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Analysis and Design of A Fully Soft Switched Two-Level DC-DC Boost Converter for Electric Vehicle Applications

Amin Mirzaei
Arak University, Iran, a-mirzaee@araku.ac.ir

Mahdi Rezvanyvardom
Arak University, Iran, m-rezvanyvardom@araku.ac.ir

Ehsan Najafi
Qom University of Technology, Iran, najafi@qut.ac.ir

ANALYSIS AND DESIGN OF A FULLY SOFT SWITCHED TWO-LEVEL DC-DC BOOST CONVERTER FOR ELECTRIC VEHICLE APPLICATIONS

Amin Mirzaei [1*], Mahdi Rezvanyvardom [1], Ehsan Najafi [2]

[1*] *Assistant Professor, Department of Electrical Engineering, Faculty of Engineering, Arak University, Arak, Islamic Republic of Iran, email a-mirzaee@araku.ac.ir*

[1] *Assistant Professor, Department of Electrical Engineering, Faculty of Engineering, Arak University, Arak, Islamic Republic of Iran, email m-rezvanyvardom@araku.ac.ir*

[2] *Assistant Professor, Faculty of Electrical and Computer Engineering, Qom University of Technology, Qom, Iran, email najafi@qut.ac.ir*

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تحليل وتصميم محوّل ناعمًا تمامًا لمحولين للتيار المستمر DC-DC لتطبيقات السيارات الكهربائية

ملخص

في هذه الورقة ، تم اقتراح محول DC-DC البوست ذو مستويين ناعمين بالكامل. يستخدم المحول خلية مساعدة واحدة فقط لتهيئة ظروف التبديل الرخوة لجميع أجهزة أشباه الموصلات. تحتوي الخلية المساعدة على مفتاح مساعد واحد ، ومكثف رنان واحد ، ومحث رنان واحد ، وديود مساعد واحد. يعمل المفتاح المساعد على إنشاء ظروف تبديل ناعمة عن طريق التحكم في عناصر الرنين. إلى جانب ذلك ، لا توجد الخلية المساعدة في مسار الطاقة الرئيسي ولا يمكنها تقليل كفاءة المحول. لديها أوضاع تشغيل بسيطة. علاوة على ذلك ، فإن المحول ذو التبديل اللين المقترح فعال للغاية بينما دائرة التحكم بسيطة وتبقى PWM. علاوة على ذلك ، فإن استخدام الهيكل ذي المستويين في الطوبولوجيا المقترحة يخلق محولًا ذا ربح كبير. تعتبر الأشكال الموجية النظرية وأنماط التشغيل ونتائج المحاكاة لإظهار الخصائص الجيدة للمحول المقترح.

Abstract

In this paper, a fully soft switched two-level DC-DC Boost converter is proposed. The converter is used only one auxiliary cell to create the soft switching conditions for all semiconductor devices. The auxiliary cell contains one auxiliary switch, one resonant capacitor, one resonant inductor and one auxiliary diode. The auxiliary switch creates the soft switching conditions by control of resonant elements. Besides, the auxiliary cell is not located in the main power path and cannot decrease the converter efficiency. It has simple operation modes. Besides, the proposed soft-switched converter is highly efficient while the control circuit is simple and remains PWM. Furthermore, the use of two-level structure in the proposed topology creates a converter with high gain. Based on the mentioned advantages, the proposed converter is a suitable candidate to use in electric vehicles. The theoretical waveforms, operation modes and simulation results are considered to show the good characteristics of the proposed converter.

1. INTRODUCTION

Since the invention of electric vehicles (EV), there was always a perception that EVs will dominate the future of vehicular transportation [1-3]. The importance of reducing industrial and vehicular emissions to minimize the effects of global warming, along with the fact that EVs have improved significantly in terms of technology and performance in recent years, has attracted many companies and people to investigate further on EVs [4-7].

EVs can be categorized in four main types. Required energy in hybrid-electric vehicles (HEV) is supplied through two energy systems. Main energy system, which generally is a fuel cell (FC), and rechargeable energy storage system, which can be either batteries or ultra-capacitors. Both gas and electric motors are utilized in HEVs structure. HEVs are highly efficient and have rather long driving ranges among different kinds of EVs [8].

Fuel cell has unregulated and low output power as the main source. Consequently, high step-up converter with high efficiency should be used as an interface circuit between fuel cell and DC bus. On the other hand, the volume and size of the converter should be reduced as much as possible due to limited space in EVs. As a result, switching frequency is increased. However, higher switching frequency can create some problems such as; higher switching losses, higher electromagnetic interference (EMI) and lower efficiency. Therefore, soft switching techniques are used to solve these problems. The fundamental rule in soft switching technique is to switch the power device when the flowing current through it is zero known as zero current switching (ZCS) or the voltage across it is zero known as zero voltage switching (ZVS) [9-14]. They are using resonant tank in their structure to create an oscillatory (usually sinusoidal) voltage and/or current waveforms in the operation modes of the converter. Traditional soft switched converters have different kinds such as; resonant converters, quasi resonant converters, snubbers, etc. However, zero voltage transition (ZVT) and zero current transition (ZCT) are new generation of soft switched converters that are used an auxiliary circuit comprising resonant tank and an auxiliary switch to provide soft switching at switching instances. Consequently, the power can be transferred with less conduction and switching losses.

Soft switched converters have many advantages over hard switched converters such as higher total efficiency, better device utilization, higher power density, lower size of filtering elements, lower EMI, etc [14]. However, hard switched converters have simpler structure. Moreover, their control circuit is simpler than soft switched converters. The advantages and disadvantages of these converters depend on the application. In some applications such as EVs the efficiency of the converter is very important. As a result, the designers tend to use soft switched converters as an interface circuit between input source and DC bus in them.

Boost converter is usually used to step-up the voltage level in Evs. Recently, two-level Boost DC-DC Converter (TLBC) was proposed [15-19]. It has lots of advantages such as self-voltage balancing and higher voltage gain without applying an extreme duty cycle in comparison with traditional Boost DC-DC converter. The arrangement of input sources, TLBC and DC Bus in EV application is shown in Figure 1. It should be mentioned that most of the suggested TLBCs in the literatures suffer from low efficiency due to hard switching condition.

In this paper, a TLBC is used as an interface circuit between FC and DC bus in HEV. The converter is used only one auxiliary cell to create the soft switching conditions for all semiconductor devices. The auxiliary cell contains one auxiliary switch, one resonant capacitor, one resonant inductor and one auxiliary diode. The auxiliary switch creates the soft switching conditions by control of resonant elements. Besides, the auxiliary cell is not located in the main power path and cannot decrease the converter efficiency. The proposed converter only uses one auxiliary switch and one main switch that lead to simple structure. Moreover, the use of two-level structure and soft switching technique in the proposed topology create a converter with high gain and high-efficiency.

The paper is organized as follows.

Section 2 describes the converter operation. To verify the theoretical analysis, simulation results are done by PSPICE software and presented in Section 3. In the end, conclusions are provided in Section 4.

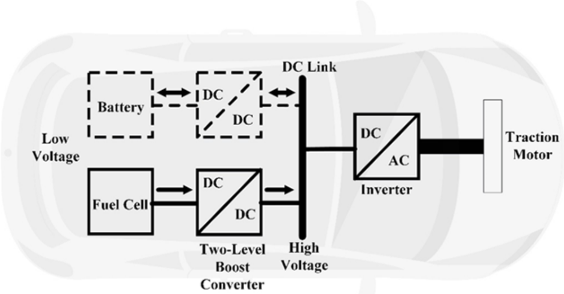


Figure 1. The arrangement of input sources, DC-DC converters and DC Bus in EV application

2. OPERATING PRINCIPLES OF THE PROPOSED CONVERTER

The proposed TLBC is shown in Figure 2.

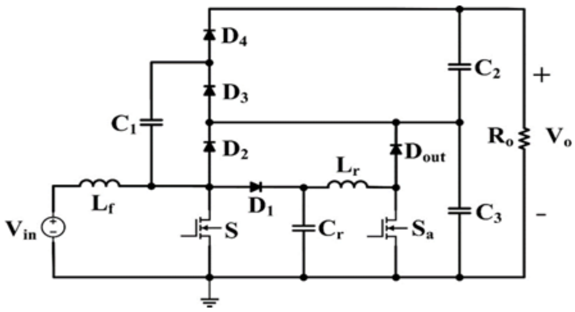


Figure 2. the proposed TLBC

In order to simplify the analysis of the converter, the following assumptions are considered:

- The voltages across the capacitors (C_1, C_2 and C_3) are constant and can be replaced with DC voltage sources.
- The current flows through the input filter inductor (L_f) is constant and L_f can be replaced by a DC current source.
- All semiconductor elements are considered to be ideal.
- The input voltage is constant during a switching period.
- The reverse recovery time of diodes is zero.

It is also assumed that the converter operates at steady-state condition.

In the proposed topology (Figure 2), an auxiliary cell is used to create soft switching conditions for all switching elements. The main switch of the converter is S. The proposed TLBC includes diodes (D_2, D_3 and D_4), input filter inductor (L_f) and capacitors (C_1, C_2 and C_3). Besides, R_o is considered as the output load resistance.

The auxiliary cell contains an auxiliary switch (S_a) and resonance elements (C_r and L_r) in its structure. Furthermore, diode D_{out} transfers the stored energy in resonant elements and also the power from the input to the output. The auxiliary switch controls the resonant elements and provides soft switching conditions for all switching elements. The auxiliary cell is not placed in the power path from the input to the output. As a result, it does not reduce the converter efficiency. The proposed TLBC operates in continuous current mode (CCM).

Due to use only one main switch and one auxiliary switch, the controller is simple (the pulse-width modulation (PWM) technique is used to trigger the power switches) and the proposed converter has a simple structure. Using a two-level structure causes the voltage gain of the converter will equal twice the conventional Boost converters.

The use of soft switching techniques also reduce switching losses for all semiconductor devices. Therefore, the converter efficiency will be increased. Voltage stress on the main and auxiliary switches in the proposed converter is equal to $\frac{C_3}{C_2+C_3}V_o$. Thus, the voltage stress on switches is also reduced in comparison with similar topologies.

The converter operation in each switching period can be divided into four modes. The theoretical waveforms of the proposed converter are shown in Figure 3.

Then, a detailed overview of the converter operation is discussed.

Mode 1 ($t_0<t<t_1$): This mode starts when the auxiliary switch (S_a) is turned on at t_0. At t_0, diode D_{out} is on, and the power is transmitted through it to the output. Moreover, I_{Dout} is equal to the resonant inductor current.

$$I_{Lr}(t_0) = I_{Dout}(t_0) \quad (1)$$

Thus, a resonance starts between the resonant capacitor (C_r) and resonant inductor (L_r). The initial voltage of capacitor C_r is equal to $\frac{V_o}{2}$. By turning on the auxiliary switch, the current flows through diode D_{out} decreases, and it is turned off under ZCS condition. Therefore, switch S_a is turned on under ZCS condition and its current is increased resonantly from zero.

$$V_{Dout} = V_{C3} \quad (2)$$

$$V_{Cr} = \frac{V_o}{2}\cos\omega_r(t-t_0) \quad (3)$$

$$I_{Lr} = I_{Lr}(t_0) + \frac{V_o}{2Z_r}\sin\omega_r(t-t_0) \quad (4)$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \qquad Z_r = \sqrt{\frac{L_r}{C_r}} \quad (5)$$

Before t_0, diode D_1 is turned on and its current is equal to the inductor current (I_{Lr}). At t_0, the current flows through diode D_1 is zero, while the voltage across it rises smoothly due to existence of capacitors C_1 and C_2. As a result, the diode is turned off under ZCS condition.

During this mode, diodes D_2 and D_4 are forward biased, while diode D_3 is reverse biased. Thus, capacitors C_1 and C_2 are connected in parallel. Therefore, the power transmission from the input to the output is done by diodes D_2 and D_4 during this mode.

As the resonance continues, the inductor current is reduced after reaching the maximum value, and the capacitor voltage reaches $-V_{Cr}(0)$. This mode ends when the main switch is turned on. The duration of the first mode is given as follows.

$$t_1 - t_0 = \frac{arccos\left(-\frac{V_{Cr}(0)}{V_o}\right)}{\omega_r} \quad (6)$$

The equivalent circuit for mode 1 is shown in Figure 4 (a).

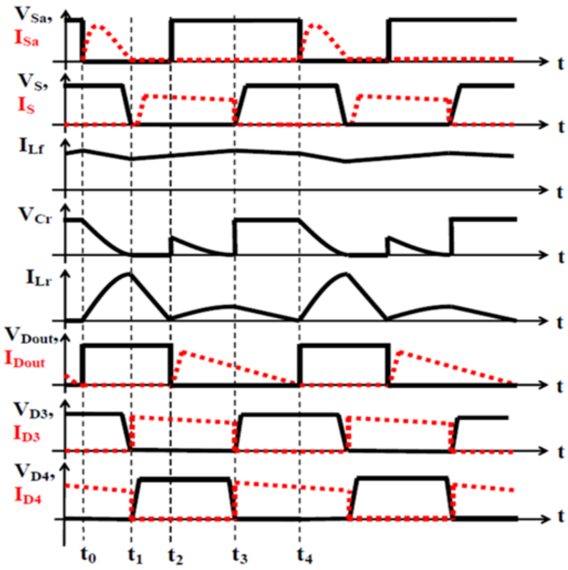


Figure 3. Theoretical waveforms of the TLBC

Mode 2 ($t_1<t<t_2$): This mode starts when switch S is turned on. By continuing the resonance between L_r and C_r, the voltage across capacitor C_r reaches $-V_{Cr}$ (0) at t1. Therefore, when the main switch is turned on, diode D_1 will be forward biased, and capacitor C_r is connected in parallel with switch S. Consequently, the main switch is turned on under ZVS condition, and the voltage across the capacitor is clamped to zero. Furthermore, diode D_1 is turned on under ZVS condition. As a result, the resonance ends. During this mode, the following equation is obtained.

$$\Delta I_{Lf} = \frac{V_{in}}{L_f}(t-t_1) \quad (7)$$

Therefore, inductor current I_{Lf} is increasing linearly. Although, this increment is negligible.

In the proposed TLBC, inductors L_f and L_r are coupled with each other. Thus, current I_{Lr} decreases linearly to reach zero at the end of this mode. During this mode, diode D_{out} is reverse biased. Besides, diode D_3 is forward biased while diodes D_2 and D_4 are reverse biased. Therefore, capacitors C_1 and C_3 are connected in parallel ($V_{C1}=V_{C3}$).

During this mode, the power is not transferred from the input to the output and capacitors C_2 and C_3 supply the output load. The equivalent circuit for the second mode is shown in Figure 4 (b).

$$I_{Lr}(t_1) = I_{Lr}(t_0) + \frac{V_o}{2Z_r}\sin\left[arc\cos\left(-\frac{V_{Cr}(0)}{V_o}\right)\right] \quad 8$$

$$t_2 - t_1 = -\frac{L_f}{nV_{in}}\left[I_{Lr}(t_0) + \frac{V_o}{2Z_r}\sin\left[arc\cos\left(-\frac{V_{Cr}(0)}{V_o}\right)\right]\right] \quad 9$$

Mode 3 ($t_2<t<t_3$): This mode starts when switch S_a is turned off. When I_{Lr} reaches zero, the current flowing through the auxiliary switch also becomes zero. Hence, switch S_a is turned off under ZCS condition. By turning off the auxiliary switch, diode D_{out} will be forward biased and the voltage across C_r will be equal to V_{C3}.

$$V_{Cr}(t_2) = V_{C3} \quad 10$$

Therefore, diode D_1 is reverse biased because the main switch is turned on during this mode. In addition, diodes D_2 and D_4 remain reverse biased and diode D_3 is forward biased.

Then, a resonance starts between C_r and L_r through diode D_{out} and the energy stored in the capacitor is transferred to the output. Thus, diode D_{out} is turned on under ZCS condition.

$$V_{Cr}(t) = \frac{C_3}{C_2 + C_3} V_o \cos\omega_r(t - t_2) \quad 11$$

$$I_{Lr} = \frac{C_3}{C_2 + C_3}\frac{V_o}{Z_r}\sin\omega_r(t - t_2) \quad 12$$

This mode ends when the voltage across the capacitor reaches zero.

$$t_3 - t_2 = \frac{1}{4f_r} \quad 13$$

In other words, this mode ends when switch S is turned off and diode D_1 is forward biased at t_3. The equivalent circuit of the third mode is shown in Figure 4 (c).

Mode 4 ($t_3<t<t_4$): This mode starts when the main switch is turned off. Since V_{Cr} is zero at t_3, diode D_1 is turned on under ZVS condition while switch S is turned off under ZVS condition.

Therefore, the capacitor voltage during this mode will be equal to V_{C3} and its current is zero. Besides, the inductor current (I_{Lr}) is transferred through diode D_{out} to the output. During this mode, diodes D_2 and D_4 are forward biased and transfer the power to the output while diode D_3 is reverse biased. The equivalent circuit of the fourth mode is shown in Figure 4 (d).

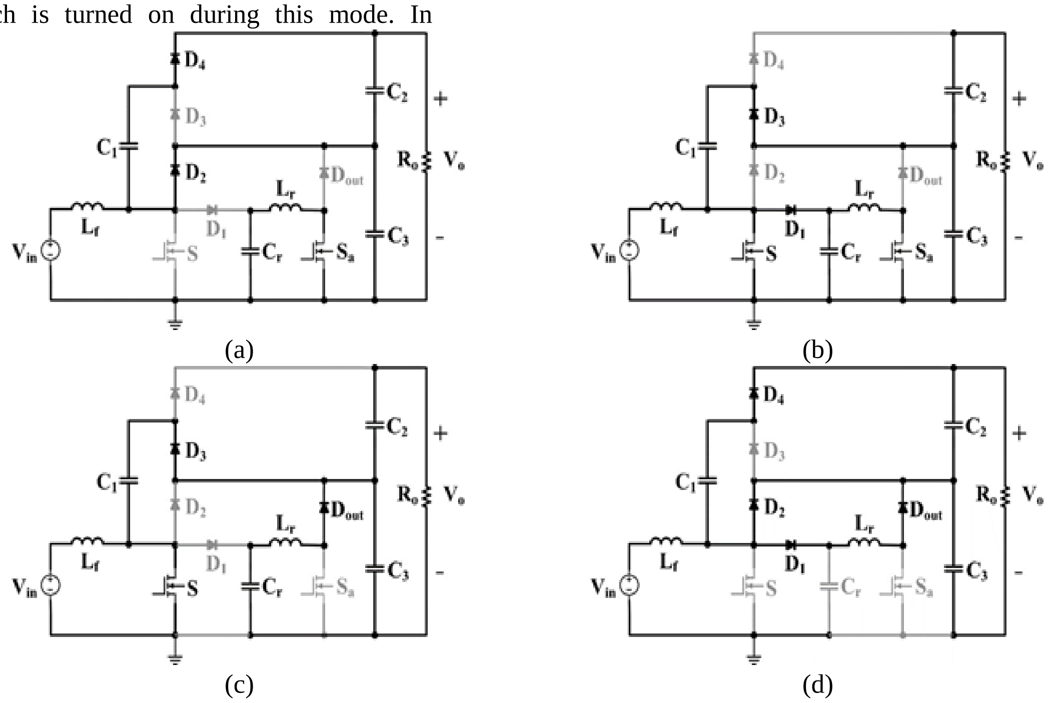


Figure 4. The equivalent circuit for operation modes (a) mode1, (b) mode 2, (c) mode3, (d) mode 4.

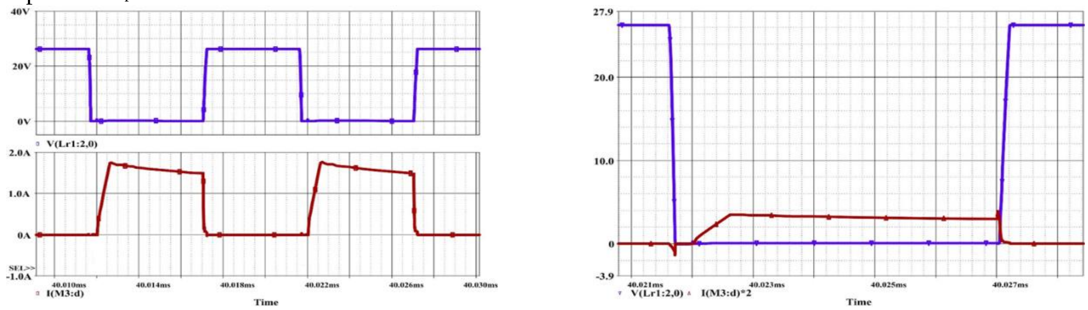
3. SIMULATION RESULTS

A 200W of the proposed TLBC is designed and simulated. The input voltage of the converter is 12 volts, and its output voltage is 54 volts. The switching frequency is 100 kHz for both main and auxiliary switches.

In the designed converter, the value of input filter inductor L_f is 1mH. The capacitors used in the converter structure are $C_1=C_2=50\mu F$, while $C_3=80\mu F$. The resonant capacitor and resonant inductor are 5nF and 20μH, respectively. Due to the voltage and current stress on the main and auxiliary switches, the type of switches is IRF540 [20].

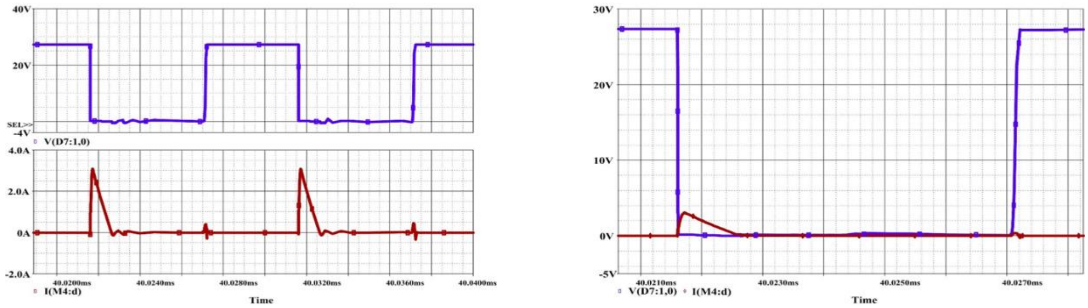
Figure 5 (a) shows the voltage and current waveforms for the main switch. Moreover, their zoom versions are depicted in Figure 5 (b). As it is clear, the main switch is turned on under ZVS condition. This is due to the parallel connection between switch S and capacitor C_r, which has zero voltage at the beginning of the second mode. This switch is also turned off under ZVS condition. This is done because diode D_1 is turned on and the voltage across capacitor C_r is zero in the fourth mode.

Figure 6 (a) shows the voltage and current waveforms for the auxiliary switch. Moreover, their zoom versions are depicted in Figure 6 (b). Due to the performance of the converter in the first mode, the auxiliary switch is turned on under ZCS condition. This is done because switch S_a is connected in series with resonant inductor L_r. This switch is turned off under ZCS condition when the inductor current reaches zero again in the third mode. Figure 7 (a) shows the voltage waveform of resonant capacitors C_r, which varies from $-V_{Cr}(0)$ to $V_{in}/2$. Furthermore, Figure 7 (b) shows resonant inductor current I_{Lr} waveform.



(a) (b)

Figure 5. (a) the voltage and current waveforms for the main switch, (b) zoom version



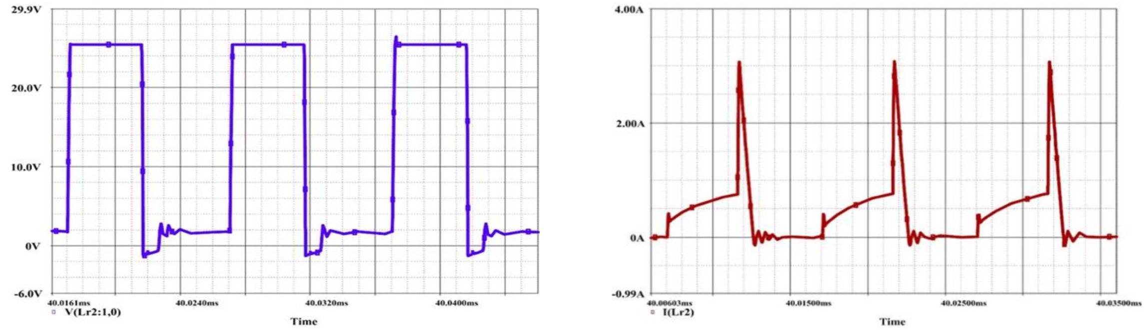
(a) (b)

Figure 6. (a) the voltage and current waveforms for the auxiliary switch, (b) zoom version

In addition, Figure 8 (a) shows filter inductor current ILf waveform, which expresses the performance of the converter in the CCM mode. Figure 8 (b) shows the voltage and current waveforms of output diode D_{out}. Based on the converter operation in the first mode and Figure 8 (b), this diode is turned off under ZCS condition. This is done because I_{Lr} flows through the auxiliary switch by turning it on. According to the converter performance in the fourth mode, this diode is turned on under ZCS condition. This phenomena occurs because the auxiliary switch is turned on and the diode is connected in series with resonant inductor L_r.

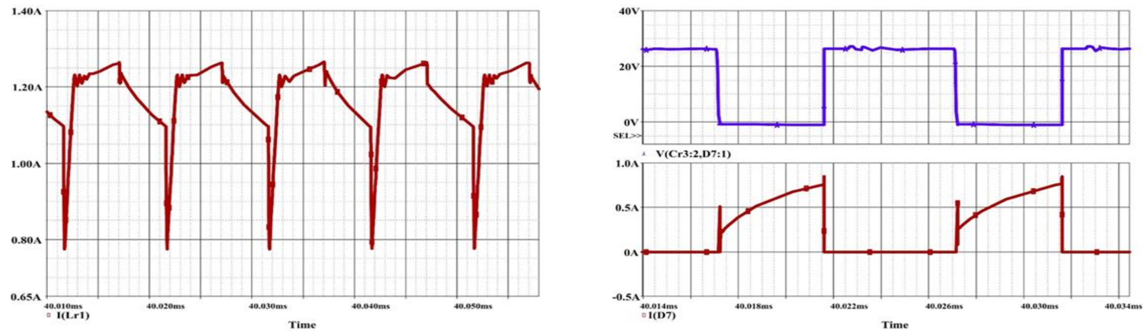
Figure 9 (a) shows the voltage waveforms across capacitors C_1, C_2 and C_3. Furthermore, Figure 9 (b) shows the input and output voltage waveforms of the proposed converter.

Figure 10 (a) shows the voltage and current waveforms of diode D_4, which is turned on and turned off under ZVS condition. This is done due to the capacitor loop created by the diode with capacitors C_1, C_2, and C_3. Figure 10 (b) shows the voltage and current waveforms of diode D_3. Diode D_3 is turned on and turned off under ZVS condition as same as diode D_4.



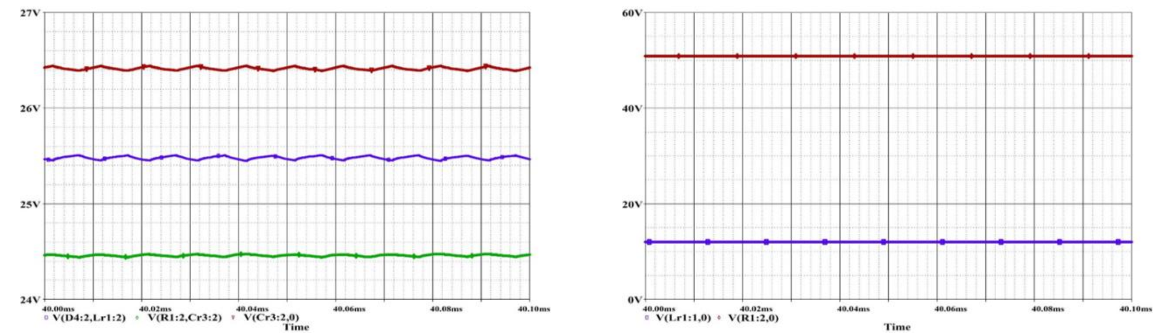
(a) (b)

Figure 7. (a) voltage waveform of resonant capacitors C_r, (b) Resonant inductor current I_{Lr} waveform



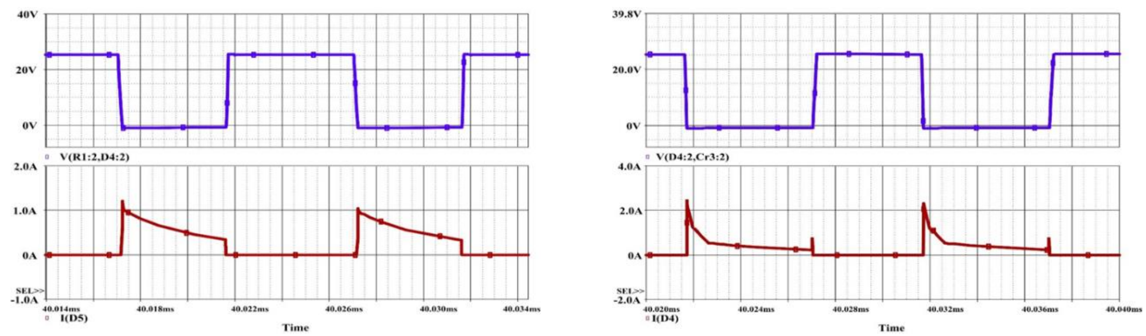
(a) (b)

Figure 8. (a) Filter inductor current I_{Lf} waveform, (b) Voltage and current waveforms of output diode D_{out}



(a) (b)

Figure 9. (a) Voltage waveforms across capacitors C_1, C_2 and C_3, (b) Input and output voltage waveforms of the proposed converter



(a) (b)

Figure 10. (a) Voltage and current waveforms of diode D_4, Voltage and current waveforms of diode D_3

Regarding to the auxiliary cell operation to provide soft switching conditions for all semiconductor devices, the efficiency curve of the proposed TLBC for various output powers is shown in Figure 11. The efficiency of the proposed TLBC is 95% at full load (as shown in Figure 11), which indicates proper operation and a significant reduction of losses in the proposed converter. Since the soft switching condition is obtained for all semiconductor devices, so there are no switching losses in the proposed converter at switching instants. Therefore, the best way is increasing the switching frequency to reduce the volume and weight of the converter. In this way, the Ohmic losses are reduced and the converter efficiency is increased.

According to the simulation results, the proposed converter is designed for a nominal power of 200 watts. Therefore, it has the highest efficiency in this power. Besides, the converter has the lowest amount of power loss because the soft switching conditions are properly obtained for all semiconductor devices at nominal power. If the converter is operated at higher power than the rated power, the output current will be increased. This increment of the output current causes an increment of the current and even the voltage across the elements. If the amount of increment goes too high, the creation of soft switching conditions in the semiconductor devises at switching instants will be lost. As a result, these elements are switched under hard switching condition, which increases the switching losses and thus reduces the efficiency. On the other hand, increasing the current level increases the Ohmic losses, which further reduces the converter efficiency. The soft switching conditions maintain up to 250 watts. However, this condition will disappear at higher power than 250 W.

The comparison between the proposed converter with other similar topologies in terms of voltage gain, soft switching condition, number of active elements, number of passive elements, efficiency and volume are considered in Table 1.

The input filter inductor volt-second balance can be obtained as follows.

$$V_{in}D = (V_{C3} - V_{in})(1 - D) \quad 14$$

Also,

$$\begin{cases} V_{C3} = V_{C2} = V_{C1} \\ V_{C3} + V_{C2} = V_O \end{cases} \quad 15$$

$$\rightarrow V_{C3} = \frac{V_O}{2}$$

Subsequently, by placing (15) in (14) the following formula is achieved.

$$\frac{V_o}{V_{in}} = \frac{2}{1 - D} \quad 16$$

It should be noted that the voltage gain of the proposed TLBC is equal twice the conventional Boost converters as follows.

As described in the proposed converter operation, the energy is stored in the input filter inductor when the main switch is on. When the main switch is turned on, the voltage across the resonant capacitor is zero and the resonance stops. In this condition, the energy stored in the input filter inductor is transferred to the output through diode D_2. Therefore, the higher value of D leads more energy is stored in the input filter inductor. Consequently, the converter voltage gain will be increased. These conditions are confirmed by Equation (16). However, the value of D cannot be increased too much and reached to one. According to the converter operation, there must be enough time for transferring the energy to the output. Otherwise, the energy stored in the inductor does not transfer properly to the output and even reduce the voltage gain of the converter when the switch is off.

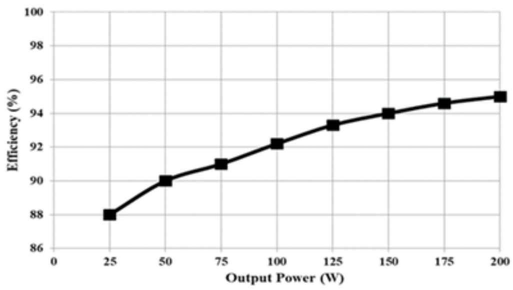


Figure 11. Efficiency curve of the proposed TLBC for various output powers

The proposed converter has highest efficiency at nominal power. This is normal when the design considerations are done well. However, when the power is less than the nominal power (because the increase of losses in the auxiliary circuit is higher than the main circuit) the efficiency is decreased. This condition can also be explained that in the case of a light load, the efficiency decreases due to the fact that the circulating energy involved in the resonant process is constant and independent of the load. This is common phenomenon for all soft switching converters.

Table 1. Comparison of the proposed topology with similar counterparts

Characteristics	**[16]-[17]**	**[18]**	**[19]**	**Proposed**
Voltage Gain	$\frac{2}{1-D}$	$\frac{2}{1-D}$	$\frac{2}{1-D}$	$\frac{2}{1-D}$
Soft Switching	No	No	No	Yes
Switch Count	1	4	2	2
Diode Count	3	0	2	5
Capacitor Count	3	2	2	4
Magnetic Core Count	1	1	2	1

Efficiency	Low	Low	Low	High
Volume	Medium-Low	Medium	High	Medium

4. CONCLUSIONS

In this paper, a TLBC is used as an interface circuit between FC and DC bus in HEV. The converter is used only one auxiliary cell to create the soft switching conditions for all semiconductor devices. The auxiliary cell contains one auxiliary switch, one resonant capacitor, one resonant inductor and one auxiliary diode. The auxiliary switch creates the soft switching conditions by control of resonant elements. Besides, the auxiliary cell is not located in the main power path and cannot decrease the converter efficiency. The proposed converter only uses one auxiliary switch and one main switch that lead to simple structure. It has simple operation modes. Besides, the proposed soft-switched converter is highly efficient while the control circuit is simple and remains PWM. Moreover, the use of two-level structure and soft switching technique in the proposed topology create a converter with high gain and high-efficiency. By using low number of elements in the converter and applying soft switching technique, the conduction and switching losses are decreased significantly. Furthermore, a 200W of the converter operating at 100 kHz is simulated by PSPICE software. Furthermore, to verify the proposed converter performance, voltage conversion of 12 V/54 V is provided. The measured efficiency of the proposed TLBC is 95% at full load.

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