A New DC-DC Buck Converter With Soft-Switching Capability

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***Abstract*—In this paper, a new DC-DC buck converter with soft-switching capability is proposed and investigated. In this structure, a simple auxiliary circuit provides soft-switching condition for the switch's turn-on and turn-off, and the reverse recovery problem of the diode has been solved. First, the proposed converter is introduced and the operational modes are mentioned. In order to prove the proposed converter's performance, a 180W prototype of the converter is simulated in PSCAD software and the results are also obtained. Finally, a 180W prototype of the converter is built and the experimental results prove the soft-switching capability of the proposed converter.**

Keywords—DC-DC converters, buck converters, soft-switching, zero voltage switching

I. Introduction

There are many global concerns about the world's energy problem. As fossil fuels have proved to be unstable and limited, it is crucial to find other energy resources. Renewable energy resources seem to be the best choice in case of their reliability and accessibility. Considering that DC-DC converters are applied for the renewable energies [1-5], there are new demands for efficient DC-DC converters. Among DC-DC converters, buck converters are applicable in cases that a reduced voltage is required like in charger applications. Efficiency is a crucial factor to be considered in DC-DC converters. Utilizing these converters in high frequencies with least possible losses, including the switching losses and the reverse recovery losses is the main reason for designing these converters. Many structures have been proposed for reducing these losses.

The presented structure in [6] provides soft-switching condition for the power switches turn-on and turn-off. However, some diodes still have reverse recovery losses and the complex auxiliary circuit of this converter causes a lot of losses which can reduce the overall efficiency.

In [7], a new soft-switched DC-DC buck converter based on resonant circuits is presented. In this structure, a resonant circuit which consists of a resonant switch, an inductor, a capacitor, and a diode is utilized to provide ZVS condition for the switches' turn-on and ZCS condition for the switches' turn-off. In this structure, using resonant circuit has led to flow an additional resonant current which can increase the conduction losses.

In [8], a new ZVS buck converter is presented. Using tapped inductor and an additional auxiliary circuit not only provides ZVS condition for the switches' turn-on but also decreases the flowing current which makes it possible to reduce conduction losses. However, the switches' turn-off losses and diodes' reverse recovery losses reduce the power efficiency.

The introduced structure in [9] can provide ZVS condition for the switches in the conventional synchronous buck converter. In this structure, an auxiliary circuit which consists of an inductor, two capacitors, and three power diodes is added to the conventional synchronous buck converter which enables the converter to operate under ZVS turn-on condition. Implementing many diodes in the auxiliary circuit which results in high reverse recovery losses and the turn-off losses of the power switches are the main drawbacks of this converter.

II. Proposed Structure and Operational Modes

A. Proposed structure

The schematic of the presented converter is shown in Fig. 1. L_m, S, D, and C_o are the conventional buck converter's components. Furthermore, the auxiliary circuit consists of L_r, C_1, C_2, and C_r.

B. Operational modes

Mode 1(t_0-t_1)**:** Considering that the switch was in "on" mode and it is conducting before this mode, in this mode, the parallel capacitor starts being charged. This leads to the switch's turn-off under zero voltage switching (ZVS) condition.

By applying KVL:

$$V_{cr} = V_i \tag{1}$$

$$V_{Lm} = V_{C1} \quad , V_{C2} = V_{Lr} - V_{Cr} \tag{2}$$

Mode 2(t_1-t_2)*:* After the capacitor gets charged in mode 1 to the input voltage value, the main diode begins to conduct due to the resulted voltage of mode 1 on the main diode.

The following relation is resulted by applying KVL:

$$V_{Lm} + V_{Lr} = V_o \tag{3}$$

Mode 3(t_2-t_3)**:** At the end of mode 2, the main diode turns off and the parallel capacitor begins to get discharged. Finally, in this mode, the parallel capacitor gets discharged and a zero voltage is resulted on the switch.

$$V_s = V_{Cr} = V_{Dr} = 0 \tag{4}$$

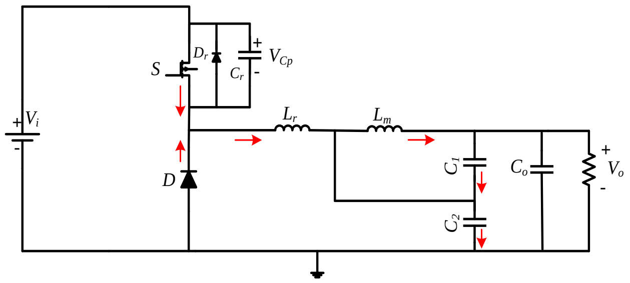
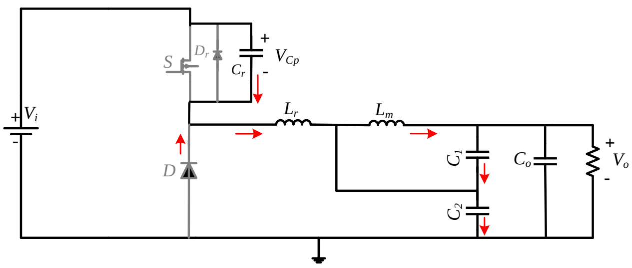
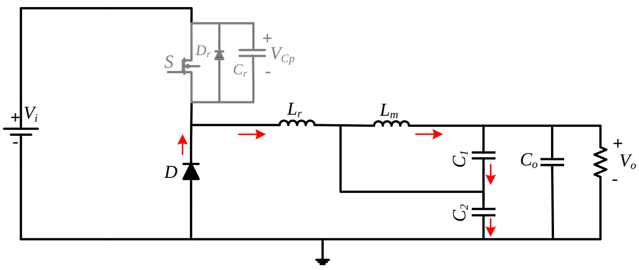


Fig. 1. Proposed soft-switched buck converter



(a)



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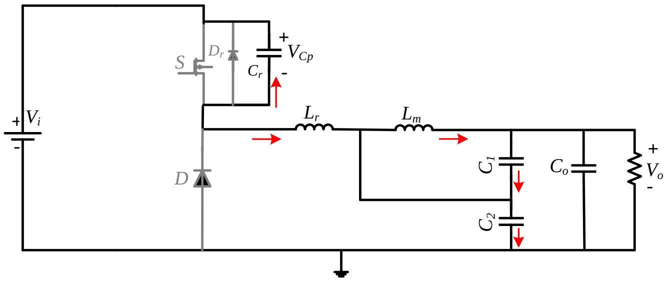

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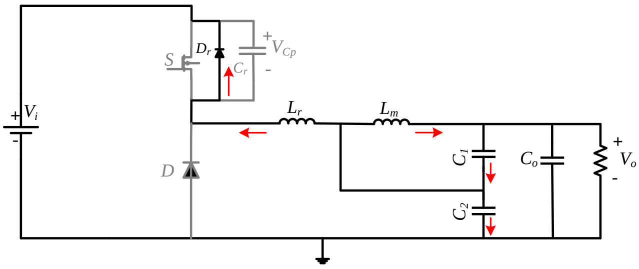

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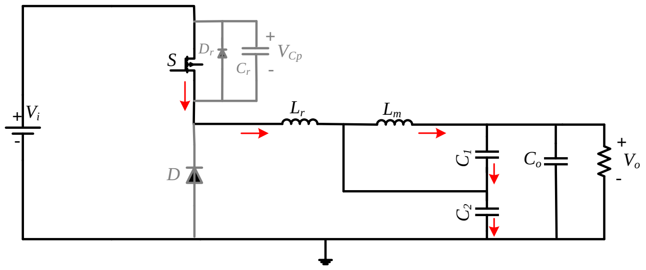


(e)

Fig. 2. Equivalent circuits. a) Mode 1, b) Mode 2, c) Mode 3, d) Mode 4, e) Mode 5

Mode 4(t_3-t_4)**:** At the end of mode 3, the parallel capacitor is completely discharged and the switch's voltage reaches zero

Due to the negative current which is flowing through the auxiliary inductor, the anti-parallel diode of the switch begins to conduct. Finally, the switch's voltage is fixed at zero and the zero voltage switching condition for the switch's turn-on is achieved.

Mode 5(t_4-t_5)*:* In this mode, the switch turns on under ZVS condition because of the zero voltage of the switch.

The period is finished and after this mode, the converter undergoes the same prior modes respectively.

C. Voltage gain and voltage stress

The voltage gain of the proposed converter is equal to the conventional buck converter's voltage gain. Hence, this relation can be achieved:

$$\frac{V_o}{V_i} = d \tag{5}$$

The voltage stresses of the main switch and the main diode is similar to the voltage stresses in the conventional buck converters. As a result, these relations can be written:

$$V_{S-Max} = V_{D-MAX} = V_i \tag{6}$$

III. EFFICIENCY EQUATIONS

In this part, the efficiency of the proposed converter is analyzed. TABLE I represents the average RMS values of voltages and currents. Total losses include the conduction losses of the components, the Forward-Voltage losses of the power diode, and inductors' core losses in this converter. Consequently, the overall losses can be obtained as follows:

$$P_{overall-loss} = P_{Conduction} + P_{Forw-Voltage} + P_{Core} \tag{7}$$

Considering the RMS values from TABLE I, the components' conduction losses can be derived as follows:

$$P_{Conduction} = R_{Switch-on} I_{S-RMS}^2 + R_{Diode} I_{D-RMS}^2 + R_{Lm} I_{Lm-RMS}^2 + R_{Lr} I_{Lr-RMS}^2 + R_{C1} I_{C1-RMS}^2 + R_{C2} I_{C2-RMS}^2 + R_{Co} I_{Co-RMS}^2 \tag{8}$$

The Forward-Voltage losses of the diode can be obtained as follows:

$$P_{Forw-Voltage} = V_{D-Avg} I_{D-Avg} \tag{9}$$

The core losses of the inductors are fixed and depend on the switching frequency and temperature. Therefore, these values can be achieved from their datasheets.

$$P_{Core} = P_{Core-Lm} + P_{Core-Lr} \tag{10}$$

Finally, the efficiency of the proposed converter will be achieved as follows:

$$Efficiency\% = \frac{P_{Out}}{P_{Out} + P_{overall-loss}} \times 100 \tag{11}$$

TABLE I. AVERAGE AND RMS VALUES

Parameter	Average Voltage	Average Current	RMS Current
Switch	$V_i(1-d)$	di_o	$i_o\sqrt{d}$
Diode	V_o	$(1-d)i_o$	$i_o\sqrt{1-d}$
Inductors	0	i_o	i_o
Output Capacitor	V_o	0	$i_o\sqrt{d}$

IV. COMPARISON RESULTS

In this part, a comparison of the proposed converter with other presented structures in [6], [7], [8] and [9] is mentioned. As it can be seen, the comparison proves the ZVS condition for the switch and ZCS condition for the diode with minimum number of components.

The proposed converter in this article has one main switch and no additional auxiliary switches, whereas the compared structures have at least one auxiliary switch. Moreover, the proposed converter operates with full soft-switching condition for the switch's turn-on and turn-off and the diode's turn-off.

V. SIMULATION AND EXPERIMENTAL RESULTS

In this section, a 180W sample of the proposed converter is simulated in PSCAD to prove the converter's performance. The obtained results are shown in Fig 3. Furthermore, a 180W concept of this converter has been built and the soft-switching waveforms are shown in Fig 4. The types and values of the simulation and the experimental concept are mentioned in TABLE III.

Fig. 3(a) shows the voltage and current of the switch. Prior to the switch's turn-on, because of the negative current of the auxiliary inductor, the switch's parallel diode conducts for a short time period. As a result, the switch's voltage is fixed at zero and provides the zero voltage switching condition for the switch. In turn-off instant, the parallel capacitor is getting charged and its voltage slowly increases and switching is accomplished near zero voltage.

Fig 3(b) shows the diode's voltage and current. The diode's current reaches zero just before the switch turns off. In addition, the diode's reverse recovery problem is solved.

It can be seen from Fig 3(a) and Fig 3(b) that the proposed converter's voltage stress is equal to the input voltage.

Fig 3(c) shows the output voltage. It is evident from the aforementioned relations that the voltage gain in this structure is equal to the common buck converter. The input voltage is 100V and the output voltage is 52V with 50% duty cycle which proves the bucking capability.

TABLE II. COMPARISON AMONG THE PROPOSED STRUCTURE AND OTHER CONVERTERS

Structure	Number of					Switch		Diode
	Switches	Diodes	Inductors	Capacitors	Total	Turn-on	Turn-off	Turn-off
[6]	2	5	2	2	11	Soft	Soft	hard
[7]	3	1	2	2	8	Soft	Soft	hard
[8]	2	2	3	4	11	Soft	Soft	hard
[9]	2	3	2	3	10	Soft	Soft	Soft
Proposed	1	1	2	3	7	Soft	Soft	Soft

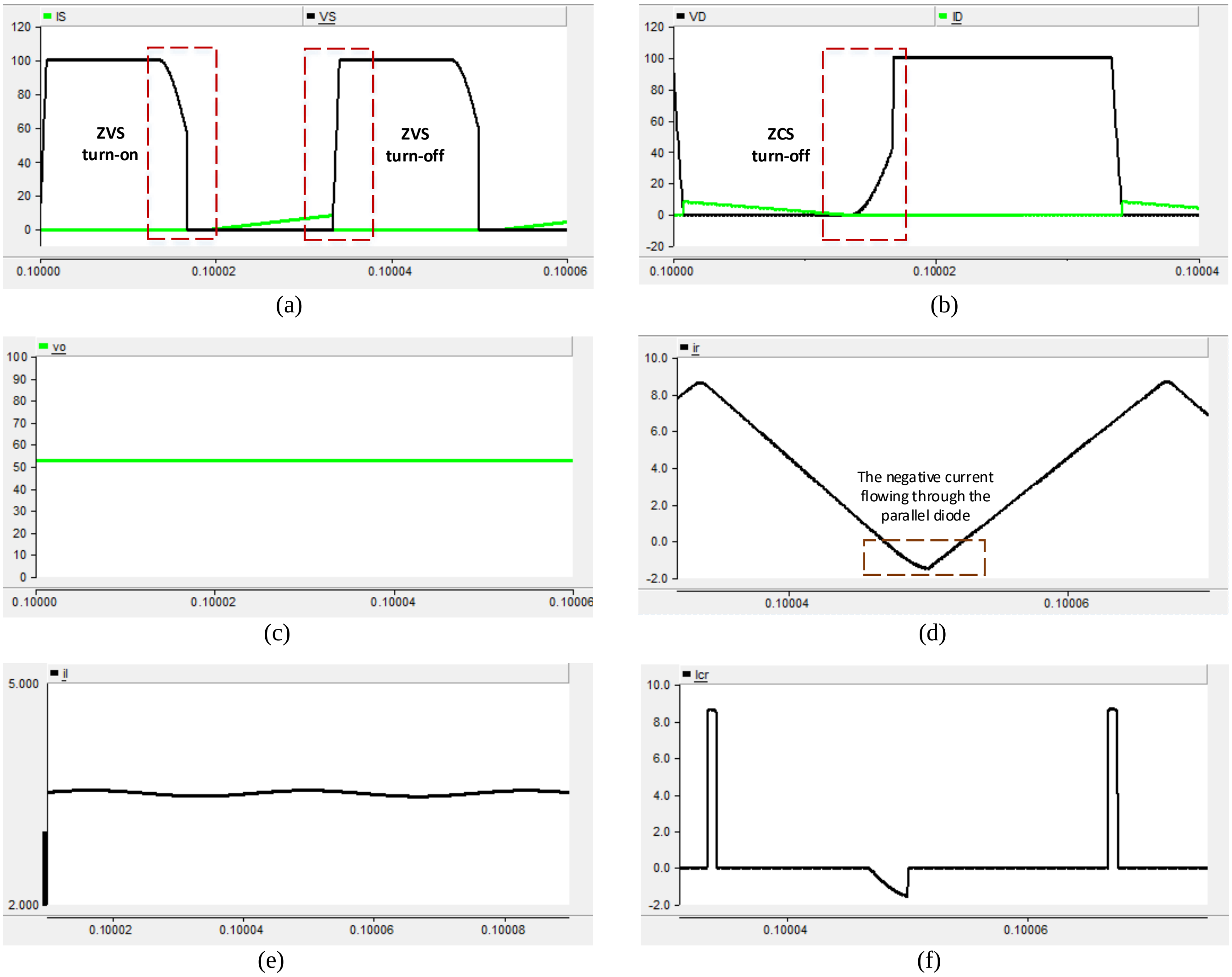
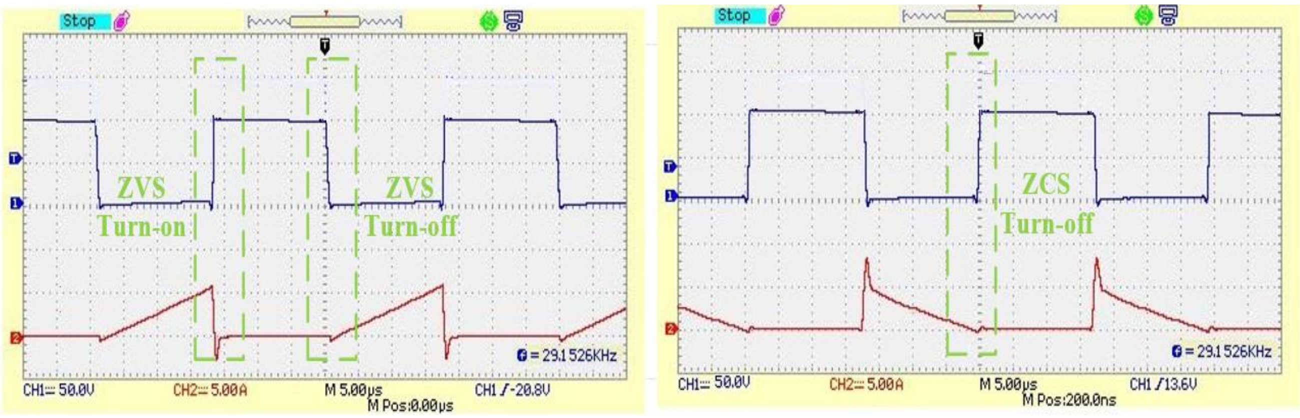


Fig. 3. Simulation Results. a) Switch's voltage and current, b) The diode's voltage and current, c) Output voltage, d) The auxiliary inductor's current, e) The main inductor's current, f) The parallel capacitor's current

TABLE III. TYPES AND VALUES OF THE IMPLEMENTED COMPONENTS

Parameter	Type and Value	Parameter	Type and Value
Power Switch	IRFP260npbf	**Power Diode**	MUR820
Core Type	EE42	**Inductor Values**	L_m=145uH
			L_r=85uH
Output Capacitor	1000uF, 100V	**Auxiliary Capacitors**	10uF, 100V
Switching Frequency	30KHZ	**Input Voltage**	100V
Output Voltage	52V	**Duty Cycle**	50%



(a) (b)

Fig. 4. Experimental Waveforms. a) Switch's Voltage and Current, b) Diode's Voltage and Current

Fig 3(d) shows the auxiliary inductor's current. As it can be seen, there is a particular zone in which the current is negative. This negative current which is obtained just before the switch's turn-on instant, flows through the parallel diode and makes it possible for the switch to turn on under ZVS condition.

Fig 3(e) shows the main inductor's current with a near to constant value.

Fig 3(f) shows the parallel capacitor's current. With due attention to this current, the parallel capacitor begins to get discharged and causes the diode's voltage to reach zero to let the parallel diode turn on. Moreover, the parallel capacitor is getting charged during the switch's turning off period in order to make the switch's voltage near to zero.

Fig 4(a) shows the experimental waveforms of the switch's voltage and current. The waveforms prove the switch's ZVS condition.

Fig 4(b) shows the experimental waveforms of the diode's voltage and current. The diode turns off under ZCS condition and the reverse recovery losses have been minimized.

VI. Conclusion

In this paper, a new DC-DC buck converter is proposed and investigated. This structure provides ZVS condition for the switch's turn-on and turn-off and ZCS condition for the diode. Furthermore, the number of components in this converter is less than other structures which are compared with the proposed converter in the comparison results. In addition, in order to show the converter's good performance, a 180W sample of this converter is simulated in PSCAD software. A concept of the proposed converter is also assembled in laboratory and the results prove the soft-switching capability in this converter.

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