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Implementation of Synchronous Buck Converter with Photovoltaic Source

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Abstract:

The Photo Voltaic (PV) energy system is a very new concept in use, which is gaining popularity due to increasing importance to research on alternative sources of energy over depletion of the conventional fossil fuels world-wide. The systems are being developed to extract energy from the sun in the most efficient manner and suit them to the available loads without affecting their performance. The converter topology uses soft switching technique such as zero-voltage switching (ZVS) and zero-current switching (ZCS) to reduce the switching losses which is found prominently in the conventional buck converter. The Soft Switching Synchronous Buck Converter system is studied in the MATLAB-Simulink environment.

Keywords: Photovoltaic(PV)array, Synchronous buck converter; MATLAB-Simulink

1. Introduction

As the days go by, the demand of power is increasing gradually and on the contrary the resources used for power generation are becoming inadequate. Apart from the reason of inadequate resources, the methods used for power generation by fossil fuels are not even environment friendly and they devote an ultimate reason for global warming and greenhouse effect. So it is the time to initiate the usage of renewable energy resources on very large scale. The three main available renewable energy resources are (i) Direct Solar Energy, (ii) Hydro Energy and (iii) Wind Energy. Hydro Energy generation and Wind Energy generation are of course two of the main sources of renewable energies, but the main disadvantage in Hydro Energy is that, it is seasonal dependent and in Wind energy is that it is geographical location dependent [1]. On the other hand Solar Energy is prevalent all over the globe and all the time. The amount of irradiance and temperature may vary from place to place and from time to time but under given conditions Solar Energy system can be implemented. Solar Energy or PV energy system is the most direct way to convert the solar radiation into electricity based on photovoltaic effect. Despite of high initial costs, they are already have been implemented in many rural areas. In future the cost of the PV panel also may diminish, because of the advancing technology and also the competition between manufacturers. And therefore, the time is not so far that almost every middle class person can afford his own solar panel at home for at least some basic requirements.

The output voltage thus obtained from the PV panel is DC. For low power applications, dc-dc converters are employed to step-up or step-down the output DC voltage according to the load requirements. As the efficiency of solar panel itself is very less and it is inevitable, so the precaution should be taken such that the efficiency of the converter should be maximum. For the efficient regulation of output DC voltage, Synchronous Buck Converter is designed in this paper.

Efficiency will be reduced (typically less than 90%) in the Buck converter which is shown in fig 1 because of the higher switching losses due to high switching frequency of operation of MOSFET and also losses will be more in the freewheeling diode due to larger forward voltage drop.

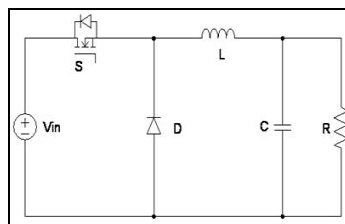


Fig. 1: Buck Converter

The possible solutions to increase the efficiency of the converter system are described as follows.

First solution is to replace the freewheeling diode by MOSFET switch which is shown in the fig 2. Here MOSFET acts as a rectifier. By this way forward voltage drop in the switch can be reduced and efficiency can be increased. The resultant dc-dc converter topology is said to be Synchronous Buck Converter.

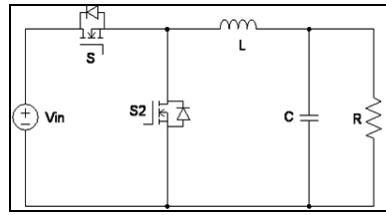


Fig. 2: Synchronous Buck Converter

Second solution is to incorporate the auxiliary MOSFET across the main MOSFET along with resonant circuits (L_r & C_r) which is shown in the fig 3. This combination constitutes a soft switching technique, so that the switching loss can be reduced in the main switch and efficiency can be increased. The resultant dc-dc converter topology is said to be Modified Synchronous buck converter topology.

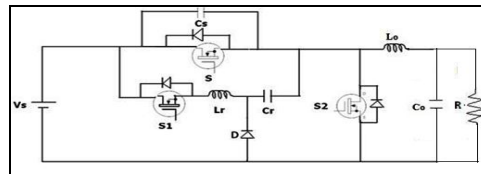


Fig. 3: Modified Synchronous Buck Converter

The PV energy system consists of a small solar module generally made of poly crystalline silicon, connected to the electrical load through a Synchronous Buck Converter for regulation of voltage at the load end.

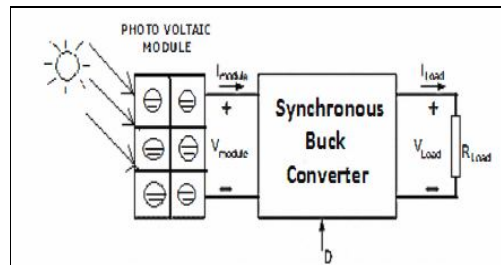


Fig. 4: Schematic Diagram for PV Based Converter System

As shown in the above Figure Fig 4 the dc voltage obtained from the PV array is regulated through dc-dc converter before it is fed to load [2]. The Simulink model of PV Cell, Buck Converter, Synchronous Buck Converter and Modified Synchronous Buck Converter is presented.

2. PV Array

The solar cell arrays or PV arrays are usually constructed out of small identical building blocks of single solar cell units. 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 [3].

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.5.

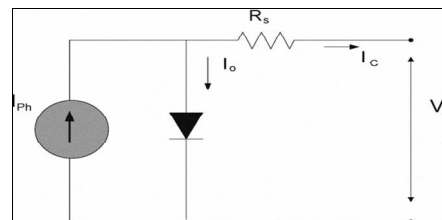


Fig. 5: Simplified equivalent circuit of PV cell

The complete PV panel Simulink model is shown in fig 6 which shows the simulation designing of PV panel for 17V, 10w. The output voltage from the PVA model is sent to the load and corresponding set of data of voltage and current output from the solar panel is measured.

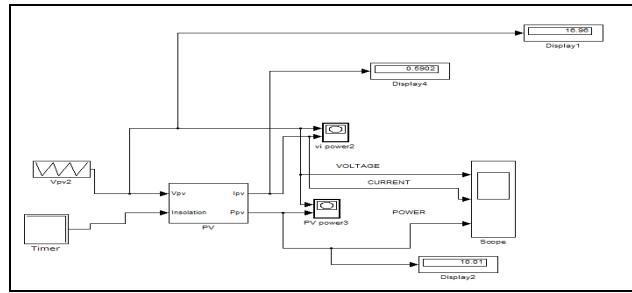


Fig. 6: Simulation Model of PV Panel

3. Analysis of Buck Converter, Synchronous Buck Converter and Modified Synchronous Buck Converter

3.1. Buck Converter

In Step down converter or Buck converter which is shown in the fig 1, the average output voltage V_o is less than the input voltage V_s . when the switch in turned ON, the voltage across the load is V_s . the current flows through the circuit as shown in the figure. When the switch is turned OFF, the current direction is same as before, but the voltage across the load is zero. The power flows from source to load, hence the output voltage is less than the source voltage, which can be determined by the duty cycle of the GATE pulse provided to the MOSFET switch [4].The inductor is used to smoothen the load current and make it a DC current and, the capacitor is used to reduce the ripples of the output voltage and supply a steady voltage [5].

3.2. Synchronous Buck Converter

Circuit diagram of Synchronous Buck Converter shown in fig 2 is same as buck converter main difference is Buck Converter uses a 2nd MOSFET in place of diode which is shown in fig 9 and the waveforms of the converter is shown in fig 10. When S_2 is on and S_1 is off, current flows upwards out of the drain S_2 . The advantage of this configuration is that 2nd MOSFET will have a much lower voltage drop across it compared to a diode, resulting in higher circuit efficiency. This is especially important for low voltage high current applications.

A Schottky diode will have a voltage drop of 0.3 to 0.4v across it while conducting, where as a MOSFET will have an extremely low voltage drop due to an $R_{ds(on)}$ as low as single digit milli ohm. This circuit has a control scheme known as synchronous rectification. The 2 MOSFET's shouldn't be ON at same time because to prevent a short circuit across a source therefore a dead time t_d is built in to a switching control such a way that one MOSFET is turned ON before the other is turned ON.

3.3. Modified Synchronous Buck Converter

In the Modified Synchronous Buck Converter shown in the fig 3 the efficiency can be increased by reducing the switching losses which can be done by providing an auxiliary MOSFET across the main MOSFET along with resonant circuits (L_r & C_r). The L_r and C_r are in resonance with each other and help in providing the time delay to minimize the switching losses. So this converter can be used for high as well as low switching frequencies.

3. Operating Modes And Analysis

The operation of modified synchronous buck converter with ZVS and ZCS technique for reducing the switching loss of main switch is described as follows [6]:

Mode 1:

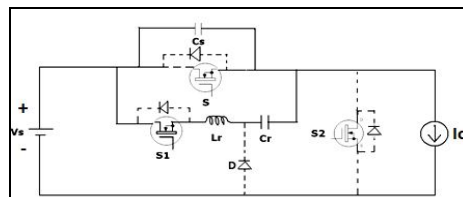


Fig. 7: Mode-1 of Modified Synchronous Buck Converter

Mode 1 equivalent circuit is shown in fig 7. At t_0 , the switch S_1 is turned on. S_1 realizes zero-current turn-on as it is in series with the resonant inductor L_r . The current through L_r and C_r increases. At the same instant, the capacitor C_s which was already charged to the supply voltage will start discharging through L_r , C_r , C_s and S_1 . The resonant network consists of L_r , C_r and S_2 . The mode ends at $t = t_1$, when the capacitor across the main switch C_s is completely discharged.

Mode 2:

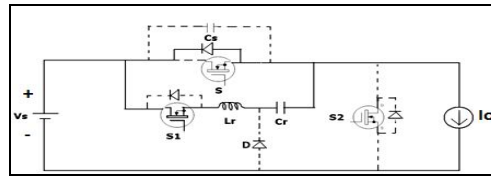


Fig. 8: Mode-2 of Modified Synchronous Buck Converter

Mode 2 equivalent circuit is shown in fig 8. At the starting of this mode, i_{Lr} reaches its peak value i_{Lrmax} . 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.

Mode 3:

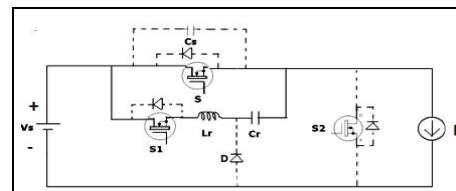


Fig. 9: Mode-3 of Modified Synchronous Buck Converter

Mode 3 equivalent circuit is shown in fig 9. In this mode, the main switch is turned-on with ZVS. During this stage the growth rate of i_s is determined by the resonance between L_r and C_r . The resonant process continues in this mode and the current i_{Lr} continue to decrease. This mode ends when i_{Lr} falls to zero and S_1 can be turned off with ZCS.

Mode 4:

Mode 4 equivalent circuit is shown in fig 10. During this mode the body diode of S_1 begins to conduct due to resonant capacitor C_r which starts to discharge. The resonant current i_{Lr} rises in the reverse direction, reaches a maximum negative and increases to zero. At this moment the body diode of S_1 is turned off and the mode ends.

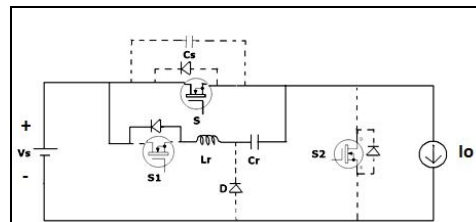


Fig. 10: Mode-4 of Modified Synchronous Buck Converter

Mode 5:

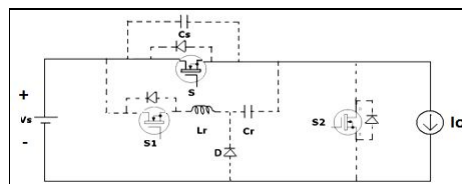


Fig. 11: Mode-5 of Modified Synchronous Buck Converter

Mode 5 equivalent circuit is shown in fig 11. The body diode is turned off at starting of this mode, now only the main switch S carries the load current. There is no resonance in this mode and the circuit operation is identical to a conventional PWM buck converter.

Mode 6:

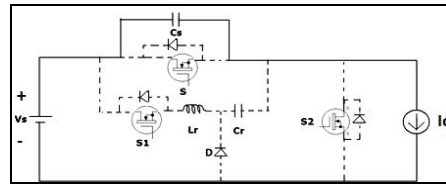


Fig. 12: Mode-6 of Modified Synchronous Buck Converter

Mode 6 equivalent circuit is shown in fig 12. In this mode current is delivered to the load through source Vs. So in this process, Cs gets charged to Vs as shown in Fig 5.8f. The capacitor gets charged till the end of this mode and the conduction starts again in the next mode.

Mode 7:

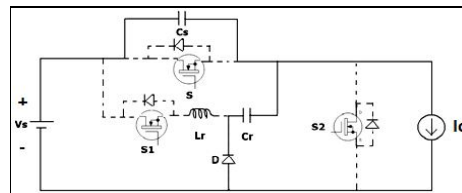


Fig. 13: Mode-7 of Modified Synchronous Buck Converter

Mode 7 equivalent circuit is shown in fig 13. 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 Cr starts discharging to the load through the high frequency Schottky diode D for a very short period of time, hence body – diode conduction losses and drop in output voltage is too low. This mode finishes when Cr is fully discharged.

Mode 8:

Mode 8 equivalent circuit is shown in fig 14. Before starting of this mode, the body diode of switch S2 is conducting. But as soon as resonant capacitor Cr is fully discharged, the Schottky diode is turned off. During this mode, as shown in fig 13, the converter operates like a conventional PWM buck converter.

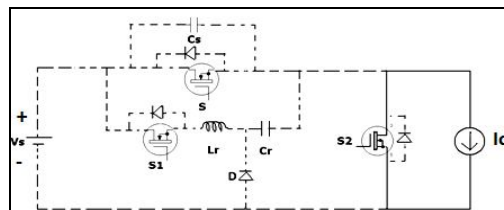


Fig. 14: Mode-8 of Modified Synchronous Buck Converter

4. Simulation Results and Discussion

The values chosen for the simulation of buck converter and synchronous buck converter are as follows. Vs= 5volts, switching frequency = 40kHz, Output voltage (Vout) = 1.5 volts, output inductor (L0) = 83.3 μH, output capacitor (C0) = 497 μF, load current 1A, Resistance 8Ω and current ripple is 30% of maximum load current . The simulation is done in MATLAB-Simulink environment.

The duty ratio is calculated using equation $D = (V_o/V_i)$ (1)

Inductance is calculated by equation $L = (V_{in}/V_o) (D / (F_{sw} * I_{ripple}))$ (2)

Capacitance is calculated by equation $C = (\Delta I * \Delta T) / (\Delta V - (\Delta I * ESR))$ (3)

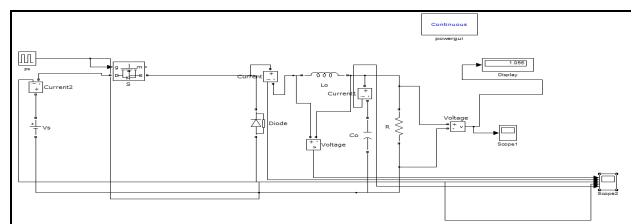


Fig. 15: Buck converter Simulink Model

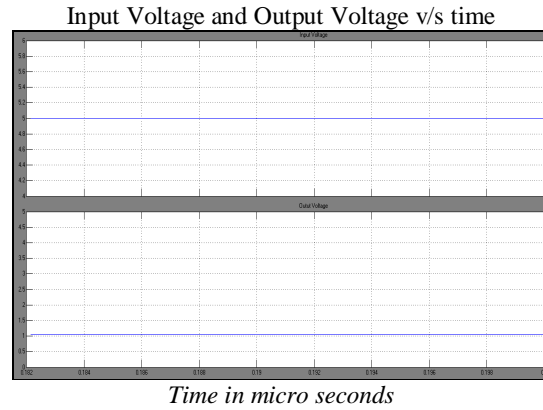


Fig. 16: Waveforms of Input Voltage and Output Voltage

As explained in section III the buck converter is a step down converter, the output voltage V_o is less than the input voltage V_s . Simulation of buck converter is carried out for input voltage of 5v and the other design parameters are described above. The obtained output voltage in simulation is 1.05v which is shown in fig 16.

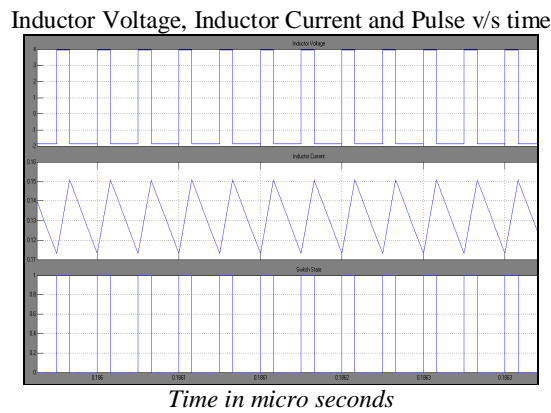


Fig. 17: Waveforms of Inductor Voltage, Inductor Current and Pulse

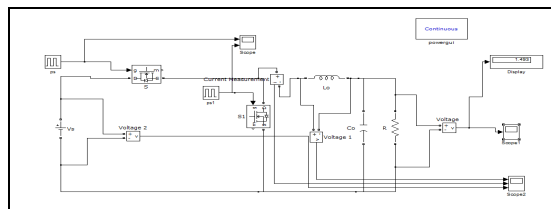


Fig. 18: Simulink Model of Synchronous Buck Converter

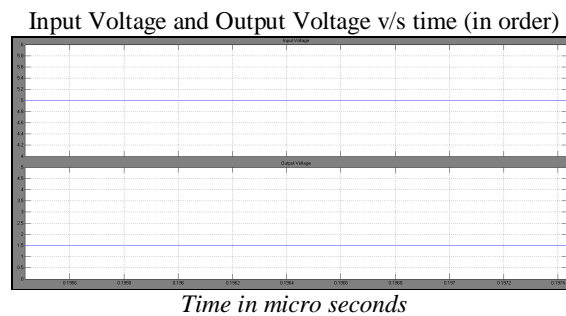


Fig. 19: Waveforms of Input Voltage and Output Voltage

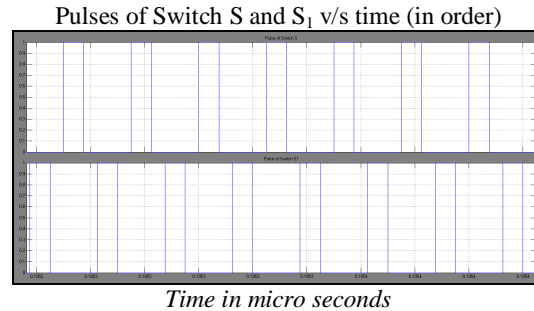


Fig. 20: Switching patterns of the PWM signals

With the Buck converter for the design parameters described above the output voltage obtained is 1.05V which is lesser than the expected level. To obtain the expected output voltage 1.5V, Synchronous Buck Converter is simulated. Simulation of Synchronous Buck converter is carried out for input voltage of 5v. The obtained output voltage in simulation is 1.49V which is shown in fig 19. In Synchronous Buck Converter the switches S and S₁ work in complementary mode which is shown in fig 20.

The values chosen for the simulation of modified synchronous buck converter are as follows. V_s= 5volts, switching frequency = 40kHz, Output voltage (V_{out}) = 1.5 volts, resonant capacitor (C_r) =0.1μF, resonant inductor (L_r) = 0.3 μH, capacitor in parallel to main switch (C_s) = 0.05nF, output inductor (L_o) = 83.3 μH, output capacitor (C_o) = 497 μF, load current 1A and current ripple is 30% of maximum load current . The simulation is done in MATLAB-Simulink environment. Fig 21 shows the simulink model of modified synchronous buck converter.

Resonant capacitor is calculated by equation

$$C_r = \frac{I_{MAX} T_D (s-1)^2}{V_o [1 + \frac{\pi(s-1)}{2}]}$$

Resonant Inductor is calculated by equation

$$L_r = \frac{V_o T_D}{I_{MAX} [1 + \frac{\pi(s-1)}{2}]}$$

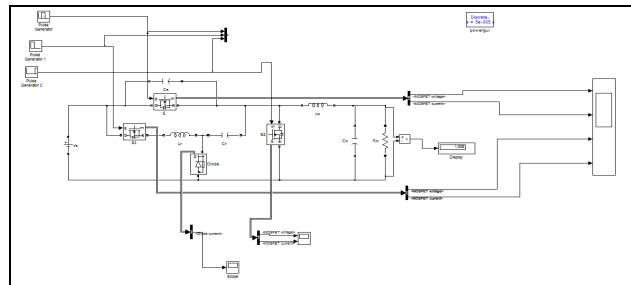


Fig. 21: Simulink model for Modified Synchronous Buck Converter

As stated above, in the Soft Switching Synchronous Buck Converter the switching loss can be minimized by applying soft switching technique such as ZCS & ZVS. This can be explained as follows.

4.1. ZVS Condition

Voltage v/s time for MOSFET 'S' time in micro seconds

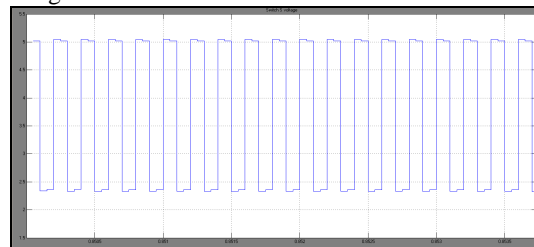


Fig. 22: Response of voltage across MOSFET 'S'

Current v/s time across MOSFET 'S' time in micro seconds

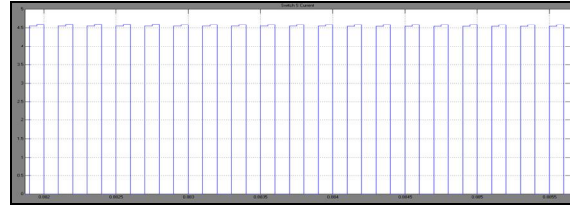


Fig. 23: Response of current flowing through MOSFET 'S'

From the Fig 22 and 23, it is clear that the MOSFET S is turned on through ZVS, when the voltage across capacitor C_S is zero. The voltage limit is not exceeded, but some current stress is observed for a short period of time. The main switch is also turned off through ZVS.

4.2. ZCS Condition

Voltage v/s time for MOSFET S_1 time in micro seconds

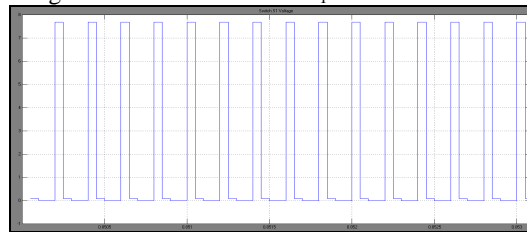


Fig. 24: Response of voltage across MOSFET 'S₁'

Current v/s time for MOSFET S_1 time in micro seconds

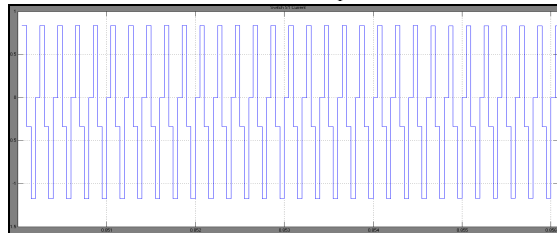


Fig. 25: Response of current flowing through MOSFET 'S₁'

From the Fig 24 and 25 of the auxiliary switch S_1 , it can be noted that it also operates on soft switching technique. It is turned on under ZCS because of resonant inductor and also turns off when current through resonant inductor falls to zero.

Input Voltage and output voltage v/s time time in micro seconds

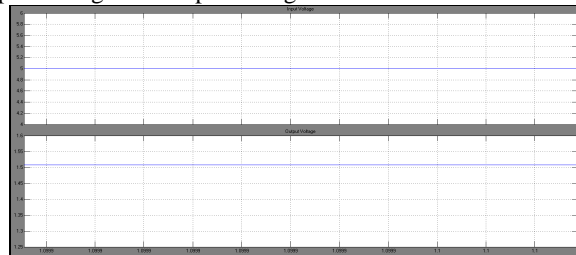


Fig. 26: Waveforms of Input and Output voltage

Simulation of Modified Synchronous Buck converter is carried out for input voltage of 5v. The obtained output voltage in simulation is 1.5V which is shown in fig 26.

Type of Converter	Input Voltage	Output voltage	Output voltage	Efficiency
Buck Converter	5V	1.5V	1V	75%
Synchronous Buck Converter	5V	1.5V	1.49V	88%
Modified Synchronous Buck Converter	5V	1.5V	1.5V	91%

Table I: Comparison of buck converter, synchronous buck converter modified synchronous buck converter

5. Hardware Implementation of Synchronous Buck Converter with PV System

The components used are PV Cell (17V, 10W), Switches (MOSFET IRFZ44N), Inductor 80 μ H, Capacitor 1000 μ F, Driver circuit (SN74HC245N). The pulses for triggering the switches were generated by using Microcontroller- ATMEGA328P for switching frequency of 40 KHz. Hardware setup of synchronous buck converter with PV energy system is shown in fig 27.

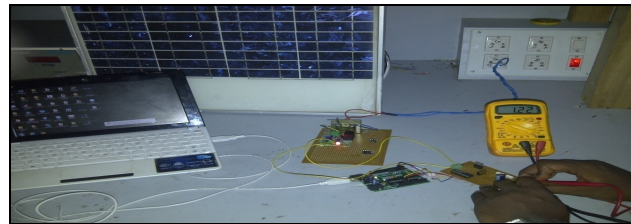


Fig. 27: Complete hardware setup

5.1. Experimental Results



Fig. 28: Gate pulse for MOSFET Switch S



Fig. 29: Gate pulse for MOSFET Switch S₁

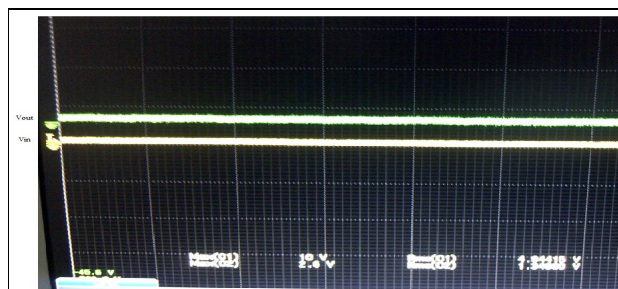


Fig. 30: Input voltage and output voltage waveforms

Fig 30 shows the input and output voltage waveform of synchronous buck converter with PV system. For a input of 5V the output is 1.34V.

Parameter	Simulation	Experimental
Input Voltage	5V	5V
Output Voltage	1.49V	1.34V
Frequency	40 KHz	39.7 KHz
Time period	25 μ s	25.2 μ s

Table II: Comparison between hardware and simulation of synchronous buck converter with PV source

6. Conclusion

The Photo Voltaic (PV) energy system is a very new concept in use, which is gaining popularity due to increasing importance to research on alternative sources of energy over depletion of the conventional fossil fuels world-wide. The output voltage obtained from the PV panel is DC. For low power applications, dc-dc converters are employed to step-down the output DC voltage according to the load requirements. The PV cell is simulated in MATLAB-Simulink environment.

The analysis and the design of Buck Converter, Synchronous buck converter and Modified synchronous buck converter are studied. The above three converters are simulated in MATLAB-Simulink environment with the Switching Frequency of 40 KHz. As we know all the three converters are step down converters. In the case of step down converters the output voltage should be less than input voltage. Simulation results of all the three converters prove the condition of step down converter. Simulation results of Modified synchronous buck converter depict the soft switching phenomena satisfying the ZVS and ZCS Condition. Finally, Comparison in the terms of efficiency improvement of the Buck Converter, Synchronous Buck Converter and Modified Synchronous Buck Converter is done with the help of MATLAB-Simulink software which shows that Synchronous Buck Converter and Modified Synchronous Buck Converter is highly efficient then Buck Converter. The hardware implementation of synchronous buck converter with photo voltaic source is carried out. The experimental gate pulses for the two MOSFETs are generated using the Microcontroller- ATMEGA328P for a switching frequency of 40 KHz and the results obtained from the experimental set up, satisfies with the simulation results.

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