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Synchronous Buck Converter based PV Energy System for Portable Applications

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***Abstract*--Synchronous buck converter based photo voltaic (PV) energy system for portable applications is presented in this paper; especially to charge the batteries used in mobile phones. The main advantage of using synchronous buck converter is to reduce the switching loss in the main MOSFET over conventional dc-dc buck converter. The switching loss is minimized by applying soft switching techniques such as zero-voltage switching (ZVS) and zero-current switching (ZCS) in the proposed converter. Thus the cost effective solution is obtained; especially in the design of heat sink in the dc-dc converter circuit. The DC power extracted from the PV energy system is synthesized and modulated through synchronous buck converter in order to suit the load requirements. The characteristic of PV array is studied under different values of temperature and solar irradiation. Further, the performance of such converter is analyzed and compared with classical dc-dc buck converter in terms of switching loss reduction and improved converter efficiency. The whole system is studied in the MATLAB-Simulink environment.**

Keywords-photovoltaic(PV)array,battery charging, synchronous buck converter, MATLAB-Simulink.

I. INTRODUCTION

For environmental concern and increase of peak power demand PV solar cells has become an alternative energy source for green and clean power generation [1]-[2]. Solar cells are steadily gaining acceptance in our society. These are usually adapted for either grid connected or standalone applications. It is becoming a boon for the rural community for whom electricity had become only an imaginary thing. Due to a sudden up rise of mobile usage, and it's cheaper availability, it has become an affordable thing to have. But its recharging is cause of concern for the rural counterparts for whom electricity is not so abundant. These lesser electrical demand can be met with these PV solar cells.

But these PV cells are not so popular due to their high initial cost. But due to stiff competition among the manufacturers these cost are also scaling down. After building such an expensive renewable energy system, the user naturally wants to operate the PV array at its highest energy conversion output by continuously utilizing the solar power developed by it at different time. For low voltage applications such as mobile charging and laptop power supply etc, the output of the PV array should be regulated in order to match the dynamic energy requirement of the load [3]. In addition, the modulation process should be very efficient so that the system losses can be decreased considerably. For this efficient regulation of DC voltage, synchronous buck converter is proposed in the paper.

Various converter topologies have been proposed in the literature [4]-[6]. In the conventional buck converter usually switching losses are higher due to high switching frequency of operation of MOSFET and losses in the freewheeling diode is more due to larger forward voltage drop (0.4V). Consequently, it reduces the overall efficiency of the converter systems (typically less than 90%). The possible solutions are to increase the efficiency of the converter system is described as follows. First solution is to replace the freewheeling diode by MOSFET switch. Here MOSFET acts as a rectifier. So forward voltage drop in the switch can be reduced. Second solution is to incorporate the auxiliary MOSFET across the main MOSFET along with resonant circuits (L_r& C_r) [7].This combinations constitute a soft switching technique, so that the switching loss can be reduced in the main switch. The resultant dc-dc converter topology is said to be synchronous buck converter. Here main MOSFET "s" is switched on and off synchronously with the operation of the MOSFET switch 's_2'.

In this paper an attempt has been taken to analyze such converter for PV energy system based low power applications: especially to charge the batteries used in mobile phones. The proposed converter topology enables to provide simple and cost effective solution in the charging circuit. The schematic diagram for proposed system is shown in fig.1, which comprises PV array module, synchronous buck converter and load. The studied system is tested on simulation models developed in MATLAB Simulink environment.

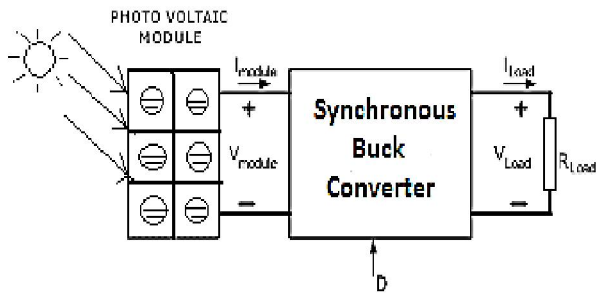

Figure 1. Schematic diagram for PV based converter system

The paper is organized as follows – PV array modeling and simulation is given in Section II. The various operating modes of proposed synchronous buck converter are explained in Section III. The simulation results are presented in Section IV, followed by conclusion in Section V.

II. PV ARRAY MODELING AND SIMULATION

The solar cell arrays or PV arrays are usually constructed out of small identical building blocks of single solar cell units. They determine the rated output voltage and current that can be drawn for a given set of atmospheric data. The rated current is given by the number of parallel paths of solar cells and the rated voltage of the array depends on the number of solar cells connected in series in each of the parallel paths [8].

A single PV cell is a photodiode. The single cell equivalent circuit model consists of a current source dependent on irradiation and temperature, a diode that conducts reverse saturation current, forward series resistance of the cell, which is shown below in fig.2.

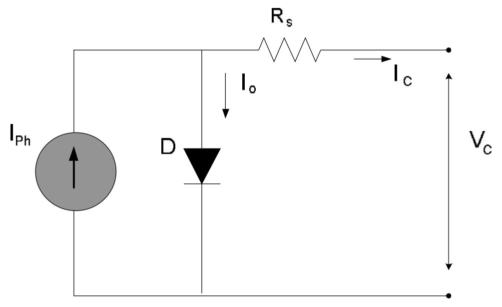

Figure 2. Simplified equivalent circuit of PV cell

The solar cell output voltage is a function of photocurrent which depends on solar irradiation and junction temperature; this depends also on current drawn by the load. It is given by,

$$V_{cell} = \frac{A\kappa T_c}{e}\ln\left(\frac{I'_{ph}+I_o-I_{cell}}{I_o}\right)-R_sI_{cell} \quad (1)$$

Where,

V_{cell}: cell output voltage
A: curve fitting factor (=1)
k: Boltzmann's constant (=$1.38\text{x}10^{-23}$J/K)
T_c: reference temperature (=293K)
e: electron charge (=$1.602\text{x}10^{-19}$C)
R_s: series resistance of the cell (=0.001A)
I_o: reverse saturation current of diode (=0.0002A)
I_{ph}: photocurrent, which is a function of temperature and irradiation.
I_{cell}: load current drawn from a single cell.

The benchmark reference output photocurrent (I_{ph}) of 5A obtained at a temperature (T_c) of 200C and solar irradiation (S_c) of 100W/m^2 is used.

The solar array operating point is determined by three factors such as load current, ambient temperature and solar irradiation. The following three operating conditions are observed from the study. 1) When load current increases the voltage drops in the PV array. 2) When the temperature increases the output power reduces due to increased internal resistance across the cell.3)When irradiation levels increases, the output power increases as more photons knock out electrons and more current flow causing greater recombination. The variation of output power acts as a function of cell voltage,and is affected by different operating conditions. Also, output I-V characteristics of the single cell model is observed under various conditions of temperature (T_x) and solar irradiation (S_x).The concerned simulations results are obtained under MATLAB-Simulink environment and are given in results and discussion section.

III. Analysis of Synchronous Buck Converter

The operation of synchronous buck converter with ZVS and ZCS technique for reducing the switching loss of main switch is described as follows [9]:

A. Modes of Operation

Mode 1: Before starting of this mode diode of S_2 was conducting and at time t_0, mosfet S_1 is turned on through ZCT which is caused by the current passing through L_r.In this mode L_r and C_r are resonance with each other and it ends when diode of S_2 stops conducting and when current through L_r reaches I_0.

$$t_{01} = \frac{1}{\omega}\left[sin^{-1}\left(\frac{I_0\,Z}{V_i}\right)\right] \quad (2)$$
$$V_{cr}\,(t_{01}) = V_{cr1}$$
$$i_{Lr}(t_1 - t_0) = I_0$$
$$t_{01} = 0.00834\,\mu s$$

Mode2:L_r and C_r continue to resonate. At t_1 the synchronous switch S_2 is turned on under ZVS. This mode ends when S_2 is switched of and i_{Lr} reaches its maximum value.

$$t_{12} = \frac{1}{\omega}\left[tan^{-1}\left(\frac{V_i - V_{cr1}}{I_0 Z}\right)\right] \quad (3)$$
$$i_{Lr}(t_{12}) = I_{Lrmax}$$
$$V_{cr}\,(t_{12}) = V_{cr2}$$
$$t_{12} = 0.306\,\mu s$$

Mode 3: At the starting of this mode, i_{Lr} reaches its peak value i_{Lmax}. Since i_{Lr} is more than load current I_0, the capacitor C_s will be charged and discharge through body diode of main switch S, which leads to conduction of body diode. This mode ends when resonant current i_{Lr}falls to load current I_0. So current through body diode of main switch S becomes zero which results turned off of body diode. At the same time the main switch S is turned on under ZVS. The voltage and current expressions for this mode are:

$I_{Lr} = I_0$; $V_{Cr} = V_{Cr1}$; V_{Cr} is some voltage which can found basing on other modes

$$t_{23} = \frac{1}{\omega}\left[tan^{-1}\left(\frac{i_{Lrmax}\,Z}{V_{cr2}}\right) - sin^{-1}(I_0)\right] \quad (4)$$
$$i_{Lr}(t_{23}) = I_0$$
$$V_{cr}\,(t_{23}) = V_{cr3}$$
$$t_{23} = 0.1973\,\mu s$$

Mode 4: In this mode, the main switch is turned on under ZVS. During this mode growth rate of i_S is determined by the resonance between $L_r$and C_r. The resonance process continues and i_{Lr}starts to decrease. This mode ends when i_{Lr} falls to zeroand S_1 is turned off through ZCS. The voltage and current equations for this mode are given by

I_{Lr} (t) = 0

$$t_{34} = tan^{-1}\left(\frac{I_0\,Z}{V_{cr3}}\right) \quad (5)$$
$$V_{cr}(t_4) = V_{crmax}$$
$$t_{34} = 0.7922\,\mu s$$

Mode 5: In the previous mode, S_1 is turned off. The body diode of S_1 begins to conduct because of discharging of C_r. The resonant current i_{Lr} starts increasing in reverse direction and finally becomes zero. The mode ends when body diode of S_1 is turned off.

$$t_{45} = \frac{\pi}{\omega}$$

$$i_{Lr}(t - t_4) = \left(\frac{V_{crmax}}{Z}\right) \sin \omega (t - t_4) \tag{6}$$

$$i_{Lr}(t_5) = 0$$

$$V_{cr}(t_5) = V_{cr4}$$

$$t_{45} = 0.628\, \mu s$$

Mode 6: Since in the previous mode, body diode of S_1 is turned off, the MOSFET S alone carries the current now. There is no resonance in this mode and circuit operation is same as conventional PWM buck converter.

$$i_s = I_0$$

$$i_{Lr}(t_6) = I_0$$

$$V_{Cr}(t_6) = -V_{Cr4} \tag{7}$$

Mode 7: At starting of this mode, the main switch S is turned off with ZVS. The schottky diode D starts conducting. The resonant energy stored in the capacitor C_r starts discharging to the load through the high frequency schottky diode D_S for a very short period of time, hence body – diode conduction losses and drop in output voltage is too low. This mode finishes when C_r is fully discharged.

$$V_{Cr}(t - t_6) = -V_{Cr4} + \frac{I_0}{C_r} \tag{8}$$

$$V_{Cr}(t_7) = 0$$

$$t_{67} = \frac{C_r V_{Cr4}}{I_0}$$

$$t_{67} = 0.47816\, \mu s$$

Mode 8: Before starting of this mode, the body diode of switch S_2 is conducting. But as soon as resonant capacitor C_r is fully discharged, the schottky diode is turned off under ZVS. During this mode, the converter operates like a conventional PWM buck converter until the switch S_1 is turned on in the next switching cycle. The equation that defines this mode is given by$I_{s2} = I_o$.

$$i_{S2} = I_0$$

$$C_r = \frac{(a-1)^2 I_{inmax} T_D}{V_0\left[1+\frac{\pi}{2}(a-1)\right]} \tag{9}$$

$$L_r = \frac{V_0 T_D}{I_{inmax}\left[1+\frac{\pi}{2}(a-1)\right]} \tag{10}$$

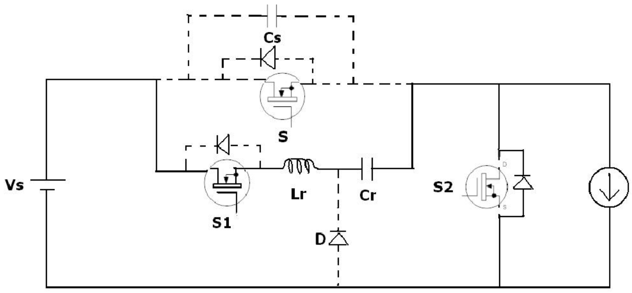

Figure 3. Mode 1

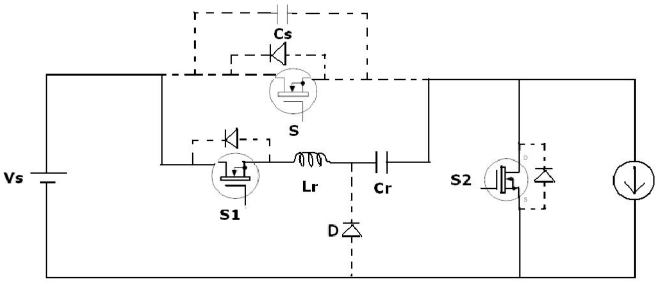

Figure 4. Mode 2

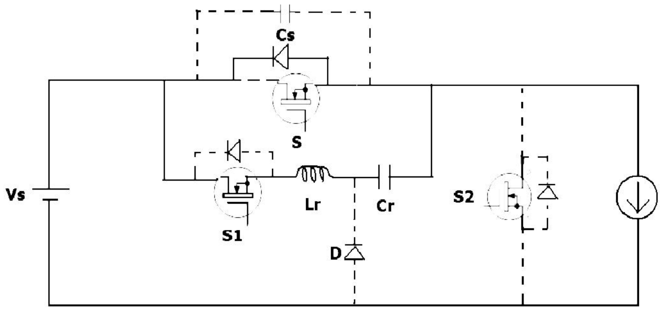

Figure 5. Mode 3

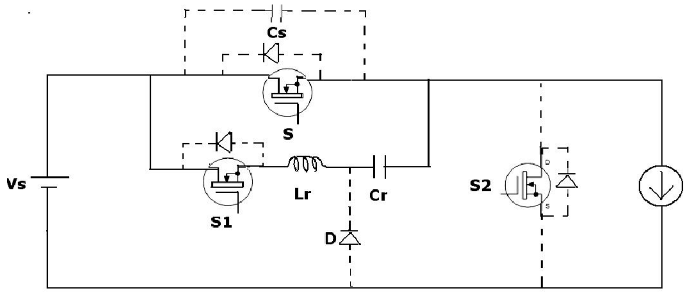

Figure 6. Mode 4

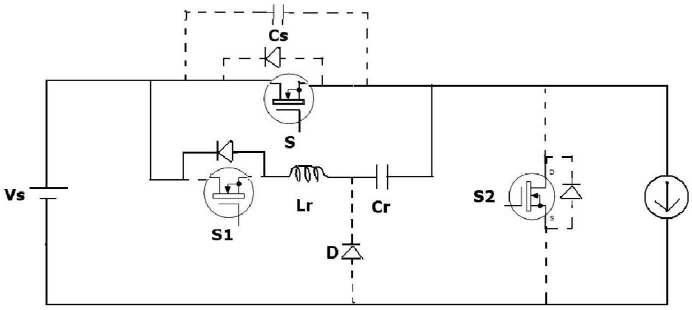

Figure 7. Mode 5

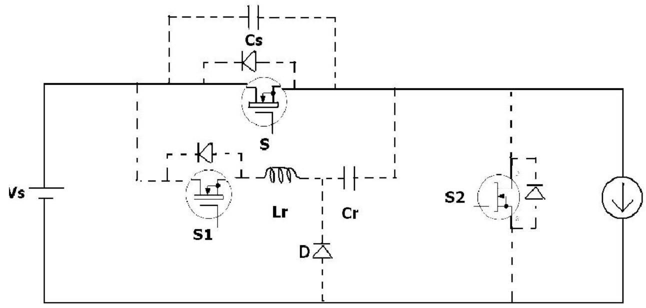

Figure 8. Mode 6

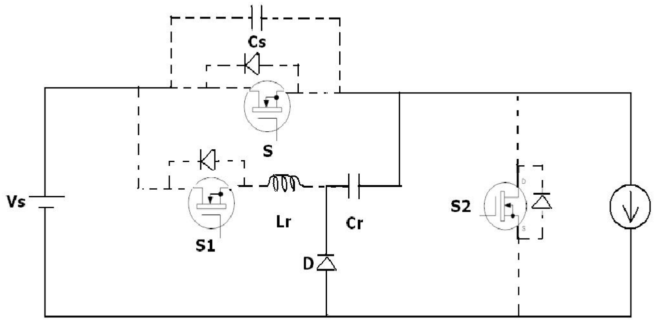

Figure 9. Mode 7

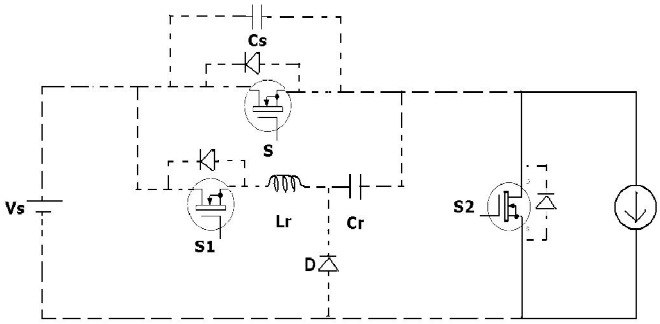

Figure 10. Mode 8

IV. SIMULATION RESULTS AND DISCUSSION

This section reveals the simulation results of PV array and proposed synchronous buck converter model. The parameters have been taken for simulation study is given in the appendix.

A. Results for PV Array:

TheI-V characteristics of PV array are plotted for different values of temperature and solar irradiation in the fig.11 & fig.12. Standard design approach shows that an increased number of cells can provide a nominal level of usable charging currents for normal range of solar insolations. In fig.8 the zero current indicates the condition of open circuit, so the value of voltage at that point gives the value of open circuit voltage of the PV array. Similarly a zero voltage indicates a short circuit condition; the current at this point is used to determine the optimum value of current drawn for maximum power. The value of the maximum current increases for increase in temperature.

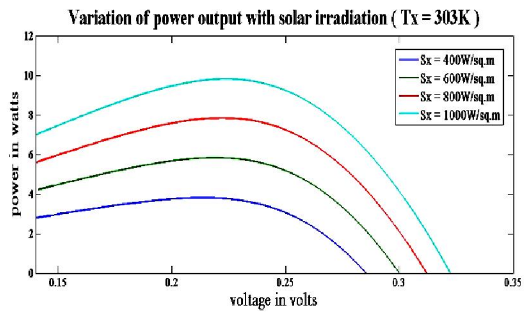

Figure 11. Variation of I-V characteristics of PV cell with Temperature.

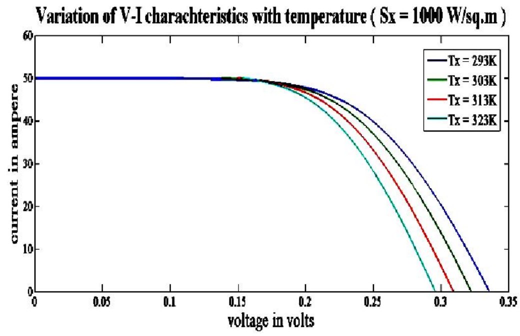

Figure 12. Variation of I-V characteristics of PV cell with Solar Radiation.

Fig.13 and fig.14 depicts the relationship between PV array and output power of PV module for different values of temperatures and solar irradiation. From this curve it was ascertained that the maximum power decreases for increase in temperature.

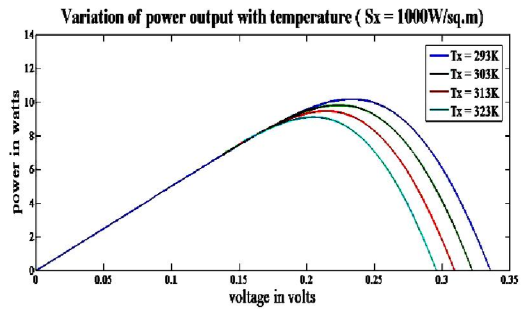

Figure 13. Variation of Power output with Voltage at Different Temperature

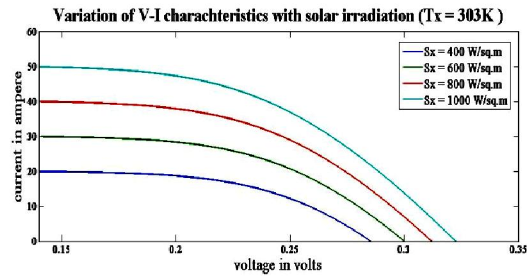

Figure 14. Variation of Power output with Voltage at Different Solar irradiation

B. Results for synchronous Buck Converter

As stated above, in the proposed synchronous buck converter the switching loss can be minimized by applying soft switching technique such as ZCS & ZVS. This can be explained as follows.

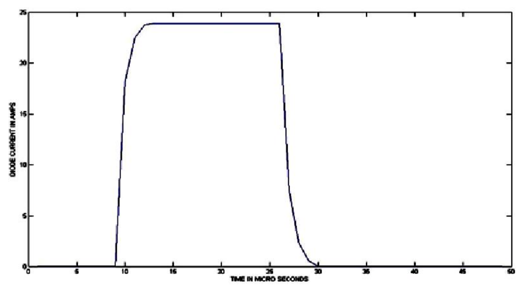

Figure 15. Response of diode Current.

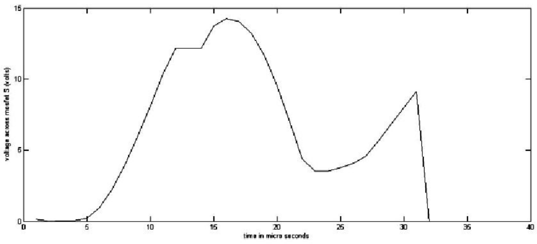

Figure 16. Response of mosfet S Voltage.

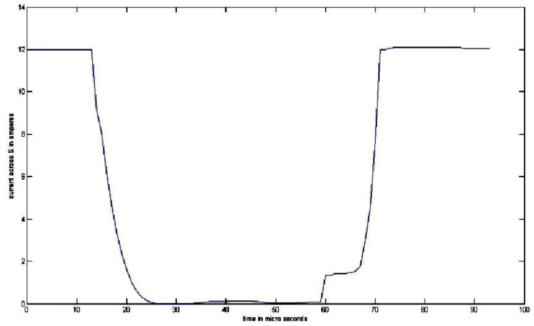

Figure 17. Response of current through main switch MOSFET ‘S’

The voltage and current waveforms of MOSFET ‘S’in fig. 16&17reveals the zero voltage switching (ZVS), which means the MOSFET is switched on when the voltage across MOSFET is zero, thereby causing zero power loss across MOSFET ‘S’.

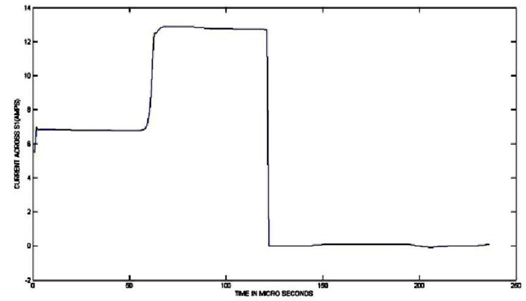

Figure 18. Current through Auxiliary switch S1

The MOSFET ‘S_1’along with resonant capacitor (C_r) and resonant inductor (L_r) is used as an auxiliary circuit for causing ZVS for MOSFET ‘S’. The waveforms shown in fig.18 and fig.19describe the current and voltage across MOSFET ‘S_1’ indicates the zero current turn off of MOSFET ‘S_1’ (ZCT). It is turned off by ZCT because of resonant inductor.

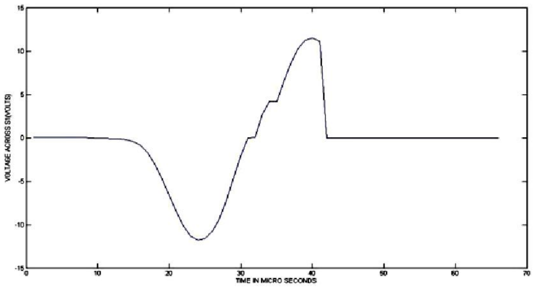

Figure 19. Voltage across Auxiliary switch S1

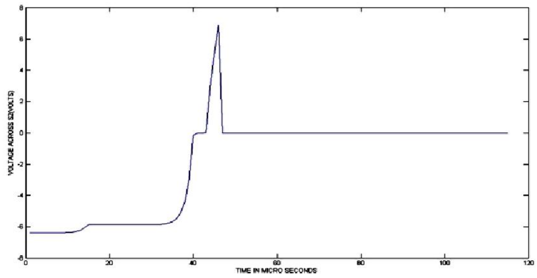

Figure 20. Voltage across Switch S2

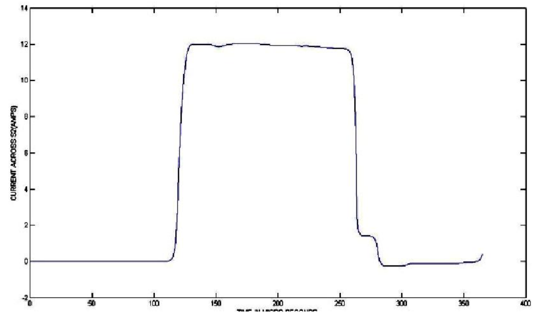

Figure 21. Current through Auxiliary switch S2

The current and voltage waveforms of MOSFET ‘S_2’ shown in fig. 21 and fig.20 respectively for ensuring zero voltage turn on (ZVT). The switching on MOSFET S_2 is occurring when the voltage across it is zero. Hence it is said to undergo ZVT. We observed that, the MOSFET S_2 is turned on according to the voltage waveform becoming zero. The corresponding response of output current is shown in fig.22.

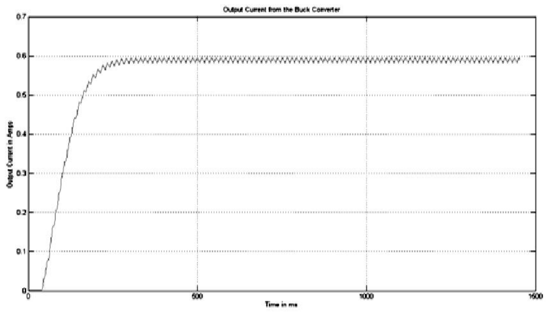

Figure 22. Response of Output Current

C. Converter Design and its efficiency

The following parameters are considered for design:

V_{in} = 12 V
V_{out} = 3 volts
I_{load} = 1 amps
F_{sw} = 200 kHz
Duty ratio (D) = V_{in} / V_{out} = 0.25
Assume I_{ripple} = 0.3*I_{load} (typically 30%)
The switching frequency is selected at 200 kHz.
The current ripple will be limited to 30% of maximum load

i) Buck Converter Design:

P_{out}= 3 watts (3 V @ 1 a)
Inductor loss= 50 mW
Output capacitor loss= 4.5 mW
Input capacitor loss= 10.8 mW

Diode loss= 300 mW
MOSFET loss=80 mW
Total losses= 445 mW
Converter efficiency = (P_{out}/P_{out}+Total losses)*100= 87 %
Here 60 % of total losses are mainly due to diode forward voltage drop (0.4 V).The converter efficiency can be raised if the diode's forward voltage drop will be lowered.

ii) Synchronous Buck Converter Design

P_{out}= 3 watts (3 V @ 1 a)
Select N-channel MOSFET with $R_{ds\,(on)}$ = 0.0044 Ω, Use same formulas for loss calculation.
Conduction loss= $I_d^2 * R_{ds\,(on)} * (1\text{-}D)$ = 15 mW
Main MOSFET (S_1) loss= 10 mW
Resonant capacitor (C_r) loss = 10 mW
Resonant Inductor (L_o) loss= 50 mW
Output capacitor loss (C_o) =4.5 mW
MOSFET (S_2)= 75 mW
Diode (D) loss= 5 mW
Inductor (L_r) loss= 20 mW
Total Losses = 190 mW
Converter efficiency= (3/3+0.190)*100= 94 %

From the above design consideration of both conventional buck and synchronous buck converter, we found that the efficiency of synchronous buck converter is more than that of conventional dc-dc buck converter for same output power rating. The relevant graphical representation is shown in fig.23 below.

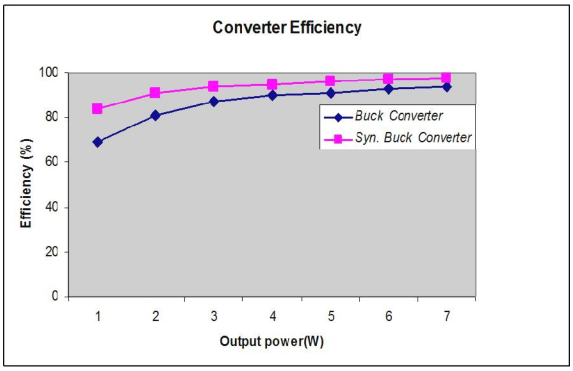

Figure 23. Converter Efficiency

V. CONCLUSIONS

The paper presents the use of smart PV energy system for portable applications; especially to charge the batteries used in mobile phones. For that a dc-dc synchronous buck converter is introduced between PV system and load to meet the dynamic energy requirement of the load in an efficient way. From the study we observed that, the synchronous buck converter largely increases the system efficiency by reducing the switching losses through soft switching techniques. Consequently, the studied system makes the device portable and cost effective. The experimental results will be validated with theoretical study on the proposed converter system in the future.

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APPENDIX -DESIGN PARAMETERS:

1) PV Array Module:	
PM 648, 18 V, 21 watts. http://www.celindia.co.in	
2) Converter Parameters:	
L_r	200nH
C_r	0.2µF
C_s	0.05nF
L_o	16.6µH
C_o	500µF
R_{load}	3 Ω
V_{out}	3 V
I_o	1amps.
$R_{D,on}$	0.004Ω
3) Device Specifications:	
Main MOSFET S	IRF1312
Auxiliary Switch	IRF1010E
Syn. Switch	IRF1010E
Schottky Diode	1N5820.