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DC-DC converter with 50 kHz-500 kHz range of switching frequency for passive component volume reduction

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ABSTRACT

This paper presents the relationship of switching frequency towards passive components volume of DC-DC boost converter. Principally, the inductor current ripple and capacitor voltage ripple must be considered in order to design the inductor and capacitor, respectively. By increasing the switching frequency, smaller size and volume of passive component can be designed. As the consequences, the switching loss increases during switching transition at turn-ON and turn-OFF conditions. This paper used soft-switching technique to reduce the switching loss at turn-ON condition. The soft-switching technique is realized by adding resonant circuit in DC-DC boost converter. The effectiveness of resonant circuit will be analysed, thus, the efficiency of the converter can be improved. The range of switching frequency considered in the experimental are 50 kHz to 500 kHz. A 100 W prototype has been developed and tested in order to verify the principle. The switching loss experimentally confirm reduced by implementing soft-switching technique with efficiency converter improved from 96.36% to 97.12% when 500 kHz of switching frequency is considered. The passive components volume reduction is achieved when high switching frequency is used where the total volume of passive component when 50 kHz and 500 kHz are 0.083 dm^3 and 0.010 dm^3, respectively.

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1. INTRODUCTION

Green technology has increase in demand in order to tackle the environmental issues. The green technology such as electric vehicles (EVs) can reduce heavy air pollution, water pollution and global warming [1]. Before the EV have been introduced, conventional internal combustion engine vehicles running on gasoline, diesel and fuels is commonly used. This source produces carbon dioxide that can cause air pollution, effect global warming and effect human body [2]. Normally, EV used batteries as a power supply to run the electric motor. The design of EV must be lightweight to ensure the performance of car and the safety of passenger [3]. Heavyweight of EV can limit their speed, reduce the efficiency and required more power to move the vehicle. This can cause large of EV batteries is required. According to [4], the main part in EV which can contribute to the EV size are large capacitor in dc link, batteries, power converters, controller, and electric motor.

Power converters are one of the main parts in the EV in order to process the power deliver from the AC grid to the load [5]. Generally, DC-DC converter consist of bulky passive component in the basic circuit structure. This can increase the overall size and volume of the power converter. Based on [6], high switching frequency can be considered to reduce the weight, size and volume of converter. Nevertheless, when high switching frequency is considered for the DC-DC converter, it can reduce the performance of converter because of high switching loss, electromagnetic interference (EMI), and switching device stress [6-8].

This paper focus to eliminate the switching loss by considering ZVS quasi-resonant circuit in DC-DC converter where the efficiency can be improved and can reduce the passive component volume. The principle of hard-switching and soft-switching (ZVS quasi-resonant) techniques are described and compared. In addition, the parameter design of DC-DC converter with hard-switching and soft-switching techniques implementations are also discussed. The derivation of voltage drop in open loop system by considering ZVS quasi-resonant in DC-DC converter is provided. The volume reduction of passive components by considering high switching frequency are discussed. Simulation and experimental results of hard-switching and soft-switching implementations are analyzed and discussed.

2. PRINCIPLE OF HARD-SWITCHING AND SOFT-SWITCHING TECHNIQUES

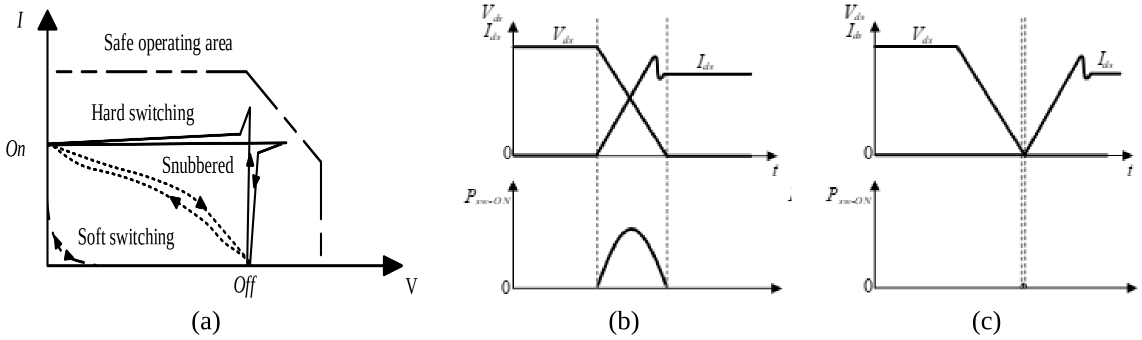
Basically, hard-switching DC-DC boost converter consist of diode, boost inductor, output capacitor and switch. Meanwhile, it consists additional of resonant inductor and resonant capacitor when soft-switching technique is considered. Principally, the value of output voltage V_{out} of DC-DC boost converter is higher than input voltage V_{in}. The output voltage is controlled independently by varying the duty cycle D. The relationship between input voltage and output voltage of DC-DC boost converter can be expressed in (1).

$$V_{out} = \frac{V_{in}}{1-D} \tag{1}$$

Figure 1(a) shows the typical switching trajectories of hard-switching, snubber, and soft-switching. During hard-switching condition, there is high voltage spike at turn-ON and high current spike at turn-OFF which cause switching loss and switching stress [7]. Then by adding RC snubber it reduces the over voltages during turn-ON and over current at turn-OFF transition in hard switching which can reduce the switching loss [9]. As stated in [7], the soft-switching can totally eliminate the switching loss where gives a better performance in terms of efficiency to the power converter.

2.1. Hard-switching technique

Normally, the conventional boost converter is operated in hard-switching condition. Hard-switching condition is called when there are overlapping between switching voltage V_{ds} and switching current Ids which produce switching loss when the switching is turn-ON and turn-OFF [10-13] as shown in Figure 1(b). Principally, the switching loss is directly proportional to the switching frequency. When high switching frequency is considered, the overlapping area between voltage and current become large. The overlapping area is called as switching loss. Thus, optimum switching frequency must be considered in order to avoid high switching loss.



(a) (b) (c)

Figure 1. Differentiation of hard-switching and soft-switching (a) Switching trajectories [10], (b) hard-switching technique during turn-ON, (c) soft-switching technique during turn-ON

2.2. Soft-switching technique

The main purpose of soft-switching technique is to avoid the overlapping between switching voltage and switching current [14-18]. The advantage of soft-switching technique is high switching frequency can be considered without decreasing the efficiency of converter. Generally, there are two type of soft-switching condition which are zero voltage switching (ZVS) and zero current switching (ZCS) [19]. These two conditions prevent the switching current and switching voltage rise simultaneously which can cause the overlapping condition. In this paper, the switching loss during turn-ON will be focused where the ZVS condition is realized by using ZVS quasi-resonant converter as shown in Figure 1(c).

3. PARAMETERS DESIGN AND DISCUSSIONS OF DC-DC CONVERTER WITH HARD-SWITCHING AND SOFT SWITCHING IMPLEMENTATIONS

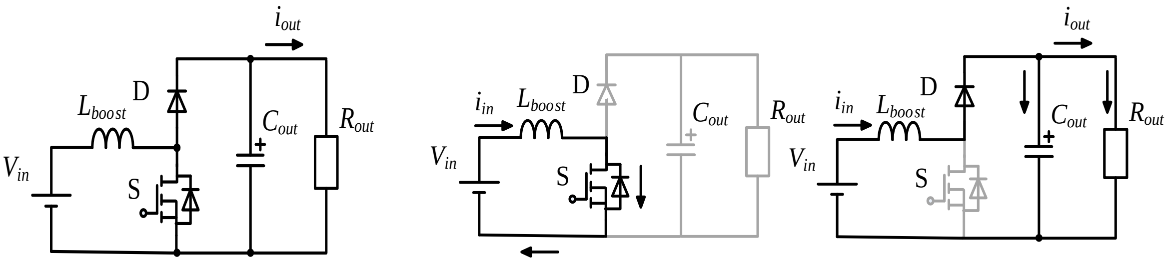
3.1. Hard-switching implementation in DC-DC boost converter

In order to design DC-DC boost converter, there are several parameters required to be considered to operate the power converter properly [20]. In this paper, continuous conduction mode (CCM) is considered for the DC-DC boost converter. Principally, the maximum of inductor current ripple is concern in order to design the inductor to ensure the inductor can be used in any condition as the duty cycle is varied. As stated in [20-22], the maximum of inductor current ripple is occurred at 0.5 of duty cycle. Normally, the best estimation of inductor current ripple is about 20% to 50% output current of the power converter. The optimum inductor of DC-DC boost converter can be expressed as (2). For output capacitor design, the output voltage ripple must be considered as stated in [9]. The capacitor of DC-DC boost converter can be expressed as (3).

$$L_{boost} = \frac{V_{Lboost} \times DT}{\Delta I_{Lboost}} \tag{2}$$

$$C_{out} = \frac{I_{Cout} \times DT}{\Delta V_{Cout}} \tag{3}$$

Figure 2 shows the main circuit structure and the operation modes of DC-DC boost converter. In Figure 2(b), it shows the DC-DC boost converter consist of two operation modes. This mode operation is crucial in order to charge and discharge the boost inductor. The boost-up energy will be transferred from input to the output sides.



(a) (b)

Figure 2. DC-DC boost converter (a) main circuit (b) operation modes

3.2. Soft-switching implementation in DC-DC boost converter

ZVS quasi-resonant converter is selected as the soft-switching technique due to the ability of totally eliminate the switching loss during turn-ON condition. The resonant condition can be achieved by adding resonant capacitor C_r in parallel and resonant inductor L_r in series with the switching device S as shown in Figure 3. Normally, the value of L_r and C_r are much lower than filtering components. In ZVS, the converter will be operated in half-wave mode [7, 19] or can called it as half-wave ZVS quasi-resonant converter if the switch used is unidirectional for voltage and bidirectional for current with anti-parallel diode. In [7], the detail principle design of L_r and C_r is shown in Figure 3.

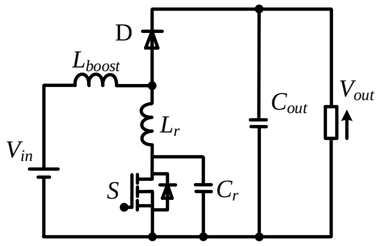
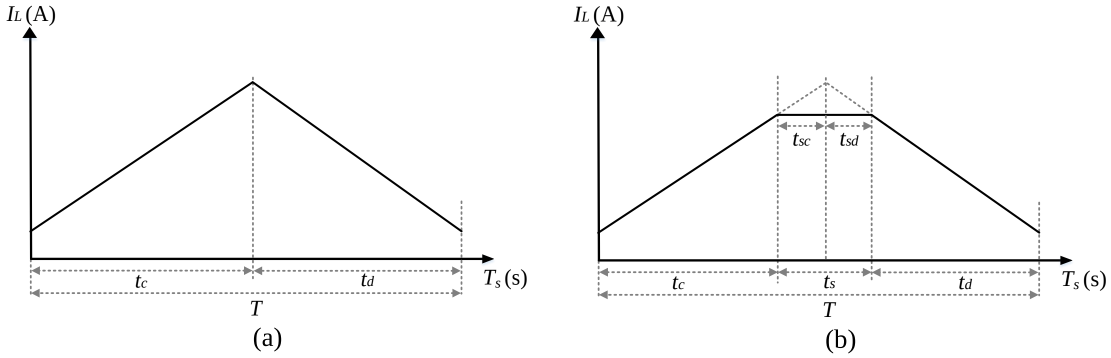


Figure 3. DC-DC boost converter with resonant circuit [7]

4. STAGNANT CONDITION ISSUE OF ZVS QUASI-RESONANT FOR DC-DC CONVERTER

The soft-switching condition is difficult to realize due to the additional of passive components to the main circuit of the power converter. The operation mode of the power converter is increased in order to achieve soft-switching condition. Referring to section 3.2, additional of passive components is required in ZVS quasi-resonant circuit. The resonant circuit required charging and discharging processes in order to realize the soft-switching condition. However, the processes caused a voltage drop at resonant circuit and affect the output voltage reduction of the power converter. Figure 4(a) shows the normal condition of inductor current ripple.

In open loop power converter system, it can be observed that the boost inductor current ripple ΔI_{Lboost} having a stagnant condition as illustrates in Figure 4(b). During stagnant condition, the boost inductor is not in charging or discharging process. Consequently, the energy stored in the boost inductor is not fully charge and discharge where it affected the energy transferred to the load. The output voltage can largely reduce as the stagnant time at the inductor current ripple is longer. The voltage drop at the resonant circuit can be derived for DC-DC converter in boost and buck operations. The charging time t_c, discharging time t_d, and stagnant time t_s are considered in the derivation process.



(a)

(b)

Figure 4. Inductor current ripple, (a) normal condition, (b) stagnant condition

In the derivation, the duty cycle is considered to calculate the voltage drop due to the relationship of duty cycle with input and output voltages of the DC-DC converter. Based on Figure 4, the duty cycle at charging condition D_c and discharging condition D_d can be obtained as follows, respectively:

$$D_c = \frac{t_c}{T} \tag{4}$$

$$D_d = \frac{t_d}{T} \tag{5}$$

where T is the switching period for full cycle process. Meanwhile, the duty cycle during stagnant charging condition D_{sc} and the duty cycle during stagnant discharging condition D_{sd} can be expressed as follows, respectively:

$$D_{sc} = D - D_c \tag{6}$$

$$D_{sd} = D - D_d \tag{7}$$

Thus, the summation of D_{sc} and D_{sd} can obtain the duty cycle of stagnant condition D_s which can be expressed as follow:

$$D_s = D_{sc} + D_{sd} \tag{8}$$

Hence, the output voltage of ZVS quasi-resonant DC-DC buck and boost converters can be expressed as follow, respectively:

$$V_{out(buck)} = (D - D_{sc}) \times V_{in} \tag{9}$$

$$V_{out(boost)} = \frac{V_{in}}{1-(D-D_{sc})} \tag{10}$$

5. VOLUME REDUCTION OF PASSIVE COMPONENTS

Principally the volume of passive components can be reduced by increasing the switching frequency. However, the implementation of high switching frequency may contribute to high switching loss. Thus, by considering soft-switching technique, the volume reduction of passive components can be realized.

5.1. Inductor and capacitor volumes

The volume estimation for the inductor of the DC-DC converter can be based on area of product theory [23]. According to the Area of Product in [24-27], the energy stored in the inductor corresponds to the volume of the inductor. Thus, the volume of the inductor can be expressed as follows:

$$Vol_L = K_{vol} \times A_p^{0.75} = K_{vol} \left[\frac{LI^2}{K_u B_m J} \right]^{0.75} \tag{11}$$

Figure 5 shows the relationship of inductor current ripple against switching time. This relationship shows by increasing the switching frequency, the inductor current ripple become smaller, consequently the inductor can be designed smaller and may also reduce the volume of inductor. Generally, the volume of the capacitor is estimated from the available ceramic capacitor in the market. Besides that, the energy stored corresponds with the volume of ceramic capacitor. For the electrolytic capacitor, the volume is proportional to the rms value of the current ripple of electrolytic capacitor. Thus, the volume of the ceramic capacitor Vol_{Cc} and electrolytic capacitor Vol_{Ce} can be expressed as follows:

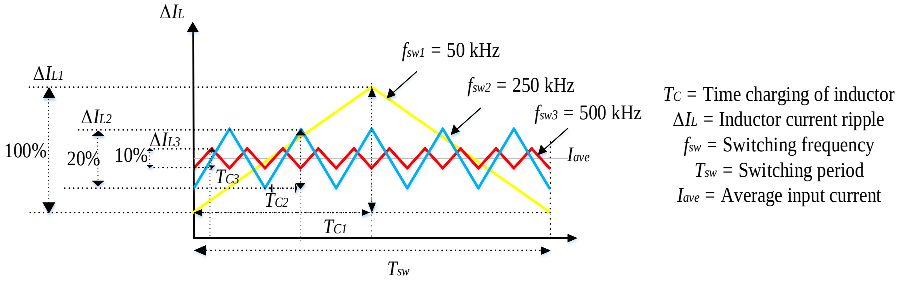


Figure 5. Relationship of inductor current ripple and switching time

$$Vol_{Cc} = \frac{\gamma_{V_{Cc}}^{-1} \times C \times V_C^{\ 2}}{2} \tag{12}$$

$$Vol_{Ce} = \gamma_{V_{Ce}}^{-1} \times I_{c,rms} \tag{13}$$

6. RESULTS AND DISCUSSIONS

A 100 W prototype of power converter has been developed and tested in order to verify the soft-switching technique in DC-DC converter where high switching frequency can be used to achieve volume reduction of passive components. In this paper, the experimental results are obtained for DC-DC boost converter. The specifications of DC-DC boost converter can be referred in Table 1, while the resonant elements/componets can be referred in Table 2.

Table 1. Specifications of DC-DC boost converter for hard-switching and soft-switching implementation

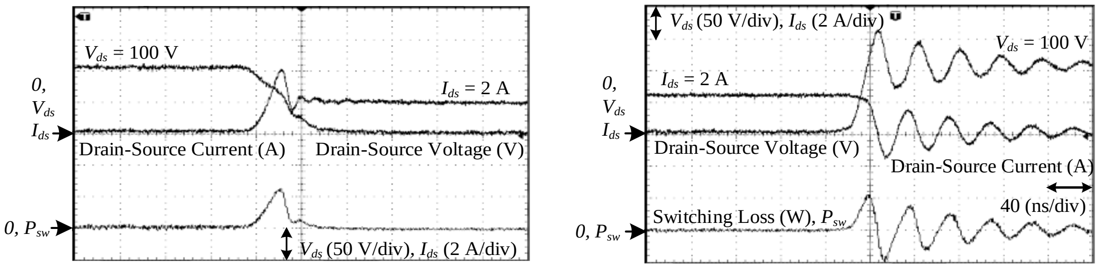
Parameter	Value
Output voltage, V_{out}	100 V
Output power, P_{out}	100 W
Duty cycle, D	0.5
Switching frequency, f_{sw}	50 kHz
Boost inductor, L_{boost}	1 mH
Output capacitor, C_{out}	220 µF

Table 2. Parameters of resonant circuit based on switching frequency

Switching frequency, f_{sw}	Resonant inductor, L_r	Resonant capacitor, C_r
50 kHz	109 µH	30 nF
250 kHz	35 µH	4.7 nF
500 kHz	27 µF	1 nF

6.1. DC-DC boost converter with hard-switching technique implementation

The simulation and experimental results have been obtained in order to validate the switching during turn-ON and turn-OFF condition is lossy. The switching frequency of 50 kHz has been considered in the simulation and experimental works to verify the hard-switching condition. Figure 6 shows the experimental results of overlapping between current and voltage of switching device is occurred during turn-ON and turn-OFF conditions. Thus, the switching loss is experimentally confirmed occurred during hard-switching condition.



(a) (b)

Figure 6. Experimental results of hard-switching condition in switching device S; (a) during turn-ON condition, (b) during turn-OFF condition

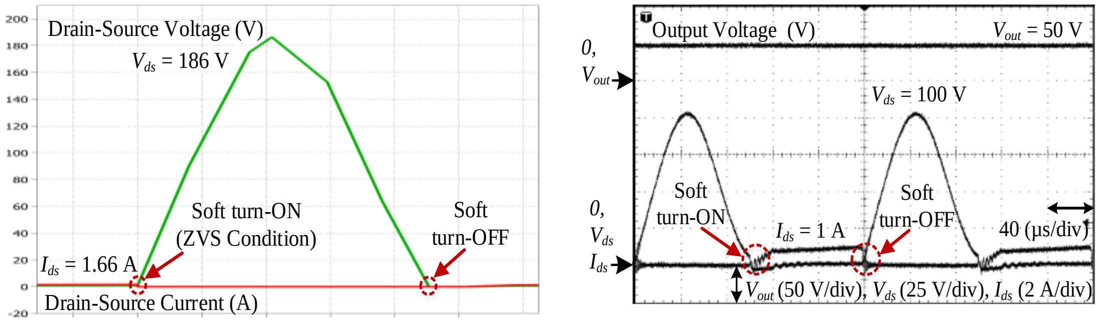
6.2. DC-DC boost converter with soft-switching technique implementation

Based on Table 2, the parameters of resonant circuit are considered for switching frequency of 50 kHz. Figure 7(a) shows the simulation results of switching device S during soft-switching condition where the switching voltage V_{ds} is approximately 186 V, while the switching current I_{ds} is approximately 1.66 A. It can be observed that the switching voltage is high as compared to the switching voltage during hard-switching condition due to the reshaping of switching voltage to realize the soft-switching condition.

Principally, the energy of switching voltage of hard-switching and soft-switching implementation is similar. However, the maximum of the peak voltage by implementing ZVS quasi-resonant is increasing. Figure 8 shows the simulation results of soft-switching condition where the overlapping between switching voltage and switching current does not occur and experimentally verified as shown in Figure 7(b). But, the output voltage of experimental results are reduced due to the component rating limitation. Soft turn-OFF is automatically achieved due to the reshaping of switching voltage where the switching loss during turn-OFF is also eliminated.

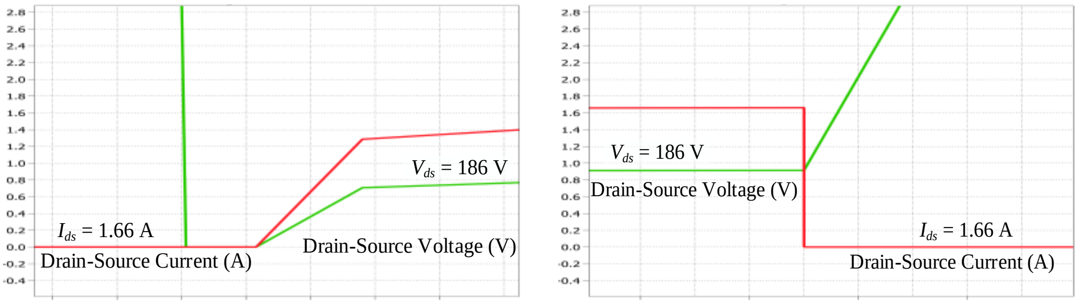
6.3. Losses and efficiency comparison

This analysis only considering the semiconductor losses in order to compare the losses and efficiency of DC-DC boost converter with hard-switching and soft-switching implementations. By referring to Table 3, the total power loss P_{loss} of DC-DC boost converter in hard-switching technique is increasing as the switching frequency varied from 50 kHz to 500 kHz but it constants when soft-switching technique is considered. By considering 500 kHz of switching frequency, the efficiency of converter with hard-switching technique implementation is 96.36% while with soft-switching technique implementation; the efficiency is 97.12% which are similar when 50 kHz of switching frequency is considered. Thus, higher switching frequency can be considered due to the efficiency of the converter is not affected with variation of switching frequency is applied.



(a) (b)

Figure 7. Switching device S during soft-switching condition; (a) simulation results, (b) experimental results



(a) (b)

Figure 8. Simulation results of hard-switching condition in switching device s; (a) during turn-ON condition, (b) during turn-OFF condition

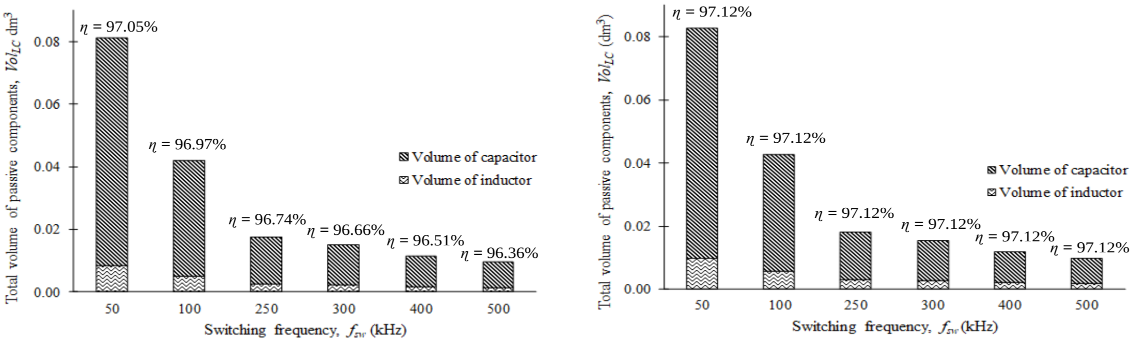
Table 3. Losses analysis in hard-switching and soft-switching techniques

Switching Technique	Switching Frequency, f_{sw} (kHz)	Switching Loss, P_{sw} (W)	Conduction Loss $P_{cond(m)}$ (W)	Conduction Loss $P_{cond(d)}$ (W)	Total Power Losses, P_{loss} (W)
Hard-switching	50	0.077	0.076	2.80	2.95
	250	0.383			3.26
	500	0.767			3.64
Soft-switching-ZVS quasi-resonant	50	Totally	0.076	2.80	2.88
	250	eliminated			
	500	0			

6.4. Passive component volume reduction

Figure 9 shows the volume reduction of passive components as the switching frequency of DC-DC boost converter is increased. However, the efficiency of power converter is decreasing as the switching frequency increased when hard-switching implementation is considered. The total volume of passive components Vol_{LC} and efficiency of converter when 50 kHz of switching frequency is considered are 0.081 dm^3 and 97.05%, respectively. Meanwhile, the total volume of passive components and efficiency of converter when 500 kHz of switching frequency is considered are 0.010 dm^3 and 96.36%, respectively.

In soft-switching technique implementation, the total volume of passive components and efficiency of converter when 50 kHz of switching frequency is considered are 0.083 dm^3 and 97.12%, respectively. When 500 kHz of switching frequency is considered, the total volume of passive components and efficiency of converter is 0.010 dm^3 and 97.12%, respectively. It can be concluded that the passive components volume reduction of the converter are achieved without affecting efficiency of the converter.



(a) (b)

Figure 9. Volume reduction and efficiency of DC-DC boost converter as the switching frequency is varied from 50 kHz to 500 kHz, (a) hard-switching technique, (b) soft-switching technique

6.5. Effectiveness of ZVS quasi-resonant converter

Table 4 shows a comparison of several common techniques in soft-switching. The comparison is made based on several features such as the number of passive components, control requirement, reliability, circuit configuration and number of components used to realize soft-switching. The resistance capacitance diode (RCD) snubber has moderate circuit configuration and only required one passive component. However, the utilisation of diode may increase the conduction loss and may increase the volume of heatsink design. Meanwhile, active snubber and passive lossless snubber has a complex circuit configuration where the number of components are seven and six, respectively. Thus, from the comparison, the ZVS quasi-resonant shows a better attributes in terms of circuit configuration and number of components. The consideration of inductor and capacitor in ZVS quasi-resonant circuit avoid bulky passive component issues as the resonant tank.

Table 4. Comparison of soft-switching techniques

Soft-switching techniques Features	RCD snubber [25]	ZVS quasi-resonant	Active snubber [26]	Passive lossless snubber [27]
No. of passive component	One	Two	Two	Three
Control requirement	No	No	Yes	No
Reliability	Less	Less	Less	Medium
Circuit configuration	Moderate	Simple	Complex	Complex
No. of component	Three	Two	Seven	Six

7. CONCLUSION

The author of this paper has discussed the relationship of switching frequency towards passive components by considering soft-switching technique implementation. Based on the analyses, the switching loss is reduced and it experimentally confirmed where the efficiency of the DC-DC boost converter is improved from 96.36% to 97.12% at 500 kHz of switching frequency. Besides, the passive components volume is reduced from 0.083 dm^3 to 0.010 dm^3 by varying the switching frequency from 50 kHz to 500 kHz. Thus, the overall volume of the converter is reduced with improved efficiency by considering higher switching frequency to the converter.

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