DESIGN OF ZERO-CURRENT SWITCHING DC-DC BUCK CONVERTER

NOR AZRINNA BINTI MUHAMAD

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To my dearest father, mother and family for their encouragement and blessing

To my beloved husband and daughter for their support and caring…….

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ABSTRACT

This project presents a zero-current switching (ZCS) DC-DC buck converter design, simulation and application. The converter control uses with ZCS technique to decrease the switching losses. Comparing to conventional buck converter, resonant buck converter includes a resonant tank equipped with resonant inductor and capacitor. Complete design-oriented mathematical calculations were done for ZCS converter. The converter is simulated in OrCAD Capture CIS software with design parameters. The simulation result show that the switching losses using ZCS technique is less compared to conventional buck converter.

ABSTRAK

Projek ini mempersembahkan rekabentuk pensuisan arus-sifar penukar buck DC-DC, simulasi dan aplikasi. Penukar tersebut dikawal dengan menggunakan teknik pensuisan arus-sifar untuk mengurangkan kehilangan kuasa semasa pensuisan. Jika dibandingkan dengan penukar buck konvensional, penukar resonan buck terdiri daripada resonan inductor dan resonan capacitor. Rekabentuk penuh berasaskan perkiraan matematik telah dijalankan bagi penukar buck. Penukar ini disimulasi dengan menggunakan perisian OrCAD Capture CIS. Keputusan simulasi menunjukkan kehilangan kuasa pensuisan menggunakan teknik pensuisan arus-sifar lebih rendah berbanding dengan penukar buck konvensional.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOL	DESCRIPTION
DC	Direct Current
AC	Alternating Current
PWM	Pulse Width Modulation
BJT	Bipolar Junctions Transistor
IGBT	Insulated Gate Bipolar Junction
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
ZCS	Zero Current switching
ZVS	Zero Voltage Switching
QR	Quasi-Resonant
QRC	Quasi-Resonant Circuit
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
LC	Inductor Capacitor
V_s	Input Voltage
L_r	Resonant Inductor
C_r	Resonant Capacitor
f_s	Switching Frequency
f_o	Resonant Frequency

V_o	Output Voltage
I_o	Output Current
L_e	Output Ripple Inductor / Filter Inductor
C_f	Output Ripple Capacitor / Filter Capacitor

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CHAPTER 1

INTRODUCTION

1.1 Overview

Advanced in power electronics in the last few decades led not only to improvements in power devices, but also to new concepts in converter topologies and controls. The various converters for different requirements are developed and related technology is studied by scientist to accomplish the research of new converters.

This work focuses on the issues related with the designing of Zero Current Switching (ZCS) buck converter. The work will append ZCS techniques, LC resonant circuits and buck topology. There is major requirement for changing the voltage from one level to another. Buck converters are one of the most important components of the circuit which operates the voltage from the desired level to fixed level.

This report presents the design procedure of a simple buck converter topology with switching resonant element MOSFET. The operating principle of the converter topology is analysed and operating modes are studied. The performance of the ZCS resonant buck converter is recorded and examined for theoretical verification, waveform results and OrCAD Capture CIS simulation.

1.2 Problem Statement

A buck converter is one of the most important and widely DC-DC converters of modern applications. The buck converters using hard switching technique generate higher switching losses and hence the efficiency becomes low. In order to improve the energy efficiency soft-switching techniques have been proposed to reduce the switching power losses across the power devices. By this reason a buck converter with soft switching technique is develop to increase the efficiency of converter.

1.3 Objectives

The designing of ZCS buck converter for USB power adapter application is the aims of this project. To achieve these aims, the objectives of this report are formulated as follow:

i. To propose soft switching buck converter with ZCS for its switch using as simple circuit as possible.
ii. To compute the optimal values of resonant converter by applying the characteristic curve and mathematical calculation from the circuit configuration.
iii. To simulate the ZCS resonant buck converter using OrCAD Capture CIS software.
iv. To analyse the resonant current and voltage waveforms and the switching voltage and current waveforms.
v. To compare the conventional DC-DC buck converter and the proposed soft-switching DC-DC buck converter in terms of switching loss reduction.

Scope of Project

The scopes of work for this project are:

i. Design ZCS resonant buck converter for 5V, 1.5A USB power adapter
ii. Simulation work using OrCAD Capture CIS as platform
iii. Verification of this resonant converter includes switching power losses, resonant current and voltage waveforms and output current and voltage waveforms

1.4 Layout of Project Report

This section outlines the overall structure of the report and provides a brief explanation for each chapter. This project report contained five chapters.

Chapter 2 describes the losses in switching semiconductor switch which are conduction losses and switching losses. Hard-switching is also known as switching losses. The soft-switching converter, its concept and types which includes zero voltage switching (ZVS) and zero current switching (ZCS) devices are explained. This chapter also discussed hard switching converter topology which is buck converter.

Chapter 3 presents the analysis of ZCS buck converter and its schematic diagram. The theoretical waveforms and mode of operation is discussed in detail.

Chapter 4 discusses the simulation results. The ZCS resonant buck converter is evaluated by simulation study using OrCad Capture CIS. For the comparison purpose, the simulation study of buck converter is also presented.

Chapter 5 summarizes the work undertaken. The chapter concludes by suggesting the potential future research that can be performed, based on the project report work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Power electronics converters are implemented with switching devices that turn on and off while power is being converted from one form to another. The power electronic converters fall generally into six categories:

i. Diode rectifier
It converts AC input voltage to a fixed DC output voltage. The input voltage to rectifier could be either single phase or three phases.

ii. AC to DC Converter (Controlled rectifier)
It converts fixed AC input voltage to a variable DC output voltage. The converter may be fed from single phase or three phases.

iii. AC to AC Converter (AC voltage regulator)
It converts a fixed AC input voltage to variable AC output voltage.

iv. DC to DC Converter (DC chopper)
It converts a fixed DC input voltage to variable DC output voltage or vice versa by varying of duty cycle.

v. DC to AC Converter (Inverter)

It converts a fixed DC input voltage to a fixed AC output voltage.

vi. Static switches

There are called as AC static switches or a DC static switch depends on the supply to these switches either AC or DC supply.

Power converters typically consist of semiconductor devices such as transistors and diodes, energy storage elements such as inductors and capacitors, and some sort of controller to regulate the output voltage. Transistor type devices like BJTs (Bipolar Junctions Transistors), MOSFET (Metal Oxide Silicone Field Effect Transistors) and IGBTs (Insulated Gate Bipolar Transistors) are used as switches in power electronic converters. These devices can be operated in higher switching frequencies which help to reduce converter size.

2.2 Literature Review

(Yuang-Shung Lee and Guo-Tian Chen, 2004) presented quasi-resonant converter to achieve the ZCS for reducing the loss of bi-directional converters as shown in Figure 2.1. The results indicate that the switching loss, switching waveform and EMI emission is reduced in the battery charging system with a battery equalizer. The most disadvantage of this topology is the power MOSFETs of the quasi-resonant ZCS converter have not been exactly turned on at the zero current states.

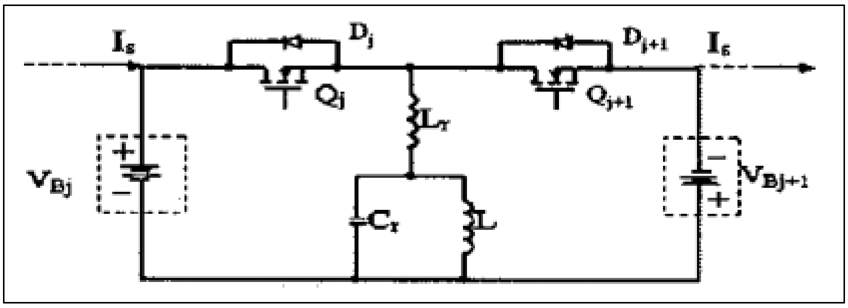

Figure 2.1: Proposed converter in [12]

(Jaroslav Dudrik and Juraj Oetter, 2007) discussed soft switching PWM DC-DC Converters using power MOSFETs and IGBTs in reduction of switching and conduction losses. The circuit configuration of this design is shown in Figure 2.2. An important advantage of the circuit is that the rectifier diodes do not suffer from reverse recovery problem since they commutate with ZCS. The limitation of this topology is soft-switching easy to achieve at light load only.

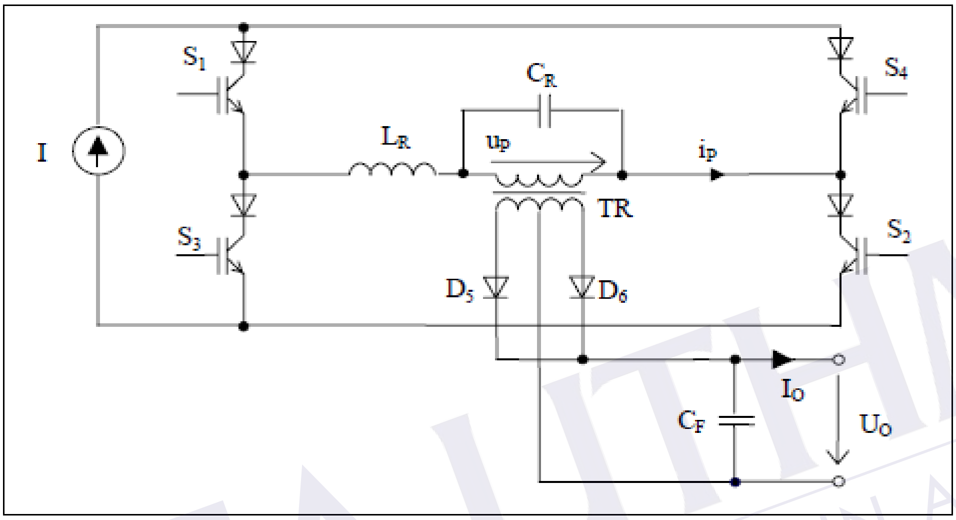

Figure 2.2: Proposed converter in [13]

(Mohammad Mahdavi, Amin Emrani and Hosein Farzanehfard, 2010) proposed a new ZCS resonant buck converter as a soft-switching DC-DC converter using only an auxiliary switch. The circuit configuration of proposed converter is shown in Figure 2.3. The proposed converter both switches are turned on or off under ZCS condition. The most disadvantage of the topology is limitation only suitable for employing IGBT for high power.

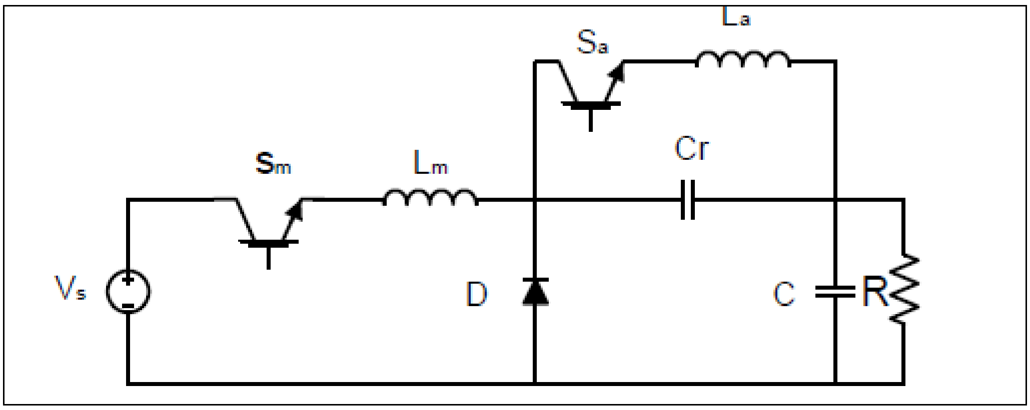

Figure 2.3: Proposed converter in [14]

(P.Preethi and R.Mahalakashmi, 2011) presented a concept which combines the resonant converters and switched-capacitor converters to reduce switching losses. A switched capacitor is used for resonant inverting wherein negative voltage is required. The main disadvantages of the topology is required a large number components which are two switches, some diodes and a number of switching capacitor cells as shown in Figure 2.4.

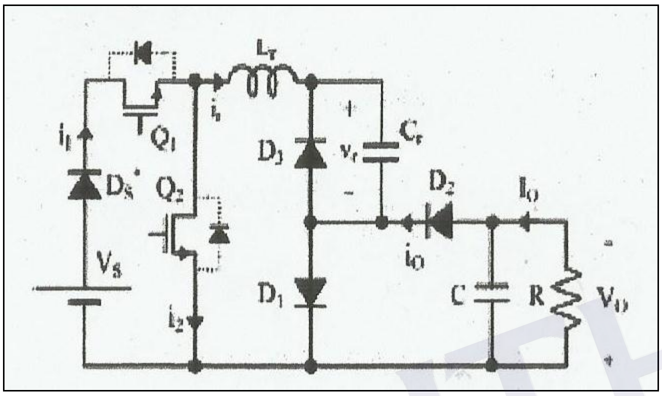

Figure 2.4: Proposed converter in [15]

(Parul Pradhan, 2012) proposed a buck converter topology with resonant configuration as shown in Figure 2.5. ZCS topology is used to diminish the switching losses in enhanced efficiency of converter. This topology is successfully done to minimize switching losses across the device, lower the current and voltage stresses formed across it and diminish the overall size of device with enhanced efficiency for use in high frequency circuits. The problem of this topology is effect of parasitic capacitance in a MOSFET that can instigate conduction without any pulse applied to its gate.

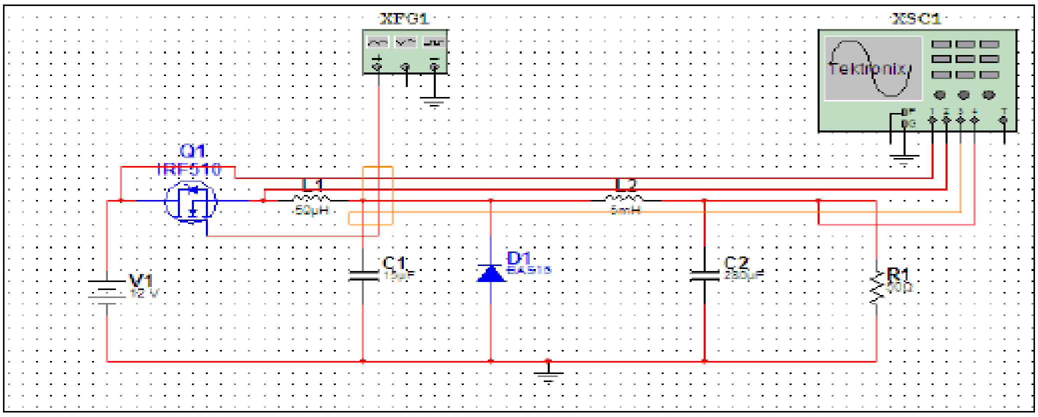

Figure 2.5: Proposed converter in [16]

(José F. da Rocha, Marcelino Bicho dos Santos and José Manuel F.Dores Costa, 2013) presented a QR-ZCS topology to overcome voltage spikes during the switches commutation in a buck converter. The circuit configuration of this converter is shown in Figure 2.6. Results show that resonant DC-DC converters generate voltage spikes which magnitude are sometimes higher than that generated in a hard switching converter and are superimposed to the overvoltage occurring in the resonant phase. The voltage spikes generated in DC-DC converters can cause circuit malfunctions or device breakdown hence gives low energy efficiency. Therefore, this topology is not considered for this project.

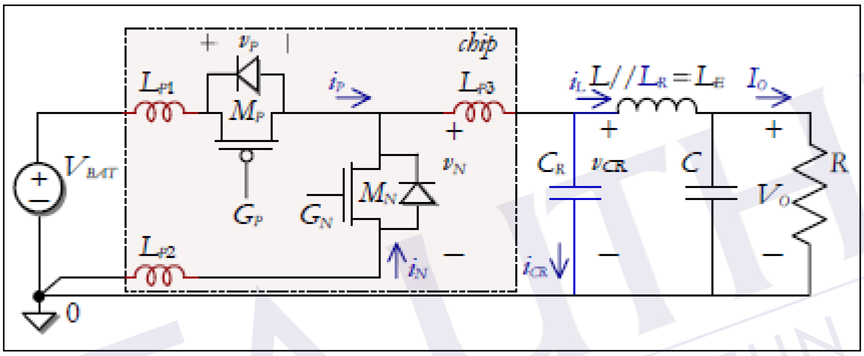

Figure 2.6: Proposed converter in [17]

(G. Yanik and E.Isen, 2013) proposed a 60W full wave quasi-resonant zero-current switching buck converter to decrease the switching losses. The result states that the switching loss is zero. Therefore this topology is considered for this project. The circuit configuration of this proposed converter is shown in Figure 2.7.

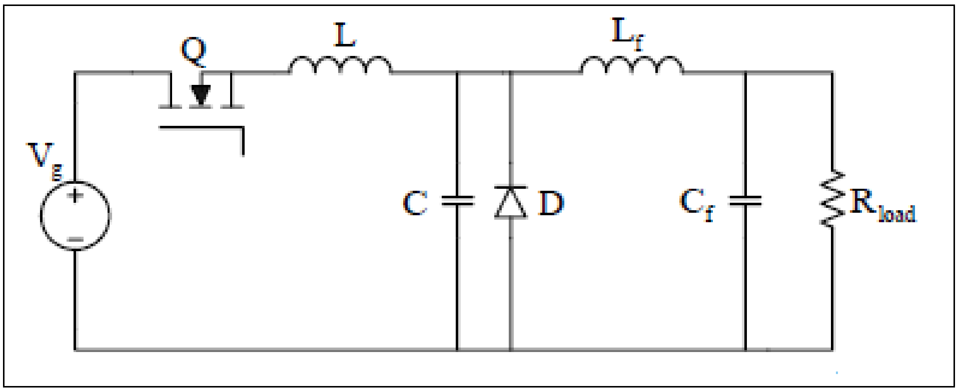

Figure 2.7: Proposed converter in [1]

2.3 DC-DC Converter

DC-DC converter converts a fixed DC input voltage to variable DC output voltage or vice versa by varying of duty cycle. There are many types of DC-DC converter such as buck converter, boost converter, buck-boost converter and cuk converter. This project focused on buck converter.

2.3.1 Buck Converters

A buck converter is a step-down DC to DC converter that uses a switching device, a diode, an inductor and a capacitor as shown in Figure 2.8. Typical waveforms are shown in Figure 2.2 under assumption that the inductor current is always positive. The state of the converter in which the inductor current is never zero for any period of time is called the continuous conduction mode (CCM). It can be seen from the circuit that when switch *S* is commanded to the on state, the diode *D* is reverse biased. When the switch *S* is off, the diode conducts to support an uninterrupted current in the inductor.

The DC-DC converters can operate in two distinct modes with respect to the inductor current, i_L. Figure 2.9 depicts the CCM in which the inductor currents always greater than zero. When the average value of the input current is low (high *R*) and/or the switching frequency f_s is low, the converter may enter the discontinuous conduction mode (DCM). In the DCM, the inductor current is zero during a portion of the switching period.

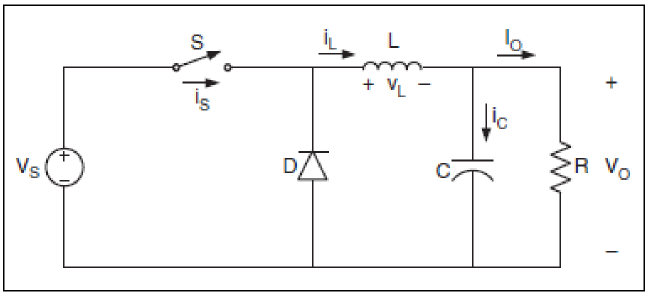

Figure 2.8: Buck converter

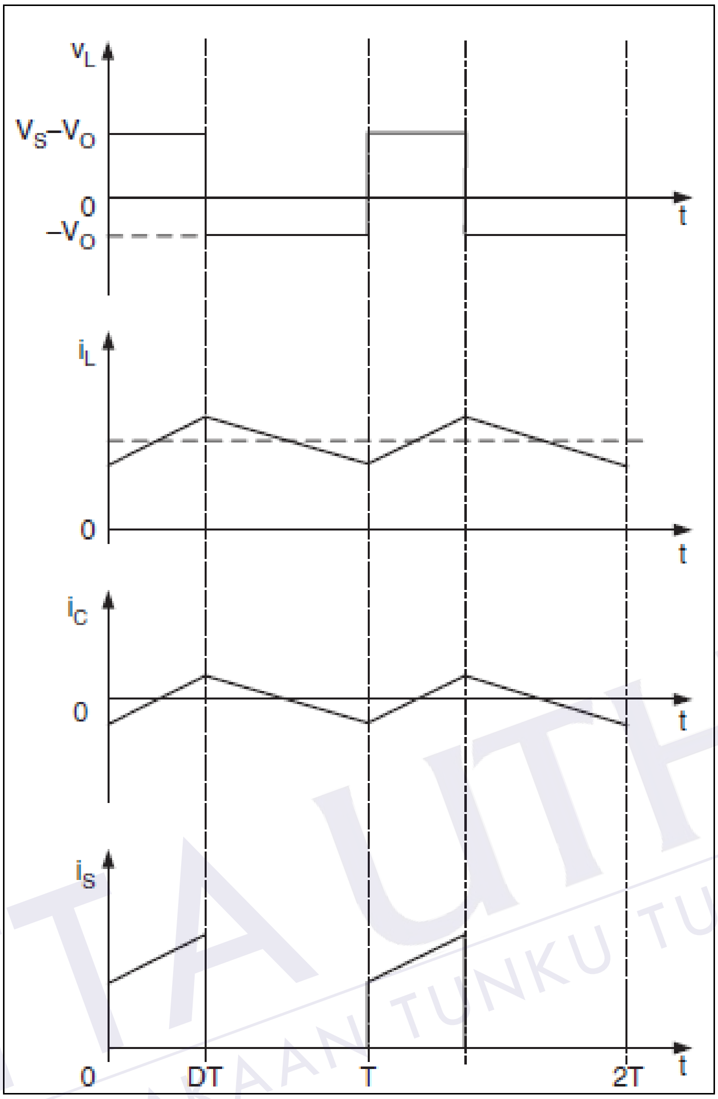

Figure 2.9: Buck converter waveforms

The key parameters that involved in buck converter design are discussed as follows.

The output voltage V_o is expressed as

$$V_o = DV_s \tag{2.1}$$

where D is the duty cycle.

The minimum value of inductance $L_{\min}$ required for continuous current is

$$L_{\min} = \frac{(1-D)R}{2f} \tag{2.2}$$

For $L > L_{\min}$ the converter operates in the CCM.

The value of filter inductance L for continuous-current as

$$L = \left(\frac{V_s - V_o}{\Delta i_L f}\right) D = \frac{V_o \left(1 - D\right)}{\Delta i_L f} \tag{2.3}$$

where Δi_L is the peak-to-peak ripple current in the inductor

The minimum value of capacitance $C_{\min}$ required for continuous current is

$$C_{\min} = \frac{1 - D}{16 L f^2} \tag{2.4}$$

The value of filter capacitance C for continuous-current as

$$C = \frac{1 - D}{8L\left(\Delta V_o / V_o\right) f^2} \tag{2.5}$$

where ΔV_o is the peak-to-peak ripple voltage at the output

2.4 Power Semiconductor Switching Devices

When semiconductor is used as switch it is possible to control large amounts of load power with relatively low power dissipation. In an ideal case, there will be no power dissipation in the switching device. In a DC-DC converter, an input voltage and the average output voltage is controlled by controlling the switch on and off durations. Normally BJTs, MOSFETs and IGBTs are used as switching devices in DC-DC converters.

BJTs are current-controlled devices, they has largely been replaced by MOSFETs and IGBTs where need to be turned on and off at very high frequencies in the kHz range. A MOSFET is a voltage-controlled device that requires only a small input current. They have a very fast switching speed and low switching losses compared to BJTs. An IGBT combined the advantages of BJTs and MOSFETs. An IGBT is a voltage-controlled device similar to MOSFET which turns on like a MOSFET and conducts like a BJT in saturation. An IGBT is faster than a BJT and slower than a MOSFET.

REFERENCES

1. G. Yanik and E. Isen, "Quasi-Resonant Full-Wave Zero-Current Switching Busk Converter Design, Simulation and Application," *Balkan Journal of Electrical & Computer Engineering*, Vol. 1, No. 2, 2013.

2. Dariusz Czarkowski, "DC-DC Converters," Department of Electrical and Computer Engineering, Polytechnic University, Brooklyn, New York, USA.

3. S.Y. (Ron) Hui and Henry S.H. Chung, "Resonant and Soft-switching Converters," Department of Electronic Engineering, City University of Hong Kong.

4. Issa Batarseh, "The Power MOSFET," School of Electrical, Engineering and Computer Science, University of Central Florida.

5. Ahmad Mousavi, "Soft-switching DC-DC Converters," University of Western Ontario London, PhD Thesis, 2013.

6. K.H. Liu and F.C. Lee, "Resonant Switches – A Unified Approach to Improve Performances of Switching Converters," in *Proc. Int. Telecomm. Energy Conf.*, 1984, pp. 344-351.

7. K.H. Liu, R. Oruganti, and F.C. Lee, "Resonant Switches – Topologies and Characteristics," in Proc. IEEE Power Electron. Spec. Conf., 1985, pp. 62-67.

8. K. D. T.Ngo, "Generalized of Resonant Switches and Quasi-Resonant DC-DC Converters," in Proc. IEEE Power Electron. Spec. Conf., 1986, pp. 58-70.

9. F.C. Lee, "High-frequency Quasi Resonant and Multi-Resonant Converter Technologies," in *Proc. IEEE Int. Conf. Ind. Electron.*, 1988, pp. 509-521.

10. Muhammad H.Rashid, "Power Electronics, Circuits, Devices and Applications," Third Edition, Pearson/Prentice Hall, 2004.

11. Gyana Ranjan Sahu, Bimal Prasad Behera and Rohit Dash, "Design and Implementation of ZCS Buck Converter," National Institute of Technology, Rourkela, Degree Thesis, May 2010.

12. Yuang-Shung Lee and Guo-Tian Chen, "ZCS Bi-directional DC-to-DC Converter Application in Battery Equalixation For Electrical Vehicles," *35th Annual IEEE Power Electronics Specialists Conference*, 2004.

13. Jaroslav Dudrik and Juraj Oetter, "High-Frequency Soft-Switching DC-DC Converters for Voltage and Current DC Power Sources," Acta Polytechnica Hungarica, Vol. 4, No. 2, 2007.

14. Mohammad Mahdavi, Amin Emrani and Hosein Farzanehfard, "A New Zero Current Switching Resonant Buck Converter," *Applied electronics (AE), International Conference*, 2010.

15. P.Preethi and R.Mahalakashmi. "Implementation of Zero Current Switching in Step-Up/Step-Down Resonant Converter," *International Journal of Engineering Science and Technology (IJEST)*, Vol. 3, No. 2, 2011.

16. Parul Pradhan, "Design of Resonant Circuits Based Embedded Controller For Power Supply of LCD TV and Monitor," National Institute of Technology, Rourkela, Degree Thesis, May 2012.

17. José F. da Rocha, Marcelino Bicho dos Santos, José Manuel F.Dores Costa, "Voltage Spikes in Integrated CMOS Buck DC-DC Converters: Analysis for Resonant and Hard Switching Topologies," Pest-OE/EEI/LA0021/2013.

18. Naseem Zaidi and Aziz Ahmad, "Analysis, Design and Control of Zero Current Switching DC to DC Buck Converter," *International Journal of Scientific and Research Publications,* Vol. 2, Issue 7, July 2012.

19. Irfan Jamil, Zhao Jinquan and Rehan Jamil, "Analysis, Design and Implementation of Zero-Current Switching Resonant Converter DC-DC Buck Converter," *International Journal of Electrical and Electronics Engineering (IJEEE)*, Vol. 2, Issue 2, May 2013.

20. S. Abinaya, A. Sivaranjani and S. Suja, "Methods of Battery Charging with Buck Converter Using Soft-switching Techniques," *Bonfring International Journal of Power Systems and Integrated Circuits,* Vol. 1, Special Issue, December 2011.

21. Yu-Lung Ke, Ying-Chun Chuang and Shao-Wei Huang, "Application of Buck Zero-Current-Switching Pulse-Width-Modulated Converter in Battery Charges," IEEE, 2007.

22. M. Salem, A. Jusoh, N. Rumzi and N. Idris, "Implementing Buck Converter for Battery Charger Using Soft Switching Techniques," International Power Engineering and Optimization Conference (PEOCO), 2013.

23. Biswajeet Panda and Ashirbad Sahoo, "Study of Soft Switching Boost Converter Using An Auxiliary Resonant Circuit," National Institute of Technology, Rourkela, Degree Thesis, May 2012.

24. Daniel W. Hart, "Power Electronics," Mc Graw Hill, 2010.

25. Muhammad H.Rashid, "Spices for Power Electronics and Electrical Power," Third Edition, Taylor and Francis Group, 2012.