# A New High Step-Up Single Switch DC-DC Converter with Soft Switching on All Semiconductor Elements

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## ABSTRACT

This paper presents a high step-up DC-DC converter. The converter has a simple structure and without adding any auxiliary switch, soft switching condition is provided in the converter. Due to the fact that any switch is not added to the converter, there is no need to design a new control circuit for this converter and the basic control circuit structure is suitable for this converter. In the proposed converter with minimum number of auxiliary elements soft switching condition provides, which in addition to have a simple structure, reduces losses and increases efficiency. soft switching condition is provided under zero current switching (ZCS) when switch is turned on and under zero voltage switching (ZVS) when the switch is turned off. The voltage stress on the switch is at a lower level than the output voltage of the converter, which the switch can use with low voltage. Also, not much current stress is imposed on the switch, which does not require a very high current switch. The proposed converter has been completely analyzed and in order to prove the theoretical analysis, the converter is implemented at a power of 500 watts and at a full load the efficiency of about 97.2% is obtained.


**Keywords**: High Step-up, Efficiency, Zero Voltage Switching (ZVS), Zero Current Switching (ZCS)

## 1. INTRODUCTION

Today, high step-up converters (with high gain) have found a wide application in energy production systems [1]. Systems such as photovoltaic [2-4], fuel cell [5,6] or hybrid systems [7,8] that the output of the DC voltage system is low and there is a need to increase the voltage level to an acceptable value for the inverters to convert to city electricity voltage. Therefore, the use of these converters has become very widespread. these converters are divided into two categories: isolated [9-11] and non-isolated [12-15]. In the isolated type, in addition to the isolation between input and output, it is possible to obtain very high gains with the transformer conversion ratio and increase low level voltages to high levels. But this type has a complex structure and the design of these circuits is difficult, also in high powers, there is a limitation of using this type due to the high losses of the transformer core. Therefore, if there is no need for isolation between the input and output, the non-isolated type is used due to its simple structure and design. The basic step-up converter cannot have high duty cycle due to the losses of the converter inductor and strong current jumps. Therefore, in order to have a higher voltage gain and to convert voltages to higher levels, the limitation of the duty cycle becomes a problem, and practically such a converter cannot be used. For this reason, the design of high step-up converters has expanded greatly. These converters are based on step-up converters that greatly increase the output voltage level at a lower duty cycle by various elements such as coupled inductors [16] and capacitors [17]. Also, from the point of view of efficiency and problems of sudden jumps in switch voltage and current, there is a need to create soft switching condition in converters. So that at the moments of turning on and off the switch, it controls the voltage and current so that they do not change suddenly and slowly reach the zero level and then change the state of the switch.

In recent years, many converters have been presented according to the conditions stated above. In [18], a high step-up converter with a simple structure is introduced. This reference has provided a suggested circuit to increase the gain without using a transformer. Although the structure and control of this converter is simple, soft switching condition is not provided in this converter and there are sudden jumps in voltage and current, and switching losses and noise on the switch still exist. There is a soft switching condition with high efficiency in the converter introduced in [19]. In this converter, by using two switches and coupled inductors, soft switching conditions and high gain have been provided. But the presence of two switches complicates the circuit, and the converter has a large number of elements, which increases the size and price of the converter. In [20], similar conditions are provided by only one switch, which is the advantage of this converter that there is high gain and good efficiency without an auxiliary switch. This converter has a suitable and good structure, but the coupled inductors used in this converter are not effective in high gain, and the current stress imposed

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on the switch in this converter is high. The converter introduced in [21] is a converter with a very high gain. In this converter, with the use of coupled inductors and its full effect on the gain, a very high voltage gain has been obtained, but the presence of many coupled inductors has increased the volume and price of the converter, and in this converter, sudden voltage and current jumps are not reduced. In [22], a converter with high gain and soft switching is introduced. This converter has low losses and high gain, but the switch current stress is high and the number of elements used in this converter is high. The interleaved technique is used to reduce the ripple of the input current, which is introduced in [23] with an example of this converter with increased gain and efficiency. Although this converter has high efficiency and gain with low input current ripple, but the interleaved technique requires two switches that have a different and complex control circuit. Also, the structure introduced in this reference is very complex with a high number of elements. The problem of too many elements in the converter introduced in [24] has been solved to a great extent, so that an interleaved converter with minimum elements has been introduced. This converter has a high gain, but the existence of two switches with specific timing of turning on and off makes the circuit complicated from the point of view of controlling the switches and makes the implementation of the circuit difficult. A two-switch converter with simple switching control is introduced in [25], which also has a very high voltage gain. Although the converter has the stated advantages, it has a large number of elements, including diodes, which increase conduction losses and decrease efficiency in practice.

In this study, a new converter with high voltage gain has been introduced. The proposed converter with a simple structure and minimal elements has soft switching condition and high voltage gain. The converter does not have an added auxiliary switch and hence the control of the converter is simple. The converter introduced in section 2 is fully introduced and the behavior of the circuit is described theoretically. In section 3, the design method of the elements is given, and then in order to prove the theoretical results, a prototype of the converter is implemented and tested, which the experimental results are presented in section 4. Also, for the purpose of discussion and comparison, the proposed converter is compared with the converters presented in recent years in terms of the general characteristics of converters, and the results are presented in part 5. Finally, Section 6 presents the conclusion of this paper.

## 2. STRUCTURE AND PERFORMANCE OF THE PROPOSED CONVERTER

The structure of the proposed converter is shown in Figure 1. By the coupled inductors L1, L2 and L3 and the series capacitor C, the gain of the converter is increased, so that the ratio of the output voltage to the input is high in the low duty cycle. Auxiliary elements Lr, Cr, D1 and D2 are placed in order to create soft switching condition. In order to simplify the analysis, the following conditions are considered:

- The input inductor is large enough, so the magnetizing inductor current at the input is considered constant in a switching cycle.
- The output capacitors and C are large enough, so the voltages of these capacitors are considered constant in one cycle.
- Semiconductor elements are considered ideal.

The proposed converter has six operating states in one switching cycle, which are fully described below. The key waveforms of the converter are shown in Figure 2.

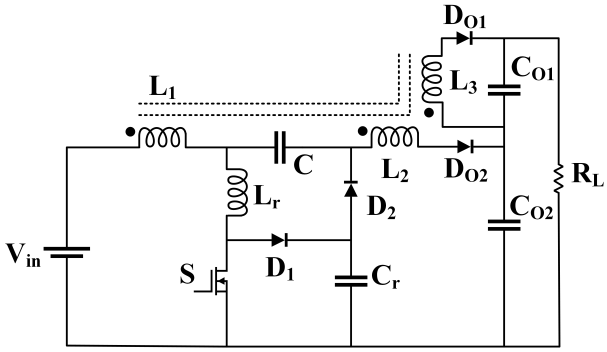


***Fig. 1:*** *The proposed converter.*

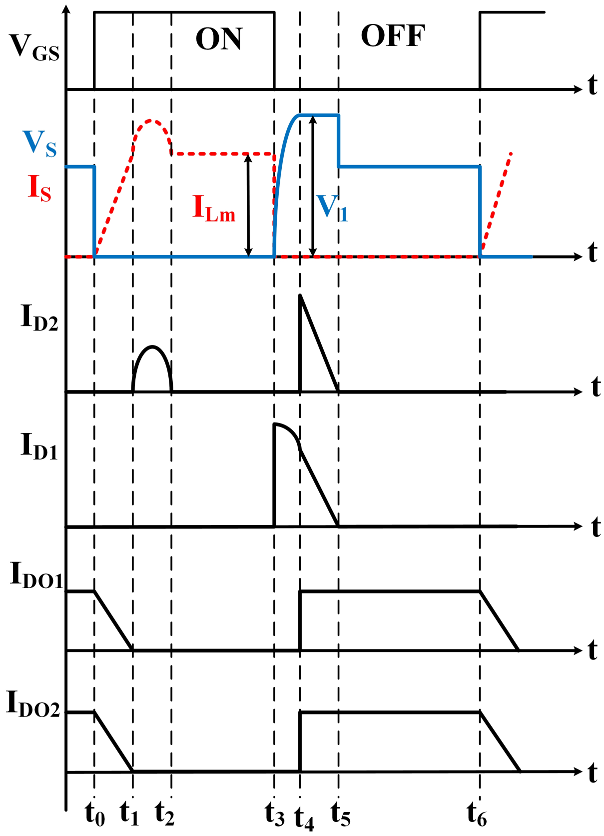


***Fig. 2:*** *The proposed converter key waveforms.*

Mode 1 ($t_0 - t_1$): This mode starts when the switch

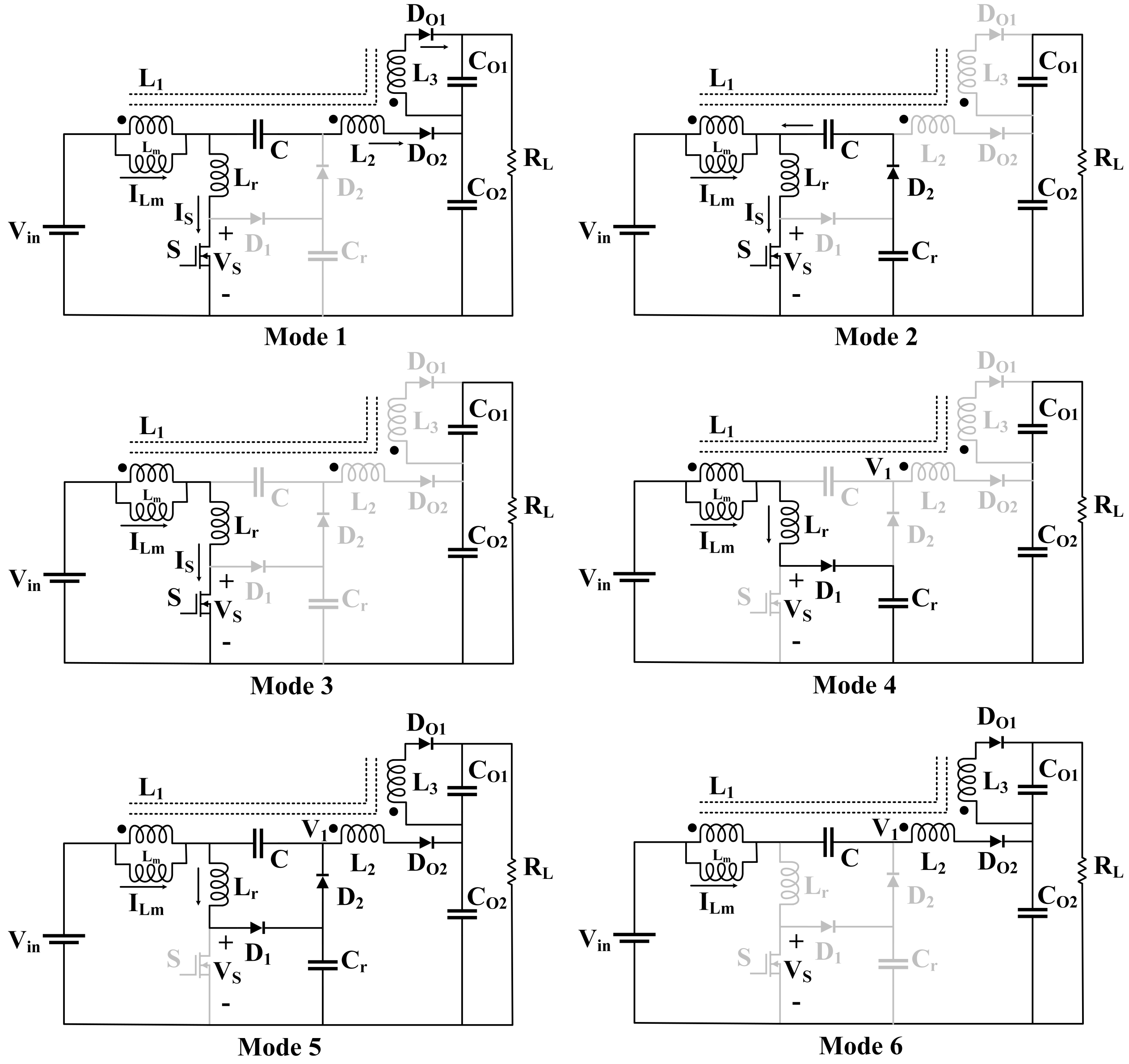


***Fig. 3**: The equivalent circuits of the proposed converter in six modes.*

is turned on at $t_0$. Due to the presence of $L_r$, the switch current does not increase suddenly and continues to increase slowly with the slope shown below. This condition continues until the switch current reaches the current of the magnetizing inductor. During this mode, the current of the output diodes also decreases with same slope until they reach zero and turn off.

$$\alpha_1 = \frac{V_{in} - V_{Lm}}{L_r} \tag{1}$$

Mode 2 ($t_1 - t_2$): When the switch current reaches the magnetizing inductor current, due to KCL at the junction of $L_r$, C and $L_m$, the current on C turns on the diode $D_2$ and resonance occurs between $C_r$ and $L_r$. so the current continues in a resonant manner. This current continues for half a cycle until it reaches zero again, and when $D_2$ current reaches zero, it turns off and this situation ends. The equations of the circuit in this mode are as follows.

$$I_{Lr} = I_S = I_{Lm} \sin \omega_r (t - t_2) + I_{Lm} \tag{2}$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \tag{3}$$

Mode 3 ($t_2 - t_3$): When the resonance half cycle is completed, $D_2$ turns off and the switch current returns to $I_{Lm}$ value. In this mode, the auxiliary circuit is completely removed from the circuit and the converter behaves like a step-up converter when the switch is on and the input inductor is charged. This mode ends when the switch is turned off.

Mode 4 ($t_3 - t_4$): When the switch is turned off due to the continuous current on $L_r$, $D_1$ conducts and the voltage of the switch increases in a resonant manner and the energy of the inductor is discharged in the capacitor. Therefore, the zero voltage switching condition have been provided to turn off the switch. The relations governing the circuit in this situation are given below.

$$V_{Cr} = V_S = V_1 \cos \omega_r \left(t - t_3\right) \tag{4}$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \tag{5}$$

$V_1$ is the voltage of $D_2$ cathode in this mode and its value is obtained as follows.

$$V_1 = V_{in} + V_C - V_{Lm} \tag{6}$$

Mode 5 ($t_4 - t_5$): When $C_r$ and switch voltage reach $V_1$, this diode turns on and the switch voltage is clamped on this voltage. Due to the simultaneous turning on of $D_1$ and $D_2$, a constant voltage is placed on $L_r$, and from this moment, the current of the inductor, which is also the current of these two diodes, decreases linearly until it reaches zero.

$$\alpha_2 = \frac{V_C}{L_r} \tag{7}$$

Mode 6 ($t_5 - t_6$): When these two diodes turn off, the voltage of the switch drops and reaches the voltage of the magnetizing inductor. This mode continues until the switch is off and ends when the switch is turned on again and returns to mode 1.

The equivalent circuits of the proposed converter states are shown in Figure 3.

## 3. ELEMENTS DESIGN

### 3.1 Snubber Capacitor Design

$C_r$ provides soft switching conditions when the switch is turned off, and its value can be obtained as follows based on the design of the snubber capacitor.

$$C_r > C_{\min} = \frac{I_S t_f}{2V_s} = \frac{I_{Lm} t_f}{2V_1} \tag{8}$$

So that $t_f$ is the switch current fall time, which is one of the characteristics of switches. $I_S$ is the current of the switch when it is on and $V_S$ is the voltage of the switch when it is off. By placing the values according to the analysis in the previous section, the value of this capacitor is calculated.

### 3.2 Snubber Inductor Design

$L_r$ provides soft switching conditions at the moment of turning on, this inductor is known as a snubber inductor, and the value of this element can be calculated with the relationship of the snubber inductor design.

$$L_r > L_{\min} = \frac{V_S t_r}{I_S} = \frac{V_1 t_r}{I_{Lm}} \tag{9}$$

$t_r$ is the rise time of the switch current. $V_S$ is the switch voltage and IS is the switch current.

### 3.3 Calculation of Voltage Gain and Coupled Inductors

The main inductor of the converter, which is actually the magnetizing inductance equivalent to the coupled inductors, can be calculated from the relations related to the calculation of the main inductor of the step-up converter. In order to calculate $L_2$ and $L_3$ that are coupled with the main inductor, the voltage gain relationship increased by this coupling can be used. Therefore, in this section, the voltage gain calculation is given.

In order to obtain the voltage gain, volt second balance is written on the magnetizing inductor. It should be noted that the conversion ratio of coupled inductors is considered as follows.

$$n = \frac{n_2}{n_1} \tag{10}$$

$$m = \frac{n_3}{n_1} \tag{11}$$

Where $n_1$ is the number of rounds of $L_1$, $n_2$ is the number of rounds of $L_2$ and $n_3$ is the number of rounds of $L_3$.

$$V_{in} DT = \frac{V_{O2} - DV_{O2} - V_{in}}{1+n} (1-D) T \tag{12}$$

By simplifying the above relationship, the voltage gain relationship between the input and output on $C_{O2}$ is finally obtained.

$$\frac{V_{O2}}{V_{in}} = \frac{1+nD}{(1-D)^2} \tag{13}$$

Considering that the output of the circuit is the sum of the two output voltages on $C_{O1}$ and $C_{O2}$, the first output voltage must also be calculated and after adding the two voltages, the final voltage gain is obtained.

$$\frac{V_O}{V_{in}} = \frac{1+nD+m(1-D)}{(1-D)^2} \tag{14}$$

According to the relationships obtained, the voltage gain can be obtained by having the conversion ratio of the coupled inductors. But if the goal is to design coupled inductors, it is possible to obtain the conversion ratio by having the voltage gain and finally calculate the values of the inductors.

Since the diagrams are very helpful in designing or obtaining values, for the ease of designing the relationship between the voltage gain of the converter and the conversion ratio, the diagrams of Figures 4 and 5 have been drawn, which show the effect of the conversion ratios on the gain. It is also possible to estimate the conversion ratios in the desired gain from these graphs. Considering that the effect of these two round ratios is particularly important in the gain, the curves of Figure 6 have also been drawn, which show the full effect of m and n on the gain in different duty ratios.

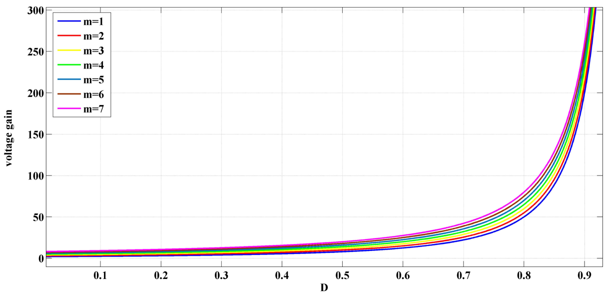


***Fig. 4**: Effect of m on voltage gain in different duty cycles.*

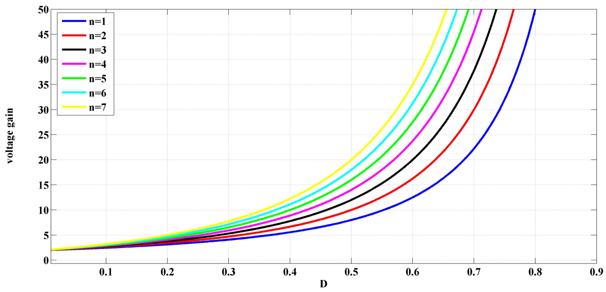


***Fig. 5**: Effect of n on voltage gain in different duty cycles.*

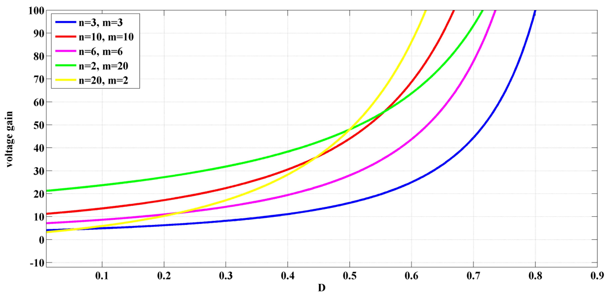


***Fig. 6**: The complete effect of m and n on the voltage gain at different duty cycles.*

***Fig. 7**: The implemented of the proposed converter.*

***Table 1**: The proposed converter specifications.*

| Components | Symbol | Value or Part number |
|---|---|---|
| Switch | $S$ | IRF540 |
| Auxiliary diodes | $D_1, D_2$ | MUR2040 |
| Output capacitors | $C_{O1}, C_{O2}$ | 10 $\mu F$ |
| Snubber Capacitor | $C_r$ | 10 $nF$ |
| Output diodes | $D_{O1}, D_{O2}$ | MURS360 |
| Turn ratios | m,n | 3 |
| Magnetic inductance | $L_m$ | 400 $\mu F$ |
| Snubber inductor | $L_r$ | 10 $\mu H$ |
| Switching frequency | $F_{sw}$ | 100 kHz |
| Power | $P$ | 500 W |
| Output voltage | $V_O$ | 410 V |
| Input voltage | $V_{in}$ | 24 V |

## 4. EXPERIMENTAL RESULTS

According to the analysis performed and the design of the elements, the converter with the specifications of Table 1 has been implemented, which is shown in figure 7. The proposed converter is tested and the experimental results are shown in Figures 8. As it is clear in this figure, at the moment of turning on the switch, the current increased with a slope and did not change suddenly, which the zero current switching condition is established. When the switch is turned off, the voltage has not increased suddenly and reaches its maximum value with a slope, which the zero-voltage switching condition is cleared. The current of the diodes is decreased slowly with slope when the diodes turn off. Therefore, the zero current switching is established for all diodes and reverse recovery problem does not exist.

In Table 1, the values are calculated based on the relations of the design section. Values of $C_r$ and $L_r$ are obtained based on design relations (8) and (9), along with the auxiliary design diagrams available in the same section. n and m are obtained according to the voltage gain relationship and the amount of conversion required, which in this study is based on the conversion of 24 volts to 410 volts, and based on these values, coupled inductors can be implemented. The type of diodes and switch selected is based on their current and voltage, which can be selected in different ways. In this article, the values mentioned in the table have been selected, which have received a better answer in the construction and design.

The proposed converter has been tested in different loads and the output voltage has been obtained in these loads. The changes in the output voltage in different loads have been drawn as a curve and shown in Figure 9. As can be seen, in lighter loads, the output voltage is almost equal, but in heavy loads, there is a voltage drop, which is caused by the high current of the load.

The proposed converter has been tested in terms of dynamic response with load changes from 25% to 100% and vice versa, and the response results for changes in output voltage, input voltage and input current are given to determine the effect of load changes on these parameters. The results are shown in Figure 10.

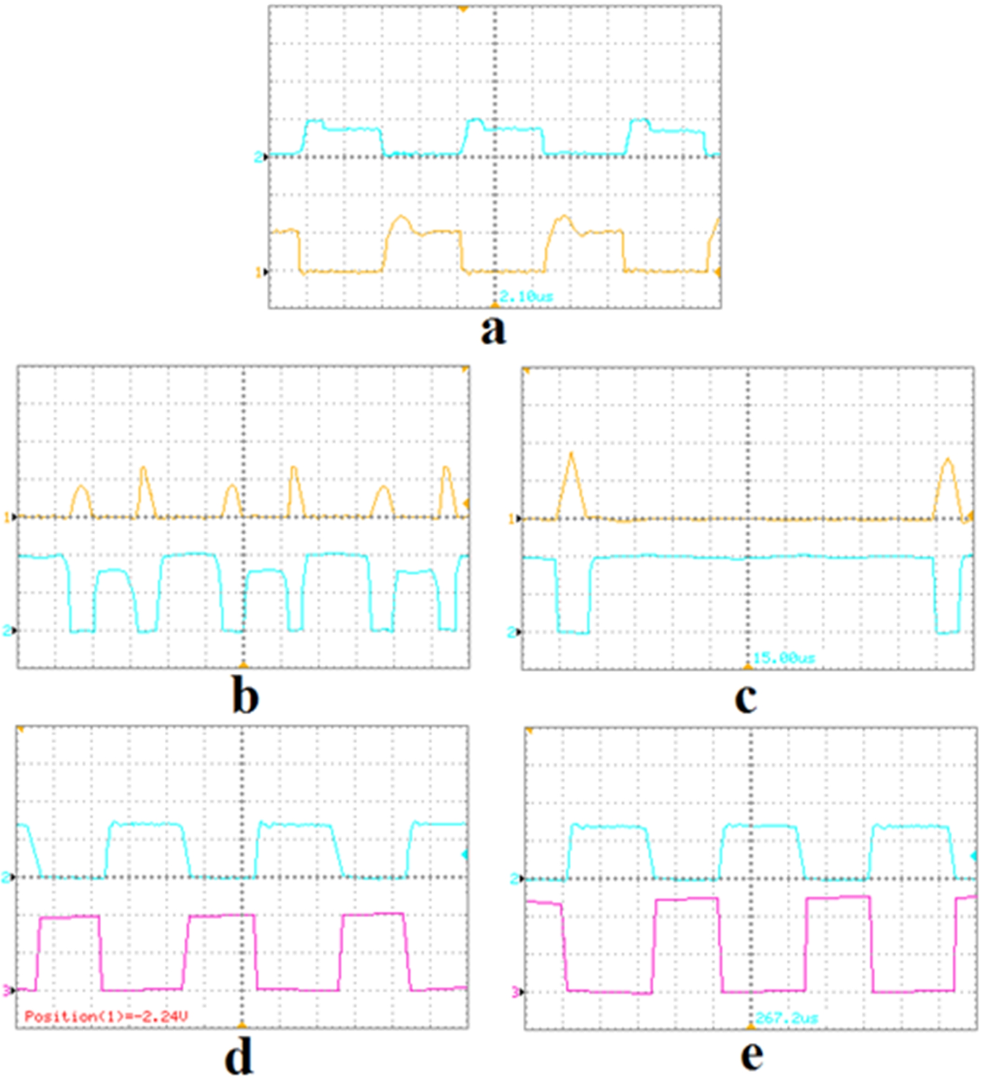


***Fig. 8**: The experimental results of the proposed converter.*
*a) voltage (up) and current (down) of the switch (vertical scale is 50 volts/div or 20 A/div and horizontal scale is 2.5 μs/div)*
*b) the current of D1 (vertical scale is 10 A/div or 25 volts/div and horizontal scale is 2.5 μs/div)*
*c) the current of D2 (vertical scale is 10 A/div or 25 volts/div and horizontal scale is 1 μs/div)*
*d) the current of DO1 (vertical scale is 2 A/div or 100 volts/div and horizontal scale is 2.5 μs/dive)*
*e) the current of DO2 (vertical scale is 2 A/div or 100 volts/div and horizontal scale is 2.5 μs/div)*

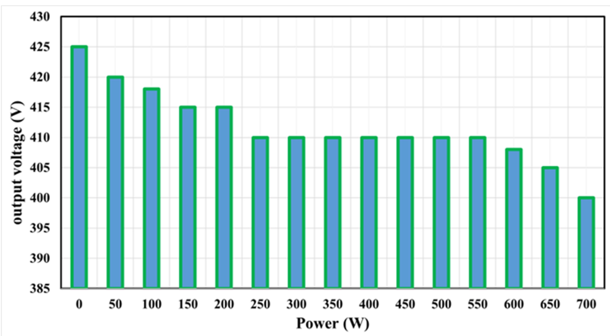


***Fig. 9**: Output voltage changes in different output.*

Figure 11 shows the relationship between changes in duty cycle and efficiency. As it is known, with the increase of the duty cycle, the efficiency drops a bit, which is quite reasonable and is due to the increase in losses, especially the ohmic losses of the coils.

## 5. COMPARISON OF THE PROPOSED CONVERTER WITH OTHER CONVERTERS

Due to the creation of soft switching conditions in the proposed converter, it is expected that the efficiency of the converter will increase. Therefore, in terms of efficiency, the proposed converter has been compared with a converter without soft switching (hard switching) and the results of this comparison are shown in a diagram in Figure 12. Also, the compared circuit shape as hard switching is shown in Figure 13. It is clear that the hard switching circuit is the same as the proposed converter

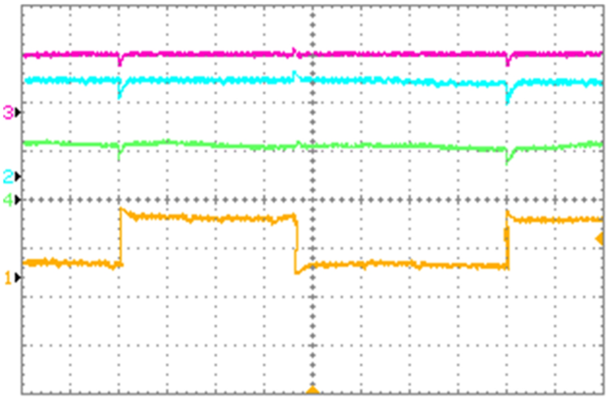


*Fig. 10*: *Dynamic response for load change from 25% to 100% and vice versa. (output current (1- orange) with 1 A/div, output voltage (2- blue) with 200 volts/div, input voltage (3- purple) with 20 volts/div and input current (4- green) with 20 A/div. horizontal scale is 50 ms/vid).*

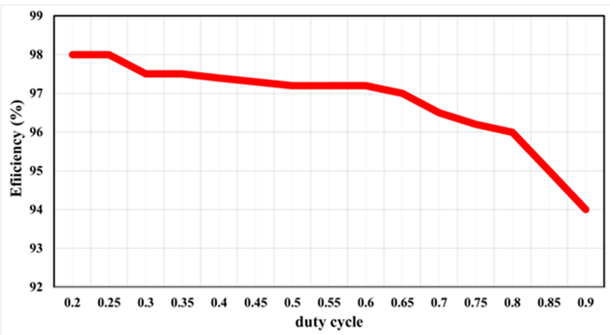


*Fig. 11*: *Efficiency changes versus duty cycle.*

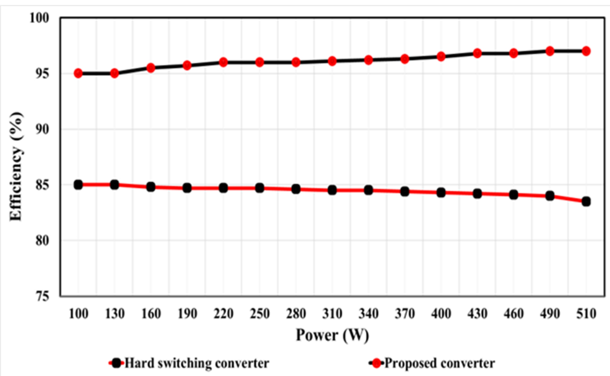


*Fig. 12*: *Efficiency comparison between the proposed converter with hard switching converter.*

without the auxiliary circuit to be completely similar to the proposed converter. As it is clear from this figure, the efficiency level of the proposed converter is higher than the converter without soft switching. At low powers, the efficiency level of the proposed converter drops a little, which is because soft switching conditions are not fully established.

The proposed converter without snubber shown in Figure 13 has been subjected to experimental testing and

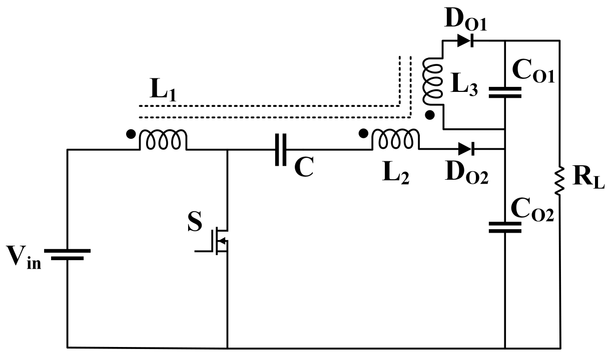


*Fig. 13*: *Hard switching converter to compare with the proposed converter.*

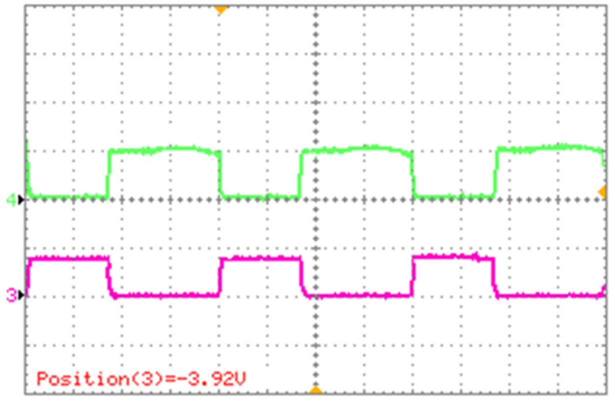


*Fig. 14*: *hard switching experimental results of voltage and current of the switch (current (up- green) with 50 volts/div scale and voltage (down- purple) with 20 A/div scale. Horizontal scale is 2.5 μs/div).*

the experimental results of switch voltage and current are given in Figure 14, as it is clear from this figure that compared to Figure 8, the soft switching on voltage and current of the switch is not observed and the voltage and current change suddenly at the moment of state change.

In terms of the important and applied parameters of a converter, the proposed converter has been compared with eight converters introduced in recent years, and the results are categorized in Table 2. As it is clear from the table, although the converter introduced in [18] has a simple structure and a small number of switches and diodes, the efficiency and voltage gain of this converter is low. Also, the voltage stress on the converter switch is equal to the output voltage, which is high. The rest of the converters compared in this table have high efficiency and are the optimal option from the point of view of this parameter. Also, the converters presented in [19], [20], [23], [24] and [25] have a low voltage stress on the switch, which due to the high voltage gain of these converters and the increase of the output voltage level to very high level, the amount of stress stated in the table is very low in relation to the output voltage. But as can be seen, apart from the converter [20] which has one switch, the rest of the introduced converters have

***Table 2:*** *Comparison between the proposed converter with other soft switching converters.*

| Converter | Number of diodes | Number of switches | Efficiency | Voltage stress on main switch | Voltage gain |
|---|---|---|---|---|---|
| [18] | 1 | 2 | 92.43 % | $V_O$ | $2/(1-D)$ |
| [19] | 3 | 2 | 95.3 % | $V_i n/(1-D)$ | $(N(n+1)(1+D)+2)/(1-D)$ |
| [20] | 4 | 1 | 96.9 % | $V_i n/(1-D)$ | $(1+2n_3 1-n_2 1)/(n_3 1-n_2 1)(1-D)$ |
| [21] | 6 | 1 | 96 % | $V_i n/(1-D)^2$ | $D/(1-D)((n_2+n_3)/n_1+n_5/n_4)+1/(1-D)^2$ |
| [22] | 5 | 1 | 95 % | $(2G-n)/G(3n+4)V_O$ | $G=(2+n(2-D))/(1-2D)$ |
| [23] | 8 | 2 | 97.5 % | $V_i n/(1-D)$ | $(2n_2+2)/(1-D)$ |
| [24] | 6 | 2 | 93.56 % | $V_i n/(1-D)$ | $N/(1-D)$ |
| [25] | 4 | 3 | 96.80 % | $V_i n/(1-D)$ | $((2-d)(N+n(1-d))+(1-d))/(1-d)^2$ |
| proposed | 4 | 1 | 97.2 % | $V_i n/(1-D)$ | $(1+nD+m(1-D))/(1-D)^2$ |

two or three switches, which increases the complexity of the converter in terms of the control circuit. Also, apart from the complexity of these converters, they need a complete design and discussion on the control circuit because a switch has been added to their structure. In the converters [21] and [22], the number of diodes used is also high, and the conduction loss and reverse recovery problem of the diodes are more in these converters. The converter [20] does not have an additional switch and is desirable from this point of view, but in this converter, according to its structure, which is also known from its gain relationship, a large number of coupled inductors have been used, which the volume and cost of the converter is increased. The converters introduced in [21] and [22] have a simple single-switch structure. But the converter [21] has many coupled inductors with a higher voltage stress than other converters, which increases the size and price of the converter. Converter [22] is also a single switch, but the efficiency of this converter is lower than the other introduced converters. Also, according to the relationship presented for gain in this converter, there is a duty cycle limitation and this converter cannot work at a duty cycle of 0.5. Therefore, although the converter is a single switch, the structure of the control circuit must be modified in such a way that it works at a duty cycle higher than 0.5, which requires the design and presentation of a new control circuit. According to the comparison table, the converter introduced in this paper has good efficiency and the voltage stress on the switch is low compared to the output voltage. Also, only one switch and four diodes are used in this converter. Although the gain of the proposed converter may be a little lower than the gain of some compared references, it has a simple structure and simple control.

## 6. CONCLUSION

A new high step-up DC-DC converter was presented in this paper. The presented converter provides soft switching conditions for the switch in both turning on and off time, which leads to a reduction in switching losses and an increase in efficiency. The proposed converter diodes were turned off under soft switching conditions with zero current, which in addition to reducing the switching losses of these diodes, the reverse recovery problem of these diodes was solved. The converter has three coupled inductors on one core, which, in addition to increasing the voltage gain by these coupled inductors, due to the winding of the coupled inductors on one core, the volume of the converter does not increase, and the presence of the coupled inductor does not have much effect on the volume of the converter. The proposed converter has only one switch and does not have an additional auxiliary switch, which is no different from the basic converter in terms of its control and circuit, and there is no need to design a new control circuit for this converter. In the experimental test performed on the proposed converter, improved efficiency, high gain and soft switching were observed, which proved the design and theory results.

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