IN THE NAME OF GOD

In the name of Allah

Charter of research ethics

With the help of God Almighty and the belief that the world is the presence of God and always observes human actions and in order to pass the high position of knowledge and research and considering the importance of the position of the university in the promotion of human culture and civilization, we, the students and the members of the academic board of the university units Azad Islami undertakes to consider the following principles in carrying out research activities and not to exceed them:

1- The principle of truth-seeking: trying to find the truth and being loyal to it and avoiding any concealment of the truth.

2- The principle of respect for rights: commitment to fully respect the rights of researchers and researched (humans, animals and plants) and other rights holders.

3-Principle of material and moral ownership: commitment to fully respect the material and moral rights of the university and all research partners.

4-Principle of national interests: commitment to respect national interests and considering the progress and development of the country in all stages of research.

5- The principle of respect for fairness and trust: commitment to avoid any unscientific bias and protection of property, equipment and resources.

6-Principle of confidentiality: commitment to protect the secrets and confidential information of individuals, organizations and the country and all individuals and institutions related to research.

7- The principle of respect: the commitment to observe sanctity and sanctity in conducting research and to observe the aspect of criticism and refrain from any violation of sanctity.

8- The principle of promotion: the commitment to the spread of knowledge and the dissemination of research results and their transmission to scientific colleagues and students, except for the cases that are prohibited by law.

9-Principle of acquittal: commitment to seek acquittal from any unprofessional behavior and declare a position towards those who bring unscientific suspicions to the field of science and research c

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A Thesis Submitted in Partial Fulfillment of the Requirements for
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Title

A New High Step-up and High Step-down Bidirectional Converter for Photovoltaic Applications

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Abstract

Nowadays, due to the growing need for systems with the capability to transfer energy in two directions, such as fuel cell power systems, electric power systems of hybrid cars, DC uninterruptible power supplies, battery chargers, and photovoltaic power systems, special attention has been paid to these converters. These converters are capable to transmit power between two DC sources in both directions. Since in converters with hard switching, the existence of at least two main switches for power transfer in two directions is inevitable, hence the performance and handling of these converters are convoluted. In contrast, many methods have been proposed to create soft switching conditions in these converters, because reducing switching losses and increasing switching efficiency and frequency are the goals of researchers. In this research, the latest bidirectional converter is presented, so that in addition to the feature of switching at zero voltage, the stress of voltage on switches is also reduced due to the high gain of converter, and consequently, switches with lower drain-source on resistance and cheaper can be used. The proposed converter has been completely analyzed in each performance mode and compared with previous similar converters. The suggested converter is simulated in a software which is called PSPICE and its results confirm the theoretical analysis of the converter.

chapter 1

The research generalities

1-1- Preface

These days, the expansion of bidirectional DC-DC converters is a very important subject in the power electronics discussion. These converters are able to change the flow of current in both directions, as a result they can transfer power in two directions so that the polarity of the voltage at both ends also remains unchanged. Due to their ability to transfer power in two directions, these converters have been widely used in uninterruptible DC power supplies, fuel cell power systems, battery charger circuits, and hybrid cars [1]-[1] .

In these applications, energy storage elements including supercapacitors and batteries are used so that these converters are placed to control the stored charge or charge and discharge and protect these elements.These converters can also change the voltage level, which can be used to place the energy storage elements with a smaller volume by choosing a low voltage level.

We can divide bidirectional DC-DC converters into two general categories: isolated converters [11]-[19] and non-isolated convertors [20]-[29], each of which has its own usage depending on the application. If the two sides of the circuit cannot be connected and high voltage gains are needed, the isolated type is used. Being isolated also increases the security and protection of the system. In these converters, by regulating the turn ratio of isolated transformer, the desired voltage gains can be reached.

Although isolated converters are widely used in the industry, non-isolated converters are used if high gains and isolation are not required. Because these converters compared to the isolated type need a simpler structure and control; therefore they can achieve higher efficiency.

1-2-Research background

With a small change in the basic isolated and non-isolated converters, it is possible to reach a bidirectional converter and enable the flow of current in both directions. In bidirectional DC-DC converters, like unidirectional converters, in order to lessen the volume, weight and cost, frequencyof switching must be risen, but since power switches do not change state quickly at the moment of switching, an overlap is created between current and voltage of switches at the time of switching, which by raising the frequency,this overlap has also increased and the circuit switching losses increases a lot. Therefore, by increasing the switching frequency without considering these conditions, high switching losses are imposed on the converter, and the presence of noise and the issue of EMI (Electromagnetic Interference) in these circuits is due to the sudden change in current or voltage at the moment of switching that the increase of the frequency leads to the intensification of this noise. Therefore, in converters with hard switching,the increase of the frequency causes the rise of the switching losses and intensification of noise.

Also, in bidirectional converters, since the diode of the switch body acts as a converter diode and the reverse recovery time of these diodes is longer, it causes losses and noise in these converters. Hence, a lot of techniques in soft switching have been suggested to solve the above difficulties. These techniques can generally be divided into four categories: resonance [30], pseudo-resonance [31], phase shift [32-[35] and pulse width modulation (PWM)[18]- [21] and [36]-[40].

In resonant and pseudo-resonant converters, by adding a resonant circuit including inductor and capacitor, the switch voltage and current become resonant, therefore by frequency control, switching can be done at desired moments when the current or voltage has reached zero. Therefore, soft switching conditions are provided. By creating soft switching conditions, we can redude the converter volume and weight by raising frequency of switching, hence we can increase the efficiency and power density of converter . However, due to the nature of resonance in the auxiliary circuit, resonant and pseudo-resonant converters have high voltage stress or high current compared to PWM (pulse width modulation) converters. On the other hand, due to the variable frequency control, it is not possible to design inductors and transformers optimally.

ZVS phase shift techniques without adding an auxiliary switch by changing the switching start time and changing the phase on the control circuits of the converter create soft switching conditions, according to the phase control these converters have very complex control circuits and the design and implementation of this converter is difficult, so that the possibility of accurate response of these converters is very low in practice. Also, the soft switching conditions in this technique are not provided in light loads. For these reasons, PWM (pulse width modulation) converters have received more attention. In PWM converters, the frequency of switching is constant, and relatively, start time or the phase of each command is also constant in the entire period, and output power control is created only by controlling the duty ratio. In these converters, we often add an auxiliary circuit to the main circuit in order to create soft switching conditions with the presence of PWM (pulse width modulation) control.

Some auxiliary circuits are active clamp [41] and [42], which provide soft switching conditions for the main switch by using one or more additional switches and passive elements. In these converters, when the passing current is minimized, it creates soft switching and the power conversion efficiency increases.

Some other auxiliary circuits reduce the voltage, current or both to zero at the moment of switching by creating one of the soft switching conditions ZVS,ZCS or ZVZCS [13]-[16] and [36]-[38] that this leads to a reduction in the overlap of voltage and current of switch at the time of switching, therefore switching losses will be reduced. In these auxiliary circuits, we often use one or more auxiliary switches to create soft switching conditions. But since it is inevitable to use two main switches to transfer power in two directions in hard bidirectional converters, the implementation and control of these circuits is very complicated. In addition, the added auxiliary circuits themselves causes to impose conduction losses to the main circuit, which lowers the total efficiency of the converter.

In ZVTand ZCT converters [39] and [40] and [23], by observing the PWM conditions, an attempt has been made to supply soft switching conditions. In these converters, soft switching conditions are prepared by adding an auxiliary switch and a resonant element and a diode that comes into action at the moment of switching and reduces the switch voltage and current to zero. These converters usually do not impose additional stress on the switches, but the disadvantage of these converters is the addition of an auxiliary switch for every main switch.

1-3-Research innovation

Therefore, the aim of this thesis is to provide a bidirectional converter with minimum auxiliary element and low stress imposition to the main switches and to create switching conditions at zero voltage for all the switches. Also, the suggested converter has a high gain in step-up mode and a low gain in step-down mode, which has reduced the voltage stress on the elements.

1-4-Thesis structure

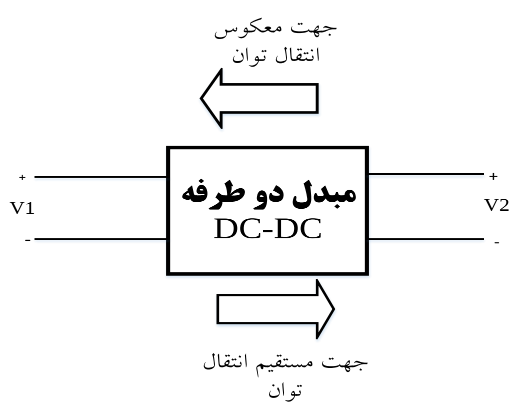
First, in the second chapter, the design method of the bidirectional converter is explained based on the basic converters with hard switching and their performance, and in the third chapter, some examples of the bidirectional converters presented in recent years with soft switching are examined and their advantages and disadvantages will be mentioned. In the fourth chapter, the new bidirectional non-isolated converter is introduced under the switching conditions at zero voltage, the converter is fully analyzed and simulated in PSPICE software. Finally, in the fifth chapter, conclusions and recommendations are presented.

Chapter 2

Base bidirectional converters

2-1- Introduction

Bidirectional DC-DC converters can transfer power in both directions. As shown in figure (1-2), this power transfer is done by bidirectional current transfer, while the voltage polarity remains unchanged at both ends of the converter. Due to such features, these converters are broadly used in battery chargers/dischargers, hybrid electric cars starter motor systems, telecommunications equipment, uninterruptible DC power supplies, computer systems, etc.



The reverse direction of power transfer

Bidirectional DC_DCconverter

The straight direction of power transfer

Figure (2-1): Bidirectional DC-DC converter

We can divide bidirectional DC-DC converters into two types, isolated and non-isolated which in bidirectional isolated converters, a transformer is used to create isolation, that increases the cost and conduction losses. Non-isolated bidirectional converters have higher efficiency and higher power density due to their simpler structure, so if the high voltage conversion ratio and isolation of both sides are not significant in circuit, the non-isolated type is used. Of course, since isolation has increased the flexibility and security of the circuit, isolated converters have found wider usage in the industry. High voltage gains can also be obtained by regulating the ratio of isolated transformer turns. Thus if high voltage gains are needed and both sides of the circuit cannot be grounded, we use the isolation type.

Base bidirectional DC-DC converters cannot transfer power in two directions, because there is a diode in the structure of these converters that prevents flow of current in the opposite route. Therefore, by replacing diode of base converters with a switch, it is possible to create current in the reverse direction, and therefore, in this chapter, the design method of bidirectional DC-DC converters resulting from unidirectional base converters is presented and then we briefly mention the features of each.

2-2- The method of deducing base bidirectional converters

By replacing the switch instead of the diode in the base converters, a bidirectional converter will be created, provided that the diode of the new switch body is in the same direction as the converter diode. Therefore, with a slight change in the base unidirectional converters, a bidirectional converter can be reached. Figure (2-2) shows a step-down converter or a base buck, and as seen in figure (3-2), a bidirectional buck/boost converter can be achieved by replacing the diode with a switch.

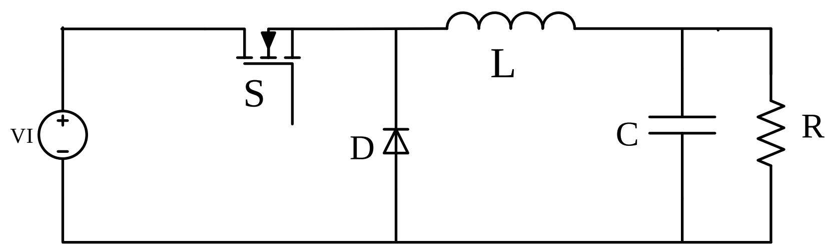


Figure (2-2): Schematic of the base unidirectional buck DC-DC converter

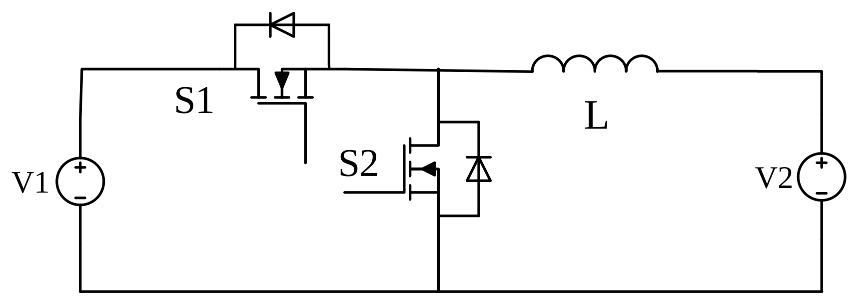
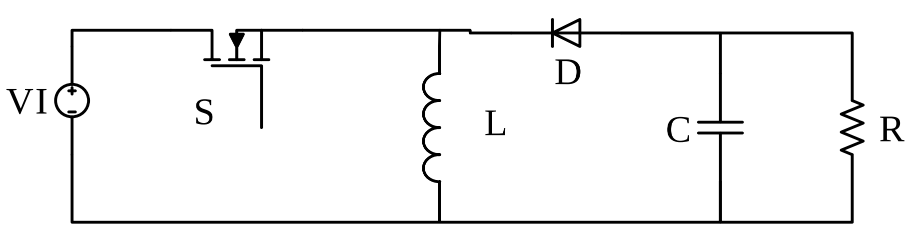


Figure (2-3): Schematic of the base bidirectional buck / boost DC-DC converter

While the power is transferred from V1 to V2, switch S1 is commanded and switch S2 is off and acts only like a diode. As the power is transferred from the V2 side to the V1 side, S2 switch is commanded and S1 switch is turned off, and it only works as a diode. Therefore converter acts similar to a buck converter in power transfer side from V1 to V2 and in the power transfer from V2 to V1 acts as a boost converter.

In figures (4-2) to (8-2) you can see some base DC-DC converters with their conversion to the bidirectional type, similar to the buck example that is shown , it's just enough

in base unidirectional converters by observing the direction of its body diode, a switch added to it instead of converter diode, in order to convert the converter into a bidirectional type, which this process is presented with some examples below. In all converters, direct power control is done by left side switches of the converter and reverse power control is done by right side switches of the converter.



(A)

(B)

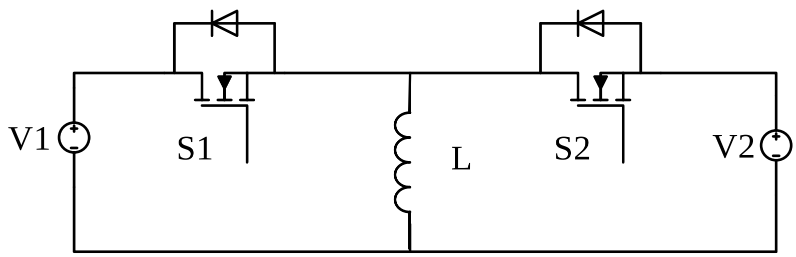
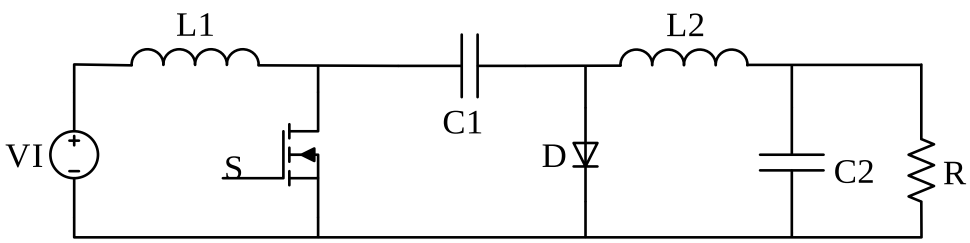
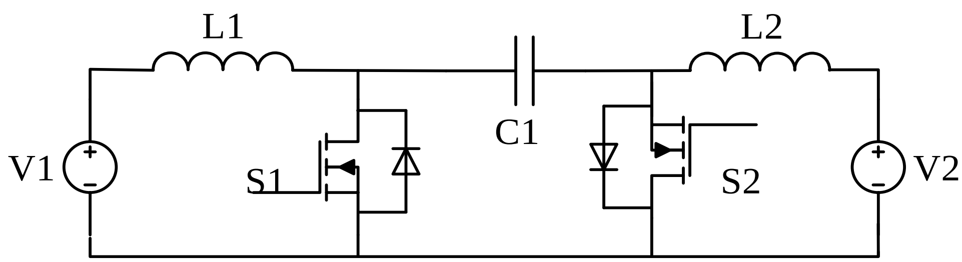


Figure (2-4): (A) Unidirectional buck / boost DC-DC converter

Unidirectional buck / boost DC-DC converter(B)



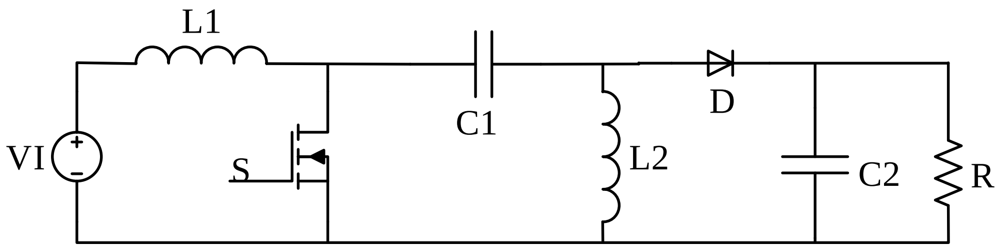
(A)



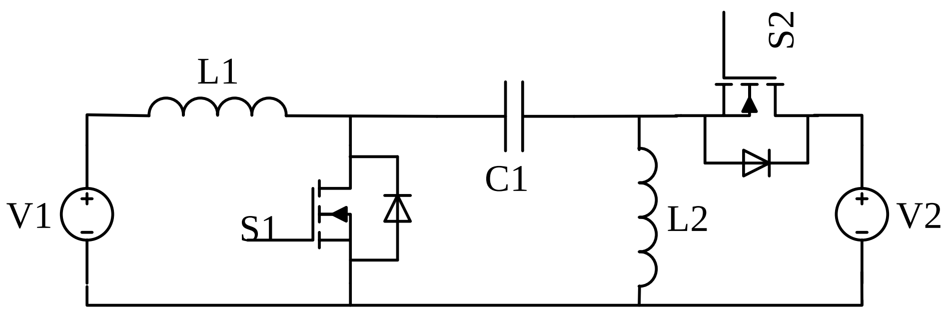
(B)

Figure (2-5): (A) unidirectional choke converter

(B) bidirectional DC-DC choke converter

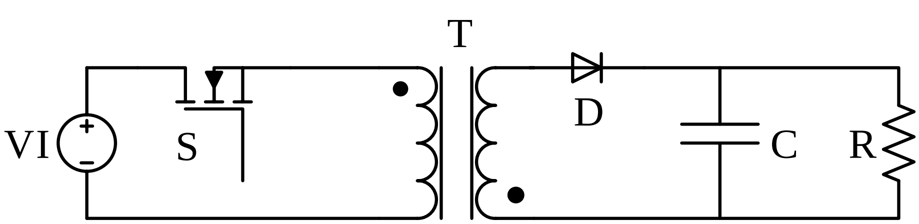


(A)

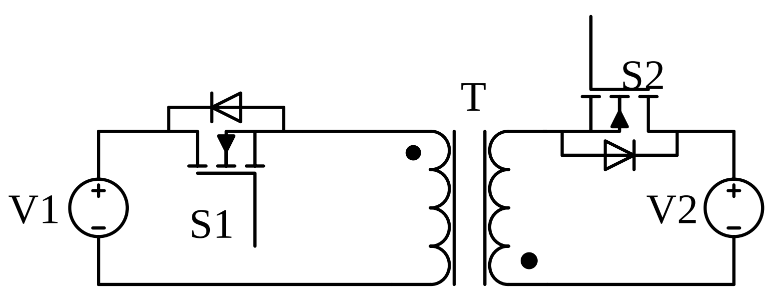


(B)

Figure (6-2): (A) unidirectional sepic converter (B)) bidirectional sepic / zeta DC-DC converter

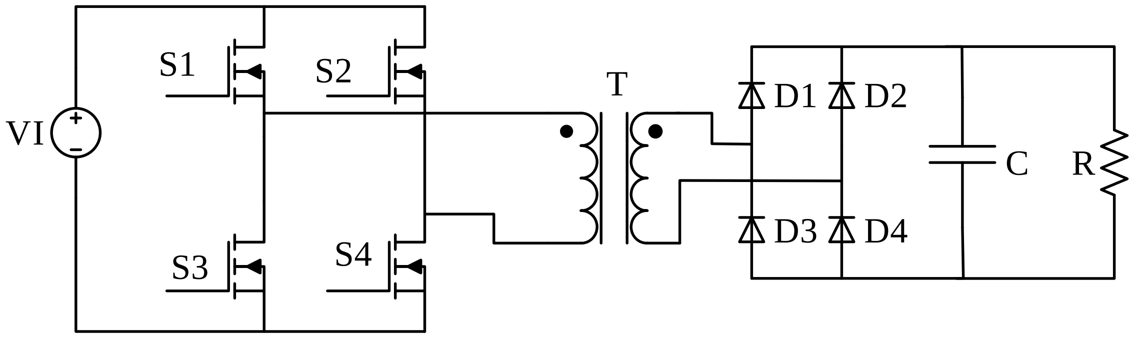


(A)

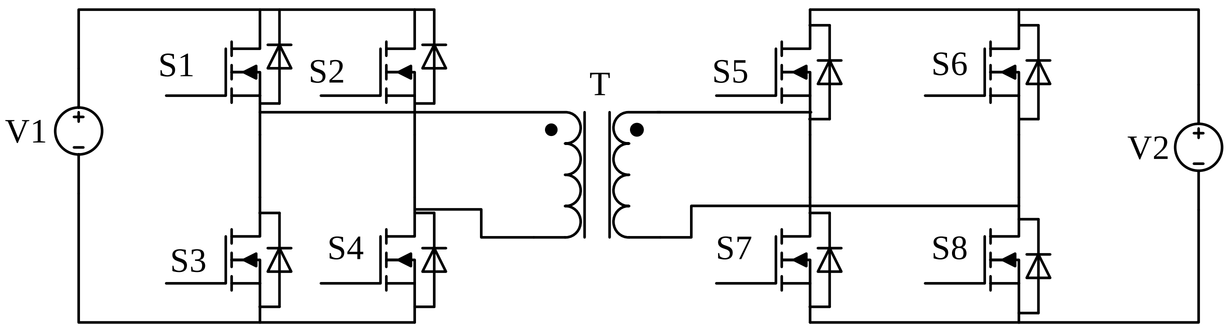


(B)

Figure (7-2): (A)|Unidirectional flyback DC-Dc converter (B) Bidirectional flyback DC-DC converter



(A)



(B)

Figure (2-8): (A)|Unidirectional full bridge DC- DC converter Bidirectional full bridge DC- DC converte(B)

2-3- Features and applications of bidirectional DC-DC converters

Some features and also applications of bidirectional DC-DC converters are shown in Table (1-2). As it is clear, the simplest structure belongs to the buck/boost structure, but one of the problems of these base converters, in addition to the hard switching of switches and existence of switching losses, is the very low gain in the boost mode and very narrow duty factor in the reduction mode. Various methods have been suggested to solve the problem, some of them will be mentioned in the third chapter.

Table (2-1): Features and applications of bidirectional converter

choke/choke	sepic / zeta		flyback	Buck/boost Buck/boost	Buck/boost	Bidirectional converters
$\frac{-D}{(1-D)}$	$\frac{D}{(1-D)}$	ND	$\frac{ND}{(1-D)}$	$\frac{-D}{(1-D)}$	D	DC voltage conversion ratio
٢	٢	٨	٢	٢	٢	Number of converter switches
medium	medium	medium	high	Low	Low	Stress of the elements
no	no	yes	yes	no	no	isolation
low power	low power	high power	Uninterruptible Power Supplies low power	Electric cars	DC Uninterruptible Power Supplies	application

In table (2-1) D is the duty factor and N=N2/N1 is the conversion ratio of the isolated transformer.

Chapter 3

Step-up converters with lossless snubbers

3-1- Introduction

In bidirectional DC-DC converters, in order to lessen the volume of elements, cost and weight, the frequency of switching should be risen. But because switches cannot change their status quickly and at the moments of switching, voltage and current overlap in the voltage and current of the switches occurs, which causes imposition of high switching losses to the converter. Therefore, by increasing the switching frequency, high losses are imposed on the converter. Also, the main cause of noise in circuits is sudden changes in voltage or current, which by increasing the switching frequencythis noise also increases.

It should be noted that in bidirectional converters with hard switching, the switches of the converter are increased to transfer power in both directions, so switching losses are higher in bidirectional converters compared to unidirectional converters.

Therefore, in order to solve the above problem, many converters with the techniqueof soft switching have been introduced. In those converters, in addition to reducing switching losses and rising efficiency, it is possible to increase switching frequency, which reduces the volume of magnetic elements.

Therefore, in this chapter, four examples of DC-DC converters with soft switching technique that have been introduced in recent years will be examined. In this chapter, four examples of the techniques presented in non-isolated converters will be analyzed, at the end of each part, the related converter is evaluated and its advantages and disadvantages will be stated.

3-2- Non-isolated active clamp bidirectional converter [41]

In the Buck/Boost converter introduced in [41], which is shown in Figure (1-3), soft switching conditions in the form of ZVS (Zero Voltage Switching) are created by an auxiliary circuit in the form of an active clamp for both main switches.

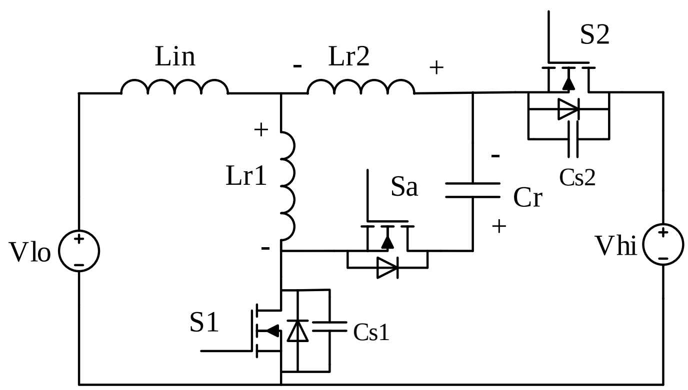


Figure (3-1): Proposed converter in [41]

As it is clear from the figure, by two inductors, a capacitor and a switch, ZVS (Zero Voltage Switching) conditions are provided for either direction of power transfer. Converter works as a buck or boost in two directions, which works as a boost converter in power transfer from Vlo to Vhi and as a buck converter in the power direction from Vhi to Vlo.

3-2-1- Bidirectional converter performance [41]

The proposed converter is completely tested for boost. Since the performance of circuit in the symmetrical mode is the same as the boost, the converter is not fully checked in the buck mode and only the form of the waves and the form of the states are given in general, and the performance is similar to the boost mode, and instead of the S1 switch, the S2 switch is in buck mode of main switch. As shown in Figure (3-1), it is clear that the circuit has two inductors Lr1 and Lr2, capacitor Cr and switch Sa as an auxiliary circuit added to the converter to generate ZVS conditions for main switch.

3-2-1-1-Converter performance in boost mode

So as to simplify description of converter areas, we consider the following conditions.

• All circuit elements are considered ideal.

• Due to the large output capacitor or input source, we consider a constant voltage on both sides of the circuit .

•.We consider the input inductor current of the converter to be constant considering its high amount in a dutycycle.

The converter in the boost duty mode has 8 performance states which are checked separately and completely, and in Figure (10-3) the wave forms of different areas of the circuit are displayed based on the performance states.

In the boost mode, S1 switch acts as the main boost switch and Sa switch acts as an auxiliary switch. During this entire period, the S2 switch is off and its body diode acts only as a boost converter diode.

State 1 [t < t0] : In this state, which is before time t0, the circuit acts like a regular boost converter in the state of S1 being on and the output diode being off and charging the input inductor. This state is shown in figure (2-3).

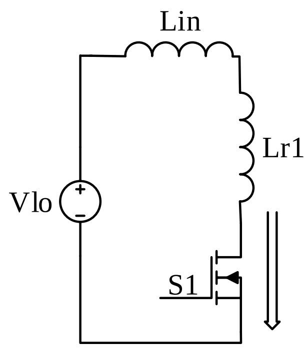


Figure (3-2): Comparable circuit of state 1 of converter performance in boost mode

State 2 [t0<t < t1] : At t = t0 switch S1 turns off, since inductor current cannot suddenly become zero, and the inductor continues its current, starts charging Cs1 and flows towards Cs too. During this state, the input current reaches the inductor Lr2 and causes the discharge of the capacitor Cs2. You can see the comparable circuit of this state in figure (3-3).

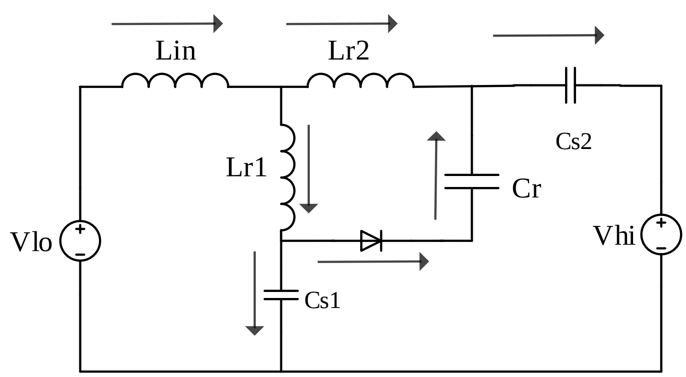


Figure (3-3): comparable circuit of state 2 of converter in boost mode

State 3 [t1< t < t2] : This state continues the previous state, the only difference is the complete discharge of the capacitor Cs2 at t = t1 and the switching on of body diode of switch S2 in this state. You can see the comparable circuit of this state in figure (3-4).

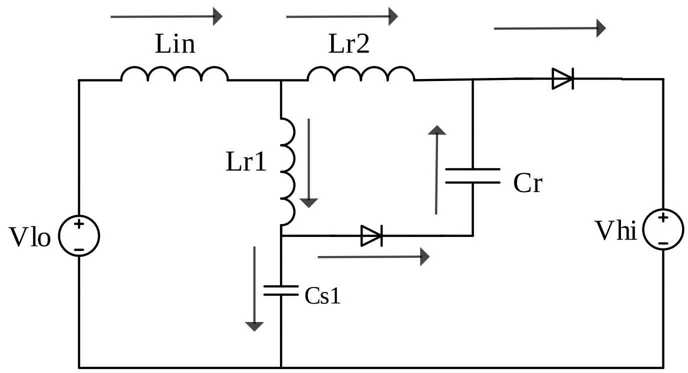


Figure (3-4): comparable circuit of the state 3 of converter in boost mode

State 4 [t2< t < t3] : At t = t2, current of active clamp auxiliary circuit is stopped and the converter acts like a regular boost converter when the switch is off. Current of input inductor decreases and the voltage at both ends is negative. You can see the comparable circuit of this state in figure (3-5).

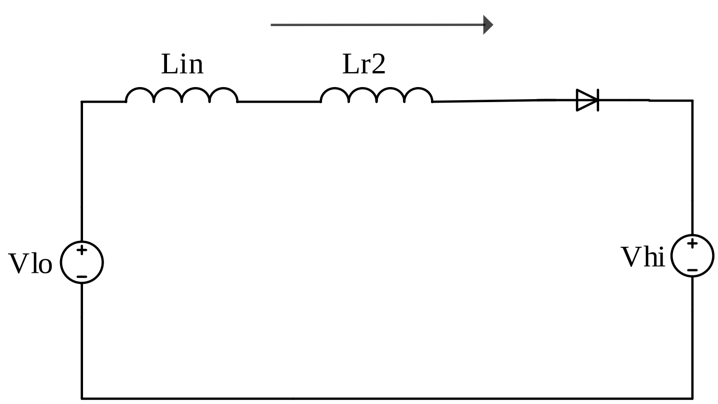


Figure (3-5): comparable circuit of state 4 of converter in boost mode

State 5 [t3< t < t4]: The comparable circuit of this state is demonstrated in figure (6-3). A period of time before main switch is turned on, Auxiliary switch S_a is turned on under the ZCS condition at time $t = t_3$. Capacitor Cr starts discharging through Lr1 and Lr2, while the input inductor current is still decreasing.

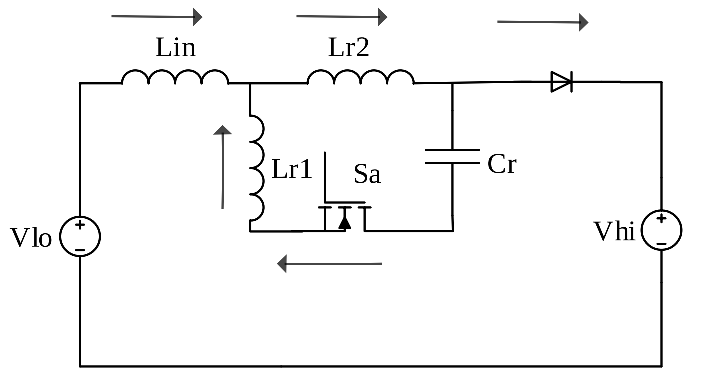


Figure (3-6): comparable circuit of state 5 of converter in boost mode

State 6 [t4< t < t5]: This state begins when the Sa switch is turned off and because inductor Lr1 wants to continue its current, as a result, it starts discharging the capacitor Cs1. This state ends with the complete discharge of the capacitor. The comparable circuit of this state is demonstrated in figure (3-7).

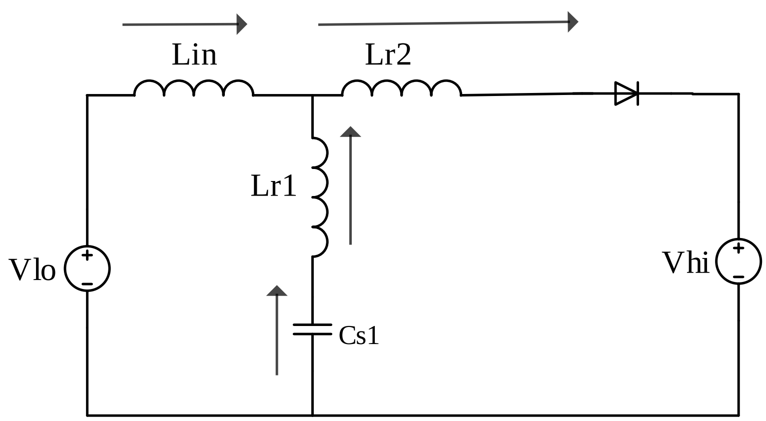


Figure (3-7): comparable circuit of state 6 of converter in boost mode

State 7 [t5< t < t6] : With the complete discharge of the capacitor Cs1 at t = t5, body diode of switch S1 turns on. From now on, main switch will be turned on under zero voltage conditions. The equivalent circuit of this state is demonstrated in figure (3-8).

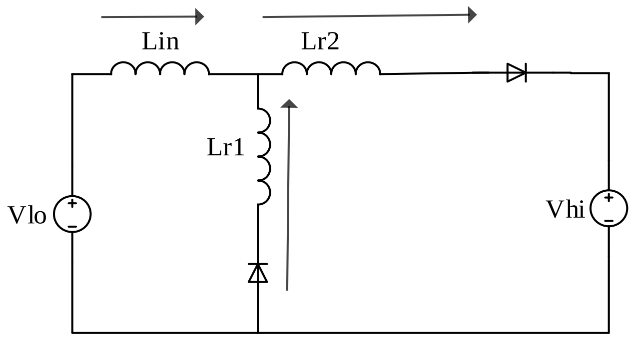
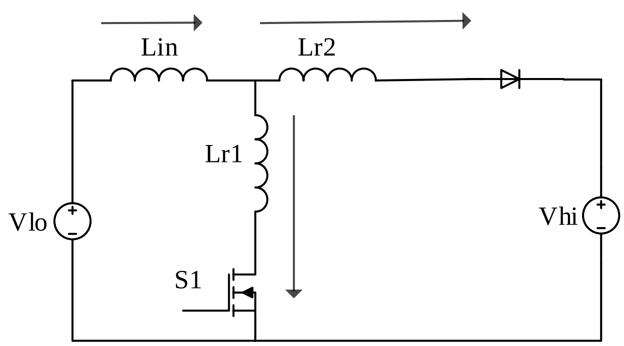


Figure (3-8): comparable circuit of state 7 of converter in boost mode

State 8 [t6< t < t7] : A short time after switch S1 is turned on at time t = t6 , current of Lr1 is reversed and the current is transferred from the body diode to the switch, this current continues until it reaches its maximum. At t = t7, the converter returns to state 1 again. You can see comparable circuit of this state in figure (3-9). The equations describing this state are given below.



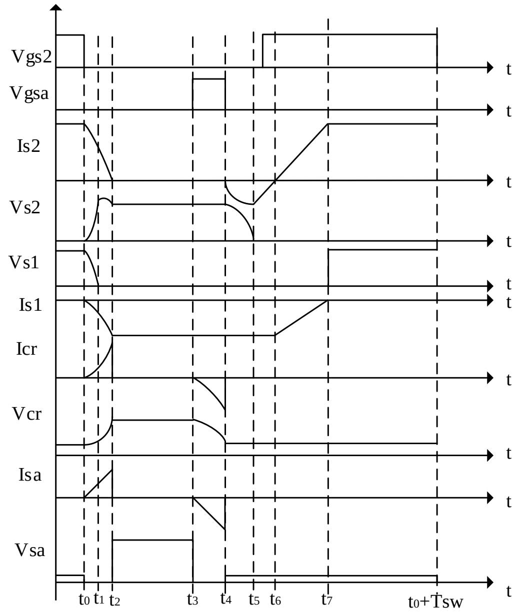


Figure (3-9): comparable circuit of state 8 of converter in boost mode

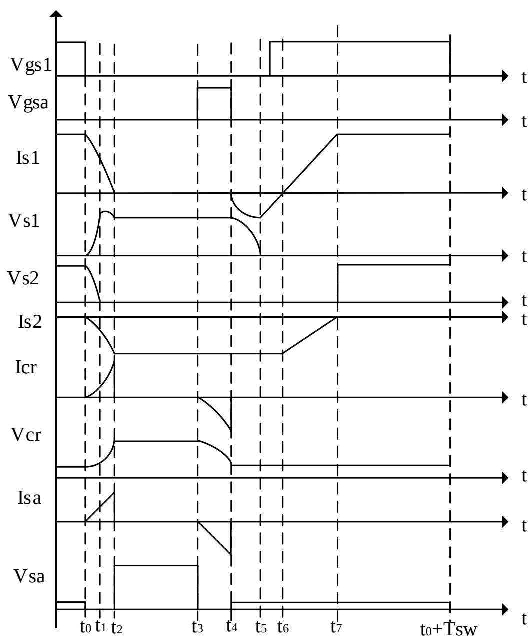


Figure (3-10): Wave forms of different areas of suggested converter in boost mode

3-2-1-2- Converter performance in buck mode

Owing to similarity of states in the buck and boost mode, only the form of the waves and form of the states have been placed in general. In figure (11-3) you can see switching wave forms of the converter in step-down mode. In figure (12-3) you can see the comparable circuit of converter states in step-down mode.

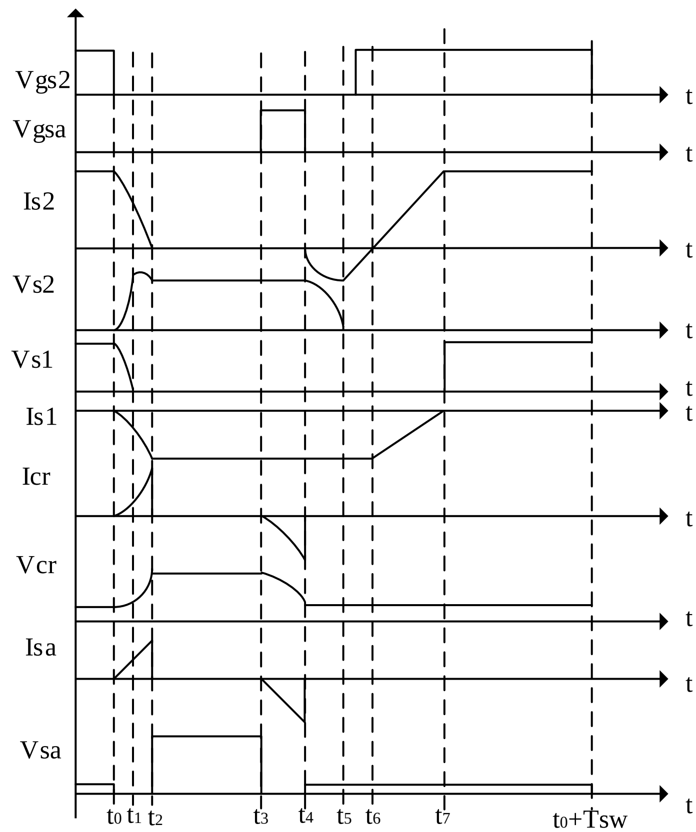


Figure (3-11): Wave forms of different areas of suggested converter in step-down mode

In figure (12-3) you can see the comparable circuit of converter states in the step-down mode. As it can be seen, the states of the converter are similar to the working states in step-up mode, and in this mode, the direction of current and power transfer is from Vhi side to Vlo side.

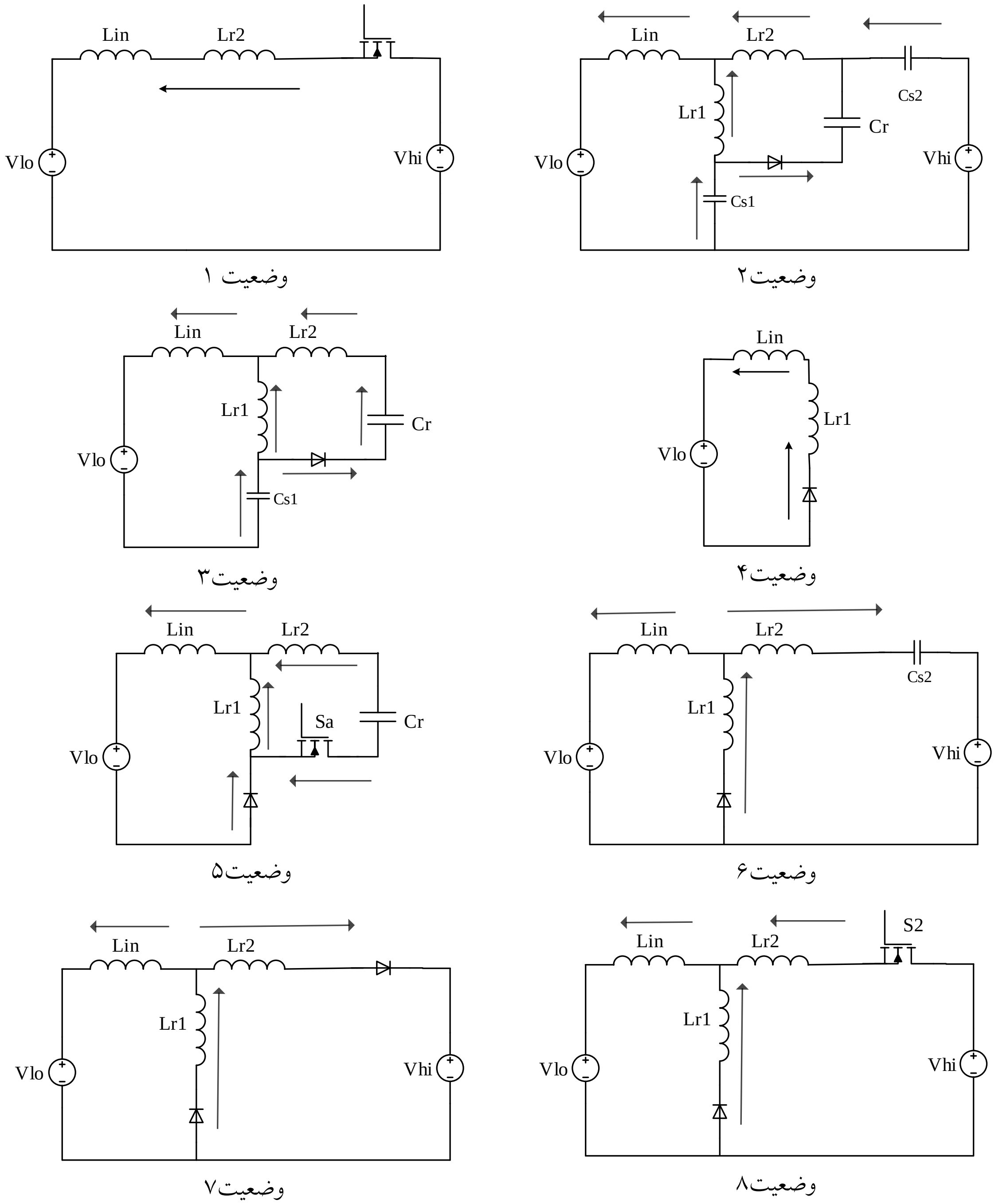


Figure (3-12): The entire working areas of suggested converter in buck mode

3-3- Bidirectional PWM converter zero voltage transition (ZVT) with the coupled inductors [42]

Zero voltage transition (ZVT) and zero current transition (ZCT) are two soft switching methods to reduce switching losses that are commonly integrated with PWM converters.

In [43], a new non-isolated ZVT converter with coupled inductors is introduced. This converter can be seen in figure (13-3). In this converter, by using two auxiliary switches and coupled inductors, soft switching conditions are provided for every semiconductor parts. In addition, placing all inductors coupled on one core reduces the overall volume of the converter. Also, simple switching conditions and not imposing additional stress of voltage and current on converter are among advantages of this type of converters.

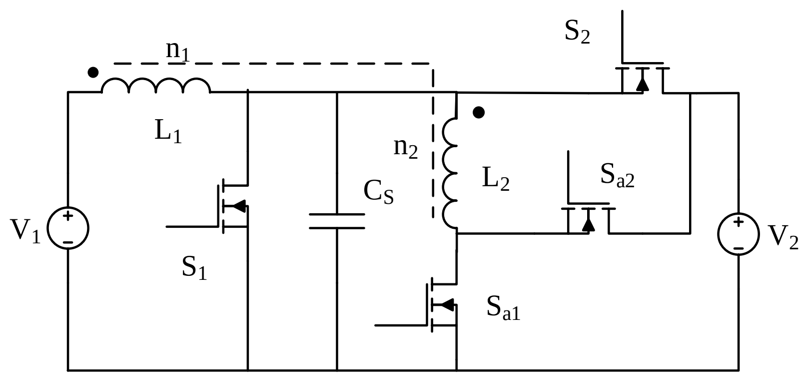


Figure (3-13): Proposed converter in [42]

3-3-1 Bidirectional converter performance [42]

The seggested buck and boost converter is completely examined in both buck and boost modes. As it is seen in figure (12-3), the converter has two main switches S1 and S2, two auxiliary switches Sa1 and Sa2, a snubber capacitor CS and two coupled inductors L1 and L2 with a turn ratio n1/n2. We can model the coupled inductors by a mixture of a magnetizing inductor (LM), an ideal transformer with turns ratio n1/n2, and a magnetizing inductor (Llk). The comparable circuit of the proposed converter is demonstrated in Figure (14-3).

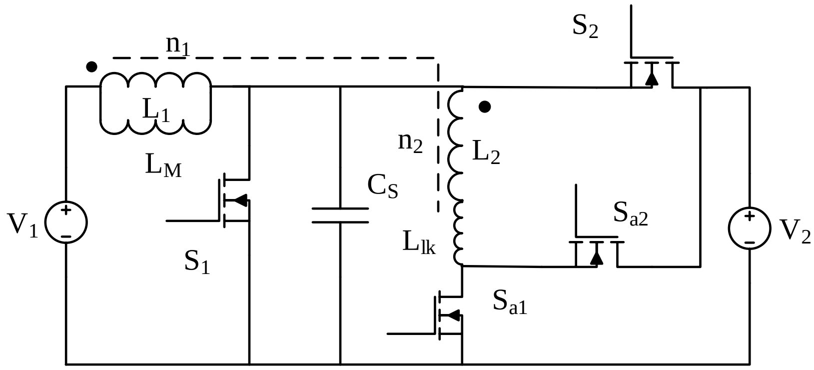


Figure (3-14):The comparable circuit of suggested converter in [42]

3-3-1-1 The performance of the suggested converter in boost mode

Since performance of converter in both buck and boost modes is similar, only performance of converter in the boost mode will be completely described and the buck mode will be given generally.

The proposed converter has seven performance states in each buck and boost mode, which are analyzed separately. In this state, S1 and Sa1 are the main and auxiliary switches, respectively, prior to the first state, it is expected that all the switches are off and the magnetizing inductor current LM is transmitted to V2 through body diode S2. It is also supposed that no current flows in the coil of the ideal transformer and the voltage Cs is equal to V2.

State 1 [t0-t1]: The comparable circuit of this state is demonstrated in Figure (15-3).

At t0, owing to the existence of inductor Llk, the auxiliary switch Sa1 turns on under the approximate condition of ZCS. As this switch is turned on, current of Sa1 begins to rise linearly, hence the current of body diode of S2 begins to decrease till it reaches zero. So this diode will turn off under ZCS condition.

The current ISa1 enters the dotted end of the secondary side of the ideal transformer and exits from primary end of the transformer nISa1. At the end of this state, current ISa1 is equal to ILM/(n+1)

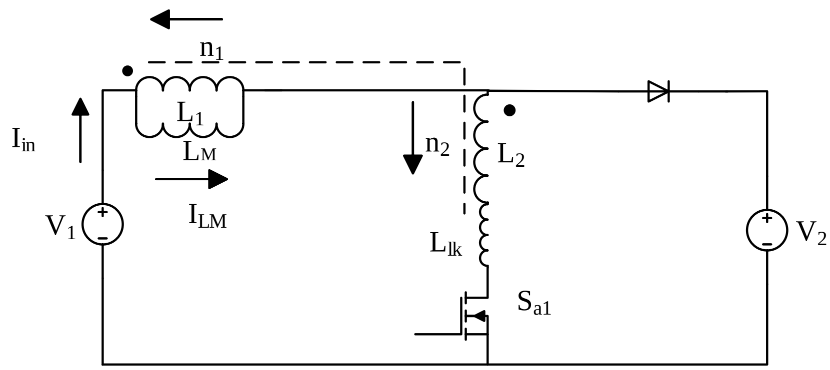


Figure (3-15):The comparable circuit of state 1 of suggested converter in boost mode

State 2 [t1-t2]: At time t1 the body diode S2 turns off, and resonance starts between Llk and CS. Throughout this resonance, CS is discharged from V2 to zero, and switching conditions under zero voltage are provided for switch S1. At the end of this state, the current Llk is equal to IO. The comparable circuit of this state is demonstrated in figure (3-16).

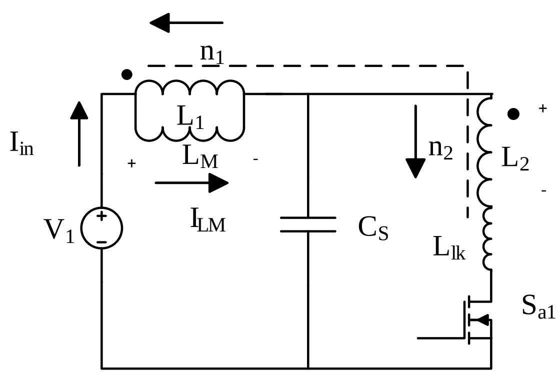


Figure (3-16):The comparable circuit of state 2 of the suggested converter in boost mode

State 3 [t2-t3] :At t2, body diode S2 turns on, when this diode conducts, switch S1

can turn on under the ZVS condition. |Throughout the time of this state, voltage at both ends of the primary winding of transformer is equal to V1, so its secondary voltage is equal to nV_1. Negative voltage at two ends of leakage inductor Llk reduces the inductor current linearly to zero.

When the I_{S1} current gets to zero, this state ends and the S1 body diode turns off as ZCS. At the end of this state, current Sa1 is equal to ILM/(n+1) The comparable circuit of this state is demonstrated in figure (3-17).

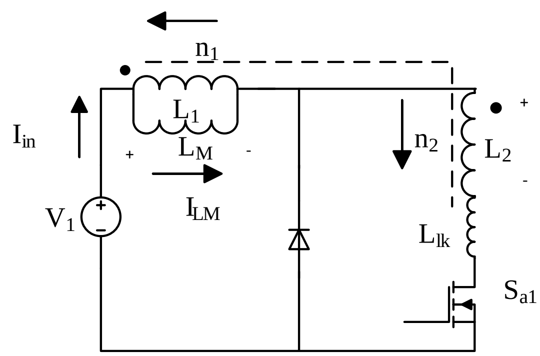


Figure (3-17):The comparable circuit of state 3 of the suggested converter in boost mode

State 4 [t3-t4]: The comparable circuit of this state is demonstrated in figure (3-18).

In this state, the current on the switch S1 changes its direction and is transferred from body diode to the switch itself, and IS1 starts to increase from zero. The current ISa also decreases and gets to zero at the end of this state. When the auxiliary switch current becomes zero it provides the conditions for ZCS to turn it off.

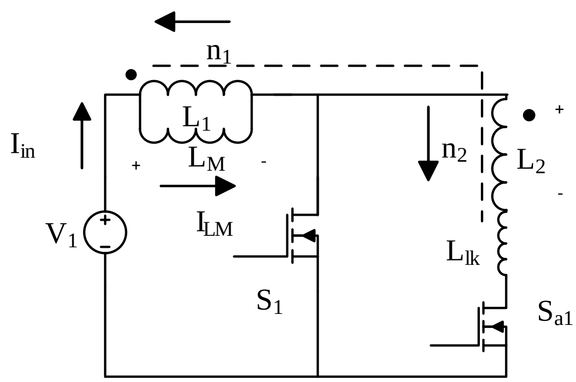


Figure (3-18):The comparable circuit of state 4 of suggested converter in boost mode

State 5 [t4-t5] :The comparable circuit of this state is demonstrated in figure (3-19).

In this mode, ILM current is provided through S1. The performance of this state is exactly the same as the regular boost converter in the charging mode of the input inductor.

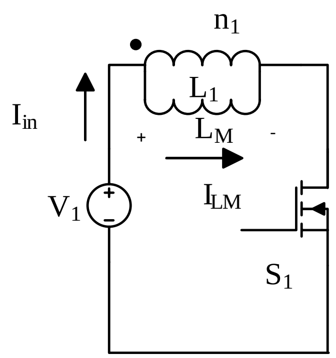


Figure (3-19):The comparable circuit of state 5 of suggested converter in boost mode

State 6 [t5-t6] :This state begins when the main switch is turned off. Owing to the presence of capacitor CS, voltage at both ends of the switch S1 changes slowly, and S1 turns off under the approximate condition of ZVS. At the end of this state CS will be charged up to the value of V2 and the body diode of main switch S2 starts to conduct. The comparable circuit of this state is demonstrated in figure (3-20).

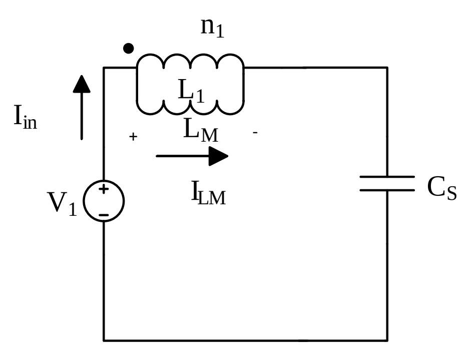


Figure (3-20):The comparable circuit of state 6 of the suggested converter in boost mode

State 7 [t6-t0+T]: The comparable circuit of this state is demonstrated in figure (3-21). The performance of this state is exactly the same as that of the regular boost converter when converter switch is off and diode is on and inductor current is transferred to the output.

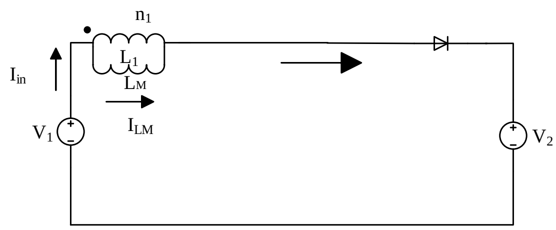


Figure (3-21):The comparable circuit of state 7 of suggested converter in boost mode

Switching wave forms of different parts of the suggested converter circuit in boost mode are demonstrated in Figure (3-22).

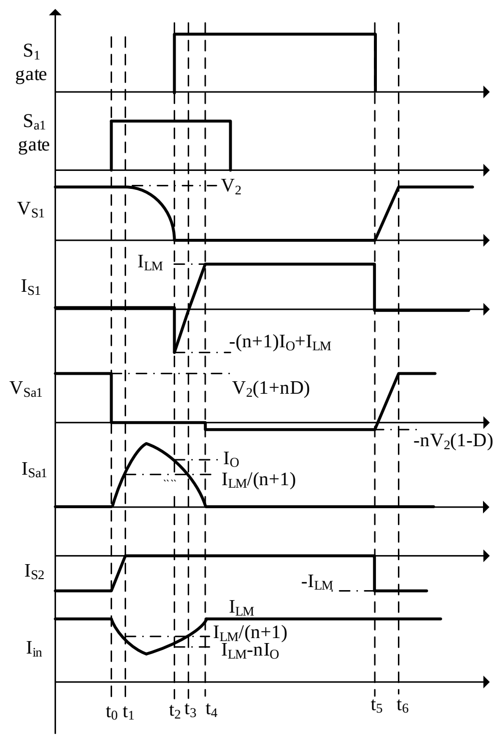


Figure (3-22):The switching wave forms of suggested converter in [42] boost mode

3-3-1-2 Converter performance in the buck mode

Switching wave forms of the converter in the buck mode are demonstrated in figure (3-23).

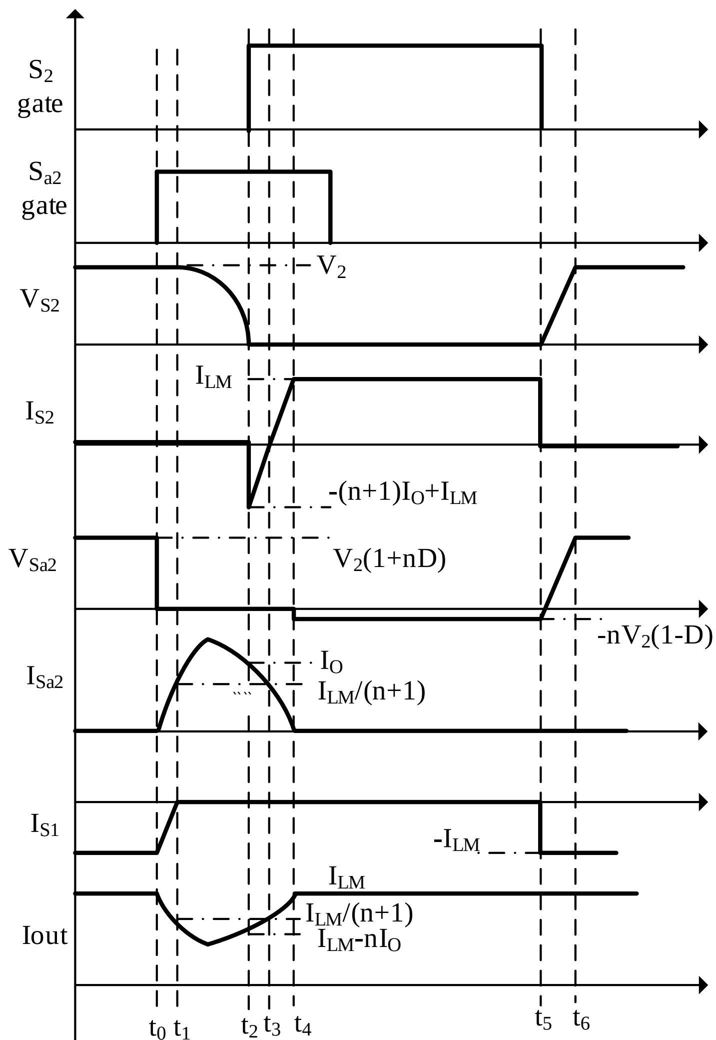


Figure (3-23):The switching wave forms of suggested converter in [42] boost mode

Since the performance of auxiliary and main circuit in buck mode is similar to boost mode, only the equivalent circuit form in each state is generally shown in Figure (3-24).

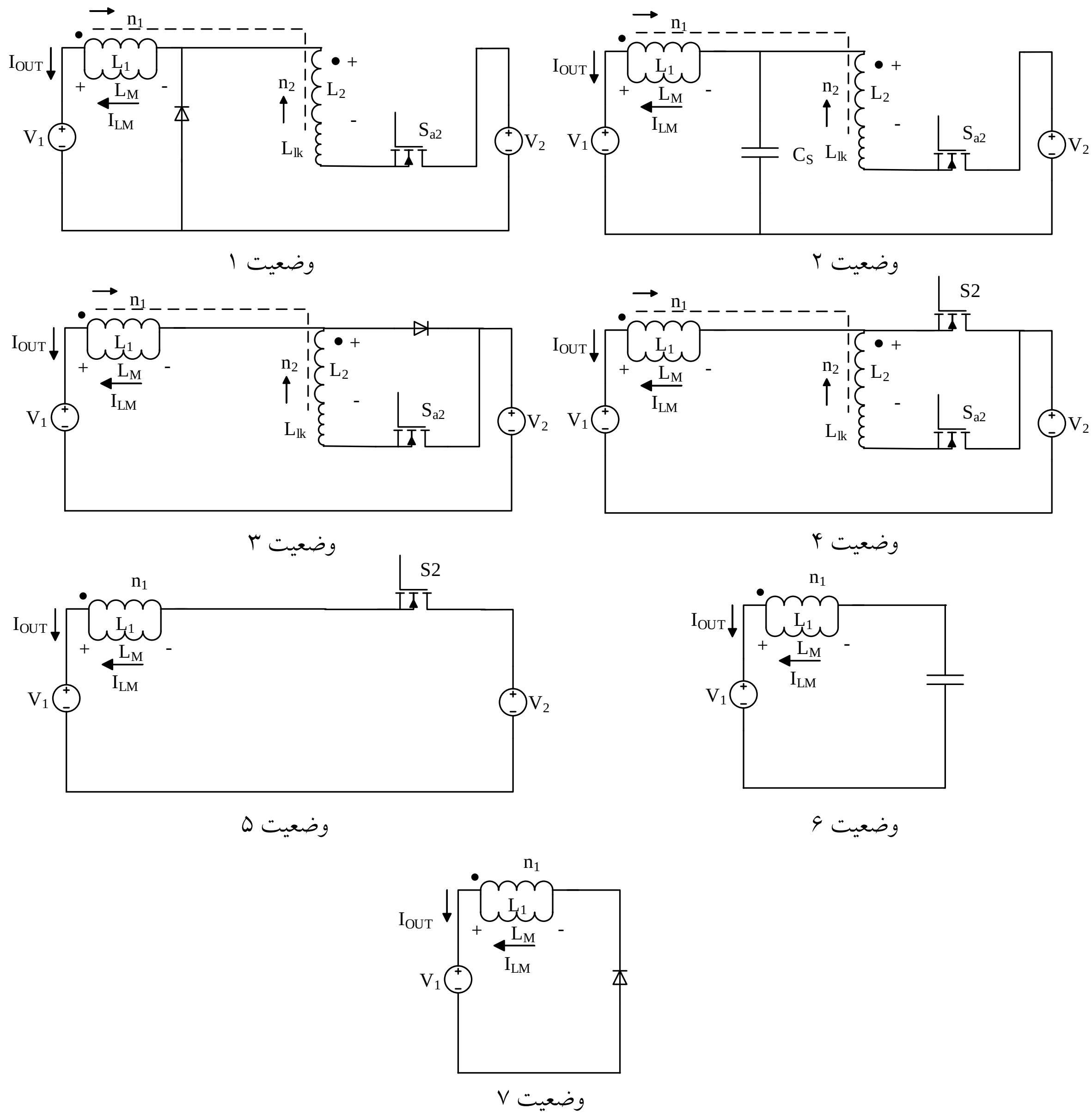


Figure (3-24): The comparable circuit of each state of suggested converter in buck mode

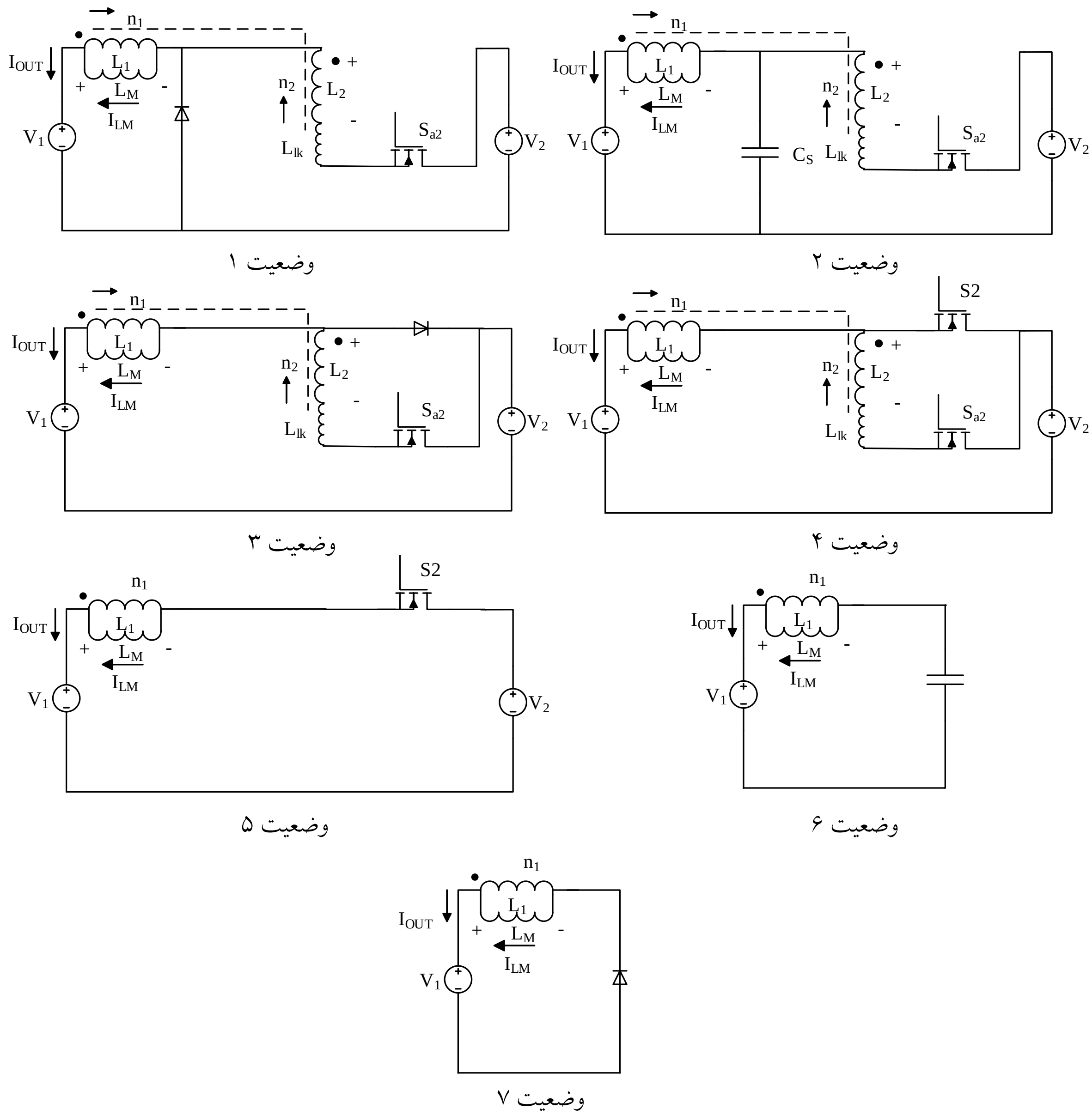


Figure (3-24): The comparable circuit of each state of suggested converter in buck mode

3-4- Bidirectional soft switching converter using lossless active snubber [43]

Lossless snubber circuits are used to reduce total converter losses and increase efficiency. These circuits are used in practice to enhance the converter efficiency.

In this article, a soft-switching bidirectional DC-DC converter is presented using an introduced example of lossless snubber ,which is shown in Figure (3-25). The difference between this converter and the regular converter is the addition of two auxiliary switches and an inductor along with two diodes and a capacitor. In this converter, all switches are commanded in any mode and no switch is off in the converter mode. These elements provide soft keying conditions in the form of ZVS for the keys.

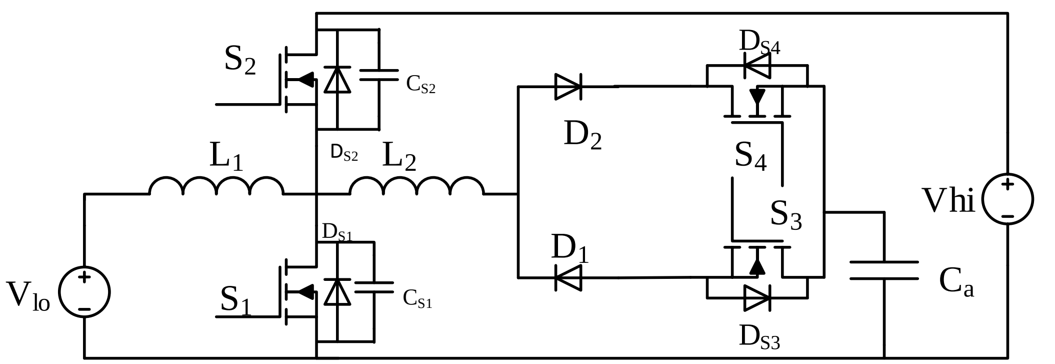


Figure (3-25): The suggested converter circuit in [43]

3-4-1- Bidirectional converter performance [43]

This converter has 8 performance modes in both boost and buck modes which the states are like in buck and boost mode and only boost mode is described completely and buck mode is displayed with the general form of the states. Also, the converter wave forms in buck mode are generally displayed.

3-4-1-1- Converter performance in boost mode

The key waveforms of boost mode are demonstrated in figure (3-26).

State 1 [t0-t1]:At t0, switch S2 turns off. Capacitor CS1 starts to discharge and capacitor CS2 starts to charge. Since these capacitors have small amounts, a short period of time is required for charging and discharging. Therefore, the current of the inductor L1 and L2 is assumed to be constant, as a result, their voltage is completely linear. The comparable circuit of this state is demonstrated in figure (3-27).

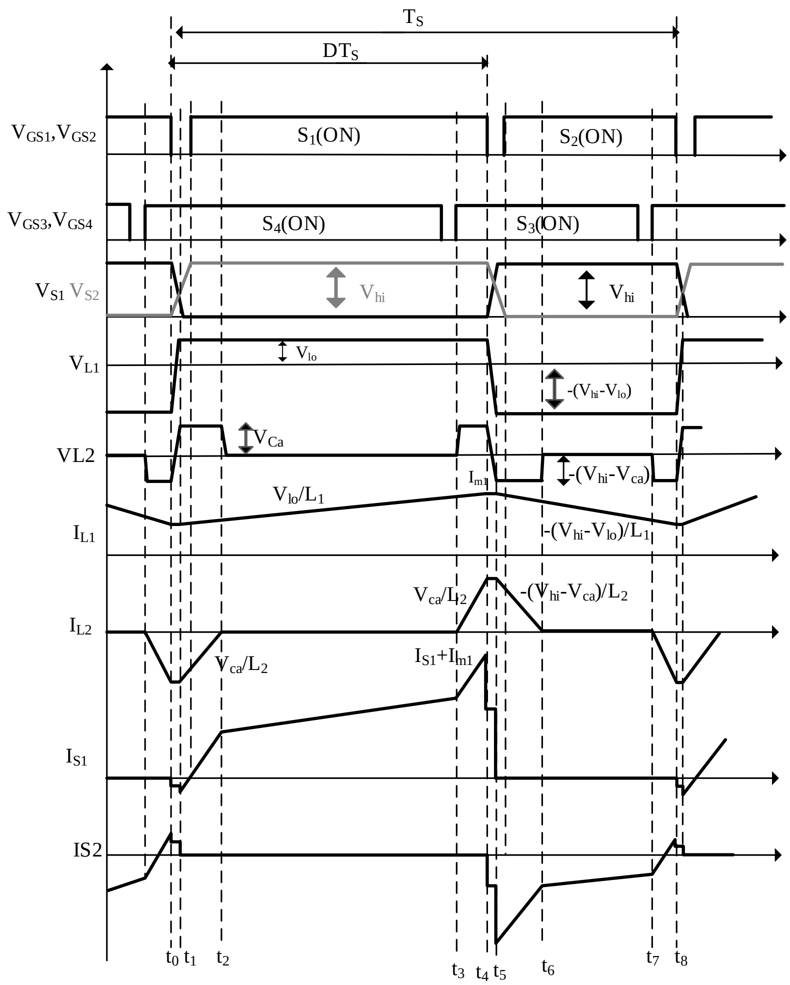


Figure (3-26): The switching wave forms of different parts of the suggested converter in boost mode

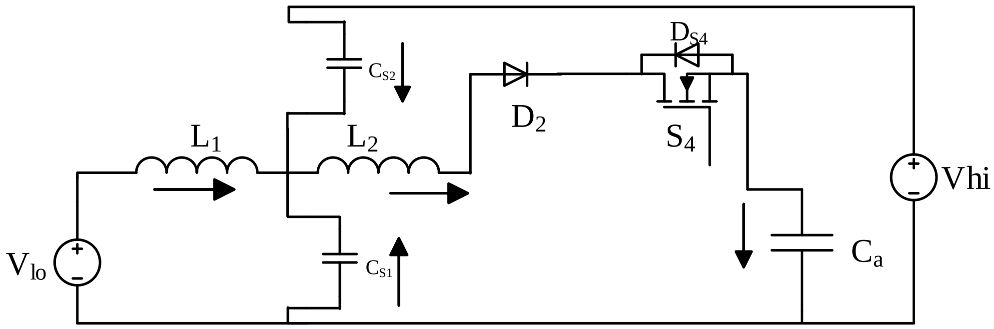


Figure (3-27): comparable circuit of state 1 of suggested converter in boost mode

State 2 [t1-t2] :At time t1, the S2 voltage remains at Vhi and the S1 voltage remains at zero when body diode turns on. Hence, ZVS switching condition is prepared for S1 and S1 turns on under zero voltage. The voltage of L1 and L2 is equal to Vlo and Vca, respectively, and the current of these two inductors starts to increase linearly. The comparable circuit of this situation is demonstrated in figure (3-28).

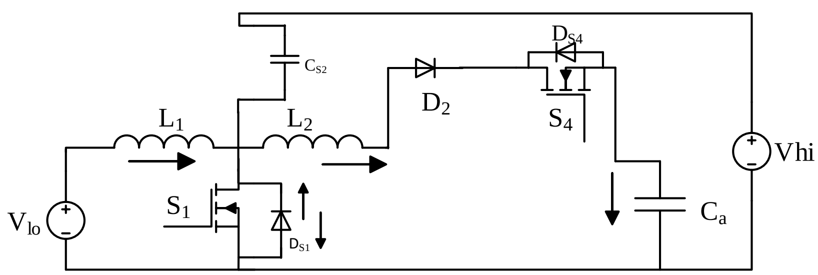


Figure (3-28): comparable circuit of state 2 of suggested converter in boost mode

State 3 [t2-t3]:This state starts while the current of inductor L2 gets to zero and diode D2 turns off. After that switch S4 is turned off under ZCS condition. Current of main switch S1 is equal to the current of inductor L1. The comparable circuit of this state is demonstrated in figure (3-29).

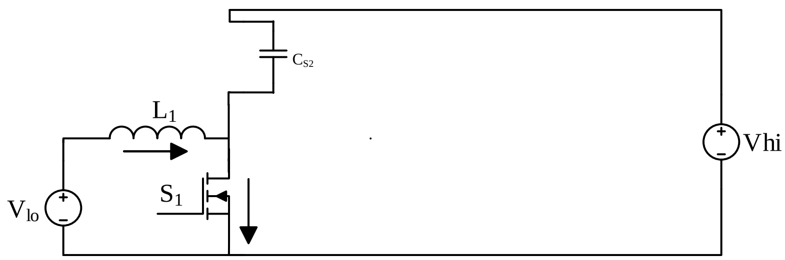


Figure (3-29): Comparable circuit of state 3 of suggested converter in boost mode

State 4 [t3-t4]: At t3 auxiliary switch S2 turns on. Because the voltage at two ends of L2 is equal to VCa, the inductor current of L2 begins to increase linearly. At the end of this state, the current of inductors are at their maximum value. The comparable circuit of this state is demonstrated in figure (3-30).

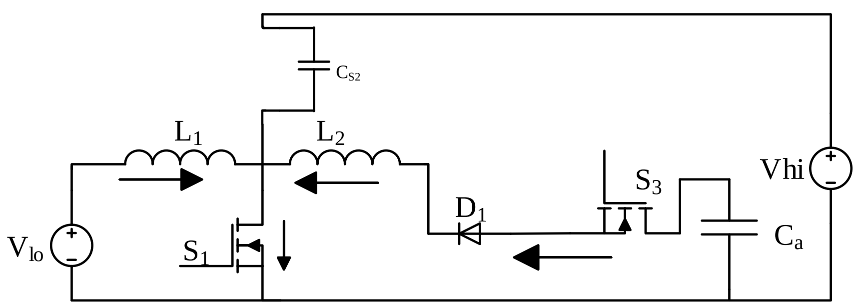


Figure (3-30): comparable circuit of state 4 of suggested converter in boost mode

State 5 [t4-t5] : At t4, switch S1 turns off, CS1 starts charging and CS2 starts discharging. Since the values of these two capacitors are very small, the charging and discharging time is very short, hence the current of L1 and L2 is assumed to be constant, as a result, the voltage of these two inductors is linear. The comparable circuit of this state is demonstrated in figure (3-31).

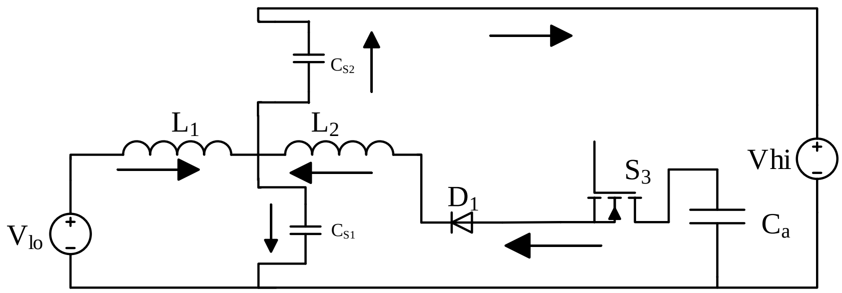


Figure (3-31): Comparable circuit of state 5 of suggested converter in boost mode

State 6 [t5-t6] : At t5, the S1 voltage gets to Vhi and S2 voltage gets to zero when body diode turns on. Hence, at this momement, ZVS condition is provided for S2. The comparable circuit of this state is demonstrated in figure (3-32).

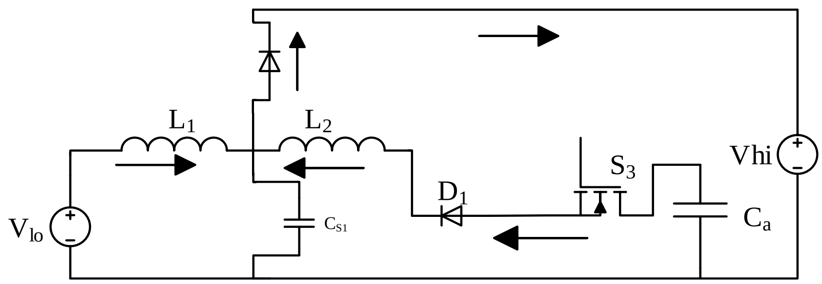


Figure (3-32): comparable circuit of state 6 of suggested converter in boost mode

State 7 [t6-t7]:The comparable circuit of this state is demonstrated in figure (3-33). This state starts when the L2 current becomes zero. Diode D1 turns off when the current becomes zero. After this mode, auxiliary switch S3 will turn off under ZCS condition. The current of the switch S2 is the same as the current of main inductor L1.

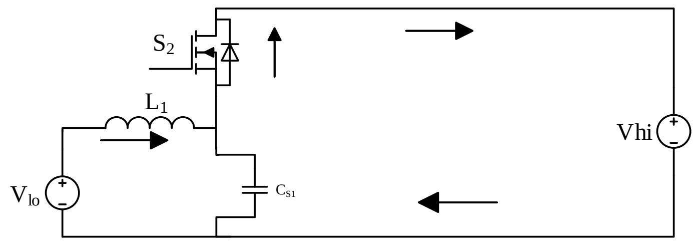


Figure (3-33): comparable circuit of state 7 of suggested converter in boost mode

State 8 [t7-t8]: At time t7, switch S4 turns on. The L2 current starts to decrease linearly with a negative slope. The switch current S2 is transferred from body diode to switch itself. At the end of the state, the inductor currents reach their minimum value and after this state, the converter returns to state 1 when S2 turns off. The comparable circuit of this state is demonstrated in figure (3-34).

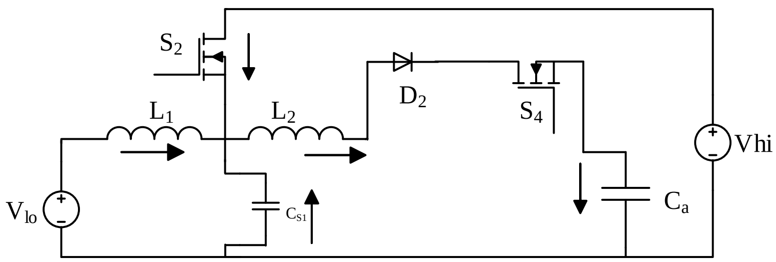


Figure (3-34): Comparable circuit of state 8 of suggested converter in boost mode

3-4-1-2- Converter performance in buck mode

Since the performance and states of the converter are similar to the boost mode, this mode is shown only by the wave forms of the circuit and the general shape of the converter states in figures (3-35) and (3-36).

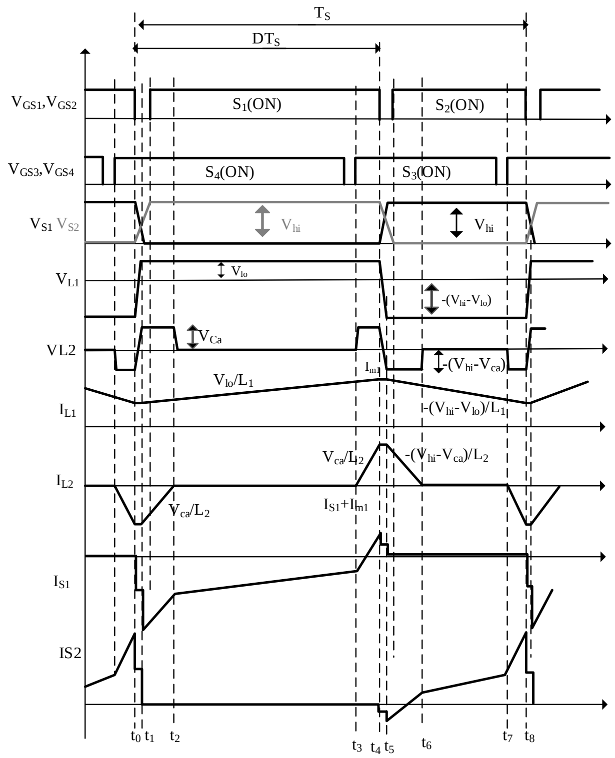


Figure (3-35): The Switching wave forms of different parts of the suggested converter in buck mode

3-5- New bidirectional soft switching converter with resonant auxiliary circuit [44]

In this article, a new example of bidirectional soft switching converters is introduced. This converter is shown in figure (3-37). For soft switching conditions, an auxiliary circuit including Lr and Cr, D1 and D2 and two auxiliary switches Sa1 and Sa2 are used for the circuit parts.

3-5- New bidirectional soft switching converter with resonant auxiliary circuit [44]

In this article, a new example of bidirectional soft switching converters is introduced. This converter is shown in figure (3-37). For soft switching conditions, an auxiliary circuit including Lr and Cr, D1 and D2 and two auxiliary switches Sa1 and Sa2 are used for the circuit parts.

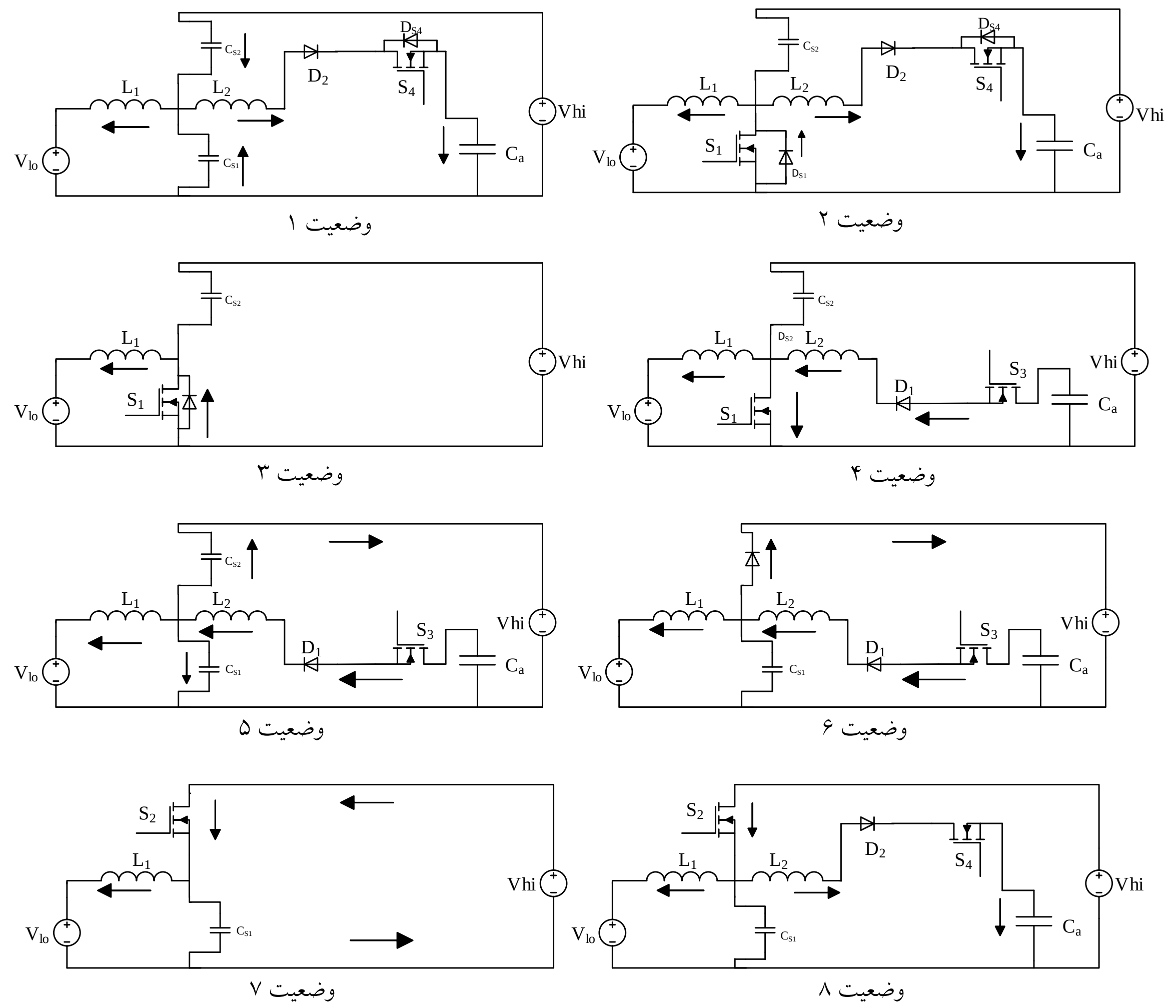


Figure (3-36): The performance states of suggested converter in buck mode

3-5- New bidirectional soft switching converter with resonant auxiliary circuit [44]

In this article, a new example of bidirectional soft switching converters is introduced. This converter is shown in figure (3-37). For soft switching conditions, an auxiliary circuit including Lr and Cr, D1 and D2 and two auxiliary switches Sa1 and Sa2 are used for the circuit parts.

3-5-1 The performance of the proposed bidirectional converter in [44]

The converter has 9 performance modes in both buck and boost modes. The performance of converter in both modes is exactly the same and symmetrical to each other, only main and auxiliary switches are different in both modes. Therefore, converter is checked only in full boost mode and buck performance is not analyzed and is symmetrical with the boost. The proposed converter circuit is shown in figure (3-35).

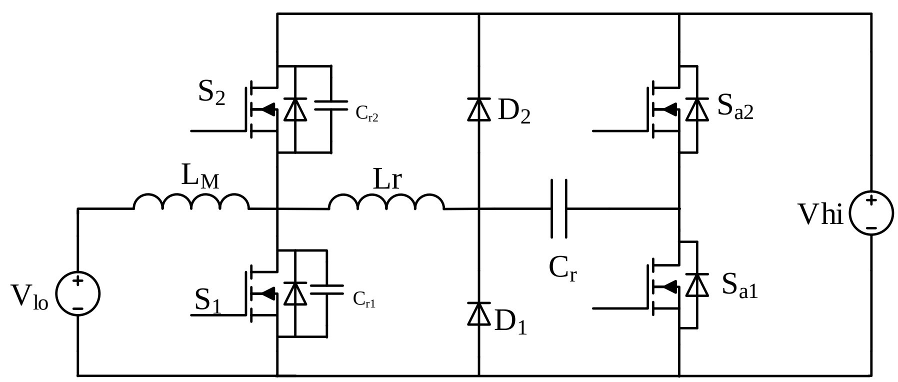


Figure (3-37): Suggested converter circuit in [44]

3-5-1-1 Converter performance in boost mode

Switching wave forms of converter in boost mode are demonstrated in figure (3-38). The converter has 9 performance modes, all of which are fully described. In this mode, main switch is S1 and auxiliary switch is Sa1, and the other two switches, which are symmetrical to the buck, are off in this mode.

A resonant circuit Lr and Cr together with an auxiliary switch is applied to generate soft switching conditions that by resonating voltage and current of switch, the conditions for soft switching will be provided.

State 1 [t0-t1]: The comparable circuit of this state is demonstrated in figure (3-39). Since the converter is examined in boost mode, the Vhi side is assumed to be the output, so output capacitor and load resistance are placed at the output. At t0 the auxiliary switch Sa1 turns on under the ZCS condition. Main inductor current reaches the output through body diode S2. Also, resonant current is established in the path of

Lr and Cr. Therefore, the main inductor current cuts down linearly. At the end of the state, the same current is established in the main inductor and the resonant circuit.

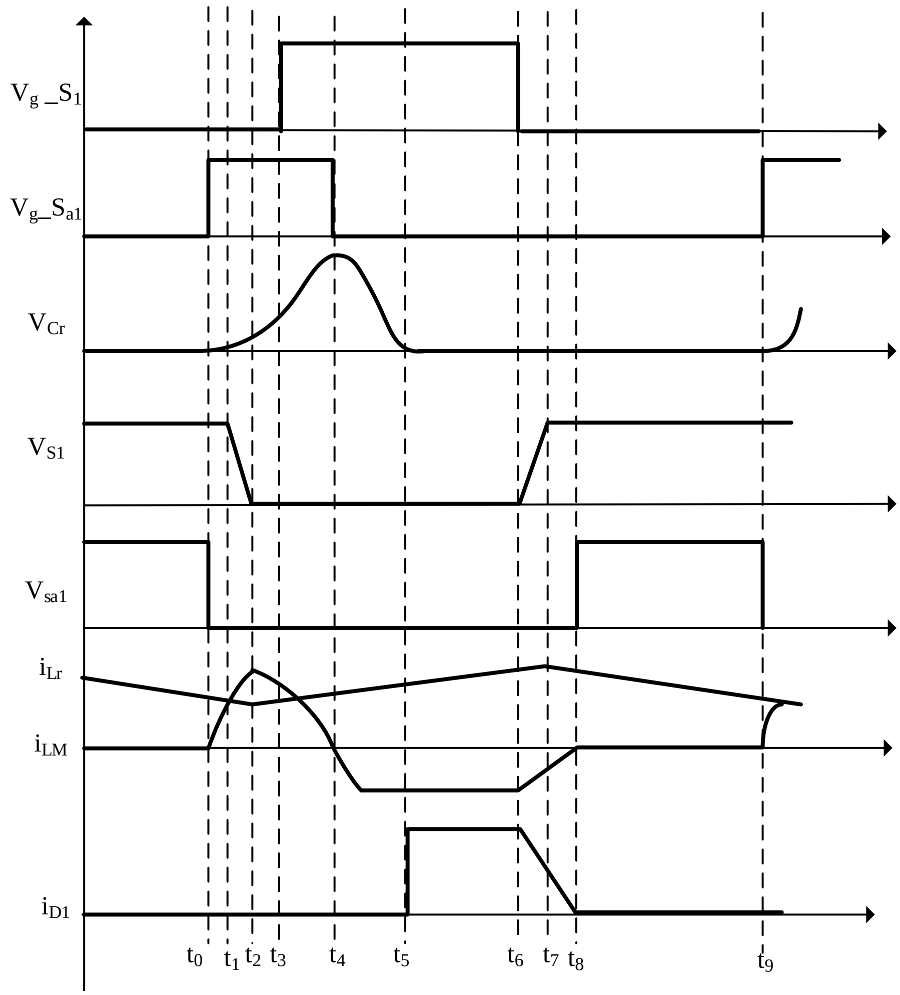


Figure (3-38): Switching wave forms of the suggested converter in boost mode

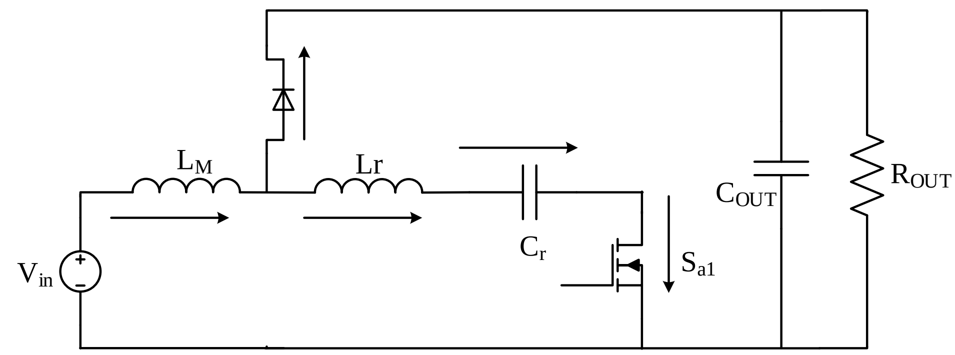


Figure (3-39): State 1 the performance of suggested converter in boost mode

State 2 [t1-t2] :During this period, a resonance occurs between the resonance capacitors Cr1 and Cr2 and the resonance buck, which discharges Cr1 and charges Cr2 at the same time. This state continues until the capacitors are fully discharged and charged. The comparable circuit of this state is demonstrated in figure (3-40).

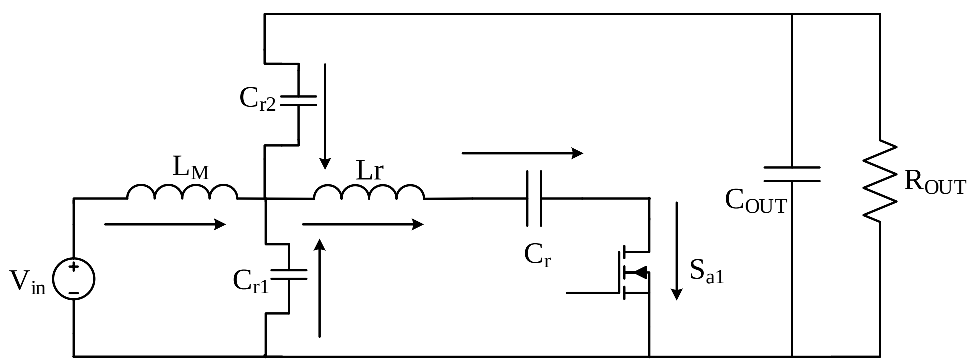


Figure (3-40): Comparable circuit of state 2 of suggested converter in boost mode

State 3 [t2-t3] : In t2, charging and discharging of the capacitors will be completed,which at this time this state begins. When the voltage becomes zero on the S1 switch capacitor, the body diode turns on and the resonance on the resonance buck continues through this diode. From this time, switch S1 will be turned on as ZVS. Throughout this state, output current is provided through output capacitor. The comparable circuit of this state is demonstrated in figure (3-41).

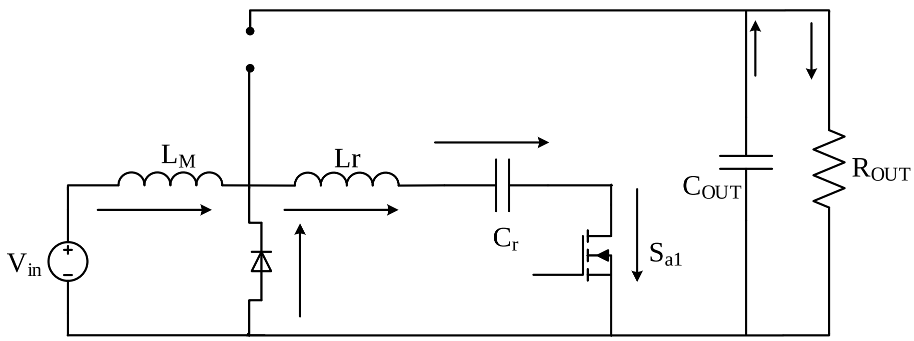


Figure (3-41): Comparable circuit of state 3 of suggested converter in boost mode

State 4 [t3-t4]: This state starts while main inductor current becomes more than the current of resonant circuit. Also, in this state, main switch S1 turns on under the ZVS condition. At time t4, the current of resonance inductor becomes zero and resonance capacitor voltage reaches its maximum. Under these conditions, the auxiliary switch is turned off as ZCS. The comparable circuit of this state is demonstrated in figure (3-42).

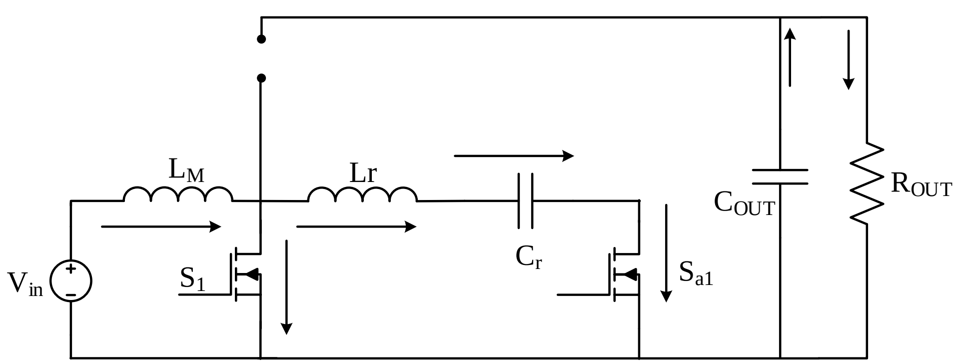


Figure (3-42): Comparable circuit of state 4 of the suggested converter in boost mode

State 5 [t4-t5]: At t4, the resonance between the resonant buck circuit is reversed. Therefore, the current is transferred from the auxiliary switch to its body diode. In the end of this state, the resonance ends and the current of the resonant circuit becomes zero. The comparable circuit of this state is demonstrated in figure (3-43).

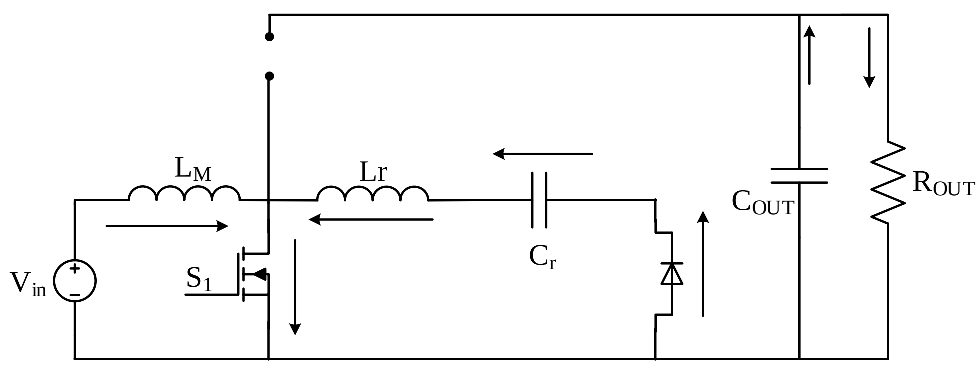


Figure (3-43): comparable circuit of state 5 of the suggested converter in boost mode

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State 6 [t5-t6] With the completion of circuit resonance.The capacitor buck is completely discharged. Since the inductor current does not become zero suddenly, it chooses another path. Therefore, the current path is established through diode D1. During this state, current of main inductor increases, but current of resonant inductor is constant. The comparable circuit of this state is demonstrated in figure (3-44).

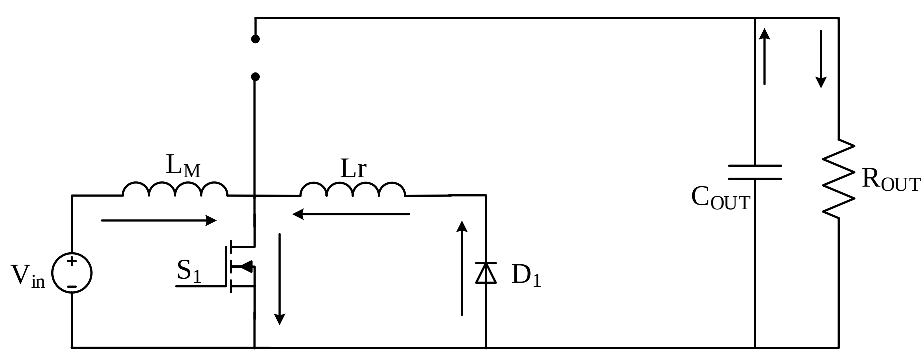


Figure (3-44): comparable circuit of state 6 of the suggested converter in boost mode

State 7 [t6-t7]: The comparable circuit of this state is demonstrated in figure (3-45). In this state, all switches are off. The above state is the second state of auxiliary resonance. Therefore, current direction changes. Unlike state 2, capacitor Cr1 is charged and capacitor Cr2 is discharged. At the end of this state, voltage of main switch is equal to the output voltage.

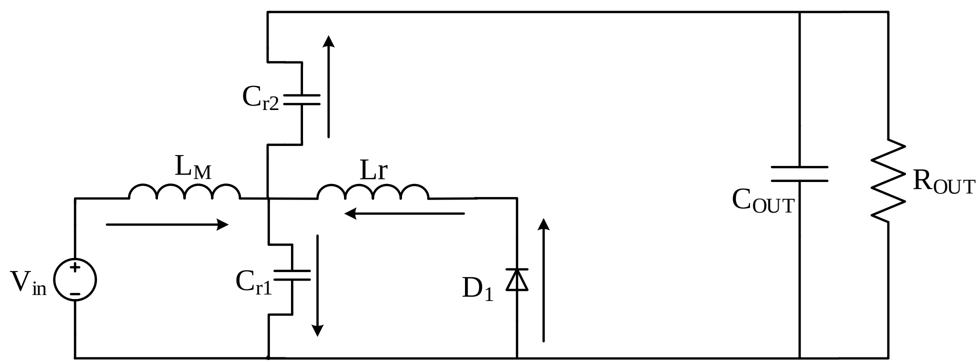


Figure (3-45): comparable circuit of state 7 of the suggested converter in boost mode

State 8 [t7-t8]: With the full discharge of the Cr2 capacitor, the switch body diode turns on and continues to conduct resonant inductor current. This state ends when the inductor resonance current reaches zero. The comparable circuit of this state is demonstrated in figure (3-46).

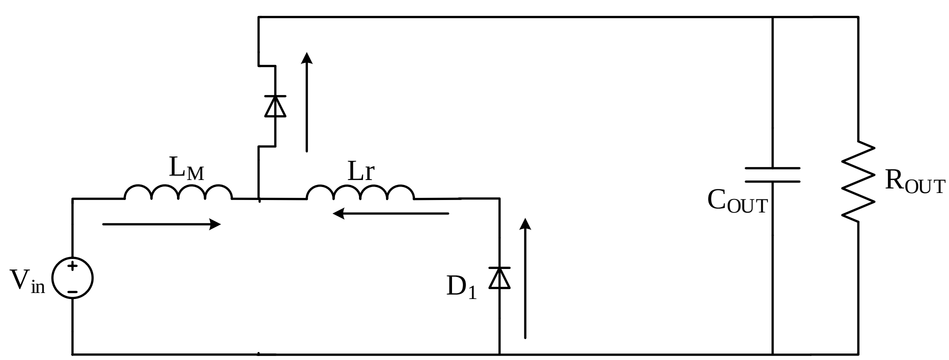


Figure (3-46): comparable circuit of state 8 of the suggested converter in boost mode

State 9 [[t8-t9]: At t8, the inductor resonance has no energy. Also, evere switche is off. consequently, current of main inductor is transferred to output by the body diode S2. In

the end of this state, auxiliary switch is turned on and states of the converter are repeated. The comparable circuit of this state is demonstrated in figure (3-47).

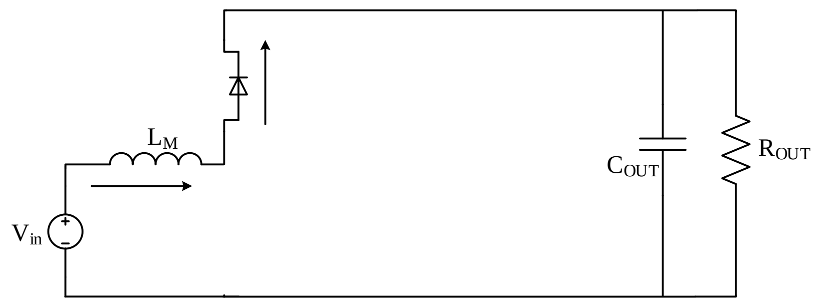


Figure (3-47): Comparable circuit of state 9 of suggested converter in boost mode

In buck mode, the converter has 9 performance modes. The performance of the circuit is similar to the boost mode, only in this mode, main switch is S2 and auxiliary switch is Sa2. Freewheeling diode in this mode is D2.

Chapter four

Bidirectional high step-up _step-down converter with switching at suggested zero voltage

4-1- Introduction

As mentioned in the previous chapters, reducing voltage stress on the switches of step-up converters is very important because it reduces the price and conduction losses of the converter. According to the investigations carried out in the third chapter, most of the auxiliary circuits presented to create soft switching conditions either had a high number of elements or have a complex control circuit. Lossless snubbers do not have high conduction losses due to not using an auxiliary switch and do not complicate the control circuit of converter.

In this chapter, a high step-up converter with a new lossless snubber is presented. The lossless snubber in the proposed converter does not have a coupled inductor and does not have the problems caused by its leakage inductor. In contrast, owing to the high voltage gain, voltage stress on switch has been reduced.

4-2- The suggested bidirectional converter

As demonstrated in Figure 1-4, the suggested converter is a bidirectional very high step-up –step-down converter. To increase the gain, the coupled inductors L1 and L2 have been used.

Also, capacitors C1 and C2 help to increase the gain in addition to absorbing the energy of leakage inductor. Switching at zero voltage is established for all switches in both step-up and step-down modes.

4-2-1- The description of suggested bidirectional converter

According to Figure 1-4, the proposed converter consists of four switches, in each mode only two of the switches conduct, and the body diode of the other two switches operates. Also, inductors L1 and L2 are coupled inductors of the circuit and capacitors C1 and C2 and c0 are all big. Capacitors C1 and C2 have been used to increase the voltage and absorb energy of leakage inductor, and capacitor C0 has been used to reduce the output voltage ripple. Coupling inductors are modeled with magnetizing inductor Lm and leakage inductor Lk.

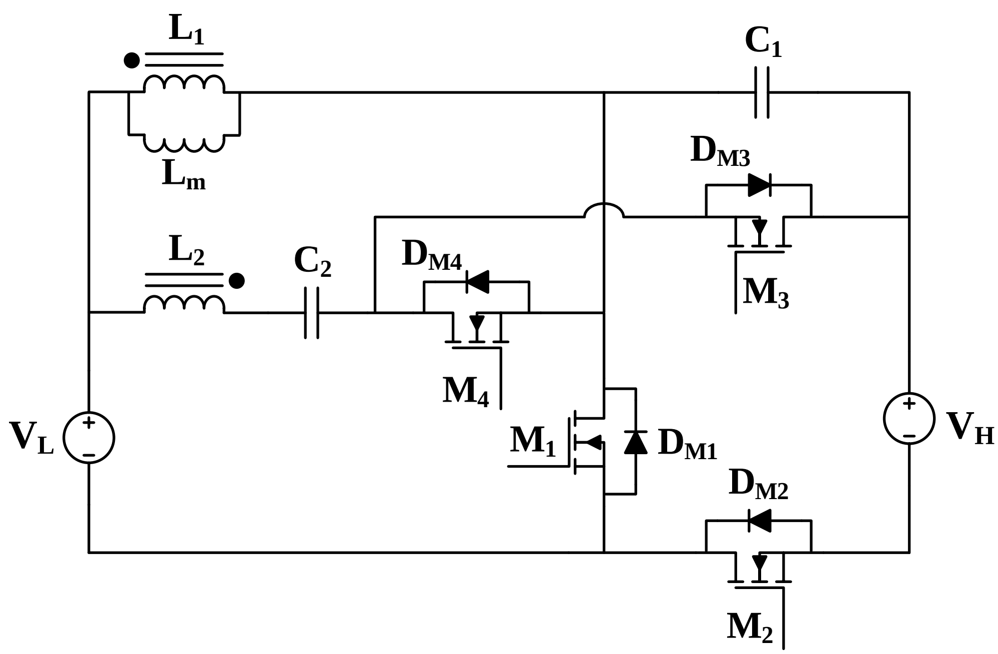


Figure 1- Schematic of suggested high step-up step-down bidirectional converter

4-2-2- Performance of suggested converter

The suggested bidirectional converter has five performance modes in either step-up and step-down states.That is examined separately. In order to simplify the analysis, the following assumptions are considered:

The elements are ideal and parasitic values such as internal resistance have been omitted.

Circuit capacitors are large and its voltage is constant in one cycle.

The magnetizing inductor is large and is constant at half of its current in a cycle.

4-2-2- 1-Performance in step-up mode

In step-up mode, switches M1 and M2 receive signals, and switches M3 and M4 are off, and only their body diode conducts. In this mode, body diodes DM3 and DM4 play the role of voltage multiplier diodes. Figure 4-2 shows the key wave forms in this mode and Figures 3-4 to 7-4 show the equivalent circuits in each state.

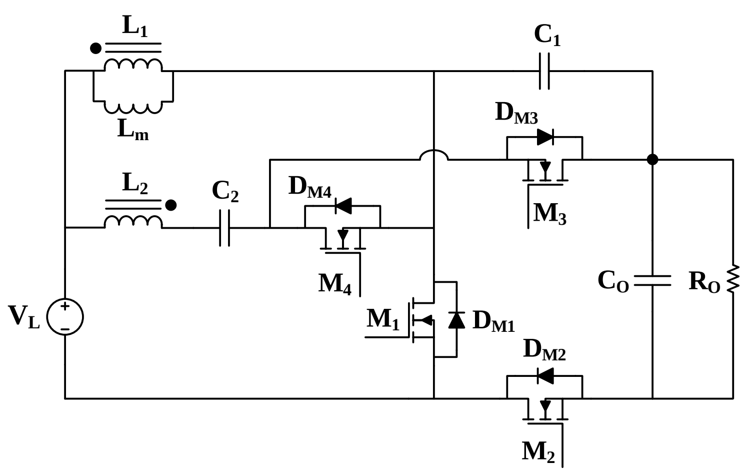


Figure 4-1- Schematic of suggested bidirectional converter in high step-up mode

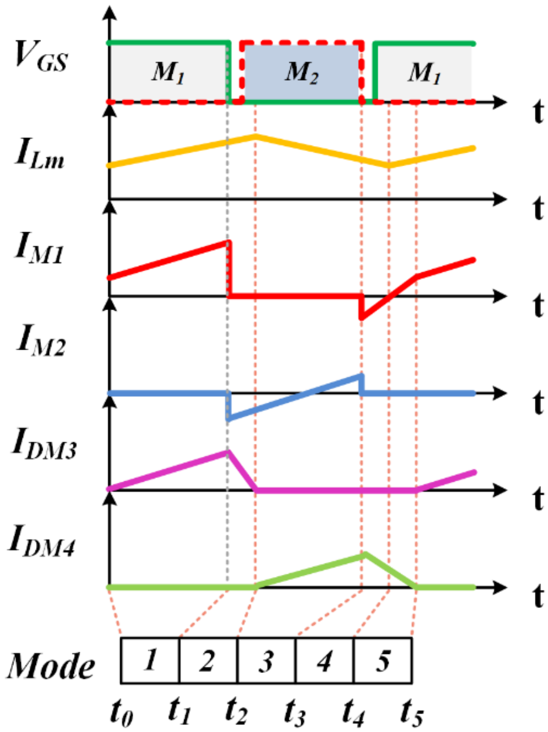


Figure 4-2- Switching wave forms of suggested bidirectional converter in step-up mode

First state:

In this state, M1 and also body diode M3(DM3) are on, and capacitor C1 is charged through DM3 and C2 is discharged. In this mode, the linear magnetizing inductor charges and output capacitor C0 supplies the load current.

$$I_{Lm}(t) = I_{Lm}(t_0) + \frac{V_{C1} - V_{C2} + V_L}{nL_m}(t - t_0) \qquad (۱-۴)$$

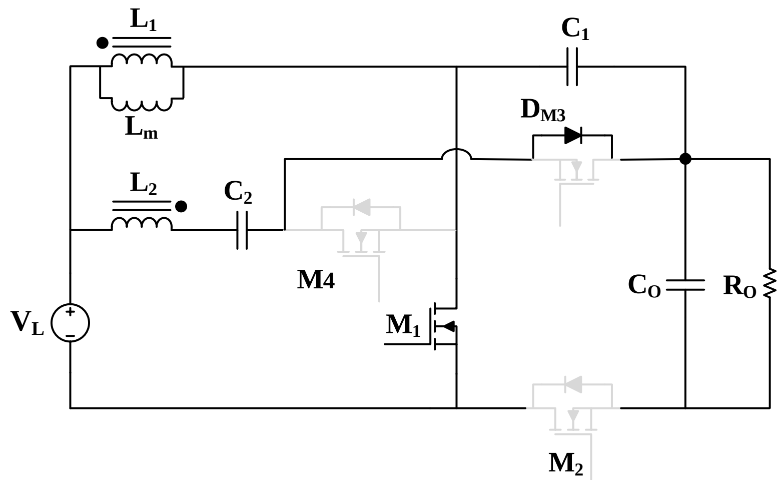


Figure 4-3- The comparable circuit of first state in step-up mode

Second state:

This state starts when M1 turns off. DM3 is still on. Since the leakage inductor LK discharges the capacitor M2, the body diode M2 is turned on and from now on M2 can turn on under ZV condition. At the end of this state, DM3 is turned off under ZC condition.

$$I_{Lm}(t) = I_{Lm}(t_1) + \frac{V_{C2}+V_{in}-V_0}{nL_m}(t - t_1) \quad (۲-۴)$$

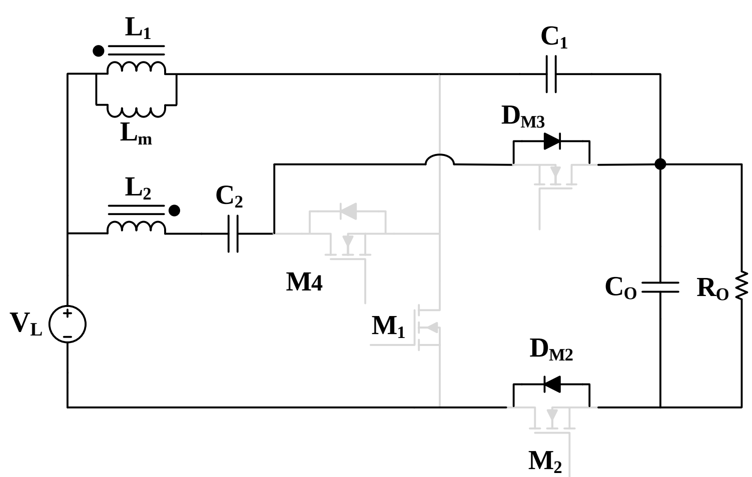


Figure 4-4- The comparable circuit of second state in step-up mode

Third state:

In this state, DM3 turns off and DM4 turns on. As a result, capacitor C2 is charged through DM4. C1 is also charged through the path of switch M2 and the output capacitor continues to provide the load current.

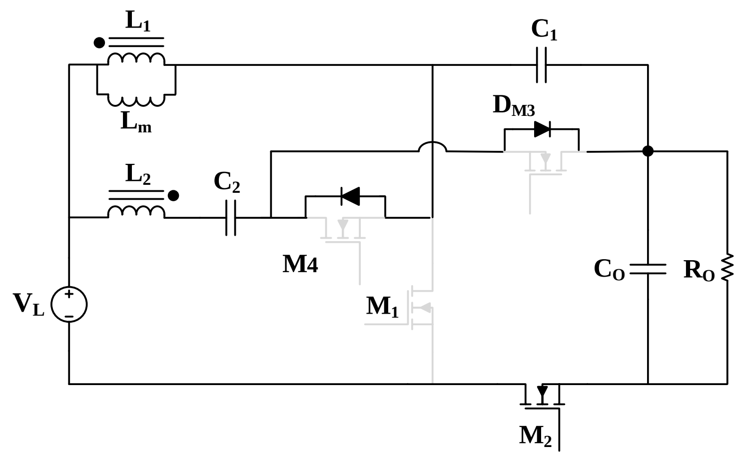


Figure 4-5- The comparable circuit of the third state in step-up mode

Fourth state:

In this state, DM1 diode will be turned on to let leakage inductor current to pass. So from now on M1 can turn on under ZV conditions.The capacitor C2 is still charging and capacitor C0 is discharging at the output.

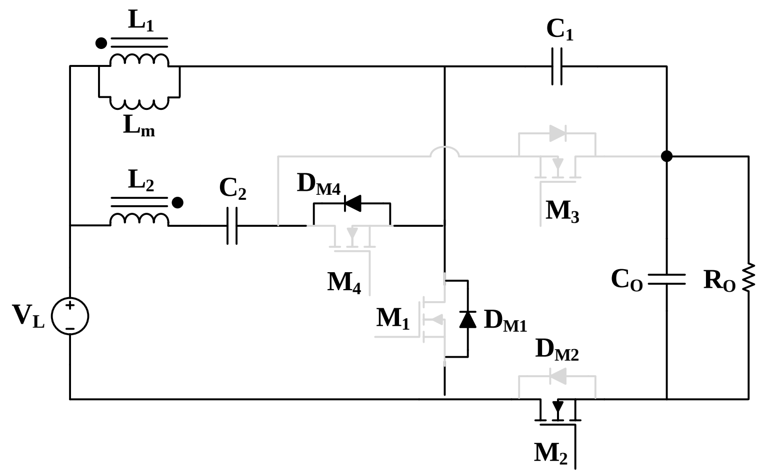


Figure 4-6- The comparable circuit of the forth state in step-up mode

Fifth state:

In this state, the direction of the leakage inductor current is changed and the current is transferred from DM1 to M1. At the end of this state, the DM4 diode is also turned off as ZC due to the leakage inductor.

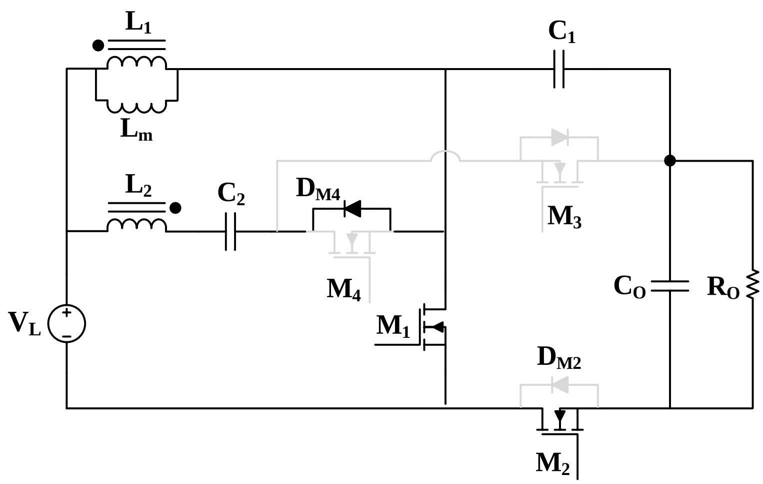


Figure 4-7- The comparable circuit of fifth state in step-up mode

4-2-2-2- Converter operation in the reducing mode

In the step-down mode, all switches receive a signal. In this mode, switch M4 provides switching conditions at zero voltage for both switches with the help of leakage inductor and capacitor C2 and also absorbs energy of the leakage inductor to prevent voltage jumps at both ends of the switch. Figure 4-9 demonstrates the switching wave forms of suggested converter in step-down mode, also Figures 4-10 to 4-14 explain the comparable circuits of converter in each state.

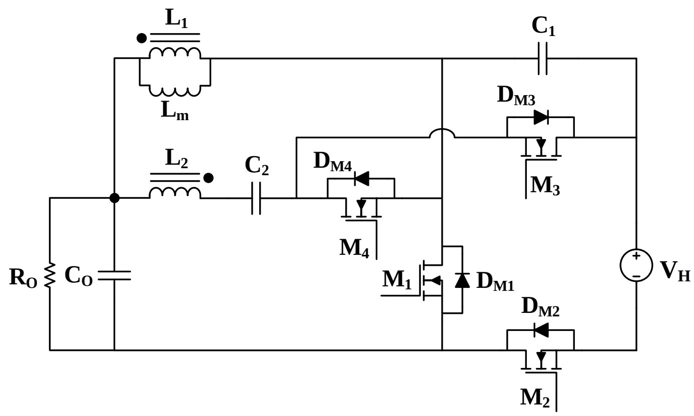


Figure 4-8- Schematic of suggested bidirectional converter in high step-down mode

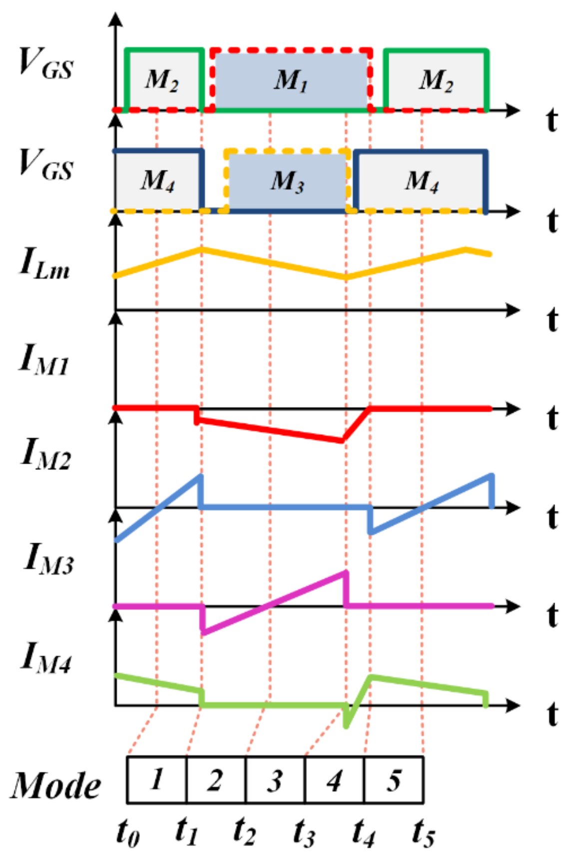


Figure 4-9- Switching wave forms of suggested converter in high step-down mode

First state:

In this state, switches M2 and M4 are on and the magnetizing inductor is charged. Also, capacitor C2 is discharged through M4. Also, the output capacitor and C2 are charged through a high voltage source. At the end of this state, switches M2 and M4 are turned off.

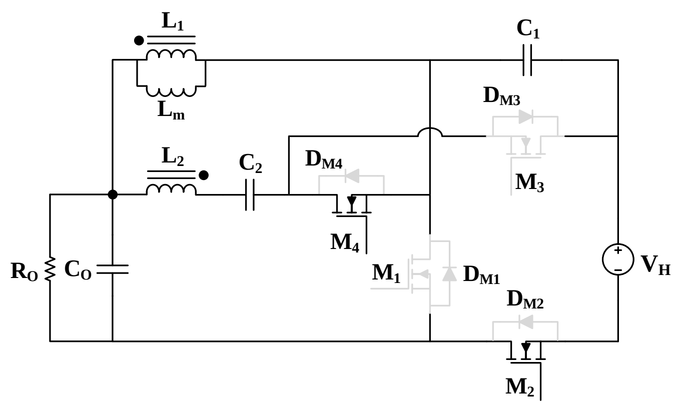


Figure 4-10- Comparable circuit of the first state in step-down mode

Second state:

When M2 and M4 are turned off, body diodes DM1 and DM3 conduct and from this moment switches M1 and M3 will be turned on under ZV conditions. At this state, the leakage inductor is discharged and the magnetizing inductor is charged. Capacitors C1 and C2 are charged and discharged respectively through DM3 furthermore the magnetizing inductor is discharged in the load.

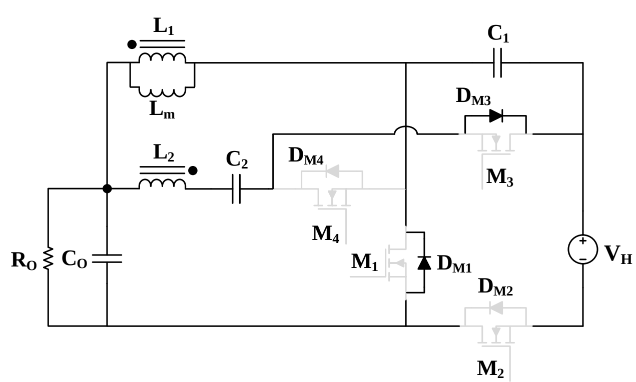


Figure 4-11 Comparable circuit of the second state in step-down mode

Third state:

In this state, because the leakage inductor current is greater than the magnetizing current, body diode M3(DM3) turns off. Also, capacitor C2 starts charging from C1 and M3 path. At the end, switch M3 is turned off

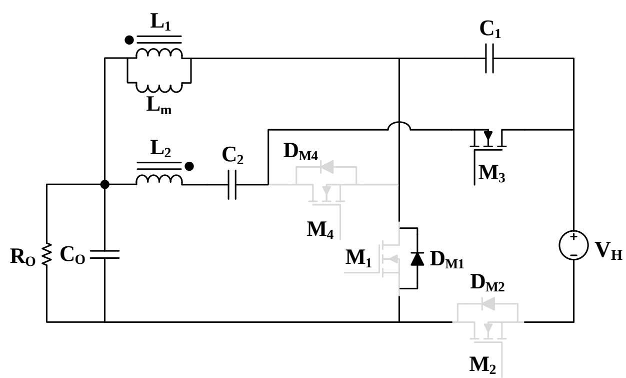


Figure 4-12- Comparable circuit of the third state in step-down mode

Fourth state :

In this state, DM1 is on and when M3 turns off, it turns on the diode DM4 from the current of L2. Therefore, from now on, M4 can turn on ZV. At this state, the capacitor C2 will be charged through the secondary current, and since the reverse voltage of the two ends of the leakage inductor LK has dropped, its current decreases rapidly. At the end of this state, DM1 turns off as ZC.

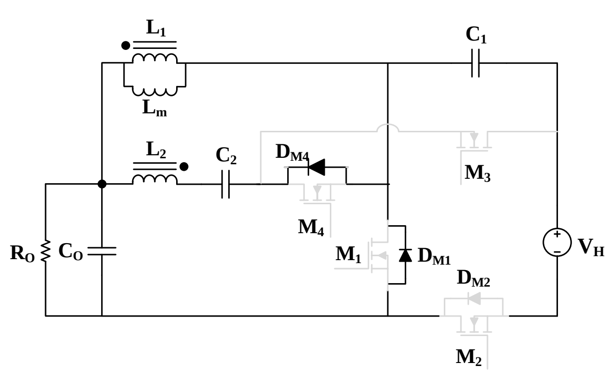


Figure 4-13- Comparable circuit of the forth state in step-down mode

Fifth state :

This state started when DM1 turns off and DM2 turns on. Therefore, from now on, switch M2 can be turned on under ZV. In this state, energy of leakage inductor is returned to input high voltage source from C1 and DM2 path. This state ends when the LK current becomes zero and the current direction change from DM2 to M2.

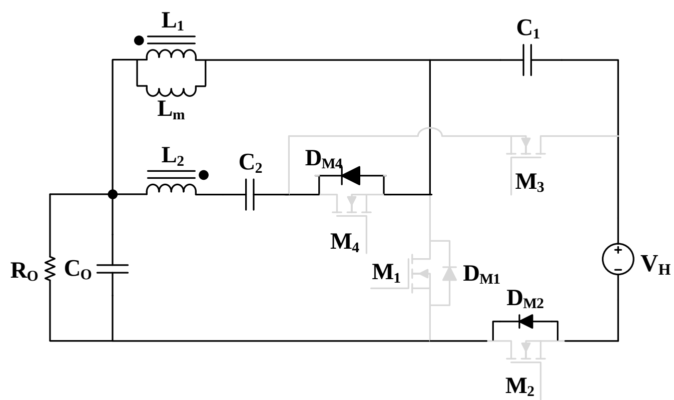


Figure 4-14- Comparable circuit of the fifth state in step-down mode

4-3- Analysis of suggested converter

For analysis of suggested bidirectional converter, it is assumed that the converter works at the CCM continuous mode. Also, the leakage inductor effect has been ignored due to its small value.

4-3-1- The converter gain in step-up mode

By writing volt-second balance function on LM as well as the KVL function in the first state, the following functions are obtained:

$$V_L DT + (1-D)T(V_L - V_H + V_{C1}) = 0 \quad (۳-۴)$$

$$V_L - (1-D)V_H + (1-D)V_{C1} = 0 \quad (۴-۴)$$

$$V_{C1} = V_{C2} + V_{L1} + V_{L2} = V_{C2} + (n+1)V_L \quad (۵-۴)$$

$$V_{C2} = \frac{(n+1)D}{1-D} V_L \qquad (۶-۴)$$

$$V_{L1} = \frac{nDV_L}{1-D} \qquad (۷-۴)$$

$$V_{L2} = \frac{DV_L}{1-D} \qquad (۸-۴)$$

$$V_{C1} = \frac{(n+1)D}{1-D} V_L + (n+1)V_L \qquad (۹-۴)$$

$$V_H = \frac{V_L}{1-D} + V_{C1} = \frac{V_L}{1-D} + \frac{n+1}{1-D} V_L \qquad (۱۰-۴)$$

$$\frac{V_H}{V_L} = \frac{n+2}{1-D} \qquad (۱۱-۴)$$

As it can be seen from the function 11-4, the gain of the converter is much larger than a conventional boost converter. Figure 4-15 shows the gain diagram according to the duty factor and different values of the turn ratio.

4-3-2- Stress of switches

The stress on the switches is easily calculated by writing the KVL in their loop when the switch is off.

$$\mathrm{V_{M1}} = \mathrm{V_{M2}} = \mathrm{V_{C1}} - \mathrm{V_H} = \frac{(\mathrm{n}+2)\mathrm{v_L}}{1-\mathrm{D}} - \frac{(\mathrm{n}+1)\mathrm{v_L}}{1-\mathrm{D}} = \frac{\mathrm{V_L}}{1-\mathrm{D}} \qquad (۱۲-۴)$$

$$V_{M1} = V_{M2} = \frac{V_H}{n+2} \qquad (۱۳-۴)$$

$$V_{M3} = V_{M4} = V_{C1} = \frac{(n+1)V_L}{1-D} = \frac{(n+1)V_H}{(n+2)} \qquad (۱۴-۴)$$

Figure 16-4 shows the normalized stress of the switches, which is actually considered in the step-up mode for M3 and M4 of the stress of their body diodes

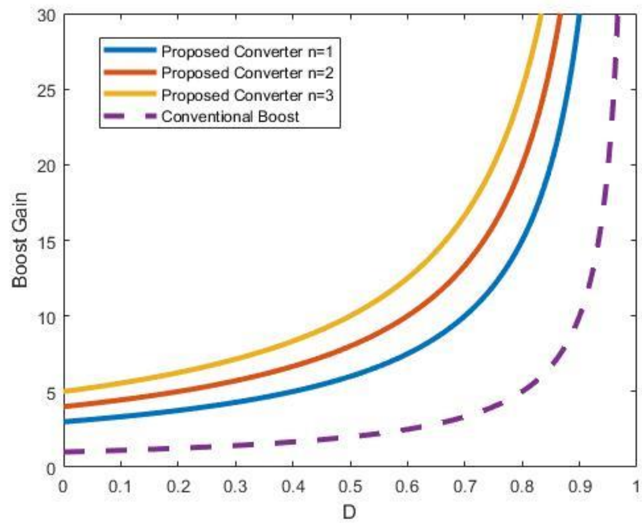


Figure 4-15- The gain diagram according to duty factor and different values of the turn ratio of suggested converter

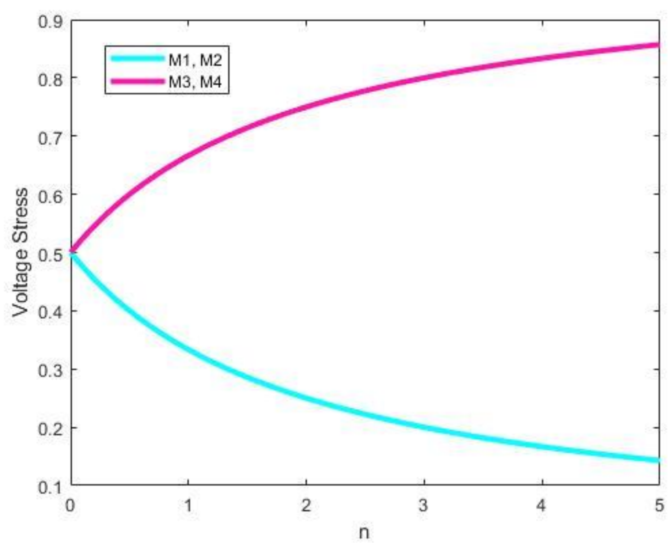


Figure 4-16- Normalized stress diagram of suggested converter switches according to ratio of turns

4-3-3- The converter gain in step-down mode

By writing volt-second balance on LM and also writing KVL when D1 is on, the gain function can be obtained in this state. In second state

In second state

$$V_{C1} - V_{C2} = V_{L1} + V_{L2} = V_L + nV_L = (n+1)V_L \quad (۱۵-۴)$$

The volt-second balance function for LM

$$(1-D)TV_L - DT(V_H - V_L - V_{C1}) = 0 \quad (۱۶-۴)$$

$$(1-D)TV_L - DT(n+1)V_{C2} = 0 \quad (۱۷-۴)$$

$$V_{C2} = \frac{(1-D)(n+1)}{D}V_L \quad (۱۸-۴)$$

$$V_{C1} = (n+1)V_L + V_{C2} \quad (۱۹-۴)$$

$$V_{C1} = \frac{n+1}{D}V_L \quad (۲۰-۴)$$

$$V_H - V_L - V_{C1} = {V_{C2}}/{n+1} \quad (۲۱-۴)$$

$$V_H - V_L - \frac{n+1}{D}V_L = \frac{(1-D)}{D}V_L \quad (۲۲-۴)$$

$$V_H = \frac{D+n+1+1-D}{D}V_L \quad (۲۳-۴)$$

$$\frac{V_L}{V_H} = \frac{D}{n+2} \quad (۲۴-۴)$$

Diagram 17-4 shows the gain curve of converter compared to the conventional buck converter.

4-3-4- Soft switching condition

So as to bring the switching conditions to zero voltage, the internal capacitors of the switches must be completely discharged. Therefore, the energy of the leakage inductor must be greater than the energy of these capacitors. Figure 18-4 shows the permissible area of soft switching in theproposed converter.

$$\frac{1}{2} L_K I^2 \geq \frac{1}{2} (C_{M1} + C_{M2}) {V_M}^2 \tag{۲۵-۴}$$

$$L_K \geq (C_{M1} + C_{M2}) \left(\frac{V_L}{(n+2)I}\right)^2 \tag{۲۶-۴}$$

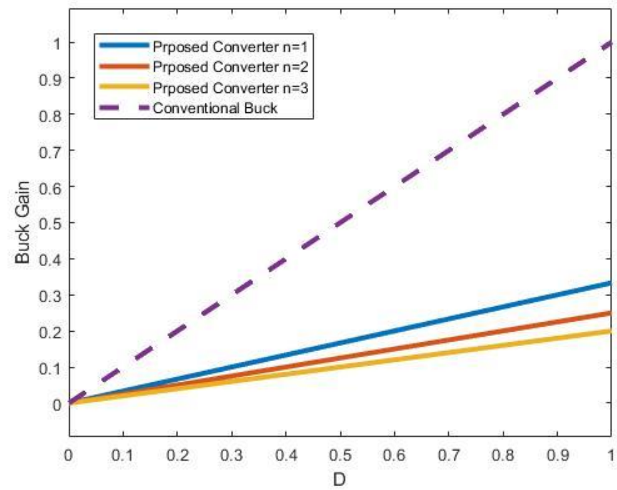


Figure 4-17- Gain diagram of suggested converter compared to conventional buck converter (dashed line)

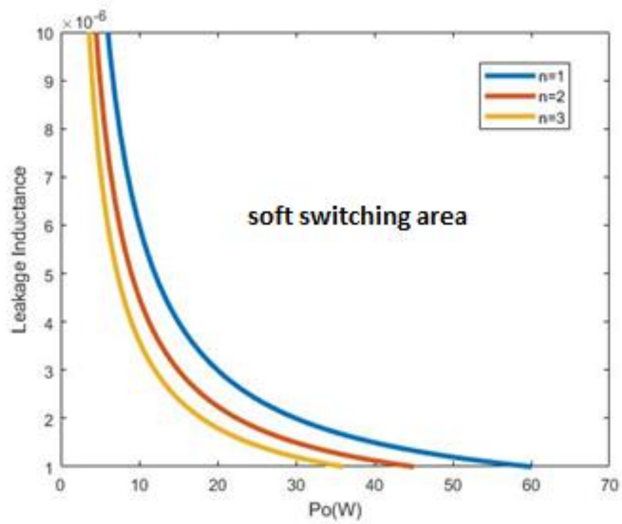


Figure 4-18- Soft switching area according to value of leakage inductor and power of suggested converter

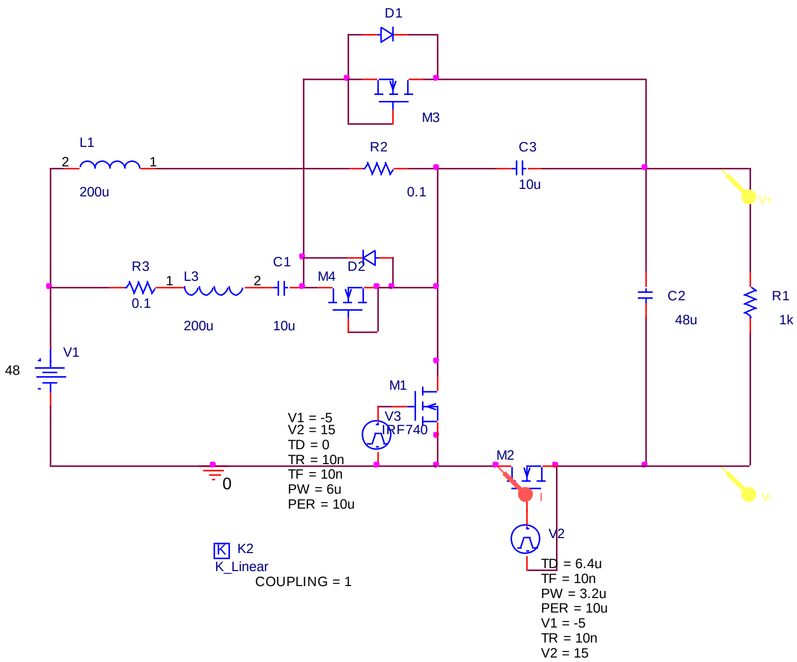
4-4-Simulation of suggested high step-up converter

To prove the correctness of the analyzes of suggested converter, it has been simulated for output voltage of 350 volts, input voltage of 48 volts and power of 120 watts in PSPICE software. Table 4-1 shows the specifications of the designed elements. The schematic of suggested simulated high step-up converter is demonstrated in two high step-up and step-down modes in Figure 19-4 and the simulation results in either high step-up and step-down modes are demonstrated in Figures 4-20 to 4-27.

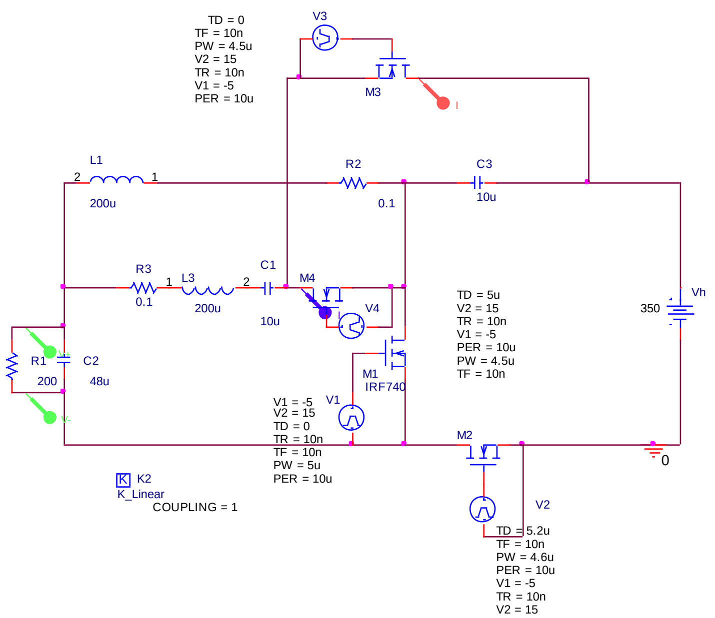
Figures 4-20 and 4-21 demonstrates the current and simulation voltage wave forms of M1 and M2 switches in high step-up mode. As it is clear in these forms. The current at the moment the switches are turned on is negative, and as a result, the body diode is on and the switching conditions are provided for them at zero voltage. On the other hand, as shown in Figures 4-22 and 4-23, body diodes M3 and M4 due to the gradual increase in their current when turning on and gradually decreasing when turning off, due to the leakage inductor, they are switched at zero current and therefore do not have the problem of reverse recovery.

Table (4-1) specifications of suggested converter and values of its elements

Specifications Elements/	value /name of part
Vin	48V
VO	350V
Power switch	IRF740
L1,L2	200μH
Turns ratio=N	1
Lk	4μH
C2-C1	10μF
Co	48μF
PO	120W
fS	100kHz



A



B

Figure (4-19) The schematic of simulated converter of suggested bidirectional converter in PSPICE software A – step-up mode B- step-down mode

Figure (4-20) wave form of current (red) and voltage (green) of switch M1 of simulated converter in step-up mode in scale (0.5µs/div, 2A/div, 20V/div)

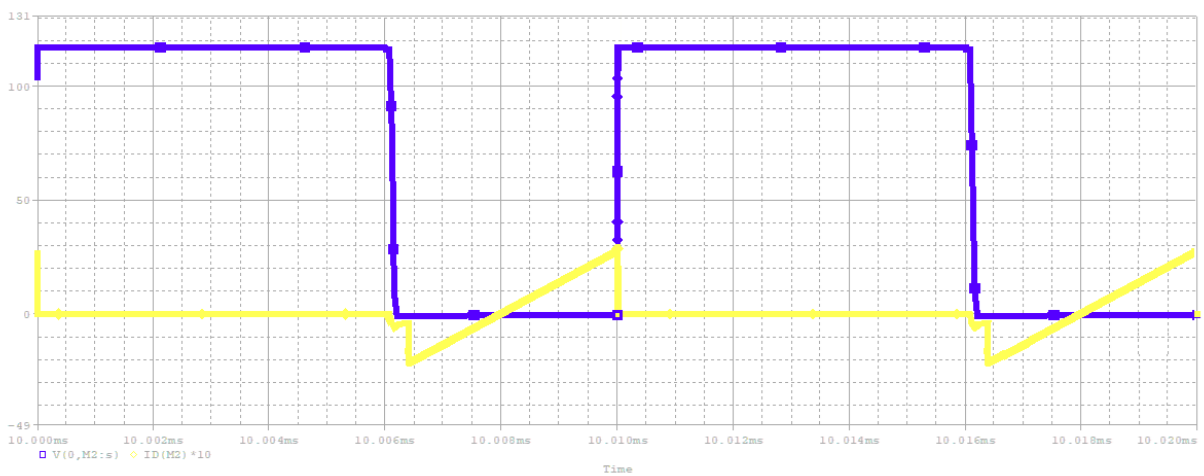


Figure (4-21) wave form of current (red) and voltage (blue) of switch M2 of simulated converter in step-up mode in scale(0.5µs/div, 1A/div, 10V/div)

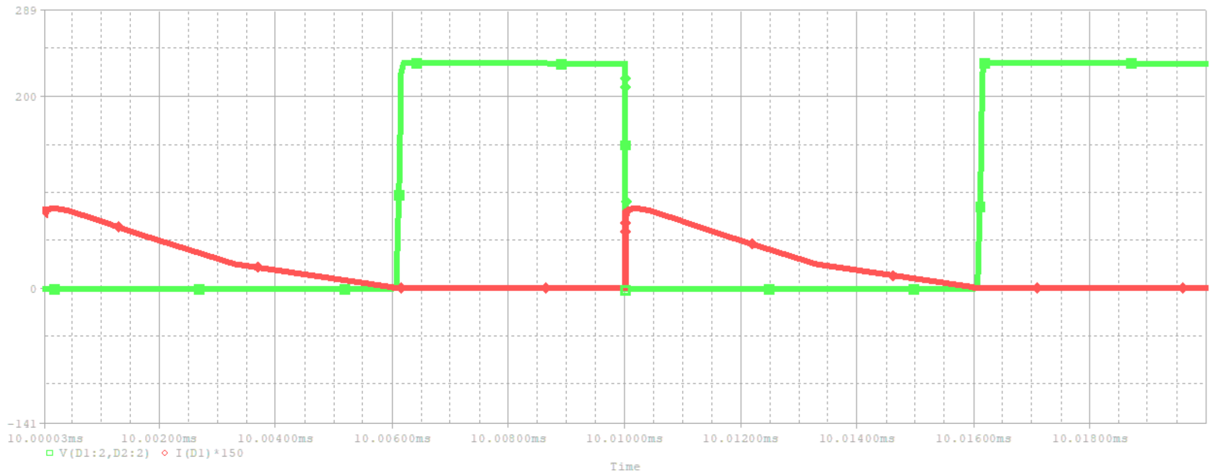


Figure (4-22) wave form of current (red) and voltage (green) of DM3 of simulated converter in step-up mode in scale(0.5μs/div, 0.33A/div, 50V/div)

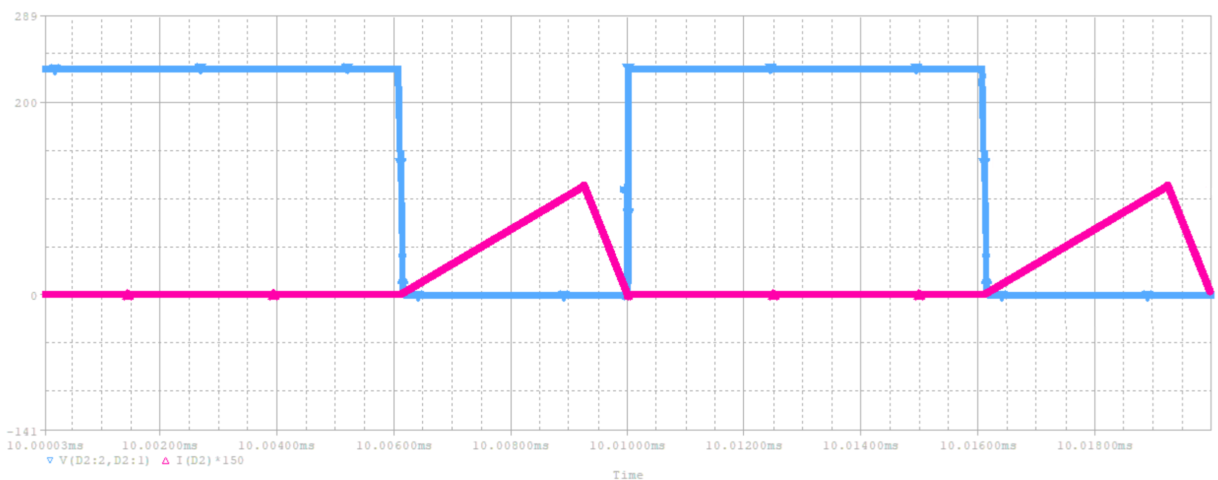


Figure (4-23) wave form of current (pink) and voltage (blue) of DM4 of simulated converter in step-up mode in scale (0.5μs/div, 0.33A/div, 50V/div)

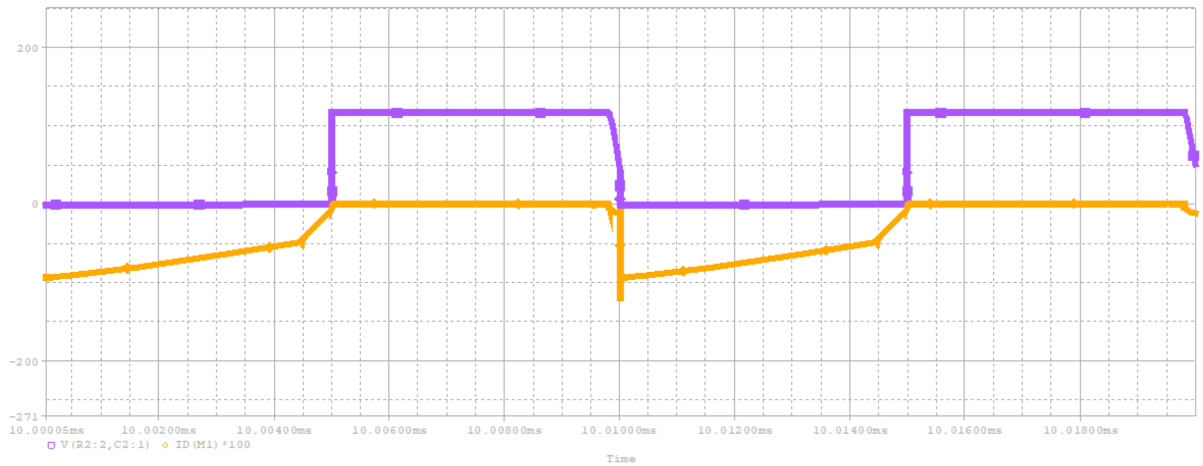


Figure (4-24) wave form of current (orange) and voltage (purple) of switch M1 of simulated converter in step-down mode in scale (0.5µs/div, 0.5A/div, 50V/div)

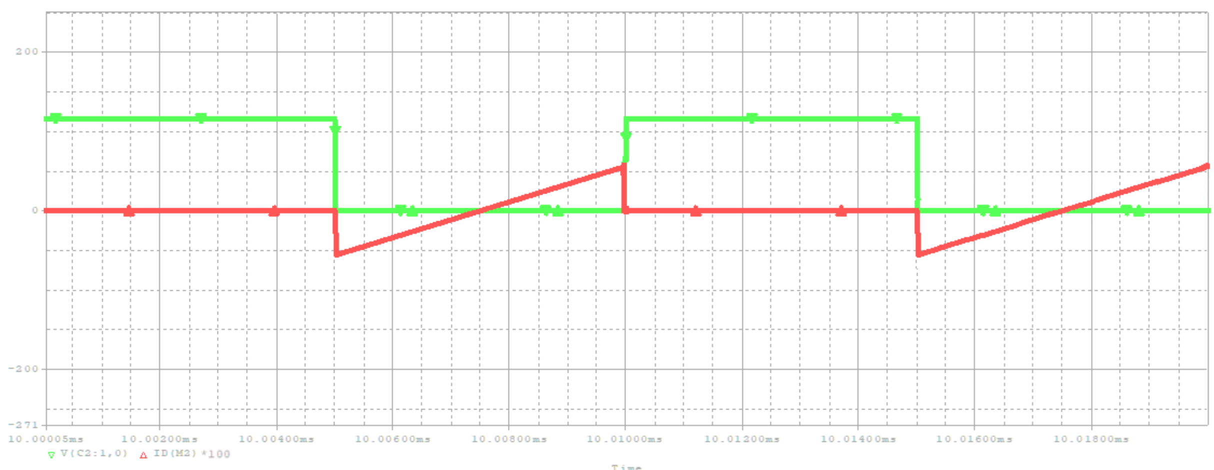


Figure (4-25) wave form of current (red) and voltage (green) of switch M2 of simulated converter in step-down mode in scale(0.5µs/div, 0.5A/div, 50V/div)

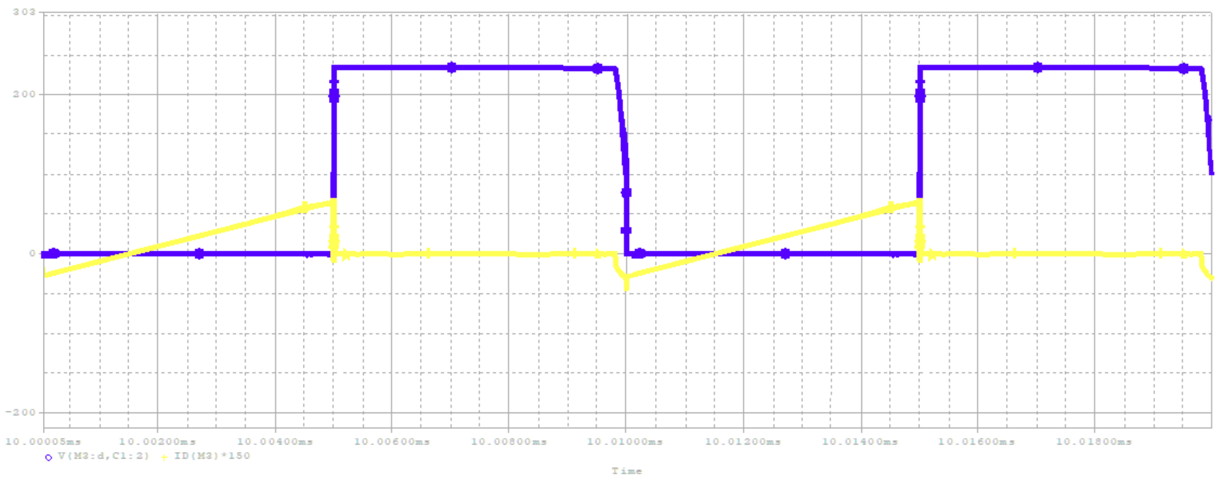


Figure (4-26) wave form of current (red) and voltage (green) of switch M3 of simulated converter in step-down mode in scale(0.5μs/div, 0.33 A/div, 50V/div)

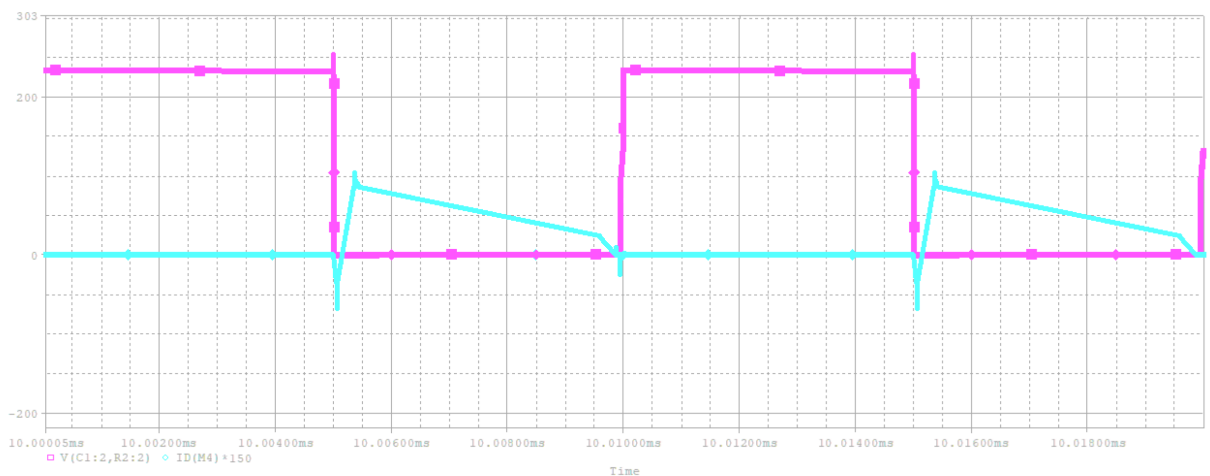


Figure (4-27) wave form of current (red) and voltage (green) of switch M4 of simulated converter in step-down mode in scale (0.5μs/div, 0.33A/div, 50V/div)

4-5-The comparison of the efficiency of suggested bidirectional converter in either high step-up and step-down modes

In Figure 4-28, efficiency of suggested converter is shown in either step-up and step-down modes. As it can be seen, the best efficiency has been achieved at full load, due to the circulating current in auxiliary circuit by reducing power efficiency of converter has decreased in two modes, in contrast, at light load, owing to loss of soft switching conditions the drop in efficiency is more noticeable.

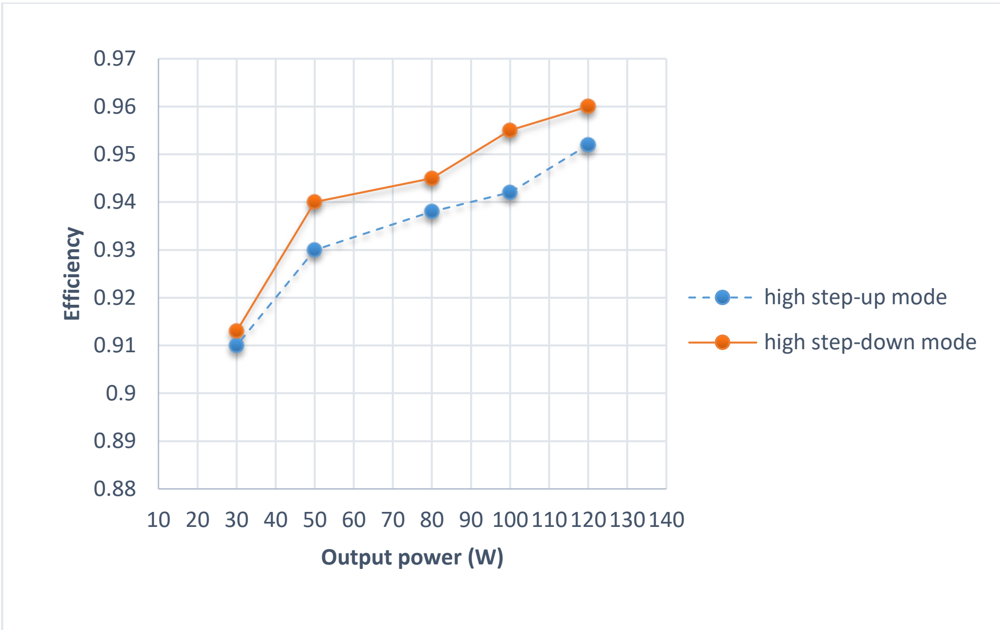


Figure (4-28) efficiency diagram of the suggested bidirectional converter in both high step-up and step-down modes

4-6- Comparison of suggested bidirectional converter with previous similar converters

In Table 4-2, the suggested bidirectional converter is compared with the previous bidirectional converters in terms of voltage gain, number of elements and also soft switching type. As it is clear from the table, converters [41] and [43] have gains similar to regular buck and boost. And as a result, the voltage stress on their switches is also high. On the other hand, the number of their elements is also more than the proposed converter. The converter [44] has a suitable gain, but the number of its elements is high and it has high conduction losses. Converter [42] has the lowest number of elements in the comparison table. The floating switch also has only one auxiliary switch, which is why there is no need for an isolated gate driver for the two main switches. But the mentioned converter has a lower gain compared to the proposed converter and the auxiliary switch is also switched as ZC and has capacitor switching losses.

Table 4-2 Suggested bidirectional converter with previous bidirectional converters

Soft switching type	Step-down mode gain	Step-up mode gain	Number of elements	
ZV	D	1/(1-D)	۹	]۴۱[
ZV-ZC	D/(nD+1)	(nD+1)/(1-D)	۶	]۴۲[
ZV	D	1/(1-D)	۱۱	]۴۳[
ZV	D/n	n/(1-D)	۱۱	]۴۴[
ZV	D/(n+2)	(n+2)/(1-D)	۷	proposed converter

Chapter 5

Conclusion and Recommendations

5-1- Conclusion

As previously stated, bidirectional converters are widely used in the industry due to the ability to transfer energy in both directions. These converters have the ability to reverse and control the current and thus transfer power in both directions, while the polarity of the voltage on both sides is unchanged. Therefore, bidirectional converters have been used in power systems that have the ability to store energy, such as charging and discharging systems for batteries and capacitors. These systems usually have a battery or supercapacitor for energy storage. In these systems, bidirectional converters are used to control the direction of power and charge and discharge of batteries or supercapacitors. Energy storage elements are designed according to the required voltage, which often have a high volume and cost, but by controlling the voltage in terms of step-up or step-down converter, it is possible to change the voltage on both sides of the converter, which reduces the volume and cost of the energy storage systems. Basic unidirectional DC-DC converters, both isolated and non-isolated, can be changed to a bidirectional converter with a simple change, and the conclusion method of these converters was fully reviewed in the second chapter.

In bidirectional DC-DC converters, like unidirectional DC-DC converters, in order to reduce the volume and cost of manufacturing converter, switching frequency must be increased, but since with the increase of the switching frequency in a converter with hard switching, the switching losses and electromagnetic interference or EMI increases, as with unidirectional DC-DC converters, many soft-switching techniques have been introduced for these converters. Therefore, in the third chapter, several examples of these bidirectional converters with soft switching have been examined and the weaknesses and strengths of each have been fully explained.

Finally, in the fourth chapter, a new non-isolated bidirectional converter was introduced. Due to its high gain, this converter does not require a huge or very small duty factor, so current stress of the elements is not high, on the other hand, the elements voltage stress is also low, and also you can use cheaper switches with a smaller drain source on resistance. On the other hand, all switches are switched in the ZV form and switching losses are negligible.

Therefore, the advantages of the presented converter can be categorized as follows.

• Creating ZVS conditions for turning on switches and consequently reducing switching losses

• Switching off the body diodes in the form of ZCS and as a result solving the problem of reverse recovery

• The minimum possible number of auxiliary elements in the suggested bidirectional converter and therefore reducing the conductive losses of converter

• PWM control of suggested converter and therefore simple implementation of the control circuit

• Auxiliary circuit energy transfer to input in step-up mode and to output in step-down mode

• Absence of capacitive switching losses in switches due to switching at zero voltage

• Reducing voltage stress on switches

• No need for very small or very large duty factor

• Absorption of leakage inductor energy in circuit capacitors

Also, the converter has disadvantages compared to converters of the same type, which are as follows:

• The aabsence of ground sharing between input and output circuit

• The floating of three switch sources

• Loss of soft switching at light loads

5-2- Recommendations

In order to continue the above research process, the following items are recommended.

• Using solutions to share input and output ground

• Converter modeling for optimal control circuit design.

• It is suggested to provide solutions to lessen circulating current of auxiliary circuit.

• It is suggested to provide solutions to reduce the number of converter switches.

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