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Evaluation of a FPGA controlled distributed PV system under partial shading condition

Ru-Min Chao[*1,2], Shih-Hung Ko[1a] and Po-Lung Chen[1b]

[1]*Department of Systems and Naval Mechatronics Engineering, National Cheng Kung University, Tainan, Taiwan 701, ROC*
[2]*Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan, Taiwan 701, ROC*

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Abstract. This study designs and tests a photovoltaic system with distributed maximum power point tracking (DMPPT) methodology using a field programmable gate array (FPGA) controller. Each solar panel in the distributed PV system is equipped with a newly designed DC/DC converter and the panel's voltage output is regulated by a FPGA controller using PI control. Power from each solar panel on the system is optimized by another controller where the quadratic maximization MPPT algorithm is used to ensure the panel's output power is always maximized. Experiments are carried out at atmospheric insolation with partial shading conditions using 4 amorphous silicon thin film solar panels of 2 different grades fabricated by Chi-Mei Energy. It is found that distributed MPPT requires only 100ms to find the maximum power point of the system. Compared with the traditional centralized PV (CPV) system, the distributed PV (DPV) system harvests more than 4% of solar energy in atmospheric weather condition, and 22% in average under 19% partial shading of one solar panel in the system. Test results for a 1.84 kW rated system composed by 8 poly-Si PV panels using another DC/DC converter design also confirm that the proposed system can be easily implemented into a larger PV power system. Additionally, the use of NI sbRIO-9642 FPGA-based controller is capable of controlling over 16 sets of PV modules, and a number of controllers can cooperate via the network if needed.

Keywords: module integrated converter (MIC); field programmable gate array (FPGA); partial shading; maximum power point tracking (MPPT); quadratic maximization; distributed photovoltaic system

1. Introduction

In recent years, photovoltaic power generation has become an important renewable energy resource, since it exhibits numerous merits such as cleanness, low maintenance, and noise free. Several new applications employing this technology have been developed, for example, the use of building-integrated photovoltaic (BIPV), in which the solar panel is used to replace conventional building materials in parts of the building facade or the roof of a house, has become a popular

[*]Corresponding author, Professor, E-mail: rmchao@mail.ncku.edu.tw
[a] Ph.D. candidate, E-mail: yalato_ko@hotmail.com
[b] Ph.D. Student, E-mail: darmsta@hotmail.com

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application in the photovoltaic industry. However, due to the intensity of solar insolation and environmental restrictions on the buildings, the efficiency of the traditional photovoltaic system was decreased due to partial shading conditions, panel mismatch by dust on the panel, falling leaves, aging, etc. That is, the total power generated by the entire string of PV panels can be affected by one panel in the power circuit due to afore-mention reasons. Besides, the electrical characteristics of the PV system contains possible multiple maximum power points when panel mismatch is encountered, and the need for novel global MPP tracking algorithm increases. PV system exhibits multiple maxima has been discussed by many researchers (Woyte *et al*. 2003), (Petrone *et al*. 2007), (Martinez *et al*. 2010), (Paraskevadaki and Papathanassiou 2011). Several MPPT methods also have been proposed for tracking the global maxima for the centralized PV system dealing with multiple-peak phenomenon. For example, the adaptive perceptive particle swarm optimization algorithm is used to approach the global MPP (Chowdhury and Saha 2010). A new MPPT method based on the current-voltage characteristic of PV arrays, which can not only track the MPP under uniform insolation conditions, but also can find the global MPP under partially shaded conditions (Kouchaki *et al*. 2013). However, regardless the maximum power point tracker can identify the absolute maximum power point (MPP) of the PV string or not, the absolute maximum power output is always less than the sum of the individual panels' maximum power due to its design philosophy (Petrone *et al*. 2010), (Maki *et al*. 2012).

Different approach has to be made in order to harvest most energy out of a PV system, and the distributed PV systems were proposed as solutions to the problems inherent in the centralized systems (Walker and Sernia 2004), (Roman *et al*. 2006), (Xiao *et al*. 2007). Because a DC-DC converter is installed on every solar panel in the distributed PV system, each panel in the distributed system has to be operated at its own maximum power point during operation and the maximum energy available from the PV system can be harvested. An example for the grid-connected distributed PV system is shown in Fig. 1. Each PV panel is connected by its respective module-integrated converter (MIC), and the total electrical energy is sent to the utility grid using a unified DC-AC inverter. Because each PV panel has its own power module and measurement unit, this configuration allows real-time monitoring of the operating condition for each panel.

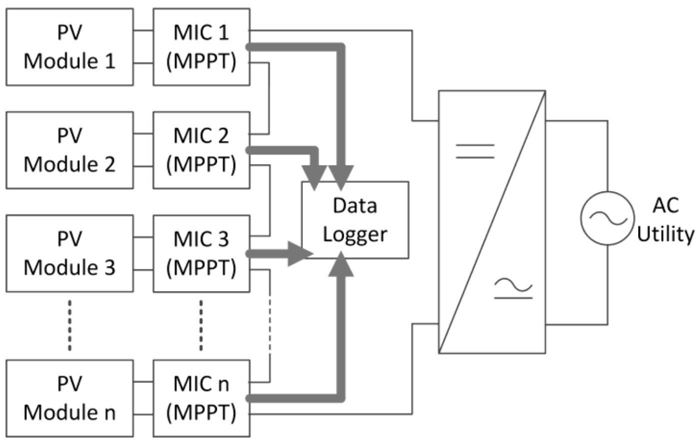


Fig. 1 Block diagram of grid-connected distributed PV system containing serial string panels and module integrated converters

Previous design of the distributed PV system, for example, (Roman *et al*. 2008) and (Linares *et al*. 2009), focused on the fundamental differences from the centralized system and neglected the fact that the emerging computing technology can also improve the total energy efficiency of the PV system. In this paper, a photovoltaic distributed MPPT system using a FPGA controller with open hardware architecture is proposed. This study also implements the modified quadratic maximization algorithm for MPPT calculation which had been proven can be fast response to change of solar insolation and temperature conditions (Chao *et al*. 2009), (Pai and Chao 2010), (Ko and Chao 2012). The detail is discussed.

2. Distributed PV system design

Consider a grid-connected distributed PV system design where a controller is used to perform panel level MPPT. The controller requires to regulate the power output of the PV panel and estimate the optimal operating voltage. When buck/boost converter design is used, the operating voltage update rate for MPPT operation shall be slower than the voltage regulator sampling frequency. Besides, every MIC requires sensors for voltage and current measurement and I/O ports for tracking purpose. While a new MPPT technology has been developed and a powerful microcontroller is available to the market, it is possible to take advantage of both design methodologies by using panel level maximum power point tracking with minimum number of microcontrollers. This paper proposes a novel distributed PV system as described next.

The idea of the proposed system has the following benefits. It is not an all-in-one solution for photovoltaic application. Actually, the distributed PV system can be divided into three parts: (1) the solar panels, which can be provided by any module manufacturers, (2) the DC/AC inverter: for grid-connection purpose or DC/DC converter for standalone application (battery management system) from any power supply venders, and (3) DMPPT system for distributed power harvesting, see Fig. 2.

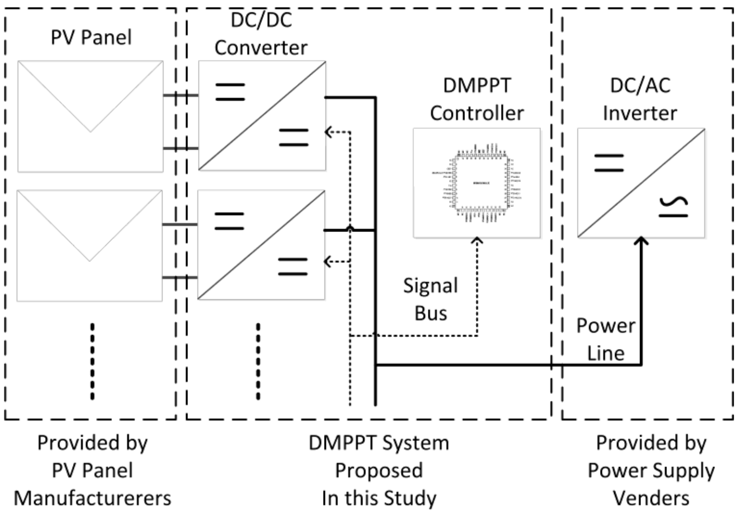


Fig. 2 The proposed distributed PV system using DMPPT controller: FPGA controller for parallel signal measurement, PI voltage regulation; microprocessor for MPPT operation

The distributed MPPT system proposed by this study uses field-programmable gate array, FPGA microcontroller to perform parallel signal measurement and voltage regulation for all panels, and the panel level MPPT operation is carried out by another microprocessor. The hardware is partially realized by using the single-board RIO controller introduced by National Instruments as the DMPPT controller. As shown in Fig. 3, the power produced by each photovoltaic panel is controlled by the MPPT algorithm through a boost converter. The outputs of the boost converters are then connected in serial or in parallel according to the operational voltage and power requirement. The voltage and current information are measured by the FPGA driven ADC through the voltage divider and the current sensing circuit. That is, first-level MPPT operation is completed at the FPGA controller including parallel signal sampling and voltage regulation. Power measurement result is then sent to the real-time embedded processor for maximum power point tracking for each of the solar panels.

The system’s operational flowchart, shown in Fig. 4, illustrates the processes for power measurement, distributed MPPT calculation, updating PWM signal output, data recording, and remote communications. The DMPPT calculation can be divided into two steps: the PI voltage regulation and the MPPT algorithm. The PI voltage regulator controls the PV panel’s voltage output according to the command V_{ref}, which is evaluated by the MPPT algorithm. The performance of the close-loop PI voltage control was examined with a DC/DC converter which has been tested using a solar array simulator, E4351B. Quadratic maximization MPPT algorithm is used in this study because it responds to the changes in solar insolation and environmental temperature more effective than P&O MPPT method.

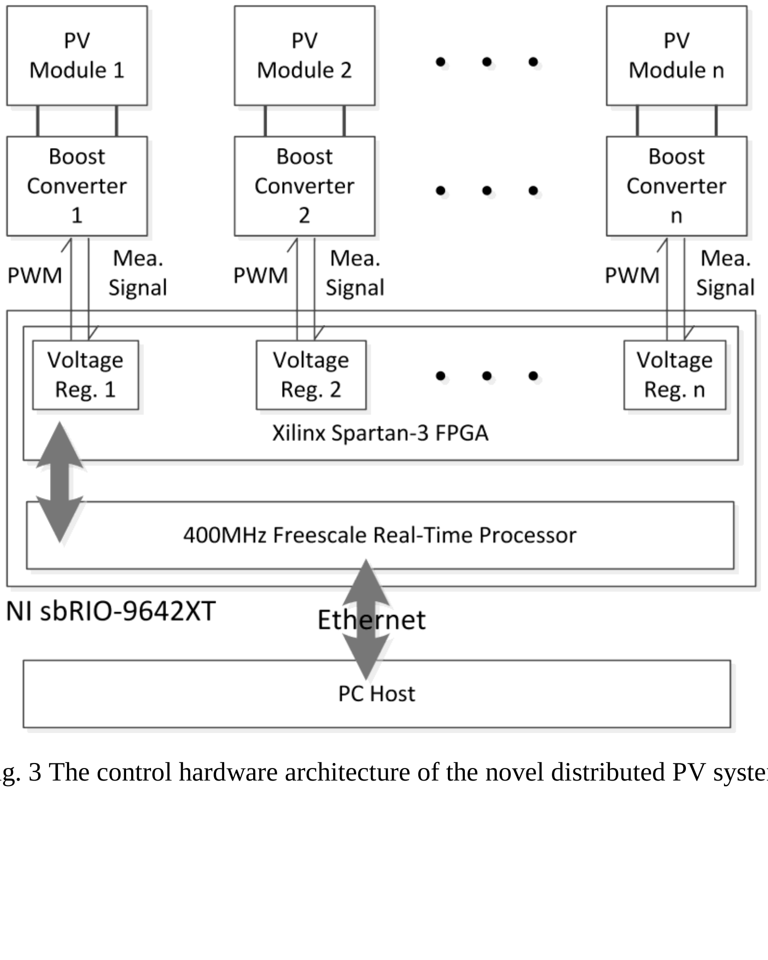


Fig. 3 The control hardware architecture of the novel distributed PV system

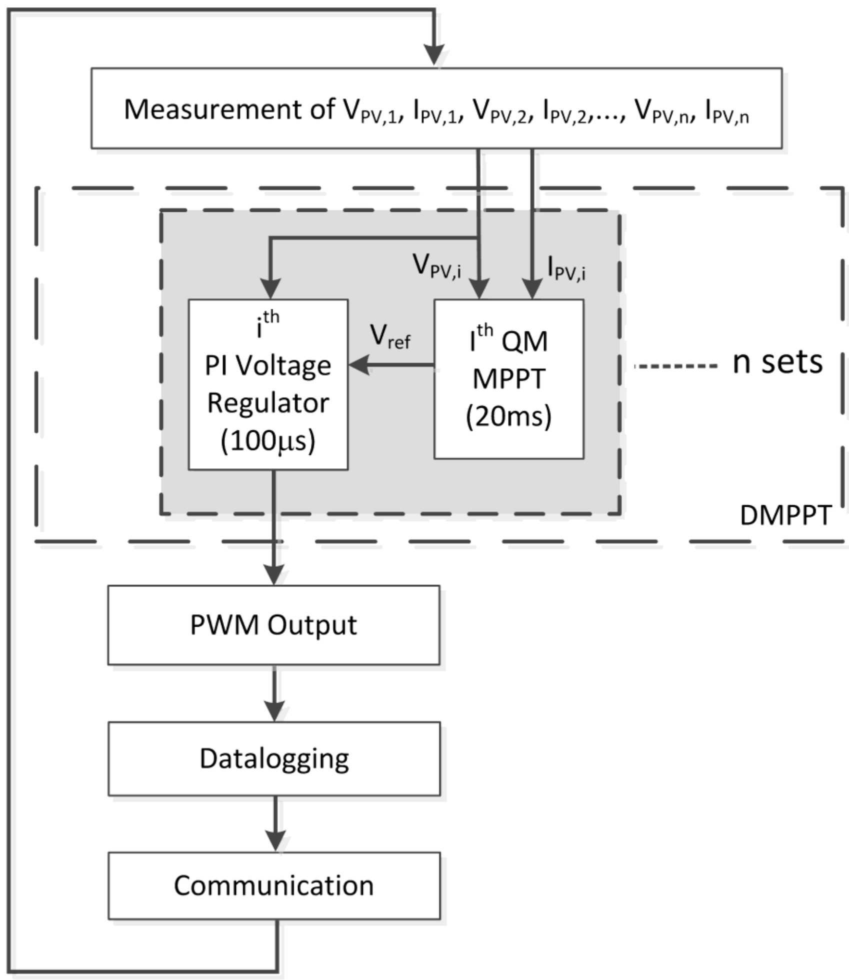


Fig. 4 The DMPPT algorithm for the novel distributed PV system

3. Quadratic maximization MPPT algorithm

The quadratic maximization (QM) algorithm for maximum power point tracking was developed recently. Different from our previous work is that PI voltage regulation is enforced. The tracking algorithm based on the operational output voltage is briefly shown in Fig. 5, where the solid line represents the power characteristic curve of a PV array, and the dash line represents a quadratic curve calculated from three operating points in order to estimate the maximum power point. The three operating voltages are V_1, V_2, and V_3, where $V_1 < V_2 < V_3$. By applying the three operating points V_1, V_2, and V_3 to the PV system, the corresponding PV array power output P_1, P_2, and P_3 can be measured. A quadratic curve (the dashed line) can then be calculated to identify the approximated operating voltage at maximum power point. For more details, the readers can refer (Chao *et al*. 2009), (Pai and Chao 2010), and (Ko and Chao 2012).

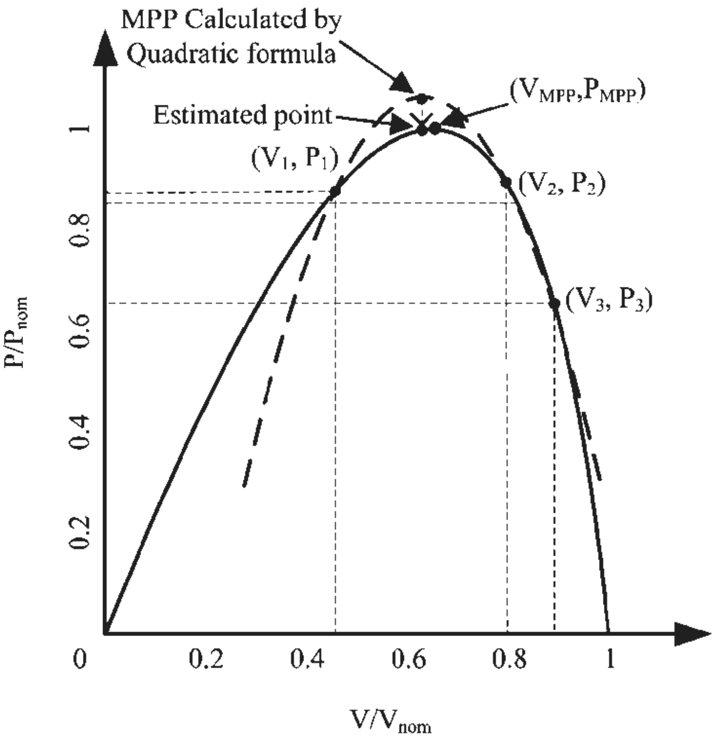


Fig. 5 Illustration of the quadratic maximization MPPT mechanism: solid line—original PV curve; dash line—quadratic approximated PV curve

4. Experimental results

The experimental setup for the proposed distributed PV system is shown in Fig. 6. Four thin-film photovoltaic panels were connected in series through the output of the boost converters in order to increase the total voltage output to 360 V DC for optimum inverter conversion efficiency, and the DC power was then inverted to 220 V AC for utility grid connection. PV panel mismatching arrangement is also considered in this setup. The manufacturer's specification data is shown in Table 1. Each of the four panels is equipped with its own measurement and control module and is connected to NI sbRIO-9642 controller. This controller board equips a 400 MHz Freescale MPC5200 real-time processor, a 2 M gates Xilinx Spartran-3 FPGA core and total of 110 DIO channels. The DC/DC converter circuitry, the I-V measurement and the MOSFET control of a PV converter module are shown in Fig. 7. In general, the panel's voltage output is boosted and its MOSFET switch is controlled by the 80 kHz PWM signal generated by Xilinx FPGA processor. The panel's voltage is measured through a voltage divider and the current is sensed using a small resistor. The computer program used in this experiment is programmed under NI LabVIEW environment. While calculating system resource requirement, it is found that the control over 4 PV power output takes only about 22.5% of the FPGA resource (Mult18X18) and the sbRIO-9462 distributed MPPT controller is therefore possibly controlling over 16 distributed PV modules.

Table 1 Specification of photovoltaic panels used for the distributed PV system

No. of PV module	1	2	3	4
Model	CSSS-90A	CSSS-90A	CSSS-90A	CSSS-100A
Voltage at MPP @ STC	77.14 V	77.15 V	78.17 V	83.11V
Current at MPP @ STC	1.47 A	1.48 A	1.46 A	1.528 A
Short-circuit current @ STC	1.69 A	1.69 A	1.68 A	1.723 A
Open-circuit voltage @ STC	104.73 V	103.96 V	105.12 V	102.97 V
Photovoltaic cells	Amorphous Thin-Film			
Manufacturer	Chi Mei Energy			
Dimensions	1410*1114*35 mm			

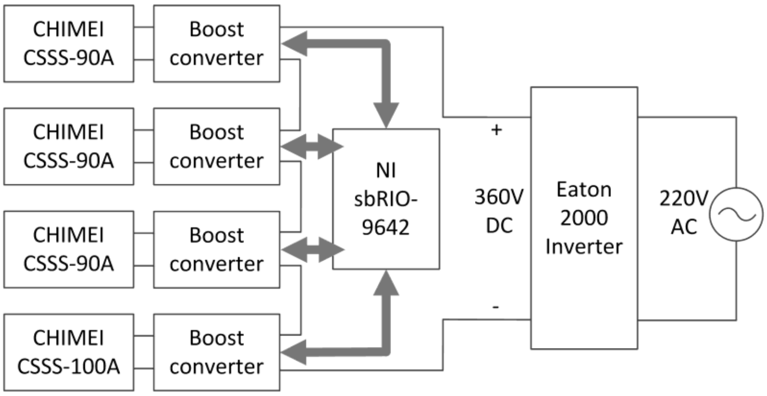


Fig. 6 The distributed PV system design for DMPPT test using 4 PV panels

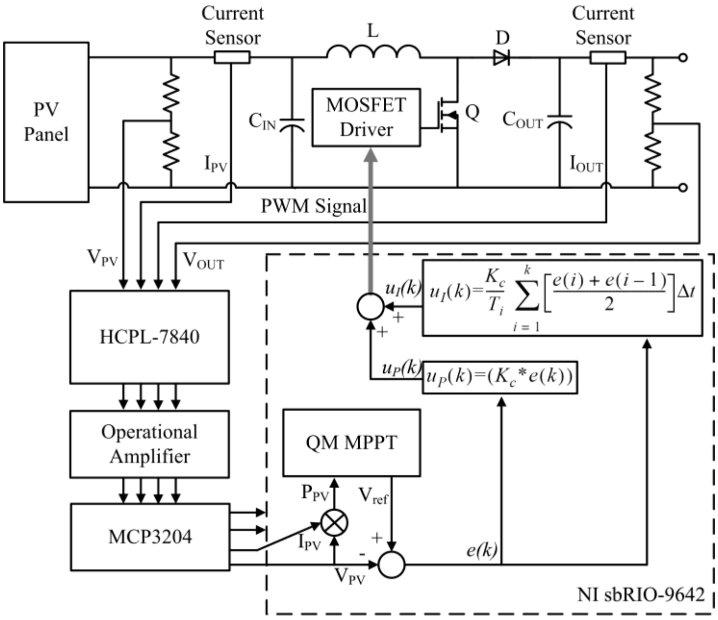
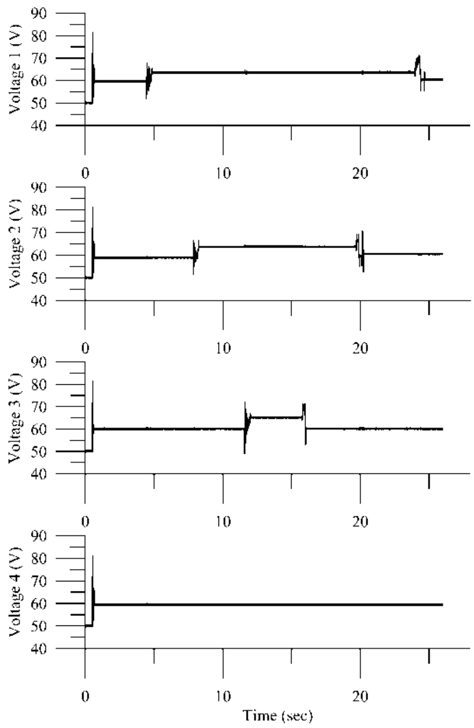


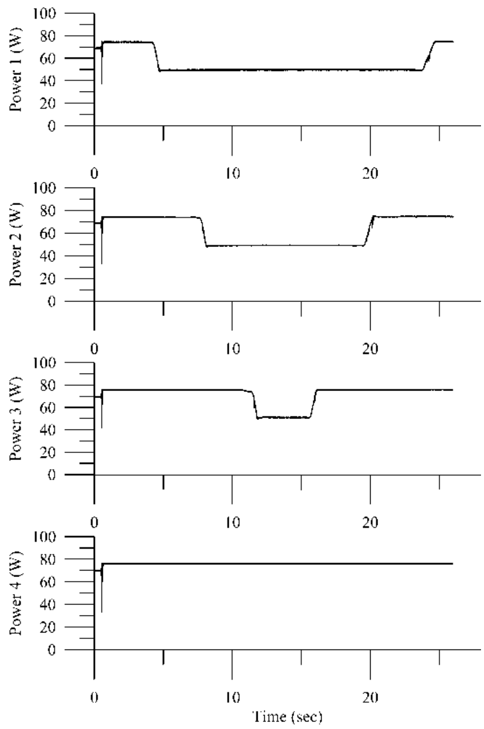
Fig. 7 Schematic design for DC-DC converter, measurement unit, and FPGA operation

For partial shading test, a 50 x 60 cm sun visor is used to cover one of the PV panels, covering 19% of the surface area of one panel. The maximum power point operational voltage for the partially shaded panel was 62.5 V and the maximum power output was about 45 W. Despite of the influence of shading on the first panel, other photovoltaic panels maintained a power output approximately at 70 W.

Fig. 8 shows the tracking results when four PV panels are progressively partially shaded. The MPPT calculation waits for 0.5 seconds after the testing system is turned on. Fig 8(a) shows the PV panels' output voltages (input side of the DC/DC converter) where the voltage output is changed when the panel is shaded. Partial shading test starts 4 seconds after testing began, then panel #2 at 7.5 seconds, and panel #3 at 11 seconds are also partial shaded sequentially. The sun visors of panel #3, #2 and #1 are then moved away at 15.5, 19.5 and 24 seconds on the time frame, respectively. Since the maximum power point tracking algorithm is executed by the real-time processor and the PI regulator in each of the MIC is parallel controlled by the FPGA core, the power generated from any PV panel will be changed only if its own operating conditions is changed (such as temperature, irradiation, and individual MPPT operation), see Fig. 8(b). Fig. 9 shows the voltage out of each MIC during the progressive shading test. It also indicates voltage output will drop for a panel when it is partially shaded and will be boosted when other panels encounter shading in order to compensate the current change of the system while keeping maximum power output for every PV panel.



(a)



(b)

Fig. 8 DMPPT test results from the PV output: (a) voltage and (b) power; panel #1, #2 and #3 were sequentially partial shaded; also note that perturbing a PV panel will not affect other's performance

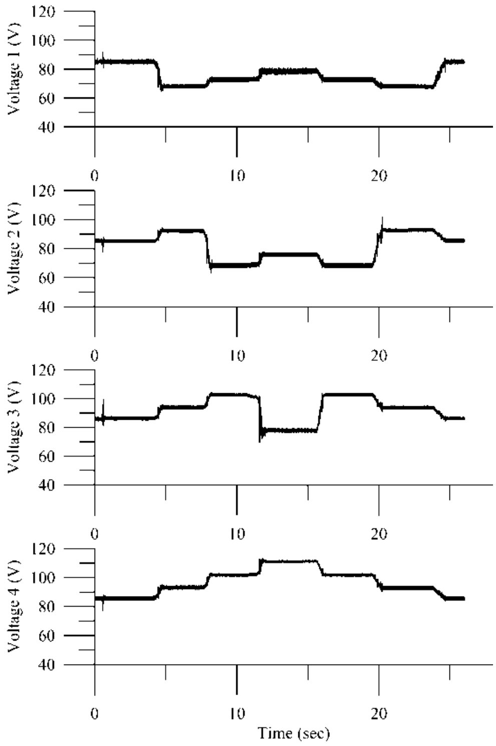


Fig. 9 Voltage measured at MIC output side when panel #1, #2 and #3 were sequentially partially shaded; also note that when a panel was shaded, its output voltage drops whereas others rise in order to keep the panel output power at maximum

5. Conclusions

In this paper, a novel distributed PV harvesting system using FPGA controller is presented. The control of the module-integrated converter is operated by the FPGA controller for parallel signal processing and voltage regulation. Because all of the MIC information is measured and collected by a single controller, the difficulty associated with data collection between PV panels is reduced.

We have compared the performance of the distributed with the centralized photovoltaic systems and confirm that the distributed system harvests 4% more energy than the centralized system in regular weather condition if panel mismatching is considered, and is 20% more energy efficiency if partial shading condition is also encountered. Test results for a 1.84 kW rated system composed by 8 poly-Si PV panels using another DC/DC converter design also confirm that the proposed system can be easily implemented into a larger PV power system. The performance of the sbRIO-9642 FPGA controller is tested in the paper, and the DMPPT controller is expected to control over 16 PV modules, approximately equivalent to 3 kW rating for one system if 230 W PV panels are used. With parallel processing in mind, low cost microcontroller at the converter side has also been demonstrated successfully.

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References

Chao, R.M., Ko, S.H., Pai, F.S., Lin, I.H. and Chang, C.C. (2009), "Evaluation of a photovoltaic energy mechatronics system with built in quadratic maximum power point tracking algorithm", *Sol. Energy*, **83**(12), 2177-2185.

Chowdhury, S.R. and Saha, H. (2010), "Maximum power point tracking of partially shaded solar photovoltaic arrays", *Sol. Energ. Mat. Sol. C.*, **94**(9), 1441-1447.

Ko, S.H. and Chao, R.M. (2012), "Photovoltaic dynamic MPPT on a moving vehicle", *Sol. Energy*, **86**(6), 1750-1760.

Linares, L., Erickson, R.W., MacAlpine, S. and Brandemuehl, M. (2009), "Improved energy capture in series string photovoltaics via smart distributed power electronics", *Proceedings of the IEEE Applied Power Electronics Conference and Exposition*, Washington D.C., USA, February.

Kouchaki, A., ImanEini, H. and Asaei, B. (2013), "A new maximum power point tracking strategy for PV arrays under uniform and non-uniform insolation conditions", *Sol. Energy*, **91**, 221-232.

Mäki, A., Valkealahti, S. and Leppäaho, J. (2012), "Operation of series-connected silicon-based photovoltaic modules under partial shading conditions", *Prog. Photovoltanics*, **20**(3), 298-309.

MartínezMoreno, F., Muñoz, J. and Lorenzo, E. (2010), "Experimental model to estimate shading losses on PV arrays", *Sol. Energ. Mat. Sol. C.*, **94**(12), 2298-2303.

Pai, F.S. and Chao, R.M. (2010), "A new algorithm to photovoltaic power point tracking problems with quadratic maximization", *IEEE T. Energy Conver.*, **25**(1), 262-264.

Paraskevadaki, E.V. and Papathanassiou, S.A. (2011), "Evaluation of MPP voltage and power of mc-Si PV modules in partial shading conditions", *IEEE T. Energy Conver.*, **26**(3), 923-932.

Petrone, G., Spagnuolo, G. and Vitelli, M. (2007), "Analytical model of mismatched photovoltaic fields by means of Lambert W-function", *Sol. Energ. Mat. Sol. C.*, **91**(18), 1652-1657.

Petrone, G., Spagnuolo, G. and Vitelli, M. (2010), "A new technique for distributed maximum power point tracking PV applications", *Proceedings of the IEEE International Conference on Ind. Technology*

Roman, E., Alonso, R., Ibanez, P., Elorduizapatarietxe, S. and Goitia, D. (2006), "Intelligent PV module for grid-connected PV systems", *IEEE T. Ind. Electron.*, **53**(4), 1066-1073.

Roman, E., Martinez, V., Jimeno, J.C., Ibañez, P. and Elorduizapatarietxe, S. (2008), "Experimental results of controlled PV module for building integrated PV systems", *Sol. Energy*, **82**(5), 471-480.

Walker, G.R. and Sernia, P.C. (2004), "Cascaded DC-DC converter connection of photovoltaic modules", *IEEE T. Power Electr.*, **19**(4), 1130-1139.

Woyte, A. Nijs, J. and Belmans, R. (2003), "Partial shadowing of photovoltaic arrays with different system configurations: literature review and field test results", *Sol. Energy*, **74**(3), 217-233.

Xiao, W., Ozog, N. and Dunford, W.G. (2007), "Topology study of photovoltaic interface for maximum power point tracking", *IEEE T. Ind. Electron.*, **54**(3), 1696-1704.