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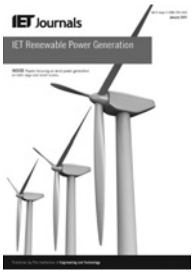

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Energy models for photovoltaic systems under partial shading conditions: a comprehensive review

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Abstract: The partial shading phenomenon and its implications on the electrical response and energy yield of photovoltaic (PV) systems have received increased attention in the last years. In order to study, foresee and mitigate such effects, several energy models are proposed in the bibliography, presenting different degrees of complexity, accuracy and applicability. This study presents an overview of the state of the art in the development of models for PV systems under partial shading conditions. Alternative modelling approaches are analysed, highlighting their advantages and shortcomings and models available in the literature are reviewed and classified according to important attributes, related to their accuracy and implementability. Current research trends, as well as topics that warrant further investigation, are identified and discussed.

1 Introduction

The penetration of photovoltaic (PV) technology has significantly increased worldwide in the last decade, with applications ranging from small rooftop or building-integrated PV systems to multi-MW PV power plants, at all kinds of installation locations, from isolated rural spaces to residential areas inside large cities. The variety of installation locations, especially in urban environment, often leads to operation at non-uniform illumination conditions because of surrounding obstacles, whereas the pressure for reducing land use usually leads to compact installations, introducing shading from one array to another.

Partial shading has a strongly non-linear effect on the power output and the electrical response of a PV system. Depending on the extent and intensity of the shade, multiple local maximum power points (MPP) may arise, hindering the effective tracking of the globally optimum operating point, thus leading to suboptimal performance, as well as to hot spot creation and fast deterioration of the shaded cells. In order to study this phenomenon and mitigate its effect on PV system performance, a suitable energy model is required, flexible enough to estimate the response under the variety of different shading patterns that may occur in actual operating conditions. Such a model would prove valuable for application in energy yield calculations, as for PV installation planning, array topology optimisation and technoeconomic studies. Furthermore, another application of such models is the evaluation of the effectiveness of MPP tracking (MPPT) algorithms for partially shaded PV systems.

In this paper, a wide selection of the most representative papers available in the literature, regarding PV modelling at partial shading conditions, is reviewed and studied, focusing on crystalline-Si technologies [1–46]. The models reviewed are analysed in terms of their accuracy and reliability, ease of use and specific scope of implementation. Further, they are classified according to the modelling method employed, the parameter extraction technique used, the level of granularity, their computational complexity, the number of irradiance levels considered and the provision of experimental results for their validation. A taxonomy is presented based on these attributes, along with a detailed list of their perceived contribution to PV modelling theory. Concerning the modelling method employed, in particular, a comprehensive analysis is presented related to the accuracy, robustness, computational efficiency, ease of implementation, simplicity and scope of application, pointing out the strong points and weaknesses of each method. Based on the review of the available literature, research topics open to further investigation are identified and discussed. This is also supplemented by novel and promising ideas recently introduced in the field, which provide fertile ground for future research.

In Section 2 of the paper, the problem formulation is presented and the reviewed models are analysed and classified. A detailed discussion regarding the advantages and weaknesses of the modelling methods is given in Section 3. Future research topics are suggested in Section 4, followed by the main conclusions in Section 5.

2 PV modelling at partial shading conditions – Problem formulation

2.1 Introduction

A PV energy yield model consists of an electrical equivalent circuit, mathematical equations, a set of parameters and a clear methodology to calculate the electrical response of a PV system and especially the electrical power output. Inputs to this procedure are the PV installation characteristics, such as the type and properties of the PV modules, the layout and interconnection scheme of the PV generator, as well as the operating conditions in terms of irradiance and temperature over the PV plant. Outputs of the model may be either specific operating points, such as the global MPP and local MPPs, or the entire *I-V* and *P-V* characteristic curves, depending on the scope of application. Especially for the general case of non-uniform operation, that is, uneven irradiance and temperature distribution (partial shading), the electrical response of the PV system may become quite complex, necessitating sophisticated modelling methods to determine the energy yield with sufficient accuracy.

A typical electrical equivalent for the PV cell is depicted in Fig. 1*a*. It consists of a photocurrent source I_{ph}, two diodes D_1 and D_2, series and shunt resistances R_s and R_{sh}, as well as an extension term to represent the negative diode breakdown operation $I(V_d)$. Similar equivalents are adopted in most modelling approaches reviewed, all being based on fundamentals of the electronics theory [1–12, 14, 16, 17, 19–22, 24–26, 28–37, 39, 41–46]. The basic commercially available PV unit is the module, comprising several cells connected in series, with one or more bypass shunt-connected diodes to prevent hot-spot phenomena (Fig. 1*b*). The group of cells connected in parallel with a bypass diode is denoted hereafter as the 'cell string', whereas other similar terms are found in the bibliography (cell-group, sub-module etc.). To achieve higher output power levels, several PV modules are connected in series and in parallel, in various configurations, forming the PV array. The most simple and widely used scheme is the series–parallel (SP) configuration (Fig. 2*a*), in which the PV array comprises a few parallel-connected branches, denoted as the PV strings, each consisting of several PV modules connected in series. Other configurations proposed in literature are the bridge–linked (BL) and total-cross-tied (TCT) schemes (Figs. 2*b* and *c*) [4, 6, 7, 9, 16, 19, 26, 32, 44].

The PV cell operation may not be characterised as an independent voltage or current source, but it exhibits a non-linear characteristic as shown in Fig. 3*a*. At small load resistance values it operates close to short circuit (SC) region producing high current, whereas high voltage is achieved close to open circuit point (OC). However, the most favourable operation is at the MPP, where the power output is maximised. Under partial shading conditions, the current of the shaded cells is reduced, thus limiting the current of the entire cell string. This may drive the shaded cells in negative voltage, leading to significant power dissipation and creating hot spots. This condition is circumvented by the inclusion of the bypass diodes which effectively separate the series connected cells into several groups. The *I-V* characteristic of a cell string with and without a bypass diode is illustrated in Fig. 3*b*. If the cell string is forced to carry a current higher than its SC current, the negative terminal voltage developed causes the conduction of the bypass diode (dashed line), whereby the terminal voltage is clipped to the diode's forward voltage drop. In the case of a partially shaded PV module, string or array, this may happen only to certain cell strings, which operate at reduced irradiance levels, with a direct effect on the shape of the resulting *I-V* and *P-V* characteristics. Indicatively, in Fig. 4*a* a PV array comprising three strings is depicted, experiencing three irradiance levels. The effect of the bypass diodes leads to step-wise *I-V* characteristic and to a *P-V* curve with multiple local peaks (Fig. 4*b*), which hinder the identification of the global maximum power point.

The identification of the MPPs is performed in the literature using a variety of different models and methodologies, which present varying degrees of accuracy, simplicity, efficiency and scope of application. A taxonomy of the reviewed PV energy models and methodologies at partial shading conditions is presented in Table 1, according to the attributes further analysed in the following Sections 2.2–2.7.

2.2 Modelling method

The majority of the study-case papers employ an electrical equivalent circuit for the fundamental element modelled, that is, the PV cell, module or array, depending on the level of granularity. The most widely used model is the single-diode electrical equivalent (or one-diode model or five parameters model), which employs the circuit of Fig. 1*a*, without the second diode D_2 and the reverse

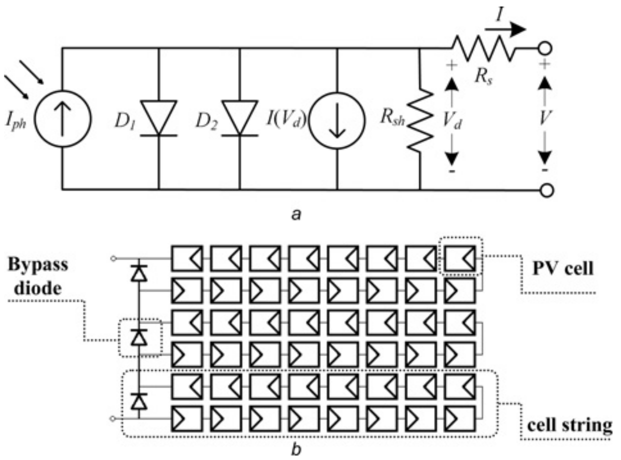

Fig. 1 *Schematic diagrams*

a PV cell double-diode electrical equivalent enhanced by a term for reversed operation
b PV module structure [43]

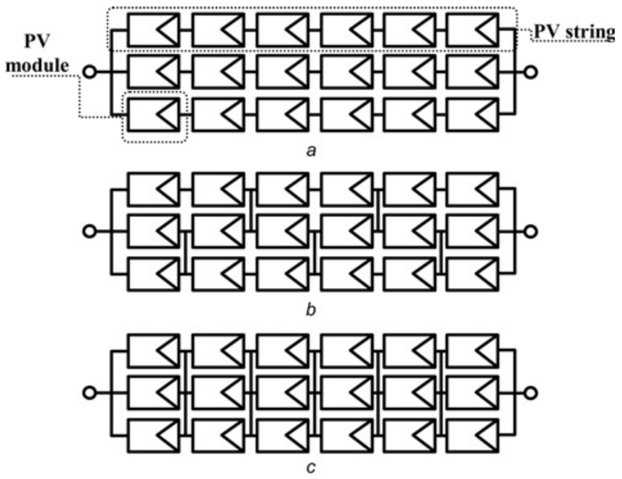

Fig. 2 *PV array interconnection schemes*

a Series–parallel
b Bridge–linked
c Total-cross-tied configuration

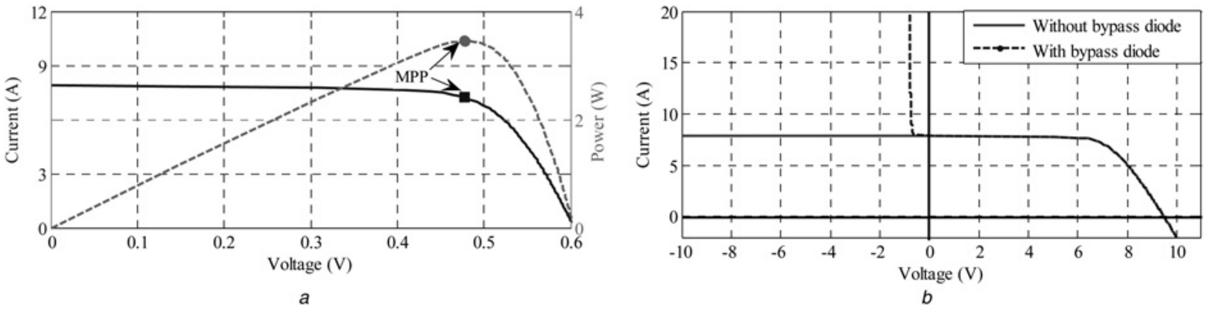

Fig. 3 *Characteristic curves*

a I-V (continuous line) and *P-V* (dashed line) curves of a typical PV cell
b I-V curve of a typical cell string without (continuous line) and with (dashed line) a bypass diode [43]

operation term $V(I_d)$ [4, 7, 9, 10, 12, 16, 20, 22, 29–31, 34, 35, 37, 42, 46]. More simplified versions of this model are also reported, where the series and/or shunt resistances R_s and R_{sh} are neglected [6, 21, 32, 33]. In order to describe more accurately the operation at negative voltage, several enhancements are proposed in the bibliography as expansions of the single-diode model (in the following, *+neg* is used to identify them) [1, 3, 5, 8, 11, 28, 43]. The most comprehensive model employs the double-diode equivalent, with or without the reverse operation term [2, 14, 17, 19, 24, 25, 41], as shown in Fig. 1*a*, whereas various piecewise simplifications are reported in [26, 39, 45]. All these methods utilise the adopted model as the main modelling block, building a more extended circuit to describe the entire PV installation, which is solved using suitable electric circuit analysis algorithms and software.

Alternative approaches are proposed in the literature, which attempt to avoid the detailed and laborious circuit-based modelling of the entire PV system. These methods focus on specific operating points of particular interest, such as the global or local MPPs, instead of providing the entire *I-V* or *P-V* characteristic. They usually employ simple and easy-to-use expressions, often incorporating empirical terms, with an impact on accuracy [15, 18, 27, 36, 38, 40, 43, 44]. Artificial neural network (ANN) approaches may also be found [13, 23].

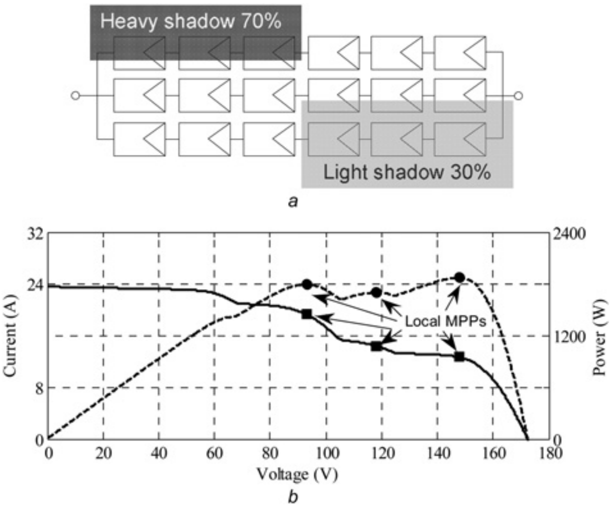

Fig. 4 *PV array comprising three strings illuminated at three irradiance levels*

a Shading pattern
b I-V (continuous line) and *P-V* (dashed line) curves, presenting multiple local MPPs

2.3 Parameter extraction

In equivalent circuit-based approaches, parameters employed refer to the circuit elements (I_{ph}, R_s, diode characteristics etc.); such data are usually not given on the PV module datasheets and therefore need to be estimated. Some of the reviewed methods identify these parameters at standard test conditions (STC) and then extrapolate them to the actual operating conditions, based solely on module datasheet information [12, 18, 19, 21, 24, 29, 30, 32, 39, 42]. For this purpose, a set of equations is solved, derived for the characteristic operating points (MPP, SC point, OC point), via a suitable numerical method or iterative algorithm. In [21, 32], in particular, this procedure is explicit because of the simplicity of the three-parameter model employed. Other approaches require a set of measurements, such as the *I-V* characteristic or specific operating points at certain conditions, which are combined with the datasheet to estimate the electrical parameters via a curve fitting technique [3, 16], an ANN [9, 13, 23] or using simplified explicit expressions [22, 33, 41].

Similarly, the empirical methods that are not based on equivalent circuits also employ a set of parameters, which supplement the module's datasheet information and, along with the irradiance and temperature, constitute the input data of the mathematical expressions that evaluate the output of the PV system [15, 18, 25, 27, 38, 40, 43, 44].

The rest of the reviewed papers do not provide a method to determine the required parameters. They usually consider specific study-case parameter values [2, 5, 6, 8, 10, 11, 14, 17, 26, 28, 31, 34, 36, 37], in certain cases derived randomly from a normal distribution [1, 4], whereas in other parameter values are not reported at all [7, 20, 35, 45, 46].

2.4 Modelling scale

The level of granularity varies significantly among the reviewed papers. The most comprehensive circuit-based approaches support a 'Cell to array' modelling scale to describe the electrical response at non-uniform operating conditions with maximum accuracy [1–4, 6, 7, 9, 12, 14, 17, 19, 22, 28–30, 33, 38, 39, 41, 42, 44, 46], whereas others employ simplifications and consider the PV cell string or module as the fundamental block, in order to reduce modelling complexity [10, 16, 21, 24, 26, 32, 34, 37, 40, 45]. More restrictive approaches are limited to series connected PV structures, supporting a 'Cell to string' [8, 35, 43], 'Module to string' [31], or even 'Cell to module' [5, 11, 20, 23, 25, 36] modelling scale. Some of the empirical methods, which do not adopt the modular

Table 1 Taxonomy of the PV energy models reviewed

Ref.	Modelling method	Parameter extraction	Experimental validation	Modelling scale	Computational technique	Irradiance levels
[1]	single-diode equivalent + neg	random from normal distribution	yes	cell to array	evaluation of explicit equations + linear interpolation	any
[2]	double-diode equivalent + neg	specific values assumed	yes	cell to array	numerical solution of system of equations	any
[3]	single-diode equivalent + neg	measurements + datasheet	no	cell to array	not stated	any
[4]	single-diode equivalent	random from normal distribution	no	cell to array	numerical solution of system of equations	any
[5]	single-diode equivalent + neg	specific values assumed	yes	cell to module	numerical solution of system of equations	any
[6]	single-diode equivalent – No Rs	specific values assumed	no	cell to array	alternative iterative algorithm	any
[7]	single-diode equivalent	not stated	no	cell to array	numerical solution of system of equations	any
[8]	single-diode equivalent + neg	specific values assumed	no	cell to string	not stated	any
[9]	single-diode equivalent	measurements + datasheet	no	cell to array	numerical solution of system of equations	any
[10]	single-diode equivalent	specific values assumed	no	module to array	numerical solution of system of equations	any
[11]	single-diode equivalent + neg	specific values assumed	yes	cell to module	circuit simulation in SIMULINK	any
[12]	single-diode equivalent	datasheet	yes	cell to array	numerical solution of individual equations + linear interpolation	any
[13]	ANN	measurements + datasheet	yes	PV plant	ANN	2
[14]	double-diode equivalent + neg	specific values assumed	yes	cell to array	circuit simulation in PSPICE	any
[15]	empirical mathematical expressions	empirical constants + datasheet	yes	PV plant	evaluation of empirical explicit expressions	2
[16]	single-diode equivalent	measurements + datasheet	yes	module to array	numerical solution of system of equations	any
[17]	double-diode equivalent + neg	specific values assumed	no	cell to array	circuit simulation in PSPICE	any
[18]	empirical mathematical expressions	datasheet	yes	PV plant	evaluation of empirical explicit expressions	2
[19]	double-diode equivalent	datasheet	yes	cell to array	numerical solution of individual equations + linear interpolation	any
[20]	single-diode equivalent	not stated	no	cell to module	circuit simulation in SIMULINK + PSPICE	any
[21]	single-diode equivalent – no Rs/Rsh	datasheet	no	cellstring to array	numerical solution of system of equations	any
[22]	single-diode equivalent	measurements + datasheet	yes	cell to array	circuit simulation in PSCAD	any
[23]	ANN	measurements + datasheet	yes	module	ANN	2
[24]	double-diode equivalent	datasheet	yes	module to array	circuit simulation in SIMULINK	any
[25]	double-diode equivalent + neg/mathematical expressions	empirical constants + datasheet	yes	cell to module	evaluation of explicit equations	2
[26]	piecewise model	specific values assumed	no	module to array	numerical solution of system of equations	any
[27]	empirical mathematical expressions	empirical constants + datasheet	yes	PV plant	evaluation of empirical explicit expressions	2
[28]	single-diode equivalent + neg	specific values assumed	no	cell to array	numerical solution of system of equations	any
[29]	single-diode equivalent	datasheet	no	cell to array	circuit simulation in SIMULINK	2
[30]	single-diode equivalent	datasheet	yes	cell to array	circuit simulation in SIMULINK	2
[31]	single-diode equivalent	specific values assumed	no	module to string	numerical solution of system of equations	any
[32]	single-diode equivalent – no Rs/Rsh	datasheet	no	module to array	numerical solution of system of equations	any
[33]	single-diode equivalent – no Rsh	measurements + datasheet	yes	cell to array	circuit simulation in SIMULINK	any
[34]	single-diode equivalent	specific values assumed	yes	module to array	numerical solution of system of equations	any

Continued

Table 1 Continued

Ref.	Modelling method	Parameter extraction	Experimental validation	Modelling scale	Computational technique	Irradiance levels
[35]	single-diode equivalent	not stated	no	cell to string	numerical solution of individual equations + linear interpolation	2
[36]	empirical mathematical expressions	specific values assumed	yes	cell to module	numerical solution of a single equation	2
[37]	single-diode equivalent	specific values assumed	yes	module to array	numerical solution of system of equations	any
[38]	empirical mathematical expressions	empirical constants + datasheet	no	cell to array	evaluation of empirical explicit expressions	2
[39]	piecewise model	datasheet	yes	cell to array	numerical solution of system of equations	any
[40]	empirical mathematical expressions	empirical constants + datasheet	yes	module to array	evaluation of empirical explicit expressions	2
[41]	double-diode equivalent	measurements + datasheet	yes	cell to array	circuit simulation in PSPICE	any
[42]	single-diode equivalent	datasheet	no	cell to array	circuit simulation in SIMULINK	2
[43]	single-diode equivalent + neg/mathematical expressions	empirical constants + datasheet	yes	cell to string	evaluation of explicit equations	any
[44]	empirical mathematical expressions	empirical constants + datasheet	yes	cell to array	evaluation of explicit equations	any
[45]	piecewise model	not stated	yes	module to array	evaluation of explicit equations + linear interpolation	any
[46]	single-diode equivalent	not stated	no	cell to array	numerical solution of system of equations	any

structure of the circuit-based techniques, are applicable to any 'PV plant' regardless of its configuration [13, 15, 18, 27].

2.5 Computational technique

The computational procedure employed is a key factor for the ease of implementation, robustness and computational efficiency of the modelling method. The circuit based techniques use either equation solving algorithms implemented on a computational platform, such as MATLAB, or circuit simulation software, where the complete circuit of the entire PV system is built and simulated. Such software is MATLAB/SIMULINK [11, 24, 29, 30, 33, 42], PSPICE [14, 17, 41], PSCAD/EMTDC [22] or a combination of them [20]. This approach is convenient in order to study the electrical response of the PV system, especially when power electronics are simulated at the same time, but requires developing the entire circuit model, while simulation times are usually long.

The equation solving approach, on the other hand, offers increased versatility in the implementation, but is often susceptible to numerical issues, such as convergence failures [2, 4, 5, 7, 9, 10, 16, 21, 26, 28, 31, 32, 34, 37, 39, 46]. Variations of this approach include the solution of a set of individual equations, rather than simultaneously solving a system of equations and linear interpolation [12, 19, 35], whereas a single equation is numerically solved in [36], but this method may model only a single PV module. Such computational methods typically lack in robustness and reliability, drawbacks afflicting to a certain extent alternative iterative algorithms [6], as well.

A few analytical circuit-based approaches are found in the bibliography, which introduce explicit expressions for MPP calculation [25, 43, 44]. These methods utilise empirical coefficients to directly evaluate the global and local MPPs, rather than the entire characteristic. These straight-to-the-point techniques avoid laborious simulation and present improved computational efficiency and complexity, but at the cost of decreased applicability and accuracy. On the other hand, the methods in [1, 45] provide an explicit way to determine the *I-V* curve of the component PV units (cell or module) and then apply interpolation for the entire PV array characteristic. However, these procedures apply only when the entire characteristic needs to be calculated, rather than specific operating points.

Other alternatives, not based on equivalent circuits, formulate simple empirical equations that utilise macroscopic observations regarding the relation of the power output to the intensity and extent of the shadow [15, 18, 27, 38, 40]. They are mainly based on the definition of the PV module efficiency, which is extended to the entire PV plant and at non-uniform illumination conditions. These approaches, denoted hereafter as 'empirical efficiency-based' methods, offer a quite simple and computationally efficient way to calculate the energy yield of a PV system, but the lack of a solid theoretical basis limits their scope.

ANN methods are also found in the bibliography [13, 23], which avoid the detailed electrical modelling by building a neural network to estimate the energy yield of a PV system at partial shading. These techniques present in general sufficient accuracy and computational efficiency, but they suffer from the need for training the ANN and its limited applicability beyond the specific PV installation for which it has been trained.

2.6 Irradiance levels supported

The majority of the models supports multiple irradiance levels across the PV system, because of the modular structure of the circuit-based equivalents, which permits accounting for different operating conditions on each modelling block (cell, module etc.). On the other hand, the empirical efficiency-based methods [15, 18, 27, 38, 40] and the ANN approaches [13, 23] are restricted to the common

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simplifying assumption of two irradiance levels (one for the shaded and one for the unshaded part). This consideration provides the basis for the derivation of explicit MPP expressions in [25], the improvement of the calculation procedure in [35] and the formulation of a single equation for the entire PV module in [36], whereas in [42] a thorough partial shading analysis and correlation with various parameters is presented based on this simplification.

2.7 Experimental validation

The experimental validation of the proposed methods, where it is provided, offers confidence in the results, quantifies their expected accuracy levels and demonstrates the applicability of the models in practical conditions. This procedure usually consists in comparing the measured and simulated *I-V* characteristics in several operating conditions and shading scenarios. Among the reviewed papers, experimental validation is performed in [1, 2, 5, 11–16, 18, 19, 22–25, 27, 30, 33, 34, 36, 37, 39–41, 43–45].

3 Comparative assessment of the methods reviewed

The modelling method and computational technique are directly related to the accuracy, ease of implementation, robustness and calculation efficiency, whereas they strongly vary among the reviewed papers. A classification is given in the following, in which the characteristics of each category are analysed and compared with the others. The main contribution of each work reviewed is described in detail and presented in chronological order in Table 2.

3.1 Modelling based on equivalent circuits

These methods adopt an equivalent electrical circuit for the fundamental modelling block (PV cell, module etc.), which is expanded to the entire PV system. Their theoretical foundation is quite strong, however their implementation may be tedious and long simulation times are involved for the majority of these methods.

3.1.1 Implementation in standard circuit simulation software: Several commercially available circuit simulation software packages have been used to build and simulate a PV system, including SIMULINK [11, 20, 24, 29, 30, 33, 42], PSPICE [14, 17, 20, 41] and PSCAD/EMTDC [22].

This approach presents the significant advantage that a single circuit model can be built, incorporating the PV system itself, along with any other relevant devices, such as power converters, which may be appropriate when the PV array needs to be studied as part of a greater system, for example, for dynamic response, control evaluation etc. On the other hand, the development of the circuit model may become quite laborious and not easy to automate. For example, for every change in the PV system, the entire circuit may have to be manually altered by the user, rendering these methods more suitable for theoretical studies, rather than for practical application and integration in PV software tools. Moreover, some equations of the model may be difficult to be properly included in software focused specifically on electrical circuits (e.g. the dependence of the circuit parameters on irradiance and temperature).

3.1.2 Mathematical formulation – System of equations: Instead of employing an electrical circuit simulation package, the equations of a circuit-based model can be directly implemented in a suitable computational platform, such as MATLAB and the system of equations can be numerically solved, usually with a Newton-like method, [2, 4–6, 7, 9, 10, 16, 21, 26, 28, 31, 32, 34, 37, 39, 46]. In this case, the most time-consuming task is the determination and inversion of the Jacobian matrix, which is the focus of [10, 21, 37]. Specifically, in [10] the Lambert W function is employed to formulate the Jacobian matrix in a straightforward manner, whereas in [21] a simplified three-parameter model is adopted to permit efficient inversion of the Jacobian via LU factorisation. Recently, an elegant explicit symbolic formulation of the inverse Jacobian matrix has been proposed in [37], with the use of Lambert W function.

Beyond that, the robustness and reliability of the iterative procedure is improved in [28], where a dumped Newton method is proposed, and in [31], where an analytical initialisation strategy is adopted to provide good starting point and quicker convergence. Moreover, various simplifications are reported in the bibliography to effectively reduce the complexity of the system of equations, such as in [26, 39] in which a piecewise linear model is used for the PV cell and in [21, 32], where the series and shunt resistances are neglected. In [4, 6], other improvements are reported using linear programming and an alternative iterative algorithm, respectively, whereas in [34] a single explicit equation is formulated for each PV string using the Lambert W function, significantly reducing the size of the system of equations.

An important advantage of this approach is the versatility in formulating the model, without any compromise in accuracy, as the fundamental equivalent of the PV cell may be as complicated as necessary. The system of equations for the entire PV system at any operating conditions can then be parametrically formulated using any suitable programming language or computational platform, rather that specific software for the analysis of electrical circuits.

On the other hand, the numerical solution of the resulting system of equations is the main source of difficulties for this family of methods. Special treatment of the calculation algorithm is often needed, convergence issues exist and requirements arise concerning the initialisation and robust implementation to prevent convergence failures or inefficiencies. Hence, although such issues have been partially addressed in certain studies, the implementation of these methods remains quite complicated and tedious, whereas their computational cost is typically the highest among all methods.

3.1.3 Mathematical formulation – Independent equations: The drawbacks of the previous methods are mitigated in [12, 19, 35, 36], where the system of equations is replaced by separate equations, solved independently via a numerical method. In [12, 19], the fundamental equation for every modelling block is numerically solved to produce the entire *I-V* characteristic and curve superposition is subsequently applied to estimate the electrical response of series and parallel connected PV structures. A similar concept is presented in [35], except that the equations solution and linear interpolation procedures are performed simultaneously in the proposed algorithm and one level of shade is assumed. An interesting formulation of a single

Table 2 Main topic/contribution of the reviewed papers

Ref.	Published	Contribution
[1]	October-88	The most widely used model for reversed operation of the PV cell. A curve superposition technique is proposed.
[2]	June-96	First formulation of a system of equations for mismatched operation, numerically solved by the Newton-Raphson method.
[3]	August-96	The reversed operation of shaded cell is studied and the accuracy of Bishop's term is verified.
[4]	April-02	Linear programming is used to efficiently formulate the system of equations.
[5]	February-03	Systematic investigation of shading impact on the electrical response at module level.
[6]	March-03	An alternative iterative algorithm for the solution of the system of equations is introduced.
[7]	September-06	A model for changing illumination conditions is proposed.
[8]	October-06	Series connected PV structure is modelled employing a sophisticated term for reversed operation of the cell.
[9]	January-07	ANN is used for the five parameters determination.
[10]	November-07	First use of the Lambert W function in PV modelling. Utilised for explicit evaluation of the Jacobian matrix.
[11]	March-08	A circuit-based model implemented in SIMULINK is provided and used to study partial shading at module level.
[12]	May-08	A curve superposition technique is presented for the extraction of the entire characteristics of PV arrays.
[13]	September-09	An ANN is introduced that correlates the sun position and ambient temperature to the power output under shading conditions.
[14]	September-09	Implementation of the double-diode + neg electrical equivalent in PSPICE.
[15]	June-10	Empirical model for a simplified evaluation of the power losses.
[16]	July-10	The Lambert W function is employed, approximated by an asymptotic formula.
[17]	September-10	Study of the correlation between the shading intensity and extent with the presented MPPs.
[18]	December-10	Alternative simple empirical method for rough approximation of the shading losses.
[19]	January-11	A model based on the double-diode equivalent and curve superposition technique is presented with an efficient parameters extraction method.
[20]	March-11	A hybrid model implementation in both SIMULINK and PSPICE is presented.
[21]	April-11	A simplified single-diode equivalent is used for efficient Jacobian inversion and calculation of the infection voltages.
[22]	July-11	Circuit-based modelling employing extrapolation of the SC, MPP and ÒC operating points in actual operating conditions.
[23]	August-11	Implementation of an ANN to estimate five operating points and approximate the form of the characteristic curves.
[24]	September-11	Sophisticated SIMULINK implementation of the double-diode model for the PV array.
[25]	September-11	Circuit-based simulations in PSPICE and derivation of simple analytical expressions for the MPPs of a partially shaded PV module.
[26]	September-11	A piecewise linear model is introduced speeding up the computational procedure.
[27]	November-11	Simple empirical relations for self-shading losses in PV plants.
[28]	November-11	A robust damped Newton method is proposed for efficient solution of the system of equations.
[29]	March-12	Systematic investigation of the power losses dependence on the shading parameters.
[30]	May-12	Qualitative analysis of the shading impact on the presented MPPs.
[31]	September-12	An analytical initialisation strategy is proposed, prior to the numerical evaluation of the system of equations, to ensure convergence.
[32]	November-12	A simplified version of the single-diode model is employed for TCT configuration, and infection voltages are used for improved computational procedure.
[33]	December-12	A SIMULINK implementation of a simplified single-diode equivalent is introduced based on analytical parameters extraction method.
[34]	March-13	First formulation of a single equation for the PV string in the form of $V = f(I)$, employing the Lambert W function.
[35]	January-13	The entire characteristic of a PV string is calculated by separate solution of the component modules equations.
[36]	June-13	A single equation is proposed for a partially shaded PV module considering the reversed operation of the shaded cells.
[37]	July-13	An improvement of the Lambert W-based methods is presented, providing the inverse Jacobian matrix symbolically.
[38]	July-13	Simple empirical expressions for the shading losses estimation with increased accuracy.
[39]	September-13	Piecewise linear approximation of the exponential term in the single-diode model to reduce the computational cost.
[40]	October-13	Empirical relations for the power losses estimation at a uniformly shaded PV array.
[41]	November-13	PSPICE implementation of the double-diode model with analytical parameters extraction method.
[42]	December-13	Study of the correlation between the number of MPPs in a partially shaded PV string and the physical properties of the component modules.
[43]	January-14	Explicit modelling of the PV string using the Lambert W function and derivation of simple empirical relations for direct evaluation of the MPPs.
[44]	January-14	Explicit relations for the MPPs approximation at a partially shaded PV array.
[45]	June-14	A simple piecewise model is proposed for the component modules, using the SC, MPP and OC operating points as input parameters.
[46]	August-14	The impact of shade is inherently modelled into the system of equations by reducing the photocurrent of the shaded cells.

equation is introduced in [36], yet limited to the PV module and to the simplified case of two irradiance levels.

These methods present reduced calculation time and increased robustness and reliability, since every equation is separately solved rather than within a system of equations. They involve a simpler and easier implementation, as well as a less demanding numerical algorithm. Their accuracy is not reduced, provided that the characteristics are calculated at a sufficient number of operating points for the subsequent linear interpolation procedure [12, 19, 35].

Still, the disadvantages of the iterative procedures, that is, calculation uncertainty, initialisation and convergence issues, are only mitigated, rather than fully addressed. In addition, these methods have a limited applicability to the case that the entire characteristic curve has to be determined, rather than specific operating points [12, 19, 35], or to small scale PV systems and two irradiance levels [36].

3.1.4 Mathematical formulation – explicit equations: In [1, 25, 43–45], analytical methods are proposed to completely avoid the iterative procedure. In [1], the fundamental PV cell equation is manipulated to explicitly determine the *I-V* curves of all component cells and linear interpolation is applied thereafter for the array. A similar technique is adopted in [45], except that a simplified piecewise model is used for the PV unit to achieve analytical formulation. On the contrary, the methods in [25, 43, 44] provide only the local MPPs of a partially shaded PV module [25], string [43] and array [44], rather than every operating point of the *I-V* curve.

The models above have effectively addressed the computational issues of all previous approaches, eliminating the calculation uncertainty and significantly reducing the execution time and modelling complexity. In particular, the MPP-determination methods [25, 43, 44] provide a simple way to directly evaluate the local and global MPPs, when this is the main objective of the simulation, dispensing with the need for calculation of the entire characteristic.

Conversely, the accuracy and applicability of these methods are reduced because of the simplifications involved. None of them supports determination of any specific operating point; the techniques in [1, 45] are applicable only when the entire *I-V* curve is to be determined, whereas the models presented in [25, 43, 44] may provide only the MPPs and no other operating point.

3.2 Empirical efficiency-based methods

Alternative approaches are found in the bibliography, in which the modelling is based on empirical observations, rather than on equivalent circuits [15, 18, 27, 38, 40]. These methods correlate the shadow extent and intensity with the power losses in simple analytical mathematical expressions, which essentially are extended versions of the efficiency definition for the PV module. The models presented in [15, 27, 40] concern row-to-row shading, whereas in [15, 18, 38] the energy models proposed include the irradiance modelling as well.

These methods are the most simple and easy-to-use option to roughly estimate the power output of a PV system at partial shading conditions. The mathematical expressions derived are readily implemented and the variables and parameters involved are easy to understand and manipulate by any user.

However, this simplicity comes at the cost of decreased accuracy and reliability. The theoretical foundation is not particularly strong, since it is based on empirical observation rather than on electrical parameters, whereas they involve various assumptions and simplifications, such as a single level of shade, portrait orientation of the modules, consideration only row-to-row shading etc. The estimated power output practically corresponds to a specific MPP, which is arbitrarily considered as the global, rendering these methods a convenient way to roughly estimate power losses because of shading, rather than a comprehensive energy model.

3.3 ANN methods

Limited applications of ANN to predict the output of a PV system under partial shading are reported in the bibliography [13, 23]. In [13], the shading phenomenon is simplified to be described only by a few parameters (irradiance, solar angles and ambient temperature), whereas the output of the ANN is the maximum power produced. The ANN itself is relatively simple and presents sufficient accuracy, since it is trained on measurements of the actual installation. This is an obvious limitation which is mitigated in [23], where a circuit-based model of the type described in Section 3.1.2 is considered only for training the ANN. A detailed thermal model is also adopted, supporting different operating temperature on each module, whereas the sophisticated ANN proposed calculates five operating points of the *I-V* curve (according to Sandia Laboratories formulation [47]), rather than just the global MPP. These five points may not completely describe the *I-V* curve at partial shading, unlike in uniform illumination conditions, but the maximum power is still estimated.

The advantage of an ANN modelling approach is that complicated circuit modelling with several electrical parameters is completely avoided. The implementation does not consider the fundamental principles of the complex phenomenon and thus no special PV-related knowledge is required. If properly trained, the ANN may provide fast and sufficiently reliable estimations.

The main drawback of such an approach is the training procedure and the lack of generalising capability, beyond the specific PV installation on which the ANN has been trained. The training set is provided either by measurements [13], which is impractical for most applications of an energy model (installation planning, array topology optimisation etc.), or by simulations using a detailed circuit-based model [23], thus negating the benefits in modelling complexity. In conclusion, this method is more suited for theoretical studies, rather than for practical implementation.

4 Future research

4.1 Improvement of the computational methods

4.1.1 Circuit-based modelling: The circuit-based models represent the most faithful modelling approach, achieving best accuracy, albeit at the cost of increased complexity, low robustness and high computational cost. The system-of-equations approaches could benefit from improved numerical algorithms, either variations of the Newton method or other specialised iterative techniques, which would employ proper initialisation and more robust execution to ensure convergence and minimise simulation time. Another way to accomplish this is by simplifying the modelling, either by making assumptions or utilising modern mathematical tools, such as the increasingly popular Lambert W function. The latter has already been used to explicitly formulate a single equation for the PV string [34, 43], thus a future step would be to extend it to PV arrays of various configurations (SP, BL, TCT). Furthermore, recent papers have attempted to avoid the detailed modelling and the calculation of the entire *I-V* curve, by providing simple analytical relations to directly evaluate local MPPs [25, 43, 44]. This is a relatively new and promising approach that deserves more attention and investigation.

4.1.2 Empirical modelling: The empirical methods reviewed provide a simple way to estimate power output, but lack in their theoretical foundation and accuracy in the general case. There is considerable research in this field, especially on the justification of empirical models and their correlation with fundamental principles of PV modelling theory, on their applicability (multi-irradiance cases, various configurations and orientations etc.), on their accuracy and other relevant topics.

4.2 Improvement of the electrical equivalent circuits

Regarding the circuit-based approaches, the equivalent circuit still needs improvement, especially the term that describes reverse operation. The widely used Bishop's term [1] has been reported to lead to inaccuracies in some cases, whereas other physically-based models do not face wide acceptance because of complicated formulation [8]. Moreover, the majority of the reviewed works concerns the widespread crystalline Si technology, whereas other commercial PV cell technologies (thin film, organic etc.) have not been sufficiently modelled at partial shading conditions yet.

4.3 Optimisation of the parameter extraction methods

The determination of the model parameters, especially for the circuit-based methods, is usually a quite laborious procedure, often leading to poor results or convergence failures. Analytical methods have been proposed to tackle these problems, but their accuracy is only moderate. This is a topic of special interest that might possibly make use of AI techniques, the Lambert W function and other tools. Minimum dependence on measurements should be achieved, to maximise applicability. Some steps have been made towards this direction, but further investigation is still needed to formulate accurate and computationally efficient parameter extraction techniques, ideally based only on datasheet information.

4.4 Expansion of the applicability

Most of the circuit-based methods that employ a system of equations may model any PV system, regardless of its configuration, using the PV cell as the fundamental block and for the general multi-irradiance case. However, in order to improve the computational efficiency, some of the reviewed works make simplifications and assumptions that reduce their applicability to smaller PV systems than the PV array with a building block of cell string or module, rather than the cell. Many studies also consider a single level of shade, which is the common case but not the general one, whereas other approaches, particularly the empirical methods, adopt additional assumptions that further constrain their use. The simplifications above lead to simpler and more cost-efficient implementation, albeit at the cost of reduced applicability and accuracy. This issue deserves more investigation in order to ideally combine computational efficiency and practical applicability so that these methods face wider acceptance.

4.5 Application to MPPT algorithms

The global MPPT algorithm is a very popular field of research. Most of the relevant works employ sophisticated control that utilises real time measurements, whereas a model-based approach employing an accepted PV energy model would also be a promising alternative. Relevant papers [45] adopt a very simplified model, because of the computational constraints imposed by the microprocessors, leading to moderate efficiency. Therefore an interesting research topic is to implement an accurate analytical model and analyse the capability of the MPPT algorithm to locate the global MPP. A most challenging task in such an investigation would be the real-time identification of the model's parameters and operating conditions from the measurements.

5 Conclusions

This paper presents a comprehensive review of the state of the art PV models for non-uniform illumination conditions. A classification according to the modelling method and computational complexity, as well as other noteworthy attributes, is provided, whereas a comparative assessment is given regarding the calculation requirements, robustness, applicability and ease of implementation. Most methods employ an electrical equivalent circuit for the main building block (PV cell, cell string or PV module, according to the level of granularity of the model) and formulate an extended circuit to model the entire PV system. The electrical equivalent is usually based on the single/double diode model, with several variations to increase accuracy or reduce complexity, whereas the calculation procedure is realised either in circuit simulation software (SIMULINK, PSPICE and PSCAD/EMTDC) or by specialised algorithms (usually Newton-based methods). The main drawback of these approaches lies in the computational uncertainty and burden. Several papers propose simplifications to reduce modelling complexity and computational cost, as well as to increase robustness and reliability, however at the expense of reduced accuracy or applicability. A detailed discussion is provided on these topics, highlighting strengths and weaknesses of each option and highlighting available alternatives, in order to aid researchers to select the method best suited to their specific application.

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