Applied Energy 86 (2009) 1632–1640

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Study of bypass diodes configuration on PV modules

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ARTICLE INFO

Article history:
Received 4 September 2008
Received in revised form 20 January 2009
Accepted 20 January 2009
Available online 5 March 2009

Keywords:
Bypass diodes
Hot spot
Modelling
Simulation
PV modules

ABSTRACT

A procedure of simulation and modelling solar cells and PV modules, working partially shadowed in Pspice environment, is presented. Simulation results have been contrasted with real measured data from a commercial PV module of 209 Wp from Siliken. Some cases of study are presented as application examples of this simulation methodology, showing its potential on the design of bypass diodes configuration to include in a PV module and also on the study of PV generators working in partial shading conditions.

1. Introduction

The solar PV market has been growing spectacularly over the last years and is forecast confirm this trend in the coming years. The reduction of PV generation costs and the implantation of grid connected PV systems are mainly responsible of this trend. As a result, manufacturers of PV modules are offering new powerful PV modules, incorporating solar cells of bigger size, specially designed for integration in buildings or forming part of tracking systems. These grid connected PV systems are frequently mounted on building roofs, facades, or urban environment, where partial shading can be frequent.

The reduction of output power in PV modules can be attributed to many factors, but maybe the most important are mismatch effects and shadows. Most manufacturers include bypass diodes in their PV modules in order to prevent hot spot formation, in partial shadowing conditions of work. Hot spots appear when a solar cell, normally forming part of a solar cell string of serially connected solar cells, becomes reverse biased and dissipates power in form of heat. This happens as effect of mismatch or in presence of shadows on the PV module. If the power dissipated by the solar cell in hot spot conditions, exceeds the maximum power which can be sustained by the cell, it will be full damaged, and an open circuit appears. The PV array design and the configuration of bypass diodes on the PV modules forming part of the array have an important influence in the possibility of hot spot apparition. This paper presents a simulation methodology to study different possible configurations of bypass diodes as part of the PV module.

2. Model and simulation procedure

The electrical behaviour of a solar cell, in illumination and darkness operation, is commonly reproduced using the single diode solar cell model, taking into account the physical characteristics of the solar cell under study. Some more sophisticated models introduce a second diode in order to obtain a better approach to the solar cell electrical behaviour, considering the effect of the recombination at the space charge region.

In the study of the reverse characteristic, where the solar cell working in reverse bias has to be considered, the solar cell model must be revised including the effect of breakdown voltage [1,2]. This is important to be taken into account in the study of solar cells working partially shadowed, forming part of a PV module.

Despite other models can be found in the literature [3–5], Bishop's model [2] is still the most used model in this case. However, these works are limited to module-level study and do not discuss the shading effects on an entire PV array.

The equation proposed by Bishop incorporate the avalanche effect as a non-linear multiplication factor that affects the shunt resistance current term, as Eq. (1) shows below.

$$I = I_{\mathrm{PH}} - I_o\left[\exp\left(\frac{V+R_sI}{mV_t}\right)-1\right] - \left(\frac{V+R_sI}{R_p}\right)\left[1+a\left(1-\frac{V+R_sI}{V_b}\right)^{-\beta}\right] \quad (1)$$

where I_o and m *are, respectively,* the inverse saturation current and the ideality factor of the diode, V_b is the breakdown voltage, a and β are constants, V_t is the thermal voltage, and R_s and R_p the series and shunt resistance, respectively. The last term of Eq. (1), shown

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doi:10.1016/j.apenergy.2009.01.020

by Eq. (2) as $\psi(V)$, is added to the leakage current into the shunt resistance term modelled as a controlled current source:

$$\psi(V) = 1 + a\left(1 - \frac{V + IR_s}{V_b}\right)^{-\beta} \tag{2}$$

In this work we propose a new approach to the study of solar cells working partially shadowed, based on the combination of the two-diode classic model of the solar cell and Bishop's one, shown below by Eq. (3).

$$I = I_{PH} - I_{o1}\left[\exp\left(\frac{V + R_s I}{m_1 V_t}\right) - 1\right] - I_{o2}\left[\exp\left(\frac{V + R_s I}{m_2 V_t}\right) - 1\right] - \left(\frac{V + R_s I}{R_p}\right)\left[1 + a\left(1 - \frac{V + R_s I}{V_b}\right)^{-\beta}\right] \tag{3}$$

Fig. 1 shows the equivalent circuit of the solar cell from Eq. (3).

The study of PV modules working partially shadowed has been analysed using different methodologies, models and simulation techniques [4–9]. Some of these works do not predict the presence of multiple steps and peaks, which use to be common in the *I–V* and *P–V* characteristics of PV arrays working at non-uniform irradiance levels [4–6]. In other cases the inclusion of bypass diodes to investigate its influence is not taken into account. Finally, other models do not reproduce the PV module and solar cell behaviour working in reverse bias [7,9].

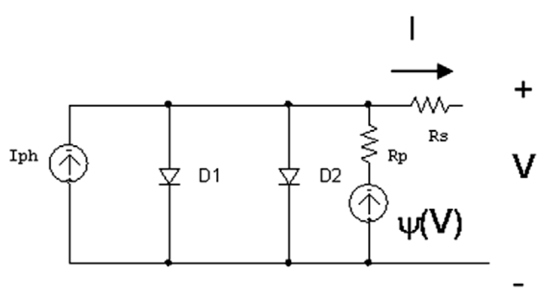

Fig. 1. Solar cell equivalent circuit.

All the above mentioned models, including Bishop's one, are easier to implement into Pspice simulation environment [10–11] than into other simulation tools as Matlab [6,9]. Pspice has been used with success to model and simulate photovoltaic devices and systems under real conditions of work [11–13] and nowadays is a standard simulator for most electrical and electronic engineers. Another reason for using Pspice is the possibility of interfacing PV modules with existent Pspice models of different element of PV systems: batteries, charge regulators, DC/DC voltage converters and inverters [11–13]. We have chosen this simulation environment to reproduce the solar cell model described by Eq. (3) and to study different configurations of bypass diodes forming part of the PV module. The developed simulation procedure allows also the study of PV array behaviour in presence of partial shadow over some of the PV modules, giving relevant information about power losses and evolution of the maximum power point of the array, as well as on the influence of bypass diodes configuration.

As example of simulation, Fig. 2 shows *I–V* characteristics of a solar cell obtained from Pspice using the model above described, working at 25 °C under irradiances of: 450, 750 and 1000 W/m^2. The solar cell parameters used in this simulation, from model shown at the equivalent circuit of Fig. 1 or Eq. (3), are the following:

–Diode d1: $m_1 = 1$, $I_{o1} = 1.26 \times 10^{-9}$ A; diode d2: $m_2 = 2$, $I_{o2} = 2.53 \times 10^{-6}$ A, $R_s = 1$ mΩ, $R_p = 1$ kΩ; Bishop's term: $V_b = -15$ V, $a = 2 \times 10^{-3}$ and $\beta = 3$.

The current source I_{pH} is controlled by the irradiance level and temperature, the solar cell active area and its short circuit current density. In the simulation we have chosen an area of 126.6 cm^2 and a short circuit current density of: $J_{sc} = 30$ mA/cm^2.

The presented solar cell model is easily scalable to a PV module model. Taking the solar cell model as sub-circuit in Pspice environment [11], the PV model can be defined as connection of a number of sub-circuits in series and parallel, equal to the number of solar cells associated in series and parallel forming the PV module. Solar cell parameters, irradiance and temperature levels can be controlled by separate for each one of the PV module solar cells. This independent control could be really interesting in the case of the breakdown voltage and also in the case of the shunt and serial resistance, because these resistances can strongly vary when the

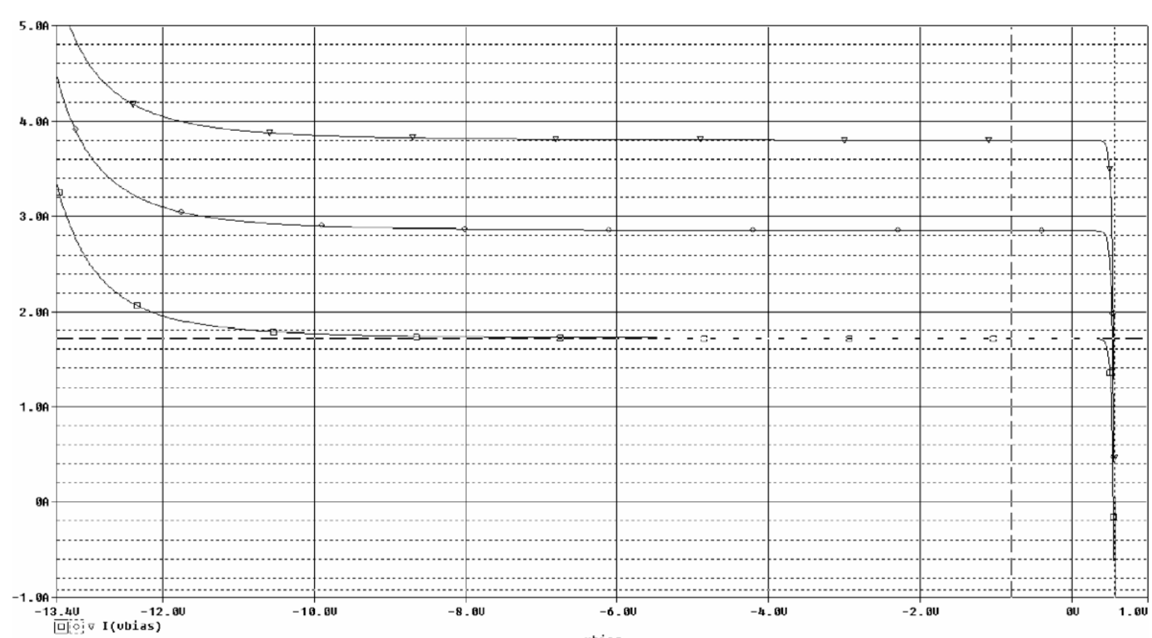

Fig. 2. *I–V* characteristics of a solar cell working under different irradiance levels.

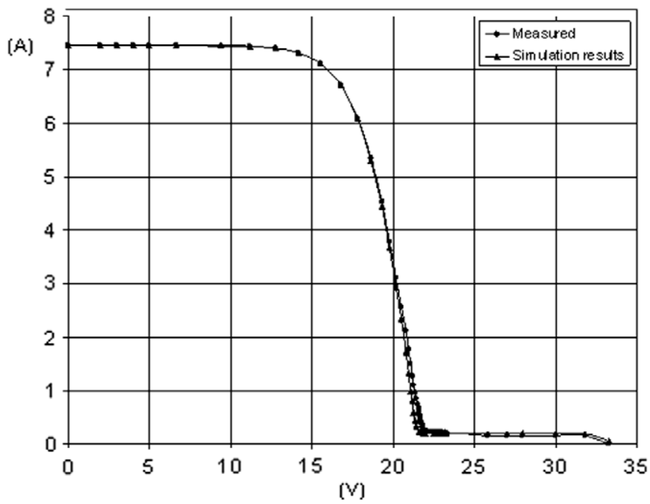

Fig. 3. Simulation results and measures obtained.

solar cell is working in dark conditions [6–8]. The introduction of bypass diodes in the PV module model, results also easy using Pspice, connecting the bypass diodes to the solar cells nodes protected by each bypass diode.

In order to validate the presented model and simulation procedure some experimental measurements have been carried out using a commercial PV module of 209 Wp. This PV module includes two bypass diodes and 60 solar cells serially connected. Main PV module parameters at standard conditions are: $I_{sc} = 7.9$ A, $V_{oc} = 36.4$ V, maximum power point: $I_{mpp} = 7.25$ A, $V_{mpp} = 28.7$ V.

Fig. 3 shows the *I–V* characteristic of this PV module measured under an irradiance of 966 W/m^2 and a solar cell temperature of 50.2 °C, having two solar cells totally shaded. The simulation results are also shown in the same figure. The solar cell parameters used in the simulation are the following:

–Diode d1: $m_1 = 1$, $I_{o1} = 4.55 \times 10^{-10}$ A; diode d2: $m_2 = 2$, $I_{o2} = 2.27 \times 10^{-7}$ A, $R_s = 1$ μΩ, $R_p = 1$ kΩ; Bishop's term: $V_b = -25$ V, $a = 2 \times 10^{-3}$ and $\beta = 5$, solar cell area: 227.58 cm^2, and a short circuit current density of: $J_{sc} = 34$ mA/cm^2. The irradiance and temperature used in the simulation are the measured in real conditions of work.

As can be seen in Fig. 3, one of the two bypass diodes is activated as effect of the two solar cells working in dark conditions, both covered by this bypass diode. A good agreement is obtained between simulation results and measured data. The root mean squared error (RMSE) for the current is a 3.1%. Finally, Fig. 4 shows the output power of the PV module, comparing again measured data with results obtained in the simulation process. The output power reduction due to shading is clear, a reduction of a 31% is observed in the maximum power point, in the same order as previous results reported before in the literature [6].

3. Simulation study of bypass diodes configuration in a PV module

Most commercial PV modules are formed by association of solar cells serially connected and use to include one or two bypass diodes. Some PV modules are offered without bypass diodes. This can be understood because in stand-alone applications, where the PV array is just formed by association of PV modules in parallel, charging a battery of 12 or 24 V, the inclusion of bypass diodes is not necessary at all [14]. On the other hand, in large PV modules, having for example 72 solar cells in series, some manufacturers include six bypass diodes, one for each 12 solar cells.

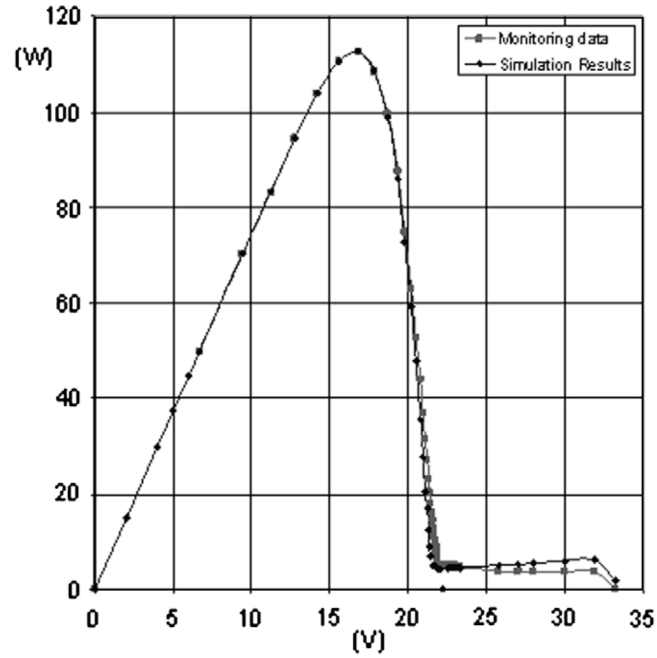

Fig. 4. PV module output power, measured and simulation results obtained.

The PV array design and the configuration of bypass diodes in the PV modules forming part of the array has a big influence on the probability and severity of hot spot apparition in any point of the PV array. The presented model and simulation procedure can help to a better understanding of the PV module behaviour in function of the configuration of bypass diodes included in the design.

As example of study of bypass diodes configuration on a PV module, using the above described method, some cases of study are analysed below in the following section. The PV module chosen for these cases of study is formed by 36 solar cells, each one of 126.6 cm^2, serially connected, having a total power of 70 Wp, a short circuit current of 3.8 A and an open circuit voltage of 22.2 V. The temperature used as input parameter is the same for all simulations, $T = 30$ °C, and the solar cell parameters used in the simulations are the following:

–Diode d1: $m_1 = 1$, $I_{o1} = 1.26 \times 10^{-10}$ A; diode d2: $m_2 = 2$, $I_{o2} =$! 1.26×10^{-7} A, $R_s = 1$ mΩ, $R_p = 1$ kΩ; Bishop's term: $V_b = -25$ V, $a = 2 \times 10^{-3}$ and $\beta = 4$, and a short circuit current density of: $J_{sc} = 30$ mA/cm^2.

When some solar cells are covered, at the same time, by more than one bypass diode we call these cells overlapped solar cells.

3.1. PV module with two bypass diodes without overlapped solar cells

Fig. 5 shows the PV module under study having two bypass diodes, covering each one, half of the solar cells forming the PV module. This is one of the most popular configurations that we can found in the market of PV modules.

A first simulation has been carried out considering standard values of irradiance over all solar cells except for solar cell number 35. This solar cell has been forced to work with shadow rates of 0%, 25%, 50%, 75% and 100%. Fig. 6 shows the activation of diode dbypass2, the current across the bypass diode has been plotted for all shadow rates considered.

Fig. 6 shows also the obtained *I–V* characteristics of the whole PV module and the PV module output power, the product $v_{mod} * i(v_{mod})$ in the plot. At low voltage values, a new local maximum power point appears. This local maximum can be the new maximum power point, depending on the shadow rate, the number

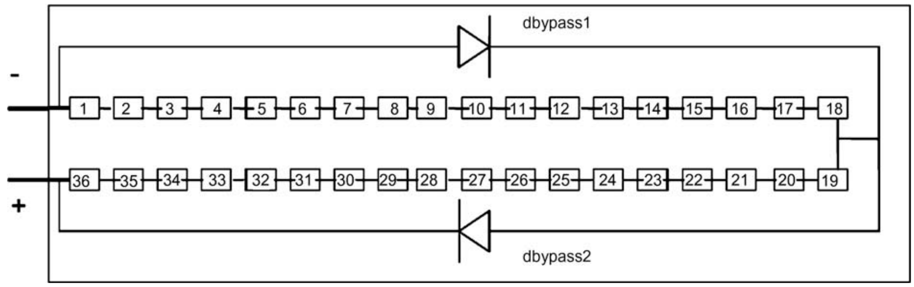

Fig. 5. PV module.

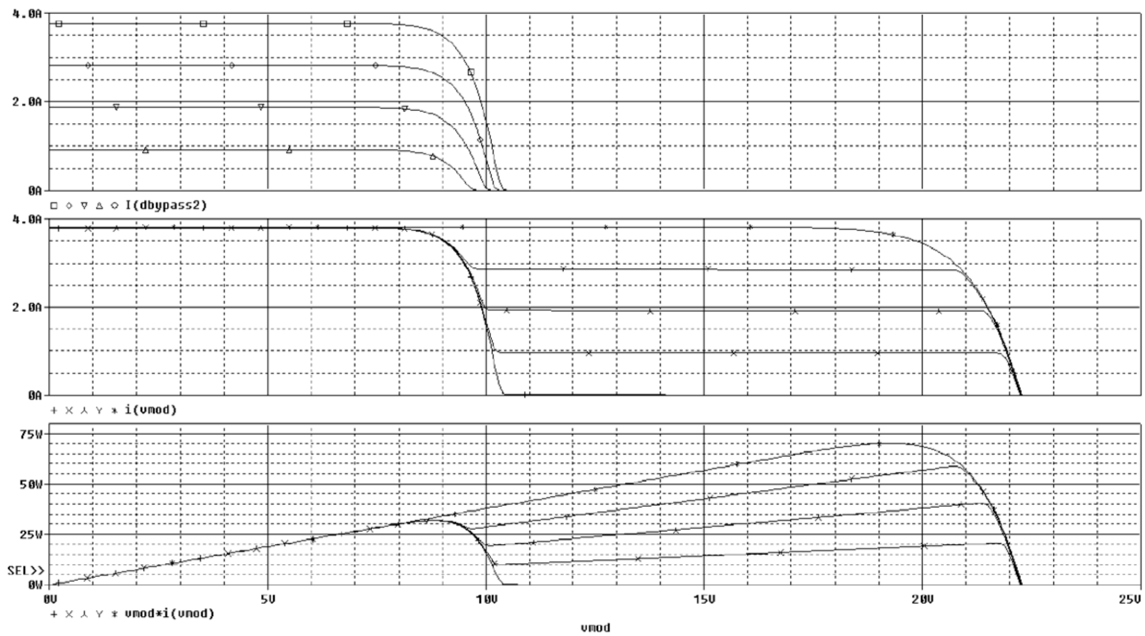

Fig. 6. Simulation results for different shadow rates over cell number 35.

of solar cells covered by the bypass diode, and the value of the breakdown voltage of the shaded cell.

A second simulation has been carried out, considering this time standard values of irradiance over all solar cells except for solar cells number 35 and 2. Results obtained are shown in Fig. 7. The current across both bypass diodes is the same, and lowest than in the previous case. No local maximum power points appear in this case.

3.2. PV module with two bypass diodes with overlapped solar cells

Sometimes, modules are manufactured including bypass diodes with overlapped solar cells. Fig. 8 shows the PV module considered in the previous section, including now two bypass diodes overlapping cells 13–20, the rest of non-overlapped solar cells are covered just by one bypass diode, cells 1–12 by diode dbypass1 and cells 21–36 by diode dbypass2.

The effect of shading one of the non-overlapped solar cells, using the same shadow rate values that in the previous section, is the same that the observed in Section 3.1. The diode covering the shadowed solar cells enters in conduction and the *I–V* characteristic of the PV module, as well as the output power show the same trends observed in Fig. 6.

In case of shadow over two non-overlapped solar cells, one covered just by dbypass1 and the second one covered just by dbypass2, the *I–V* characteristic an PV module output power are also the same than results obtained in previous section and shown in Fig. 7, but the current across diodes dbypass1 and dbypass2 varies.

Important differences can be observed in case of shadowing one of the overlapped solar cells. Fig. 9 below shows simulation results considering shadow rates of 0%, 25%, 50%, 75% and 100% over cell number 15.

As can be seen in Fig. 9, for low voltage values both bypass diodes are in conduction, and the current across them is the same, resulting in an increase of the short circuit current of the PV module. This result, previously reported [15], can be easily analysed thanks to Pspice facilities, that allow quickly access to all voltages and currents of the simulated circuit. Fig. 10 shows the current flow across the PV module when both diodes are in conduction.

Where I_1 is the current across the solar cells without shadowing, I_{lim} is the current across the overlapped cells in presence of some shadow, and I_{exc} the current across the bypass diodes. At low voltage values, both bypass diodes are in conduction and the total current at the output of the PV module I_{tot} is given by Eq. (4) below.

$$I_{\text{tot}} = I_1 + I_{\text{exc}} \tag{4}$$

where I_1 can be expressed as follows:

$$I_1 = I_{\text{lim}} + I_{\text{exc}} \tag{5}$$

When the voltage increases, diode dbypass2 turns off reducing the output current of the PV module.

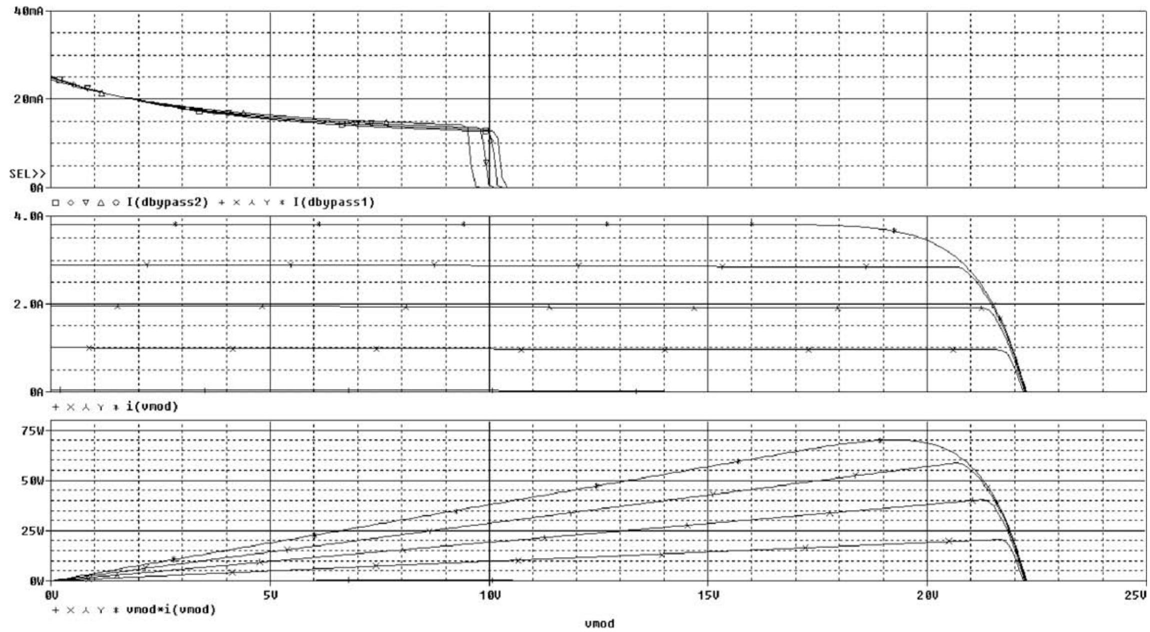

Fig. 7. Simulation results for different shadow rates over one solar cell of each branch, cells 2 and 35, covered by one bypass diode.

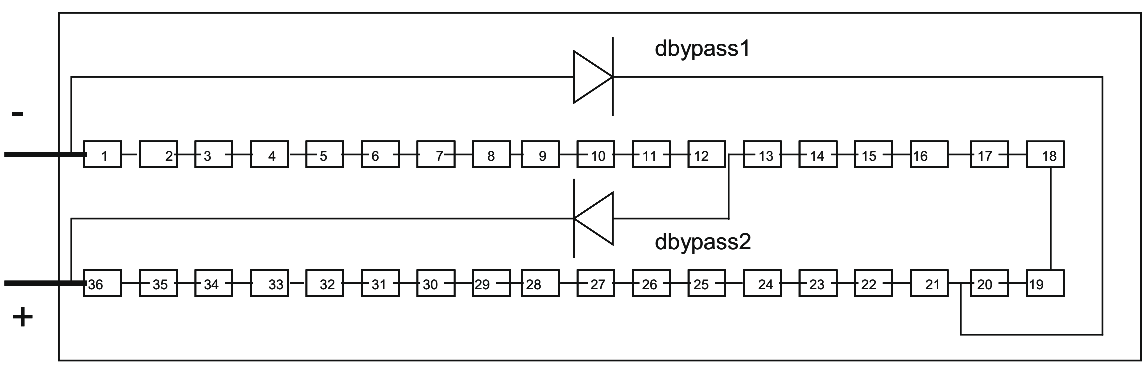

Fig. 8. PV module including two bypass diodes having some solar cells overlapped.

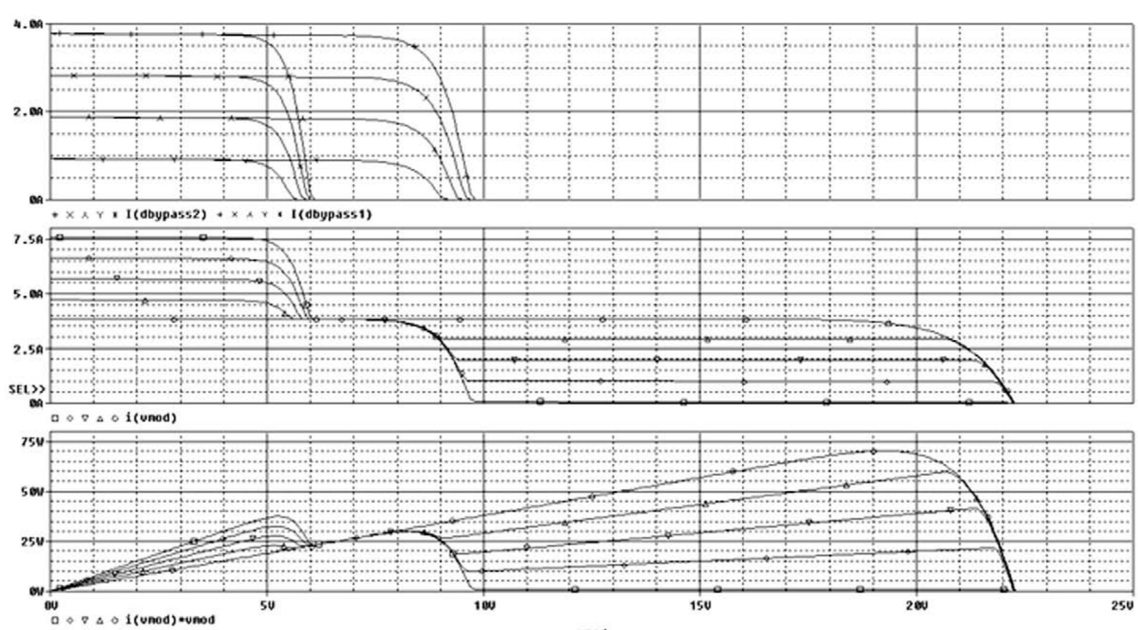

Fig. 9. Simulation results for different shadow rates over cell number 15.

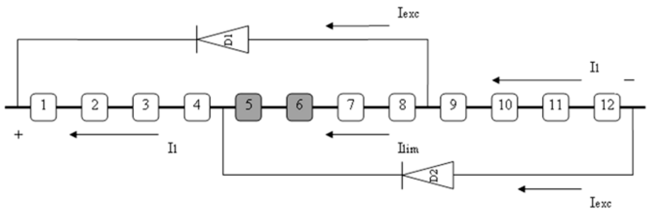

Fig. 10. Current flow across the PV module.

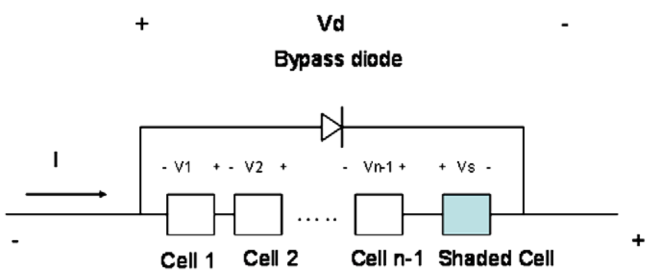

Fig. 11. Bypass diode covering n solar cells, one of these cells is working in shading conditions while the rest are free of shadow.

4. Estimation of bypass diodes to include in a PV module

Some authors gave the idea that the number of bypass diodes in a PV module should not be determined by the number of cells in the module, but by the bypassed power capacity of the cells in the string protected by each bypass diode [16]. This conclusion results as consequence of the extreme scatter observed on the reverse I–V characteristics of similar solar cells, even solar cells fabricated in the same batch, where very different breakdown voltage can be observed. Despite this fact, some guides can be observed to optimize the number of bypass diodes included in a PV module. Each solar cell has a maximum power that can be dissipated by the cell without irreversible damage. In reverse bias, the current across the solar cell does not increase drastically until the breakdown voltage is achieved. If we fix a safety factor of 80% of the breakdown voltage, V_b, as maximum reverse voltage supported by a solar cell shaded in a PV module, the power dissipated at the cell will be below the maximum allowed power. Fig. 11 shows a bypass diode covering n solar cells, one of these cells is working in shading conditions while the rest are free of shadow. The voltage V_d is the voltage at the bypass diode in conduction state.

To force the bypass diode entering in conduction, the reverse voltage at the shaded solar, V_s, cell must be:

$$V_s \geqslant V_d + \sum_{i=1}^{n-1} V_i \tag{6}$$

Considering the open circuit voltage, V_{oc}, as the maximum voltage allowed at each solar cell in direct bias, Eq. (6) can be rewritten as follows:

$$V_s \geqslant V_d + (n-1)V_{oc} \tag{7}$$

Introducing the above described safety factor of $0.8V_b$, as the maximum voltage permissible at the shaded cell working in reverse bias, the maximum number of solar cells, n_{max}, protected by the bypass diode can be obtained:

$$n_{max} \leqslant 1 + \frac{0.8V_b - V_d}{V_{oc}} \tag{8}$$

Considering a $V_{oc} = 0.6$ V, $V_d = 1$ V, and a breakdown voltage $V_b = 15$ V in Eq. (8), the maximum number of solar cells protected by a bypass diode should be of 16. This indicates a minimum of two bypass diodes for a PV module of 32 solar cells serially connected. Temperature effects must be also taken into account to estimate the number of bypass diodes to include in the PV module. Under bud conditions of work, the temperature of the shaded cell increases and the result can be the irreversible damage of the cell or the cell encapsulation.

5. Study of partial shadowing effects in the PV generator behaviour

The performance of a PV generator is affected by temperature, irradiance conditions, mismatch effects, shading and array configuration. The presented model and simulation procedure can be applied to the study of PV arrays working in partial shadowing conditions. The application of this Pspice-based simulation procedure can help to a better understanding and prediction of the I–V and P–V characteristics of PV arrays. It can be used to study the effect of temperature and irradiance variation conditions, hot spot apparition and effects in output power reduction. It can be also useful in the study of bypass diodes configuration in the PV array and its effects in output power variation and apparition of peaks and new maximum power points in the power–voltage characteristic. This simulation methodology can be used in the development of new maximum power point tracking algorithms in presence of shadowing on the PV modules [9,17].

The usefulness of the proposed simulation procedure is demonstrated below with the help of several illustrative examples. The study is focused on the PV system shown by Fig. 12, having nine PV modules of 85 Wp, $N_s = 3$, $N_p = 3$, each formed by 36 solar cells in series providing a short circuit current of 5 A and an open circuit voltage of 22.3 V. One bypass diode has been included by PV module.

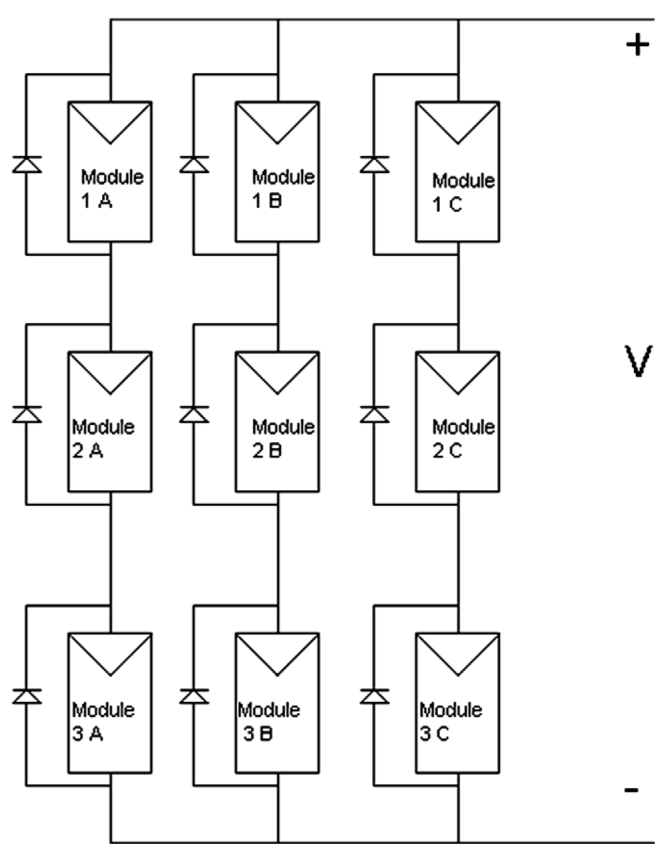

Fig. 12. PV system under study.

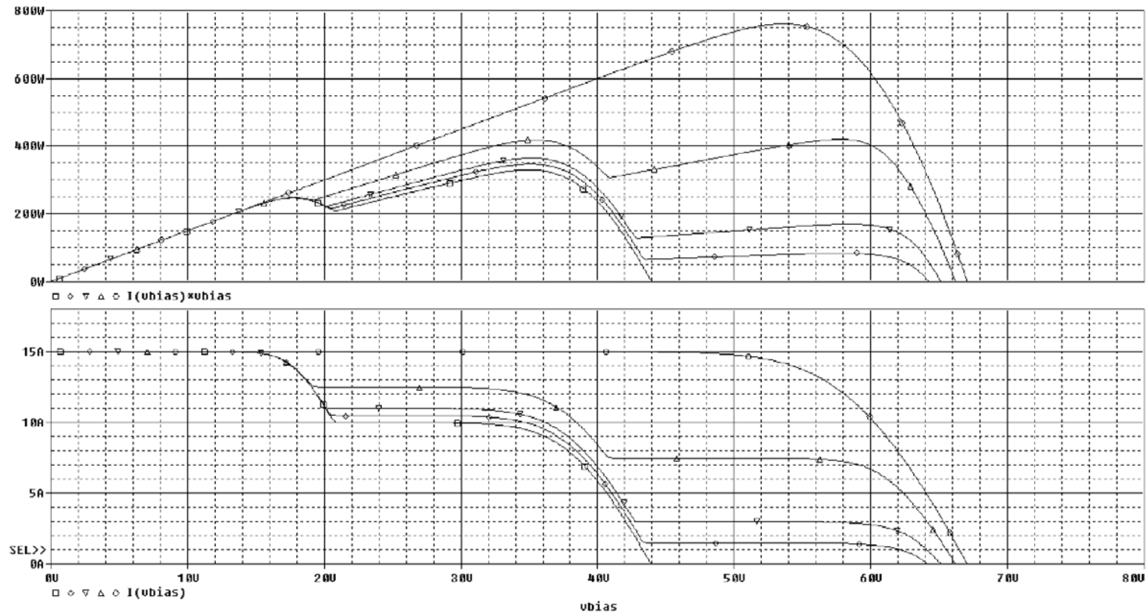

Fig. 13. *P–V* and *I–V* characteristics.

A first simulation has been carried out considering variable shading on four of the PV modules forming part of the PV array, the rest of PV modules are working under a constant irradiance of 1000 W/m^2. Shadow rates of: 100%, 90%, 80% and 50% have been introduced on PV modules: 1A, 3A, 2B and 2C shown by Fig. 12. The PV system has been also simulated working in total absence of shadow and standard conditions of irradiance and temperature. Fig. 13 shows results obtained for *I–V* and *P–V* characteristics of the array at the different irradiation conditions under study.

As can be seen in Fig. 13 in total absence of shadowing the maximum power point of the PV array results 765 W. The effect of the different shadowing patterns introduced in the simulation can be observed in *I–V* and *P–V* characteristics shown by Fig. 13. The presence of bypass diodes reduces the output power lowering, reducing the current limitation of the shaded PV modules. The presence of the bypass diodes adds multiple steps in the *I–V* characteristic and new local peaks in the *P–V* characteristics, that in determinates conditions became new maximum power points of the array. Fig. 14 shows the current flow across the bypass diodes 1A, 3A, 2B and 2C. *I–V* characteristics of diodes 2B and 2C are the same because strings B and C work in the same conditions, with one PV module affected by shadowing. Currents across diodes 1A and 2A are also the same due that both bypass diodes are in the same string, but this time *I–V* characteristics present a voltage limitation because two PV modules of the string are working in shadow conditions.

If bypass diodes are not present, the shadowed modules will introduce a limitation on the current in the series strings and also on the total output power. This effect is shown in Fig. 15, where the *I–V* and *P–V* characteristics of the array are again reproduced with the same shadow patterning conditions but in absence of bypass

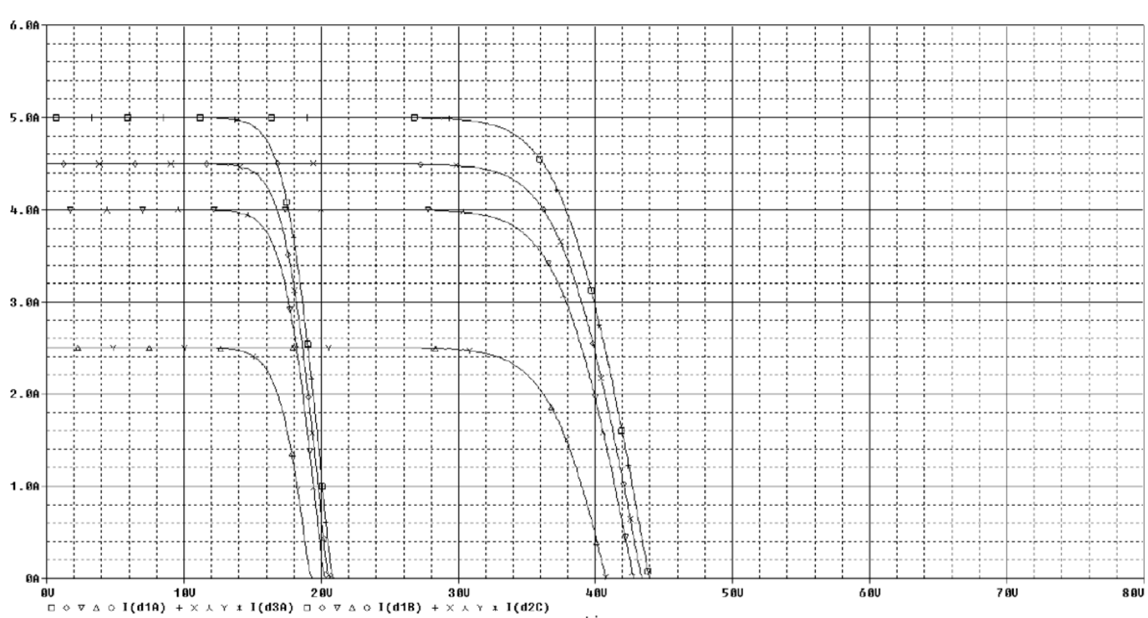

Fig. 14. Current across bypass diodes.

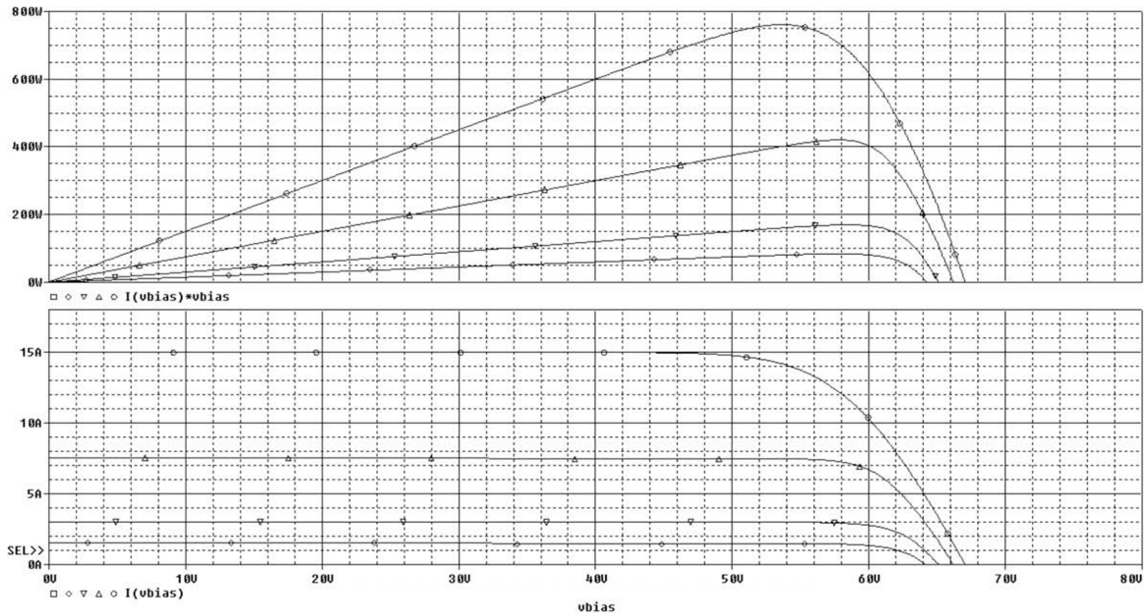

Fig. 15. *P–V* and *I–V* characteristics without bypass diodes.

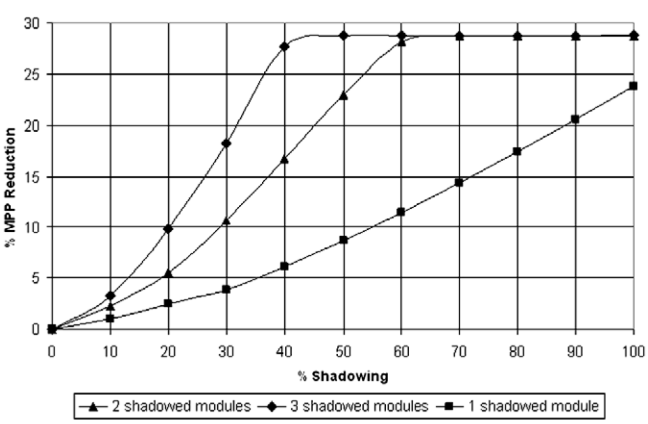

Fig. 16. MPP reduction in function of shadow rate.

diodes. Now, no local peaks are detected in *I–V* and *P–V* characteristics.

A second set of simulations has been carried out for the PV system presented above, Fig. 12, in order to study the effect of bypass diodes configuration in the maximum power point evolution of the array working in shading conditions. The PV modules are working at 20 °C of temperature and solar cells forming part of the PV modules have a Normal Cell Operating Temperature: NOTC = 46 °C. Different shadow rates are considered for one, two or three PV modules of the PV array, each one in a different branch of the PV array. The rest of PV modules are working in standard conditions of irradiance. Fig. 16 shows results obtained for the maximum power point evolution of the PV array.

When just one PV module is affected by shadow the reduction of current in the branch where the PV module is connected is proportional to the irradiance reduction, as well as the maximum power point reduction. In this case the bypass diode protecting the PV module working in shadow conditions, introduces a new peak in the *P–V* array characteristic, but does not become a new maximum power point for any conditions of shadowing. When two PV modules are shadowed, the maximum power point shows the same evolution that in the previous case except for shading rates over 60%. When shadow rates are over this limit, new peaks introduced by the bypass diodes in the *P–V* characteristic of the array, will become new maximum power points, and the maximum power point reduction of the array will remain constant despite shadow rates increase. The same trend is observed having three PV modules working in shading conditions; in this case the maximum power point reduction remains constant at shadow rates around the 40%.

In all cases the bypass diodes configuration maintain the maximum power point reduction below the 29%.

6. Conclusions

In this work we propose a new approach to the study of solar cells working partially shadowed, based on the combination of the two-diode classic model of the solar cell and the model proposed by Bishop. A simulation methodology for solar cells and PV modules working partially shadowed using the developed models in Pspice environment is proposed. These models have been successfully contrasted by comparison of simulation results with real measured data.

The solar cell and PV module models developed in Pspice environment are used in different cases of study showing some application examples.

The shadow rate over the PV module, the breakdown voltage value of the solar cells forming part of the PV module and the placement and number of bypass diodes included in the design of the PV module, have an strong influence on the PV module output power characteristic. The application of the presented simulation methodology can help to optimize the bypass diodes configuration and the prevention of hot spot apparition in PV modules. An expression to estimate the maximum number of solar cells, $n_{\max}$, protected by one bypass diode in a PV module is proposed.

An advantage of the presented simulation procedure is the possibility of simulation the whole PV array introducing different input parameters for each one of the solar cells presents in the PV generator, making possible the study of multiple shadow patterns as well as temperature and resistance variations in particular solar cells that can introduce hot spot apparitions. It can be also useful in the study of bypass diodes configuration in the PV array and its effects in output power variation and apparition of peaks and new maximum power points in the power–voltage characteristic. This simulation methodology can be a powerful tool in the development of new maximum power point tracking algorithms in presence of shadowing on the PV modules.

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