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Soft Switching Buck Converter for Battery Charging With MPPT

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Abstract: Photovoltaic power generation system implements an effective utilization of solar energy, but generally has very low conversion efficiency. Maximum power point tracking (MPPT) is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics. A MPPT system has been developed, consisting of a soft switching Buck-type dc/dc converter. It overcomes the problem of mismatch between the solar arrays and the given load. In order to improve the efficiency of energy conversion for a photovoltaic (PV) system, this paper develops a soft-switching approach with MPPT for rechargeable batteries. By inserting an auxiliary switch in series with a resonant capacitor, the proposed topology can obtain a soft-switching buck dc–dc converter for battery charger and significantly decrease the switching losses in active power switches. The proposed soft switching buck converter for battery charger with MPPT has a straight forward structure, low cost, easy control, and high efficiency. In this paper, we have analyzed the operational principles of the adopted soft-switching buck converter, and it is designed for PV generation system with MPPT. Simulation results are presented.
Keywords: DC-DC converter; Maximum Power Point Tracking (MPPT); Photovoltaic power generation; Perturb and Observe (P&O) method.

I. Introduction

Before increased research about renewable energy, most of the energy used in industry depended on fossil fuel. But these days, because of fuel fossil exhaustion, which is due to limited reserves and environmental problems, the development and demand for renewable energy has increased. Fuel cells, water, wind, and photovoltaic (PV) energy are all renewable energy sources. Of these, PV energy generates electricity from solar radiation and, at present, represents one of the renewable energy sources emerging technologies due to the continuous cost reduction and technological advancements.

Rechargeable batteries are extensively utilized in many applications, including renewable energy generation systems, Electrical vehicles, uninterruptible power supplies, laptop computers, personal digital assistants, cell phones, and digital cameras. Since these appliances continuously consume electric energy, they need charging circuits for rechargeable batteries. Efficient charging shortens the charging time and extends the battery service life, while harmless charging prolongs the battery cycle life and achieves a low battery operating cost. Moreover, the charging time and lifetime of the rechargeable battery depend strongly on the properties of the charger circuit. The solar cell has nonlinear *V –I* and *P–V* characteristics, which depend on the irradiance, the operating temperature and load condition of the cell. Therefore, the dc–dc converter for a PV system has to

control the variation of the maximum power point of the solar cell output[1]. In other words, modulation of the duty ratio of the dc–dc converter controls maximum power point tracking (MPPT)[2-4].
Converters with the maximum power point tracking (MPPT) feature use an algorithm to continuously detect the maximum instantaneous power of the PV array. Because the operating conditions of the array (solar irradiation and temperature) may change randomly during the operation of the system an MPPT algorithm is necessary so that the maximum instantaneous power can be extracted and delivered to the load.
Many MPPT algorithms[5] have been proposed in the literature. Many theoretical improvements and even advanced techniques of artificial intelligence have been proposed to enhance a few basic MPPT methods in order to obtain questionable performance improvements. The simplest MPPT method and soft switching buck converter analyzed is the Perturb and Observe (P&O) method.

II. Modeling Of Pv Module

A PV module[4] consists of a number of solar cells connected in series (N_s=36) and parallel (N_p=1) to obtain the desired voltage and current output levels. Each solar cell is basically a p-n diode. As sunlight strikes a solar cell, the incident energy is converted directly into electrical energy without any mechanical effort. Transmitted light is absorbed within the semiconductor by using this light energy to excite free electrons from a low energy status to an unoccupied higher energy level. When a solar cell is illuminated, excess electron-hole pairs are generated throughout the material, hence the p-n junction is electrically shorted and current flows. For simplicity, the single-diode model of Fig.1 is used in this paper. This model offers a good compromise between simplicity and accuracy with the basic structure consisting of a current source and a parallel diode.
The current-Voltage relationship of a PV module is given by (4) and Fig.2 shows the I-V characteristics of the 74 W_p solar panel with different radiation.

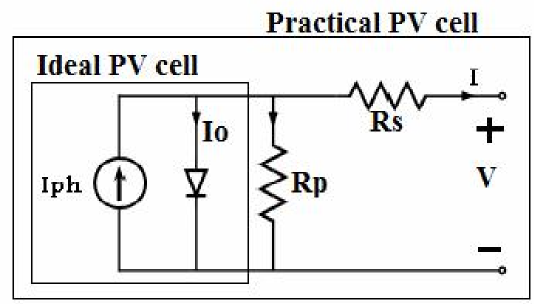


Fig.1. Equivalent circuit of a solar cell.

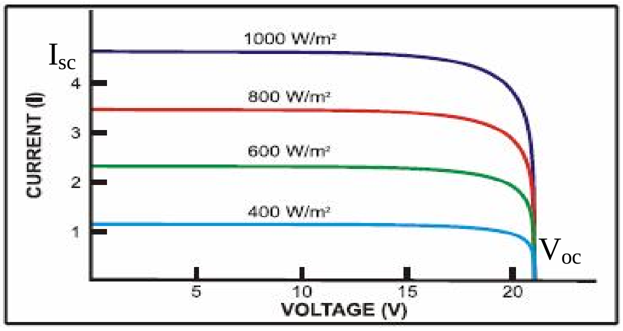


Fig.2 I-V characteristics of 74Wp solar panel at 25 ^{o}C.

A. PV Module Characteristics

PV cells are grouped in larger units called Modules, which are further interconnected in a series-parallel configuration to form PV array. The following are the basic equations from the theory of semiconductors and photovoltaic's[6,7] that mathematically describes the I-V characteristic of the photovoltaic cell and Module.

The photocurrent (I_{ph}) mainly depends on the solar irradiation in W/m^2 (G) and cell's working temperature in degree Kelvin (T_c). It is described as

$$I_{ph} = \left(\frac{G}{G_{ST}}\right) * \left[I_{SC} + K_1\left(T_c - T_{ref}\right)\right] \qquad (1)$$

Module reverse saturation current, I_{rs}, is given by (2) $I_{rs} = \dfrac{I_{SC}}{\left[\exp\left(qV_{oC}/N_S kAT_C\right) - 1\right]}$ (2)

Where A : Ideality factor; q: Carrier charge(1.6×10^{-19} in Coulombs); k: Boltzmann's constant $(1.38\times10^{-23} W\sec^0 .k^{-1})$; G_{ST} :Standard insulation in W/m^2; V : Output voltage in Volts; I_{sc} :Short circuit current in Amps; V_{oc} :Open circuit voltage in Volt; I_L :Load current in Amps; V_m :Maximum voltage in Volt;

I_m : Maximum current in Amps; E_g : Bang-gap energy; T_{ref} : Standard temperature in degree Kelvin; K_1 : The cell's short-circuit current temperature coefficient.

The Module saturation current (I_s) varies with the cell temperature as described by

$$I_s = I_{rs}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{qE_g\left(T_c - T_{ref}\right)}{T_{ref}T_c kA}\right] \qquad (3)$$

The basic equation that describes the current output of PV module I of the single diode model is given by

$$I = N_p I_{ph} - N_P I_s \left\{ \exp\left[\frac{q\left(\frac{V}{N_s} + \frac{R_s I}{N_P} R_S I\right)}{AKT_c}\right] - 1 \right\} \qquad (4)$$

The parallel resistance (R_p) has its greatest effect when the voltage is lowest, that is, when the current passing through the diode of the equivalent circuit is very small. The effect of parallel resistance, when it is sufficiently small, is to reduce the open-circuit voltage (V_{oc}) and the fill factor. The short-circuit current is not affected by it. When R_p is very large, we can neglect the same. In such case simulation values would be higher than the actual values by 3 to 5 percent at low values of irradiation only. However there would not be any appreciable variation at normal/higher values of irradiation.

The use of simplified circuit model in this paper makes this model suitable for power electronics designers who are looking for an easy and effective model for simulation of photovoltaic devices with power converters. The value of parallel resistance R_p is generally high and hence neglected to simplify the model as given in Fig.1. The series resistance R_s is the sum of several structural resistances of the PV module and its influence is stronger especially near the maximum power point region. The Power and voltage relationship curve is as shown in Fig.3.

III. Proposed System

With the variation of irradiation and temperature, the power output of PV module varies continuously. The maximum power point tracking (MPPT) algorithm is used for extracting the maximum power (P_m) from the solar PV module and transferring that power to the load. A DC-DC converter (Step down), serves the purpose of transferring maximum power from the PV module to the load and acts as an interface between the load and the module[8-10]. By changing the duty cycle of the PWM control signal, the load impedance as seen by the source varies and matches the point of the peak power of the source so as to transfer the maximum power.

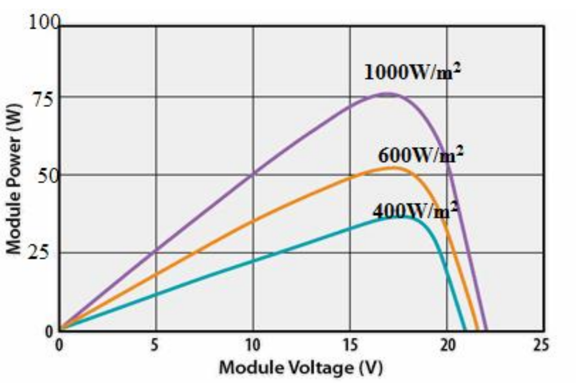


Fig.3 P-V characteristics of 74Wp solar panel at 25 °C.

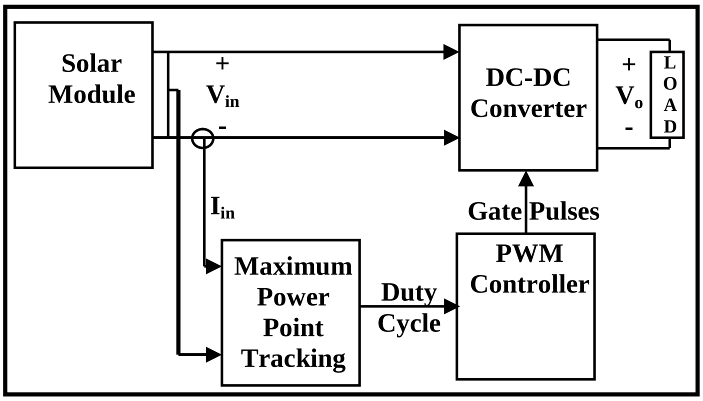


Fig. 4. DC-DC converter for operation at the MPP.

In power electronic circuit, the PV modules are always used with DC-DC converters to obtain the maximum power point operation. The types of converters used are buck, boost, and buck-boost. For battery charging applications buck-boost configuration is preferred whereas boost converters are used for grid-connected applications. DC-DC buck converters are used often in Battery charging application for standalone PV system. Hence, DC-DC buck converter is used for the design of MPPT controller. Fig.4. shows the block diagram for the proposed system.

IV. Buck Converter Analysis

The buck converter circuits are designed for the battery charging purpose. Buck converter is designed using soft switching technique[11].

A. Buck Converter Analysis

The proposed ZCS battery charger incorporates an auxiliary switch in series with the resonant capacitor in the buck ZCS converter.

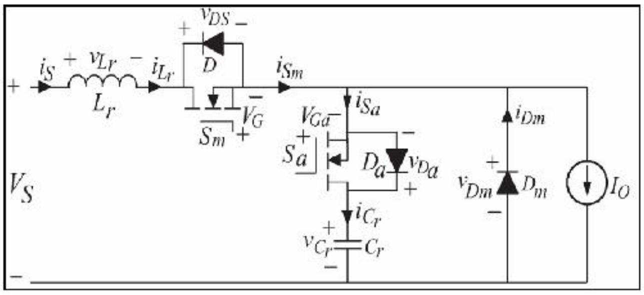


Fig. 5(a) Circuit Diagram of ZCS Buck Converter for Battery charging.

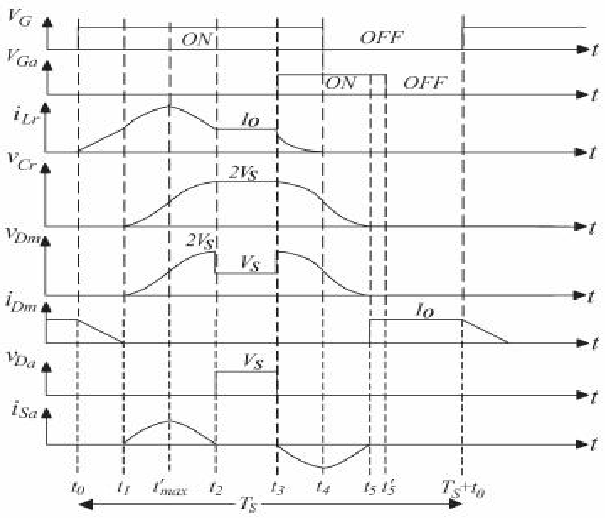


Fig. 5(b) Key waveforms of the proposed for Battery charging.

The ZCS quasi-resonant approach applies additional LC resonant tanks to shape the switching device's current waveform at on time in order to generate a zero-current condition for the device to turn off. Fig. 5(a) shows the circuit structure of a ZCS buck resonant converter for a battery charger which, unlike a traditional buck PWM converter, has an extra resonant tank that consists of a resonant inductor L_r, a resonant capacitor C_r, and a diode D_m. The inductor L_r is connected in series to a power switch S to limit the di/dt of the power switch, and capacitor Cr is installed as an auxiliary energy transfer element. The diode D_m is a freewheeling diode. The capacitor C_f and inductor L_f have low-pass filters, which not only filter high-frequency ripple signals but also provide a stable dc source for battery charging. The diode D_f prevents energy from transferring from the battery to the ZCS charger circuit.

B. Design of Buck Converter

The design procedure of the battery charger with ZCS buck converter for a 12-V 48-Ah lead acid battery is summarized as follows.

The normalized switching frequency f_{ns} = 0.7 was set based on the normalized voltage gain $M=V_o/V_s$ = 14/17 =0.8.

= 14/6 = 2.33 Ω.

The characteristic impedance is determined by substituting

Load resistance (R_o) = 2.33 Ω and Quality factor (Q) = 1

The necessary resonant frequency is derived from

$f_r=f_s/f_{ns}$= 16 kHz/0.7 = 22.25 kHz.

$$W_O = \frac{1}{\sqrt{(LrCr)}}$$

From above eq... $W_O / Z_O = 1/L_r$

$$C_r = 1/W_o Z_o$$

$$C_f = 100C_r$$

$$L_f = 100L_r$$

Where Z_0 : Output impedance in Ohm; W_0 : Angular frequency in rad/s; f_r : resonant frequency in Hz; f_s : Switching frequency in Hz.

V. Design Of MPPT

The DC-DC converter is simulated with DC supply. The converter voltage boost ratio is directly proportional to the duty cycle.

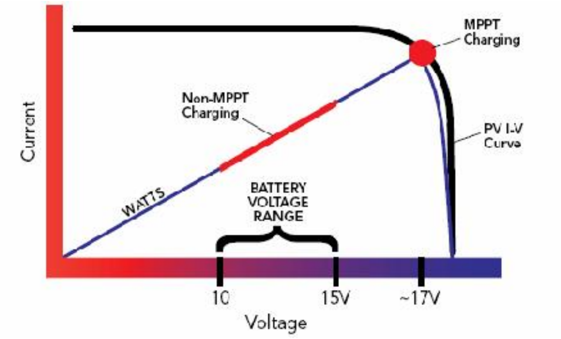


Fig.6. Maximum power point.

A.MPPT Control Algorithm

Many MPPT (Maximum power point tracking) techniques have been proposed in the literature; examples are the Perturb and Observe (P&O), Incremental Conductance (IC), Fuzzy Logic and so forth. The P&O algorithm is very popular and simple. So it is used in this paper. In P&O algorithm, a slight perturbation $(\Delta D = 0.01)$ is introduced in the system. This perturbation causes the power of the solar module to change. If the power increases due to the perturbation, then the perturbation is continued $(D + \Delta D)$ in that direction. After the peak power is reached, the power at the next instant decreases and after that the perturbation reverses $(D - \Delta D)$. The MPP tracking process is shown in Fig.7 and Table I shows different cases of P&O method. Where D is the duty ratio of the converter.

The P&O MPPT algorithm is shown in Fig.8. The starting point may vary, depending on the atmospheric conditions, while the duty cycle is changed continuously, according to the above mentioned algorithm, resulting in the system steady state operation around the maximum power point. The Detailed simulink model for closed-loop control of developed circuit model of PV module with MPPT control unit is shown in Fig.9 and Table II shows parameters of buck converter.

Table I: P&O Cases

ΔP	ΔD	Next Duty Cycle
+	+	$(D + \Delta D)$
+	-	$(D - \Delta D)$
-	+	$(D - \Delta D)$
-	-	$(D + \Delta D)$

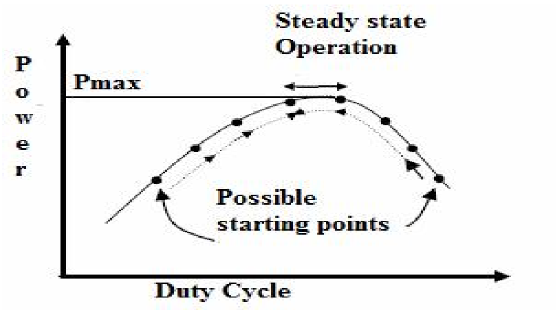


Fig.7. MPPT Tracking process

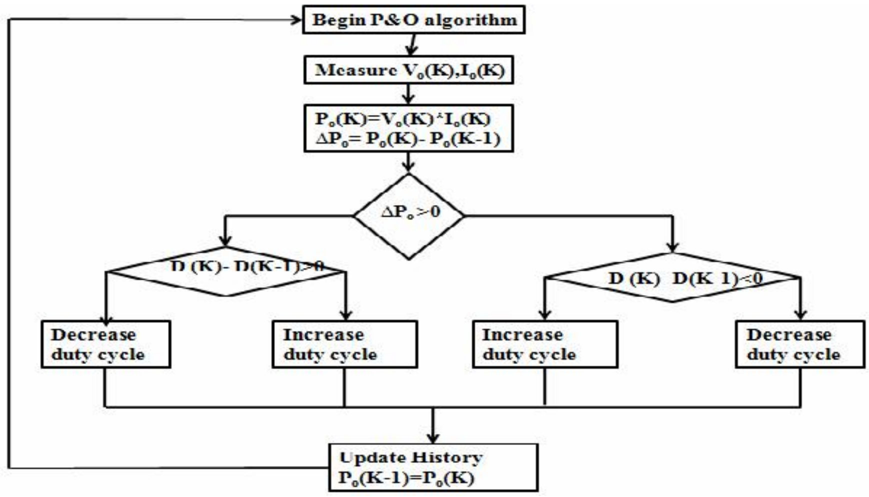


Fig.8. P&O MPPT algorithm

Table II. Buck Converter Parameters

Maximum Power($P_{o, max}$)	$74W_p$(optional)
Switching frequency(f_s)	16 kHz
PV Module Voltage (V_i)	15-17.5V
Output Voltage (V_o)	14V
Filter Inductor(L_f)	160µH
Resonant Inductor(L_r)	16.96µH
Filter capacitor(C_f)	300µH
Resonant Capacitor(C_r)	2.98µF

VI. Simulation Results

Using Matlab software the DC to DC soft switching buck converter with MPPT is simulated and output waveforms are observed. Fig.9 shows **s**imulation diagram. Fig.10 shows simulation of solar PV module. Fig.11 shows simulation of soft switching buck converter. Fig.12 shows simulation of MPPT algorithm. Fig.13 and Fig.14 shows V-I and P-V characteristics of solar module at different radiations respectively. Fig.15 shows the simulation of power, voltage and current of the PV module. Fig.16 shows simulation of the power, voltage and current with MPPT. Fig.17 shows simulation of the power, voltage and current with with step increases in radiation, MPPT. Fig.18-20. Shows the simulated waveforms of soft switching DC-DC Buck converter.

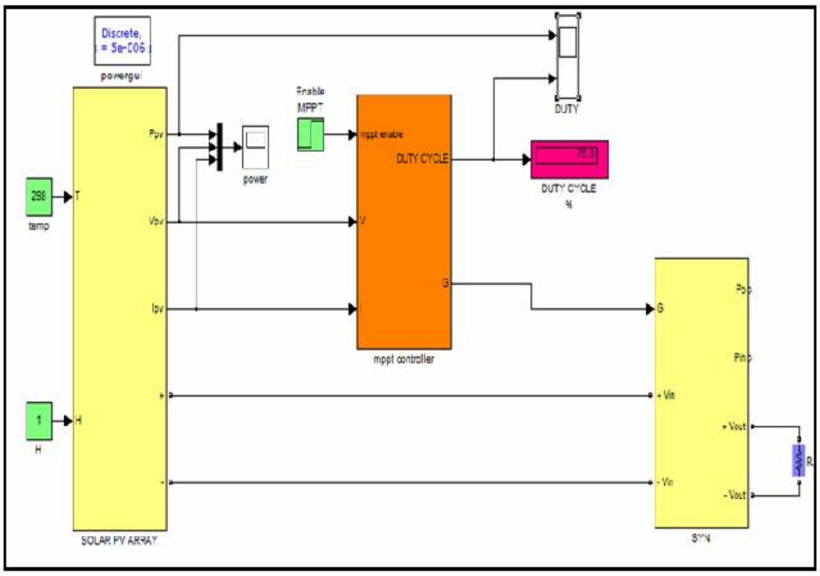


Fig.9. Simulation of Soft switching Buck Converter with MPPT.

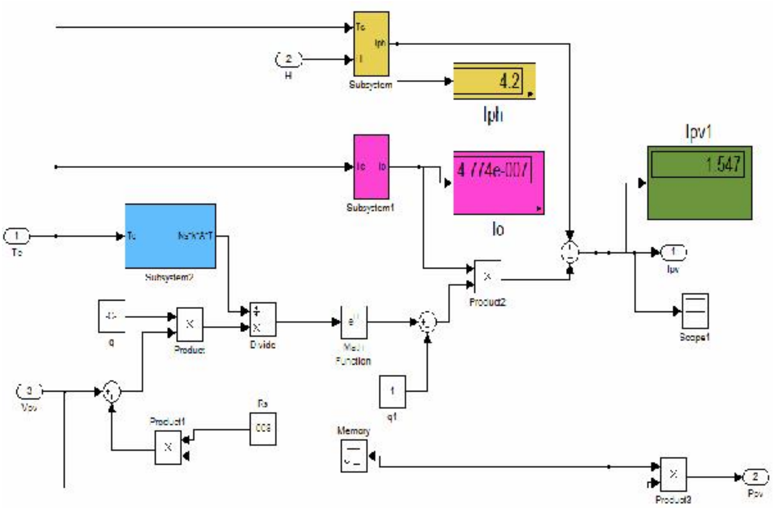


Fig.10.Masked diagram of solar module

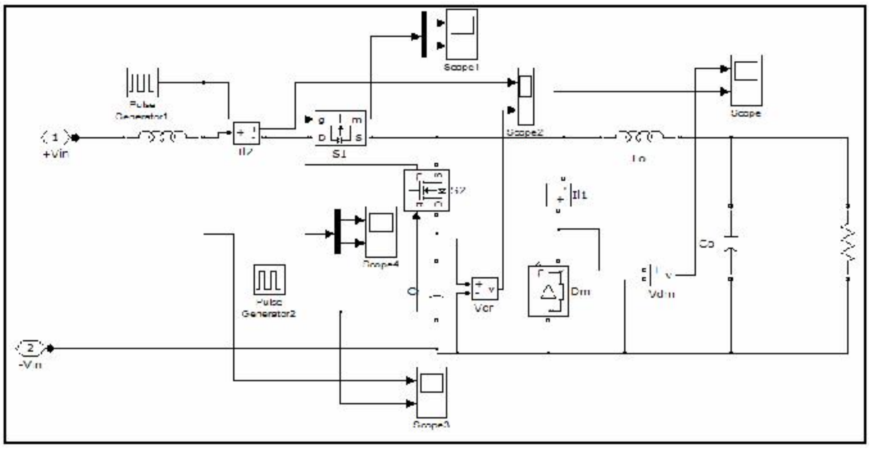


Fig.11 Simulation diagram of soft switching of DC-DC Buck converter.

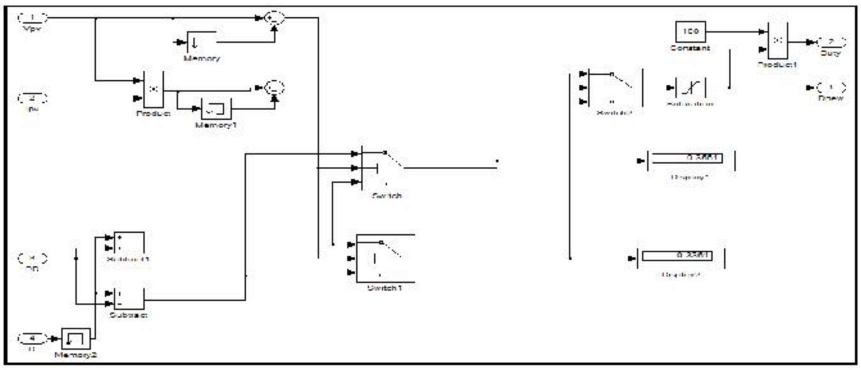


Fig.12.Simulation of MPPT P&O Method

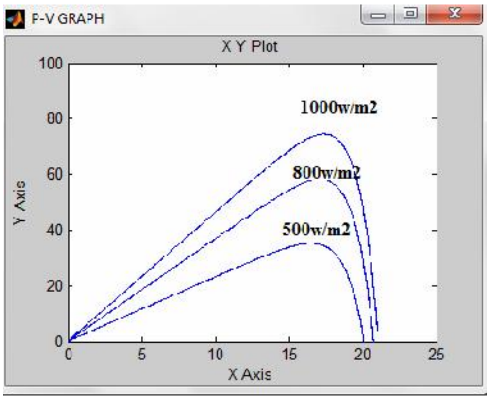


Fig.13.P-V characteristics of solar module at 1000 W/m^2,800 W/m2, and 1000 W/m^2

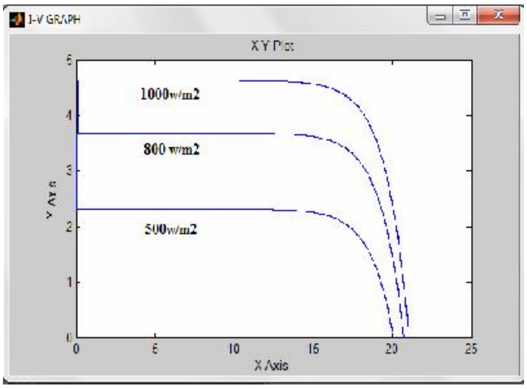


Fig.13.I-V characteristics of solar module at 1000 W/m^2,800 W/m2, and 1000 W/m^2

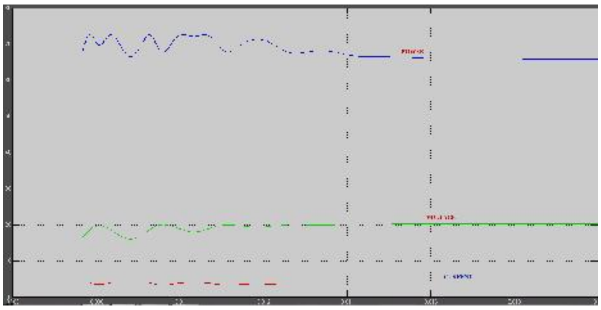


Fig.15. Waveforms of PV module power, voltage, and current.

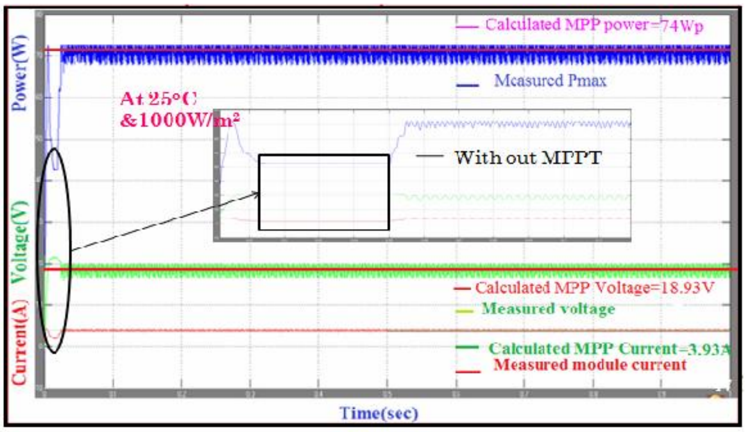


Fig.16. Waveforms of power, voltage, and current with MPPT.

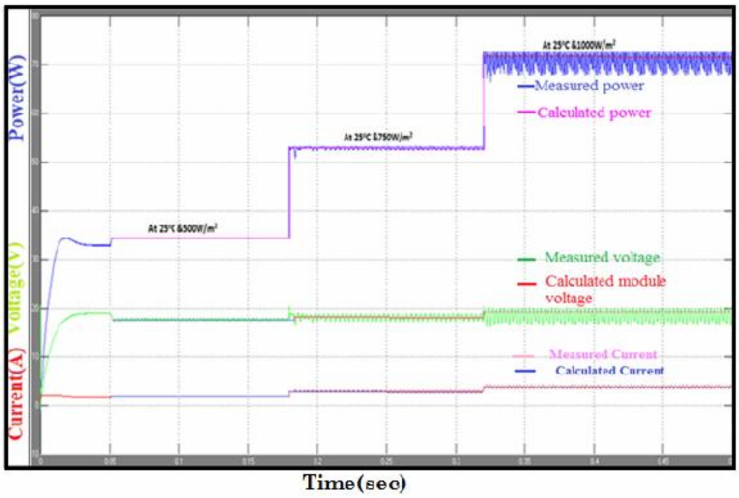
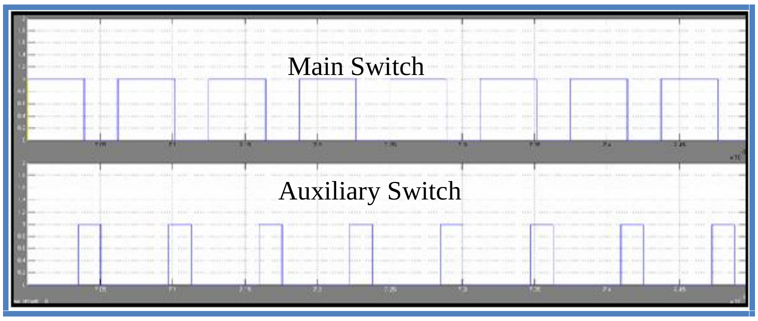
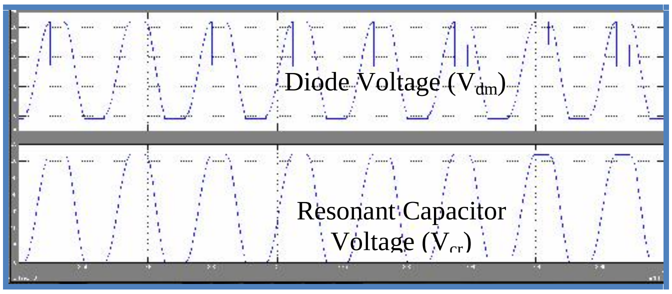


Fig.17. PV module power, voltage, and current (with step increases in radiation).



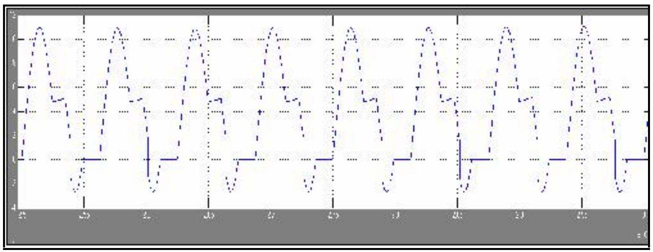
Time(sec)

Fig.18. Waveforms of the trigger signal Vg and the control signal V_{ga}.



Time(sec)

Fig. 19. Waveforms of the freewheeling diode voltage V_{dm} and the resonant capacitor voltage V_{cr}.



Time(sec)

Fig.20.The resonant inductor current I_{lr}.

Conclusion

This paper has developed a soft switching buck dc–dc converter with MPPT for a battery charger. The circuit structure is simple. The P&O MPPT algorithm is a simple algorithm that does not require previous knowledge of the PV generator characteristics or the measurement of solar intensity and cell temperature. This buck converter topology provides battery charger with an alternative choice to convert renewable energy efficiently and can also be extended easily to the requirements of other power conversion systems.

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