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Modeling and Performance Analysis of New Cuk Converter Topology for Photovoltaic Applications

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Abstract

Photovoltaic (PV) is a technical name in which radiant (photon) energy from the sun is converted to direct current (dc) Electrical Energy. PV power output is still low, continuous efforts are taken to develop the PV converter and controller for maximum power extracting efficiency and reduced cost factor. The maximum power point tracking (MPPT) is a process which tracks one maximum power point from array input, varying the ratio between the voltage and current delivered to get the most power it can. The selection of right converter for different application is a key factor for the optimum performance of the photo voltaic system. This paper details the study on state of the art in research works on Cuk power converters and their characteristics. A new cuk converter topology has also been proposed for the optimal performance of the photovoltaic system. Modeling of the PV array and simulation of basic cuk converter and the proposed cuk converter is carried out in Matlab/Simulink Software.

Index Terms - PV Module, MPPT, Incremental Conductance (IC) Algorithm, Cuk converter, Optimal performance

1. Introduction

Solar Energy is the ultimate source of energy, which is naturally replenished in a short time period of time, for this reason it is called “Renewable Energy” or “Sustainable Energy”. Due to the severity of the global energy crisis and environmental pollution, the photovoltaic (PV) system has become one kind of important renewable energy source. Solar energy has the advantages of maximum reserve, inexhaustibleness, and is free from geographical restrictions, thus making PV technology a popular research topic. Currently more research works has been focussed on how to extract more power effectively from the PV cells. Abu-Khader MM, *et al* (2008) proposed a solar tracking system with different modes of operation to have a maximum efficiency.

In the literature survey, Gules R, *et al* (2008), proposed a maximum point tracking system which shows there will be an increasing percentage of 30-40 % of energy will be extracted compared to the PV system without solar tracking system. The Maximum Power Point Tracking (MPPT) is usually used as online control strategy to track the maximum output power operating point of the Photovoltaic generation (PVG) for different operating condition of insolation and temperature of the PVG. Hohm D, Ropp M (2004) compares and evaluates the percentage of power extraction with MPPT and without MPPT. Her-Terng Yau (2012) use MPPT techniques with the PV system for optimal charging of Li-ion Battery. M.H. Taghvaee (2013) investigated the optimal operating performances by different converter topologies which is one of the main points in this research work. Enrique JM (2007) used different converter topologies for analysing the maximum power point tracking efficiency. The overall block diagram of PV panel with Dc-Dc converter and MPPT is shown in this figure 1. This paper reviews the basic characteristics of the PV cell and the simulation model of the circuit with the help of Matlab/simulink software. The MPPT Controller is necessary for any solar systems need to extract maximum power from PV module. It forces PV module to operate at close to maximum power operation point to draw maximum available power. The MPPT algorithm used in this paper is of fixed step size Incremental Conductance (IC) Method. Then the optimal performance of the PV system mainly depends on the power converter. Then in the final phase the synchronous cuk converter, a new topology can be implemented and the simulation results are analysed for the optimal performance.

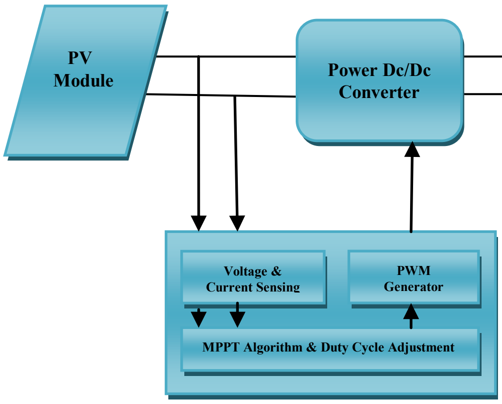

Figure 1. Overall Block Diagram

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2. Modelling of PV Cell

The solar cell is the basic unit of a PV system. An individual solar cell produces direct current and power typically between 1 and 2 W, hardly enough to power most applications. The voltage of a solar cell does not depend strongly on the solar irradiance but depends primarily on the cell temperature. PV modules can be designed to operate at different voltages by connecting solar cells in series. When solar cells absorb sunlight, free electrons and holes are created at positive/negative junctions. If the positive and negative junctions of solar cell are connected to DC electrical equipment, current is delivered to operate the electrical equipment. The equivalent circuit of the PV cell is shown in figure 2.

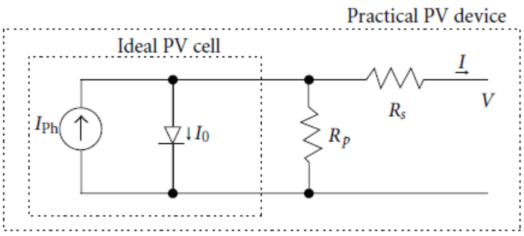

Figure 2. PV cell Modelled as a diode circuit

For simplicity, the single-diode model of Figure 2 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. In Figure 2, I_{ph} represents the cell photocurrent while *R*sh and *Rs* are, respectively, the intrinsic shunt and series resistances of the cell. The module photocurrent I_{ph} of the photovoltaic module depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation:

$$I_{ph} = [I_{SC} + K_i\,(Tk - T\mathrm{ref})] * \lambda / 1000 \qquad (1)$$

where I_{ph} [A] is the light-generated current at the nominal condition (25◦C and 1000W/m^2), K_i is the short-circuit current/temperature coefficient (0.0017A/K), T_k and T_{ref} are, respectively, the actual and reference temperatures in *K*, λ is the irradiation on the device surface (W/m^2), and the nominal irradiation is 1000W/m^2. The value of module short-circuit current is *I*SC taken from the datasheet of the reference model. The detailed simulink model of PV cell is presented in Figure 3. Iph for different values of insolation and temperature is shown in Table 1.

Table1. Iph for various Insolation and Temperatures

S. No	Insol W/m^2	Value of Iph (A)			
		20^{o}c	30^{o}c	40^{o}c	50^{o}c
1	1000	2.54	2.557	2.578	2.593
2	500	1.278	1.279	1.288	1.299

3	100	0.252	0.254	0.257	0.259

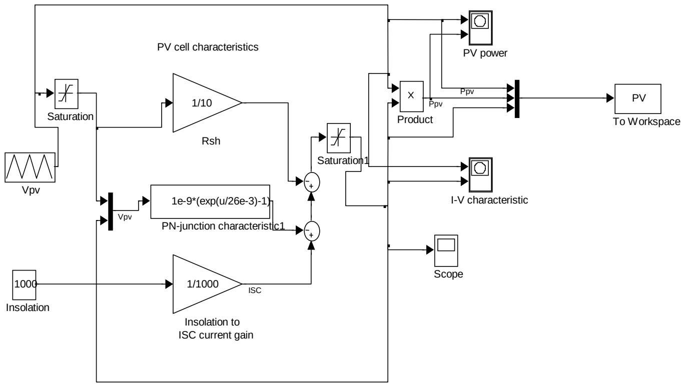

Figure 3. Simulink Model of PV cell

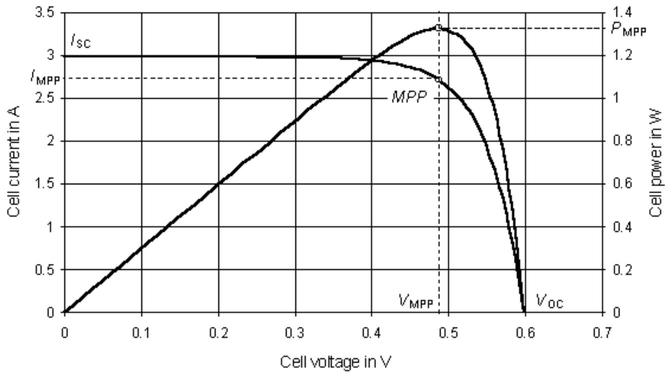

Figure 4. I-V & P-V Characteristics of PV cell

3. Incremental-Conductance Mppt Algorithm

MPPT or Maximum Power Point Tracking is algorithm that included in charge controllers used for extracting maximum available power from PV module under certain conditions. The voltage at which PV module can produce maximum power is called 'maximum power point' (or peak power voltage). Maximum power varies with solar radiation, ambient temperature and solar cell temperature. Typical PV module produces power with maximum power voltage of around 17 V when measured at a cell temperature of 25 ℃, it can drop to around 15 V on a very hot day and it can also rise to 18 V on a very cold day. MPPT checks output of PV module, compares it to battery voltage then fixes what is the best power that PV module can produce to charge the battery and converts it to the best voltage to get maximum current into battery. It can also supply power to a DC load, which is connected directly to the battery. MPPT algorithm can be applied to both buck and boost power converter depending on system design. Normally, for battery system voltage is equal or less than 48 V, buck converter is useful. On the other hand, if battery system voltage is greater than 48 V, boost converter should be chosen. In incremental conductance method the array terminal voltage is always adjusted according to the MPP voltage it is based on the incremental and instantaneous conductance of the PV module.

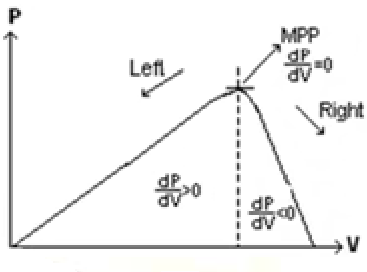

Figure 5. Basic Concept of Incremental Conductance on a PV Curve

The basic concept of Incremental conductance on a PV curve of a solar module is shown in figure 5. The slope of the P-V module power curve is zero at The MPP, increasing on the left of the MPP and decreasing on the Right hand side of the MPP. The basic equations of this method are as follows.

$$dP/dV = 0 \text{ at MPP} \quad (2)$$

$$dP/dV > 0 \text{ left of MPP} \quad (3)$$

$$dP/dV < 0 \text{ right of MPP} \quad (4)$$

$$dP/dV = d(VI)/d(V) = I + V*dI/dV \quad (5)$$

The *dP/dV* is defined as Maximum power point identifier factor. By utilizing this factor, the IC method is proposed to effectively track the MPP of PV array. The following definitions are considered to track the MPP.

$$\Delta I/\Delta V = -I/V \qquad at\ MPP,\ \Delta V_n = 0 \quad (6)$$

$$\Delta I/\Delta V > -I/V \qquad left\ of\ MPP,\ \Delta V_n = +\delta \quad (7)$$

$$\Delta I/\Delta V < -I/V \qquad right\ of\ MPP,\ \Delta V_n = -\delta \quad (8)$$

The MPPT regulates the PWM control signal of the dc to dc power converter until the condition: (dI/dV) + (I/V) = 0 is satisfied. Consider the n^{th} iteration of the algorithm as a reference, and then n+1 iteration process can be determined by using the above equations. The Flow chart of incremental conductance MPPT is shown in figure 6. The output control signal of the IC method is used to adjust the voltage reference of PV array by increasing or decreasing a constant value ($\Delta V=\delta$) to the previous reference voltage. In this method the tracking of MPP is accomplished by a fixed step size ($\pm\ \delta$) regardless to the gap between the operating point of PV and MPP location. In this method the peak power of the module lies at above 97% of its incremental conductance.

4. Dc-Dc Power Converter

DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage. The regulation is normally achieved by PWM at a fixed frequency and the switching device is generally BJT, MOSFET or IGBT. There are several different types of dc-dc converters, buck, boost, buck-boost and cuk topologies, have been developed and reported in the literature to meet variety of application specific demands. The important requirement of any DC–DC converter used in the MPPT scheme is that it should have a low input-current ripple. Buck converters will produce ripples on the PV module side currents and thus require a larger value of input capacitance on the module side.

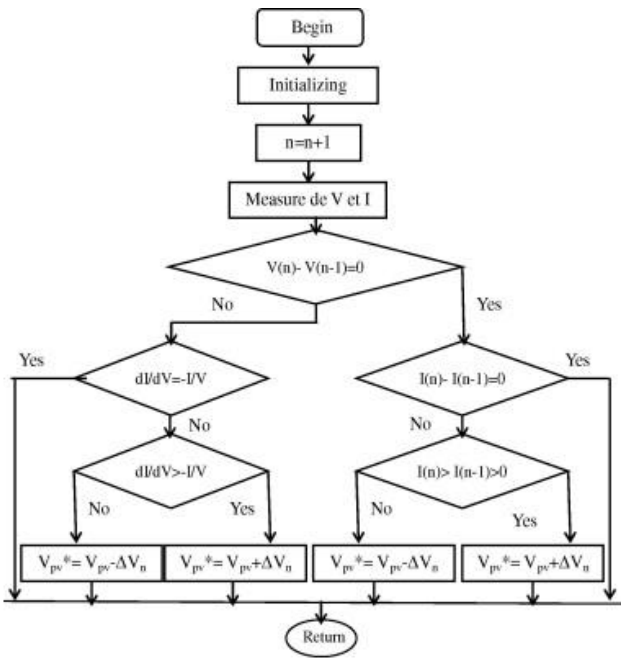

Figure 6. Flow chart of MPPT Incremental Conductance

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On the other hand, boost converters will present low ripple on the PV module side, but the load current exhibits more ripple and gives a voltage higher than the array voltage to the loads. The buck– boost converters can be used where the requirement of load voltage, either low or higher than the array voltage. However, with this converter the input and load currents are pulsating in nature. Furthermore, the load voltage will be inverted with buck–boost or CUK converters. Among the three basic topologies of DC–DC converters (buck, boost, and buck–boost) with resistive load connected to the PV panels the author conclude that buck– boost DC–DC converter topology is the only one allowing tracking of PV MPP whatever the temperature, irradiance, and load connection condition. It also verified that connecting a PV buck–boost DC–DC converter to the PV panel output possibly improves performance. Despite the study being theoretical, buck and boost converters practically are notably the most effective topologies at any price. Its voltage flexibility varies, but buck–boost converter is always either efficiency, or price, disadvantaged.

4.1. Cuk Converter

The Cuk switching topology is shown in figure 7. Ouput voltage magnitude can be either larger or smaller than that of the input, and there is a polarity reversal on the output. This topology can be used for connecting nearly matched battery or load to module voltages. The changes in the duty cycle enables them to operate through short-circuit current to open-circuit voltage. The main difference between Cuk converter and basic DC–DC configurations is the addition of a capacitor and an inductor. Inductor L1 filters the DC input (to prevent large harmonics) and capacitor C1 is the energy- transfer device (unlike inductor in the basic configurations).

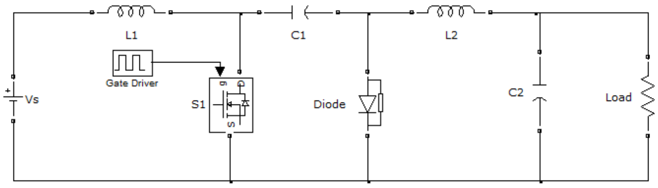

Figure 7. Cuk converter

An important advantage of this topology is the continuous current at the converter input and output. The sweep of the I-V characteristic is thus more reliable and the converter is less noisy. The disadvantages of the Cuk converter are the high number of passive components and high electrical stress on the switch, diode and capacitor C1. In higher order application the converter topologies have the disadvantage that the high voltage ripples are present on both the input and the output sides of the converter. Thus, a soft switching based converter is required for reducing the power loss.

4.2. Proposed Cuk Converter

The review of the recent research works reveals that, the Cuk converter based photo voltaic (PV) energy system is applied various convenient applications. It converts one DC voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. In the time of conversion process, the MOSFET switching frequency is increased so switching power loss is occurred. Therefore, the switching driver circuit is needed for driving the device without switching losses. To overcome this problem, in this paper a proposed Cuk converter based PV system is shown in figure 8.

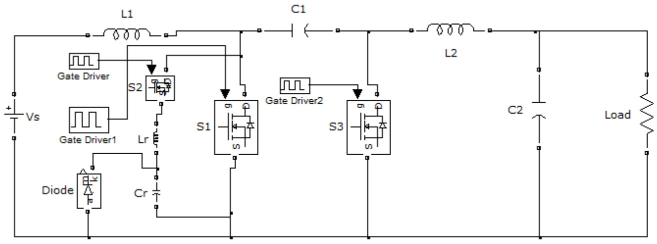

Figure 8. Proposed Cuk converter

In this new modified topology, the input side and output side inductors are denoted as L_1 and L_2 respectively. The output capacitor and inductor acts as a filter circuit providing only the dc component and filtering the AC component. The diode D_1 of the basic cuk converter is replaced by the Mosfet switch in order to reduce the conduction loss. The supplementary circuit consists of one auxiliary Mosfet switch, with resonant Inductor L_r and resonant capacitor C_r. The whole supplementary circuit is connected parallel to the main switch. In order to minimize the switching losses of the converter, the resonant capacitor C_r provides the time delay by charging and discharging during normal and abnormal operation. By having this new topology the main Mosfet switch and other switches are not subjected to additional voltage stresses. The output inductor and capacitor are chosen properly in such a way that the output current and voltage remains constant and ripple free as well. The equations (9) & (10) are used for calculating the resonant capacitor and resonant inductor are

$$C_r = \frac{I_{in(\max)} T_D (a-1)^2}{V_o(1+\Pi(a-1)^2)} \quad (9)$$

$$L_r = \frac{V_o T_D}{I_{in(\max)}\left(1+\frac{\Pi(a-1)}{2}\right)} \quad (10)$$

5. Simulation Models and Results

The proposed Dc-Dc cuk converter was designed and simulated in the Matlab/Simulink working platform. The simulink model of cuk converter and the proposed cuk converter with PV module along with MPPT are illustrated. The figure 9 shows the modeling of the PV module with proposed converter topology. The PWM outputs of the MPPT, the output current of the PV module, the converter output signal are shown in the figure 10-13. The subsystem in the figure 9 is nothing but the proposed cuk converter. From the comparison of the above two cuk converter topology, the efficiency of the proposed converter is good compared to the classic cuk converter. The converter efficiency can be calculated as

$$\text{Converter Efficiency} = \frac{\text{Output power X 100}}{\text{(Output power + converter losses)}} \quad (11)$$

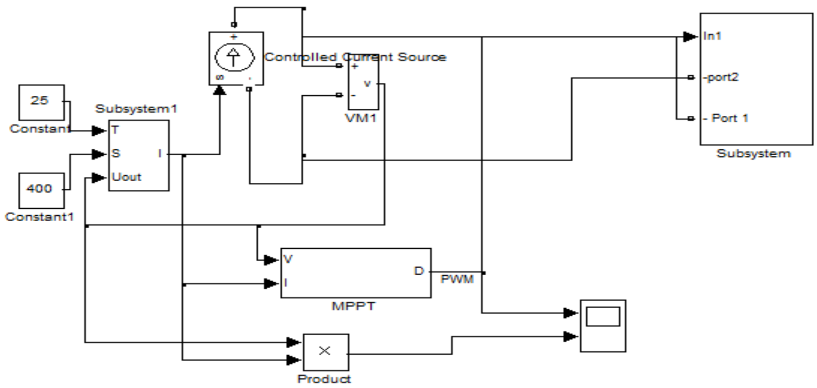

Figure 9. Modeling of Proposed converter in Matlab/Simulink

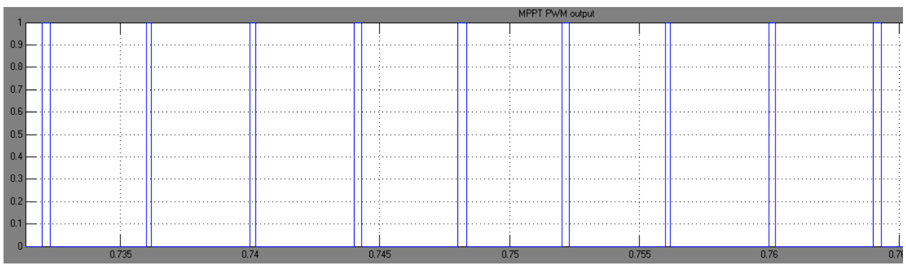

Figure 10. MPPT PWM output

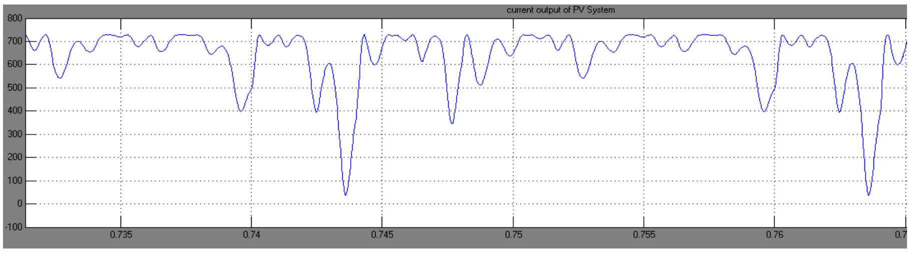

Figure 11. Output current of PV Module

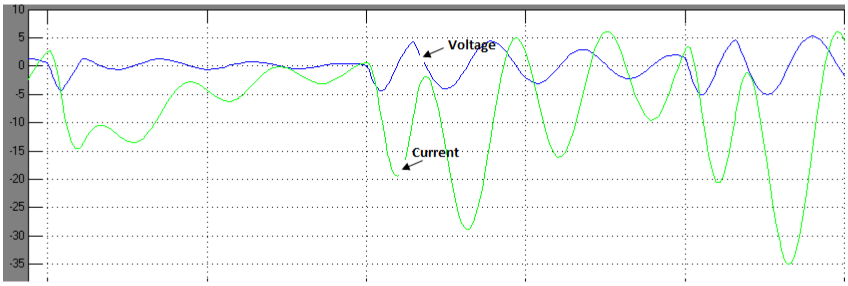

Figure 12. Output current and voltage of proposed cuk converter

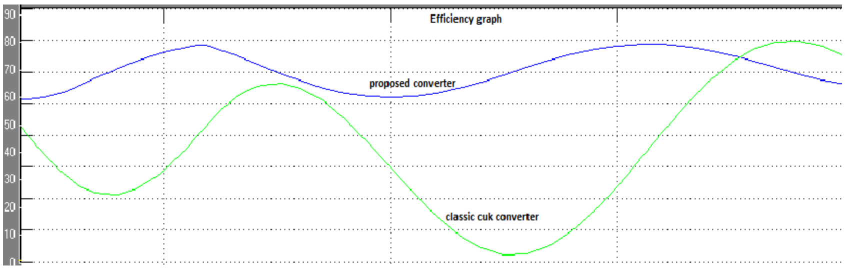

Figure 13. Comparison of Efficiency

6. Conclusion

The proposed cuk converter along with the Incremental conductance MPPT algorithm improves the performance of PV system so that the converter performance is also improved. In the proposed converter, the conduction loss is to be reduced by replacing the diode with MOSFET, but also switching losses is reduced by providing an supplementary circuit. The modelling and simulation results verifies the proposed cuk converter with the MPPT algorithm are having better efficiency results compared to the classical cuk converter based PV system. The proposed converter system is operated based on the soft switching techniques. These switching techniques are used to provide for smooth transition of voltage and current. So, the conversion efficiency of the PV system is improved and the load meeting the dynamic energy requirement is in an efficient way.

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