Maximum power point controller for large-scale photovoltaic power plants using central inverters under partial shading conditions

Karanayil, Baburaj; Ceballos, Salvador; Pou, Josep

2018

Karanayil, B., Ceballos, S., & Pou, J. (2019). Maximum power point controller for large-scale photovoltaic power plants using central inverters under partial shading conditions. IEEE Transactions on Power Electronics, 34(4), 3098-3109. doi:10.1109/TPEL.2018.2850374

<https://hdl.handle.net/10356/141681>

<https://doi.org/10.1109/TPEL.2018.2850374>

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: <https://doi.org/10.1109/TPEL.2018.2850374>.

Downloaded on 26 Apr 2023 19:35:54 SGT

Maximum Power Point Controller for Large Scale Photovoltaic Power Plants Using Central Inverters under Partial Shading Conditions

Baburaj Karanayil, *Senior Member, IEEE*, Salvador Ceballos and Josep Pou, *Fellow, IEEE*

Abstract—The central inverter topology based on three-level converters is widely used in large scale photovoltaic (PV) power plants because of its simple and reliable structure and high efficiency. However, when two PV arrays are connected in series for higher dc-link voltage, single maximum power point tracking (MPPT) operation cannot function properly when there is partial shading between the arrays. This paper presents a configuration where the two PV arrays are connected in series together with an auxiliary power converter feeding a neutral-point-clamped central inverter. This configuration ensures maximum power production from both PV arrays during partial shading conditions, achieving the MPPT operation for both PV arrays. The proposed converter together with their controls are verified by simulation and experiment.

Index Terms—Photovoltaic systems, grid-connected inverters, maximum power point tracking.

I. INTRODUCTION

The global solar photovoltaic (PV) energy conversion systems grew significantly, to at least 75.4 GW in 2016, which represents a 50% growth year-on-year [1]. The total global installed capacity at the end of 2016 amounted to at least 303 GW. Grid-connected PV systems account for more than 99% of PV installed capacity compared to the stand-alone systems [2].

Large scale PV power systems up to 1 MW are made of PV arrays usually connected to 1000V dc central inverters. As the technology becomes mature, there has been continuous effort in improving the system efficiency and in reducing the cost. The effective way to achieve these goals is to increase the system voltage. Also, the voltage constraint imposes a limit on the maximum number of modules that can be connected. Over time, PV inverter technology has settled for installations under 1000 V (open-circuit), and a typical MPPT bus range covers from 575 V (lower dc-bus limit) to 850 V (upper dc-bus limit). At certain extreme temperatures (-20°C and 70°C) will position the MPP and power curves well outside the inverter dc-bus voltage operating area, compromising the inverter ability to shield maximum power extraction [3]. Lower dc-bus limit extension allows energy capture under low radiation and high PV temperatures (70°C) and the extension of the upper dc-bus voltage allows for greater energy extraction under high

radiation and low temperatures (-20°C). There are currently developments of 2.3 MW at 1500 V, PV inverters reported [4], [5]. These inverters at 1000 V -1500 V dc have only a single MPPT operation.

Central inverters are usually connected to several PV arrays, each made up of many PV panels connected to the dc-link of the inverter [6]. This solution offers the cheapest price of the inverter in \$ /kW. Central inverters thus provide a simple structure, reliable and efficient converter, making it one of the most common solutions for large-scale PV plants. Because the whole array is connected to a single inverter, this configuration can only provide a single MPPT operation and hence it is not a good solution when operating under partial shading, where part of the PV array will bring down the generated power output from the array significantly.

Improvement of the MPPT control without dc-dc converters for three-phase inverter have been reported in [7], [8]. In [7], the two capacitor voltages are controlled by adding or subtracting the minimum turn-on time to the three-phase turn-on times. The output distortions are then eliminated by modifying the reference voltages. In [8], a zero-sequence voltage was used for the asymmetric control of dc-link voltages. This method does not need additional hardware investment. However, the effectiveness of the MPPT algorithm is limited, especially when the main converter is working at high modulation indexes and the power distribution between the PV sources is very unbalanced. Under these conditions, the MPPT algorithm is not able to work at the maximum power point.

A dc-bus voltage balancing algorithm for three-level neutral-point-clamped (NPC) traction inverter drive is proposed in [9] using modified virtual space vector PWM (VSVPWM) strategy, which uses both the positive and negative redundant voltage vectors alternatively as a virtual vector.

A single power stage topology was proposed for grid-connected inverter using three-level central NPC inverter [10] by adding an auxiliary converter in parallel to the dc-link. This solution follows a similar approach to the one proposed in this paper. However, it requires additional inductive and capacitive elements that make it a bit more complex and potentially expensive.

In [11], the main focus is to develop a control strategy for the three-level NPC inverter when the different zones receive different solar irradiance levels. Such a strategy would increase power production under partial shading without additional dc/dc converters and without communication between individual inverter controllers. A real MPPT method for mismatching

B. Karanayil is with the School of Electrical Engineering and Telecommunications, UNSW Sydney, NSW 2052, Australia (e-mail: baburaj@ieee.org).

S. Ceballos is with Tecnalia Research and Innovation, Derio, Spain (e-mail: salvador.cebillos@tecnalia.com).

J. Pou is with the School of Electrical and Electronic Engineering, Nanyang Technological University, 639798 Singapore (e-mail: j.pou@ntu.edu.sg).

compensation in PV array under partial shading conditions is presented in [12]. In this case, the full PV array power flows through a dc-dc converter to the grid-connected inverter. The distributed MPPTs enables better power generation during partial shading at the expense of higher switching losses in the additional power converters during less shading conditions and vice versa for the central MPPTs [13]. The annual energy yield with the help of distribution of dc-dc converters and MPPT controllers in a large scale PV power plant, where the dc-dc converters are connected between the PV arrays and central inverter [14]. In common large-scale installations, hundreds or even thousands of PV panels are arranged in arrays and connected to a single inverter. Even though central converter uses a simple topology, has high reliability and good conversion efficiency, it has poor MPPT capabilities, which impacts the overall system performance [15]. The effect of partial shading in a large scale PV power plant is investigated in [16], but here, microinverters are connected to the PV panels. In the power plant proposed in [17], the PV module output feeds the inverter through a current fed dual-active bridge dc-dc converter with high-frequency isolation. A new architecture for PV grid-connected converters based on a string mini boost stage was introduced in [18]. In [19], an energy storage system is added at inverter level; enabling the PV system to store energy during standard operation, and releasing stored energy when performing PV curve scan, hence achieving global MPPT in central inverter PV power plants.

The methods previously proposed in [8]–[18] can be categorized in two groups. The first category is where the MPPT control is implemented without the need of an additional power converter. The implementation of these methods does not need additional investment in power converters which make them attractive. In particular, the method proposed in [8] uses an NPC converter as the main converter, similar to the solution proposed in this paper. However, as discussed above, the effectiveness of the MPPT in [8] is reduced at high modulation indexes when the power production of the PV arrays is highly unbalanced. The method proposed in this paper overcomes this issue and guarantees the maximum power extraction over the whole range of working conditions.

The second category is where additional power converters are required as in [11]–[18]. Most of them use a dc-dc converter in series with the dc-link. This causes the entire dc power to go through this converter irrespective of the fact that there is partial shading, which reduces the overall system efficiency. In addition, whenever a dc-dc converter is added in series between the PV array and the inverter, not only the power loss of that converter reduces the overall system efficiency, but also the power rating of the dc-dc converter will be the same as that of the inverter, which makes this option expensive. In large central inverters, the decision to invest in extra power converters to gain power generation during partial shading is overshadowed by the additional cost of this extra converter. These issues are overcome with the proposed solution. It consists of a partially-rated modular auxiliary power converter leg that is inserted in parallel to the dc-link. The auxiliary converter comes into operation only during excessive partial shading, which indirectly makes it

operate at higher efficiency. Besides, the power rating of this auxiliary unit is considerably low which will make the system economically feasible and operate with reduced switching and conduction losses. The generated power from the PV array is maximized to achieve the best system efficiency. All these features make the proposed solution particularly feasible for large power plants with central inverters, where the system efficiency is very critical.

This paper is organized as follows. Section II presents the conventional and the proposed MPPT schemes for central NPC inverter topology. The operation of the auxiliary converter for the proposed MPPT is described in Section III. The elimination of low-frequency ripples is explained in Section IV. Simulation results for both MPPT schemes and their comparison are presented in Section V. Experimental results are discussed in Section VI. A comparative analysis of MPPTs is provided in Section VII. Finally, Section VIII summarizes the main conclusions of this work.

II. PV TO GRID INTERFACE TOPOLOGIES

A typical large scale PV inverter operates up to 1000 V dc and has a single PV array connected to a the dc-bus. When the dc-link voltage is increased to 1500 V dc, it becomes necessary to connect more panels in series or two PV arrays in series as in Fig. 1, similar to a configuration described in [20]. The single MPPT controller uses the total PV array voltage v_{PV} and current i_{PV} to estimate the MPP voltage $v_{PV_Conv}^*$ which sets the dc-link voltage reference v_{dc}^* to the inverter. The disadvantage is that when there is partial shading on one of the arrays, the MPP operation fails and the net power extracted from the whole PV array is reduced. The optimal PV terminal voltage was calculated using an MPP algorithm dP/dV control [21]. Few typical modelling results for this scenario are described in Section V.

In order to extract the maximum power from the PV arrays during partial shading, the conventional MPPT of the central inverter is modified as shown in Fig. 2. Here, an auxiliary converter unit is inserted in parallel to the dc-link. This system operates in two different modes based on the solar radiation levels on the two arrays. The ratio $(p_{PV_1} - p_{PV_2}) / P_{max}$ of the measured powers of PV arrays PV_1 and PV_2 is used to switch between conventional and proposed MPPT modes. When the ratio $(p_{PV_1} - p_{PV_2}) / P_{max}$ is $< 20\%$, it operates in conventional MPPT mode. On the other hand, when $(p_{PV_1} - p_{PV_2}) / P_{max}$ is $\geq 20\%$, it operates on the proposed MPPT mode.

The grid-connected inverter control used in Figs. 1 and 2 are voltage oriented control (VOC) implemented in the rotational dq reference frame.

As it is observed, it is based on the use of three proportional-integral (PI) regulators to control the dc voltage and the dq components of the current. This control scheme is well known and there are multiple publications dealing with it. In order to tune the PI regulators, the guidelines given in the Appendix of [22] can be followed.

Fig. 1. Large scale grid-connected PV energy conversion system: Conventional MPPT for central NPC inverter topology (two arrays in series forming the dc-link).

Fig. 2. Large scale grid-connected PV energy conversion system: Proposed MPPT for central NPC inverter topology.

A. Conventional MPPT Mode

In this case, the two PV arrays PV_1 and PV_2 are connected to the grid only with the three-level NPC inverter as in Fig. 1. During this conventional MPPT mode, the dc voltage reference for the maximum power point is calculated by a MPPT controller based on the total dc voltage of two arrays in series (v_{PV}) and the PV array current (i_{PV}) to the inverter. If the solar radiation level in the two arrays is similar which satisfies:

$$\left| \frac{p_{PV_1} - p_{PV_2}}{P_{max}} \right| < 20\% \quad (1)$$

then the MPPT tracks the total power of the two arrays as if it was only one. The calculated total dc-link voltage reference $v_{PV-Conv}^*$ is provided to the NPC inverter control in Fig. 1.

B. Proposed MPPT Mode

In this case, the auxiliary converter is added in parallel to the dc-link and its output is connected to the midpoint of the two PV arrays PV_1 and PV_2 . In this mode, there are two independent MPPT controllers for both PV arrays PV_1 and PV_2 . The sum of the two voltage references calculated by the MPPT controllers ($v_{PV_1}^* + v_{PV_2}^* = v_{PV-Prop}^*$) becomes the

and improves the efficiency of the whole system.

IV. ELIMINATION OF LOW FREQUENCY RIPPLES IN DC-LINK

A drawback of the NPC converter is that a low frequency voltage oscillation appears in the NP under certain operating conditions. Therefore, the dc-link capacitors and the power devices have to be oversized to withstand higher voltages caused by the oscillation. This is totally eliminated using the method proposed in [23]. However, this method requires an extra control loop for voltage balancing. A voltage balance compensator for the NPC converter is proposed in [24]. Nevertheless, in the proposed implementation, the inverter does not need to take care of regulating capacitor voltages, since the auxiliary leg will perform this task.

In order to eliminate low-frequency capacitor voltage ripples, the locally averaged value of NP current must be zero. This is achieved by generating two reference signals per phase, which are obtained as follows [23]:

$$v_{ip} = \frac{v_i - \min(v_a, v_b, v_c)}{2} \quad (3)$$

$$v_{in} = \frac{v_i - \max(v_a, v_b, v_c)}{2} \quad (4)$$

for $i \in \{a, b, c\}$, where v_i is the normalized reference signal for phase i , and v_{ip} and v_{in} are the new reference signals for that phase ranging in the intervals $v_{ip}=[0,1]$ and $v_{in}=[0,-1]$ under linear operation mode.

The three phase sinusoidal modulation signals of the inverter are modified according to (3) and (4) so that locally-averaged NP current i_0 is always zero.

This modulation strategy does not introduce low frequency distortion in the output voltages even when the two dc-link capacitor voltages are unbalanced. This is demonstrated in this paper for the first time, as follows.

The locally-averaged voltage generated at phase i of the NPC converter is:

$$\overline{v_{i0}} = v_{in}v_{C1} + v_{ip}v_{C2} \quad (5)$$

Substituting (3) and (4) in (5):

$$\overline{v_{i0}} = \frac{1}{2} \left[(v_i v_{dc} - \max(v_a, v_b, v_c) v_{C1} - \min(v_a, v_b, v_c) v_{C2}) \right] \quad (6)$$

where $v_{dc} = v_{C1} + v_{C2}$.

Considering the line-to-line voltage $\overline{v_{ij}} = \overline{v_{i0}} - \overline{v_{j0}}$ for $i, j \in \{a, b, c\}$, and $i \neq j$:

$$\overline{v_{ij}} = v_{ij} \frac{v_{dc}}{2} \quad (7)$$

where $v_{ij} = v_i - v_j$ is the normalized reference for the corresponding line-to-line voltage. As it can be observed in (7), the locally-averaged line-to-line voltage does not depend on each capacitor voltage, but on the sum of the two capacitor voltages, i.e. the total dc-link voltage v_{dc} . Therefore, no low-frequency distortion will be produced in the line-to-line voltages due to capacitor voltage imbalances when using this modulation technique. This is important in this application because the dc-link capacitors will be unbalanced during partial shading of the PV arrays.

Fig. 6. Simulation results for comparison of generated grid power in conventional and proposed MPPTs, from top to bottom: Irradiance of PV Array PV_1 , irradiance of PV Array PV_2 , generated grid power for 14th May, 2016.

TABLE I
GAIN IN THE POWER GENERATION DUE TO THE PROPOSED MPPT-SIMULATION

Day	Conventional MPPT	Proposed MPPT	Gain
4 May 2016	12.95 kWhr	14.32 kWhr	10.57 %
14 May 2016	10.35 kWhr	12.76 kWhr	23.28 %
18 May 2016	12.45 kWhr	13.71 kWhr	10.15 %
31 May 2016	11.28 kWhr	13.06 kWhr	15.78 %
1 June 2016	4.48 kWhr	8.84 kWhr	97.29%
9 June 2016	9.69 kWhr	12.63 kWhr	30.3%

V. SIMULATION RESULTS

The grid-connected NPC inverter was simulated to study the effects of partial shading on PV array, both conventional and the proposed MPPT controllers are tested. The solar irradiance data on different days were used where the depth of partial shading were different. The gain in the power generation due to the proposed MPPT was compared for different days in a season for a solar power plant with the specifications listed in Table II. The solar radiation data was taken from a solar power plant in operation in Brisbane, Australia.

The power delivered to the grid was found when the two PV arrays, PV_1 and PV_2 , PV_1 without shading and PV_2 with partial shading, for the solar irradiance data of 14th May, 2016 and the results are shown in Fig. 6. The simulation was repeated with different solar radiation data of 1st June, 2016 and the results are shown in Fig. 7.

The modelling was repeated for six different days of the season and the cumulative gains in power generation in the day due to the proposed MPPT technique are listed in Table I.

Fig. 7. Simulation results for comparison of generated grid power in conventional and proposed MPPTs, from top to bottom: Irradiance of PV Array PV_1 , irradiance of PV Array PV_2 , generated grid power for 1st June, 2016.

VI. EXPERIMENTAL RESULTS

The standard MPPT controller of a central NPC inverter, where two equal PV arrays connected in series and the proposed MPPT controller with an auxiliary power converter connected in parallel to the dc-link, were investigated in detail with a three-phase grid-connected NPC inverter set up in the laboratory. Two 1000 V/10 A Regatron PV simulators (TC16.1000.20 Q1-LIN) were used as two PV arrays PV_1 , PV_2 shown in Figs. 1 and 2. The specifications of the experimental setup are listed in Table II. The grid-connected inverter and the auxiliary converter in Fig. 2 were controlled with a dSPACE 1006 system with two DS5203 FPGA boards. A photograph of the experimental setup is shown in Fig. 8. Experiments were conducted at around 2.0 kW power level.

The main parts of the prototype are:

- 1) Personal computer
- 2) Oscilloscope
- 3) Yokogawa WT1800 power meter
- 4) Sensor panel
- 5) DYN11 isolation transformer
- 6) Yokogawa current sensor
- 7) Yokogawa voltage sensors
- 8) dSPACE DS1106 system
- 9) NPC inverter
- 10) Regatron photovoltaic simulator
- 11) Regatron photovoltaic simulator
- 12) Inductor
- 13) Grid filter inductors

The three-level NPC inverter was controlled to connect to the 400-V ac grid through a step-up isolation transformer. The two Regatron PV simulators were used to function the two PV arrays PV_1 , PV_2 whose solar irradiance can be programmed to change from 1000 W/m² to 100 W/m².

Fig. 8. Experimental setup of the proposed MPPT for three-phase grid-connected NPC inverter.

A. Partial Shading on PV_2 with Conventional MPPT

To investigate the effect of partial shading of one PV array, the PV array was split into two equal arrays PV_1 and PV_2 connected in series. At first, both Regatron PV simulators were programmed to produce 1 kW output power each at irradiance of 1000 W/m². The steady state MPP curve was recorded from the Regatron simulator. The MPPT curve of PV_1 is shown in Fig. 9. Similarly, the MPPT curve of PV_2 is shown in Fig. 10. Both PV sources produced 1 kW output at their MPP with a PV voltage $v_{MPP} = 125$ V. Then, the solar irradiance of PV_2 was changed to 100 W/m² over one second time period. The array voltages v_{PV_1} and v_{PV_2} were measured with differential voltage probes. The array currents i_{PV_1} and i_{PV_2} were measured with differential current probes. The array powers were computed using the math function in the oscilloscope. The steady state MPP curve was recorded

TABLE II
SPECIFICATIONS OF THE NPC THREE-PHASE PV-INVERTER IN THE
EXPERIMENTAL SETUP

Parameter	Value
Maximum power of the PV array at V_{mp} , P_{max}	1.0 kW
Open circuit voltage of the PV array, V_{oc}	173.5 V
Voltage at maximum power, P_{max}	125.0 V
Rated power of Regatron ACS grid simulator	50 kVA
Line-to-line voltage of Regatron ACS grid simulator, E_{LL}	400 V
Grid-side line-line voltage, DYN11 isolation transformer	400 V
Inverter-side line-line voltage, DYN11 isolation transformer	200 V
Dc-link capacitance, $C_1 = C_2 = C$	4950 μ F
External line inductor, $3 \times L_g$	10 mH
Auxiliary converter inductor, L	20 mH
Inverter switching frequency, f_s	10 kHz
Auxiliary converter switching frequency, f_c	10 kHz
MPPT controller frequency	100 Hz

Fig. 9. Experimental results: Power of PV Array PV_1 with full solar irradiation on PV arrays PV_1 and PV_2 with conventional MPPT.

from the Regatron simulator. The power of PV_1 dropped to 190 W at 168 V. The MPPT curve of PV_1 is shown in Fig. 11, and the power of PV_2 dropped to 90 W at 105 V, as indicated by the MPPT curve in Fig. 12. The total output power from the two PV arrays dropped to 280 W. The variations in the array voltages, currents and powers were recorded in the oscilloscope and are shown in Fig. 13. The harmonic spectrum of grid voltage and current were measured with the power analyzer WT1800. The total harmonic distortion (THD) of the grid voltage U_{thd} is 1.552 % and that of the grid current I_{thd} is 3.828 %, as shown in Fig. 14. The THD values are calculated by averaging the individual THD values of the three phases.

B. Partial Shading on PV_2 with Proposed MPPT

In this test, the auxiliary converter was added, as shown in Fig. 2. As before, both Regatron PV simulators were programmed to produce 1 kW output power at irradiance of

Fig. 10. Experimental results: Power of PV Array PV_2 with full solar irradiation on PV arrays PV_1 and PV_2 with conventional MPPT.

Fig. 11. Experimental results: Power of PV Array PV_1 with partial shading on PV Array PV_2 with conventional MPPT.

1000 W/m². The steady state grid currents are recorded and they are shown in Fig. 15. The THD of the grid voltage U_{thd} is 1.13 % and that of the grid current I_{thd} is 2.49 %, as shown in Fig. 16. The THD values are calculated by averaging the individual THD values of the three phases. Then the same test as in Section VI-A was repeated. In this case, the power of PV_2 was found to drop to 92 W at 123 V as indicated from the MPP curve in Fig. 17, recorded from the first Regatron simulator. However, the power of PV_1 was maintained at 1000 W as shown in the MPP curve in Fig. 18 recorded from the Regatron simulator. The total power output from the two PV arrays dropped to 1092 W. The variations in the array voltages, currents and powers were recorded in the oscilloscope and is shown in Fig. 19. Here the current in the inductor L of the

Fig. 12. Experimental results: Power of PV Array PV_2 with partial shading on PV Array PV_2 with conventional MPPT.

Fig. 13. Experimental results for partial shading on PV Array PV_2 with conventional MPPT, from top to bottom: PV array voltages v_{PV_2} and v_{PV_1} (100V/div), v_{PV} (250V/div), PV array currents i_{PV_2} and i_{PV_1} , (10A/div), PV array powers p_{PV_2} and p_{PV_1} (1000W/div).

auxiliary power converter, rises to 7.25 A as shown in Fig. 19. The difference between the two PV array currents $i_{PV_2} - i_{PV_1}$ because of the partial shading flows through the inductor (L) as i_L . The voltages v_{PV_1} and v_{PV_2} are not balanced now, still there is no low frequency distortion in the grid currents because of the modified PWM strategy described in Section IV.

The steady state grid currents are recorded and shown in

	Element1	Element2	Element3	Element4	Element5	$\Sigma A(3P4W)$
Voltage	1000V	1000V	1000V	1000V	1000V	
Current	50A	50A	50A	50A	50A	
Urms [V]	0.1319k	0.1311k	0.1238k	0.1239k	0.1241k	0.1239k
Irms [A]	7.452	7.598	6.597	6.483	6.552	6.544
P [W]	0.980k	0.993k	0.620k	0.610k	0.610k	1.840k
S [VA]	0.982k	0.995k	0.817k	0.803k	0.813k	2.433k
Uthd [%]	86.349	84.396	1.559	1.535	1.562	
Ithd [%]	86.110	83.858	3.814	3.676	3.994	

Fig. 14. Experimental results with Conventional MPPT: THD values of grid currents and voltages without partial shading.

Fig. 15. Experimental results with proposed MPPT: Grid currents i_a , i_b , i_c (5A/div) without partial shading.

	Element 2	Element 3	Element 4	Element 5	$\Sigma A(3P4W)$
Voltage	1000V	1000V	1000V	1000V	
Current	50A	50A	50A	50A	
Urms [V]	0.1355k	0.1233k	0.1231k	0.1237k	0.1233k
Irms [A]	7.177	6.057	6.022	6.037	6.039
P [W]	0.967k	0.586k	0.584k	0.586k	1.756k
S [VA]	0.968k	0.747k	0.741k	0.747k	2.235k
Uthd [%]	90.705	1.118	1.199	1.081	
Ithd [%]	89.237	2.432	2.386	2.679	

Fig. 16. Experimental results with proposed MPPT: THD values of grid currents and voltages without partial shading.

TABLE III
COMPARISON OF THD VALUES

Grid variables	Conventional MPPT	Proposed MPPT
voltage e_a	1.559 %	1.118 %
voltage e_b	1.535 %	1.199 %
voltage e_c	1.562 %	1.081 %
current i_a	3.814 %	2.432 %
current i_b	3.676 %	2.386 %
current i_c	3.994 %	2.679 %

Fig. 20. It was found that the THD of the grid voltage U_{thd} is 1.13 % and that of the grid current I_{thd} is 3.25 %, as shown in Fig. 21. A comparison of THD values of grid voltages and currents with the conventional and the proposed MPPTs is shown in Table III.

Fig. 17. Experimental results: Power of PV Array PV_2 with partial shading on PV Array PV_2 with proposed MPPT.

Fig. 18. Experimental results: Power of PV Array PV_1 with partial shading on PV array PV_2 with proposed MPPT.

C. Partial Shading on PV_1 with Conventional MPPT

The test carried in Section VI-A was repeated here for the solar irradiance change from 1000 W/m^2 to 100 W/m^2 in PV_2 to confirm the full operation of the auxiliary converter. The power of PV_1 dropped to 90 W. And the power of PV_2 dropped to 190 W. The total power output from the two PV arrays dropped to 280 W. The variations in the array voltages, currents and powers were recorded in the oscilloscope and is shown in Fig. 22.

D. Partial Shading on PV_1 with Proposed MPPT

The test performed in Section VI-B with the auxiliary converter was repeated here for solar irradiance of PV_2 changing

Fig. 19. Experimental results for partial shading on PV Array PV_2 with proposed MPPT, from top to bottom: PV array voltages v_{PV_2} and v_{PV_1} (100V/div), v_{PV} (250V/div), PV array currents i_{PV_2} and i_{PV_1} (10A/div), current i_L (10A/div), PV array powers p_{PV_2} and p_{PV_1} (1000W/div).

Fig. 20. Experimental results with proposed MPPT: Grid currents i_a , i_b , i_c (5A/div) with partial shading on PV Array PV_2 .

	Element 2	Element 3	Element 4	Element 5	$\Sigma A(3P4W)$
Voltage	1000V	1000V	1000V	1000V	
Current	50A	50A	50A	50A	
Urms [V]	0.1458k	0.1227k	0.1222k	0.1230k	0.1226k
Irms [A]	6.040	3.382	3.378	3.370	3.377
P [W]	0.876k	0.281k	0.282k	0.283k	0.846k
S [VA]	0.877k	0.415k	0.413k	0.414k	1.242k
Uthd [%]	94.561	1.142	1.188	1.062	
Ithd [%]	94.289	3.199	3.217	3.341	

Fig. 21. Experimental results with proposed MPPT: THD values of grid currents and voltages with partial shading on PV Array PV_2 .

Fig. 22. Experimental results for partial shading on PV Array PV_1 with conventional MPPT, from top to bottom: PV array voltages v_{PV_2} and v_{PV_1} (100V/div), v_{PV} (250V/div), PV array currents i_{PV_2} and i_{PV_1} (10A/div), PV array powers p_{PV_2} and p_{PV_1} (1000W/div).

from 1000 W/m^2 to 100 W/m^2 . The power of PV_1 dropped to 92 W, and the power of PV_2 remained at 1000 W. The total power output from the two PV arrays dropped to 1092 W. The variations in the array voltages, currents and powers were recorded in the oscilloscope and are shown in Fig. 23. It can be noted that the voltages v_{PV_1} and v_{PV_2} are not balanced during the shading, nevertheless because of the modulation strategy employed, the grid currents could be controlled without low frequency distortion.

VII. COMPARISON OF MPPTs

It was found in Section VI.A, that when the conventional MPPT controller is in operation, a partial shading of PV array PV_2 from 1000 W/m^2 to 100 W/m^2 , the combined output of two PV arrays ($p_{PV_1} + p_{PV_2}$) dropped to 280 W. Whereas, after changing to the proportional MPPT controller as discussed in Section VI.B, the total power output of the two PV arrays PV_1 and PV_2 increased to 1092 W. This is a 290% gain as indicated in Table IV.

Similarly, it was mentioned in Section VI.C, that when the conventional MPPT controller operates, a partial shading on PV_1 from 1000 W/m^2 to 100 W/m^2 , the total PV array output dropped to 280 W. After replacing the conventional MPPT controller with a proportional MPPT controller, the total power ($p_{PV_1} + p_{PV_2}$) increased to 1092 W as discussed in Section VI.D. This is also 290% gain as shown in Table IV. As explained in Section II.A, the conventional MPPT controller uses only two sensors, one for voltage and another one for current. However, the proposed MPPT controller described in Section II.B, needs four sensors for two voltages and two

Fig. 23. Experimental results for partial shading on PV Array PV_1 with proposed MPPT, from top to bottom: PV array voltages v_{PV_2} and v_{PV_1} (100V/div), v_{PV} (250V/div), PV array currents i_{PV_2} and i_{PV_1} (10A/div), current i_L (10A/div), PV array powers p_{PV_2} and p_{PV_1} (1000W/div).

TABLE IV
GAIN IN THE POWER GENERATION DUE TO THE PROPOSED MPPT-EXPERIMENT

Mode	Conventional MPPT ($p_{PV_1} + p_{PV_2}$)	Proposed MPPT ($p_{PV_1} + p_{PV_2}$)	Gain
Shading on PV_1	280 W	1092 W	290 %
Shading on PV_2	280 W	1092 W	290 %

currents, therefore the cost is higher. Nevertheless, the benefits of producing more energy justifies by far the extra cost of the auxiliary leg, control and sensors.. A comparative analysis of proposed method with the previously proposed methods is shown in Table V.

VIII. CONCLUSION

The auxiliary power converter proposed in this paper enables the maximum power production from the PV arrays used in central inverters for large scale PV power plants during partial shading in one of the PV arrays. This modular unit adds only a small additional cost to the total system as the power ratings are only a fraction of that of the inverter. As this unit is switched off and goes to standby when there is no partial shading, there are no power losses with this MPPT unit and thus maximum conversion efficiency is achieved.

This configuration together with central inverters combines the best features of central inverters together with the complete

TABLE V
COMPARITIVE ANALYSIS OF MPPTS

	Real MPPT [12]	Distributed MPPT [13]	Conventional MPPT [15]	Proposed MPPT
Reliability	High	Low	High	High
Number of sensors	High	High	Low	High
Cost	Low	Highest	Low	High
Conversion efficiency	High	Low	High	High
Number of converters	Only one power converter	High number of power converters in addition to main one	Only one power converter	Additional converter of lower power rating
Rated power of MPPT	Same as that of the inverter	Same as that of the inverter	Same as that of the inverter	Can be selected depending on the partial shading
MPPT algorithm	Complex	Simple	Complex	Simple
Redundancy	All the power is lost if the dc-dc converter fails	If one or more dc-dc converter fails only part of the available power is lost	All the power is lost if the main converter fails	All the power is lost if the main converter fails and no power loss if the auxiliary converter fails and there is no partial shading. Otherwise a fraction of the available power is lost.

maximum power extraction of the PV arrays, besides being economically feasible. Since the modulation strategy applied to the NPC inverter does not produce any low frequency oscillations in the NP voltage, operation of the MPPT units is not affected by such oscillations. This proposed converter can also replace a standard series MPPT module in multi-string inverters to reduce system cost and improve efficiency. Because of modularity of the proposed auxiliary converter unit, it can also be added to the NPC inverters of any existing solar PV power plant.

REFERENCES

- [1] International Energy Agency, "Photovoltaic power systems programme report: Snapshot of global photovoltaic markets 2016," Rep. IEA PVPS T1-31:2017.
- [2] S. Kouro, J. I. Leon, D. Vinnikov, and L. G. Franquelo, "Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology," *IEEE Ind. Electron. Mag.*, vol. 9, no. 1, pp. 47-61, Mar. 2015.
- [3] E. Serban, M. Ordonez, and C. Pondiche, "DC-bus voltage range extension in 1500V photovoltaic inverters," *IEEE Jour. Emerg. Sel. Topics in Power Electr.*, vol.3 no.4, pp. 901-917, Dec. 2015.
- [4] Xin Hao, Kwok-wai Ma, Jia Zhao, and Xin-Yu Sun, "Design of NPC1 power stack beyond megawatt for 1500V solar inverter application," in *Proc. 3rd Int. Future Energy Electron. and ECCE Asia 2017*, pp. 1155-1161, Jun. 2017.
- [5] R. Inzunza, R. Okuyama, T. Tanaka, and M. Kinoshita, "Development of a 1500VDC photovoltaic inverter for utility-scale PV power plants," in *Proc. IEEE 2nd Int. Future Energy Electron. Conf.*, pp. 1-4, Nov. 2015.
- [6] S. Kouro, K. Asfaw, R. Goldman, R. Snow, B. Wu, and J. Rodriguez, "NPC multilevel multistring topology for large scale grid connected photovoltaic systems," in *Proc. 2nd IEEE Int. Symp. Power Electr. for Dist. Gen. Systems (PEDG)*, pp. 400-405, Jun. 2010.
- [7] U.M Choi, F. Blaabjerg, and B.K. Lee, "Control strategy of two capacitor voltages for separate MPPTs in photovoltaic systems using Neutral-Point-Clamped inverters," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3295-3303, Jul./Aug. 2015.
- [8] Y. Park, S. K. Sul, C. H. Lin, W. C. Kim, and S. H. Lee, "Asymmetric control of dc-link voltage for separate MPPTs in three-level inverters," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2760-2769, Jun. 2013.
- [9] A. Choudhury, P. Pillay, and S.S. Williamson, "DC-Bus voltage balancing algorithm for three-level Neutral-Point-Clamped (NPC) traction inverter drive with modified virtual space vector," *IEEE Trans. Ind. Appl.*, vol. 52, pp. 3958-3967, Sep./Oct. 2016.
- [10] T. Naik, R.G. Wandhare, and V. Agarwal, "Three-level NPC inverter with novel voltage equalization for PV grid interface suitable for partially shaded conditions," in *Proc. Power and Energy Conf. PECTI 2013*, pp. 186-193, Feb. 2013.
- [11] S. Essakiappan, H.S. Krishnamoorthy, P. Enjeti, R.S. Balog, and S. Ahmed, "A new control strategy for megawatt scale multilevel photovoltaic inverters under partial shading," in *Proc. 2nd Int. Symp. on Power Elect. for Dist. Gen. Systems*, Jun. 2012.
- [12] J. Young-Hyok, J. Doo-Yong, K. Jun-Gu, K. Jae-Hyung, L. Tae-Won, and W. Chung-Yuen, "A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions," *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1001-1009, Apr. 2011.
- [13] J.D Bastidas-Rodriguez, E. Franco, G. Petrone, C.A Ramos-Paja and G. Spagnuolo, "Maximum power point tracking architectures for photovoltaic systems in mismatching conditions: a review," *IET Pow. Electron.*, vol. 7, issue. 6, pp. 1396-1413, Aug. 2014.
- [14] A. Elasser, M. Agamy, J. Sabate, R. Steigerwald, R. Fisher, and M. Harfman-Todorovic, "A comparative study of central and distributed MPPT architectures for megawatt utility and large scale commercial photovoltaic plants," in *Proc. of Ind. Electron. Conf. IECON*, pp. 2753-2758, Nov. 2010.
- [15] N. Foureaux, A. Machado, E. Silva, I. Pires, J. Brito, and F. B. Cardoso, "Central inverter topology issues in large-scale photovoltaic power plants: Shading and system losses," in *Proc. IEEE Photovolt. Spec. Conf.*, pp. 4-9, Jun. 2015.
- [16] C. Rahmann, V. Vittal, J. Ascui, and J. Haas, "Mitigation control against partial shading effects in large-scale PV power plants," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 173-180, Jan. 2016.
- [17] Y. Shi, R. Li, Y. Xue, and H. Li, "High-frequency-link-based grid-tied PV system with small DC-link capacitor and low-frequency ripple-free maximum power point tracking," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 328-339, Jan. 2016.
- [18] E. Serban, F. Paz, and M. Ordonez, "Improved PV inverter operating range using a miniboost," *IEEE Trans. Power Electron.*, vol. 32, no. 11, pp. 8470-8485, Nov. 2017.
- [19] N. Müller; H. Renaudineau; F. Flores-Bahamonde, S. Kouro, and P. Wheeler, "Ultracapacitor storage enabled global MPPT for photovoltaic central inverters," in *Proc. IEEE Int. Symp. on Ind. Electron. (ISIE)*, pp. 1046-1051, Jun. 2017.
- [20] T. Kerekes, R. Teodorescu, M. Liserre, C. Klumpner, and M. Sumner, "Evaluation of three-phase transformerless photovoltaic inverter topolo-

gies," *IEEE Trans. Power Electron.*, vol. 24, no. 9, pp. 2202–2211, Sep. 2009.

- [21] T. Eram, and P.L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. on Energy Conv.*, vol. 22, no. 2, pp. 439–449, June 2007.
- [22] S. Ceballos, J. Rea, I. López, J. Pou, E. Robles, and D. O'Sullivan, "Efficiency optimization in low inertia wells turbine-oscillating water column devices," *IEEE Trans. on Energy Conv.*, vol. 8, no. 3, pp. 553–564, Sep. 2013.
- [23] J. Pou, J. Zaragoza, P. Rodriguez, S. Ceballos, V.M. Sala, R.P. Burgos and D. Boroyevich, "Fast-processing modulation strategy for the neutral-point-clamped converter with total elimination of low-frequency voltage oscillations in the neutral point," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2288–2294, Aug. 2007.
- [24] J. Jaragoza, J. Pou, S. Ceballos, E. Robles, C. Jaen, and M. Corbalan, "Voltage-balance compensator for a carrier-based modulation in the neutral-point-clamped converter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 305–314, Feb. 2009.

Baburaj Karanayil (M'86-SM'09) was born in Kerala, India. He received the B.Tech. (Hons) degree from the University of Calicut, Kerala, India, the M.Tech. degree from Indian Institute of Technology, Bombay, India, and the Ph.D. degree from the University of New South Wales (UNSW Sydney), Australia, in 1984, 1986, and 2005, respectively, all in electrical engineering.

From 1986 to 1994, he was a Senior Engineer in the power electronics and electrical drives industry in India. From 1995 to 2011, he was a Professional Officer in power electronics and electric drives research in the School of Electrical Engineering and Telecommunications, UNSW Sydney. From February 2012 to June 2016 he was a Research Fellow with the Australian Energy Research Institute, UNSW Sydney. From July 2016 he is a Professional Officer in power electronics and power systems in the School of Electrical Engineering and Telecommunications, UNSW Sydney, Australia.

Salvador Ceballos received the M.S. degree in physics from the University of Cantabria, Santander, Spain, in 2001, and the M.S. and Ph.D. degrees in electronic engineering from the University of the Basque Country, Bilbao, Spain, in 2002 and 2008, respectively. Since 2002 he has been with Tecnalia Research and Innovation, Derio, Spain, where he is currently a Researcher in the Energy and Environment Division. From May 2008 to May 2009 he was a Visiting Researcher at the Hydraulic and Maritime Research Centre, University College Cork (UCC), Cork, Ireland. From November 2014 to May 2015 he was a Visiting Researcher at the Australian Energy Research Institute, UNSW, Sydney, Australia. He has authored more than 120 published technical papers. His research interests include multilevel converters, fault-tolerant power electronic topologies, and renewable energy systems.

Josep Pou (S'97–M'03–SM'13–F'17) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Technical University of Catalonia (UPC), in 1989, 1996, and 2002, respectively.

In 1990, he joined the faculty of UPC as an Assistant Professor, where he became an Associate Professor in 1993. From February 2013 to August 2016, he was a Full Professor with the University of New South Wales (UNSW), Sydney, Australia. He is currently an Associate Professor with the Nanyang Technological University (NTU), Singapore, where

he is Program Director of Power Electronics at the Energy Research Institute at NTU (ERI@N) and co-Director of the Electrical Power Systems Integration Lab at NTU (EPSIL@N). From February 2001 to January 2002, and February 2005 to January 2006, he was a Researcher at the Center for Power Electronics Systems, Virginia Tech, Blacksburg. From January 2012 to January 2013, he was a Visiting Professor at the Australian Energy Research Institute, UNSW, Sydney. He has authored more than 270 published technical papers and has been involved in several industrial projects and educational programs in the fields of power electronics and systems. His research interests include modulation and control of power converters, multilevel converters, renewable energy, energy storage, power quality, HVDC transmission systems, and more-electrical aircraft and vessels.

He is Associate Editor of IEEE Transactions on Industrial Electronics and IEEE Journal of Emerging and Selected Topics in Power Electronics.