International Journal of Engineering Research and General Science Volume 3, Issue 4, Part-2, July-August, 2015
ISSN 2091-2730

Switched Inductor Quadratic Buck Converter

Rosemary Mathai[1], Sheela Joseph[2], Sini Paul[3]
M.Tech Student[1], Professor[2], Associate Professor[3]
rosemarymathai.mec@gmail.com

Abstract— A dc-dc converter featuring a steep step down of the input voltage is presented. The proposed converter uses two quadratic buck converters integrated with switched inductor structure. The structure formed by two inductors and two diodes is known as switched inductor structure. When the switch is on, the inductors are charged in series and when the switch is off, the inductors are discharged in parallel in switched inductor structure. The dc voltage conversion ratio of this converter has a quadratic dependency on duty cycle, providing a large step down. The stress voltage over the switches is reduced as compared to the quadratic buck converter. A complete theoretical analysis of the converter is done in continuous conduction mode. Also simulation results are presented which verify the theoretical analysis.

Keywords— quadratic, switched inductor, switch voltage stress, voltage conversion ratio

INTRODUCTION

The conventional buck converter whose voltage conversion ratio is the duty cycle, cannot provide a steep step-down of the line voltage, as required by modern applications. Certain applications such as microprocessors and on-board voltage regulators in PCs and laptops require very wide voltage step-down factor. The buck converter when integrated with switched inductor structure [2], high voltage conversion can be achieved. But the switch voltage stress is greater than input voltage. The buck quadratic PWM soft-single-switched (SSS) converter can provide a voltage conversion which have a quadratic dependency on duty cycle, but again switch stress is greater than input voltage [3]. The quadratic buck self-resonant (SR) PWM converter can achieve quadratic voltage gain and also switch stress is low [4]. But the number of switches is three and number of components is high.

The quadratic buck converter can achieve quadratic voltage gain and also one switch is used [5]-[7]. Here also switch voltage stress is high. Then double quadratic buck converter can achieve quadratic voltage gain and switch voltage stress is less than input voltage [1].

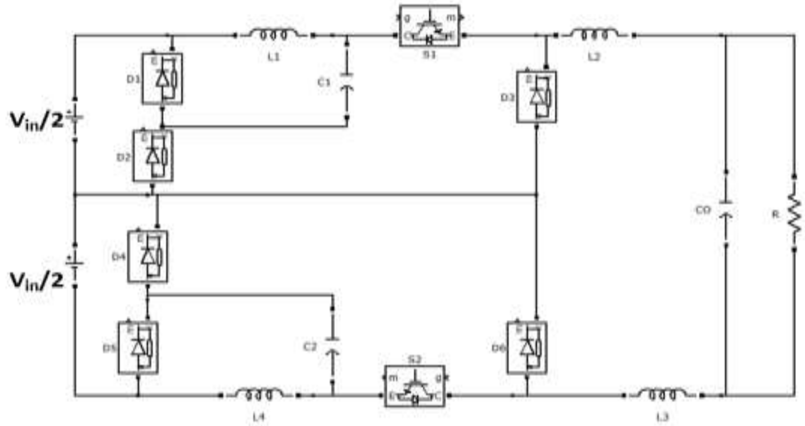

Fig 1: Double quadratic buck converter

Double quadratic buck converter is shown in fig.1 [1]. The double quadratic buck converter is characterized by average output voltage to be lower than input voltage, and the voltage of intermediate capacitor also to be lower than the input voltage. Furthermore, it has high gain ratio compared to the conventional buck converter. In this structure, both the power supply and the intermediate capacitor will behave as voltage source. The load should behave as a current source and the current on the intermediate capacitor is given by the difference between the current across the inductor L_1 and the current in the switch S_1. Because of its symmetrical topology, the lower components have the same behavior of the respective upper component.

When switched inductor structure is combined with buck, buck-boost, Cuk, Sepic, Zeta converters to get a step down function. In this paper two quadratic buck converter are integrated with switched inductor structure to obtain a steep step down of the input voltage.

SWITCHED INDUCTOR QUADRATIC BUCK CONVERTER

The proposed converter is shown in fig.2. For symmetry, the value of inductors L_1 and L_4 are equal and also L_2 and L_3. Also, the capacitors C_1=C_2 and voltage across each capacitor is taken as $V_C/2$. When compared to double quadratic buck converter, the proposed converter uses only one source.

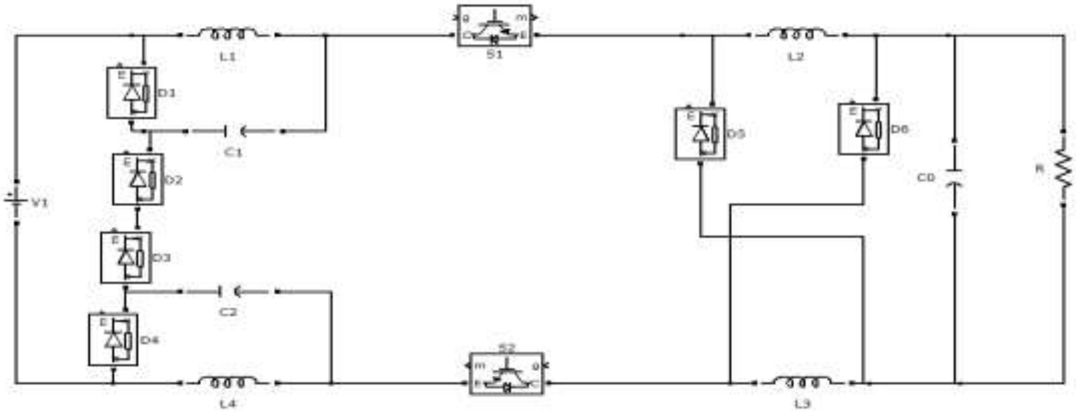

Fig 2: switched inductor quadratic buck converter

PRINCIPLE OF OPERATION

Fig.2 shows the basic circuit diagram of the switched inductor quadratic buck converter in CCM. The inductors L_1, L_2 and diodes D_4, D_5 form the switched inductor structure. There are two stages of operation for this circuit.

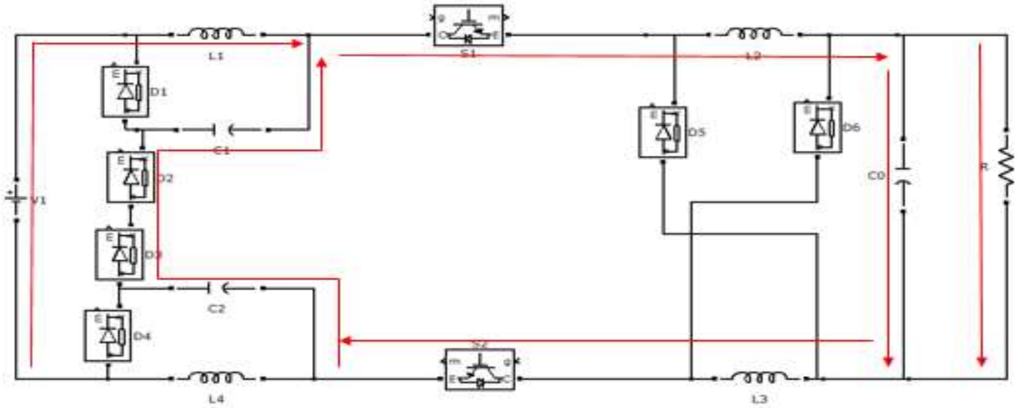

Fig 3: mode 1 operation

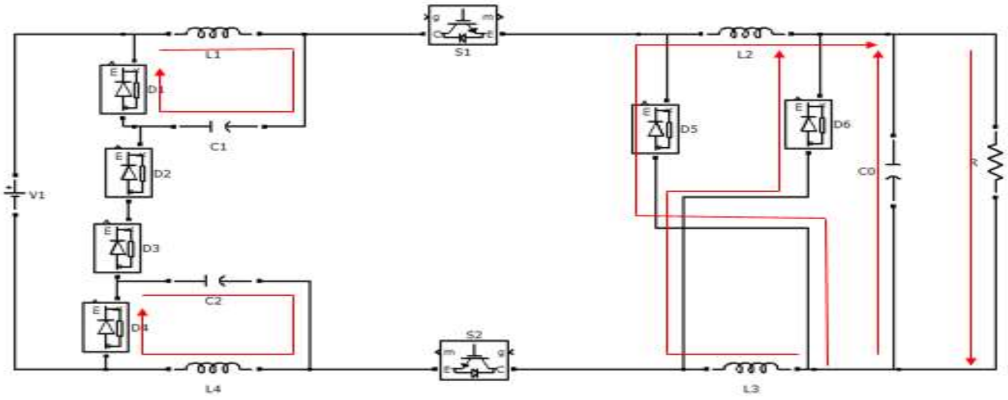

Fig 4: Mode 2 operation

The equivalent circuit corresponding to stage 1 is shown in fig.3. During this interval, both the switches are ON. The input voltage V_1 appears in series across the inductors. The voltage across L_1 is given by

$$v_{L1(t)} = \frac{V_1 - V_C}{2} = L_1 \frac{di_{L1}(t)}{dt}$$

The current through L_1 is given by,

$$i_{L1(t)} = \frac{1}{L_1}\int_0^t v_{L1(t)dt} = \frac{V_1 - V_C}{2L_1}(t) + i_{L1}(0),$$

Where $i_{L1}(0)$ is the initial current in the inductor L_1 at time t=0. The peak current through L_1 is

$$i_{L1}(DT) = \frac{V_1 - V_C}{2L_1}DT + i_{L1}(0),$$

And the peak to peak current of L_1 is

$$\Delta i_{L1} = i_{L1}(DT) - i_{L1}(0) = \frac{V_1 - V_C}{2L_1}DT$$

The voltage across inductor L_2 is given by

$$v_{L2(t)} = \frac{V_C - V_0}{2} = L_2 \frac{di_{L2}(t)}{dt}$$

Similarly,
The peak to peak current of L_2 is

$$\Delta i_{L2} = i_{L2}(DT) - i_{L2}(0) = \frac{V_C - V_0}{2L_2}DT$$

The equivalent circuit corresponding to stage2 is shown in fig.4. During this interval, both the switches are OFF. The inductor L_1 and L_4 begins to discharge through capacitors C_1 and C_2 respectively. The voltage across L_1 is given by

$$v_{L1(t)} = \frac{-V_C}{2}$$

The current through L_1 is given by,

$$i_{L1(t)} = \frac{-V_C}{2L_1}(t - DT) + i_{L1}(DT),$$

Where $i_{L1}(DT)$ is the initial current in the inductor L_1 at time t=DT. At time t = T, the value of inductor current is

$$i_{L1}(DT) = \frac{-V_C}{2L_1}(T - DT) + i_{L1}(DT),$$

Thus, the peak to peak current of L_1 is

$$\Delta i_{L1} = i_{L1}(T) - i_{L1}(DT) = \frac{-V_C}{2L_1}T(1 - D)$$

The voltage across inductor L_2 is given by

$$v_{L2(t)} = -V_0$$

Similarly,
And the peak to peak current of L_2 is

$$\Delta i_{L2} = i_{L2}(T) - i_{L2}(DT) = \frac{-V_0}{2L_2} T(1-D)$$

CIRCUIT ANALYSIS

By the principle of volt-sec balance, the average steady state DC voltage across the inductor is zero. Let us first derive the voltage-time relation for L_1.

$$\frac{(V_1 - V_C)}{2} DT + (\frac{-V_C}{2})(1-D)T = 0$$

Yielding,

$$V_C = DV_1$$

Similarly, applying volt-sec balance for L_2,

$$\frac{(V_C - V_0)}{2} DT + (-V_0)(1-D)T = 0$$

Yielding,

$$V_0 = \frac{DV_C}{2-D}$$

Thus, voltage gain

$$\frac{V_0}{V_1} = \frac{D^2}{2-D}$$

The peak value of inductor current is given by,

$$i_{L2}(DT) = \frac{(V_C - V_{0)}}{2L_2} DT + \ i_{L2}(0)$$

At boundary between continuous and discontinuous modes, the inductor current is zero, i.e., $i_{L2}(0)$=0. Therefore, above eq. reduces to

$$\Delta i_{L2} = i_{L2}(DT) = \frac{(V_C - V_{0)}}{2L_2} DT$$

Similarly,

$$\Delta i_{L1} = i_{L1}(DT) = \frac{V_1 - V_C}{2L_1} DT$$

Since, the L-C filter networks are similar to the conventional buck stage, the equations for minimum values of filter capacitors can be obtained by similar methods.

$$C_{Omin} = \frac{(1-D)V_O {T_s}^2}{8L_2 \Delta V_{c0}}$$

$$C_{1min} = \frac{(1-D)V_c {T_s}^2}{8L_1 \Delta V_c}$$

SIMULATION RESULTS

The switched inductor quadratic buck converter with the following specifications is considered: $V_1 = 400$ V, $f_s = 50$ kHz and duty ratio, D= 0.5 and is constructed using MATLAB/Simulink simulator. The ripple voltage at the output is designed to be 1% of the average output voltage. The ripple current in the inductor is designed to be 10% of the total current, in continuous conduction mode. Using the design equations obtained in above section, the values of inductors and capacitors are found to be: L_1= 8mH, L_2= 0.866mH, C_o = 1μF and C_1 = 22μF. Fig. 5 shows the Simulink diagram of the proposed converter.

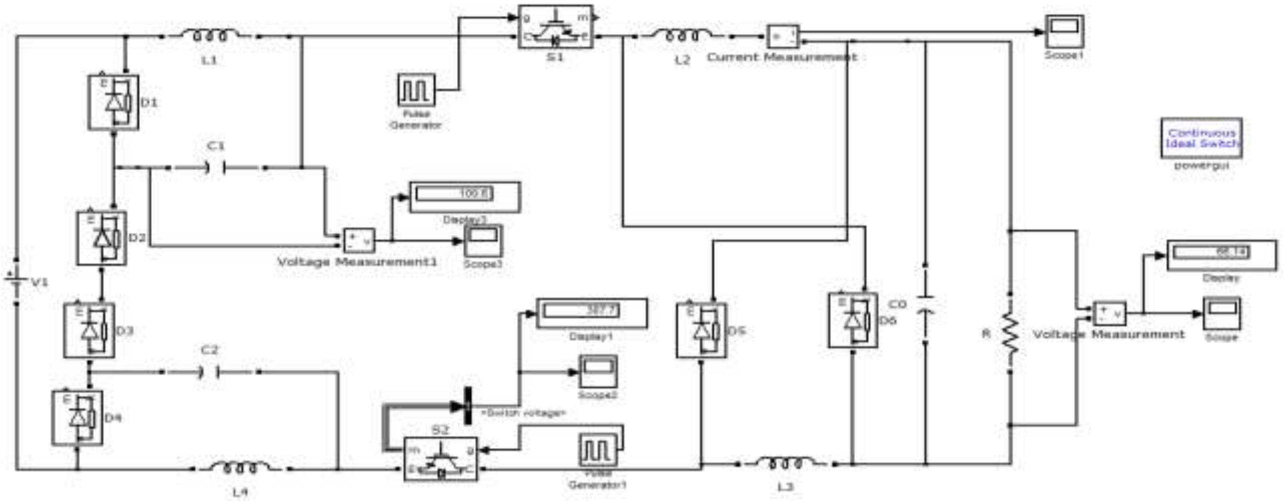

Fig 5: Simulink model of switched inductor quadratic buck converter

Gate pulse is given with a duty ratio of 50%. The gate pulse given to both the switches are same and is shown in fig.6. The voltage stress across the switch is measured to be 300V and is shown in fig. 7. The output voltage is shown in fig. 8 and is measured to be 66V.

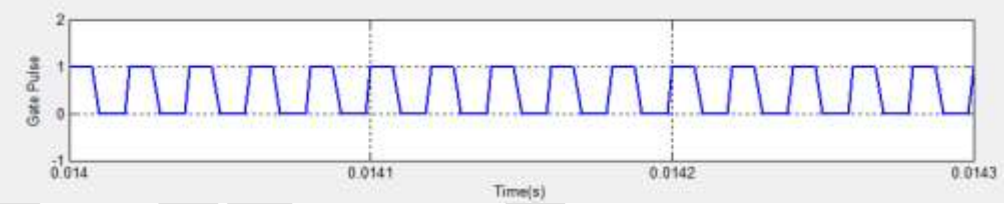

Fig 6: Gate pulse to switch

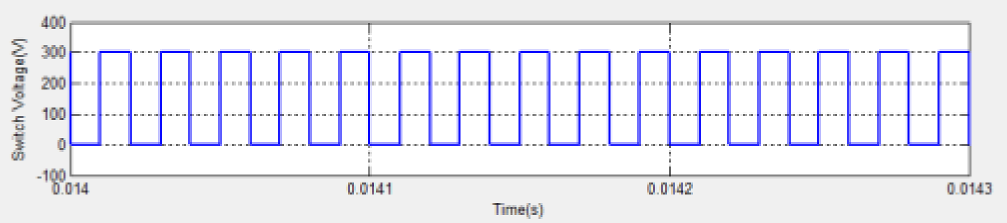

Fig 7: Voltage across the switch

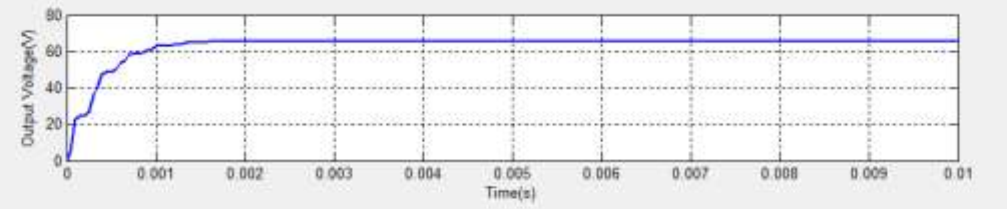

Fig 8: Output Voltage

Then the performance analysis of four converters is done. The performance comparison is done with following parameters: Input voltage=400V, switching frequency=50 kHz, Duty Cycle=50%.The performance is summarized in the following table.

Table 1: Comparison of topologies

Converter Type	Output Voltage(V)	Switch Voltage(V)
Conventional Buck Converter	200	400
Quadratic Buck Converter	100	600
Double Quadratic Buck Converter	100	300
Switched Inductor Quadratic Buck Converter	66	300

From the table it can be seen that when switched inductor quadratic buck converter is used high voltage conversion can be achieved with less switch voltage stress.

CONCLUSIONS

The study of switched inductor quadratic buck converter is presented in this paper. The stages of operation and circuit analysis of the proposed converter is done in continuous conduction mode. Simulation results are presented for continuous conduction mode and show low value in the output voltage over the input voltage, providing the high conversion rate of the converter. With the help of proposed converter, high switching frequencies can be obtained. From the above table, it can be seen that switched inductor quadratic buck converter can provide steep step down of the voltage and reduced switch voltage stress can be obtained.

REFERENCES:

[1] Francieli L. de Sa, Caio V. B. Eiterer, Domingo Ruiz-Caballero, Samir A. Mussa, “Double Quadratic Buck Converter,” IEEE Proc. In Circuits and Systems, pp. 36-43, 2013.

[2] Boris Axelrod, Yefim Berkovich, Adrian Ioinovici, “Single-Stage Single-Switch Switched-Capacitor Buck/Buck-Boost-Type Converter,” IEEE Trans. On Aerospace and Electronic Systems, vol. 45, no. 2, pp. 419-430, April 2009.

[3] Lucio dos Reis Barbosa, Joao Batista Vieira, Luiz Carlos de Freitas, Marcio da Silva Vilela and Valdeir Jose Farias, “A Buck Quadratic PWM Soft-Switching Converter Using a Single Active Switch,” IEEE Trans. on Power Electronics, vol. 14, no. 3, pp. 445-453, May 1999.

[4] Vincius Miranda Pacheco, Acrisio Jose do Nascimento, Valdeir Jose Farias, Joao Batista Vieira, and Luiz Carlos de Freitas, “A Quadratic Buck Converter with Lossless Commutation,” IEEE Trans On Industrial Electronics, vol. 47, no. 2, pp. 264-272, April 2000.

[5] Carbajal Gutierrez, “Modeling of a Single-Switch Quadratic Buck Converter,” IEEE Trans. on Aerospace And Electronic Systems, vol. 41, no. 4, pp. 1451-1457, Oct. 2005.

[6] Agasthya Ayachit and Marian K. Kazimierczuk, “Steady-State Analysis of PWM Quadratic Buck Converter in CCM,” IEEE Proc. on Aerospace and Electronic Systems, pp. 49-52, 2013.

7] Agasthya Ayachit and Marian K. Kazimierczuk, “Power Losses and Efficiency Analysis of the Quadratic Buck Converter in CCM,” IEEE Proc. In Circuits and Systems, pp.463-466, 2014

[8] Boris Axelrod, Yefim Berkovich, Adrian Ioinovici, “Switched-Capacitor/Switched-Inductor Structures for Getting Transformerless Hybrid DC–DC PWM Converters,” IEEE Trans. On Circuits and Systems, vol. 55, no. 2, pp. 687-696, Mar. 2008.

[9] Yuanmao Ye, K. W. E. Cheng, “A Family of Single-Stage Switched-Capacitor–Inductor PWM Converters,” IEEE Trans. On Power Electronics,” vol. 28, no. 11, pp. 5196-5205, Nov. 2013.

[10] K. I. Hwu , T. J. Peng, “A Novel Buck–Boost Converter Combining KY and Buck Converters,” IEEE Trans. On Power Electronics,” vol. 27, no. 5, pp. 2236-2241, May. 2012.

[11] Il-Oun Lee, Shin-Young Cho, and Gun-Woo Moon, “Interleaved Buck Converter Having Low Switching Losses and Improved Step-Down Conversion Ratio,” IEEE Trans. On Power Electronics,” vol. 27, no. 8, pp. 3664-3675, May. 2012.

[12] Yu Chen, Zhihao Zhong, and Yong Kang, “Design and Implementation of a Transformerless Single-Stage Single-Switch Double-Buck Converter With Low DC-link Voltage, High Step-Down, and Constant Input Power Factor Features,” IEEE Trans. On Power Electronics,” vol. 29, no. 12, pp. 6660-6671, Dec. 2012