Microcontroller Based ZVS Resonant Buck Converter for Solar Home Lighting System

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Abstract
This paper presents the design and development of a Microcontroller (8051) based Soft switching ZVS DC-DC Resonant Buck Converter for Solar Battery Charger System. In this work, 17.5V DC voltage received from solar panel is stepped down to 15V and lead acid battery of 12V/45Ah is charged. Soft-switching (ZVS-zero voltage switching technique) of the Buck converter is implemented to improve the efficiency of the converter and it is observed that efficiency of the converter is between 55% to 88 %. For load variation from 4W to 48W.KEIL Micro vision software is used as a compiler to generate required hex file for the Microcontroller.

***Keywords**: -Auxiliary resonant circuit, Microcontroller, photovoltaic (PV), soft-switching buck converter, zero voltage switching (ZVS).*

INTRODUCTION

Electrical energy is the basic need of human beings. Its demand is increasing day by day with rapid growth in population. On the other hand, power generation through conventional sources of energy is limited due to diminishing trend of its raw material such as coal; oil etc. and raw materials are expected to be exhausted in near future. As the sources of conventional energy deplete day by day, restoring to alternative sources of energy like solar and wind energy has been the need of life. Due to power crises in rural sector of India, solar energy was found to be the most appropriate solution for the same. An approach has been adopted to develop a cost effective solar power converter which can produce pollution- free green electricity and can have a better socio- economic impact on the society. Among them, photovoltaic sources are used today in many applications such as battery charging, water pumping, home power supplies, and satellite systems. Photovoltaic systems in most applications require a DC-DC converter for the load. Energy storage equipment is a commonly used form of power electronic products. Solar powered lighting systems are already available in rural as well as urban areas. All of them consists of following components: solar photovoltaic module, rechargeable battery, DC-DC Converter and load. However, this solution brings side effects, such as an increased switching loss and degradation of system efficiency. Therefore, Soft-switching techniques can alleviate switching losses, and thus, they allow for higher frequency operation.

In the literature many authors have proposed low cost and highly efficient design of DC-DC Buck/Boost converter. Nashed has suggested attractive advantages of PV technology which include a free and abundant fuel supply; little or no pollution or operation/maintenance costs (once installed), and unlimited system life[1]. Wai et al. have proposed to make the PV generation system more flexible and expandable [2]. Masheleni and Carelse explained Microcontroller based optimal battery chargers [3]. Siwakoti et al. have presented the Microcontroller Based Intelligent DC-DC Converter to track Maximum Power Point for Solar Photovoltaic Module [4]. X. Long et al. have proposed the development of battery-buffered photovoltaic (PV) power conditioning systems (PCSs) which is challenged by its cost/W. It compels the users to optimize the system's configuration in order to maximize the power generation[5].The design of the Charge Controller is derived from the linear approximation model resolving prior probability distribution and dynamic DC/DC topology with microcontroller to meet the low-cost application. Low-cost charge collector of photovoltaic power conditioning system based dynamic DC/DC topology is explained by the authors. Ying-Chun Chuang has suggested obtaining zero-current switching (ZCS) operation to develop a novel soft-switching approach for rechargeable batteries [6]. By inserting an auxiliary switch in series with a resonant capacitor, the proposed topology by the authors can obtain a novel ZCS buck dc–dc battery charger and significantly decrease the switching losses in active power switches. Pattanaik et al. have proposed the Efficiency Improvement of Synchronous Buck Converter by Passive Auxiliary

Circuit [7]. A case study of solar PV system is presented for Sagar deep Iceland in [8].Different DC-DC topologies are compared for dynamic climatic conditions of PV systems in Egypt [9]. The analysis of microcontroller based solar charge controller for solar home lighting system is covered in [10]. A topology of Microcontroller based Soft switching buck converter for Solar Home Lighting System is explained in [11].

This paper proposes a soft switching buck converter using microcontroller 89V51. The Buck converter which converts voltage from solar Panel to 15V is designed using a main switch, resonant inductor and capacitor. It has a significant impact on the efficiency of the system. The study analyzes the switching losses and power dissipation of a buck zero-voltage-switching resonant converter. The proposed circuit is a part of a standalone photovoltaic system and this solar buck converter can be used in DC power supply for charging lead acid battery.

This paper is organized as follows. Characteristics of Solar Cell and module are briefly explained in Section II. The proposed System Design is explained in Section III. Section IV shows the simulation results of the Microcontroller and Buck Converter. Section V shows Experimental results. In Section VI, conclusion and future scope is covered

CHARACTERISTICS OF SOLAR CELL AND MODULE

Fig.1 shows the equivalent Circuit of a Solar Cell. (1)-(3) describe the behavior of a Solar Cell in mathematical form.

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + R_S I)}{nKT_K} \right] - 1 \right\} - \frac{V + R_S I}{R_{th}}$$

$$\Delta I = \alpha_{SC-T} \left(\frac{G}{G_{ST}} \right) * (T_{ST} - T) + \left(\frac{G}{G_{ST}} - 1 \right) * I_{SC-ST}$$

$$\Delta V = -\beta_{OC-T} * (T_{ST} - T) - R_S * \Delta I$$

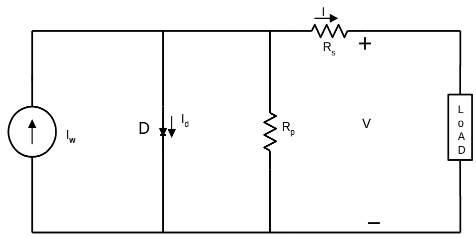

Fig.1: The equivalent Circuit of a Solar Cell

Fig. 2 and Fig. 3 show I-V and P-V characteristics of 37 Wp solar panel. Simulation is carried out using PSpice Software. Isc is decreased significantly when there is decrease in solar radiation at constant temperature of 270C.

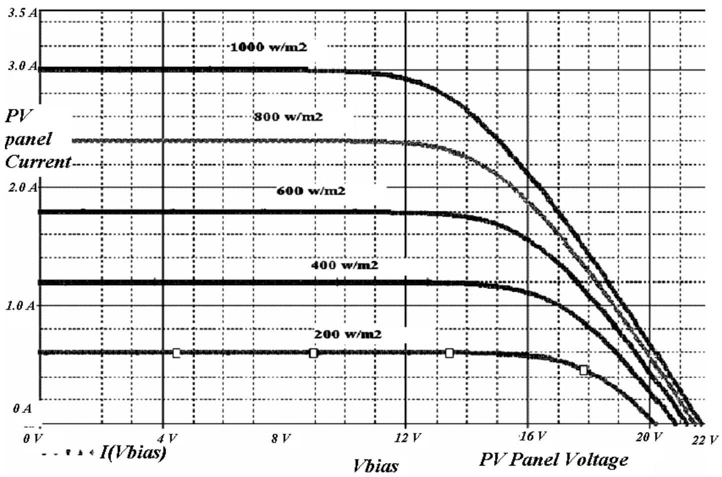

Fig.2: I-V characteristics of 37Wp solar panel of solar home lighting system

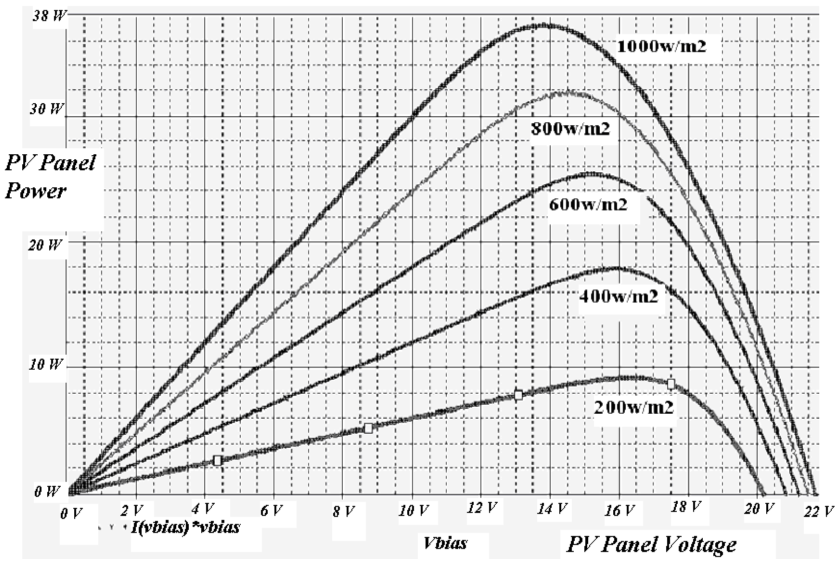

Fig. 3: P-V characteristics of 37Wp Solar panel solar home lighting System

The Solar Cell has nonlinear I-V and P-V characteristics which depend on the irradiation, operating temperature and load condition of the cell. Therefore, DC to DC converters play an important role in the PV systems where they find application as charge controllers, maximum power point trackers and for interfacing the PV source with various categories of loads.

MICROCONTROLLER BASED ZVS BUCK CONVERTER FOR SOLAR HOME LIGHTING SYSTEM

In this section, the brief design of ZVS Buck Converter is covered. Subsection A covers the design calculations of Buck converter and subsection B covers brief summary of Buffer and driver circuit.

A) Design of Buck Converter for Solar Home Lighting System

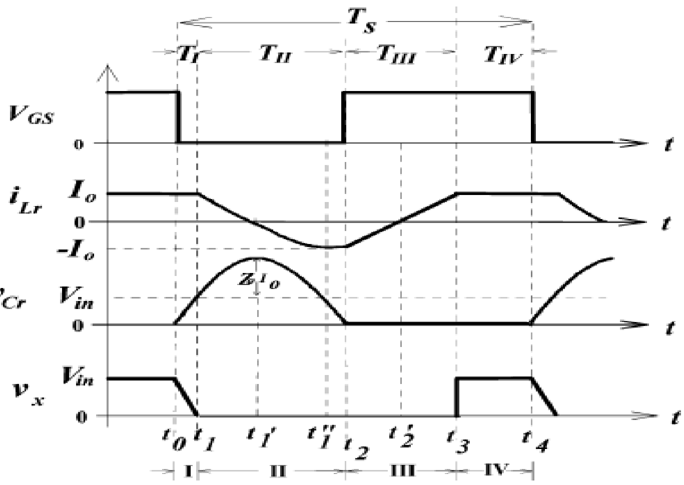

Fig.4: Theoretical waveforms of ZVS resonant buck converter [10]

The distinguishing feature of soft switching ZVS converters is that they switch ON and OFF at zero voltage.

$$V_i = 17.5V, V_o = 15V \quad (4)$$

$$P_o = 15 \times 2 = 30W \quad (5)$$

Load Resistance

$$R_L = \frac{V_0^{\,2}}{P_o} = \frac{15^2}{30} = 7.5\Omega \quad (6)$$

Load current,

$$I_o = \frac{V_o}{R_L} = \frac{15}{7.5} = 2.0A \quad (7)$$

DC Voltage Transfer Function is,

$$M_{VDC} = \frac{V_o}{V_i} = \frac{15}{17.5} = 0.857 \quad (8)$$

For buck half wave ZVS, with

$$n = 1, Q = M_{vdc} = 0.857, f_s = 30KHz \quad (9)$$

both ZVS & ZDS are satisfied,

$$Z_o = \frac{R_L}{Q} = \frac{7.5}{0.857} = 8.751\Omega \quad (10)$$

Resonant frequency,

$$f_r = \frac{0.9092 \times f_s}{1 - M_{vdc}} = \frac{0.9092 \times 30 \times 10^3}{1 - 0.857} = 190.74KHz$$

(11)

The duty cycle at $h = 0$ is,

$$D = 1 - \frac{0.9092 \times f_s}{f_r} = 0.8569 \quad (12)$$

Resonant Inductance,

$$L_r = \frac{R_L}{\omega_o \times Q} = \frac{7.5}{2 \times \pi \times 190.74 \times 10^3 \times 0.8569} = 7.3\mu H$$

(13)

Resonant capacitance,

$$C_r = \frac{Q}{\omega_0 \times R_L} = \frac{0.857}{2 \times \pi \times 190.74 \times 10^3 \times 7.5} = 95.34nF$$

(14)

For Switch,

Peak switch current,

$$I_{SM} = I_o = 2A \quad (15)$$

Peak switch voltage,

$$V_{SM} = (\frac{M_{VDC}}{Q} + 1) \times V_i = (\frac{0.857}{0.857} + 1) \times 17.5 = 35V \quad (16)$$

For Diode,

Peak Diode current,

$$I_{DM} = 2 \times I_o = 2 \times 2 = 4A \quad (17)$$

Peak diode voltage,

$$V_{DM} = V_i = 17.5V \quad (18)$$

Fig.5 and 6 show various power supply circuits required for the design of ZVS Buck Converter

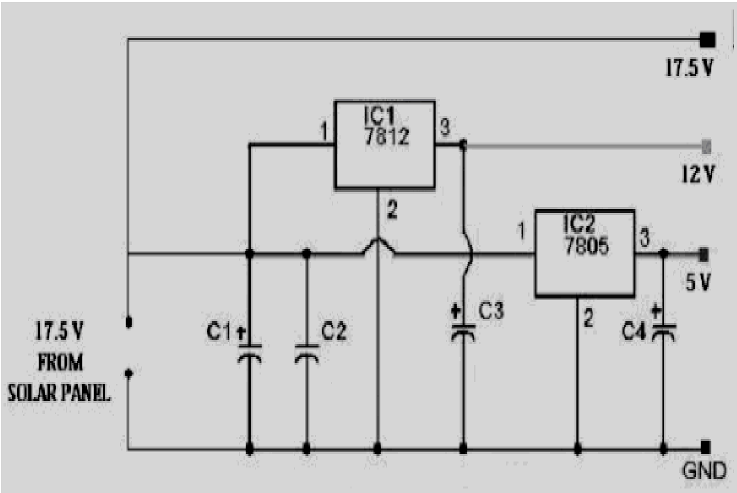

Fig.5: Power Supply circuits from Solar Power Supply

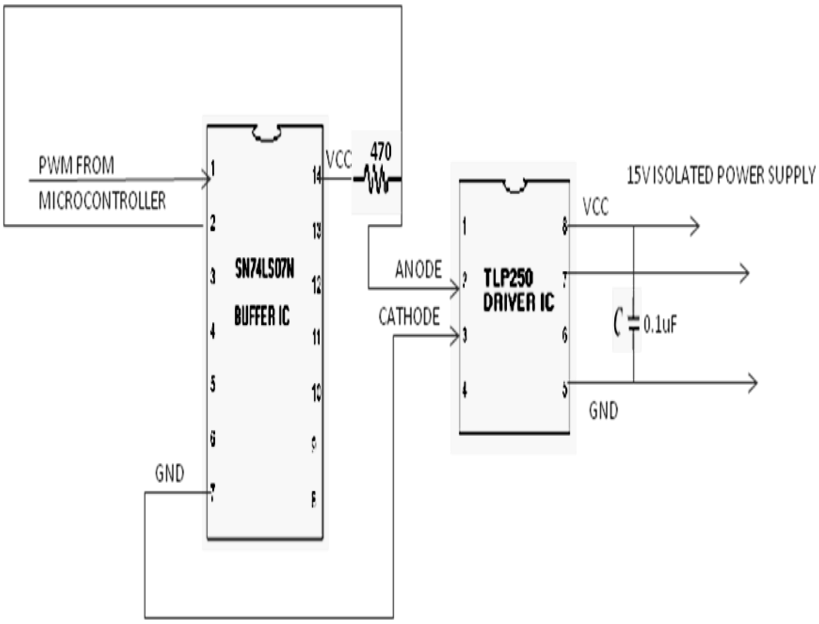

Fig.6: MOSFET driver circuit using TLP250.

- There is the requirement of three different voltages for its operation from 17.5 Volts of Solar Panel for ZVS buck converter, 5 Volts for the microcontroller IC and 12 Volts for driver circuit.
- The circuit consists of the direct 17.5 volts supply from the solar panel, filter and the regulator IC's
- The regulator ICs 7805 and 7812 are used to give output of 5 volts and 12 volts regulated voltages respectively

B) Buffer and Driver Circuit

The PWM so obtained from the microcontroller is applied to the gate of the buck converter through a driver circuit.IC SN74LS07N acts as a Buffer IC that protects the microcontroller. The driver IC TLP250 used has been provided with an isolated power supply. The output so obtained in the form of PWM is used to drive gate of the MOSFET of the buck converter. Fig.5 shows the MOSFET driver circuit using TLP 250

Simulated Results

Fig.7 shows the circuit diagram of the Microcontroller Based ZVS Buck Converter for Solar Home Lighting System. Here microcontroller 89V51 is interfaced to display the message "ZVS BUCK Converter" also it is used to display the output voltage. Subsection A) covers the Simulation of Microcontroller and LCD interfacing and Subsection B) covers Simulation of Designed Buck Converter on Multisim 10 software.

A) Microcontroller LCD Interfacing

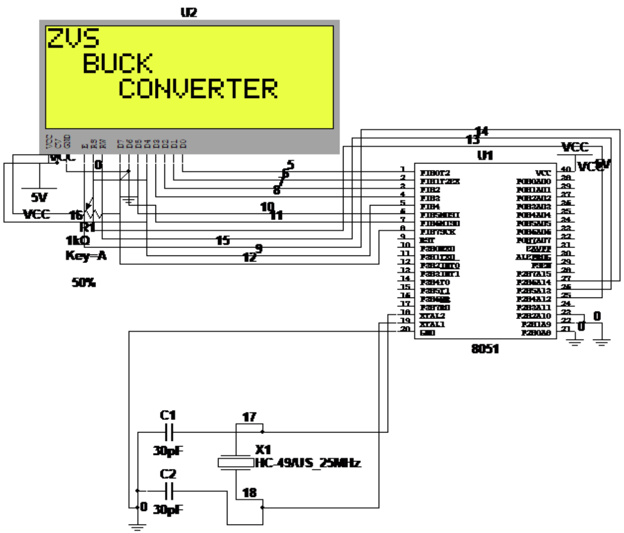

Fig.7: Simulation diagram of LCD interfacing with microcontroller 89V51

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Fig.8 shows the demonstration circuit diagram of the programmed microcontroller circuit used in the buck converter with crystal oscillator and power supply

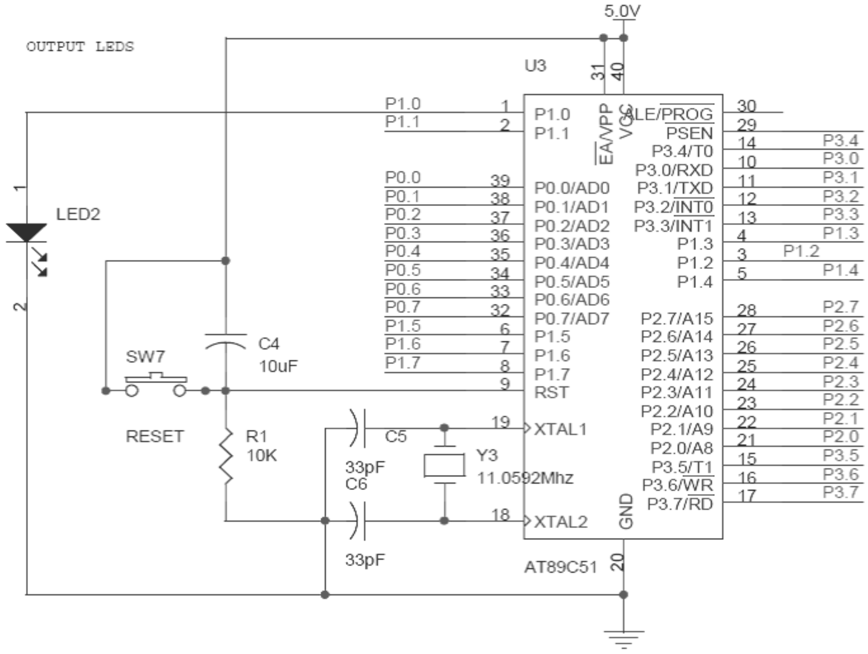

Fig.8: Microcontroller 89V51 demonstration PCB circuit diagram used for the Buck converter

B) Simulation of Buck Converter:

Fig. 9 shows the simulation circuit diagram of the designed ZVS buck converter suitable for charging the lead acid battery

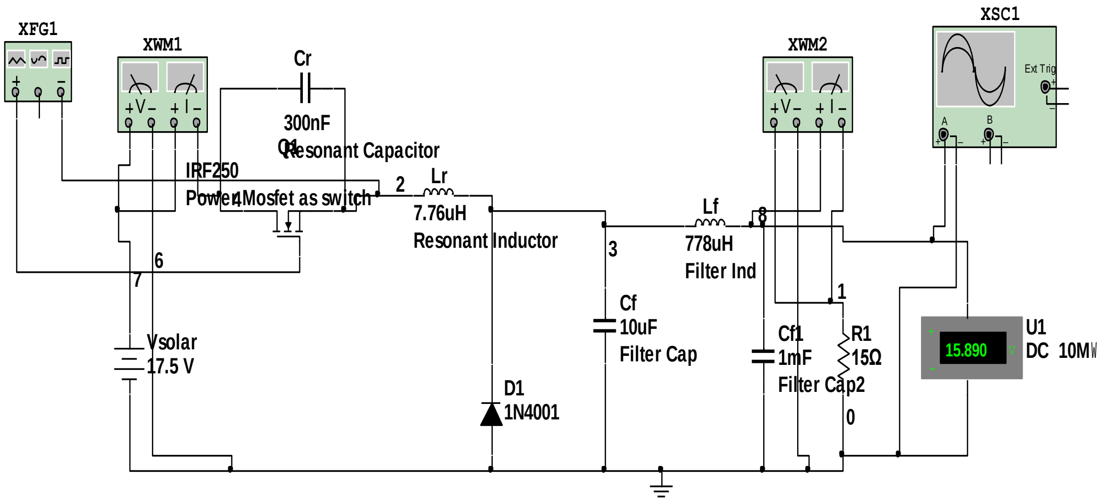

Fig.9: Circuit Diagram of Microcontroller based ZVS Buck Converter for Solar Home Lighting System

Figures 10 to 17 show the results of the various parameters of the simulated circuit

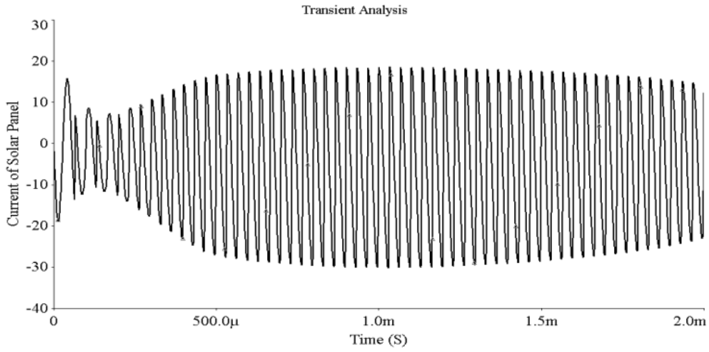

Fig.10: Current Supplied by the Solar Panel

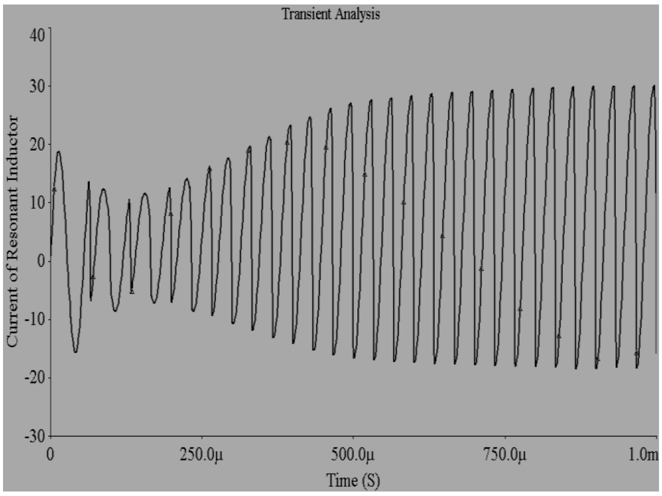

Fig.11: Current of Resonant Inductor(ILr)

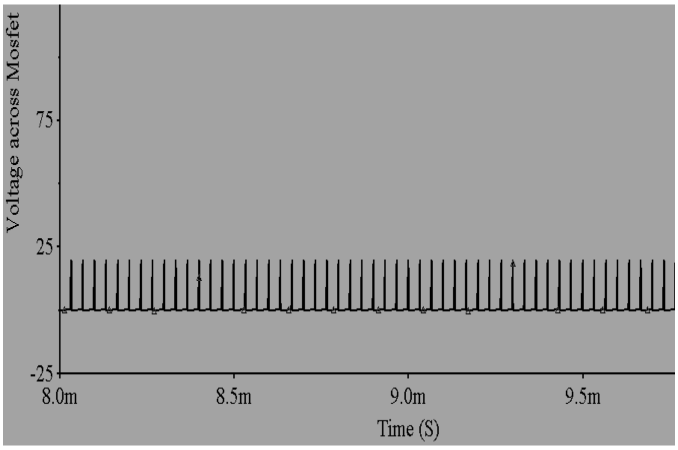

Fig.12: Drain to Source Voltage of MOSFET IRF250(Vds)

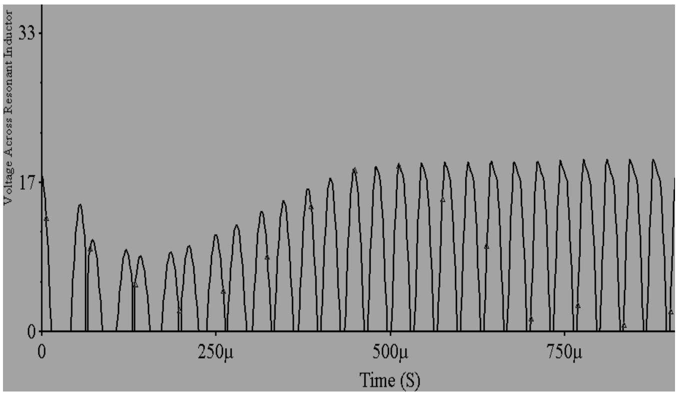

Fig.13: Voltage across Resonant Inductor (VLR)

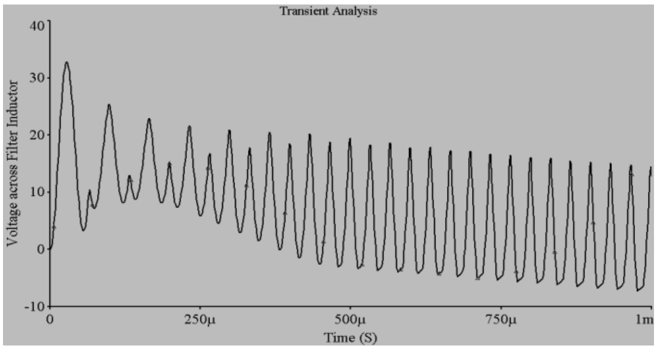

Fig.14: Voltage across Filter Inductor (VLf)

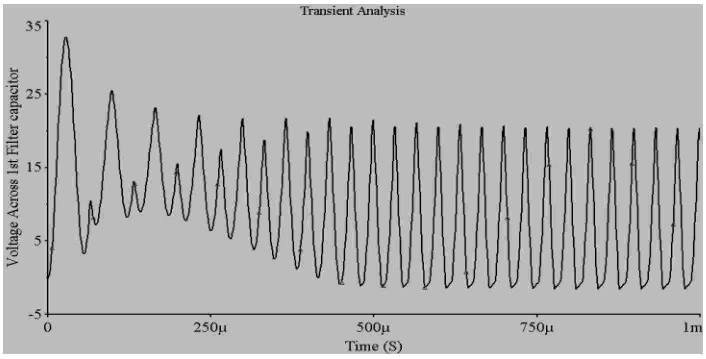

Fig.15: Voltage across 1st filter capacitor (Vcf)

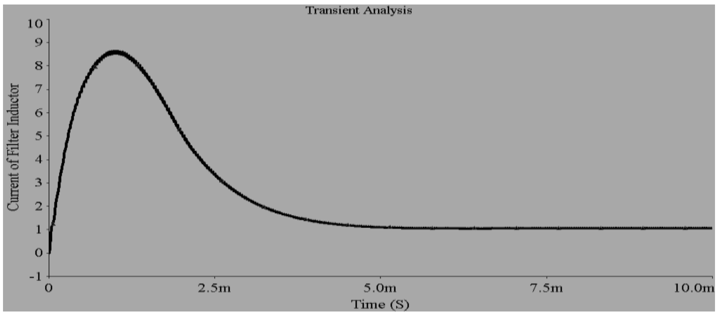

Fig.16: Filter Inductor Current

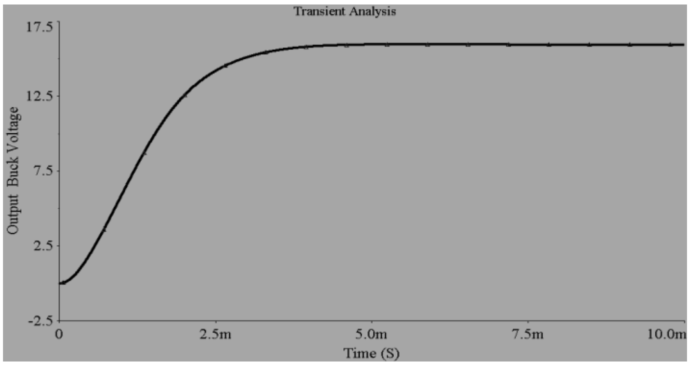

Fig.17. Output Voltage of Buck Converter

EXPERIMENTAL RESULTS:

The experimental results are divided into two parts, A) Microcontroller section and B) Buck Converter Section.

A) MICROCONTROLLER SECTION:

Figures 18 and 19 show the pulses of various duty cycle generated from 89V51 microcontroller with various parameters .The duty cycle was varied between 30 % to 60 %.These pulses are required for switching the MOSFET of the buck converter. The MOSFET driver is used in between the microcontroller and MOSFET switch. Here roll of microcontroller is to generate pulses and interface LCD. Caddo make 9100 series DSO is used to observe experimental results.

1)33% PWM PULSES GENERATED BY MICROCONTROLLER

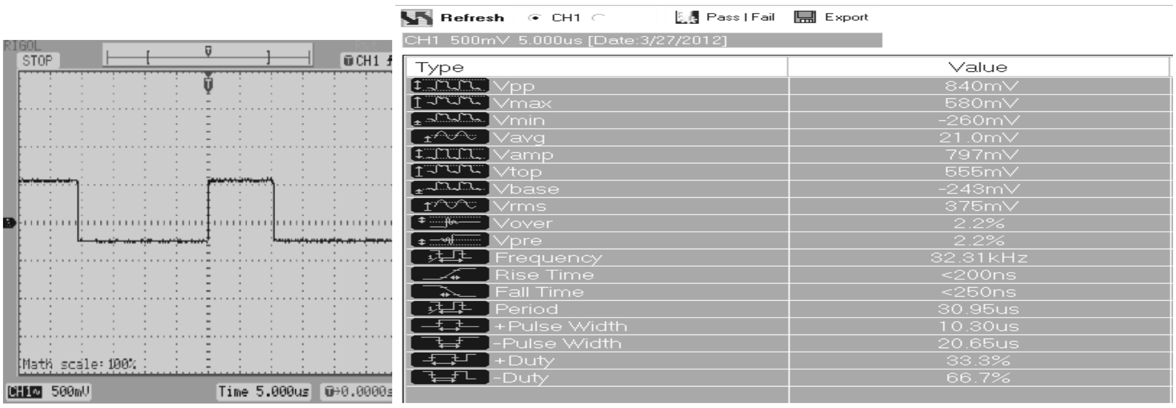

Fig.18: 33% PWM Pulses generated By Microcontroller 89V51

2)54% PWM PULSES GENERATED BY MICROCONTROLLER

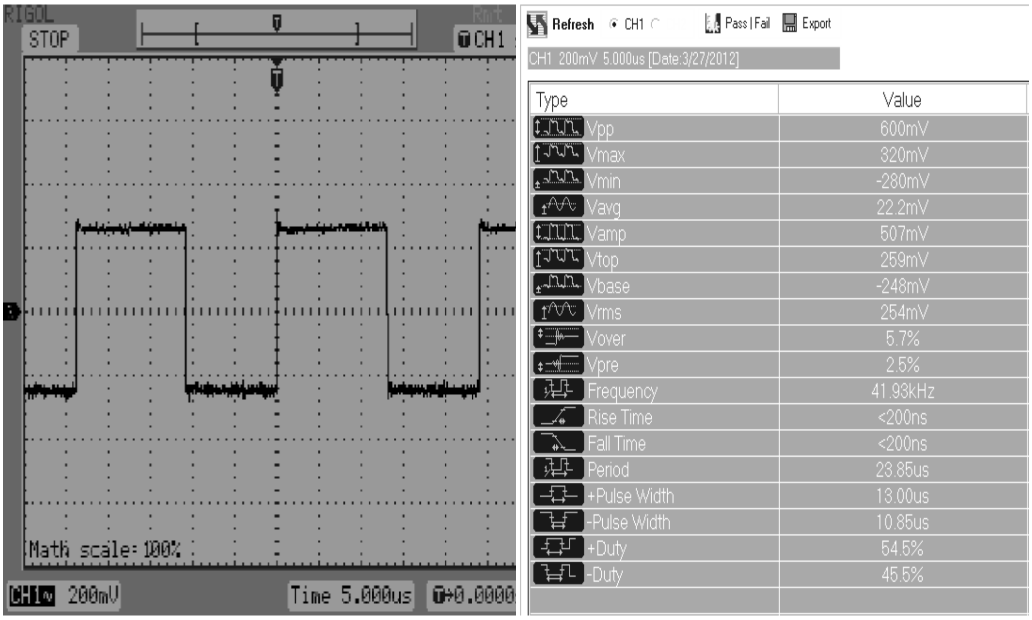

Fig.19: 54%PWM Pulses generated By Microcontroller 89V51

B) BUCK CONVERTER SECTION

Fig. 20 shows the current waveform of the Resonant Inductor

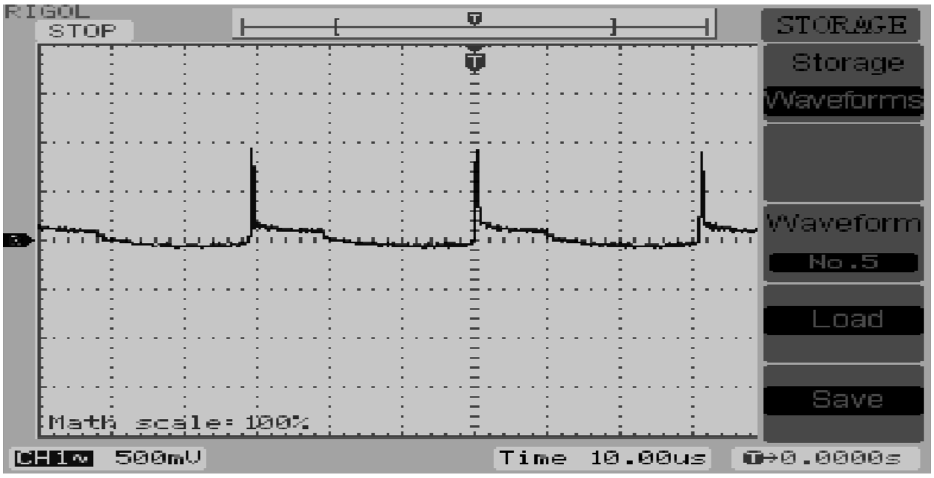

Fig.20: Current through inductor in DSO

Figure 21 shows the Voltage through diode in DSO, Multisim simulated output and related parameters

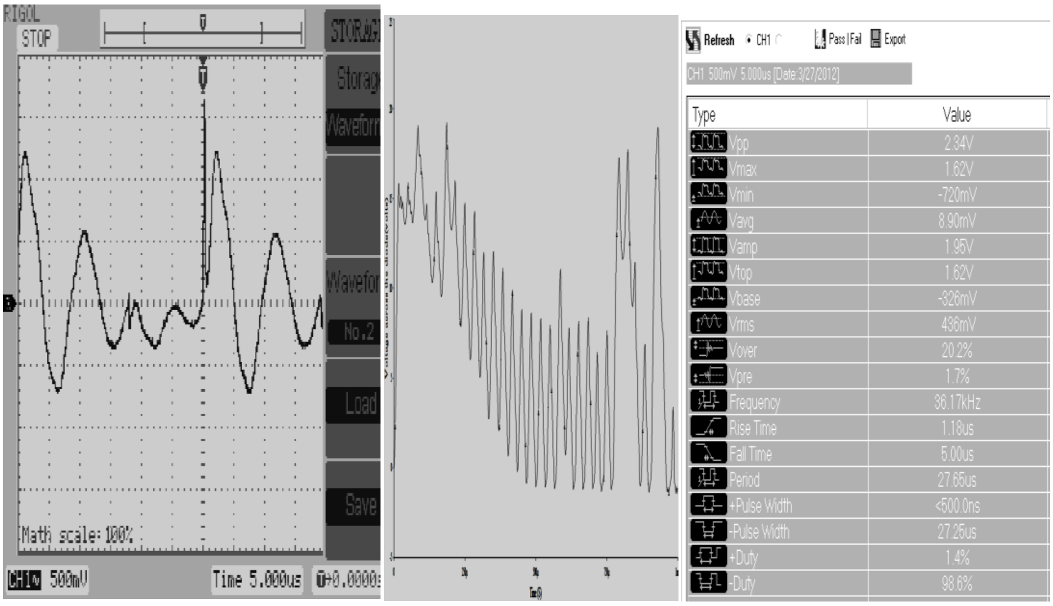

Fig.21: Waveform of Voltage through diode in DSO and multisim simulated output and diode parameters

The voltage through the diode provides ripple in its waveform but at the output this is not observed as the diode clips off the negative voltage and provides only the positive output voltage. Thus the ripples in the diode voltage can be observed in both the theoretical and the hardware practical waveforms.

Figure 22 shows the final output ripple voltage

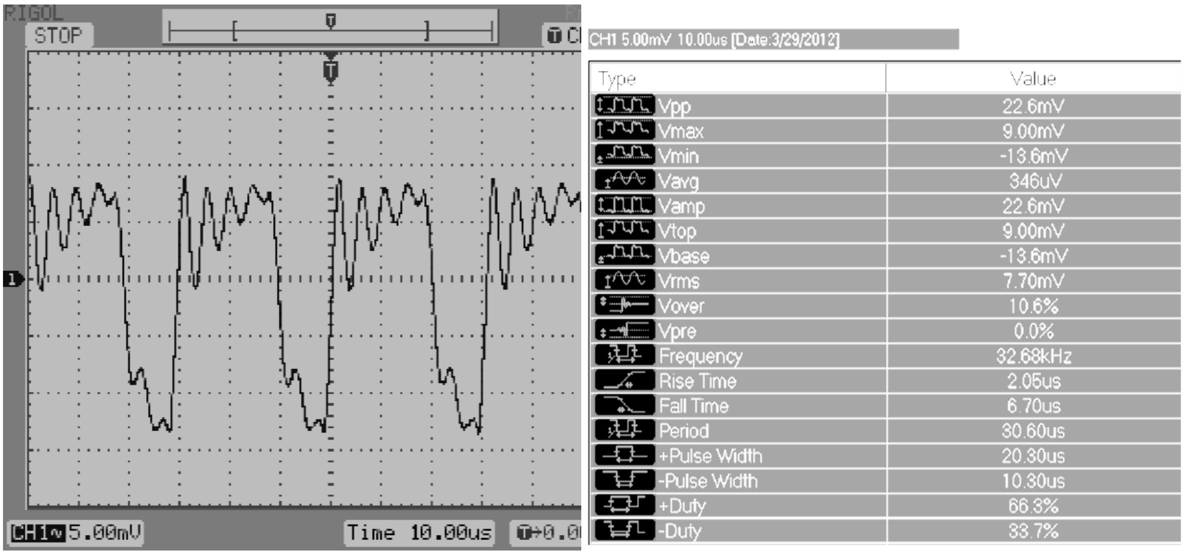

Fig.22: Waveform of the output ripple voltage with parameters

The ripple voltage is found to be 22mV which is under the required specifications i.e. below 40mV. Thus the load voltage can be considered to be constant DC. The characteristics of the output is as shown with the help of DSO seems to be distorted but practically it is in the acceptable range.

Fig.23 shows the graph of Efficiency Vs output power. Here an additional panel of 75Wp is used in parallel to increase the load up to 48 W.A 200Ω/10A Rheostat is used to vary the load upto 48W through solar panels

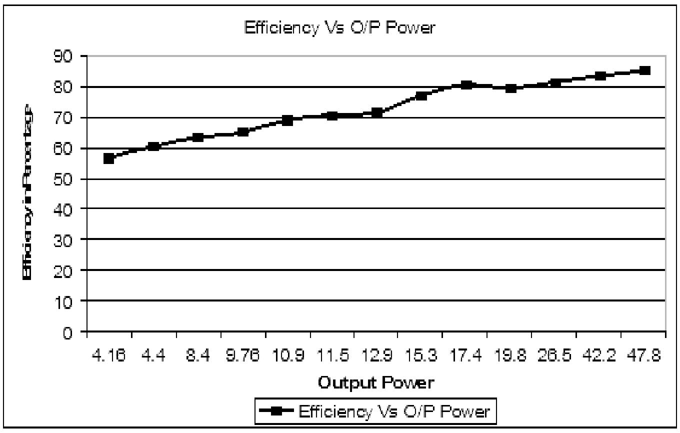

Fig.23: Efficiency Vs output power

Table I shows the specification and Implementation Details of soft switching ZVS Buck converter

Table 1: Buck Converter Design Parameters

Input voltage V_s	$17.5\,V$
Switching frequency f_s	$30\,KHz$
Resonant frequency f_0	$183.06\,KHz$
Output voltage V_0	$15V$
Resonant inductor L_r	$7.78\mu H$
Resonant capacitor C_r	$300n$ F
Filter Capacitor 1	$10\mu F$
Filter capacitor 2	$1000\mu F$
Diode	1N4007
Microcontroller	89V51

Figure 24 shows the final working photograph of the ZVS Buck Converter

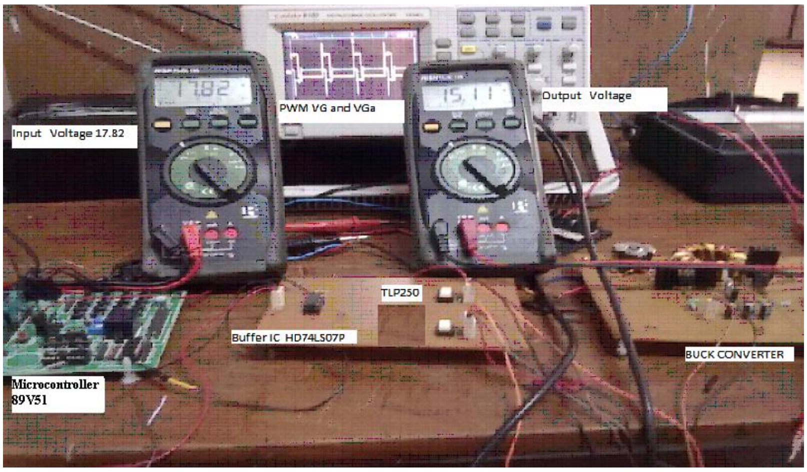

Fig.24: Final photograph of ZVS Buck Converter

CONCLUSION

This paper has proposed a high efficiency ZVS buck Converter which is suitable for battery charging applications. The basic 8051 microcontroller helps to generate the required PWM signals and complexity of circuit is reduced due to use of Microcontroller. The efficiency of the converter changes from 55% to 88 % with the load variation from 4W to 48W.

Appendix (Specifications of Solar Home Lighting System in EE Dept.)

Solar Photovoltaic Panel 12V, 37Wp, Battery: - Low maintenance Exide 12V, 75 Ah, Solar PV Charge Controller: - -Max. Charging current - 5 A-Max. Load current - 5 A-Nominal voltages - 12 V -Fuse - 5A, DC Fan:-Volts – 12 V DC, 14 W, Compact Florescent Lamps Volts – 12 V DC, 9 W, Qty- 2 No.s

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NOMENCLATURE

I	Output current, A
Q	Carrier charge $\left(1.6\times10^{-19}C\right)$
V	Output voltage, V
R_s	Series resistance, Ω
R_{sh}	Parallel resistance, Ω
I_{sh}	Short circuit current, A
I_0	Reverse saturation current of the Equivalent diode, A

T_k Absolute temperature, ^{0}K

n Dielectric constant

K Boltzman's constant $(1.38 \times 10^{-23} W\sec^0 .k^{-1})$.

G_{ST} Standard insolation

T_{ST} Standard temperature, ^{0}K

G Environmental insolation

T Environmental temperature, ^{0}K

α_{SC-T} Short circuit current temperature coefficient

β_{SC-T} Open circuit voltage temperature coefficient

a, b Constants (depends on location)

i_L Main inductor current, A

i_{LR} Resonant inductor current, A

$I_{\min}$ Minimum current of the main inductor, A

$I_{\max}$ Maximum current of the main inductor, A

$I_{LR\max}$ Maximum current of the resonant inductor, A

Δi_L Current ripple of the main inductor, A

$V_{s,\min}$ Minimum output voltage of the solar cell, V

$V_{s,\max}$ Maximum output voltage of the solar cell, V

V_L Main inductor voltage, V

V_{Lr} Resonant inductor voltage, V

V_{cr} Resonant capacitor voltage, V

V_{FW} Freewheeling voltage drop at mode 4, V

$Deff$ Effective duty ratio.

V_i Input voltage from the solar panel, V

V_o Output voltage of the buck design, V

R_L Load resistance, Ω

I_o Load current/ charging current, A

P_o Output power, W

M_{VDC} DC voltage transfer function

f_S Switching frequency, KHz

Q Quality factor

f_r Resonant frequency, KHz

D Duty cycle

L_r Resonant inductor, H

C_r Resonant capacitor, F

I_{SM} Peak switching current, A

V_{SM} Peak switching voltage, V

I_{DM} Peak diode current, A

V_{DM} Peak diode voltage, V