Design and Application of a Photovoltaic Array Simulator with Partial Shading Capability

Ersoy Beser[†]

[†]Department of Electrical Engineering, Kocaeli University, Kocaeli, Turkey

Abstract

PV system performance is dependent on different irradiations and temperature values in addition to the capability of the employed PV inverter / maximum power point tracker (MPPT) circuit or algorithm. Therefore, it would be appropriate to use a PV simulator capable of producing identical repeatable conditions regardless of the weather to evaluate the performance of inverter / MPPT circuits and algorithms. In accordance with this purpose, a photovoltaic (PV) array simulator is presented in this paper. The simulator is designed to generate current-voltage (I-V) and power-voltage (P-V) curves of a PV panel. Series connected cascaded modules constitute the basic part of the simulator. This feature also allows for the modeling of PV arrays since the number of modules can be increased and high voltage values can be reached with the simulator. In addition, the curves obtained at the simulator output become similar to the actual curves of sample PV panels with an increase in the number of modules. In order to show the validity of the proposed simulator, it was simulated for various situations such as panels under full irradiance and partial shading conditions. After completing simulations, experiments were realized to support the simulation study. Both simulation and experimental results show that the proposed simulator will be very useful for researchers to carry out PV studies under laboratory conditions.

Key words: I-V curve, Irradiation, PhotoVoltaic (PV) energy, P-V curve, Partial shading, PV array, PV inverters, PV simulator

I. INTRODUCTION

Energy demand has been increasing in the world as a result of the increase in human population and the growth of countries' economies [1]-[3]. Most of this increased energy demand is provided by fossil fuels. However, due to the decrease in fossil fuels, rising oil prices, increasing damage of fossil fuels to the environment and global warming, people have turned to renewable energy sources to meet their ever-increasing energy needs [1]-[5].

Among renewable energy sources such as wind, tidal and geothermal energy, photovoltaic (PV) energy is the most promising [3], [5]. PV energy stands out due to its advantages of direct electricity generation, state support in some countries, easy and low-cost maintenance, being noiseless and pollution-free [1], [2], [5]-[7]. However, it has some disadvantages such as high setup cost, low energy conversion efficiency and discontinuous sunlight [1], [2], [4]. Many PV systems have been developed due to the fact that they are the most direct method for converting solar energy into electrical energy, the long-term benefits of solar energy, and the provision of government programs to promote the use of renewable energy sources [1], [4].

One of the difficulties in feeding a load or connecting to the grid with PV systems is that the PV modules act as a current source at a high output current and as a voltage source at a low output current [7]. Due to this feature, it is necessary to connect a circuit capable of tracking the maximum power point (MPP) between the PV and the load or the grid to maximize the efficiency of the modules when feeding a load or connecting to the grid [7]. The performance of a PV system is dependent on irradiation and temperature. However, it also depends on the talent of the MPPT circuit or algorithm [8]. For this reason, a wide range of maximum power point tracking (MPPT) techniques have been developed in the literature.

In order for researchers to measure the success of the MPPT techniques they have developed, the tests applied to a MPPT technique must always be performed under the same

repeatable conditions. However, when a real PV module is used, since the I-V and P-V curves of the PV module vary due to irradiation and temperature, the developed MPPT is not always subjected to the test under the same conditions. It may also be difficult to repeat the same test with actual panels when multiple PV panels are connected in series / parallel. In addition, there are partial shading states where each panel is exposed to different irradiation. In this case, it would be better to use a PV simulator instead of a real panel or panels. By using a simulator, researchers are able to experimentally test MPPT circuits or algorithms under different temperature and irradiation conditions in the laboratory. They can even simulate partial shading conditions, regardless of weather conditions. In addition, PV simulators can be used to examine the grid connection problems of PV inverters in the laboratory [9].

In PV simulators, there are generally power and control parts to obtain I-V and P-V curves of PV panels. The control part is usually designed by microcontrollers. Meanwhile, low-power transistors [10], [11] or dc/dc converters are used in the power part of a PV simulator. Using low-power transistors is a simple method and a fast dynamic response can be obtained. However, this method is not suitable for high power applications. Since there is no power limitation, dc/dc converters are generally preferred in high power applications in spite of their slow dynamic response [12]. There is one switching element in dc/dc converters. As a result, the operating voltage of the switch determines the voltage of the simulator. This is a drawback for this type of converter.

Various power converter constructions have been proposed to design PV simulators in the literature. These types can be listed as LLC resonant dc/dc converters [13]-[15]; dc/dc buck step down converters [12], [16]-[21]; ZVS full bridge type converters [22]; two-stage synchronous dc/dc converters [23]; two stage converters including a PWM voltage source rectifier and a bidirectional converter [24]; dc/dc buck-boost converters [25]; three phase interleaved buck converters [9], [26]; two quadrant dc/dc power converters [27] and single phase front end converters with a buck-chopper-based dc/dc converter [28].

A new PV array simulator is proposed in this paper. The proposed simulator includes series connected cascaded modules in the power converter. This can be mentioned as the significant originality of the proposed simulator when compared to existing studies. In literature, there are no similar structures created by cascaded series-connected modules. Most of the existing studies are single switch PV simulator applications designed with dc/dc converter structures. These constructions are not suitable for high voltage applications. This is due to the fact that the voltage stress (dv/dt) on the switch is high. In addition, their operating voltage is limited by the voltage of the switch.

In the proposed simulator, when the number of modules is increased, the voltage steps increase exponentially. Therefore, better quality I-V and P-V curves are obtained. Since the number of modules can be increased, the simulator is allowed to be used in high voltage PV applications. The ability of operating with high voltage PV applications enables the modeling of high voltage PV arrays with this simulator. This feature contributes to existing studies in the literature. In order to demonstrate the performance of the PV simulator, simulations and experimental studies were carried out under full irradiance and partial shading conditions. When the results of the simulation and experimental studies are evaluated, it is seen that the proposed PV simulator has a good performance.

II. DESIGN OF THE PROPOSED PV SIMULATOR

The construction of the proposed PV simulator comprises of a control circuit, an adjustable load and cascade connected modules. The modules basically consist of a MOSFET, a diode and a dc voltage source [29]. The main task of the modules is generating a multi-level voltage form at the simulator output. Two advantages can be mentioned since the system has modules.

First, by increasing the number of modules, the number of output voltage levels is increased and higher quality I-V characteristics are obtained. Latter, an increase in the number of modules allows high voltage levels to be reached. As a result, series-connected PV systems or PV arrays can be simulated. The construction of the proposed PV simulator, including 3 modules, is illustrated in Fig. 1.

A set of equations can be used to explain the properties of the proposed system. Owing to the modules in the system, the output voltage is produced in a stepped shaped. There is a relationship between the number of modules (m) and the number of levels (s). This relationship can be defined by Equation (1).

$$s = 2^m \tag{1}$$

According to Equation (1), it can be said that the maximum output level of s can be obtained by m module. In Fig. 1, the proposed structure has 3 modules. Therefore, an 8-level output voltage can be generated at the load.

In order to determine the dc source voltages and to generate switching signals, first, the maximum value of the output voltage and the number of desired levels in the output voltage need to be determined. Equation (2) defines voltage V_d in the first module.

$$V_d = \frac{V_{max}}{s-1} \tag{2}$$

The dc voltages in the other modules are set to the value $2^{(j-1)}V_d$ as shown in Fig. 1. j is expressed by Equation (3).
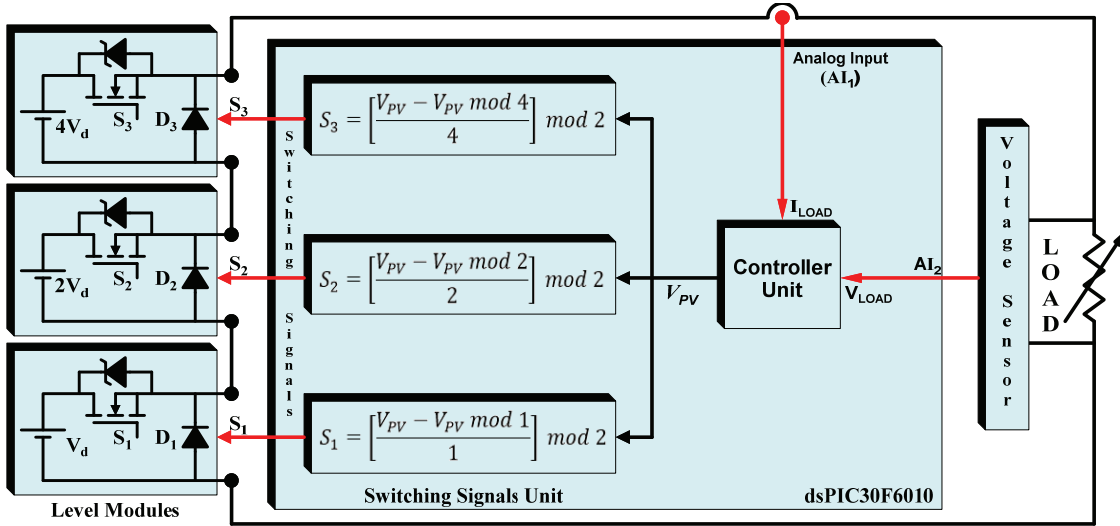
$$j = 1,2,3, \ldots, m \tag{3}$$

Fig. 1. Construction of the proposed PV simulator including 3 modules.
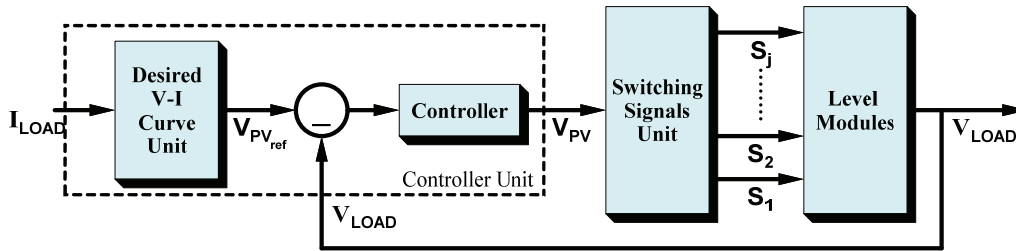

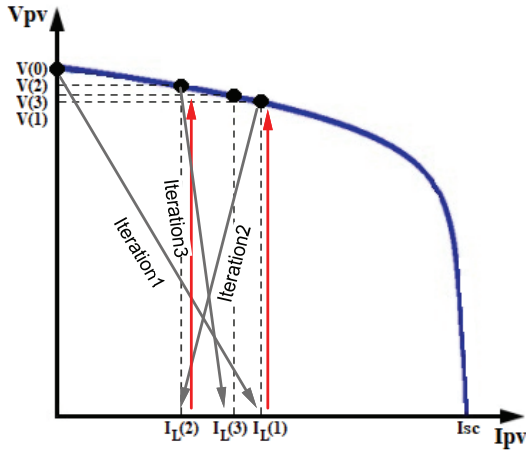Fig. 2. Control block diagram.

Fig. 3. Desired V-I curve of a PV panel.

Through the determined module number and the dc source voltages, the converter part of the proposed system is configured as seen in Fig. 1.

The next most important point is the generation of switching signals. In order to achieve this, first, the V_{PV} value must be obtained as can be seen from the control block diagram in Fig. 2. This value is produced in the control unit in the control block diagram.

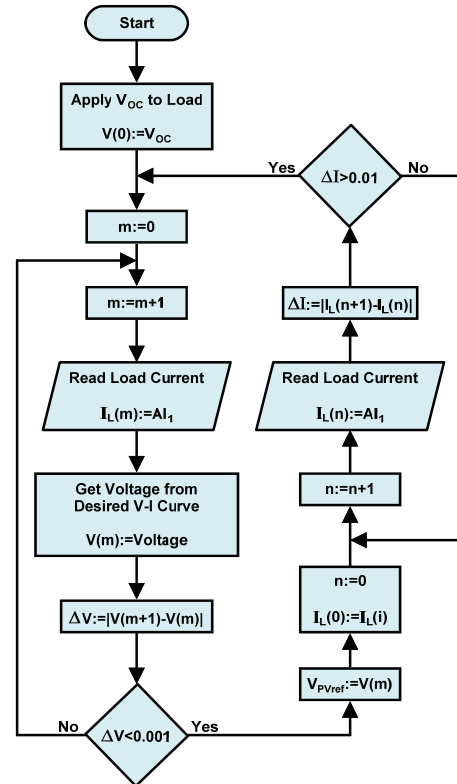The control unit consist of a PI controller, a comparator and
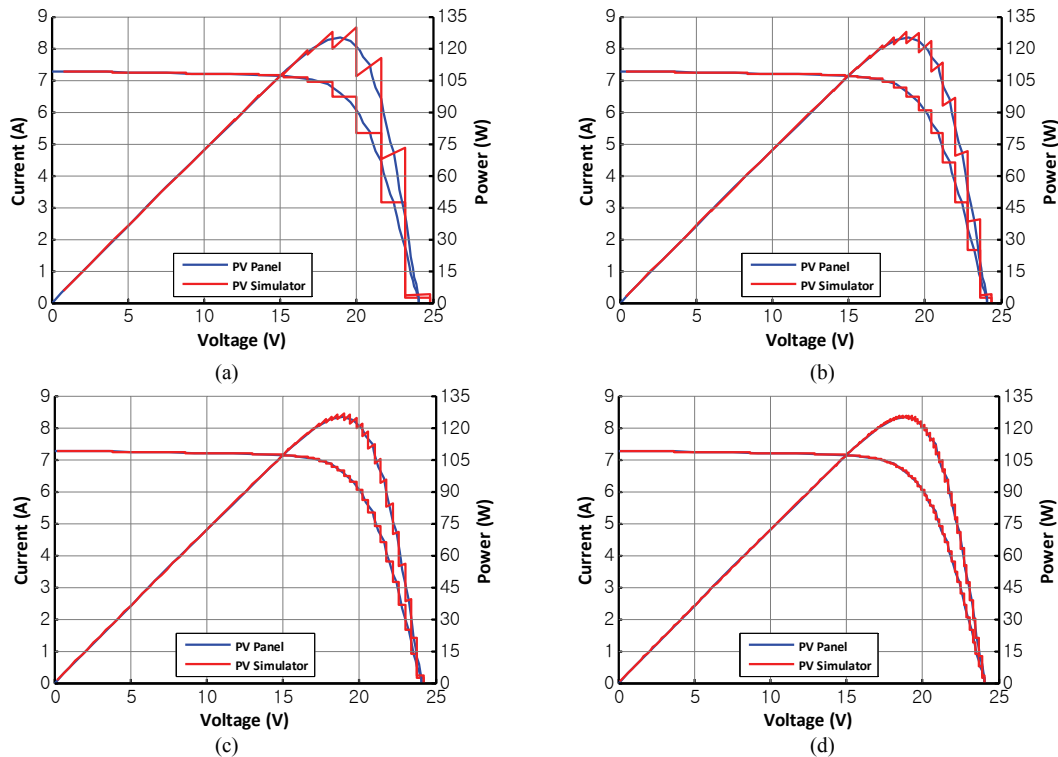

Fig. 4. Flowchart of a desired V-I curve unit.

Fig. 5. Simulated I-V and P-V curves for different module number at a 1000 W/m² solar irradiance value. (a) 4 modules. (b) 5 modules. (c) 6 modules. (d) 7 modules.

the desired V-I curve unit. The desired V-I curve unit includes a V-I curve belonging to an actual PV panel. In this unit, the V-I curve of the panel to be modeled by the simulator should be used. In order to produce V_{PV}, the V_{PVref} value must be found first. The flowchart in Fig. 4 shows how to obtain the V_{PVref} value. The flowchart consists of two parts. The left side is used to find the V_{PVref} value, and the right side is used to check if there is a change in the load. The flowchart actually operates using the desired V-I curve of the PV panel in Fig. 3.

It can be seen from the flowchart that the V_{oc} voltage in the V-I curve in Fig. 3 is first applied to the system. The load current (I_{LOAD}) is measured corresponding to the applied voltage. Then, the voltage value is determined corresponding to a measured current value from the desired V-I curve. ΔV is obtained by finding the absolute value of the difference between the found voltage and the previous applied voltage values. Iterations are realized until ΔV is approximately zero. The voltage value determined at the end of the iteration is the V_{PVref} value at that load. The V_{PVref} value does not change and get updated unless the load changes. If there is a change in the load, it is re-entered to the left side of the flow diagram to find a new V_{PVref} value.

After finding the V_{PVref} value, the load voltage (V_{LOAD}) is also read and sent to the controller with V_{PVref}. The V_{PV} value is obtained at the controller output. Here, the controller keeps the output voltage constant at the desired reference value. The controller performs a closed-loop control to prevent the output

voltage from being affected by fluctuations of the input dc source voltages or the voltage drop across the switching devices.

The V_{PV} value is sent to the switching signals unit and the switching signals (S_1, S_2, …, S_j) are produced using Equation (4).

$$S_j = \left[\frac{V_{PV} - V_{PV} \bmod 2^{j-1}}{2^{j-1}} \right] \bmod 2 \qquad (4)$$

Switching signals are applied to the MOSFETS in the modules, and the output voltage shape is produced corresponding to the current value in this way.

The proposed simulator can be considered as a current controlled voltage source. In actual PV panels, output voltage depends on the flowing current. The same situation applies to the proposed simulator. The only difference is that the output voltage changes in the multi-level form.

III. SIMULATIONS, RESULTS AND DISCUSSION

A simulation study was performed to observe the success of the proposed system as a PV simulator. A Schüco S 125-SP photovoltaic panel was used for the I-V data. I-V and P-V curves of the sample panel were obtained for different numbers of modules and different voltage levels. In addition, the cases of more than one panel and partial shading conditions were examined. In order to carry out the simulations, the desired I-V data was formed in the simulation program. Later, the maximum value and level number of the output voltage
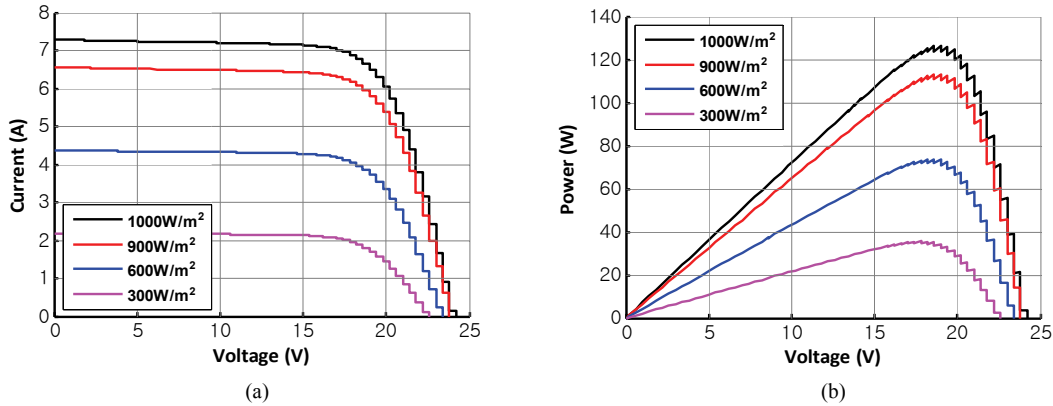
Fig. 6. Simulated results. (a) I-V curves. (b) P-V curves for 6 modules at different solar irradiances.
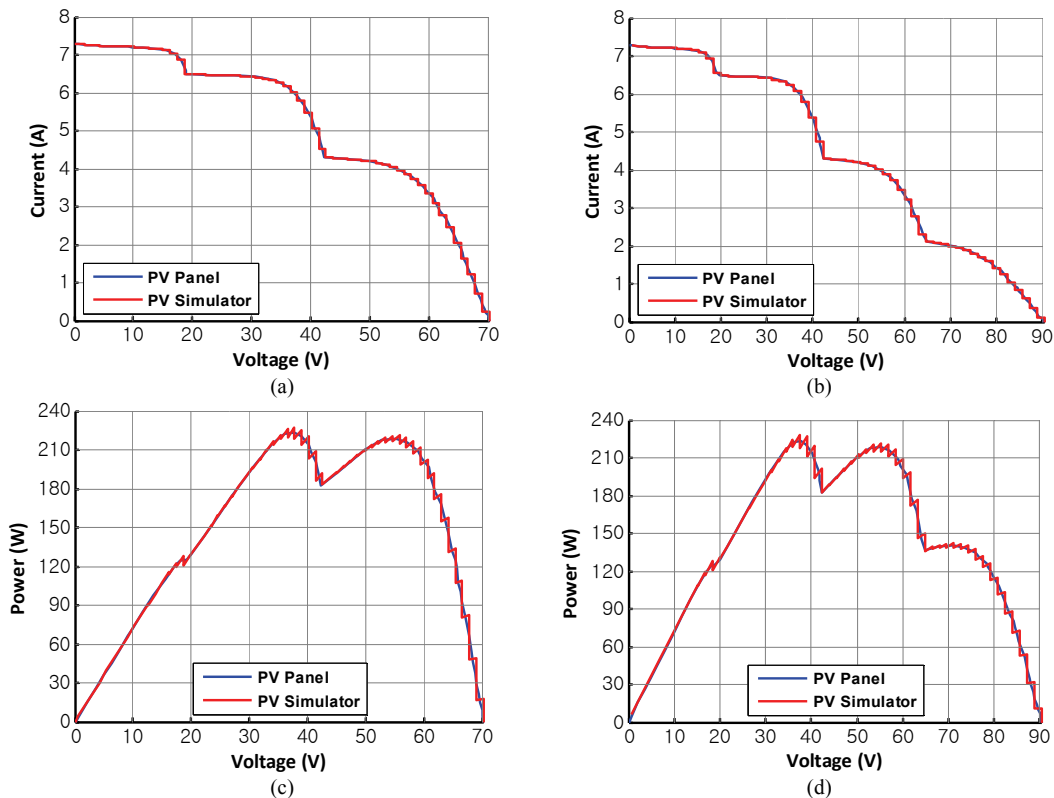

Fig. 7. Simulated results. (a) I-V curves of Case 1. (b) I-V curves of Case 2. (c) P-V curves of Case 1. (d) P-V curves of Case 2 for 6 modules under partial shading conditions.

was determined.

According to the determined values, V_d was calculated and the dc source voltage values were arranged in the converter circuit. Then switching signals were produced and characteristic curves were obtained.

The proposed simulator was considered to have 4, 5, 6 and 7 modules and corresponding I-V and P-V curves were obtained. Simulation results are illustrated in Fig. 5 for a 1000 W/m² solar irradiance value.

In order to compare these simulation results with the curves of an actual PV panel and to show the success of the proposed simulator, actual and simulated curves were presented in the same graph. It can be seen from Fig. 5 that when the number

of modules increases, the curves obtained at the simulator output converge to the actual PV panel curves. In other words, when the number of modules increases, the voltage difference between the steps decreases. Therefore, the resulting I-V and P-V curves are closer to the actual data. This is especially true near the maximum power point (MPP) in case of using more module number. In cases where the number of modules is low, an LC filter can be placed at the simulator output and the curves can approach the actual curves.

In the case of using 4, 5, 6 and 7 modules in the converter circuit, 16, 32, 64 and 128-level output voltages were generated at the simulator output, respectively. I-V and P-V curves were also obtained for 6 modules at solar irradiance values of 1000,
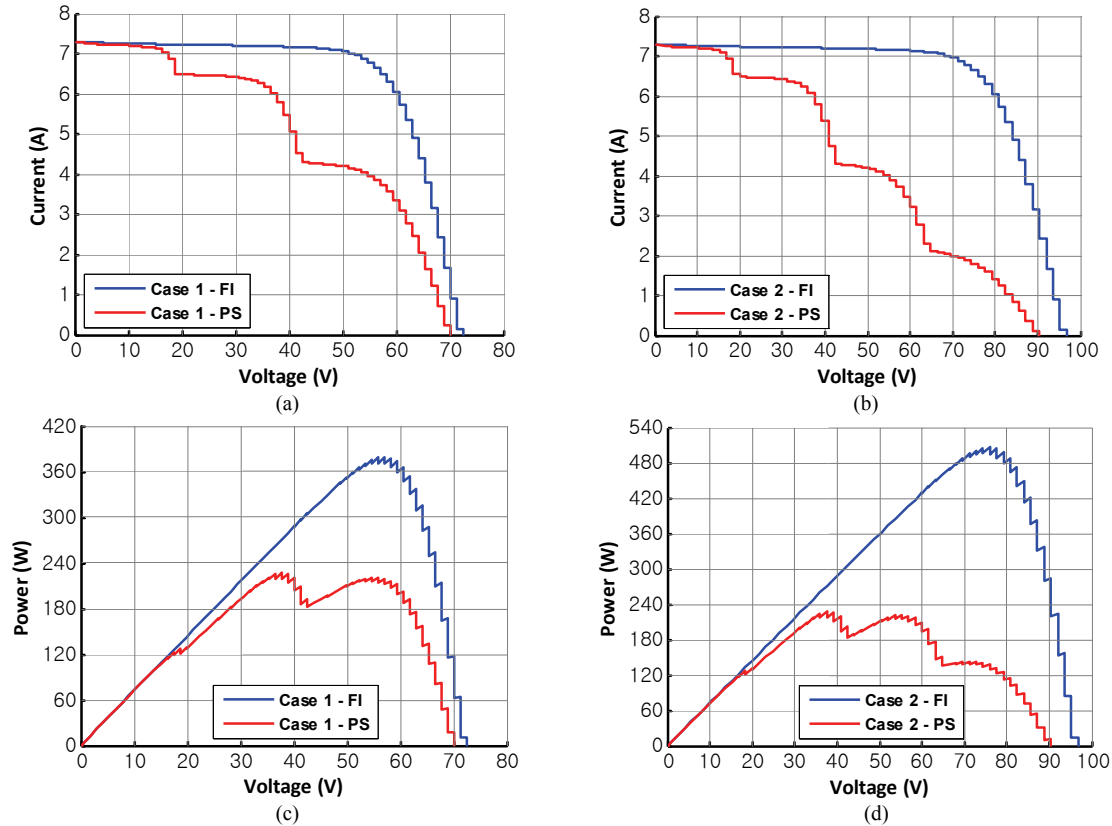
Fig. 8. Simulated results. (a) I-V curves of Case 1. (b) I-V curves of Case 2. (c) P-V curves of Case 1. (d) P-V curves of Case 2 for 6 modules under full irradiation and partial shading conditions.

900, 600 and 300 W/m², and the results are given in Fig. 6.

An additional simulation study was performed to show the performance of the proposed simulator for partial shading conditions. It was considered that 3 panels were connected in series (Case 1) and that they received solar irradiance values of 1000, 900 and 600 W/m², respectively. Another situation was constituted when 4 panels were connected in series (Case 2) and they received solar irradiance values of 1000, 900, 600 and 300 W/m², respectively. Simulation results of Case 1 and Case 2 are illustrated in Fig. 7.

I-V and P-V curves of cases in which series-connected panels are under partial shading (PS) conditions are given in Fig. 8. They are shown together with situation results of the panels under full irradiation (FI).

The simulation results in Fig. 7 and Fig. 8 show that the proposed PV simulator can achieve partial shading conditions. When all of the simulation studies are examined, the improved structure is shown to be quite successful as a PV simulator and will provide convenience to researchers.

IV. EXPERIMENTS, RESULTS AND DISCUSSION

After the simulation studies were completed, experimental studies were performed on a prototype. IRFP4368 MOSFETS were used as a switching element in series connected cascaded modules. A dsPIC30F6010 microcontroller was used in the
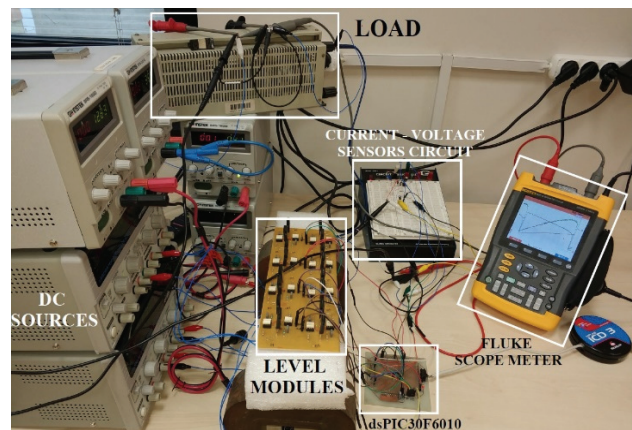

Fig. 9. Simulator prototype and experimental setup.

control circuit. Fig. 9 shows the prototype and experimental setup.

Experimental studies were realized to verify the validity of the simulation study. Therefore, the same situations in the simulations were constituted in the tests.

The simulator prototype was arranged with 6 modules and I(t), V(t), P(t) and I-V curves were obtained by a Fluke 225C scope meter for 64 levels. Oscilloscope waveforms are shown in Fig. 10, Fig. 11 and Fig. 12 for one panel, 3 series-connected panels and 4 series-connected panels at a 1000W/m² solar irradiance value. Partial shaded conditions were also investigated
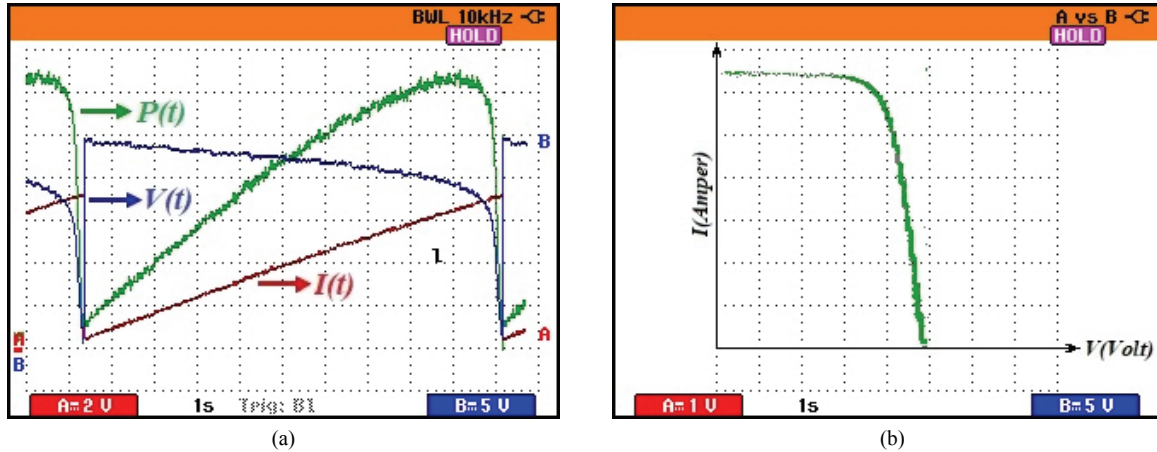
(a)

(b)

Fig. 10. Oscilloscope views of one panel for 6 modules at a 1000W/m² solar irradiance value. (a) V(t), I(t) and P(t) waveforms (Watt/div: 20 for P(t)). (b) I-V curve.

(a)

(b)

Fig. 11. Oscilloscope views of 3 series-connected panels for 6 modules at a 1000W/m² solar irradiance value. (a) V(t), I(t) and P(t) waveforms (Watt/div: 80 for P(t)). (b) I-V curve.

(a)

(b)
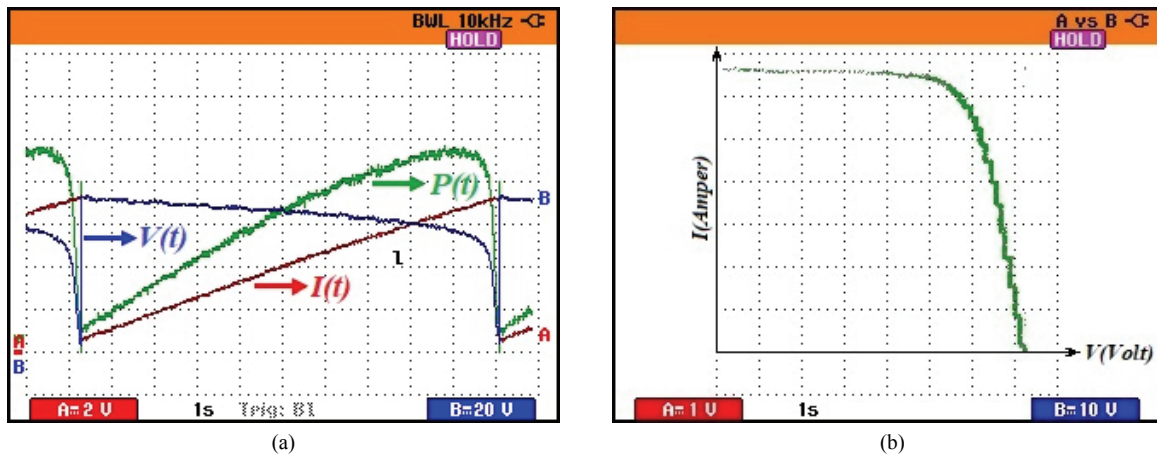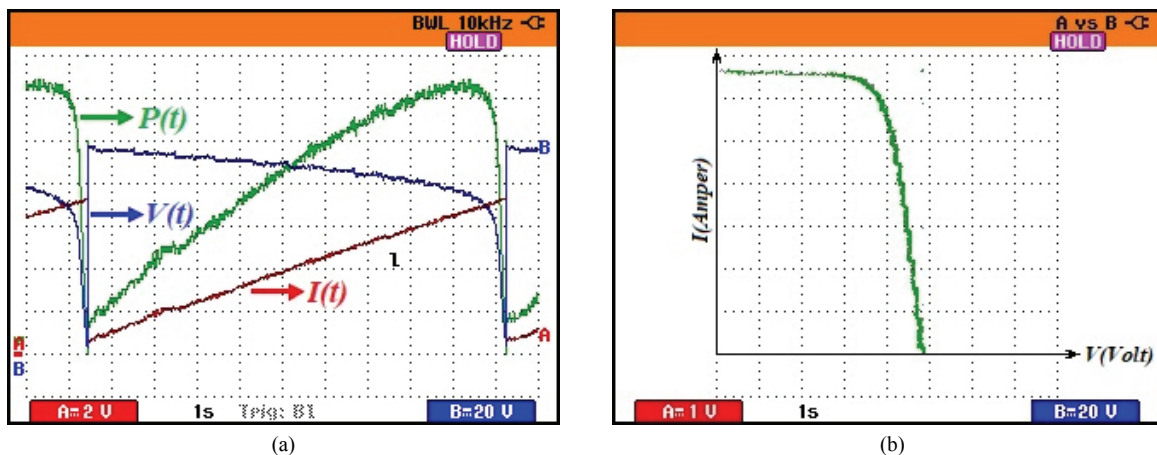
Fig. 12. Oscilloscope views of 4 series-connected panels for 6 modules at a 1000W/m² solar irradiance value. (a) V(t), I(t) and P(t) waveforms (Watt/div: 80 for P(t)); (b) I-V curve.

and oscilloscope waveforms are given in Fig. 13 and Fig. 14 for Case 1 and Case 2, respectively. In the oscilloscope views, 1 Volt corresponds to 1 Ampere for the current curves. In order to compare the experimental results with the curves of an actual PV panel (Schüco S 125-SP) and to show the success

of the proposed simulator, time-dependent waveforms were converted to I-V and P-V curves and the actual and experimental curves were given in the same graph.

For this purpose, the time dependent voltage, current and power curves shown in Fig. 10 - Fig. 14 were recorded by a
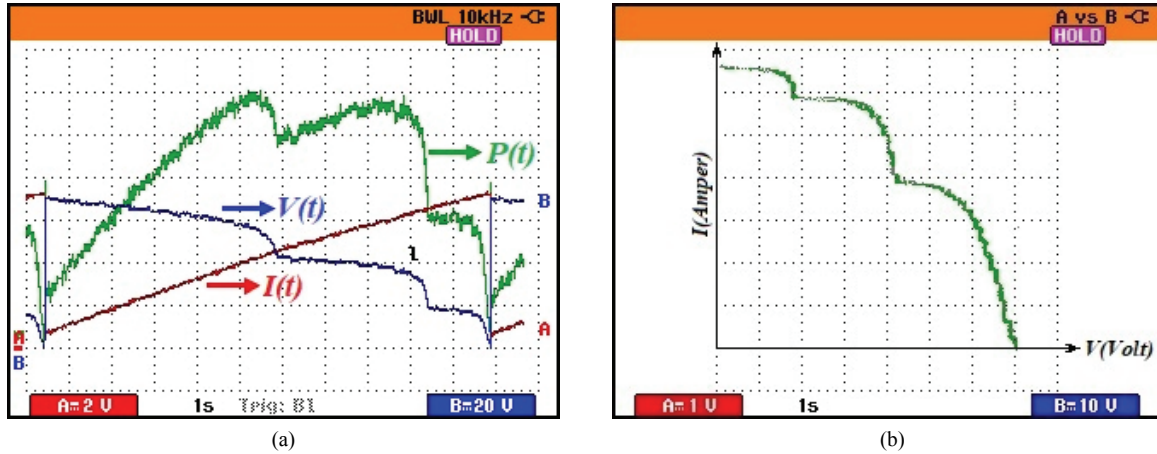
(a)   (b)

Fig. 13. Oscilloscope views of Case 1 for 6 modules. (a) V(t), I(t) and P(t) waveforms (Watt/div: 40 for P(t)). (b) I-V curve.

(a)   (b)
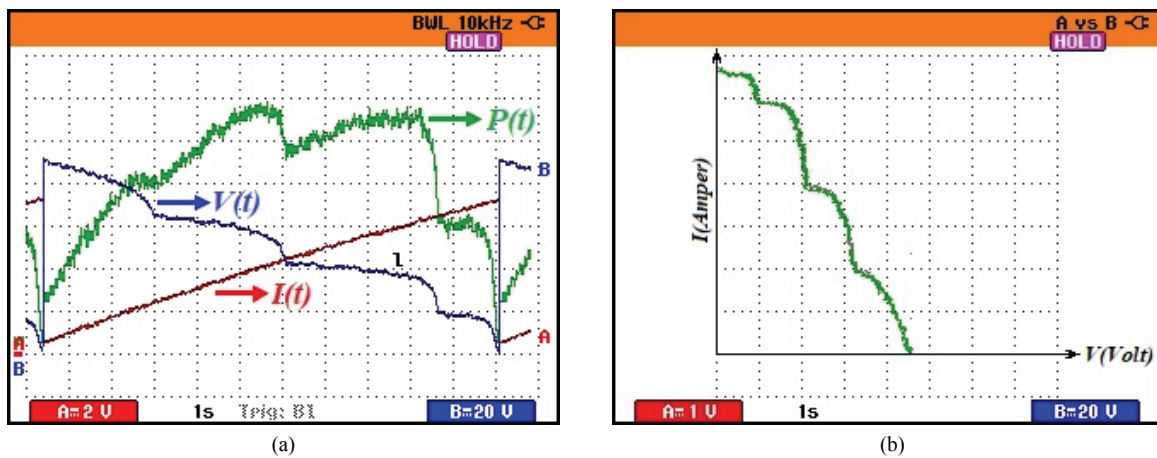
Fig. 14. Oscilloscope views of Case 2 for 6 modules. (a) V(t), I(t) and P(t) waveforms (Watt/div: 40 for P(t)). (b) I-V curve.
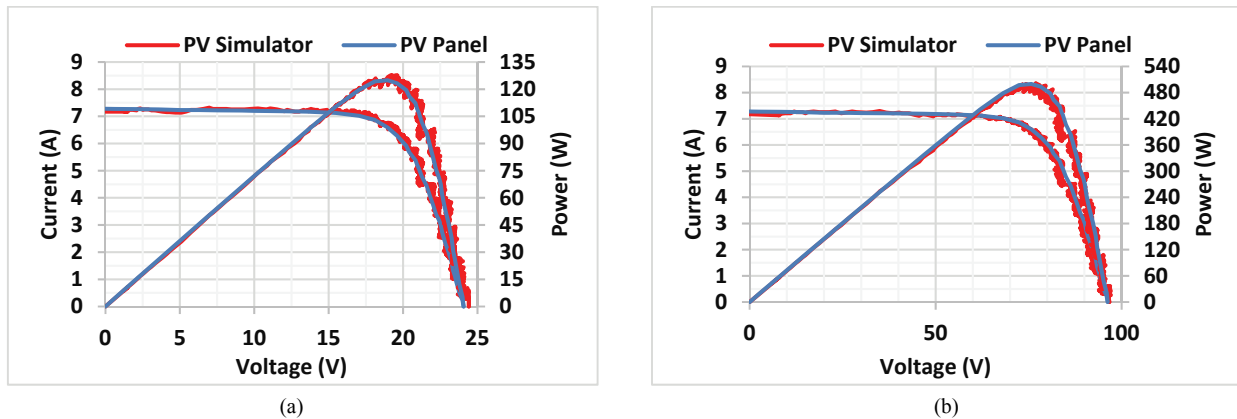

(a)   (b)

Fig. 15. Experimental I-V and P-V curves for 6 modules at a 1000 W/m² solar irradiance value. (a) For one panel. (b) For 4 series-connected panels.

scope meter. Then the recorded data was converted to I-V and P-V curves. Therefore, I-V and P-V curves of a Schüco S 125-SP PV panel were obtained by the proposed simulator.

Test results are given for one panel and 4 series-connected panels with the curves of an actual PV panel under a 1000 W/m² solar irradiation in Fig. 15.

It can be seen from Fig. 5 (c) and Fig. 15 (a) that the simulation and experimental results of the simulator for 6 modules are very close.

Similar to the simulation study, two cases were constituted and partial shading conditions were validated by tests. Experimental curves for Case 1 and Case 2 are shown in Fig. 16. The red lines show experimental curves of the proposed PV simulator and the blue lines show curves of an actual PV
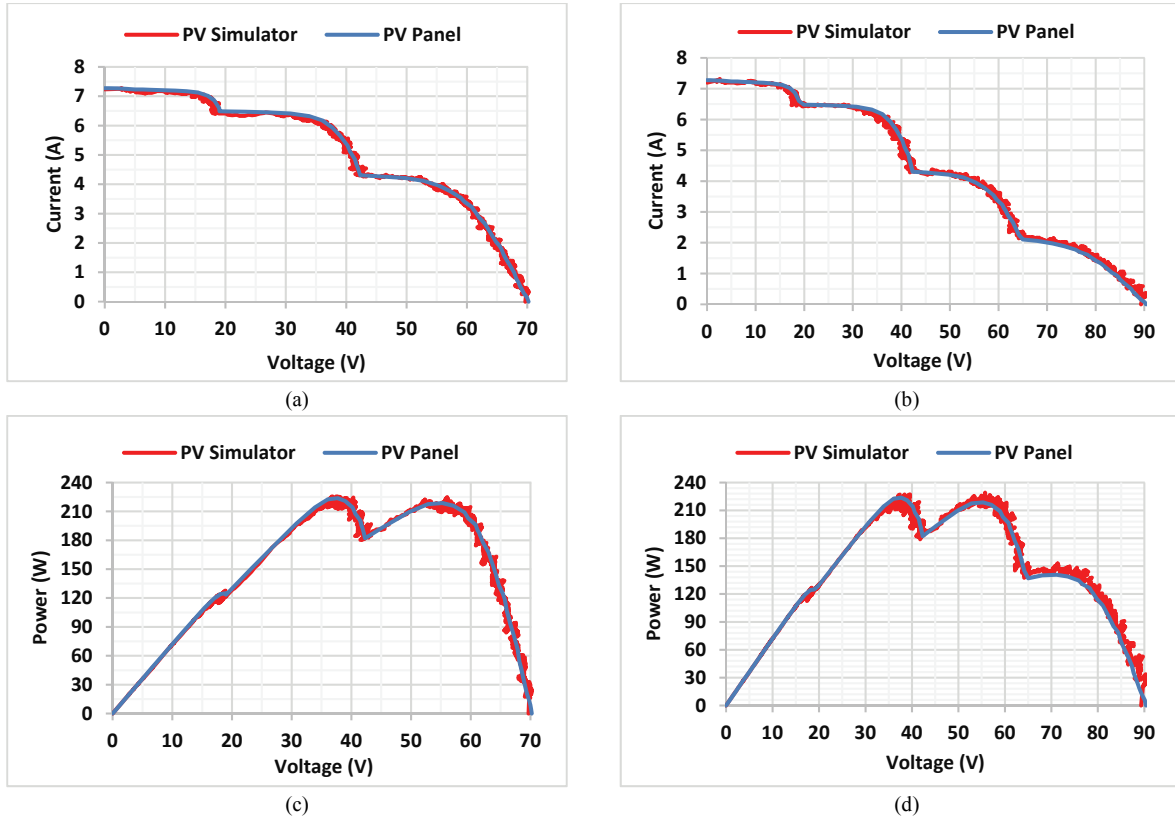
Fig. 16. Experimental results. (a) I-V curves of Case 1. (b) I-V curves of Case 2. (c) P-V curves of Case 1. (d) P-V curves of Case 2 for 6 modules under partial shading conditions.
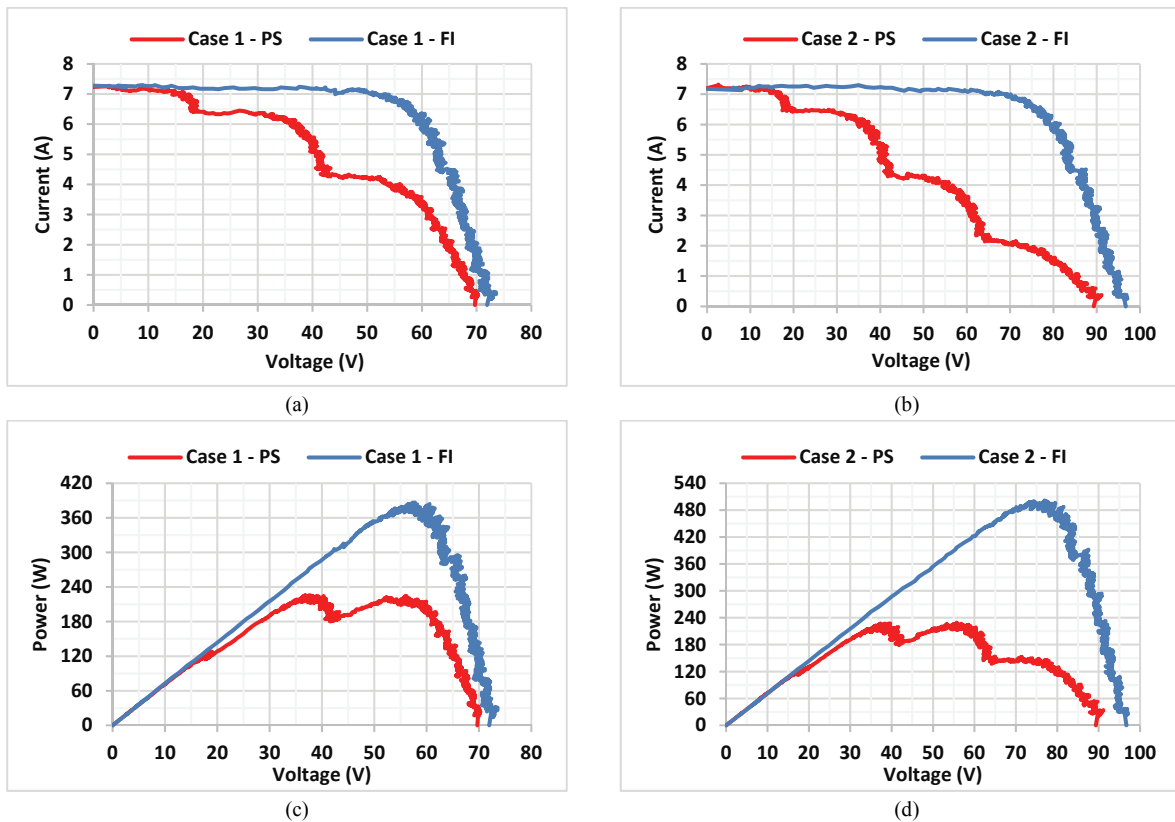

Fig. 17. Experimental results. (a) I-V curves of Case 1. (b) I-V curves of Case 2. (c) P-V curves of Case 1. (d) P-V curves of Case 2 for 6 modules under full irradiation and partial shading conditions.

panel in Fig. 15 and Fig. 16. I-V and P-V curves are also given under full irradiation and partial shading conditions in Fig. 17 for Case 1 and Case 2.

It is shown from the obtained experimental results that the proposed simulator can provide partial shading conditions quite well. The output curves have some ripples at low module numbers. When the number of modules increases, the ripples on the curves decrease. This can be overcome by connecting an LC filter to the simulator output for low module numbers. Thus, curves can be obtained more accurately.

Characteristic curves of a panel or PV arrays in series can be obtained with this structure. All of the conditions that can occur in a panel or a PV array can be generated with this structure. This feature will be very useful for studies done with panels in laboratory environments. In particular, the testing of MPPT algorithms will be quite easy.

V. CONCLUSIONS

This paper discussed the simulation and realization of a new PV simulator construction. A simulation model of the simulator was developed and then a prototype was built to demonstrate the effectiveness of the proposed structure. I-V and P-V curves were obtained for different situations including partial shading conditions. Both simulations and experimental results verified the feasibility of the PV simulator.

The most important novelty of the proposed PV simulator is the presence of modules in the structure. Having modules brings some advantages since the characteristic curves are obtained more accurately and it becomes easier to arrive at high-voltage values by an increase of the module number. Since the system is modular, the voltage stress *(dv/dt)* on the switching elements is low while high voltage PV systems are being modeled.

The proposed system has a structure that can simulate all of the possibilities that can occur in PV systems, including partial shading. It is expected that the proposed simulator will be used by researchers in estimating the performance of MPPT algorithms, designing PV systems such as PV plants, PV arrays and grid connected PV arrays, and also testing the converters used for distributed generation and smart grid applications.

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Ersoy Beser was born in Kocaeli, Turkey, in 1977. He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Kocaeli University, Kocaeli, Turkey, in 2000, 2004 and 2009, respectively. He is presently working as an Assistant Professor in the Department of Electrical Engineering, Kocaeli University. His current research interests include power electronics, solar energy, photovoltaic systems, multi-level inverters, inverters, converters, electrical machines, motor control and microcontrollers.