Naturally Commutated Bidirectional Half-Bridge High Efficient DC/DC Converter for Biomedical Imaging Systems

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ABSTRACT

DC/DC Converters play a vital role in biomedical imaging systems such as x-ray, ultra sound and Magnetic Resonance Imaging systems. These applications require low ripple voltage waveforms, low voltage spikes and variable output voltages. This paper presents a naturally clamped bidirectional secondary modulation based zero current switching (ZCS) current fed half-bridge DC/DC converter for biomedical imaging systems. The proposed bidirectional converter achieves zero current switching (ZCS) of the main switches at the primary side and zero voltage switching (ZVS) of the rectifier switches at the secondary side. In the proposed converter, the secondary modulation clamps the voltage across the main switches in the primary side naturally, so that voltage spike at the switch turn-off is not seen. The operation of the proposed converter is explained, analyzed, and the performance of the converter is implemented in MATLAB for a model of 20 kHz switching frequency and 20 W output power.

Key words: Voltage fed inverter, current fed inverter, zero voltage switching (ZVS), zero current switching (ZCS), and bidirectional converter.

INTRODUCTION

Commercial medical imaging systems employ either unipolar or bipolar pulse generators. Very high voltage ultra-short unipolar pulse signals are generated by unipolar pulse generators which are widely employed in many applications because of their ease of use and wide bandwidth [1]. Due to high sensitivity, signal to noise ratio, and high efficiency, bipolar pulse generators are preferred over unipolar pulse generator [2, 3] but these are difficult to implement.

There have been many techniques that are employed for the generation of on-chip bipolar supply voltages. Comercial products developed in [4,5] generate a positive supply voltage by using a boost power converter, while such an implementation is simple, the use of additional bulky inductors, off-chip pins, I/O pads and multiple controllers lead to low efficiency, some amount of EMI noise and large system volume.

Current fed topologies have been used widely for applications with more input source voltage variations and for higher voltage conversion ratio [6-11]. These converters give smaller input current ripple, no duty cycle loss and small diode ringing. For high voltage converters, these converters are very useful. Current fed bidirectional half- bridge DC/DC converter is analyzed in [12], where to absorb the serge voltage, active clamp circuit is used. Current fed bidirectional push-pull DC/DC converter is analyzed in [13], where the leakage inductance and the parasitic capacitance are utilized to achieve the ZCS but resonant current is much higher than the input current. So, there is increase in the current stress of the devices.

Generally bidirectional DC/DC converters are used for transfer of power in both forward and reverse directions. Current fed bidirectional DC/DC converters are very popular which gives small input ripple, small diode ringing, and no duty cycle loss [14-17].

The above literatures do not deal with natural clamp soft switched half-bridge DC/DC converter for biomedical imaging systems. The objective of this paper is to present the steady state operation, analysis, and implementation in MATLAB of the proposed converter in forward mode only. Although the converter can works in both mode, only forward mode has been presented here.Operation and steady-state analysis of the proposed converter

Fig.1 shows the proposed bidirectional half-bridge DC/DC converter. For the analysis of the converter, the following assumptions are made.

(1) Inductor L1 and L2 are assumed large because constant current should flow through both the inductors.
(2) The magnetizing inductance of the transformer is considered to be very large.
(3) Lk is the leakage inductance of the transformer or it is the external series inductor which also includes the leakage inductance of the transformer.

The steady state operating waveforms of the proposed converter is shown in Fig.2. Due to the symmetry in nature, only half cycle of the converter is explained here in eight intervals.

Interval 1 (t_0 to t_1): In this interval, primary side switch S_1 and body diode of S_5 and S_6 (D_5 and D_6) are conducting. Positive power is transferred from source to load in this interval. At the end of this interval,

$$i_{S_1}(t_1)=I\ ,\ i_{S_2}(t_1)=0\ ,\ i_{L_K}(t_1)=\frac{-I}{2},$$

$$i_{D_6}(t_1)=\frac{-I}{2n}$$

Where I=input current
n= transformer turns ratio.

Interval 2 (t_1 to t_2)

In this interval, at $t=t_1$, S_2 is turned on. So, the snubber capacitor of S_2, (C_2) discharges quickly.

Interval 3 (t_2 to t_3)

In this interval, current through (S_2), starts increasing and current through S_1, starts decreasing. The current in S_2, starts from zero provides ZCS turn on for switch S_2, which reduces losses at S_2. The current through several components are,

$$i_{L_K}=-\frac{I}{2}+\frac{V}{n.L_K}(t-t_2) \quad ...(1)$$

$$i_{S_1}=I-\frac{V}{n.L_K}(t-t_2) \quad ...(2)$$

$$i_{S_2}=\frac{V}{nL_K}(t-t_2) \quad ...(3)$$

$$i_{D_6}=\frac{-I}{2n}+\frac{V}{n^2L_K}(t-t_2) \quad ...(4)$$

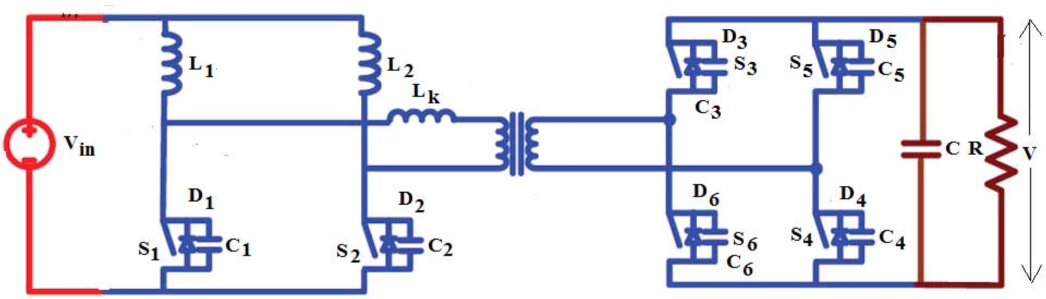


Fig.1: Proposed bidirectional half-bridge converter

At the end of this interval at t=t_3,

$$i_{S_1}(t_3)=\frac{I}{2},\ i_{L_K}(t_3)=0\ ,\ i_{S_2}(t_3)=\frac{I}{2},\ i_{D_6}(t_3)=0$$

Current across D_6, (i_{D6}) is zero so switch S_6 is commutated naturally.

Interval 4 (t_3 to t_4)

In this interval, secondary switches, S_5 and S_6 are turned on with ZVS. At the end of this interval,

$$i_{S_1}(t_4)=0\ ,\ i_{S_2}(t_4)=I\ ,\ i_{L_K}(t_4)=\frac{I}{2},\ i_{S_6}(t_4)=\left(\frac{I}{2n}\right)$$

Interval 5 (t_4 to t_5)

The body diode of S_1, (D_1) starts conducting which provides zero voltage across switch S_1, ensuring its ZCS turn off at t_5.The current through the several components are,

$$i_{L_K}=\frac{I}{2}+\frac{V}{nL_K}(t-t_4) \qquad ...(5)$$

$$i_{S_2}=I+\frac{V}{nL_K}(t-t_4) \qquad ...(6)$$

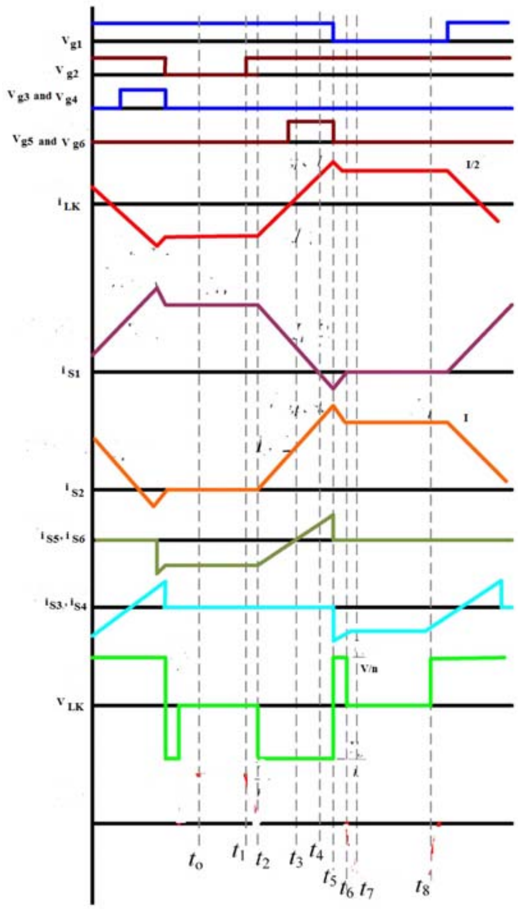


Fig. 2: Waveforms of the Proposed bidirectional half-bridge converter

Interval 6 (t_5 to t_6)

In this interval, secondary switches S_5 and S_6 are off. Current flows through the body diodes of secondary switch S_3 and S_4. At the end of this interval,

$$i_{S_2}(t_6)=I\ ,\ i_{D_1}(t_6)=0\ ,\ i_{L_K}(t_6)=\frac{I}{2},\ i_{S_6}(t_6)=\frac{I}{2n}$$

Interval 7 (t_6 to t_7)

In this interval, the capacitance of S1, (C1) charges to V/n.

Interval 8 (t_7 to t_8): In this interval, constant current is flowing through the switch S2, secondary leakage inductance LK and body diode of secondary switch. For the next half cycle, the intervals are repeated.

Simulation results

The proposed converter is simulated by MATLAB simulink. The specifications and the component values of the simulink model are shown in Table 1.

Simulink output of the proposed converter is shown in Fig.3. Gating signals for S_1, S_2, S_3, S_4, S_5 and S_6 are shown in Fig. 3(a). It is observed that, conduction time of the primary side main switches S_1, and S_2 are equal and 180 ^{0} phase shift with each

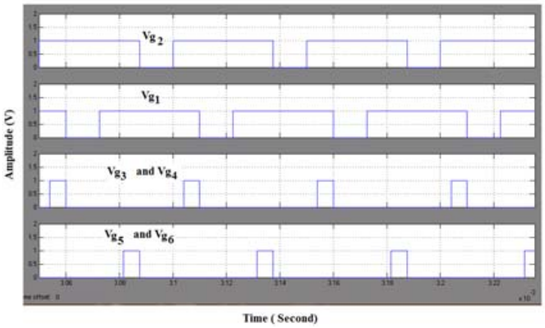
Table 1: Specifications and component values

Specifications	Component values
Input voltage Vin =48 V	Input inductance L1=1 H
Output voltage V=12 V	Input inductance L2=1 H
Switching frequency f= 20 KHz.	Primary inductance LK=5 µF
Power P= 20 W	Filter capacitance C= 500 µF

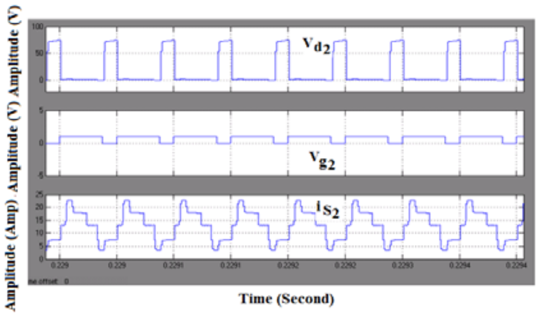
other. The conduction time of S_3, S_4, S_5, and S_6 all are same and the duty cycle is less than 50%.

Fig. 3(b) shows, gate to source voltage (V_{g2}), drain to source voltage (V_{d2}), and current through the switch S_2, (i_{S2}). We observe that, gate to source voltage (V_{g2}), falls to zero, and after that, drain to source voltage (V_{d2}), starts rising. The current across the switch S_2, naturally reduced to zero, and negative current shows that, antiparallel diode conduction across the switch. So, primary side main switch is turn off at ZCS.

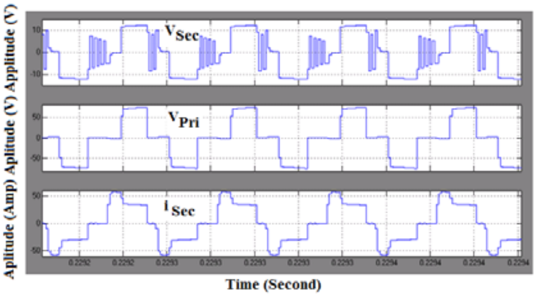
Fig. 3(c) shows voltage across the primary (V_{Pri}), voltage across the secondary(V_{Sec}) and current across the secondary (i_{Sec}) of the transformer. We observe that, the current through the secondary is almost continuous. We also observe that, input and output voltage across both side of the transformer is without ringing and spikes.



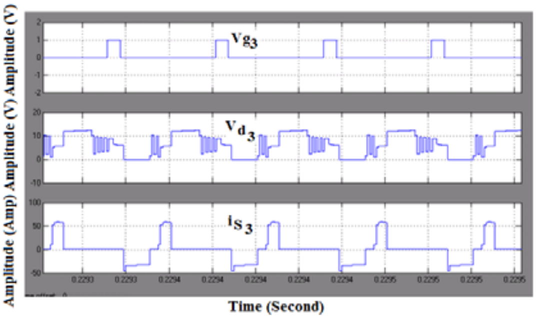
(a)



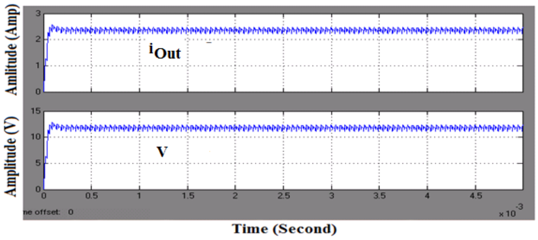
(b)



(c)



(d)



(e)

Fig. 3: Simulation waveforms. (a) Driving pulses of S_1, S_2, S_3,S_4, S_5, and S_6. (b) Gate to source voltage (V_{g2}), drain to sourcevoltage (V_{d2}), and current through the switch S_2, (i_{S2}) (c) voltage across the primary (VPri), voltage across the secondary(VSec) and current across the secondary (i_{Sec}) (d) gate to source voltage of S_3, (V_{g3}), drain to source voltage of S_3, (V_{d3}), and current across the switch S_3, (i_{S3}) (e) output voltage (V) and output current I_{Out}.

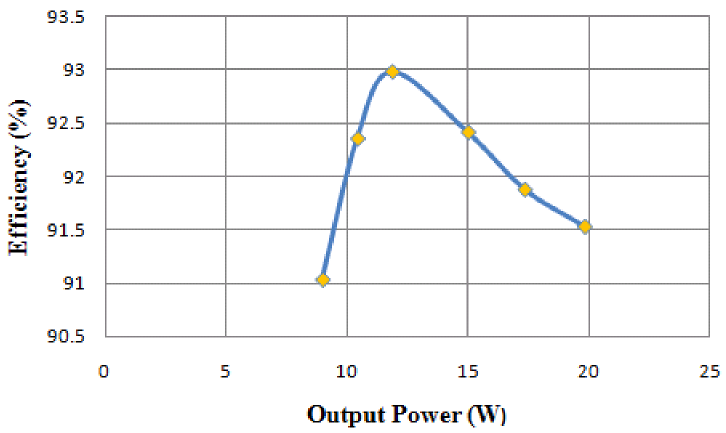


Fig.4: Efficiency versus output power for different load condition

Fig. 3(d) shows the gate to source voltage of S_3, (V_{g3}), drain to source voltage of S_3, (V_{d3}), and current across the switch S_3, (i_{S3}).We observe negative current across the switch, which is due to the body diode conduction. Due to negative current, voltage across the switch (V_{d3}) is zero and the gate signal V_{g3} is applied. So, secondary side switch S_3 is turned on at ZVS.

Fig.3(e) shows the output voltage (V) and output current i_{Out}, at a load resistance of 5&!.

Fig.4 shows the measured efficiency with different load for the proposed converter in the MATLAB simulink model. The maximum efficiency of 92.99% for 11.89W and full load efficiency of 91.53% for 19.86 W are obtained. So, we observe that, although efficiency decreases at higher load, but over a wide load range, the efficiency curve remains almost high and flat.

CONCLUSION

This paper presents a soft switching bidirectional current fed half-bridge DC/DC converter for biomedical imaging systems where low ripple voltage waveforms, low voltage spikes and variable output voltages is required. The primary side switches are naturally voltage clamped and it causes ZCS. The secondary switches are naturally voltage clamped and it undergoes ZVS. Due to secondary modulation method, without any extra snubber circuit, primary side clamping takes place naturally. The proposed converter is independent of duty cycle and it works in both directions with high efficiency. The conversion of 48 V to 12 V is done by taking different loads. It has found that, the proposed converter has high efficiency and it can be used in biomedical imaging system applications due to ripple free output, very simple design and high efficiency.

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