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# COMPARATIVE STUDY OF SOFT SWITCHING METHODS USED IN DC-DC CONVERTERS

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## ABSTRACT

*High frequency switched-mode DC-DC converters are widely used in industry such as battery charging, renewable energy, fuel-cell, power factor correction, LED lighting applications, due to their low response time, easy controlling and high power density. However, at high switching frequency, switching losses, electromagnetic interference (EMI) and lower efficiency become substantial problem. These problems must be eliminated or reduced by using additional passive and active snubber cells in order to operate the converter with soft switching (SS) instead of hard switching (HS). In this paper, properties of soft switching methods named as zero voltage transition (ZVT), zero current transition (ZCT), and zero voltage zero current transition (ZVZCT) developed by combining the ZVT and ZCT, zero voltage switching (ZVS) and zero current switching (ZCS) are studied and discussed, simulations of soft switching DC to DC boost converters including these methods are accomplished for 500W and 1kW power at switching frequency of 100 kHz.*

## ÖZ

*Yüksek frekanslı anahtarlamalı DC-DC dönüştürücüler, kontrol kolaylığı, süratli tepki verme ve yüksek güç yoğunluğu avantajları nedeniyle endüstride; batarya şarj istasyonları, yenilenebilir enerji sistemleri, yakıt pili, güç faktörü düzeltme, LED aydınlatma, gibi uygulamalarda yaygın olarak kullanılmaktadır. Ancak, anahtarlamalı DC-DC dönüştürücülerde anahtarlama frekansı arttıkça güç yoğunluğunun daha da artmasına rağmen anahtarlama kayıpları, elektromanyetik girişim (Electromagnetic Interference-EMI) gürültüleri ve düşük verim sorunları ortaya çıkmaktadır. Bu sorunların üstesinden; dönüştürücünün sert anahtarlama (Hard Switching-HS) ile çalıştırılması yerine, dönüştürücüye pasif ve aktif bastırma hücreleri ilave edilerek dönüştürücünün yumuşak anahtarlama (Soft Switching-SS) ile çalıştırılmasıyla gelinebilmektedir. Bu çalışmada, literatürde yumuşak anahtarlama teknikleri olarak yer alan; sıfır akımda geçiş (Zero Current Transition-ZCT) ve sıfır gerilimde geçiş (Zero Voltage Transition-ZVT) tekniklerinin birleştirilmesiyle geliştirilen sıfır gerilim ve akımda geçiş (Zero Voltage Zero Current Transition-ZVZCT) tekniği ile sıfır akımda anahtarlama (Zero Current Switching-ZCS) ve sıfır gerilimde anahtarlama (Zero Voltage Switching-ZVS) tekniklerini içeren aktif bastırma hücreli DC-DC dönüştürücüler incelenmiş, 500W-1kW güçlerinde ve 100 kHz anahtarlama frekansında yükseltici DC-DC dönüştürücülerin simülasyonları yapılmıştır.*

**Keywords:** *Switched-mode DC-DC Converters, Hard Switching (HS), Soft Switching (SS), Zero Current Switching (ZCS), Zero Voltage Switching (ZVS), Zero Voltage Transition (ZVT), Zero Current Transition (ZCT), Zero Voltage Zero Current Transition (ZVZCT*

**Anahtar Kelimeler:** *Anahtarlamalı DC-DC Dönüştürücüler, Sert Anahtarlama (HS), Yumuşak Anahtarlama (SS), Sıfır Akımda Anahtarlama (ZCS), Sıfır Gerilimde Anahtarlama (ZVS), Sıfır Akımda Geçiş (ZCT), Sıfır Gerilimde Geçiş (ZVT), Sıfır Gerilim ve Akımda Geçiş (ZVZCT).*

## 1. INTRODUCTION

The switched-mode DC-DC converters are widely used in the industry. They possess higher power density, faster transient response are derived and sizes of transformer, inductance and capacitor become smaller when they are operating at high frequency. However, by increasing frequency of the converter, switching losses and EMI noises increase accordingly. Therefore, to eliminate or reduce switching losses, EMI noises, current and voltage stresses, the converter need to be operated with soft switching instead of hard switching In literature, numerous soft-switching techniques have been proposed [1-8].

The switching losses in converter occur during semiconductors are turning off and on. When the semiconductors are turning on, its voltage decreases and it current increases at the same time. On the contrary, during the semiconductors are turning off, its voltage increases and its current decreases at the same time. In process of turning on, losses due to discharge of parasitic capacitor and reverse recovery of the main diode are added to switching losses [1]. Zero current switching (ZCS), zero voltage switching (ZVS), zero voltage transition (ZVT), zero current transition (ZCT) methods are commonly used for soft switching techniques.

As seen in Figure 1; ZCS limits the rising speed of the current flow through the switch in turning on process while ZVS limits the rise speed of the voltage across switch. In turning off process, ZCT makes switch’s current down to zero for a short time in turning off process and ZVT makes switch’s voltage down to zero for a short time in turning on process.

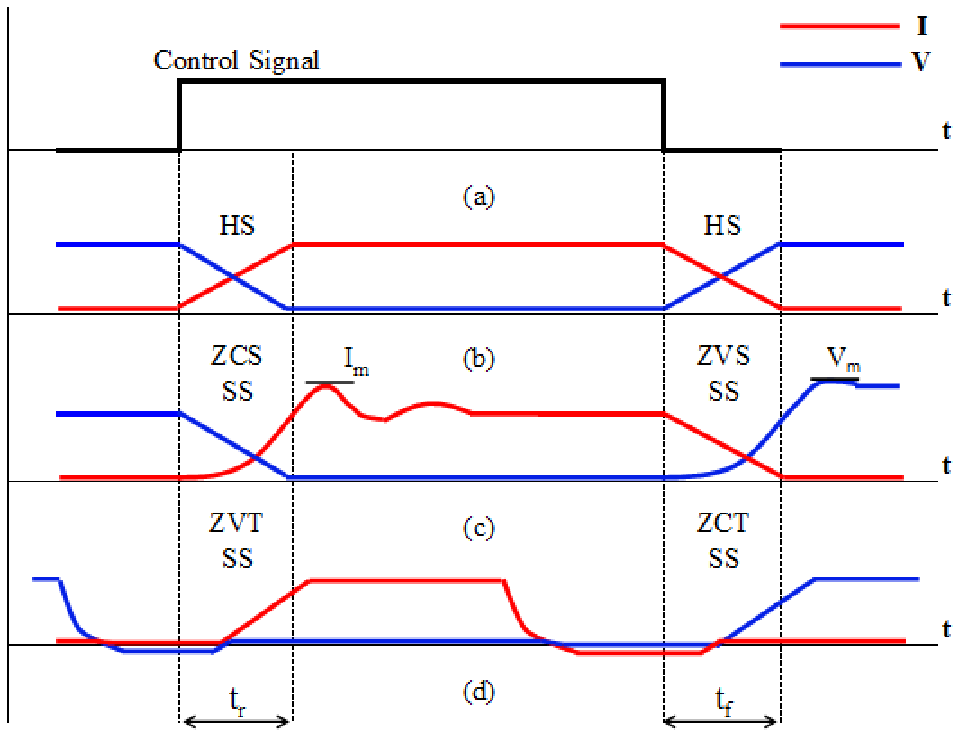


Figure 1. (a) Switching signal, (b) HS, (c) ZCS and ZVS, (d) ZCT and ZVT waveforms

The auxiliary circuits realizing soft switching techniques are called snubber cells. The snubber cells are divided into active or passive snubber cells according to whether or not additional one or more an auxiliary switches are used.

## 2. ACTIVE SNUBBER CELLS

The active snubber cell is used to perform ZVT and ZCT, and has been studied in the literature for about thirty years. This snubber cell contains one or more an auxiliary switches to operate the main switch with soft switching. In last years, it has been improved and proposed ZVZCT technique which obtained by combining ZCT and ZVT techniques. In this paper, ZVT, ZCT, two different ZVZCT active snubber cells are studied, and moreover boost DC-DC converter including two different ZVZCT active snubber cells analyzed and simulated respectively.

### 2.1. BASIC ZCT CONVERTER

In ZCT technique, it is aimed to make the main switch turn off when a current flows over it is zero, due to make transition without losses. In the basic ZCT converter shown in Figure 2, the snubber cell is consist of an auxiliary switch, resonant inductance and capacitor and an auxiliary diode. The general features of the converter are as follows [2].

- Low voltage/current stress on the main switch and diode.
- Minimum circulating energy.
- Operating at wide load range.
- Fixed switching frequency.

One of the disadvantages of this converter is, the main switch is turned on and the main diode is turned off simultaneously with HS, so a short circuit occurs at the same time. It is very difficult to realize the avoidance of this short circuit causing losses and EMI problems [3]. Besides, energy in the parasitic capacitor can not be recovered and the main diode turns off with HS, so that reverse recovery loss of this diode is large. The current stress of main switch increases cost of the converter [4].

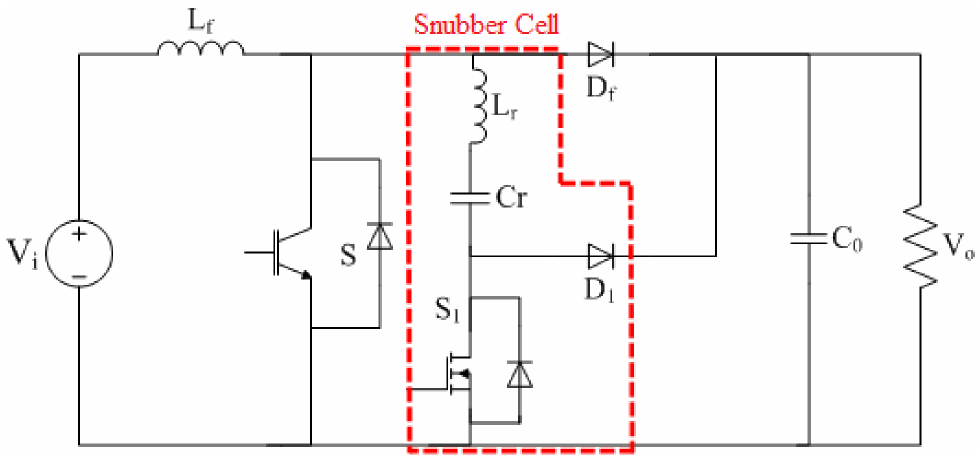


Figure 2. The basic ZCT converter circuit [2]

As shown in Figure 3, the main switch current is subjected to zero by the snubber cell in Figure 2 just before the main switch is in turn off position. and after that, switching signal of the main switch is removed. Thus, the main switch turns off without switching losses. In converter, the main diode turns on with ZVS whereas an auxiliary switch turns on with ZCS. Both of them turn off with HS [4].

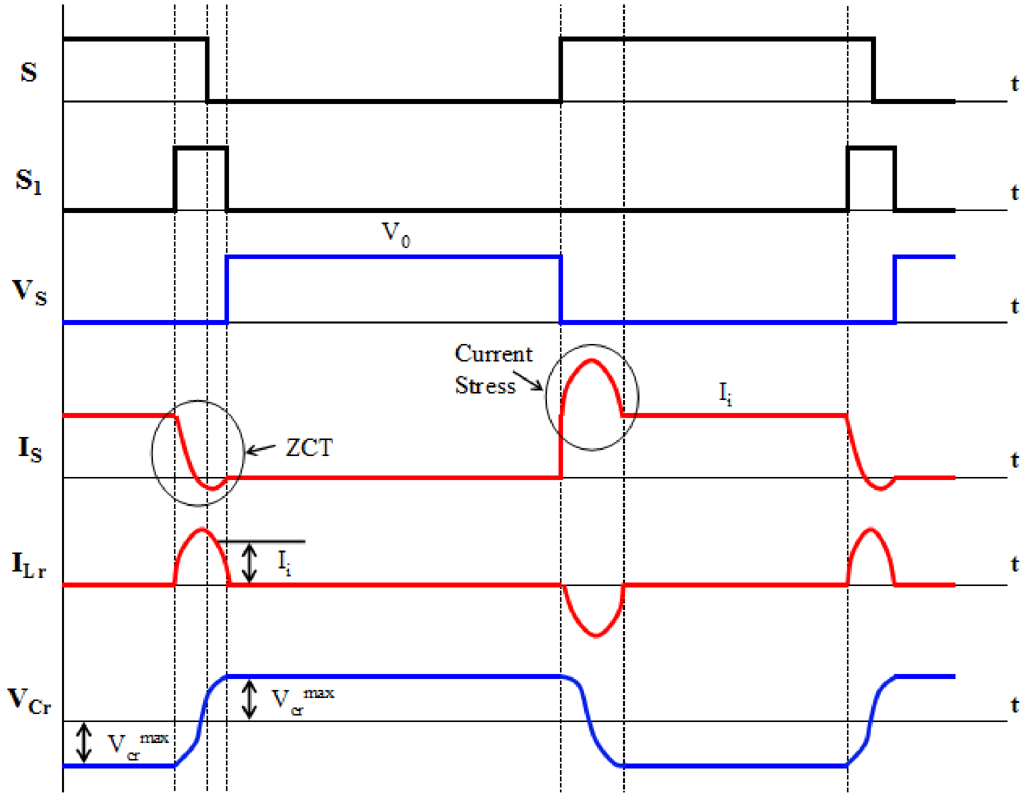


Figure 3. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main switch voltage ($V_S$), the main switch current ($I_S$) and $L_r$ inductance current ($I_{Lr}$), the voltage of $C_r$ ($V_{Cr}$) [2].

### 2.2. THE BASIC ZVT CONVERTER

In ZVT technique, it is intended to make the main switch turn on from turn off state as voltage of switch is zero. As seen in Figure 4, the basic ZVT converter has a snubber cell including resonant capacitor and inductance, an auxiliary switch and two an auxiliary diodes connected in parallel to the main switch. The general features of the converter are;

- Both the main switch and diode with soft switching,
- Lowest voltage/current stress on the main switch and diode,
- Fixed switching frequency [5].

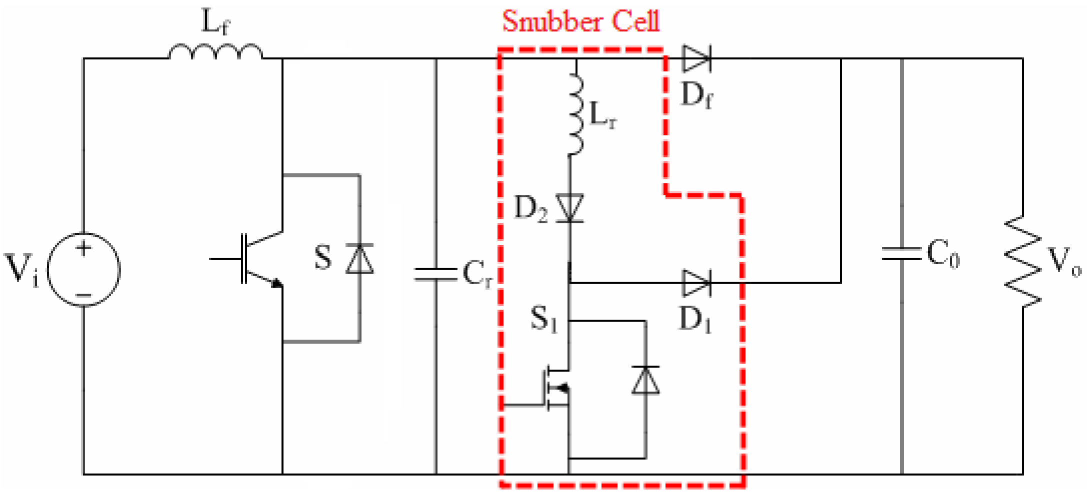


Figure 4. The basic ZVT converter circuit [5]

The waveforms in Figure 5 show that the snubber cell in Figure 4 makes the main switch turns on with ZVT, without losses and any voltage and current stress. Furthermore, the main switch turns off with ZVS by $C_r$ capacitor. The main diode turns off with ZCS and turn on with ZVS by $L_r$ inductance so that reverse recovery losses of the main diode are mostly reduced. Besides, the auxiliary switch turns on with ZCS and voltage or current stress does not occur in other components of the converter other than the acceptable current stress on the auxiliary switch [4,5].

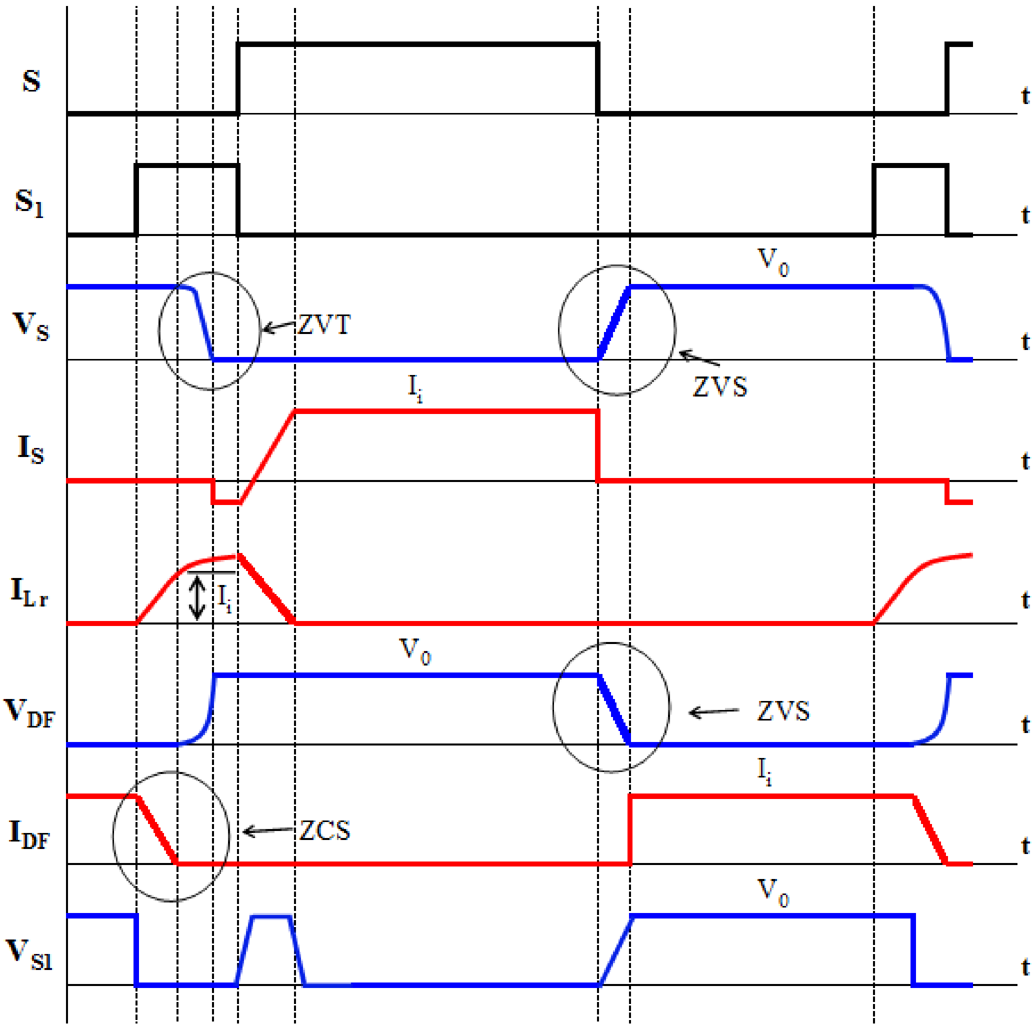


Figure 5. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main switch voltage ($V_S$), the main switch current ($I_S$) and $L_r$ inductance current ($I_{Lr}$), the main diode voltage ($V_{DF}$), the main diode current ($I_{DF}$), the auxiliary switch voltage ($V_{S1}$) [5]

The disadvantages of the converter are being dependent on load, the difficulty of the transferring of the energy stored in the inductance to the load and switching losses caused by the auxiliary switch turning off with HS [6].

### 2.3. ZVZCT DC-DC CONVERTER-I

The circuit in Figure 6 is designed in order to overcome most of the problems of the basic ZCT DC-DC converter. As seen in Figure 6, the snubber cell that is connected in parallel to the main switch consists of a snubber inductance $L_s$ , a snubber capacitor $C_s$ and an auxiliary switch which are connected in serial to each other. The capacitor $C_p$ is the sum of the parasitic capacitor of the main switch and the other parasitic capacitors. ZVT and ZCT properties are obtained from the basic ZCT converter without any changing in the circuit topology. In this converter, the main switch turns on with ZVT and turns off with ZCT and all the other semi-conductors turns on and off with soft switching [7].

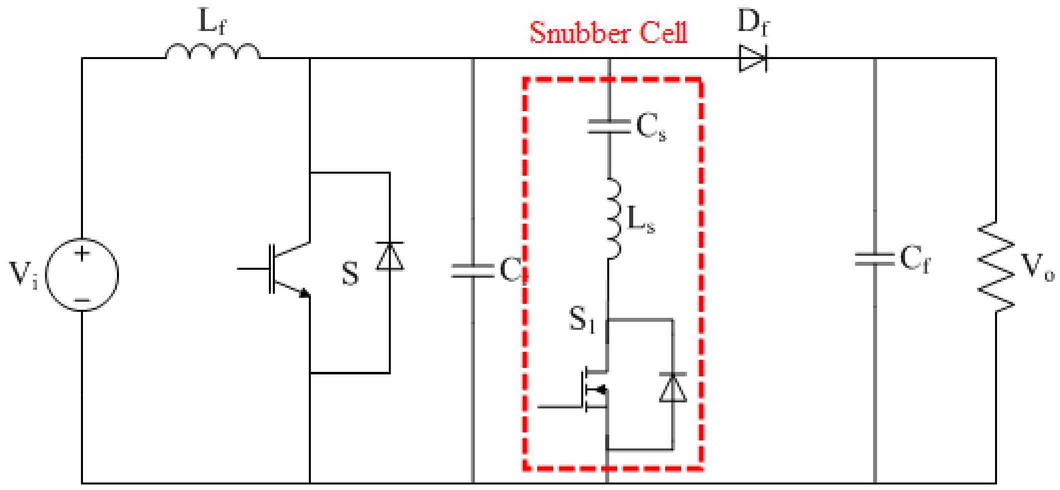


Figure 6. The ZVZCT DC-DC converter [7]

It can be seen from Figure 7 that as the auxiliary switch is in turn on position, switching signal of the main switch is applied so that the main switch turns on with ZVT. At this time, the main diode turns off with ZCS and ZVS. In this interval, there is a low voltage on the auxiliary switch. After that, the auxiliary switch turns on before the main switch turns off and then the main switch turns off with ZCT. The main diode turns on with ZVS after the main switch turns off.

Approximate output voltage occurs on the auxiliary switch until main switch turns on again [7].

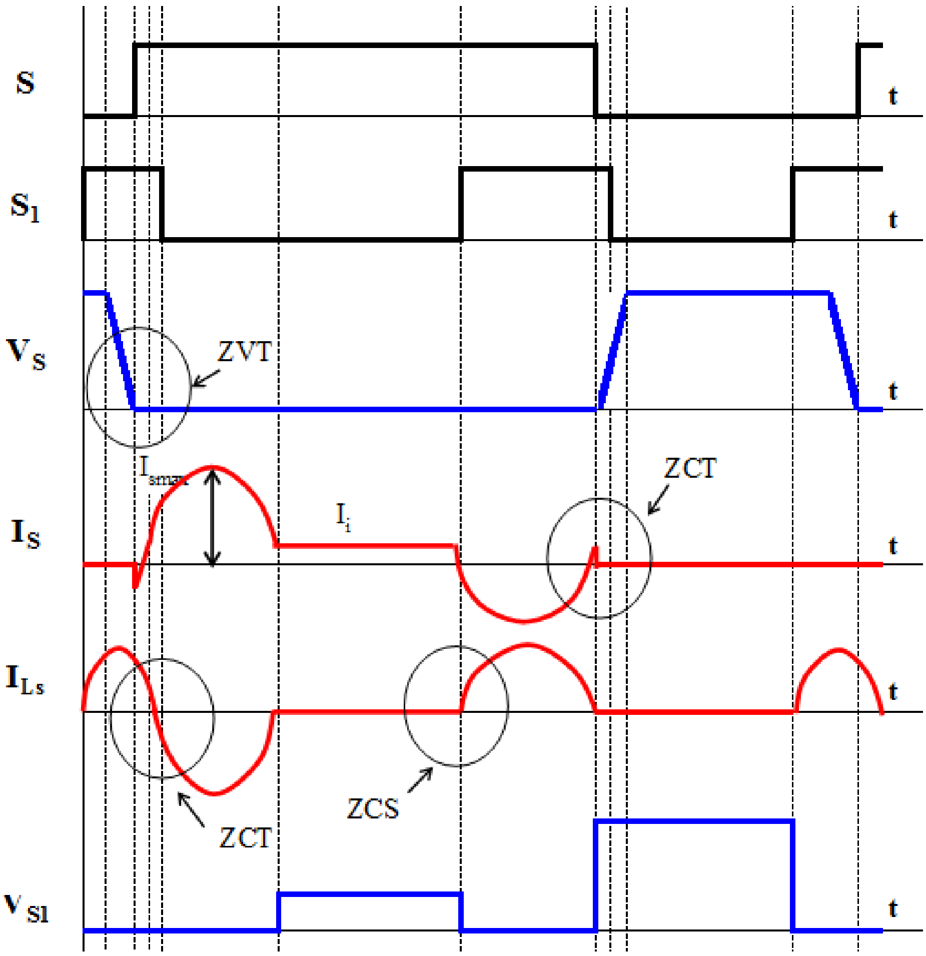


Figure 7. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main switch voltage ($V_S$), the main switch current ($I_S$) and $L_s$ inductance current ($I_{Ls}$), the auxiliary switch voltage ($V_{S1}$) [7]

For the converter shown in Figure 6, the main diode turns on with ZVS and turns off with ZCS-ZVS and is not exposed to voltage and current stress and also the other semi-conductors are not subjected to additional voltage stress. Soft switching is maintained at very wide load range. The auxiliary switch turns off with ZCT and turns on with ZCS. A small amount of circulation energy gets lost. The switching losses are not dissipated on the snubber cell, are transferred to the load [7].

### 2.4. ZVZCT DC-DC CONVERTER-II

As seen in the converter of Figure 8, the snubber cell that is connected in parallel to the main switch includes an auxiliary diode $D_2$, the resonant inductances $L_a$ and $L_b$, a resonant capacitor $C_s$, and an auxiliary switch. The capacitor $C_p$ that is connected in parallel to the main switch is the sum of the parasitic capacitor of the main switch and the other parasitic capacitors. The main switch turns on with ZVT, turns off with ZCT and the main diode turns on with ZVS and off with ZCS. Thus, reverse recovery losses of the main diode are minimized. The main switch and diode are not subjected to additional current or voltage stress. The auxiliary switch turns on and off with ZCS. The converter decreases EMI noise and operates even at a wide range of load and high frequency [8].

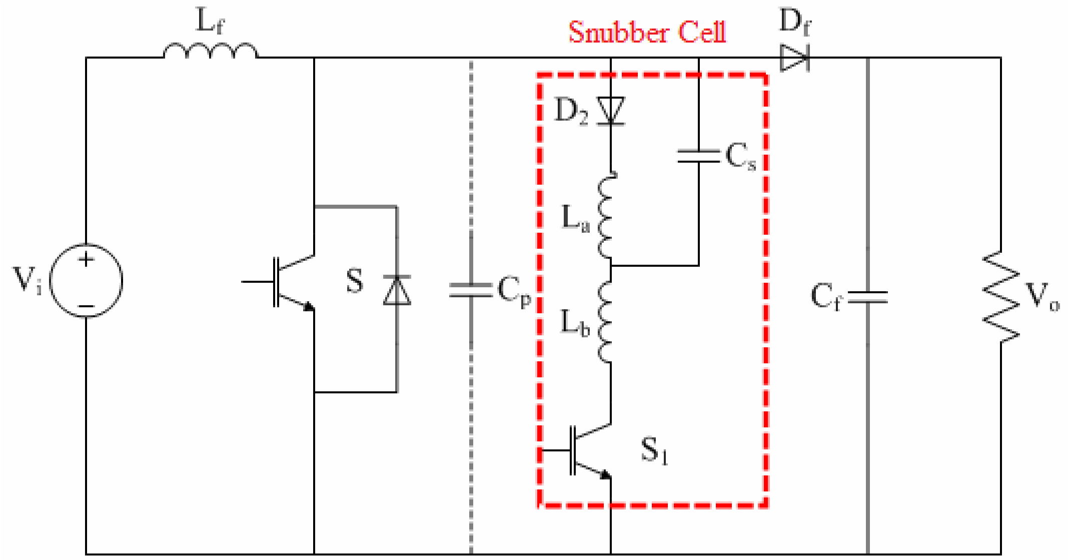


Figure 8. The ZVZCT DC-DC converter [8]

The voltage and current waveforms of the main switch, the auxiliary switch and the main diode are shown in Figure 9. In turning on interval, voltage of the main switch is reduced to zero by the snubber cell in Figure 8. The switching signal of the main switch is applied when voltage of the switch is zero and as its internal diode conducts. Thus, switching losses of the main switch as turning on are eliminated. During the turning off stage, the main switch current is reduced to zero by the snubber cell. After that the switching signal of the main switch is removed when its internal diode conducts. In this way, the main switch turns off without losses with ZCT [8].

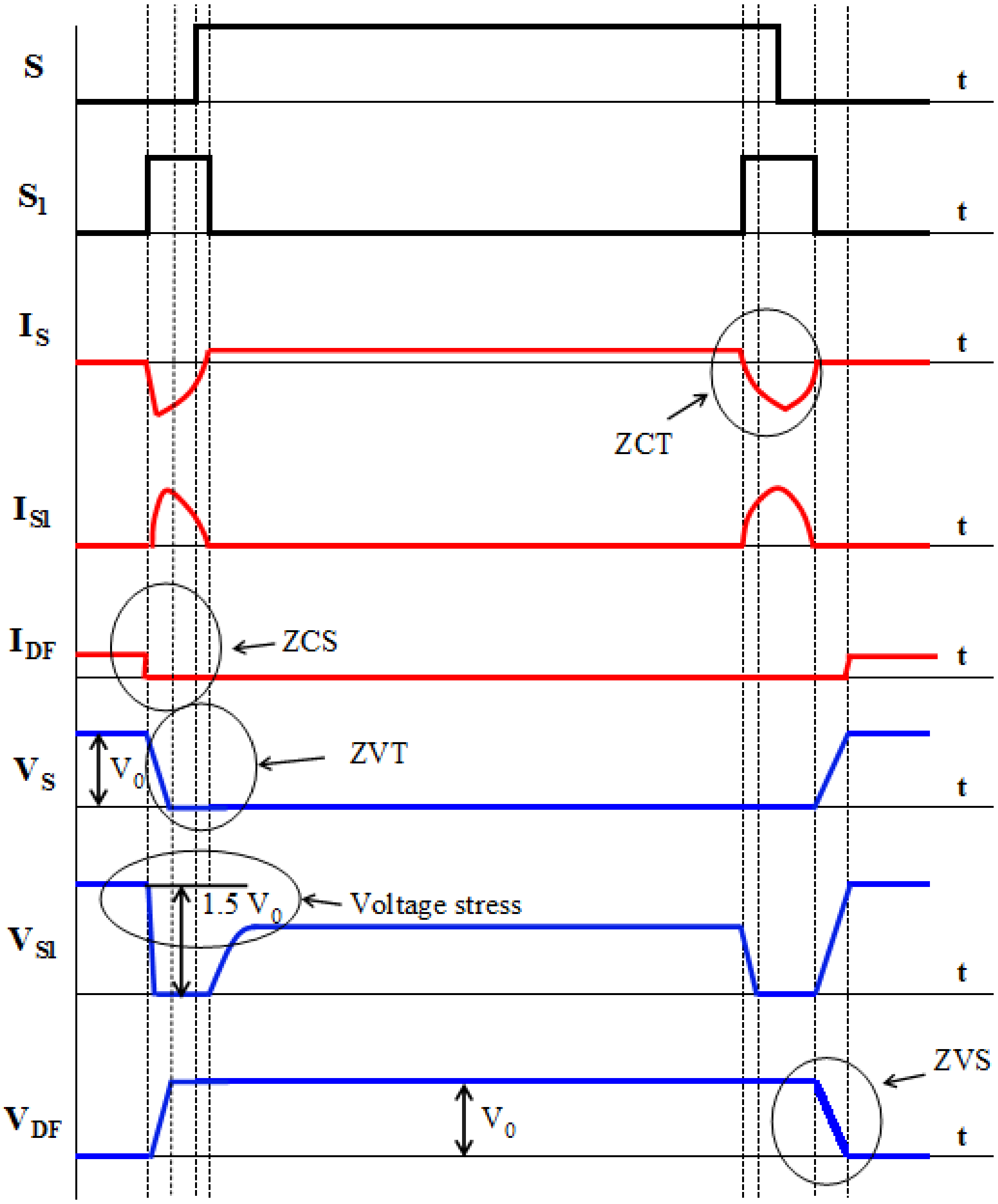


Figure 9. Waveforms of the semi-conductors in the converter [8]

Figure 9. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main switch current ($I_S$), the auxiliary switch current ($I_{S1}$), the main diode current ($I_{DF}$), the main switch voltage ($V_S$), the auxiliary switch voltage ($V_{S1}$), the main diode voltage ($V_{DF}$) [8]

## 2.5. THE COMPARISON OF ACTIVE SNUBBER CELLS

A comparison of the modern soft switching techniques studied in Chapter 2 is given in Table 1. It is deduced from Table 1 that the ZVZCT techniques are more advantageous than the other soft switching techniques mentioned in Chapter 2.

Table 1. The features of soft switching techniques [1-8]

| **Feature** | **Basic ZCT** | **Basic ZVT** | **ZVZCT-1** | **ZVZCT-2** |
|---|---|---|---|---|
| The main switch’s turning on | HS | ZVT | ZVT | ZVT |
| The main switch’s turning off | ZCT | ZVS | ZCT | ZCT |
| The aux. switch’s turning on | ZCS | ZCS | ZCS | ZCS |
| The aux. switch’s turning off | HS | HS | ZCT | ZCS |
| The main diode’s turning on | ZVS | ZVS | ZVS | ZVS |
| The main diode’s turning off | HS | ZCS | ZCS-ZVS | ZCS |
| Current stress | High | Low | No | No |
| Voltage stress | No | No | No | Low |
| Operating at wide load range | Yes | No | Yes | Yes |

## 3. SIMULATIONS

The results are obtained by performing simulation of the boost DC-DC converters including the ZVZCT techniques, which featured in the soft switching techniques studied in Chapter 2.

### 3.1. SIMULATION OF ZVZCT CONVERTER-I

In Figure 10, the model of a 1 kW converter operating at 100 kHz frequency is demonstrated. The switching signal of the auxiliary switch $S_1$ is applied before about 150 ns and removed after about 400 ns regard to the turn on signal of the main switch. Similarly, the switching signal of the auxiliary switch is applied before about 300 ns and removed after about 300 ns considering the turn off signal of the main switch [7].

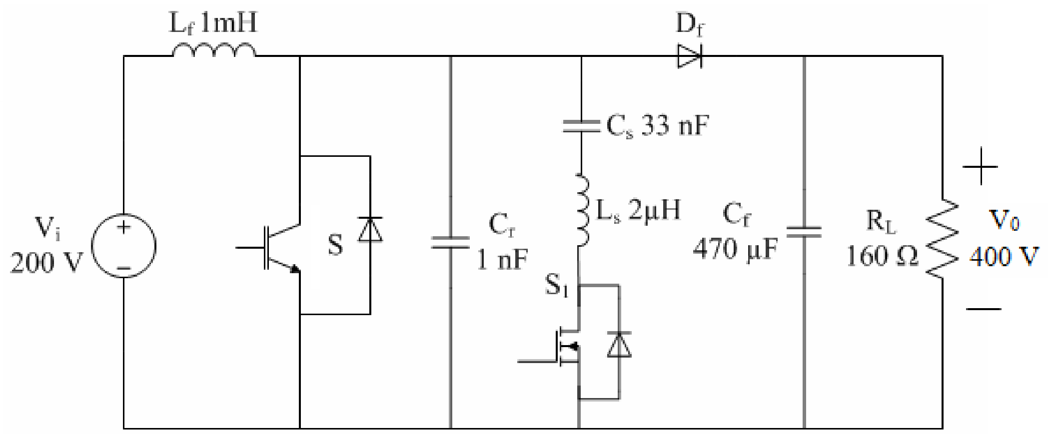


Figure 10. The model of ZVZCT Converter-I used in simulation [7]

Output voltage of the boost converter is 400 V, because of the duty cycle of the main switch is 0.5. As seen in Figure 11, the main switch turns off with ZCT and turns on with ZVT. The fall time of the main switch is 125 ns.

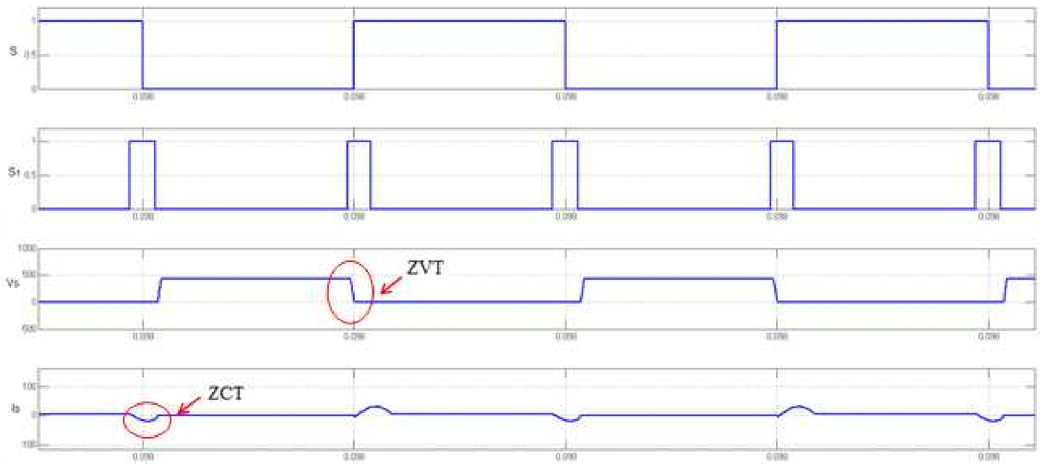


Figure 11. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main switch voltage ($V_S$) the main switch current ($I_S$)

The waveforms of the auxiliary switch are shown in Figure 12. The auxiliary switch turns off with ZCT and turns on with ZCS. The fall time of the auxiliary switch is 58 ns.

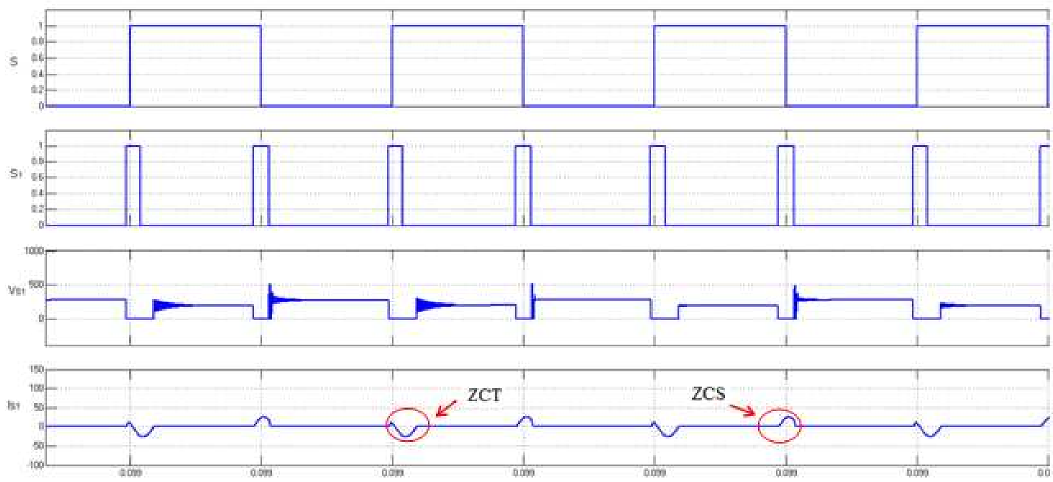


Figure 12. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the auxiliary switch voltage ($V_{S1}$) the auxiliary switch current ($I_S$)

### 3.2. SIMULATION OF ZVZCT CONVERTER-II

In Figure 13, the model of a 1 kW ZVZCT boost converter operates at 100 kHz frequency is shown. In simulation studies, the switching signal of the auxiliary switch $S_1$ is applied before about 200 ns and removed after about 50 ns regard to turn on signal of the main switch S. Correspondingly, the switching signal of the auxiliary switch is applied before about 200 ns and removed after about 200 ns considering turn off signal of the main switch. $C_p$ is the sum of the parasitic capacitor of the main switch and the other parasitic capacitors [8].

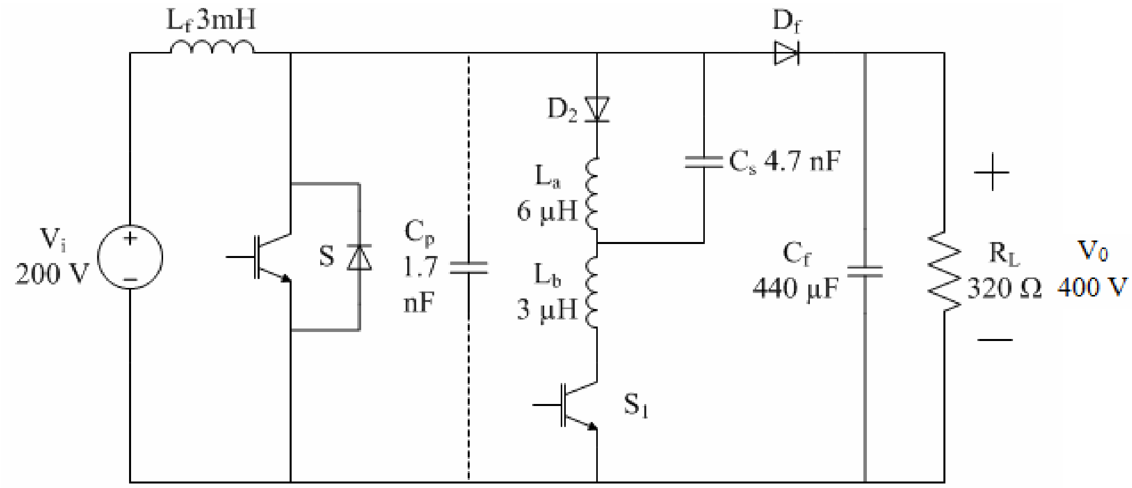


Figure 13. The model of ZVZCT Converter-II used in simulation [8]

Output voltage of the converter is 400 V because of duty cycle is 0.5. In Figure 14, the waveforms show that the main switch turns on with ZVT and turns off with ZCT. The fall time of the main switch is 40 ns.

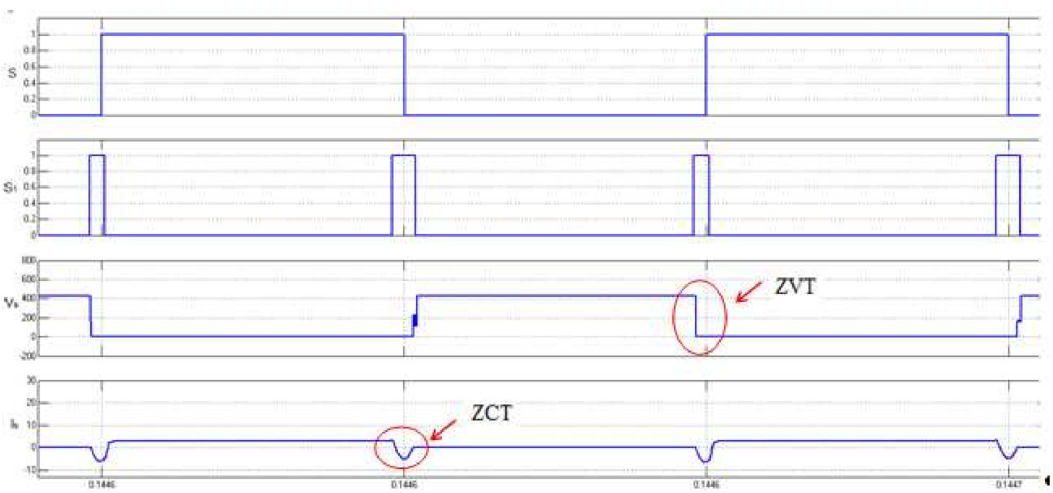


Figure 14. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main switch voltage ($V_S$) the main switch current ($I_S$)

The waveforms of the auxiliary switch are shown in Figure 15. The auxiliary switch turns on and off with ZCS. A voltage stress about 1.5 times of the output voltage occurs on the auxiliary switch. The fall time of the auxiliary switch is 20 ns [8].

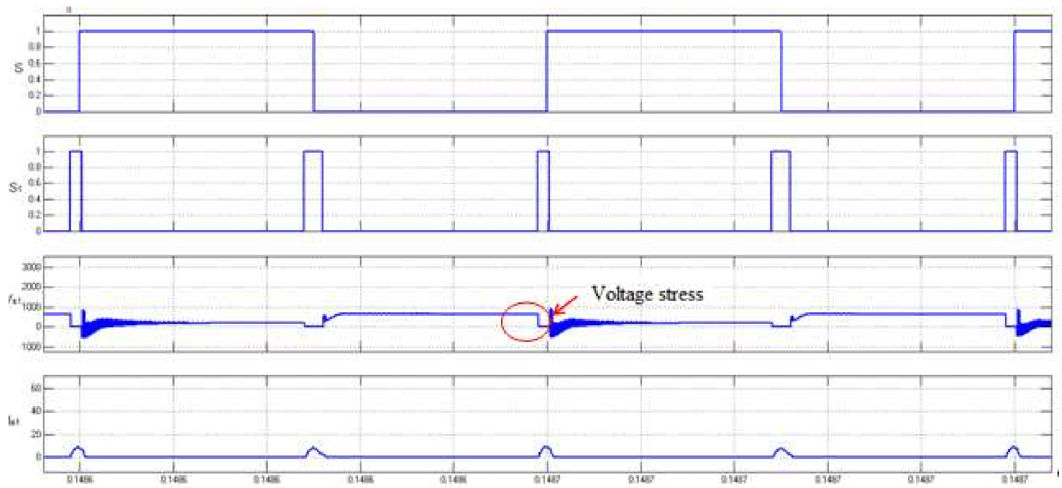


Figure 15. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the auxiliary switch voltage ($V_{S1}$) the auxiliary switch current ($I_S$)

In Figure 16, waveforms of the main diode are shown. The main diode turns on with ZVS, and it turns off with ZCS.

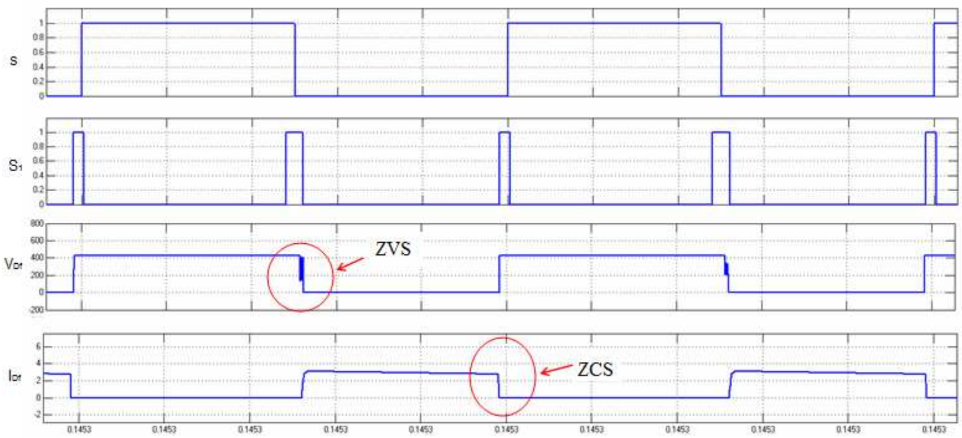


Figure 16. Switching signal of the main switch (S), switching signal of the auxiliary switch ($S_1$), the main diode voltage ($V_{DF}$), the main diode current ($I_{DF}$)

## 4. CONCLUSION

Although size of the circuit elements become smaller when the converter operates at high frequencies, power losses and EMI noises increase. Many techniques have been developed that allow converters to operate with soft switching in order to solve this problem. In this paper, zero voltage transition (ZVT), zero current transition (ZCT), and zero voltage zero current transition (ZVZCT) that is developed by combining the ZVT and ZCT soft switching methods are studied. According to the results of the comparison in Table 1, the ZVZCT converters have many advantages so that the simulations of these converters are implemented.

In simulation of the first converter the main switch turns on with ZVT and turns off with ZCT, the auxiliary switch turns on with ZCS and turns off with ZCT. As seen in simulation of the second converter, the main switch turns on with ZVT and turns off with ZCT and a voltage stress about 1.5 times of the output voltage occurs on the auxiliary switch. The main diode turns off with ZCS and turns on with ZVS.

In both converters there is no extra voltage or current stress except for the acceptable voltage stress of the second converter.

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