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REVIEW OF SOFT SWITCHED HIGH FREQUENCY BUCK CONVERTERS

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Abstract: Modern power electronic converters must possess features like reduced size, high power density, high efficiency etc. By employing soft switching cells to existing converters, performance can be improved to a great extent. Soft switching converters aim to reduce switching loss, enabling a converter to operate with very high frequency. This facilitates reduction in size and volume of the converter that improves power density and efficiency of the converter. This paper reviews detailed study on different soft switching of DC-DC Buck converters to improve converter performance. The detailed operation of few soft switched buck converter topologies along with strengths and weaknesses have been discussed thoroughly.

***Index Terms* - Pulse Width Modulation (PWM), Zero Voltage Switching (ZVS), Zero Current Switching (ZCS), Snubber circuit, Zero Current Transition (ZCT), Soft Switching.**

I. INTRODUCTION

Buck converters are found in numerous domestic and industrial applications, such as consumer electronics, appliances, general industries, and aerospace due to their simplicity, low cost etc. features. Modern power electronic converters are designed to have small size, lightweight, and high reliability. High frequency operation is desired to improve power density of converters. However, if converters work under hard-switching conditions, switching losses will be huge as switching frequency increases, which restricts hard switched converters to operate with high frequency. Soft switching technologies are the best methods to reduce switching losses, and improve efficiencies and reliabilities. Thus, the heat sink and magnetic element size reduces considerably, which in turn reduces converter weight considerably. Main problems during Hard-switching are switching losses, device stress, thermal management and energy losses etc. To overcome these issues, snubber circuits and soft switching methods are employed.

Various DC–DC converter topologies are widely used in different applications. A huge research work [1-6] is carried out in the recent past to improve converter performance. Buck converters, as the simplest DC–DC converters, are used to decrease and regulate the constant DC voltage level. To charge tablets, laptops, and other electronic devices, buck converters are widely used. Topological developments have been reported in [7-18] to improve converter performance compared to existing buck converter structure. Coupled inductor based ZVS operated Buck Converters have been presented in [7-12] to reduce output current ripple and reduced switching loss. This reduction in switching loss allows high frequency operation of the converter, which in turn reduces magnetic and thermal components. Thus, high power density can be achieved. Although these converters are partially soft switched. [15-18] used auxiliary soft switching cells to improve switching performance of the converters.

This paper presents an overview of different soft switched buck converters. Detailed operating principle of the converters along with their merits and demerits are discussed.

2.1 A ZVS Operated Synchronous Buck Rectifier

A synchronous Buck converter capable of performing switching transitions under ZVS without any auxiliary network is presented in [13]. The converter operated with extended duty cycle using coupled inductors and series capacitors. Additionally, the converter uses an interleaved network to reduce output current ripple. A detailed operation of the converter is discussed below:

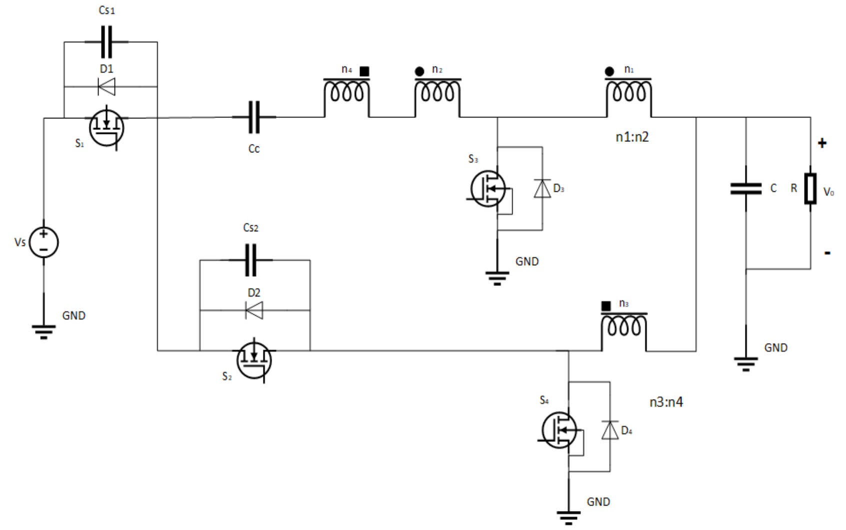

Figure 1: Circuit diagram of the converter in [13]

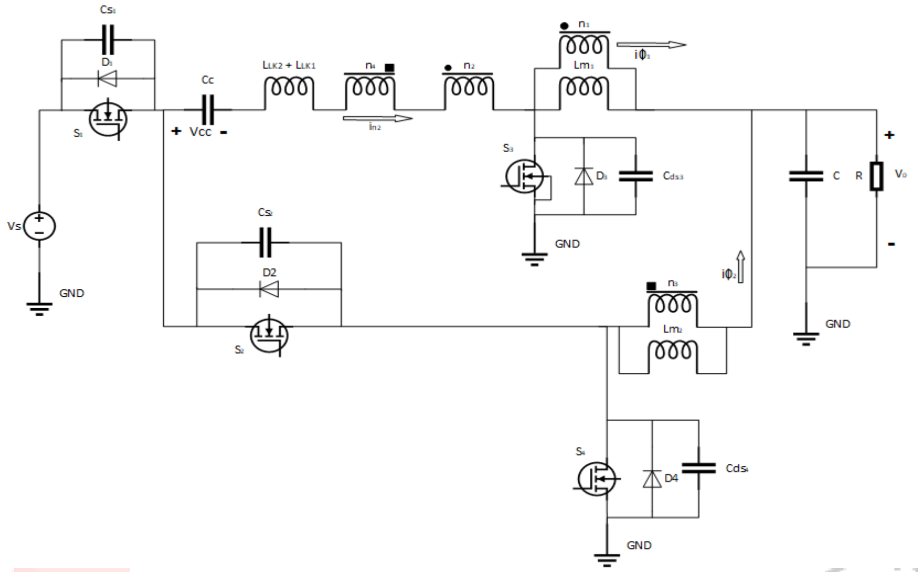

Figure 2: Equivalent circuit diagram of the converter in [13]

The circuit consists of two coupled inductors with $n_1: n_2$ and $n_3: n_4$. The turns ratio of the first and second phases are defined as $n = n_1/n_2 = n_3/n_4$. The series capacitor C_C is taken large enough to consider the voltage across it (V_{Cc}) as constant. The source voltage V_S and output voltage V_O are assumed constant and all the semiconductor elements are considered as ideal.

Operating cycle of this circuit has 6 different modes. Operating mode starts by assuming S_1, S_4 are in on state and S_2, S_3 are in off state.

Mode 1 starts by turning the switches S_1 and S_4 off. As there is no voltage stress at the beginning and due to the snubber capacitor of S_1 and body capacitor of S_4 the voltage cannot rise instantly, and the switches turn off under ZVS condition. The snubber capacitor of S_1 gets charged simultaneously; the snubber and body capacitor of S_2 and S_3 respectively continue to discharge through winding n_2.

When the snubber capacitor C_{S2} and the body capacitor C_{dS3} gets fully discharged, mode 2 begins. As the voltage stress across S_2 is 0 V so it can turn on under ZVS condition. The anti-parallel diode of S_3 starts conducting as soon as the body capacitor gets fully discharged. So, the voltage stress across S_3 becomes 0 V and it can also turn on under ZVS.

As the current through n_4 winding becomes the same as the output current the body diode D_4 turns off and mode 3 comes into action. The series capacitor C_C transfers its energy to the output.

Mode 4 begins when the main switch S_2 turns off under ZVS condition and the n_4 winding starts charging the capacitor C_{S2}. Simultaneously snubber and body capacitors of S_1 and S_4 respectively continue to discharge.

Mode 5 begins when the snubber and body capacitor of S_1 and S_4 respectively get fully discharged. At this stage no current flows through the path where main switch S_2 lies, as the voltage difference between source voltage (Vs) and the voltage across the snubber capacitor of switch S_2 (V_{CS2}) becomes 0 V.

At the end of the operating cycle mode 6 begins when the current through n_2 winding of first phase reaches the same as the output current, the body diode D_3 stops conducting. This way the converter circuit continues to operate.

The strengths and few weaknesses of the reviewed circuit are given below.

Strengths

1) Extended duty cycle to reduce current ripple.
2) No additional auxiliary circuit.

Weaknesses

1) Design consideration does not include voltage ripple into account.
2) Higher converter cost.
3) No voltage regulators employed.
4) Proper inductor design should be described for understanding.

2.2 ZVS Operated PWM Buck Converter with ZCS Auxiliary Circuit

The DC-DC Buck converter in [15] uses a soft switching technique for improving the efficiency of it in the high-frequency range. In this Buck converter, two active switches have been used i.e., main switch and auxiliary switch, which operates under soft switching condition.

The ZVS PWM buck converter with the ZCS auxiliary circuit is shown in Figure 3. It comprises two sub circuits; one part of the circuit is the main circuit while the other circuit is referred to as the auxiliary circuit. The main sub-circuit is a conventional buck converter consisting of a switch *(S_m)*, diode *(D)*, filter inductor *(L)* and a capacitor *(C)*. On the other hand, the auxiliary circuit consists of auxiliary switch *(S_a)*, L_r, C_r, D_1, D_2, D_3.

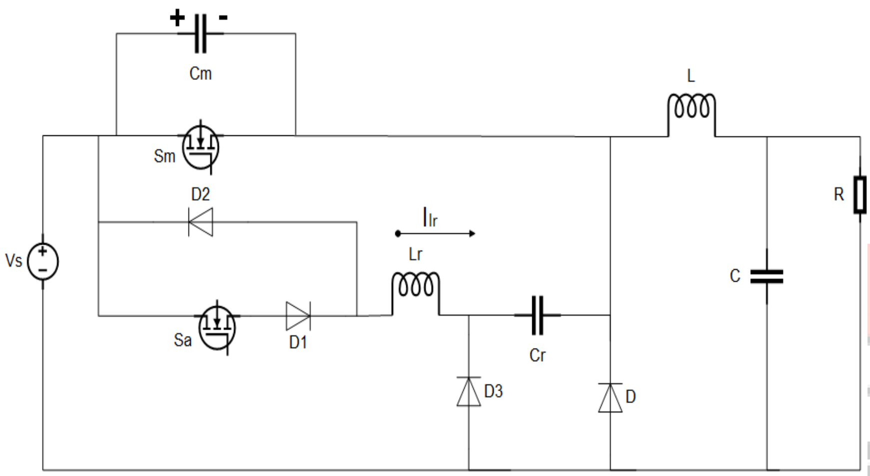

Figure 3: Circuit diagram of the proposed converter

This circuit has seven different modes of operation. Initially, voltage across the main capacitor C_m is constant and it is equal to the source voltage V_s. In this time interval, main switch (S_m) and auxiliary switch (S_a) both are off and load current flows through diode D.

Mode 1 of operation begins when the auxiliary switch is turned on. In this mode, the current through inductor L_r and the voltage capacitor across C_r are resonantly increasing. Mode 1 terminates when the current flowing through the L-C circuit becomes equal to the load current the diode D commutes softly.

In Mode 2, the current through the inductor L_r increases beyond load current. The capacitor C_m starts discharging. Mode 2 ends when the inductor L_r gets completely charged and the capacitor C_m is partially discharged.

In Mode 3, inductor L_r starts discharging by reversing its voltage polarity and the capacitor C_r is still charging. When the current through the inductor L_r becomes equal to the current through the load then at that moment the voltage across the capacitor C_m becomes equal to zero. At that time, the main switch is turned ON and hence, ZVS is achieved.

In Mode 4, the inductor L_r is still discharging and capacitor C_r is still charging. At the end of this mode, inductor L_r gets discharged and capacitor C_r gets charged fully. When L_r gets completely discharged, switch M_a is turned OFF under ZCS.

In Mode 5, capacitor C_r starts discharging and the inductor L_r starts charging in the opposite direction. At the end of this mode, the inductor L_r gets fully charged in the opposite direction.

In Mode 6, the inductor L_r starts discharging by changing the polarity of the voltage across it. This mode ends when the main switch is turned off under ZVS.

In Mode 7, current is flowing through the capacitor C_m and hence, it gets charged to V_s.

The strengths and weaknesses of the converter is pointed below:

Strengths

1) This circuit can be used in high frequency operations.
2) High power density.
3) Soft switching operation.
4) Reduced voltage and current stress across the switch.
5) Low electromagnetic interference (EMI).
6) Fast transient response.

Weaknesses

1) There is also no isolation from the input to the output side, rendering it unsuitable for certain applications.
2) This circuit is not suitable for high power operations.
3) The Design cost of this circuit is high because it uses two MOSFET switches.

2.3 A DC-DC Buck Converter with Active Resonant Snubber Cell

The DC-DC Buck converter circuit in [16] uses an improved active resonant snubber cell that overcomes most of the drawbacks of the normal zero-current transition (ZCT) pulse width-modulation (PWM) dc–dc converters. Below is the circuit diagram of the Buck converter.

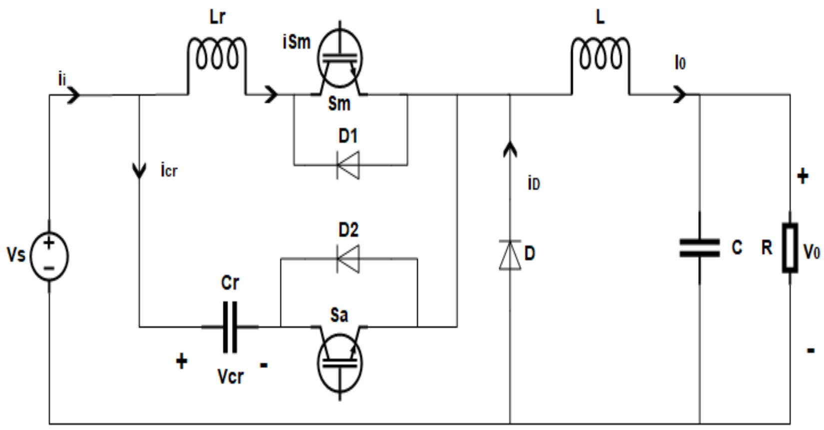

Figure 4: Circuit diagram of resonant buck converter [16]

The converter operation can be described with seven different operating stages. Initially, L_r is discharged and C_r is charged with V_s of given polarity shown in the above circuit. Before mode 1, both S_m and S_a being off the constant current I_0 drawn by the load R is flowing through the D diode. Now at the instant of start of 1st Mode, S_m is turned on and constant voltage V_s appears across L_r which causes linear increase in current flowing through the L_r inductor which causes i_D to decrease in the same fashion. This stage is completed at the end of 1st mode when i_D reaches 0A and $i_{Lr}=I_0$.

During 2nd mode, resonance occurs between L_r and C_r. Current flows through L_r-S_m-D_2-C_r. The current in L_r starts to increase to maximum and decrease. On the other hand, the voltage V_{Cr} of shown polarity decreases from V_s to 0 volt and then increases with reverse polarity. This mode ends when voltage across C_r reaches supply voltage. The 3rd stage is the active mode of the converter.

At the start of 4th stage, the transistor S_a is turned on with ZCS as the D_2 diode is not allowing any further energy exchange between L_r and C_r. With this, resonance occurs by C_r-S_a-S_m-L_r. At the end of the stage, $i_{Lr}(t)$ reaches 0 A and $i_{Sa} = I_0$ A. As the current through the L_r is 0 Amp, so S_m can now be turned off under ZCS.

During 5th Mode, diode D_1 of S_m is turned on in ZCS as current through L_r is 0 A. Resonance starts in the way of L_r-C_r-S_a-D_1. The voltage across C_r decreases to zero and then increases, whereas, the current through L_r gets to maximum and then decreases to zero again and this mode ends.

During 6th mode, $V_{Cr}(t)$ starts to rise to V_s and current through S_a starts decreasing to zero. This stage ends when S_a is turned off under ZCS.
The final stage is treated as conventional off mode of the converter.

The strengths and weaknesses of the converter is pointed below:

Strengths

1) Soft switching
2) High frequency operation.
3) Simple and cheaper compared to conventional ZCT-PWM converters.
4) Increases efficiency.

Weaknesses

1) Complex drive circuit is required.
2) High current stress across the auxiliary switch.

2.4 A ZVZCS Buck Converter with Coupled Inductor

The DC-DC Buck converter circuit shown in [17] has been analyzed in this section. The detailed circuit is shown in figure 5. In this circuit, inductors L_1 and L_2 are tightly coupled on the same ferrite core. Here the main inductor is L_1 and S_1 is the main power switch. D_1 and D_2 are the diodes.

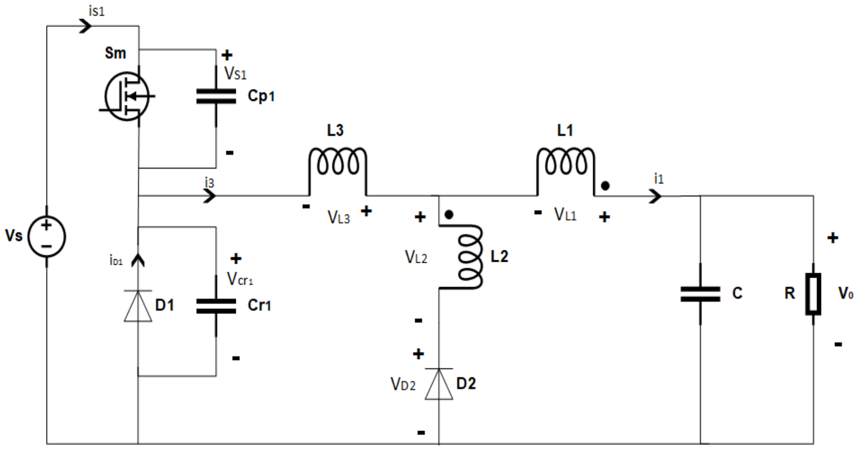

Figure 5: Topology of the zcs-zvs buck converter

This circuit has five different modes of operations. When S_1 is OFF, the converter works at the free- wheeling stage. The branches of L_2 and L_3 will supply two stream channels for current freewheeling. Because L_3 is too small, the current of L_3 drops faster than that of L_1 and also reduces to zero before S_1 turns ON. It provides the ZCS condition for S_1 at turn on. The snubber capacitor C_{r1} causes ZVS to turn off of S_1. C_{p1} is the parasitic capacitance of the switch S_1.

The detailed converter operation is explained in brief as follows:

At the starting of Mode 1, both i_3 and i_{s1} are equal to zero. Switch S_1 is turned ON. Due to L_3, i_{s1} will increase slowly. i_1 will increase and i_2 starts decreasing. At the end of this mode, i_3 reaches i_1 and i_2 becomes zero. As a result, D_2 turns OFF softly.

In mode 2, i_3 and i_1 both are increasing linearly. This mode ends when S_1 turns OFF under ZVS.

In Mode 3, a resonance occurs between the inductors (L_1, L_3) and C_{p1}, C_{r1}. During this mode, C_{p1} is charged and C_{r1} is discharged at the same time. When V_{cr1} is reduced to zero, D_1 starts conducting and this mode ends.

In Mode 4, D_1 and D_2 conduct simultaneously. In this mode, i_3 will diminish a lot quicker than i_1 because L_3 is comparatively small. As long as i_3 becomes zero, D_1 will turn OFF. At the point when Mode 4 terminates, D_1 is off then another resonance between L_3 and C_{r1} occurs, in which i_3 oscillates around zero and the amplitude is very small. So i_3 is assumed to be zero in this mode. The current will just flow through L_1 and L_2. This is the end of this mode.

The strengths and weaknesses of the converter is pointed below:

Strengths

1) Soft switching operation.
2) No auxiliary switch is needed.
3) Simple drive circuit required.
4) High frequency operation
5) Wide range of load conditions.

Weaknesses

1) High voltage and current stress.
2) Bulky magnetic elements used.
3) Increased conduction loss.

2.5 An Interleaved Buck Converter

The DC-DC Buck converter circuit in [18] has been analyzed in this section. Interleaved multiphase converters are used to achieve better dynamic performance, lower current ripple, lower losses per switch for an easier thermal design. The converter facilitates high frequency operation. Here, a ZCT scheme is proposed, which addresses the switch turn-on and diode recovery losses using an interleaved buck converter configuration with small auxiliary inductors, as shown in Figure 6.

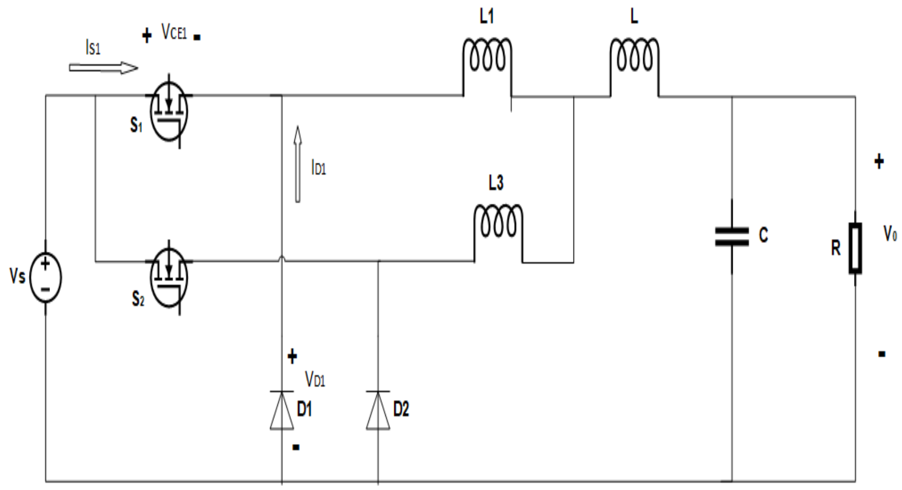

Figure 6: Interleaved zct buck converter in [18]

During one switching cycle, the circuit goes through six stages. At the beginning, the switch S_1 turns on at ZCS. The current commutes from L_2 to L_1 where V_s is the input voltage. Through inductance L_1 and L_2, the current during the transition is controlled and reduces the losses associated with the reverse recovery of D_2. When the switch S_1 turns off, the diode D_1 turns on to manage the main inductor current.

In the ZCT buck converter, two switches are operated at the same duty cycle. Since both switches use the same relatively large output inductor L, any duty-cycle mismatches would result in only small mismatches in the average switch currents. As a result, nearly equal average-current sharing between the two switches is accomplished automatically, which is consistent with the results reported in for the interleaved boost converters.

The strengths and weaknesses of the converter is pointed below:

Strengths

1) Reduced voltage and current stress on the main switch.
2) Wide range of operating duty ratios.
3) Interleaved operation.
4) Soft switching.
5) Reduced current ripple.

Weaknesses

1) High peak current in the auxiliary switch.
2) Increased conduction losses.
3) Complicated control circuit.

II. CONCLUSION

A detailed study on different soft switched buck converters is presented with their merits and demerits. Coupled inductor-based converter structure is analysed to reduce output current ripple. The buck converter performance can be greatly improved in terms of current ripple reduction, reduced switching loss, low EMI, reduced switch voltage/current stress, increased reliability, efficiency, improved power density, size, weight and space reduction with few modifications in existing buck converter structure. Coupled inductor-based converter structure is analysed to reduce output current ripple.

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