small input voltage supplied by either photovoltaic panels, batteries, fuel cells, or other sources. Whatever may be the source but it is necessary to maintain the gain and ripple at a proper rate.

Mainly dc-dc converters includes pulse width modulated (PWM) converters currently. These converters produce power supplies for a large variety of systems in electronics, telecommunications, dc motor drives, satellites, utilization of the solar energy and also for other types of power converters.
The main evolution of power converter was necessary for the increase in demand for the variety of applications. From these the buck-boost converters mainly based on Pulse Width Modulation (PWM) techniques using switching principle evolved.

In order to obtain the above high voltage, conventional boost converter is not adequate because to get high duty cycle the main switch needs to be turned on for a prolonged time which causes conduction loss. A well-known concept of cascading which operates in continuous conduction mode (CCM) can also be done in order to get a high voltage but cascading increases the complexity and reduces the efficiency.

Many modifications have been made in modern times to make these conventional boost converters useful for the voltage step up applications. These topologies vary and make themselves suitable and evolve to meet the requirements of the duty cycle. The hard switching conventional converters present low power density but with the use of filters they increase the switching losses. This conventional boost converter with two inductor and auxiliary transformer increase the efficiency but the switching losses in the inductor causes the failure of the system, as the system needs to be turned off for a period of time.

A high voltage gain with the use of switches though the efficiency can be compromised with less on resistance by losses due to leakage inductance is achieved by flyback or SEPIC converters where there is magnetically coupled inductance. The overlap of voltage and current during commutation can be reduced to avoid the switching losses. An addition of auxiliary switches in the circuit causes complication in the power and control strategy. This can be overcome by using passive lossless snubber since they reduce EMI electromagnetic interference and switching loss but they cause a main disadvantage of not supporting the entire load range.

An effort in improving the ZVS zero voltage switching technique is carried out. Though they reduce the complication in the switching losses, for higher voltage application they cause large EMI electromagnetic interference filter and energy storage inductor.

A resonant converters increases the voltage gain by increasing and adjusting the turns ratio of a high frequency transformer. But these are applicable for low power rated devices not for high power application because of high circulating energy due to LC resonant tank.

Now it is necessary to bring forth the concept of 3SSC. This three state switching cell is normally used for high voltage application. 2SSC is normally called cell type B. They can be used in high current applications. A 3SSC is made up of a 2 state pulse width modulation cells (2SSC) which are connected by a centre tap transformer making it as a dc-dc converter. This is called cell type B. Here the centre tap transformer is considered ideal with unity turns ratio where the primary and secondary windings are replaced with the magnetizing inductances.

The characteristics of the isolated converter are similar to push converter. The advantages of 3SSC are as follows: here we utilize only one winding of the transformer which has the dc current blocking capacitor in series to avoid the saturation problem in transformer, reduced magnetic cores and less copper losses are involved in transformer assembly; low commutation losses are achieved by low leakage inductance.

This paper presents high voltage gain and high current application based on the diodes and capacitor designs. This converter operates in non-overlapping mode with duty cycle less than 0.5 and overlapping mode with duty cycle greater than 0.5. but it is known that with duty cycle less than 0.5 causes magnetic induction issues and poor performance of the transformer. Here the voltage gain can be increased by adjusting the turns ratio. Thus we get a stable voltage which can be provided to a Neutral Point Clamped (NPC), half bridge and double half bridge inverters.

I.PROPOSED DC-DC BOOST CONVERTER

A. Qualitative Analysis

A converter has the following elements: input voltage V_{in}, inductor L_1, transformer T, switches S_1 and S_2, rectifier diodes D_1, D_2, D_3, D_4, D_5 and D_6 and capacitors C_1,C_2,C_3,C_4 and C_5 and output capacitors C_{o1} and C_{o2} are electrolytic capacitors.

The current flow through the inductance determines the operating stages. Although the converter can operate in different modes such as overlapping mode with continuous and discontinuous conduction and non overlapping mode with continuous and discontinuous conduction mode but here for high current and high voltage application we choose continuous conduction mode in overlapping mode with duty cycle greater than 0.5.

The equivalent circuit of the converter with a switching cycle is shown in the fig 2 with all operations and their waveforms are shown in fig 3.

First stage [t_0,t_1] Fig.2(a): The switch S1 and S2 are turned on. The diodes D_1, D_2, D_3, D_4, D_5 and D_6 are reverse biased. The current through the inductor L_1 increases linearly and energy is stored as magnetic field. In order to minimise the loss of current flow through winding P1 and switch S1 and the remaining current through P2 and S2. When this stage finishes S1 is turned OFF while S2 is still kept on.

$$L_1 \cdot \frac{di_{L1}}{dt} - V_{in} = 0 \qquad (1)$$

Besides, the time interval that defines the stage depends on the duty cycle D as

$$t_1 - t_0 = \frac{T}{2} \cdot (2 \cdot D - 1) \qquad (2)$$

Second stage [t_1,t_2] Fig. 2(b): At t=t_1, Switch S1 is turned off where as S2 is still kept on. The magnetic flux is kept continuous due to the voltage in the inductor L_1. The voltage in S1 and C_1 are equal. The diodes D_1, D_4 and D_6 remain reverse biased where as the diodes D_2,D_3 and D_5 are forward biased. The current through the inductor L_1 decreases linearly which flows through the primary windings L_{p1} and L_{p2}. The energy from inductor and source is transferred to auxiliary capacitor C_1, C_2, C_4, C_{o1} and C_{o2}.

$$-L_1 \frac{di_{L1}}{dt} + \frac{V_{in}}{2(1-D)} - V_{in} = 0 \qquad (3)$$

The time interval is

$$t_2 - t_1 = T_s \cdot (1 - D) \qquad (4)$$

Third Stage [t_2,t_3] Fig. 2(c) At t=t_2 , Switch S1 and S2 is turned on. The diodes D_1, D_2, D_3, D_4, D_5 and D_6 are reverse biased. This is similar to the first stage. This continuous till switch S2 is turned OFF. The equations are same as first stage as (1) and (2).

Fourth stage [t_3,t_4] Fig. 2(d): Switch S1 is still kept on while S2 is turned OFF. The voltage in the inductor is inverted which makes the magnetic flux continuous. This stage is similar to second stage. The equations are same as second stage as (3) and (4).

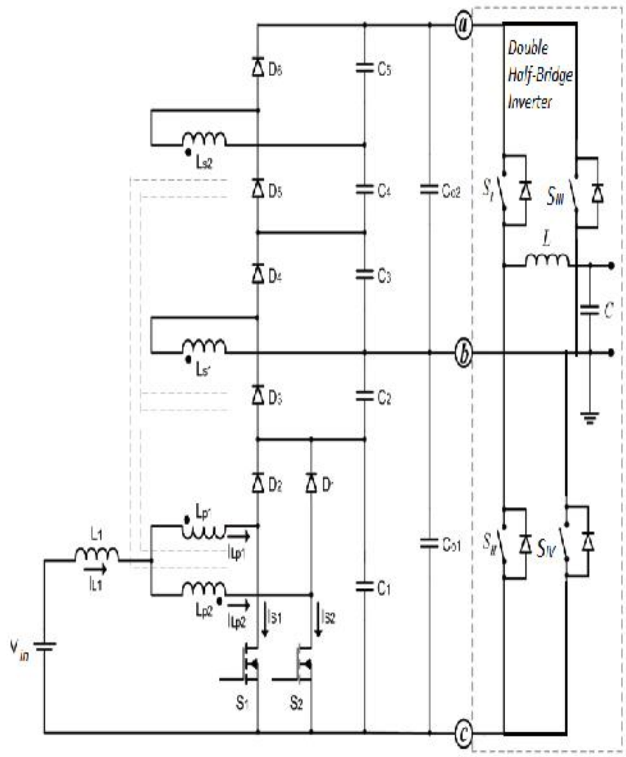
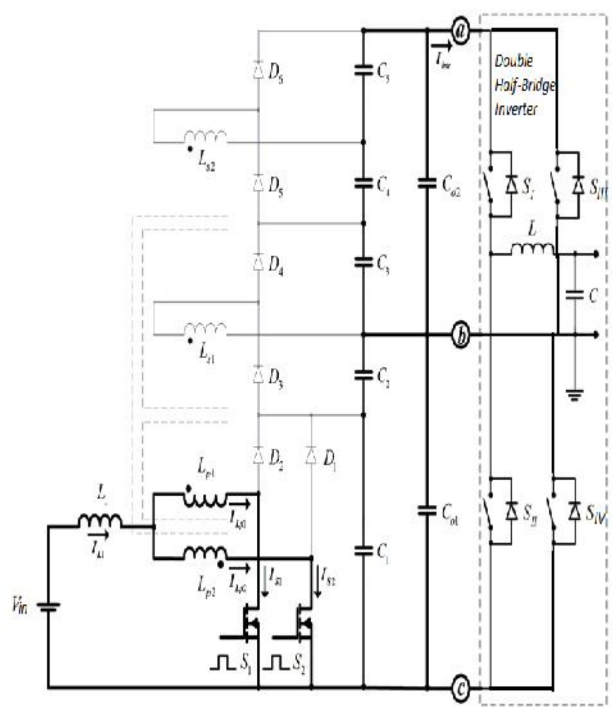
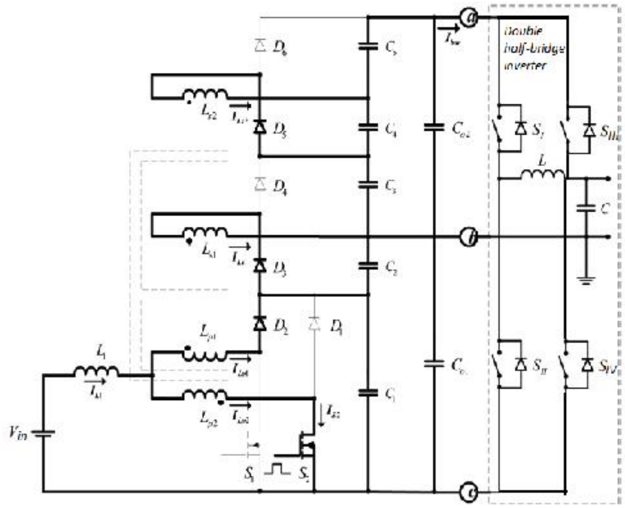


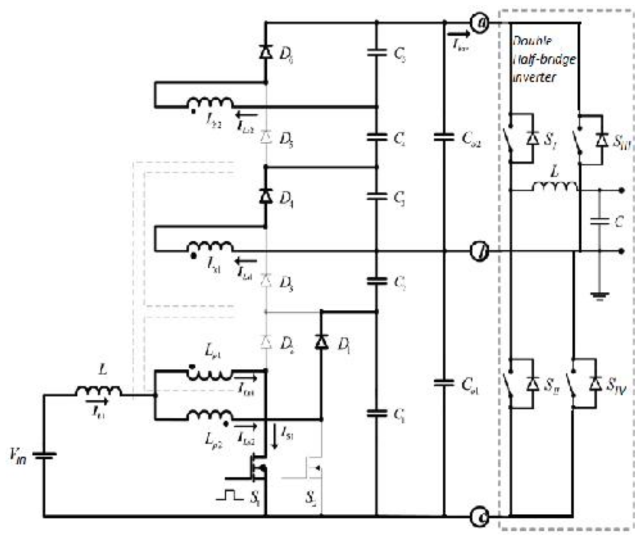
Fig. 1. Dc-dc boost converter using the 3SSC supplying a double half bridge inverter.



(a) First Stage



(b) Second Stage



(c) Fourth Stage

Fig. 2. Operating stages for the proposed converter in CCM-OM.

B.Static Gain

During one switching period Ts the voltage across the inductor L_1 (V_{L1}) is null.

$$V_{L1(avg)} = 2\frac{1}{T}\left[\int_{t0}^{t1} V_{in}\,dt + \int_{t1}^{t2} (V_{in} - V_{LP})\,dt\right] = 0 \quad (5)$$

where V_{LP} is maximum voltage in the primary windings.

Substituting (2), (4) in (5). We get

$$V_{in}\left[\frac{T_s}{2}(2D-1)\right] = V_{LP}[T_s(1-D)] - V_{in}[T_s(1-D)] \quad (6)$$

Then the maximum voltage across the primary winding is:

$$V_{Lp\,(max)} = V_{Lp1\,(max)} = V_{Lp2\,(max)} = \frac{V_{in}}{2\cdot(1-D)} \quad (7)$$

The voltage capacitor C_1 is determined by (8). Besides, the voltage across a generic capacitor is defined by (9).

$$V_{C1\,(\max)} = 2 \cdot V_{Lp\,(\max)} = \frac{V_{in}}{(1-D)} \qquad (8)$$

$$V_{C2\cdot j\,(\max)} = V_{C2\cdot j+1\,(\max)} = \frac{a_j \cdot V_{c1(\max)}}{2} \qquad (9)$$

The following ratio is also valid:

$$a_j = \frac{N_{sj}}{N_p} \qquad (10)$$

Where ***j*** is the number of secondary windings here it is two. Besides, the dimensionless quantity $\mathbf{a_j}$ represents the ratio between the number of turns for a given secondary winding ***j*** represented as N_{sj} and the number of turns for the primary winding N_p.

The output voltage V_{out} corresponds to the sum of the voltages across the capacitors:

$$V_{out} = \frac{V_{in}}{1-D} \cdot (1 + 2 \cdot a) \qquad (11)$$

Where **a** is defined as the (10) for a single secondary winding. Considering a generic converter with **n** for which several values of $\mathbf{a_j}$ exists, the output voltage can be defined as:

$$V_{out} = \frac{V_{in}}{1-D} \cdot \left(1 + \sum_{j=1}^{n} a_j\right) \qquad (12)$$

Finally, the static gain expression can be defined from (12) as:

$$G_V = \frac{V_{out}}{V_{in}} = \frac{1}{1-D} \cdot \left(1 + \sum_{j=1}^{n} a_j\right) \qquad (13)$$

According to (13), the static gain can be increased by adjusting the turns ratio, the number of secondary windings, or even both of the parameters simultaneously.

III.EXPERIMENTAL RESULTS

An experimental prototype can be developed to verify this theoretical values based on the design specified earlier. The waveforms based on these calculations are shown as follows.

Here we require an output of 300V or 440V which supplies a double half-bridge inverter or other dc-ac stage. When a classical boost converter is employed only a poor efficiency can be obtained. But this basic boost converter is the basic for non isolated topology, where the gain an be increased as necessary. The waveforms are shown below.

A reduced ripple with good current sharing among the windings are observed in the primary winding of the transformer as shown in the fig 4,5 and 6.

A MOSFET with reduced on state resistance because only half of the output voltage is passed by the switch S1 as shown in the fig 7 and 8.

The fig 9 and 10 are the waveforms of the diodes in the boost converter. This is similar to the theoretical waveform in the fig 3.

The 3SSC mentioned is derived from th push-pull converter, which works in NOM and OM of the switches. They produce high power, high current operations which are designed for twice the switching frequency.

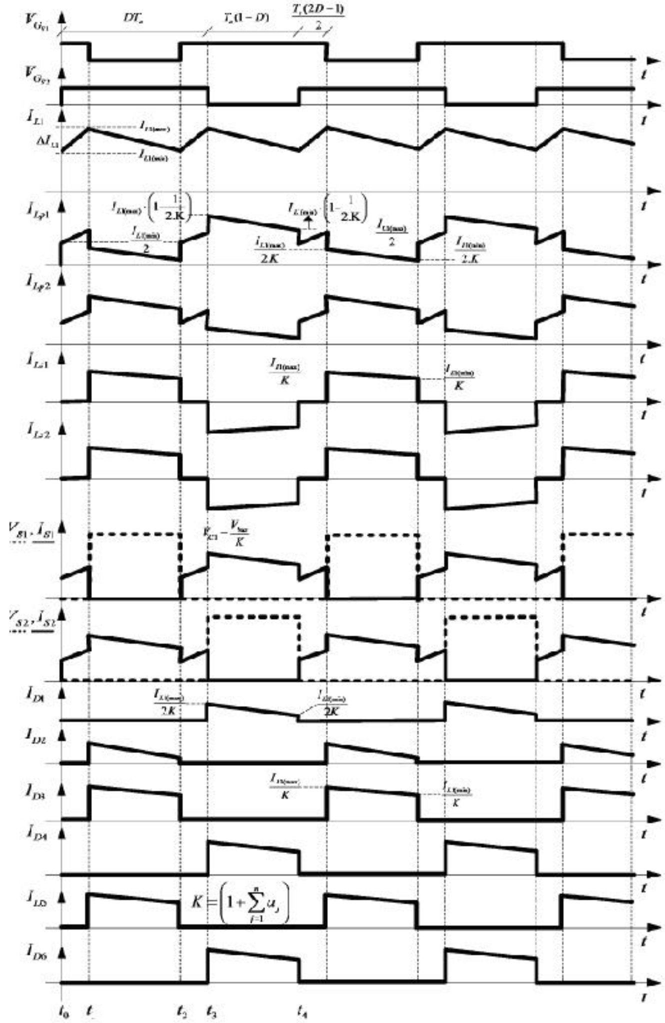
Non isolated converters are often preferred than isolated topologies in various applications such as VMCs, which is made up of diodes and capacitors to increase the static gain. In these all the parameters depend directly on the duty cycle and number of cells. In case when high static gain is required the component count has to be increased, this in turn increases the conduction losses by decreasing the efficiency.

Thus the proposed converter does not include VMCs and here the static gain is dependent on the turns ration between the primary and secondary windings, number of secondary winding and duty cycle. By increasing the number of secondary windings and turns ratio, the voltage stress across these switches can be reduced, which is the main advantages of 3SSC topology. This topology can be used when high voltage gain is required so that dc-dc converter can supply the half-bridge, double half-bridge, NPC inverter.

III.CONCLUSION

This paper presents a boost converter using 3SSC which supplies the double half-bridge inverter. The boost converter provides the necessary supply to the inverter. This system is also adequate for several applications mainly high voltage applications, photovoltaic system, UPS, inverter, industrial DC drives, etc.

The experimental prototype has been implemented and evaluated. The behaviour is similar to the proposed theoretical system. The efficiency of 92% can be obtained over an entire load range, since only a part of the energy is processed through active switches, while the remaining part is directly fed to the load without being processed by these



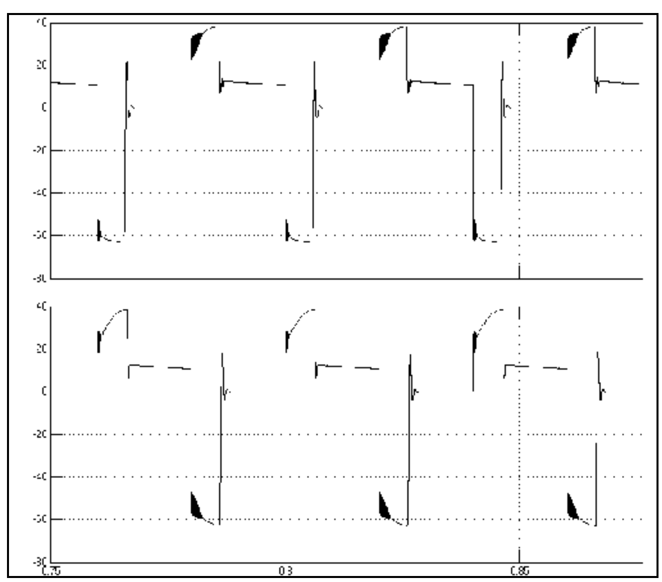


Fig. 4. Voltage waveforms of primary winding L_{p1} and L_{p2}.

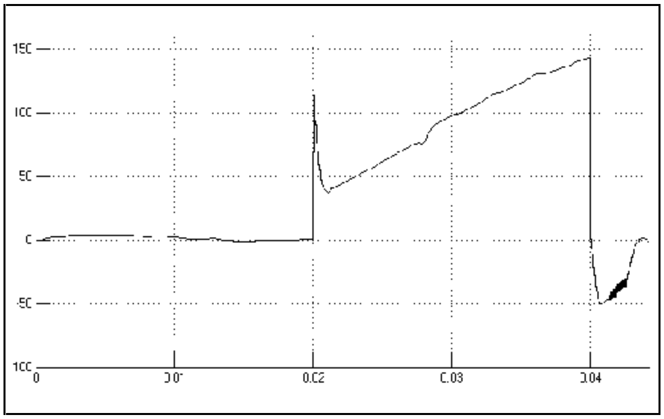


Fig 5. Current waveform of primary winding L_{p1}.

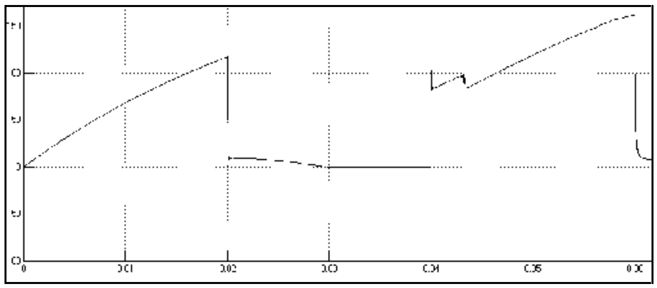


Fig 6. Current waveform of primary winding L_{p2}.

TABLE I DESIGN SPECIFICATIONS FOR THE STEP-UP CONVERTERS

Parameter	**Specification**
Rated output power	P_{out}=1000 W
Rated load	Resistors R_{o1}= R_{o2}=320Ω connected to capacitors C_{o1} and C_{o2}
Input voltage	V_{in}=42 V
Output voltage	V_{out}= 440V
Switching frequency	f_s= 25 kHz
Ripple ccurrent through inductor L_1	$\Delta I_{L1(max)}$=20% $I_{L1(avg)}$
Ripple voltage across auxiliary and output capacitors	$\Delta V_{C1 \ldots C5}$= ΔV_{co1}=ΔV_{co2}=1%*V_0
Expected theoretical efficiency	η=93%
Number of secondary windings	j=2
Turns ratio of the transformers	a_1=a_2=a= 1
Designed Elements	
Inductor	L_1=60μH
Main switches	MOSFET IRFP4227PBF
Diodes $D_{1\ldots}D_6$	Ultrafast diode HFA15PB60
Capacitor C_1...C_6	C_1=2, 2μF, polyester, 400V
Output capacitors C_{o1} and C_{o2}	C_{o1}=C_{o2}=470μF, electrolytic, 450V

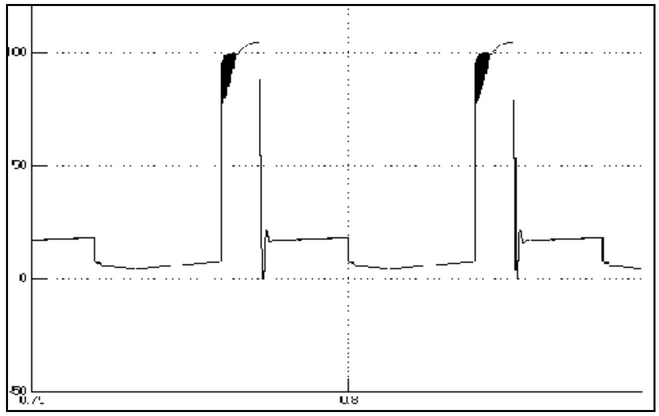


Fig 7. Voltage waveform of switch S1.

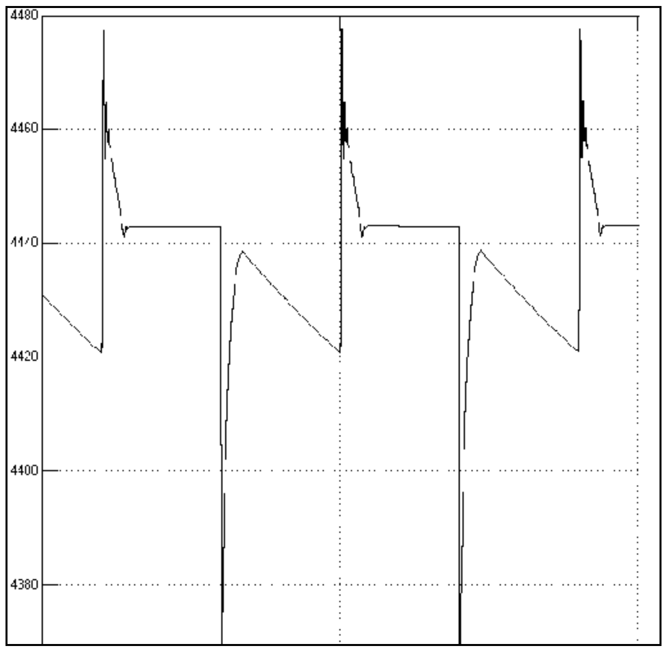


Fig 9. Current waveform of switch s1.

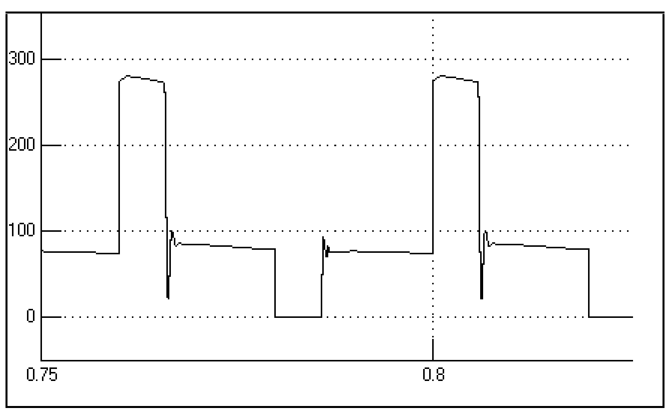


Fig 9. Voltage waveform of diode D_4.

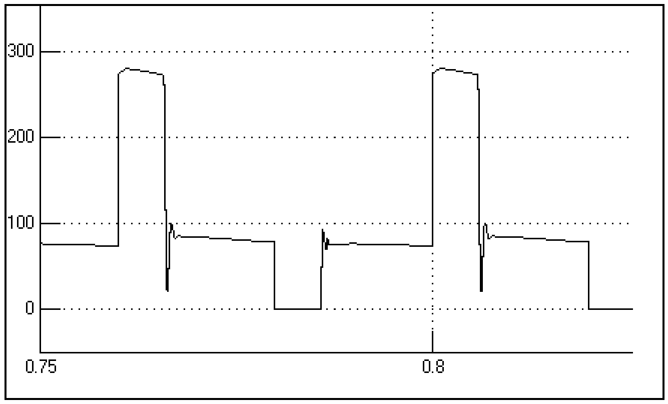


Fig 10. Voltage waveform of diode D_6.

switches i.e. energy is delivered through the passive components such as diodes and the transformer windings. These are due to the use of 3SSC which causes low conduction loss. A proper design procedure has been obtained from the quantitative and qualitative analyses of the converter. The behaviour of the converter is similar to the theoretical prototype.

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