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Controller Design for Integrated PV-Converter Modules under Partial Shading Conditions

B. V. P. Chong[*,†], L. Zhang[*]

*School of Electronic & Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK

†Corresponding Author Tel: +44 (0) 113 343 9091, Fax: +44 (0)113 3432032, Email: b.chong@leeds.ac.uk (B. Chong)

Abstract

Module–integrated PV and converter units have been a promising technique for achieving maximum power generation for mismatching and/or partially shaded PV modules. Control of a PV system with multiple such units is difficult as the operation of each unit is required to be regulated to generate the maximum power according to its respective light level. This paper presents a novel model-based, two-loop control scheme for a particular MIPC system, where bidirectional Ćuk dc-dc converters are used as the bypass converters and a terminal Ćuk boost functioning as a whole system power conditioner. Experimental tests of example systems consisting of two and three serially connected units are presented showing that the proposed system can increase power generation as much as 30%, compared to the conventional bypass diode structure. In general with n modules in series the maximum power gain is expected to be (100/n) %. The new control scheme is developed using analytical expressions for the transfer functions of the power converters. The control results showing rapid and stable responses are superior to that obtained by bypass diode structure which is conventionally controlled using Perturbation-and-Observation method.

Keywords: *Photovoltaic System; Partial Shading; Integrated Converter; Ćuk Converter; Maximum Power Point* Tracking.

Abbreviations:

DMPP: Distributed maximum power point

I-V: Current – Voltage

MIPC: Module-integrated PV and converter

MPP: Maximum power point

PV: Photovoltaic

1. Introduction

The problem of partial shading in photovoltaic (PV) arrays has been well-studied through advanced modelling and detailed investigations on various practical PV applications (Feldman et al., 1981; Quaschning and Hanitsch, 1996; Kovach and Schmid, 1996; Karatepe et al., 2006; Ishaque et al., 2008). To address this issue, bypass diodes are incorporated into PV modules (Woyte et al., 2007; Munoz et al., 2011) but it has been well recognized that this scheme alone results in power losses (Al-Rawi et al., 1994; Kajihara and Harakawa, 2005; Du and Lu, 2011; Alahmad et al., 2012). Many schemes have been proposed in which each individual module is provided with a DC-DC converter, forming an integrated PV module-converter unit known as a module–integrated PV and converter (MIPC). Connecting multiples of such units in series and/or parallel, the voltage and current levels can be raised to obtain transformerless grid connection. This approach enables independent control of individual PV modules according to their insolations, giving substantially higher output power under conditions of module mismatch and partial shading. This has also been called distributed maximum power point (DMPP) operation and the scheme is achieved by cascading the PV-converter units as shown in Fig. 1. Many researchers have studied this type of scheme (Walker and Sernia, 2004, Fernia et al., 2008; Noguchi et al., 2002; Myrzik and Calais, 2003; Kajihara and Harakawa, 2005; Du and Lu, 2011; Alahmad et al., 2012). In particular, Walker and Sernia (2004) proposed to connect multiple non-isolated per-module dc-dc converters in series to form a dc voltage string. By using a simple dc-ac inverter, grid interface can then be achieved. All well-known dc-dc converter topologies have been considered in this type of scheme and their features as well as their suitability are compared (Walker and Sernia, 2004). Subsequently Kjaer et al. (2005), Kim et al. (2010) and Alahmad et al. (2012) have investigated also various topologies for dc-ac inverter connections which can be used for MIPCs interfacing to the grid. However the key problem with this cascaded MIPC scheme is that it may not enable individual PV modules to achieve maximum power point (MPP) operation. This has been highlighted by Walker and Sernia (2004). Subsequently an alternative scheme based on bypassing MIPCs, as shown in Fig. 2, was proposed (Walker and Pierce, 2006). In this configuration the MIPCs are still chained in series but PV modules are grouped in pairs and each pair is connected to a bidirectional dc-dc converter such as buck-boost or Ćuk or flyback converter. A terminal converter, either dc-dc or dc-ac, is required for maximum power point tracking control and power conditioning of the string. The advantage of this scheme over the cascaded approach is that the integrated converters do not process power under normal uniform illumination conditions, so they do not incur power loss, but can "bypass" power between mismatched PV modules when the ambient light levels are different. The performance of this system has been shown to be much better than the cascaded one.

The main challenge lies in that this is a system with multiple units of PV-converter which requires a more complicated energy management scheme when each unit is to be controlled to generate the maximum power according to its respective light level. In particular for the scheme shown in Fig. 2 with multiple bypass MIPC units in a chain, and two pairs of adjacent units (for eg., converter units 1 & 2 and converter units 2 & 3) interleave over their middle PV module, it is difficult to decide the direction through which power should flow in each unit, hence the correct switching modes of internal converters. Also the duty ratios of the inner converters determine the proportions of power to be shuffled from the main path within each unit. Careful design, therefore, is required to set these ratios and that of the terminal converter for achieving MPP tracking of all PV modules in the system.

Nevertheless, MPP tracking for the above bypassed MIPC can still be based on the well-established schemes which have been widely applied in non-partially-shaded systems (Hussein, 1995; Kuo and Chen, 2001; Gow and Manning, 1999; Zhang and Al-Amoundi, 2000; Kobayashi et al., 2003; Petreus et al., 2011; Kulaksiz and Akkaya, 2012). Most of these algorithms only search for one power peak point. Hence, they require less computational effort and are simpler to implement comparing to those applied in bypass diode and cascaded MIPC schemes (Patel and Agarwal, 2008; Fernia et al., 2008; Du and Lu, 2011). This is mainly because under partial shading condition, several power peaks need to be estimated before deciding which is the most optimum operating point.

This paper presents a novel model-based control scheme for a particular MIPC system, where bidirectional Ćuk dc-dc converters are used as the bypass converters. Fig. 3 shows one such unit of MIPC connected to a load through a terminal Ćuk-Boost converter which functions as the power conditioner for the whole system. The Ćuk converter is chosen for its advantage of having low current ripples at both input and output ends; this potentially requires smaller capacitor across each PV terminal. Experimental tests of example systems consisting of two and three serially connected units will be presented. A novel control scheme for coordinated regulation of inner and terminal converters is developed and discussed in Section 3. Transfer functions of the power converters used for tuning the controller will be given in this section. Simulation results of the control scheme for a three-module system will be presented in Section 4 along with the comparison to the conventional bypass diode method using perturbation-and-observation scheme for MPP tracking.

2. Ćuk Converter-Bypass MIPC

2.1. Two PV Module System

2.1.1. Operating Principles

The simplest configuration of such a system is as shown in Fig. 3. This consists of two serially connected PV modules and a Ćuk bidirectional converter having one end linked to PV_1 and the other PV_2. The load terminals are between the positive end of PV_1 and negative end of PV_2 and a Ćuk step-up converter is used for output power conditioning.

When both PV modules are uniformly illuminated, the Ćuk bidirectional converter processes no power at all. Both switches, S_{11} and S_{21} are turned off, and current flow is only through PV_2 as well as PV_1 to the load. Hence the power supplied to the load is

$$P_T = V_T I_T = (V_{P1} + V_{P2})\, I_T = V_{P1} I_{P1} + V_{P2} I_{P2} \tag{1}$$

and $$I_T = I_{P1} = I_{P2} \tag{2}$$

where V_T and I_T are the system terminal voltage and current, V_{P1} and I_{P1} denote the voltage and current of PV_1 at the maximum power point, whilst V_{P2} and I_{P2} are those of PV_2. If illumination levels on two modules are different; for example, when PV_2 is shaded, the power output from PV_1 would be higher than that from PV_2. By making switch pair S_{11} - D_{21} active, i.e. switching at a fixed frequency with duty ratio, K_{11}, the converter can ‘shuffle’ the excess power from PV_1 away from passing through

PV_2. Consequently according to the Ćuk bidirectional converter (Mohan et al., 1995) operating principle, the voltages across PV_2 relates to that of PV_1 by

$$V_{PV2} = V_{PV1}\left(\frac{K_{11}}{1-K_{11}}\right) \tag{3}$$

and the current bypasses to Ćuk converter is given as

$$I_{L11} = (I_T - I_{P2})\left(\frac{K_{11}}{1-K_{11}}\right) \tag{4}$$

The terminal current is now

$$I_T = I_{P1} - (I_T - I_{P2})\left(\frac{K_{11}}{1-K_{11}}\right) = I_{P1}(1-K_{11}) + I_{P2}K_{11} \tag{5}$$

So the power output to the load without considering the losses is given as

$$\begin{aligned} P_T = V_T I_T &= \left(V_{P1} + V_{P1}\left(\frac{K_{11}}{1-K_{11}}\right)\right)\left(I_{P1}(1-K_{11}) + I_{P2}K_{11}\right) \\ &= V_{P1}I_{P1} + V_{P1}\left(\frac{K_{11}}{1-K_{11}}\right)I_{P2} \end{aligned} \tag{6}$$

The above analysis shows that by varying the duty ratio K_{11} in (6), the maximum power extraction from the shaded module can be achieved. In the limit when $K_{11} = 0$ (i.e. D_{21} is continuously forward biased), the system output power is $P_T = V_{P1}I_{P1}$, so the shaded module is totally bypassed, producing no power. This resembles the situation when a bypass diode is switched on across PV_2. However by vary K_{11} between 0 and 0.5, the output power of the shaded PV_2 is adjustable, subsequently PV_2 still generate power even though it is shaded. This analysis can be similarly applied to the case when PV_1 is shaded and $S_{21} - D_{11}$ switch pair becomes active, the duty ratio K_{21} can be adjusted in the range 0 to 0.5 for shuffling the power to the converter.

2.1.2. Experimental Verification

The above analysis has been verified using an experimental set-up in which two identical Sunsei SE-6000 PV modules are used (Sunsei, 2007). Photographs of them with two identical in-house built controllable solar simulators and Cuk converters are given in Figs. 4(a)&(b).

It must be pointed out that each of the sun-simulators used in all our experiments do not give uniform illumination within individual modules. This inevitably affects the performance of each PV module. However, the proposed system configuration and control scheme is designed to deal with differential mean illumination between modules. The level of illuminations for each sun-simulator can be set to zero or varied over a wide range. The experiment is therefore believed to be a sufficiently accurate representation of situations with more uniform panel illuminations and similar differential shadings between the modules.

The current and voltage values of two PV modules at the maximum power point are noted as 1.4A and 16.5V and the measured I-V and P-V characteristics for each module are shown in Fig. 5. Two different schemes are studied for four shading conditions; the first uses the conventional bypass diode and the other applies the MIPC with a Ćuk bidirectional converter as described above. It is noted that the I-V characteristic curves in Fig. 5 show relatively higher rates of current decline to the voltage rise before MPPs comparing to that of the same PV module under natural sunlight. This is due to the heat generated by the sun simulators causing high panel surface temperature, about 30 ^{o}C. This is with the use of strong cooling equipment, and the laboratory ambient temperature is controlled between 23 ^{o}C and 26 ^{o}C.

2.2. Three PV module system

2.2.1. Operating Principles

When two of the above MIPC units are chained together, we have a system consisting of two bidirectional Ćuk converters, and three PV modules as shown in Fig. 6. Whilst converter 1 connects PV_1 and PV_2 in the same manner as that shown in Fig. 3, converter 2 links PV_2 and PV_3 at its two terminals. Two converters overlap at the PV_2 terminals. The terminal boost converter may still be used.

As can be seen in Fig. 6, there are in total four device pairs $S_{11} – D_{12}$, $S_{12} – D_{11}$ for converter 1, and $S_{21} – D_{22}$, $S_{22} – D_{21}$ for converter 2. The two switch pairs in their respective converters are complementary, i.e. when $S_{11} – D_{12}$ in converter 1 is active, $S_{12} – D_{11}$ is idle, and vice versa. Likewise this applies to $S_{21} - D_{22}$, $S_{22} - D_{21}$. Consequently there are only four modes of operations as listed below:

$S_{11} - D_{12}$ with $S_{21} - D_{22}$, and $S_{11} - D_{12}$ with $S_{22} - D_{21}$

$S_{12} - D_{11}$ with $S_{21} - D_{22}$, and $S_{12} - D_{11}$ with $S_{22} - D_{21}$

Whichever of these modes is suitable is determined by the light level on the individual PV modules. Under uniform irradiation, and assuming no characteristic mismatching between the PV modules, both inner converters are idle with all switches inactive. The generated power from all three PV modules to the output load is controlled by the terminal boost converter. When the light levels are different the inner converters are controlled to bypass power in the desired directions, their modes of operation are selected according to the following principle.

Following the same approach as in the previous section for a two PV module system, the total output power for a three PV module system is given as

$$P_T = P_1 + P_2 + P_3 = (V_{P1} + V_{P2} + V_{P3})\, I_T = V_{P1} I_{P1} + V_{P2} I_{P2} + V_{P3} I_{P3} \tag{7}$$

When the light levels for PV_1 and PV_2 are different, the power is bypassed to or from converter 1. Current, I_{L1} is non-zero and when it is positive (i.e. excessive PV_1 power is to be bypassed), we have

$$I_{L1} = I_{P1} - I_T > 0 \tag{8}$$

This can be expressed in terms of power and voltage as

$$\frac{P_1}{V_{P1}} - \frac{P_1 + P_2 + P_3}{V_{P1} + V_{P2} + V_{P3}} > 0 \tag{9}$$

which can be re-arranged as

$$\frac{V_{P1} + V_{P2} + V_{P3}}{V_{P1}} > \frac{P_1 + P_2 + P_3}{P_1} \tag{10}$$

As the analysis focuses mainly on the MPP region and variations of PV voltages due to the light changes are less significant comparing to that of the PV power, hence a constant average value of 3 can be taken for the voltage ratio and (10) is expressed as

$$P_1 + P_2 + P_3 < 3P_1 \quad (11)$$

It can be observed from the I-V characteristics that the maximum PV power varies almost linearly with the light levels (Zhang and Al-Amoudi, 2000). Hence P_1, P_2 and P_3 in (11) can be respectively substituted by G_1, G_2 and G_3, yielding

$$G_1 + G_2 + G_3 < 3G_1 \quad (12)$$

which can be written as

$$\frac{G_2 + G_3}{2} < G_1 \quad (13)$$

Thus for a specific set of the light levels, if they satisfy (13), $S_{11} - D_{21}$ device pair should be active to ensure positive direction of $I_{L1,}$ otherwise $S_{21} - D_{11}$ pair is activated. Similar analysis can be applied to determine switching status of device pairs in converter 2 but now it is based on the current direction of I_{L22}, so $S_{22} - D_{12}$ is active if the light condition is given as

$$\frac{G_1 + G_2}{2} < G_3 \quad (14)$$

The combination of light levels and their corresponding switching status for the two inner converters 1 and 2 are summarized in Table 2.

2.2.2. Experimental Verification

Experimental test on a three PV module MIPC system was carried out. This was conducted for the specific light conditions where intensity on PV_1 varies in steps of 20% while that on PV_2 takes two values and PV_3 is maintained constant. In this test the third light emulator is added as shown in Fig. 4(c) and 100% light condition is lowered to 505 mW/cm^2 solar irradiation power. This reduction is necessary to reduce the heat generated from the three fully operating emulators which generate considerable heat causing significant ambient temperature to increase.

The converters' modes of operation were set according to Table 3 and their duty ratios were adjusted according to the light levels to obtain peak power output. For comparison the tests were repeated on the same three PV modules with bypass diodes connected across each of them; the overall P-V characteristics for bypass diode scheme under several lighting condition are shown in Fig. 7. Table 3 compares the measured results for both schemes.

Comparing the total power output of the two schemes, the full advantage of not bypassing the shaded modules becomes more apparent. It is particularly interesting to note that when PV_1 is radiated with 40% of full light condition, the gain in power is high showing how a module which has a significant amount of extractable power is impeded by the bypass diode from generating. Additionally, the power gained increases further as PV_1 and PV_2 become heavily shaded (i.e. in Case 2). Nevertheless the proposed MIPC scheme delivers a power gain of between 15% and 83% over a wide range of different shading conditions. The improvement in harvested power using MIPC can be very substantial. However it is worth noting that the power gain is not proportional to the two-panel system since, as been mentioned, the 100% light level is lower than that used in the previous case. In addition, power losses occur due to the use of non-optimally designed Ćuk converters used in the test.

2.3 Systems with more than Three Modules

A general rule can be derived to determine the appropriate switching modes of the inner bidirectional Ćuk converters for systems having more than three PV-converter modules using the same approach as for the two and three module systems discussed above.

An example system, shown in Fig. 8, has p PV modules and (p – 1) bidirectional Ćuk converters and we assume that all modules have identical electrical characteristics. Note that only the inner Ćuk converters are drawn while the terminal voltage, V_T, refers to the input voltage to the terminal Ćuk converter or load. The system is required to operate at the condition that each module delivers its maximum power corresponding to their respective light levels. Thus like the two and three module systems, variations of all PV module voltages at their respective MPPs (in percentages) are considered less significant comparing to that of their power in response to the changes of light levels.

The switching scheme for multiple PV generators follows the analysis given at the end of Section 2.2, whereby the selection for the operation mode of each inner converter is based on the bypassed power (or the inductor current) flowing through it. In general, the inductor currents for j-th Ćuk converter can be analysed through the Kirchhoff's current law at node j and thus, the currents that flow through its inductor L_1 and L_2 can be written as

$$I_{L1j} = \left(I_{Pj} - I_{P(j-1)}\right) + \left(I_{L1(j-1)} + I_{L2(j-1)}\right) - \left(I_{L2(j-2)}\right) \tag{15}$$

and $$I_{L2j} = I_{L1j}\left(\frac{K_{1j}}{1-K_{1j}}\right) = I_{L1j}\left(\frac{1-K_{2j}}{K_{2j}}\right) \tag{16}$$

where K_{1j} and K_{2j} are the duty ratios for its upper and lower switches S_{1j} and S_{2j} (referring to Fig. 3 as example). Note that $I_{L2n} = I_{L1n} = I_{Pn} = 0$ when n $\leq$ 0 since they do not exist in Fig. 8.

With the assumptions of MPP operations and lower PV voltage variation comparing to its power, (15) is simplified to a recursive equation given by

$$I_{L1j} = I_{Pj} - I_{P(j-1)} + 2I_{L1(j-1)} - I_{L1(j-2)} \tag{17}$$

where $I_{L11} = I_{P1} - I_T$ and using the development approach for Equations (9) – (11) gives rise to following conditions:

$$I_{L1j} \text{ has a positive value if } \left[p\sum_{n=1}^{j}\left(P_n\right) - jP_T \right] > 0 \tag{18}$$

otherwise I_{L1j} has a negative value and $P_T = \sum_{n=1}^{p}\left(P_n\right)$ is the total MPP power for all modules. Similar to Equations (13) and (14), the condition in Equation (18) can also be represented by light intensity level and hence for a specific set of the light levels (i.e. G_1, G_2, …, G_j, …, G_p), S_{1j} – D_{2j} device pair for j-th converter should be active (to ensure positive direction of I_{L1}) if the light condition satisfies the following:

$$p\sum_{n=1}^{j}(G_n) > j\sum_{n=1}^{p}(G_n) \tag{19}$$

otherwise $S_{2j} - D_{1j}$ pair is activated. Note that condition (19) forms the general rule for any number of PV modules including two and three module systems discussed in the previous section (i.e. corresponding to (13) and (14)). This analysis has so far tested for systems having up to 10 modules.

In this work, the proposed general rule is applied to two example systems having 5 modules and 10 modules respectively under different combinations of light levels. Table 4 summarises the results for the former while Table 5 gives the switching scheme for the latter. The listed inductor currents are computed based on all modules' optimal operating currents and voltages which can be obtained from the MPP models proposed in (Chong, 2010). Under each weather condition, the operation modes for all converters are determined using Equation (19). The value 1 indicates that the $S_{1j} - D_{2j}$ pair is to be activated; otherwise $S_{2j} - D_{1j}$ pair becomes active. It can be observed that all cases accurately match to the direction of the corresponding inductor currents; for e.g., the cells with -1 (or active $S_{2j} - D_{1j}$ pair) corresponds to negative inductor currents. Clearly, the general rule can be used to determine the operation modes for the inner Ćuk converters.

3. Closed-Loop Control for the Three PV Module System

Whilst the regulation of the converter operation in Section 2 was achieved through open-loop controllers, it is highly desirable to have a complete closed-loop control in a practical system which has the potential to eliminate any steady-state errors due to power losses in converter and also prevents any fluctuation of PV voltage and current due to sudden or rapid change in weather conditions (Chong, 2010). In addition, the control scheme for this system should also enable all three PV modules to operate at their peak power points for any illumination conditions. All these require coordinated control for the two inner bidirectional Ćuk converters and the terminal Ćuk-Boost converter.

A two loop scheme is thus proposed, which consists of a control algorithm for the inner converters adjusting the terminal voltages of individual PV modules and a feedback control scheme to regulate the entire system output voltage by the terminal Ćuk-Boost converter. A configuration of the whole system is shown in Fig. 9.

3.1 Control Algorithm for Two Inner Converters

According to the measured levels of sunlight and shading conditions within each unit, the switching modes for the two inner converters can be selected based on the scheme described in Section 2.2.1. Subsequently the duty ratios of the converters are adjusted according to a specially designed control algorithm.

For a typical dc-dc converter the voltage on one side, either the input or output side, is held constant by a voltage source and the other side is controllable (Mohan, 1995). However in this system the voltages at both sides of the inner converter are determined by their respective PV modules which are varying simultaneously when changing the duty ratio for each MIPC unit shown in Fig. 6. This can be analysed through its two derived transfer functions. The first is between the PV voltage at its upper terminal (which is denoted as v_{upper}) and the control variable which continuously adjusts the duty ratio for the upper switch (which is denoted as k_{upper}); this is given as (Chong, 2010)

$$G_1(s) = \frac{\hat{v}_{upper}(s)}{\hat{k}_{upper}(s)} = -\frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_5 s^5 + \alpha_4 s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} V_T \tag{20}$$

The other transfer function is between the voltage at the lower terminal of each MIPC, v_{lower} and k_{upper}, which is given as

$$G_2(s) = \frac{\hat{v}_{lower}(s)}{\hat{k}_{upper}(s)} = \frac{\gamma_3 s^3 + \gamma_2 s^2 + \gamma_1 s + \gamma_0}{\alpha_5 s^5 + \alpha_4 s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} V_T \tag{21}$$

In (20) and (21), V_T is the system terminal voltage and parameters, α_0, α_1, ..., α_5, β_0, ..., β_3, γ_0, ..., and γ_3, given in Appendix, are shown dependent on the circuit components (i.e. capacitors and inductors). Note that the two transfer functions also vary according to PV module's internal impedances, steady-state duty ratio values, as well as terminal voltage V_T, which all take different values according to the operating point. Thus they both are nonlinear processes.

Taking into account the effect of duty ratio change on the two terminal voltages, the closed-loop control scheme for the inner converter is so designed that control of one terminal voltage takes precedence in determining the converter duty ratio. The other, however, is treated as a disturbance signal to detune the control signal. A block diagram of the control scheme is as shown in Fig. 10.

Here v_{upper} is the main controlled voltage to determine the duty ratio k_1 and the controller $H_1(s)$ is set as a lead-lag compensator. The signal from the 'Detuning Loop' is treated as a disturbance to adjust k_{upper}. In this way, tight control of v_{upper} can be achieved (through the 'Main Loop' in Fig. 10) whilst variation of v_{lower} may be contained (through the 'Detuning Loop' in Fig. 10). Similar analysis as above can be done for the regulation scheme of k_{lower}, which is the control variable for the duty ratio of the MIPC's lower switch but now v_{lower} is taken as the main controlled voltage while v_{upper} as disturbance. Nevertheless for stability, either the regulation of k_{lower} or k_{upper} (but not both) can be done at a time; this condition is still valid as from Section 2, it is known that one device pair in each MIPC can only be active. The overall design scheme can then be applied to both MIPC units in Fig. 6.

Tuning of the lead-lag compensator is based on the transfer functions in (20) and (21). The system is stable, having 4 poles and 2 zeros in the left-hand-side of s-plane. The terminal voltage is varying inversely with the duty ratio as indicated by the negative sign. The controller is designed to increase the phase margin through phase lead compensation and to realise zero steady state error using the lag term. The controller transfer function is then given by

$$G_i = -N_i\left(\frac{\alpha_i\tau_i s+1}{\tau_i s+1}\right)\left(\frac{s+\beta_i}{s}\right) \tag{22}$$

where N_i, α_i and τ_i are chosen to give the satisfactory value for the overall phase margin and closed-loop bandwidth. For the former, a value of 60^o is required so that the closed-loop response for V_i with an overshoot of no more than 10% can be obtained (Ogata, 2002). For the latter, the closed-loop bandwidth is just low enough to attenuate the high frequency noises in the measured input voltage, and prevent unnecessary oscillation in the control signal (Erickson and Maksimovic, 2001).

It is clear from the above that this scheme requires the knowledge of the desired PV voltages to determine the set points for V_{P1}, V_{P2}, and V_{P3} a priori. This can be obtained through applying a model-based approach. In this work three computer models (Chong, 2010) respective to each of the three PV modules are established in advance and embedded in the control system as shown in Fig. 9. Upon every detected change of illumination conditions these models estimate the voltage values needed for the corresponding PV modules to generate peak power, and feed them to the corresponding control loop.

3.2 Ćuk-Boost Terminal Voltage Control

To achieve overall system maximum power generation the outer terminal voltage (i.e. v_T) is controlled by adjusting the duty ratio of the outer Ćuk-Boost converter; the source side of this converter is determined by the sum of those of the MIPC units whilst its load side voltage is kept constant by a dc voltage source such as a battery or a capacitor connected to the grid through another dc-ac converter.

The transfer function between the switch duty ratio of the Ćuk-Boost and the source side voltage for this converter can be expressed as (Chong, 2010)

$$H_u(s) = -\frac{V_B C_u (L_B + L_G) s^2 + I_T \left(L_B (1 - K_u)^2 - L_G (K_u)^2 \right) s + V_B}{q_2 s^4 + q_1 s^2 + 1} \qquad (23)$$

where $q_1 = C_u(L_B+L_G)+C_T(L_B(1-K_U)^2+L_G(K_U)^2)$, $q_2 = C_uC_TL_BL_G$, and k_u = duty cycle for S_u

From (23) the converter is a system having four poles and two zeros and the latter may move into the right hand plane, leading to non-minimum phase characteristics. This, however, can be eliminated if inductor values, L_B and L_G, can be chosen to satisfy the following condition:

$$\frac{L_B}{L_G} > \left[\frac{(K_u)_{max}}{1 - (K_u)_{max}} \right]^2 \qquad (24)$$

To obtain the desired performance we use another lead-lag compensator where the reference voltage is set as the sum of reference voltages for the three PV modules and given as

$$G_u = -N_u \left(\frac{\alpha_u \tau_u s + 1}{\tau_u s + 1} \right)^2 \left(\frac{s + \beta_u}{s} \right) \qquad (25)$$

Like the compensator for the inner converter, N_u, α_u and τ_u are chosen to give the overall phase margin of 60^o but to slow down the outer converter response, the closed-loop bandwidth is set to be half of that for the inner converter. The following summarizes the overall MPP tracking respectively for three PV modules using the above-proposed MIPC with its control scheme.

1) Measure the light levels for the three PV modules.

2) Activate the appropriate device pairs based on the light conditions Table 2.

3) Employ MPP models to determine the optimal PV voltages for individual modules

4) Measure the terminal voltages of individual PV modules.

5) Adjust the duty ratios of the inner and outer converters, respectively using the compensation-based controllers defined by (22) and (25).

The outer terminal voltage regulation is only performed 10 samples after a significant change in weather conditions is detected. This is to ensure the control action taken by the inner converters has minimal interference with that taken by the terminal converter.

4. Simulation Results and Discussions

4.1. Performance Evaluation

The performance of the above PV-Converter integrated system has been evaluated through computer simulation. The model for the three-PV-module system has been developed using MATLAB-SIMULINK software package, including SIMPOWER toolboxes. Using Control Toolbox, the model implements the lead-lag controllers for both inner and outer converters. A MATLAB algorithm for the MPP tracking is also incorporated into the model through a user-defined s-function block. System parameters and controller settings as listed below are set for the performance evaluation.

Specifications of Each PV Module

No. series cells, n_s = 60; No. parallel cells, n_p = 4;

Maximum power, P_{mpp} = 348 W at T = 20^o C and G = 1000 W/m^2;

MPP voltage, V_{mpp} = 29.12 V at T = 20^o C and G = 1000 W/m^2.

Converter Parameters

Switching frequency, f_s = 20 kHz;

Inductors: $L_{11} = L_{21} = L_{12} = L_{22}$ = 8 mH; L_B = 12.5 mH; L_G = 0.9 mH;

Capacitors: $C_{P1} = C_{P2} = C_{P3} = C_1 = C_2 = C_T$ = 10.0 μF; C_U = 2.0 μF.

Controller Parameters

Inner Controllers: α_i = 7.549; $\tau_i = 16.03 \times 10^{-6}$; β_i = 1920; N_i = 0.187;

Outer Controller: α_u = 28.9; $\tau_u = 17.35 \times 10^{-6}$; β_u = 1885; $N_u = 17.1 \times 10^{-3}$.

Fig. 11(a) displays the responses for the three PV modules with uniform light levels and also 3 different partial shading conditions. All PV modules are operating under the same temperature of 20^{o}C and initially, they are uniformly irradiated with $G_1 = G_2 = G_3$ = 600 W/m^2. The effects on the PV voltages and powers resulting from the changes of the light levels can be observed in Figs. 11(b) – 11(f).

At t = 0.6 second, PV_2 receives more solar irradiation. Subsequently, the switching devices S_2 – D_1 and S_3 – D_4 are activated and the MPP model starts to compute the new PV_2 voltage reference. This firstly causes PV voltages being regulated appropriately by adjusting the duty cycles for inner Ćuk converters. When the responses begin to stabilize, the operating point of the terminal step-up Ćuk is updated. After 0.07 second, all the PV module terminal voltages follow closely to their reference values, hence, achieving their MPPs.

At t = 0.7 second, the light levels on PV_1 and PV_3 are simultaneously changing. The control system can still quickly restore to the optimal PV operation.

At t = 0.8 second, the light level on PV_3 starts to drop significantly. Subsequently, the control actions are taken and a response with small voltage fluctuation is obtained. Hence, the proposed control system is considered robust in responding to large variation of weather conditions. The simulation has been repeated for the Perturbation & Observation (P&O) tracking method (Bose et al., 1985; Hua et al., 1998) and the amount of power extracted is found to be consistent with that for the model-based approach (Chong, 2010).

4.2. Comparison to Other Schemes

The performance of this system is compared to the conventional system using only bypass-diode connection. To implement the latter, the MPP control algorithm proposed by Patel and Agarwal (2008) can be applied. This method searches iteratively the maximum power point among the multiple power peaks. The simulated responses are shown in Fig. 12. It can be observed that the major downside for the conventional system is the terminal voltage fluctuation of within 25 – 85 volts range for every change of weather conditions. On the other hand, MIPC has substantially improved the system performance by only requiring a narrower operating voltage range. In addition, the extractable power output can be significantly increased by as much as 30%, through keeping all PV modules in optimal operation. This occurs when one of the three PV modules or a third of the total PV generating system is shaded. Using the integrated converter scheme, further power increment can be obtained for other shading levels which can be generally represented by (Chong, 2010)

$$\alpha = \frac{\text{Light level of the shaded PV}}{\text{Light level of the unshaded PV}} = \frac{G_{shaded}}{G_{unshaded}} \tag{21}$$

This is shown in Fig. 13 from which two observations can be made; 1) the maximum amount of the power increment increases with the number of shaded PV modules and 2) the shading level, at which the peak point for the power increment is located, decreases with the number of shaded PV modules.

5. Conclusions

The paper presented a newly developed control scheme of a module – integrated PV and converter structure for maximum power point tracking in a PV system under partial shading conditions. The structure and operating principles of this system were described. It is realised using Ćuk converters and this paper prescribes a novel technique in determining their switching operations when applied to the MIPC. Using both two and three PV module system as examples, the performance of this scheme was evaluated experimentally under various shading conditions, and compared favourably to the conventional system structure using bypass diodes. It was shown that the proposed solution increases the power output significantly; in a system with 3 panels connected in series it is by as much as 30%, through keeping all the PV modules operating at their respective optimal power point. In general for such a system having n PV modules in series the maximum power gain is expected to be (100 /n) %. The cost for building this type of PV system will be higher than that of the conventional ones using only by-pass diodes, due to additional power converters and control electronics. Table 6 lists the cost of building our prototype three-panel system according to published prices of components used. For mass production, to sell in market a significant reduction in price is expected.

A new model – based, two-loop control scheme was also investigated and shown to work successfully. The controllers for this scheme were optimised using analytical expressions for the transfer functions of the power converters, and their dynamical behaviour was investigated in detail, showing rapid and stable response which is superior to that obtained by bypass diode plus the perturbation-and-observation method.

It is worth mentioning that the proposed structure and control scheme have currently only been tested for cases where the whole surface of a PV module is uniformly shaded. When the shading on this module is non-uniform; say, a quarter or a small fraction of the module is shadowed, the control method can be tuned to treat the situation as if it is shaded evenly. This inevitably results in a reduction of generated power. Nevertheless, it will still offer better efficiency than that when bypass diodes are employed.

References

[1] Al-Rawi, N.A., Al-Kaisi, M.M., Asfer, D.J., 1994. Reliability of Photovoltaic Modules II. Interconnection and Bypass Diodes Effects. Solar Energy Materials and Solar Cells. 31, 469 – 480.

[2] Alahmad, M., Chaaban, M.A., Lau, S.K., Shi, J., Neal, J., 2012. An Adaptive Utility Interactive Photovoltaic System Based on a Flexible Switch Matrix to Optimize Performance in Real-Time. Solar Energy. 86, 951 – 963.

[3] Bose, B.K., Szczeny, P.M., Steigerwald, R.L., 1985. Microcomputer control of a residential photovoltaic power conditioning system, IEEE Transactions on Industrial Applications. IA-21, 1182 – 1191.

[4] Chong, B.V.P., 2010. Modelling and Control of Integrated Photovoltaic-Module and Converter Systems for Partial Shading Operation Using Artificial Intelligence. PhD Thesis at the University of Leeds, UK.

[5] Du, Y., Lu, D.D.-C., 2011. Battery-Integrated Boost Converter Utilizing Distributed MPPT Configuration for Photovoltaic Systems. Solar Energy. 85, 1992 – 2002.

[6] Erickson, R. W., Maksimovic, D., 2001. Fundamental of Power Electronics. Second edition Kluwer Academic, Norwell, USA.

[7] Feldman, J., Singer, S., Braunstein, A., 1981. Solar Cell Interconnections and the Shadow Problem. Solar Energy. 26, 419 – 428.

[8] Femia, N., Gianpaolo, G., Petrone, G., Spagnuolo, G., Vitelli, M., 2008. Distributed Maximum Power Point Tracking of Photovoltaic Arrays: Novel Approach and System Analysis. IEEE Transactions on Industrial Electronics. 55 (7).

[9] Gow, J.A, Manning, C.D., 1999. Development of a Photovoltaic Array Model for Use in Power Electronics Simulation Study. IEE Proceedings in Electric Power Applications. 146, 193 – 200.

[10] Hua, C., Lin, O., Shen, C., 1998. Implementation of DSP-Controlled Photovoltaic System with Peak Power Tracking. IEEE Transactions in Industrial Electronics. 45, 99 – 107.

[11] Hussein, K., Muta, I., Hoshino, T., 1995. Maximum Photovoltaic Power Tracking: An Algorithm for Rapidly Changing Atmosphere Condition. IEE Proceedings of Generation, Transmission and Distribution. 142, 59 – 64.

[12] Ishaque, K., Salam, Z., Syafaruddin, 2011. A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model. Solar Energy. 85, 2217 – 2227.

[13] Kajihara, A., Harakawa, T., 2005. Model of Photovoltaic Cell Circuits under Partial Shading. Proceedings of IEEE International Conference on Industrial Technology. 886 – 870.

[14] Karatepe, E., Boztepe, M., Colak, M., 2007. Development of a Suitable Model for Characterizing Photovoltaic Arrays with Shaded Solar Cells. Solar Energy. 81, 977-992.

[15] Kim, H., Kim, J., Kim, H., Lee, K., Kim, J., Yoo, D., Shin, D., 2010. A High Efficiency Photovoltaic Module Integrated Converter with the Asymmetrical Half-Bridge Flyback Converter. Solar Energy. 84, 1376 – 1381.

[16] Kjaer, S.B., Pedersen, J.K., Blaabjerg, F., 2005. A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules. IEEE Transactions on Industry Applications. 41 (5), 1292 – 1306.

[17] Kobayashi, K., Takano, I., Sawada, Y., 2003. A Study on a Two Stage Maximum Power Point Tracking Control of a Photovoltaic System under Partially Shaded Insolation Conditions. IEEE Power Engineering Society General Meeting. 4, 2612 – 2617.

[18] Kovach, A., Schmid, J., 1996. Determination of Energy Output Losses due to Shading of Building-Integrated Photovoltaic Arrays using a Raytracing Technique. Solar Energy. 57(2), 117 – 124.

[19] Kulaksiz, A.A., Akkaya, R., 2012. A Genetic Algorithm Optimized ANN-based MPPT Algorithm for a Stand-Alone PV System with Induction Motor Drive. Solar Energy. 86, 2366 – 2375.

[20] Kuo, Y., Liang, T., Chen, J., 2001. Novel Maximum Power Point Tracking Controller for Photovoltaic Energy Conversion System. IEEE Transactions on Industrial Electronics. 48, 594 – 601.

[21] Mohan, N., Undeland, T.M., Robbins, W.P., 1995. Power Electronics: Converters, Applications and Design. Second Edition, John Wiley & Sons Inc., New York, USA.

[22] Munoz, M.A., Alonso-Garcia, M.C., Vela, N., Chenlo, F., 2011. Early degradation of silicon PV modules and guaranty conditions. Solar Energy. 85, 2264 -2274.

[23] Myrzik, J.M.A., Calais, M., 2003. String and Module Integrated Inverters for Single-Phase Grid Connected Photovoltaic Systems – A Review. IEEE Bologna PowerTech Conference. 2, 1- 8.

[24] Noguchi, T., Togashi, S., Nakamoto, R., 2002. Short-Current Pulse-Based Maximum Power Point Tracking Method for Multiple Photovoltaic and Converter Module System. IEEE Transactions on Industrial Electronics. 49(1) 217 – 223.

[25] Ogata, K., 2002. Modern Control Engineering. Forth Edition, Prentice Hall, New Jersey, USA.

[26] Patel, H., Agarwal, V., 2008. Maximum Power Point Tracking Scheme for PV Systems Operating Under Partially Shaded Conditions. IEEE Transactions on Industrial Electronics. 55(4), 1689 – 1698.

[27] Petreus, D., Patarau, T., Daraban, S., Morel, C., Morely, B., 2011. A Novel Maximum Power Point Tracker based on Analog and Digital Control Loops. Solar Energy. 85, 588 – 600.

[28] Quaschning, V., Hanitsch, R., 1996. Numerical Solutions of Current-Voltage Characteristics of Photovoltaic Systems with Shaded Solar Cells. Solar Energy. 56(6), 513 – 520.

[29] Sunsei, 2007. Datasheet of Sunsei SE – 6000 Solar Panel (Available at http://cpc.farnell.com/1/1/41472-panel-solar-100w-sunsei-se-6000-icp-global-technologies.html)

[30] Walker, G.R., Sernia, P.C., 2004. Cascaded DC-DC Converter Connection of Photovoltaic Modules. IEEE Transactions on Power Electronics. 19(4), 1130 – 1139.

[31] Walker, G.R., Pierce, J.C., 2006. Photovoltaic DC-DC Module Integrated Converter for Novel Cascaded and Bypass Grid Connection Topologies – Design and Optimization. Proceedings of 37th Power Electronics Specialists Conference. 1 – 7.

[32] Woyte, A., Njis, J., Belmans, R., 2003. Partial Shadowing of Photovoltaic Arrays with Different System Configurations: Literature Review and Field Test Results. Solar Energy. 74, 217 – 233.

[33] Zhang, L., Al-Amoundi, A., 2000. Application of radial basis function networks for solar array modelling and maximum power point prediction. IEE Proceedings - Generation, Transmission and Distribution. 147, 310-316.

Appendix

Coefficients of Transfer Functions

Transfer function between the voltage at the upper terminal of each MIPC, and the control variable, k_{upper}, is given as

$$G_1(s) = \frac{\hat{v}_{upper}(s)}{\hat{k}_{upper}(s)} = -\frac{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_5 s^5 + \alpha_4 s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} V_T \tag{A1}$$

The transfer function between the voltage at the lower terminal of each MIPC, and the control variable, k_{upper}, is given as

$$G_2(s) = \frac{\hat{v}_{lower}(s)}{\hat{k}_{upper}(s)} = \frac{\gamma_3 s^3 + \gamma_2 s^2 + \gamma_1 s + \gamma_0}{\alpha_5 s^5 + \alpha_4 s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} V_T \tag{A2}$$

Simplification of Equations (A1) and (A2) are made by having a standard set of components for converters where PV terminal capacitors C_1, C_2, C_3 are equal (i.e C), all inductors (L_{11}, L_{12}, L_{21} and L_{22}) are set to be L, and all internal capacitors (C_{n1} and C_{n2}) as C_n. Therefore, the transfer function coefficients become

$$\begin{aligned}
\alpha_5 &= (CL)^2 C_n \\
\alpha_4 &= CC_n L^2\left(\frac{1}{R_{P1}} + \frac{1}{R_{P2}}\right) \\
\alpha_3 &= C_n L\left(2C + \frac{L}{R_{P1}R_{P2}}\right) + C^2 L\left(K^2 + (1-K)^2\right) \\
\alpha_2 &= L\left(C_n + CK^2 + C(1-K)^2\right)\left(\frac{1}{R_{P1}} + \frac{1}{R_{P2}}\right) \\
\alpha_1 &= C_n + \left(K^2 + (1-K)^2\right)\left(C + \frac{L}{R_{P1}R_{P2}}\right) \\
\alpha_0 &= \frac{(1-K)^2}{R_{P1}} + \frac{K^2}{R_{P2}}
\end{aligned},$$

$$\beta_3 = CC_n L \qquad \gamma_3 = CC_n L$$

$$\beta_2 = \frac{C_n L}{R_{P2}} + CL(1-K)\left(\frac{(1-K)}{R_{P1}} - \frac{K}{R_{P2}}\right) \qquad \gamma_2 = \frac{C_n L}{R_{P1}} + CLK\left(\frac{K}{R_{P2}} - \frac{(1-K)}{R_{P1}}\right)$$

$$\beta_1 = C_n + CK + \frac{L(1-K)}{R_{P2}}\left(\frac{(1-K)}{R_{P1}} - \frac{K}{R_{P2}}\right) \text{ and } \gamma_1 = C_n + C(1-K) + \frac{LK}{R_{P1}}\left(\frac{K}{R_{P2}} - \frac{(1-K)}{R_{P1}}\right)$$

$$\beta_0 = \frac{(1-K)^2}{R_{P1}} + \frac{K^2}{R_{P2}} \qquad \gamma_0 = \frac{(1-K)^2}{R_{P1}} + \frac{K^2}{R_{P2}}$$

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Fig. 1. Configurations of MIPC System using cascaded converter approach

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