SOLAR POWERED SYNCHRONOUS BUCK CONVERTER FOR LOW VOLTAGE APPLICATIONS

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ABSTRACT

The current resurgence of interest in the use of renewable energy is driven by the need to reduce the high environmental impact of fossil based energy systems. Future sustainability depends on use of different renewable energy sources. A photovoltaic generation system is becoming one of the important renewable energy due to absence of fuel cost, low maintenance and environment friendliness. This paper presents synchronous buck converter based PV energy system for portable applications; especially low power device applications such as charging mobile phone batteries are considered. Here, the converter topology used uses soft switching technique to reduce the switching losses which is found prominently in the conventional buck converter, thus efficiency of the system is improved and the heating of MOSFETs due to switching losses reduce and the MOSFETs have a longer life. The DC power extracted from the PV array is directly fed to the synchronous buck converter to suit the load requirements. The whole system is simulated using MATLAB-Simulink environment.

Keywords: MOSFET, ZVS, ZCS, Synchronous Buck Converter, PV Module.

I. INTRODUCTION

India imports more than 80% of its oil; hence it has a huge dependency on external sources for development. With depleting fossil reserves worldwide, there has been a threat to India’s future energy security. Hence, the government of India is investing huge capital on development of alternative sources of energy such as solar, small hydroelectric, biogas and wind energy systems apart from the conventional nuclear and large hydroelectric systems.

For environmental concern and increase of peak power demand PV solar cells has become an alternative energy source for green and clean power generation. 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 its 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.

1.1 PV ENERGY SYSTEMS FOR PORTABLE APPLICATIONS

This energy generation system consists mostly of capacities below 100W. They have a huge range of applications ranging from powering calculators, educational toys, solar lamps, traffic signals, mobile chargers, etc. They are usually made up of poly crystalline material of solar cells due to their higher energy density over a small area and fits in the portable applications. However, this system is not highly commercialised due to battery technology required to store the power generated and high cost of poly crystalline silicon solar cells. They generally use lithium ion batteries [4] to store energy due to its high energy capacity and light in weight. These systems come handy when power is required on move and has a potential to revolutionise the current era of electronics with free power on move. The simple mobile charger based on PV energy system consists of a small solar module generally made of poly crystalline silicon, connected to the electrical load through a buck/boost converter for regulation of voltage at the load end [5]. This regulation is usually done using a feedback loop that senses the output voltage and tries to keep it at the desired output voltage required.[21].

However, higher input voltages and lower output voltages have brought about very low duty cycles, increasing switching losses and decreasing conversion efficiency. So in this paper, the efficiency of the synchronous buck converter is optimised by eliminating switching losses using soft switching technique. The voltage-mode soft-switching method that has attracted most interest in recent years is the zero voltage transition [1],[2], [4]-[8], [10], [11], [13]-[20], [22]-[24], [26]-[27], [29].This is because of its low additional conduction losses and because its operation is closest to the PWM converters. The auxiliary circuit of the ZVT converters is activated just before the main switch is turned on and ceases after it is accomplished. The auxiliary circuit components in this circuit have lower ratings than those in the main power circuit because the auxiliary circuit is active for only a fraction of the switching cycle; this allows a device that can turn on with fewer switching losses than the main switch to be used as the auxiliary switch.

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 (Lr& Cr)
This combination constitutes 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 ‘s2’.[24-25]

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. This converter topology enables to provide simple and cost effective solution in the charging circuit. This converter using soft switching technique for low power application [20-25 ] is found in literatures but in this paper this converter is directly connected to the modelled PV module for low voltage application not known to be present in literature is presented.

1.2 OPERATION OF A 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]

Mode 1: Before starting of this mode diode of S2 was conducting and at time t1, mosfet S1 is turned on through ZCT which is caused by the current passing through Lr. In this mode Lr and Cr are resonance with each other and it ends when diode of S2 stops conducting and when current through Lr reaches I0.

Mode2: Lr and Cr continue to resonate. At t1 the synchronous switch S2 is turned on under ZVS. This mode ends when S2 is switched of and iLr reaches its maximum value.
Mode 3: At the starting of this mode, $i_{Lr}$ reaches its peak value $i_{Lr_{\text{max}}}$. 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:

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

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 zero and $S_1$ is turned off through ZCS.
Mode 5: In the previous mode, S1 is turned off. The body diode of S1 begins to conduct because of discharging of Cr. The resonant current iLr starts increasing in reverse direction and finally becomes zero. The mode ends when body diode of S1 is turned off.

![Fig 6: Mode 5](image)

Mode 6: Since in the previous mode, body diode of S1 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.

![Fig 7: Mode 6](image)

Mode 7: At starting of this mode, the main switch S is turned off with ZVS. The schotkey diode D starts conducting. The resonant energy stored in the capacitor Cr starts discharging to the load through the high frequency schottky diode DS 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.[26]

![Fig 8: Mode 7](image)
Mode 8: 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 under ZVS. During this mode, the converter operates like a conventional PWM buck converter until the switch S1 is turned on in the next switching cycle.

II. MODELLING OF PV ARRAY

The use of equivalent electric circuits makes it possible to model characteristics of a PV cell. The method used here is implemented in MATLAB Simulink for simulations. The same modeling technique is also applicable for modeling a PV module.

The simplest model of a PV cell is shown as an equivalent circuit below that consists of an ideal current source in parallel with an ideal diode. The current source represents the current generated by photons (often denoted as $I_{ph}$ or $I_L$), and its output is constant under constant temperature and constant incident radiation of light.

There are two key parameters frequently used to characterize a PV cell. Shorting together the terminals of the cell, as shown in Figure 5, the photon generated current will follow out of the cell as a short-circuit current ($I_{sc}$). Thus, $I_{ph} = I_{sc}$. As shown in Figure, when there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode. This gives the open circuit voltage ($V_{oc}$). The PV module or cell manufacturers usually provide the values of these parameters in their datasheets.
The output current \( I \) from the PV cell is found by applying the Kirchoff’s current law (KCL) on the equivalent circuit shown in Figure 10.

\[
I = I_{sc} - I_d
\]  

(1.1)

where: \( I_{sc} \) is the short-circuit current that is equal to the photon generated current, and \( I_d \) is the current shunted through the intrinsic diode.

The diode current \( I_d \) is given by the Shockley’s diode equation:

\[
I_d = I_o \exp\left(\frac{qV_d}{kT} - 1\right)
\]  

(1.2)

where:
- \( I_o \) is the reverse saturation current of diode (A),
- \( q \) is the electron charge \((1.602 \times 10^{-19} \text{ C})\),
- \( V_d \) is the voltage across the diode (V),
- \( k \) is the Boltzmann’s constant \((1.381 \times 10^{-23} \text{ J/K})\),
- \( T \) is the junction temperature in Kelvin (K).

Replacing \( I_d \) of the equation (1.1) by the equation (1.2) gives the current-voltage relationship of the PV cell.

\[
I = I_{sc} - I_o \left(\exp\left(\frac{qV}{kT}\right) - 1\right)
\]  

(1.3)

where: \( V \) is the voltage across the PV cell, and \( I \) is the output current from the cell.

The reverse saturation current of diode \( I_o \) is constant under the constant temperature and found by setting the open-circuit condition as shown in Figure 6. Using the equation (1.3), let \( I = 0 \) (no output current) and solve for \( I_o \).

\[
0 = I_{sc} - I_o \left(\exp\left(\frac{qV_{sc}}{kT}\right) - 1\right)
\]  

(1.4)

\[
I_{sc} = I_o \left(\exp\left(\frac{qV_{sc}}{kT}\right) - 1\right)
\]  

(1.5)

\[
I_o = I_{sc}/\left(\exp\left(\frac{qV_{sc}}{kT}\right) - 1\right)
\]  

(1.6)

To a very good approximation, the photon generated current, which is equal to \( I_{sc} \), is directly proportional to the irradiance, the intensity of illumination, to PV cell. Thus, if the value, \( I_{sc} \), is known from the datasheet, under the standard test condition, \( G_o=1000\text{W/m}^2 \) at the air mass (AM) = 1.5, then the photon generated current at any other irradiance, \( G \text{ (W/m}^2\text{)}\), is given by:

\[
I_{sc}G = (G/G_o) I_{sc}G_o
\]  

(1.7)

Figure shows that current and voltage relationship (often called as an I-V curve) of an ideal PV cell simulated by MATLAB using the simplest equivalent circuit model. The PV cell output is both limited by the cell current and the cell voltage, and it can only produce a power with any combinations of current and voltage on the I-V curve. It also shows that the cell current is proportional to the irradiance.
A single PV cell produces an output voltage less than 1V, about 0.6V for crystalline silicon (Si) cells, thus a number of PV cells are connected in series to archive a desired output voltage. When series-connected cells are placed in a frame, it is called as a module. Most of commercially available PV modules with crystalline-Si cells have either 36 or 72 series-connected cells. A 36-cell module provides a voltage suitable for charging a 12V battery, and similarly a 72-cell module is appropriate for a 24V battery. This is because most of PV systems used to have backup batteries, however today many PV systems do not use batteries; for example, grid-tied systems. Furthermore, the advent of high efficiency DC-DC converters has alleviated the need for modules with specific voltages. When the PV cells are wired together in series, the current output is the same as the single cell, but the voltage output is the sum of each cell voltage, as shown in Figure 12.

![I-V Characteristics of a PV Cell](image1)

**Fig 11:** I-V Characteristics of a PV Cell

Also, multiple modules can be wired together in series or parallel to deliver the voltage and current level needed. The group of modules is called an array.

### III. SIMULATION RESULTS AND DISCUSSIONS

The simple diode equivalent model is taken into consideration and PV module is modelled and various effects of temperature and irradiance are shown below.
The following parameters are considered for design:

\[ Vin = 30\text{V}, Vout = 12\text{volts}, Iload = 1\text{amps}, Fsw = 200\text{kHz}, \text{Duty ratio (D) = } \frac{Vin}{Vout} = 0.43. \]
Assume \( I_{ripple} = 0.3 \times I_{load} \) (typically 30\%). The switching frequency is selected at 200 kHz. The current ripple will be limited to 30\% of maximum load.

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**Fig 13:** I-V Characteristics with varying Irradiance for \( G = 400\text{ W/m}^2, 600\text{W/m}^2 \) and \( 1000\text{ W/m}^2 \)

**Fig 14:** I-V Characteristics with varying Temperature for \( T=25\text{°C}, 35\text{°C} \) and \( 50\text{ °C} \)

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**Fig 15:** Simulink model of synchronous buck converter without PV
Fig 16: Output Voltage of synchronous buck converter not connected to PV

Fig 17: Output current of synchronous buck converter not connected to PV

Fig 18: Voltage across main switch S
Fig 19: Current across switch S

Fig 20: Voltage across switch S1

Fig 21: Current across switch S1
The voltage waveform of MOSFET ‘S’ in fig. reveals 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’. The MOSFET ‘S1’ along with resonant capacitor (Cr) and resonant inductor (Lr) is used as an auxiliary circuit for causing ZVS for MOSFET ‘S’. The waveforms shown in fig.18 and fig.19&20 describe the current and voltage across MOSFET ‘S1’ indicates the zero current turn off of MOSFET ‘S1’ (ZCT). It is turned off by ZCT because of resonant inductor.

Fig 22: Current across switch S2

Fig 23: Synchronous buck converter connected with PV.
IV. CONCLUSION

The waveforms depict the soft switching phenomena. This converter is used as a DC-DC converter between PV array and load. Since the switching and conduction losses are reduced, the system can be used as a high efficient portable device. Besides the main switch ZVS turned-on and turned-off, the auxiliary switch ZCS turned-on and turned-off, the synchronous switch also turned-on and turned-off under ZVS. Hence switching losses are reduced and the additional voltage and current stresses on the main devices do not take place, and the auxiliary devices are subjected to allowable voltage and current values. In this paper the simulation is done for two cases i.e without connecting the PV module and with connection of the PV module in MATLAB Simulink environment and for input voltage of 30V the output voltage of 12V is obtained which can be used for any low power application fed from PV module and in most cases the of PV is around 15V to 40V depending on temperature and irradiance, hence this converter connected with PV can be used for portable applications.
REFERENCES


