Designing of PV Cell and Analysis of It Under Rapid Irradiance Changing Conditions

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***Abstract* – As we all know photovoltaic cell (PV cell) is the basic building block of solar panel. In literature we are provided with many circuits to design PV cell. This proposed paper discuss about the basic design circuit of typical PV and its dependence on temperature and irradiation. This paper also analysis the operation of PV cell under partial shading and basic circuits for overcoming partial shading are discussed. This paper summarizes the various circuits used under partial shading and algorithms are also provided. The concept is evaluated using Matlab-Simulink simulation and proven using an experimental test rig. The performance of the proposed circuit is analyzed when PV arrays are subjected to rapid changing conditions. The results showed the variation of power with respect to changes in irradiance.**

***Keywords:* PV cell, partial shading, bypass diode, power electronics.**

I. INTRODUCTION

A photovoltaic system converts sunlight into electricity. The basic device of a photovoltaic system is the photovoltaic cell. Cells may be grouped to form panels or modules. Panels can be grouped to form large photovoltaic arrays. The term *array* is usually employed to describe a photovoltaic panel (with several cells connected in series and/or parallel) or a group of panels. The electricity available at the terminals of a photovoltaic array may directly feed small loads such as lighting systems and DC motors. Some applications require electronic converters to process the electricity from the photovoltaic device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid connected systems and mainly to track the maximum power point (MPP) of the device. Photovoltaic arrays present a nonlinear I-V characteristic. The mathematical model of the photovoltaic array may be useful in the study of the dynamic analysis of converters, in the study of maximum power point tracking (MPPT) algorithms and mainly to simulate the photovoltaic system and its components using circuit simulators.

Output power of a PV cell is not constant and is factor of irradiation of sun light. Various algorithms are proposed in literature to solve the fast changing irradiation problem by which problem can be minimized but cannot be eliminated .In addition partial shading of PV cell is other problem which reduces the output power.

In a grid connected photovoltaic (PV) power system (PVPS), the partial shading or unbalanced irradiation has been identified as one of the main reasons that contribute to the output power reduction. This condition is caused by several reasons, for example (1) cloud that hits certain spots on the array, while other areas of the array remain un-shaded, (2) partial obstruction (shadowing) by objects such trees, poles etc. and (3) the damage that affect one or several modules in the array. During partial shading, current from the non-shaded modules will be focused to the shaded module− creating a hot spot, which eventually destroy the latter. To avoid this consequence, it is a practice to bypass diode central inverter, micro inverter topologies are proposed.

Central inverters with MPPT with special software algorithm that can handle partial shading condition are described in various literatures. Typically the algorithm searches for the global peak using some kind of search and optimization procedures. However, it appears that little attention has been given to solve the partial shading problem using power electronics circuit; this paper proposes a simple circuit that could be used for such purpose. The main feature of this approach is the ability to recover the power generated by the shaded module and then processes it to become part of the output power- enabling it deliver more power compared to the bypass diode topology. Furthermore, since the circuit can be independently retrofitted into the existing system, only minimum alteration in the connection is required. Over the life-time of the PV system, the additional cost for the hardware can be justified by the extra power gained by the system during partial shading.

A. *Modelling of PV cell*

A PV generator is a combination of solar cells, connections, protective parts, supports, etc.. Solar cells consist of a p-n junction; various models of solar cells have been proposed in the various papers .The simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell (photocurrent). For this paper, the electrical equivalent circuit of a solar cell is shown in Fig.1.

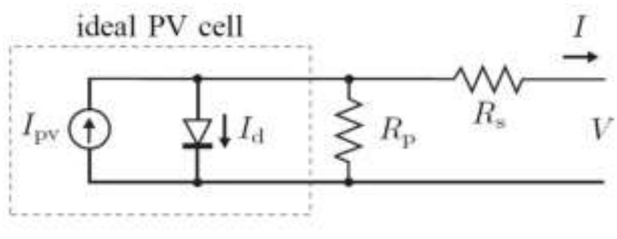


Fig 1: Electrical equivalent of Solar cell

$$I = Ipv - Io\left[exp\left(\frac{V+RsI}{aVt}\right) - 1\right] - \frac{V+RsI}{Rp} \qquad (1)$$

where I_{pv} and I_0 are the photovoltaic and saturation currents of the array and Vt = NskT/q is the thermal voltage of the array with Ns cells connected in series. Cells connected in parallel increase the current and cells connected in series provide higher output voltages. If the array is composed of Np parallel connections of cells the photovoltaic and saturation currents may be expressed as: Ipv=Ipv,cellNp, I_0=I_0,cellNp. In eqn(1) Rs is the equivalent series resistance of the array and Rp is the equivalent parallel resistance.

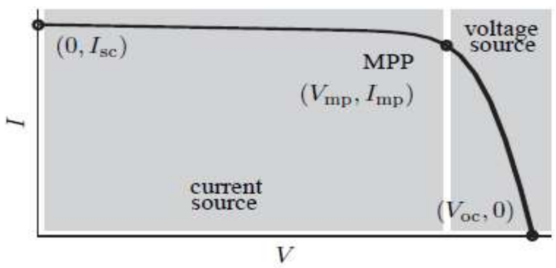


Fig. 2 I-V Characteristics of a pv array

This equation originates the I-V curves seen in Fig. 1, where three *remarkable points* are highlighted: short circuit (0, Isc), maximum power point (Vmp, Imp) and open-circuit (Voc, 0). The I-V characteristic of the photovoltaic device shown in Fig. 1 depends on the internal characteristics of the device (Rs, Rp) and on external influences such as irradiation level and temperature. The amount of incident light directly affects the generation of charge carriers and consequently the current generated by the device. The light-generated current (Ipv) of the elementary cells, without the influence of the series and parallel resistances, is difficult to determine. Datasheets only inform the nominal short-circuit current (Isc,n), which is the maximum current available at the terminals of the practical device. The assumption Isc ≈ Ipv is generally used in photovoltaic models because in practical devices the series resistance is low and the parallel resistance is high. The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation

$$Ipv = (Ipv, n + K1\Delta T)\frac{G}{Gn} \qquad (2)$$

where Ipv,n [A] is the light-generated current at the nominal condition (usually 25^{o}C and 1000W/m2), ΔT =T–Tn. (being T and Tn the actual and nominal temperatures[K]), G[W/m2] is the irradiation on the device surface and Gn is the nominal irradiation.

B. PV under Partial Shading

Partial shading of PV cell due to any reason may lead to reduction in output Power. Various topologies are proposed in literature to improve the performance of PV under partial shading conditions. In general a bypass diode is inserted in parallel to each module to avoid damage to the PV cell [1]. The idea is to divert the current away if shading occurs. However, by doing so, the energy yield is impaired because the shaded module, which may actually yield certain amount of power, is totally unusable. Furthermore, when the current flows through the bypass diode, conduction losses occur, further degrading the system's efficiency.

For PVPS, the series parallel combinations of modules connected to a central inverter are the preferred topology and are widely used [2]. However, when one or more modules are bypassed due to shading, multiple peaks in the I−V curve are created. If the maximum power point tracking (MPPT) algorithm is not sophisticated enough, it is unable to locate the global maximum point; it settles at a local peak, resulting in reduced output power. Recently, the micro -inverter topology is proposed as an alternative to the central inverter system. Since each module is equipped with a converter that has its own individual MPPT, the output from each micro-inverter can be controlled independently. Consequently, even if shading on a module is experienced, certain amount of power can still be recovered because its dedicated MPPT is not influenced by other modules. Although quite attractive, due to high number of converters and controllers, for a large PVPS, the cost and complexity of the micro-inverter can be prohibitive. Furthermore, the micro-inverter is placed just underneath the module; the ambient temperature can be quite high and thus it may cause some problems with the electronic circuitries.

C. The Proposed Circuit-Operating Principle

For simplicity, a single string array with 4 modules is depicted. Fig. 3 shows the proposed circuit. The basic idea of this topology is to transfer the power from non-shaded modules to the shaded modules until all modules in the string seem to have equal power level. Transferred energy is stored temporarily in capacitors C1−C4. This topology is divided into 2 groups. Group 1 consists of PV1 and PV2 together with their corresponding power electronics circuits, i.e. S1, D1, L1, C1, S2, D2 and C2. Group 2 includes PV3, PV4 with S3, S4, D3, D4, L2, C3 and C4. The transfer the power is from the PV with higher irradiance to the one which is shaded (within the same group). For example, when partial shading occurs on PV2, Group 1 is in operation; it transfers the unbalanced power from PV1 to PV2.

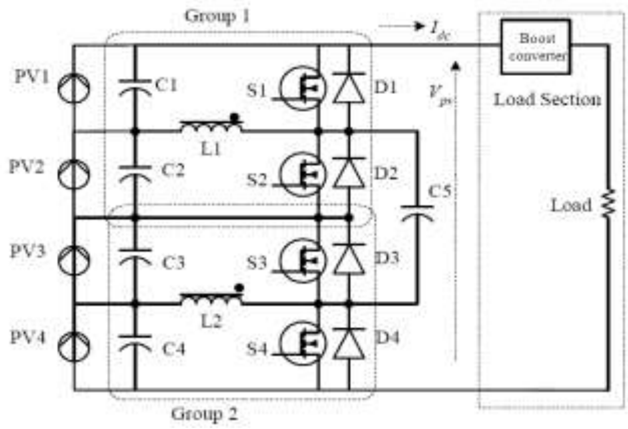


Fig 3. The proposed topology

Capacitor C5 is designed to balance the energy level between groups 1 and 2 when the total of irradiation of Group 1 and Group 2 is not equal. After equilibrium, all PV in the string will experience the same power level. As a result, maximum power is transferred even during partial shading is imposed on any of the modules.

Fig. 3 shows in detail the operating stages of each group during partial shading. The operation of the circuit can be divided into two stages.

During stage 1 ($t_0 < t < t_1$), S1 is ON and S2 is OFF while for Group 2, S3 is ON and S4 is OFF. The current flows through S1, causing I_{L1} to increase linearly due to constant voltage supply from PV1, V_1. The same current flows in $L2$. Hence, energy is stored in $L1$ and $L2$. The ripple current of the inductor during stage 1 is

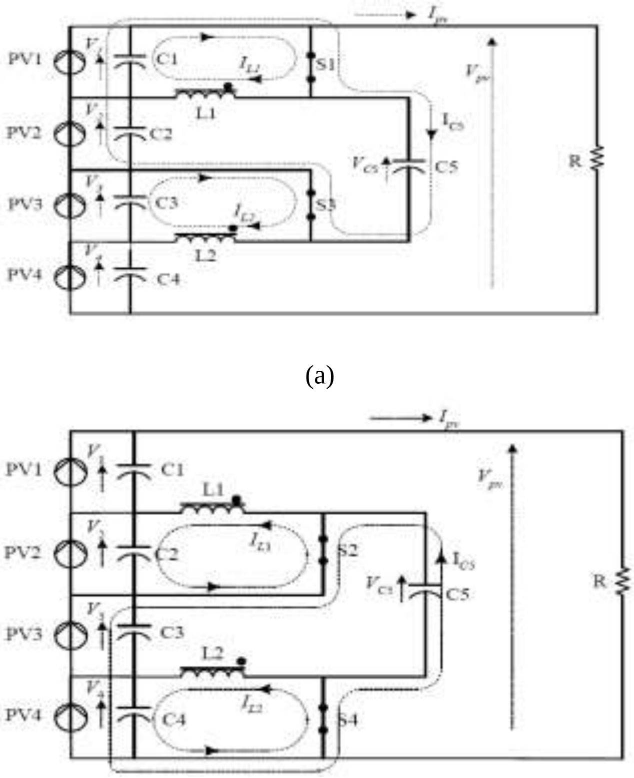
$$\frac{V1DT}{L1} = (\Delta IL1)st1 \qquad (3)$$

$$\frac{V3DT}{L2} = (\Delta IL2)st1 \qquad (4)$$

The capacitor C5 is charged by V_1 and V_2. The voltage across C5 can be expressed as

$$V_{C5} = V_1 + V_2 \qquad (5)$$

During stage 2, ($t_1 > t > t_2$), switches S2 and S4 conduct; energy in L_1 and L_2 is released. Capacitors C2, C4 are charged.



(a)

(b)

Fig 4(a). Operation during stage 1, (b) Operation during stage 2.

The ripple current of the inductor during this stage is

$$-\frac{V2}{L1}(1-D)T = (\Delta IL1)ST2 \qquad (6)$$

$$-\frac{V4}{L2}(1-D)T = (\Delta IL2)ST2 \qquad (7)$$

Consequently, the voltage across C5 can be written as

$$V_{C5} = V_3 + V_4 \qquad (8)$$

At the steady state operation: $(\Delta IL1)st1 + (\Delta IL1)st2 = 0$; the ratio V_1/V_2 and V_3/V_4 can be express as

$$\frac{V1}{V2} = \frac{D}{(1-D)} \qquad (9)$$

$$\frac{V3}{V4} = \frac{D}{(1-D)} \qquad (10)$$

By setting the duty cycle to 0.5, V_1, V_2 and V_3, V_4 will be forced to be at the same value, i.e,

$$V_1 = V_2 = V_3 = V_4$$

The charging and releasing energy process continue until all PVs and its capacitors have the same energy level. Therefore maximum power point can be achieved. The load current, I_{pv} is calculated as:

$$Ipv = \frac{V1+V2+V3+V4}{R} \qquad (11)$$

Note that, the analysis above is based on the assumption that PV2 and PV4 are shaded while PV1 and PV3 receive full irradiation. Similar analysis can be made for different shading configurations.

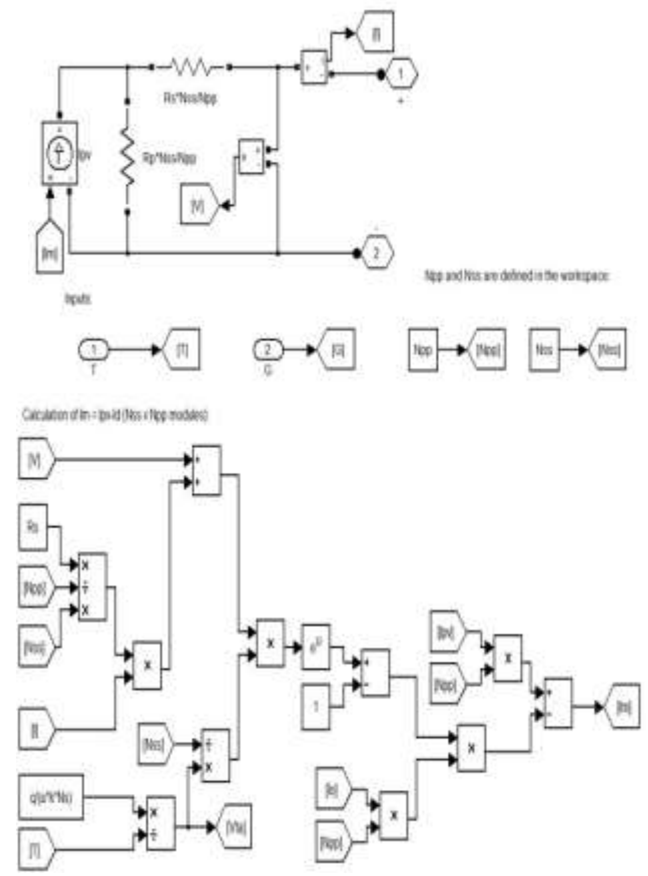
D. Simulation Result

Fig. 3 shows the Matlab-Simulink simulation of the proposed topology with a boost converter as an interface converter. The implementation using boost converter and a fixed resistive (instead of inverter and grid) is for simplicity. For MPPT, the normal perturbed and observed (P&O) scheme is used. A PI controller is applied to maintain the PV voltage, V_{pv} at the voltage reference, V_{ref}. The latter is computed using the P&O MPPT algorithm. The BP-MSX60 PV model is used. The specifications for designing BP-MSX60 are given in table 1.

TABLE 1: PARAMETERS OF THE BP MSX 60 SOLAR ARRAY AT STANDARD TEST CONDITIONS.

Imp =3.5A
Vmp =17.1V
Pmax=59.85W
Isc =3.8 A
Voc =21.1 V
K_V =-80e-3 V/K
K_I =0.003 A/K
Ns =36
Rp = 150.9 Ω
Rs = 0.35 Ω
a = 1.99

The equations for designing a solar array with number of series and parallel cells are derived from the Fig(5).



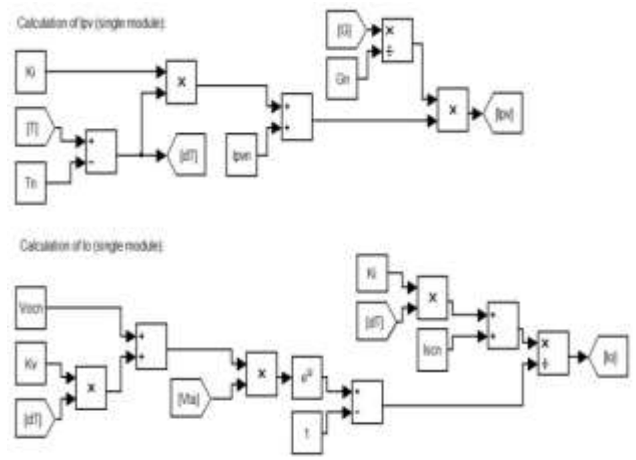


Fig. 5 Designing of PV array with Ns and Np

The proposed model is designed and modelled as the circuit to extract power from a solar cell even under partial shading conditions as shown in fig.5. Such extracted power will be unstable. So the proposed circuit processes the unstable power and feed the load there by increasing the efficiency of the array.

The proposed model is tested with a rapid changing irradiance condition. All the four modules are subjected to uniform irradiance of 1kw/m2. At this condition the power generated by all the four BP MSX-60 solar modules is 205W. The voltage generated is 64 volts and 3.25 amperes of current.

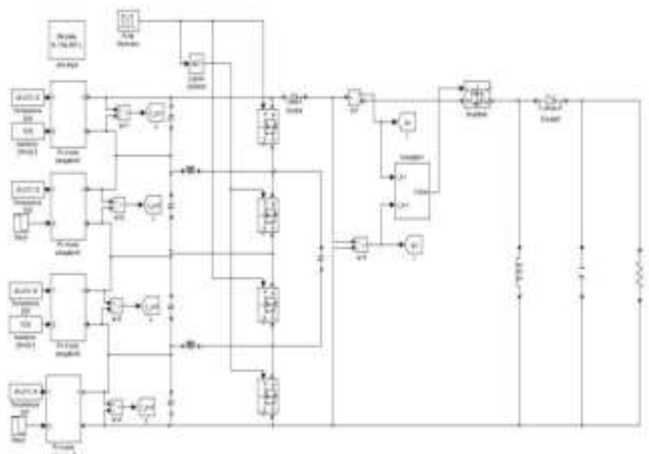


Fig 6: Simulation set-up to test the performance of proposed topology

The same proposed model is subjected to varying irradiance after particular time instant. At this instant the irradiance is varied as PV_1=PV_3= 1kW/m^2, PV_2=0.3kW/m^2, and PV_4= 0.14kW/m^2. With this irradiance the output values of array varies. The power generated by four PV cells is about 120W, current 2amperes. The voltage gets sag for small time period and then reaches to a value 60V. This sag is due to slower operation of P & O MPPT algorithm used. Hence the use of algorithms makes the module to maintain constant voltage across the array making it to act as a constant voltage source.

TABLE 2: POWER AND VOLTAGE OUTPUTS DURING DIFFERENT IRRADIATION CONDITIONS.

	Irradiation (kW/m^2)	Temp (ºC)	Voltage Generated (volts)	Power Generated (watts)
PV1	1	25	15.5	204
PV2	1	25	15.5	
PV3	1	25	15.5	
PV4	1	25	15.5	
PV1	1	25	15	120
PV2	0.3	25	15.5	
PV3	1	25	15	
PV4	0.14	25	15.5	

The increase in the voltage of shaded cells is due to the proposed circuit which makes the voltage across the modules.

To investigate its efficiency performance, the proposed method is compared with system using bypass diode. The efficiency is computed by taking the ratio of the output power to input power. Table 2 shows the values of output power and input temperature for four modules.

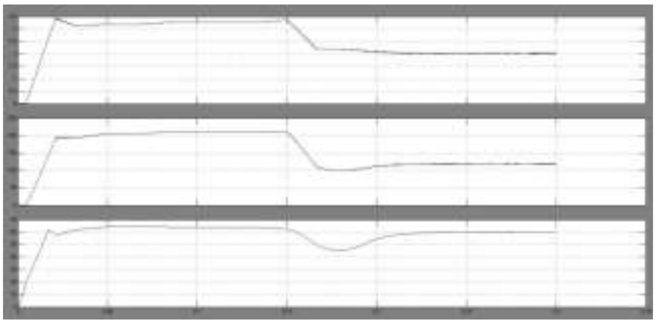


Fig. 7 Simulation results of the total generated output power, voltage and current due to changes in irradiance.

For shading pattern 1 all modules are subjected to uniform irradiance, i.e. no partial shading condition is imposed. Shading pattern 2 has two modules at full irradiance and one module is subjected to 0.3kW/m^2 and the fourth module to 0.14kW/m^2.

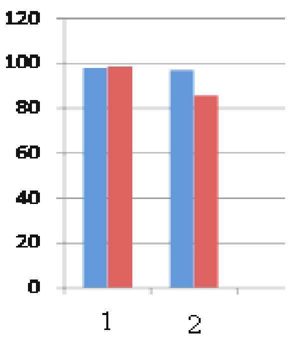


Figure: 8 Efficiency comparisons for bypass diode method & proposed method for 2shading patterns.

The efficiency of the system with bypass diode will be high during uniform insolation. This is to be expected because the switching and conduction losses of the diode are almost zero. The efficiency drop is mainly due to the losses in the central converter. During partial shading the efficiency of the system with bypass diode drops significantly. This is clearly the case because the shaded modules are not delivering power at all.

On the other hand, the proposed method maintains high efficiency despite the occurrence of partial shading; hence it appears that the shading has little effect on its efficiency. The highest achievable efficiency is 97%.

CONCLUSION

Designing of a solar array with specifications given as per data sheet of BP-MSX 60 is done. A simple circuit is also proposed to increase the output power of PV system during partial shading. The idea is to recover the power from the shaded module, divert it to a power electronics circuit and process it to become part of the output power. Consequently, the inclusion of the given circuit enables the system to deliver more power compared to traditional bypass diode method. Simulation results show marked improvement in the output power, especially under heavy partial shading condition. The comparison is based on simulation done on bypass diode and proposed model. An average efficiency 97% has been recorded for the proposed method. The extra power generated is expected to compensate for the cost of the extra components in the retrofit circuit and generates profit in the long run.

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