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ANALYSIS, DESIGN AND IMPLEMENTATION OF ZERO-CURRENT-SWITCHING RESONANT CONVERTER DC-DC BUCK CONVERTER

IRFAN JAMIL[1], ZHAO JINQUAN[2] & REHAN JAMIL[3]

[1,2]Department of Energy & Electrical Engineering, Hohai University, Nanjing China

[3]Department of Electrical Engr., Federal Urdu University of Arts, Science & Technology, Islamabad Pakistan

ABSTRACT

This paper presents a Buck type circuit structure, the designing of ZCS resonant Buck converter and analysis of the working principles involved. The designed buck converter uses ZCS technique and the function is realized so that the power form is converted from 12V DC to 5V DC (1A). A detailed analysis of zero current switching buck converters is performed and a mathematical analysis of the mode of operation is also presented. In order to reduce the switching losses in associated with conventional converters; resonant inductor and resonant capacitor (LC resonant circuit) is applied which helps to turn on-off the switch at zero current. The dc-dc buck converter receives the energy from the input source, when the switch is turned-on. If the switch is turned-off the LC resonant circuit pumps the energy by ensuring that the current does not come to zero. During the hardware implementation Ton, Toff, duty cycle & operating frequency values were determined and thoroughly tuned through the NE555 IC circuit. As a result of this various waveforms across capacitors, inductors and load resistor were observed. A simulation study was carried out and the effectiveness of the designed converter is verified by PSpice simulation results.

KEYWORDS: Dc-Dc Buck, ZCS, Resonant Converter, MOSFET, Timer, Simulation

INTRODUCTION

In recent years, with the state development of power electronic devices, development of control techniques and the increasing demand of high-quality power supply, power electronics technology has invoked widely attention from research scholars over the world. Power electronics technology has been gradually taken up in civilian industrial areas to cope with these demands. The various converters for different requirements are developed and related technology is studied by scientists to accomplish the research of new converters.

This work focuses on the issues related with the designing of ZCS buck converter. The main objective of the work is to append zero current switching techniques, LC Resonant circuits and buck topology. There is major requirement for changing the voltage from one level to another. Dc-dc converters can be utilized for this purpose because they efficiently change the dc electrical power into a different impedance level [2]. Buck converters are one of the most important components of the circuit which operates the voltage from the desired level to fixed level [10].

The dc-dc buck converter is a step down converter, if the energy is received from input source while switch is turned-on. And if the switch is turned-off the LC resonant circuit (referred to as the “Tank Circuit”) pumps the energy by ensuring that the current does not reach to zero. When the inductor current hits zero, the switch engages. Hence, it is referred to as Zero current switching. The Quasi Resonant converter can be considered as combination of resonant switching & PWM switching. The resulting hybrid converter combines the properties of a resonant switch network and a conventional PWM converter. It consists of the switch MOSFET and LC Resonant Circuit (Tank Circuit) [12].

This paper also deals with a simple buck converter topology with switching resonant element MOSFET. It is switched on and off using a 555 NE timer with switching frequency of 42KHZ. The converter is operating with Input source of 12Vdc which provides a regulated output voltage of 5Vdc (1 A). The operating principle of the converter topology is analyzed and operating modes are studied [13]. The performance of the ZCS buck converter is recorded and examined for theoretical verification, waveform results and pspice simulation.

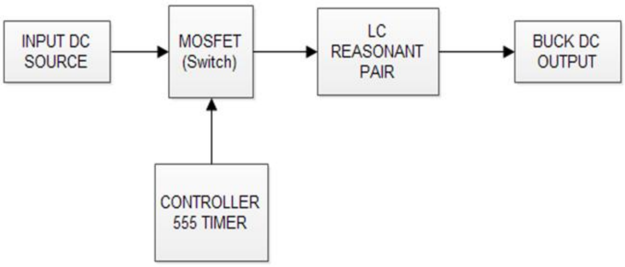


Figure 1: Block Diagram of Proposed Converter

REASONANT CONVERTER

The converters which employ ZC and/or ZV switching technique are usually called resonant converters. The resonant converters were investigated in early 1980s as they can achieve very low switching loss thus enabling the resonant topologies to work with a high switching frequency. In these converters, some form of L-C resonance is used, which is why they are known as resonant converters [1]. Resonant converters are repelled or driven with constant pulse duration at a variable frequency to maintain control over output voltage. The pulse duration is required to be equal to half of the time of resonant period for switching at the zero current or voltage crossing points. The resonant converters contain the serial or parallel connections of inductors and capacitors to enable the switch to achieve the ZCS & ZVS under resonance conditions, the result effects switching losses, switching stress and EMI problems [3], [5], [7], [15]. The switching resonant converter controls the output voltage through switching frequency, and generally can be sub-classified in ZCS Converter and ZVS Converter [5]. There are many variations that can be placed at the primary or secondary side of the transformer and alternatively called serial or parallel resonant circuit which indicates whether it is required to turn off the transistor when current or voltage is zero. So far these are distinguished as ZVS and ZCS resonant converters. Resonant converts are combination of converter topologies or switching strategies that in consequence produce zero voltage and/or zero current switching.

Zero Current Switching Technique

In switching technique, the mainly research carried out thus for pertains to hard switching and soft switching techniques. Hard switching technique relates to the stressful switching behaviors of power electronics devices whilst soft switching techniques are applied to eliminate the harmful effects of hard switching. Therefore soft switching techniques are more significantly developed and are normally applied to reduce the problems of switching losses in dc-dc power converters operating with high switching frequency [3], [5], [7].

Generally there are two types of techniques known as Zero-current switching (ZCS) and Zero-Voltage Switching (ZVS) which are called conventionally employed soft-switching methods [11].When the switch current is reached to zero at the switching instants, it is usually known as Zero-Current switching (ZCS) and if certainly the switch voltage is reached to zero at switching instants, it is usually known as Zero-voltage switching (ZVS). The main difference between the two is to do with when the switching occurs [8].

The ZCS is a type of soft switching technique which was first proposed by F C Y Lee al (1987) [12]. Reducing stress on the switching components is a major incentive for resonant operation; and we need to understand ways through which that might be fulfilled. The simplest approach and the one to which most of this paper presents ZCS operation of a converter switch must be such that involves the current flowing through the switch being induced to rise gradually just after the switch is turned-on so that it has a ZCS turn-on. The switch current must also be induced to descend gradually just before the switch is turned-off so that it can have a ZCS turn-off. The ZCS turn-on feature of a converter switch can be made certain by simply connecting an inductor in series as the current flowing through an inductor cannot change immediately. Connecting an inductor in series with a switch also ensures that the current flowing through the other devices in the converter is gradually drawn back so that they can turn-off with ZCS. The ZCS turn-off of a converter switch can be made certain by providing another path for the current to flow through, just before the switch is turned off. Since the switch has a relatively small voltage drop, the other path must be at a lower voltage potential so that current can be turned away from the switch [4].

CIRCUIT ANALYSIS DESCRIPTION

The Dc-Dc buck converter has simple principle of operation in family of converters. However circuit analysis of buck converter has widely related to discussions of topology with ZCS resonant converters in power electronics.

Buck Converter Operation

The original concept of a “Buck Converter” requires that the input voltage is chopped, in amplitude and develops the lower amplitude voltage at the output. A buck converter has switch-mode dc-dc conversion with the advantages of simplicity and low cost. The fig.1 shows a simplified non-isolated buck converter, which allows a dc input and employs pulse-width modulation (PWM) of switching frequency to control the output of an internal power MOSFET. An act in concert external diode, external inductor and output capacitor, produce the regulated dc output. A Buck or step down converters are designed to produce an average output voltage lower than the input source voltage [2].

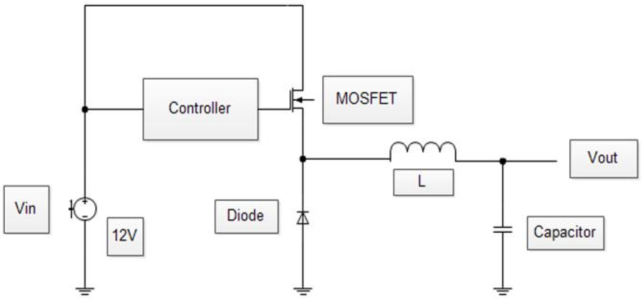


Figure 2: Buck Converter Topology

ZCS Resonant Buck Converter

The present invention relates to ZCS Resonant converters such as Buck ZCS resonant converters for resolving the high- frequency switching losses and reducing circuit volume [3]. The switches of ZCS resonant converters turn ON and OFF at zero current due to the current produced by LC resonance flows through the switch. The resonant circuit consists of a switch S, inductor L_r , and capacitor C_r . The LC circuit is used to store and transfer energy from input to output in similar manner to the resonant converters [9]. To achieve ZCS, the inductor L_r is connected in series with power switch S so that it has ZCS turn–on. C_r is connected across the main power diode. When the switch current is zero there is a current flowing through the internal capacitance due to finite slope of switch voltage at turn off. This current flow causes power dissipation in the switch and sets the high switching frequency [11]. In ZCS techniques, the turn off losing of switching devices are almost eradicated. Therefore the converter can be functioned at higher frequencies, in the range of 1MHz to 2MHz. The advantages of Buck ZCS resonant converter that they have low switching losses due to resonance techniques, easy drive on switches and low stress on switching elements (MOSFET) as well [14].

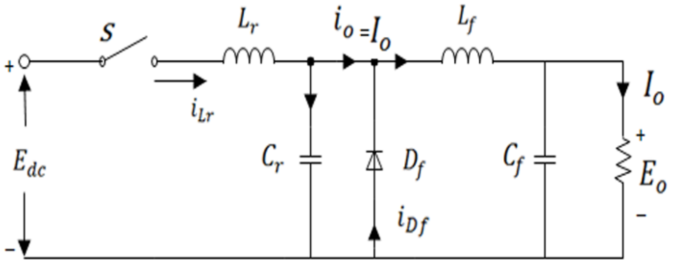
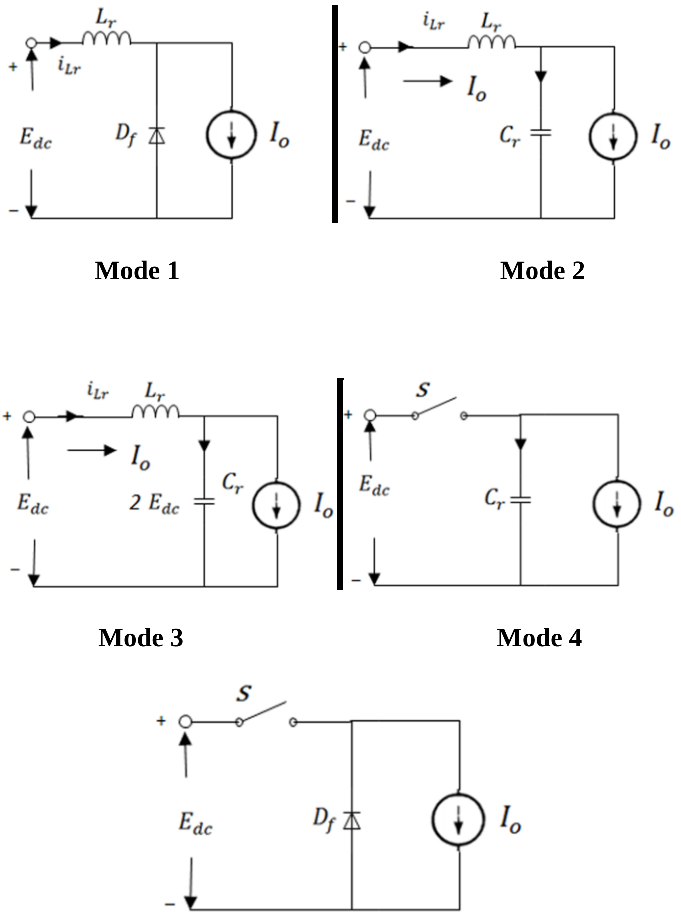


Figure 3: ZCS Reasonant Buck Converter



Mode 1

Mode 2

Mode 3

Mode 4

Mode 5

Figure 4: Equivalent Mode of ZCS Reasonant Buck Converter

Analysis Mode of Operation

The circuit discussions are made on Half-wave mode of operations which can be divided into 5 operating modes. The circuit operates in the half-wave mode if the switch is unilateral which means there is no antiparallel diode across the switch S. if the switch is bilateral that means the diode is available across the switch S and it works in full-wave mode [14]. Assume the time origin, t=0, at the beginning of each mode. We operate from a regulated DC voltage supply E_{dc}= 12V, Assuming that a purely resistive load is used approximate current flowing through the load resistance is obtained as: I_o = 12/90=0.133A. Resonant inductor L_r = 2µH, Resonant capacitor C_r=($C_3 + C_4 + C_5$)= 1.32µF , R_o= 90K

Mode 1 (0≤t≤t_1): When the switch (S) is turned-on at t=0, the current i_{L_r} through the resonant inductor which rises linearly from zero is given by

$$i_{L_r} = \frac{E_{dc}}{L_r}\, t \tag{1}$$

The remainder of I_o and i_{L_r} flows through D_f ($i_{Df} = I_o - i_{L_r}$). The voltage across C remains zero during the entire conduction period of D_f. When i_{L_r}=I_o, then i_{Df} becomes zero and D_f turns off when this mode ends at t=t_1.

$$\therefore \quad t_1 = \frac{I_o\, L_r}{E_{dc}}\ , \quad V_{cr} = 0\ , \tag{2}$$

$$t_1 = 0.022 * 10^{-6}\ Sec \tag{3}$$

Mode 2 (0≤t≤t_2): In this mode, switch (S) remains ON but diode D_f is OFF. When the diode (D_f) current reduces to zero, the resonant capacitor C_r is charged resonantly by a current (i_{L_r} -I_o).

The inductor current is given by

$$\text{Where } i_{L_r} = I_o + \frac{E_{dc}}{Z_r} \sin \omega_r\, t \tag{4}$$

$$Z_r = \sqrt{\frac{L_r}{C_r}} \tag{5}$$

$$\omega_r = \frac{1}{\sqrt{L_r . C_r}} \tag{6}$$

The capacitor voltage is given by

$$V_{cr} = E_{dc}\,(1- \cos \omega_r\, .\, t) \tag{7}$$

The peak current which occurs at

$$t = \frac{\pi}{2}\sqrt{L_r\, .\, C_r}\ \text{is given by} \tag{8}$$

$$I_p = E_{dc}\sqrt{\frac{L_r}{C_r}} + I_o \tag{9}$$

The peak capacitor voltage is given by

$$V_{c(peak)} = 2\, E_{dc} \tag{10}$$

Condition for current zero switching is

$$Z_r \leq \frac{E_{dc}}{I_o} \tag{11}$$

This mode ends at t=t_2 when i_{L_r}= I_o

Therefore $t_2 = \pi\sqrt{L_r\,.\,C_r}$ => $t_2 = 5.065 * 10^{-6}\,Sec$ (12)

Mode 3 (0≤t≤t_3): At time t= t_3 , During this mode, the voltage across capacitor and current through the inductor are given by

The inductor current i_{L_r} is

$$i_{L_r} = I_o - E_{dc}\sqrt{\frac{L_r}{C_r}}\sin\omega_r\,.\,t \quad (13)$$

The capacitor voltage is given by

$$V_{cr} = 2\,E_{dc}\,.\,\cos\omega_r\,.\,t \quad (14)$$

This mode ends at (t=t_3) , when i_{L_r}=0 and V_{cr} = V_{c_3}

Thus From the eq. (13)

$$I_o = E_{dc}\sqrt{\frac{L_r}{C_r}}\sin\omega_r\,.\,t_3 \quad \text{or} \quad (15)$$

$$t_3 = \sqrt{L_r\,.\,C_r}\,\sin^{-1}\left(\frac{I_o}{E_{dc}}\sqrt{\frac{L_r}{C_r}}\right) \quad (16)$$

$$t_3 = 1.27 * 10^{-6}\,Sec \quad (17)$$

Mode 4 (0≤t≤t_4): At time t= t_4 , The switch is OFF during this period. The capacitor C_r commences to discharge through the output with constant output current (I_o) and V_{cr} which decreases linearly.

The capacitor supplies load current and thus the capacitor voltage V_{cr} is given by

$$V_{cr} = V_{cr_3} - \frac{I_o}{C_r}\,t \quad (18)$$

This mode ends at t=t_4 when V_{cr} = 0

From above equation (18)

$$t_4 = \frac{V_{cr_3}\,.\,C_r}{I_o} \quad (19)$$

$$t_4 = 234.56 * 10^{-6}\,Sec \quad (20)$$

Mode 5 (0≤t≤t_5): In this mode, at the beginning of t_5 period, V_{cr} tends to be negative due to the resonating, $L_r\,.\,C_r$ circuit. Therefore D_f conducts and the load current I_o flows through D_f . The peak resonating current must be higher than I_o for a half-wave ZCS converter. This mode ends at time t = t_5 when the switch (S) is turned-on again and the next cycle starts. Thus, the cycle is repeated which means that t_5= T- (t_1+t_2+t_3+t_4).

For the sake of simplicity we assume $t_5 = 0$

Therefore $T_{on} = t_1 + t_2 + t_3$ (21)

$$T_{on} = (0.02 + 5.065 + 1.27)10^{-6}\,Sec = 6.36 * 10^{-6} Sec \quad (22)$$

$$T_{off} = t_4 + t_5 = 23.56 * 10^{-6} Sec \quad (23)$$

$$T = T_{on} + T_{off} = 240.92 * 10^{-6}\,Sec \quad (24)$$

Duty ratio $= {}^{T_{on}}/_{T} = 2.6\%$ (25)

Frequency of operation $= {}^{1}/_{T} = 41.50\ \mathrm{KHz}$ (26)

DESIGN CONSIDERATION

The ZCS buck converter design consists chiefly of two parts. One is power the circuit and the other is the control circuit. The power and control circuits are designed with following specifications.

Table 1: ZCS Buck Converter

Parameters	Values
Input	12V
Output	5V, 1A, 5W
Resonant Inductor	2µH
Resonant Capacitor	1.32µF
Mosfet	NR411
Switching Frequency	42KHZ
Topology	Isolated Buck Converter
Controller	NE 555 Timer
Output Resistor R_o	90K

In circuit description, resonant inductor and resonant capacitor are formed by a LC resonant pair which is used to generate the resonance. This pair is produced via sinusoidal waveforms from the dc input. The diode operates that blocks the negative half cycle of generated from the LC resonant pair. The LC filter is used to smooth the waveforms which eliminate harmonics, ripples and noise. In this circuit the topology used is an isolated buck converter & controller timer NE555 timer (Control circuit) which controls the switching element MOSFET IRFZ44 (Power circuit). For ZCS operation, the ON time is fixed and the frequency variation is achieved by varying the OFF time only. For the 555 Timer, the ON time and OFF time equation is given,

T_{on}= 0.693[R_4+R_2] C_2 (R_4= 20K, R_2=47K, C_2= 1nF)

T_{off} =0.693[R_4] C_2

The switching frequency is varied at 42 KHz and variation is done by ensuring a Trim pot R_4 and a diode in parallel across R_4 to bypass the resistor during the ON time. The ON time is set to be 3.6µs and R_2, R_4 & C_2 are calculated from the above equation.

For zero- current switching,

$$I_o = V_{in}\sqrt{\frac{C_r}{L_r}} = 9.748$$

I_o> Output current 1A, so resonant condition gets fulfilled

For Resonant Frequency =1/ (2π$\sqrt{L_r C_r}$) = 98 KHz

The resonant inductor L_r=2 µH, and Resonant capacitor C_r= 1.32µF values are from LC resonant pair. Here in ZCS, when the resonant inductor current reaches to zero then the switch is turned OFF.

SIMULATION & EXPERIMENT RESULTS

In order to understanding the operation of power circuits requires a clear knowledge of the transient behavior of current and voltage waveforms for each and every circuit element at every instant in time. To aid the understanding of the circuit's transient response computer aided simulation software PSpice is used [12]. The simulation shows that the input power supply is providing 12Vdc and output voltage calculated into 5Vdc from two probes of the load resistor Ro. The load resistor Ro probe +Vdc 12.00Vdc and other probe –Vdc 7.053Vdc are shown in fig.5, here output voltage can be gained between two probes values 12.00Vdc-7.053Vdc= 4.947~ 5.00Vdc. Hence simulation results are obtained which show that the output voltage 5Vdc from input supply 12Vdc is ensured. Once output results in the simulation were verified and PCB layout is completed. Various waveforms from an oscilloscope were absorbed and noted down during the practical examination.

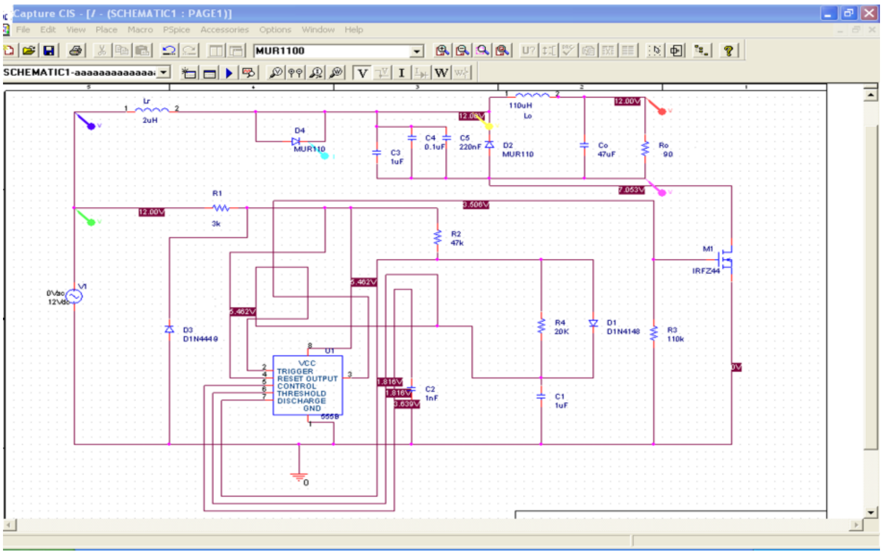
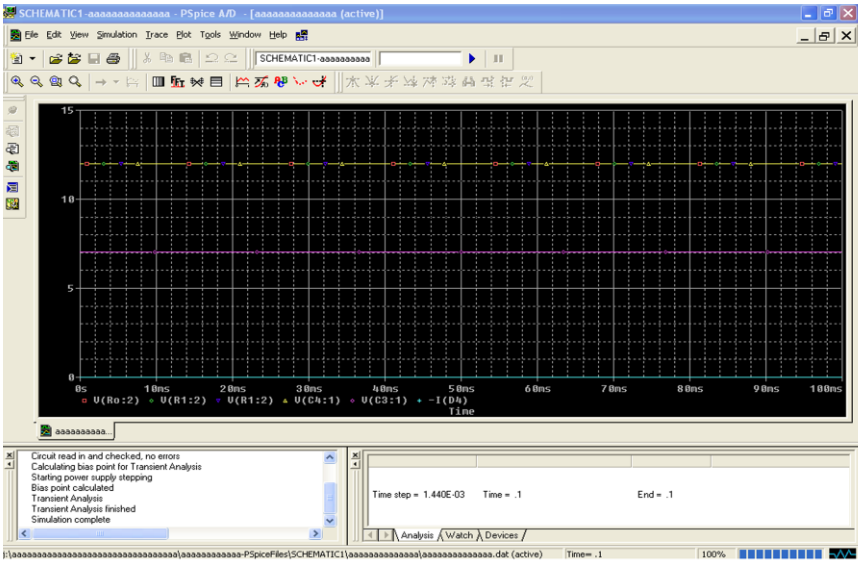


Figure 5: Simulation Results Analysis Diagram of ZCS Buck Converter

The Fig. 6 shows that Simulation results are running, reading and checking circuit and finding no errors. The calculating the bias point for transient analysis and starting power supply stepping. When the bias point calculated of the transient analysis then transient analysis is finished at meanwhile simulation is also completed. The purple color line shows transient value is 7V and yellow line shows that transient value is 12V which is called input voltage from the source. In this way the output voltage should be gained between two transient values 12Vdc-7Vdc= 5Vdc in conclusion which means that the output value of the simulation result is ensured 5V as shown in Fig.6. Simulation analysis output results.



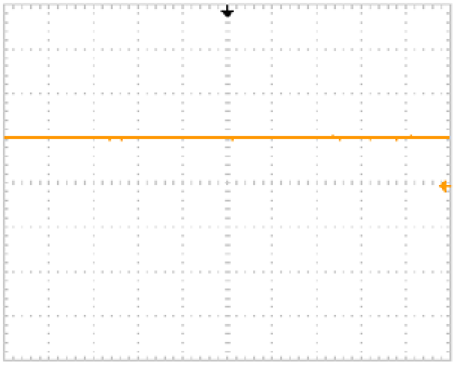
```
Circuit read in and checked, no errors
Calculating bias point for Transient Analysis
Starting power supply stepping
Bias point calculated
Transient Analysis
Transient Analysis finished
Simulation complete
```

```
Time step =  1.440E-03      Time = .1                  End = .1
```

```
j:\aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa\aaaaaaaaaaaa-PSpiceFiles\SCHEMATIC1\aaaaaaaaaaaaaa\aaaaaaaaaaaaaa.dat (active)    Time= .1
```

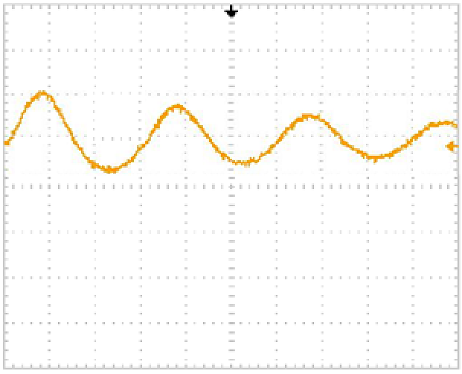
Figure 6: Simulation Analysis Output Results

Fig. 7 shows that output voltage 5Vdc is constant for particular 42 KHz switching frequency. The output voltage can be controlled via switching frequency [5]. If switching frequency increases then output voltage will also increase. In other figures (Fig. 8, Fig. 9, Fig. 10 and Fig. 11 respectively) the waveforms results were absorbed.



CH1   5.00V   M 10.0ms

Figure 7: Output Voltage



CH1   5.00V   M 10.0ms

Figure 8: Voltage across Resistor & Capacitor

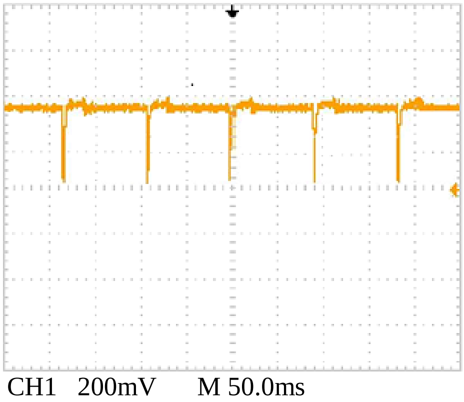


Figure 9: Voltage across Diode

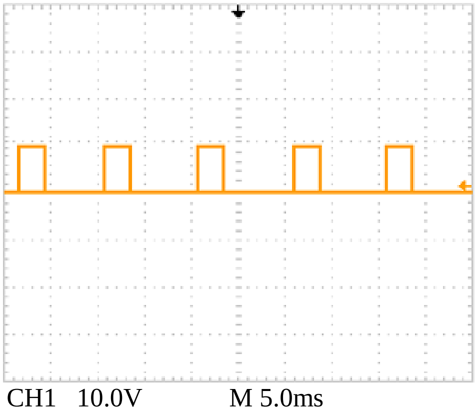


Figure 10: Pluses from 555 Timmer

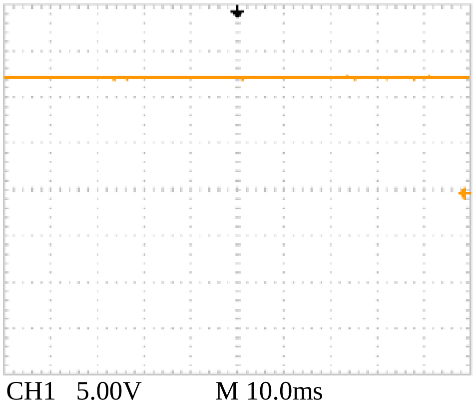


Figure 11: Input Voltage

CONCULSIONS

This paper addresses design analysis & implementation of ZCS Resonant Buck Converter which operates the input voltage from 12Vdc to output voltage 5Vdc (1A). The various modes of operation of ZCS buck converter are studied and tuning the NE 555 timer is done consequently. The waveforms across the capacitors, inductors and load resistor are tested and compared with the theoretical waveforms. The simulation is successfully executed by Pspiec software which shows that the desire output voltage is stable and the performance of the designed converter is ensured. A prototype 5-w (5V/1A) is constructed in hardware. All goals in this paper are discussed such as design analyses, data, tests, simulation, have been documented within.

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AUTHOR'S DETAILS

Irfan Jamil was born in Punjab province, City Multan, Pakistan on Feb 25, 1987. He received his bachelor degree in Electrical Engineering and its Automation from Harbin Engineering University, Harbin, China in 2011. Currently he is pursuing his Master degree at Hohai University, Nanjing, China. During these days he is doing master research as a Visiting Research Scholar at Tsinghua University, Beijing China. His research interest involves in Power electronics and Power system Automation.

Rehan Jamil was also born in Punjab province, City Multan, Pakistan on Feb 25, 1987. He received his bachelor in B.Sc. Electrical (Electronic) Engineering from Federal Urdu University of Arts, Science & Technology, and Islamabad Pakistan in 2009. Currently he is pursuing his Master degree at Yunnan Normal University, Kunming China. His research interest involves in Electronics, Renewable energy power generation.

Prof. Jinquan Zhao was born in Yangquan, Shanxi province, China, on June 26 1972. He received B.S. and Ph.D. degrees, all in electrical engineering, from Shanghai Jiao tong University, Shanghai, China, in 1993 and 2000, respectively. From 1993 to 1995, he was an engineer in Guangzhou Power Company, Guangzhou, China. From December 2000 to September 2003, he was a postdoctoral associate in Cornell University, Ithaca, NY. He was a postdoctoral associate in Tsinghua University, Beijing, China. Currently he is a professor in Electrical Engineering department, Hohai University, Nanjing, China. He has been published more than 28 papers in many international conferences. His research interests in the area of voltage stability analysis and control, OPF and its applications.