Experimental verification of a method to model the operation of PV modules during irradiance transitions

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Abstract Photovoltaic (PV) systems are prone to deep, steep and frequent irradiance fluctuations, mainly originated from overpassing cloud shadows, which cause fluctuations in PV power production. These irradiance transitions have been modelled by using a mathematical function to study their behaviour in a systematic way. Although the used methods and obtained results seem to be reliable, the simulation model has not been verified in detail. In this paper, the accuracy of the used theoretical model for irradiance transitions has been verified experimentally. The results show that the simulation model is accurate enough to study the irradiance transitions caused by moving clouds and their effects on the operation of PV systems.

1 Introduction

Photovoltaic (PV) systems are prone to irradiance fluctuations, mainly originated from overpassing cloud shadows, which cause fluctuations in PV power production. These fluctuations can be deep, steep and frequent [1]. Partial shading resulting from cloud shadows may also lead to mismatch power losses and to the occurrence of multiple maximum power points (MPPs) leading to failures in MPP tracking thereby causing extra losses.

During the past few years, several studies have been presented regarding the operation of partially shaded PV systems, e.g. [1–5]. The PV modules are usually modelled through the one-diode model, which provides a good trade-off between accuracy and complexity. However, the actual correctness and accuracy of the used simulation approaches and tools have obtained little attention. A comparison between the one and two-diode models of a PV cell under partial shading conditions has been presented in [6] using MATLAB Simulink. An LTspice simulation model, based on the one-diode model, has been presented and validated in [7]. In [8], a one-diode model based simulation model of PV arrays has been presented and compared with two earlier published approaches.

In [9, 10], studies on the effects of the length of a simulation time step, the size of a basic simulation unit, and the resolutions of *I–U* curves and irradiance data on the accuracy of the simulations of PV system operation under partial shading conditions have been presented. It has been found that the irradiance accuracy of 1.0 W/m^2 and the number of *I–U* curve points of 1000 are sufficient for PV string and array level partial shading studies. The effect of the simulation unit size up to the size of a PV module has been found to be moderately small in long-term PV analysis and a time step of 1 s has been found to be short enough for most studies. However, sharp irradiance transitions may reveal an exception.

This paper presents an experimental verification of a method to model the operation of PV modules during irradiance transitions resulting from cloud shadows. The modelling method utilises the one-diode model and a mathematical irradiance transition model presented in [11]. Irradiance and temperature measurements and *I–U* curve measurements on a single PV module with sampling frequencies of 10 and 1 Hz, respectively, of four days have been analysed. The analyses show that the model of change in irradiance based on the modified sigmoid function gives accurate simulation results compared to simulations based directly on the measured irradiance and temperature of the PV module. Thus, the model of the irradiance transitions caused by moving clouds provides a realistic and usable way for PV power fluctuation studies.

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2 Methods

2.1. Simulation model for the PV modules

The one-diode model provides the following relationship between the current I and voltage U of a PV module:

$$I = I_{\mathrm{ph}} - I_{\mathrm{o}}\left(e^{\frac{U+R_{\mathrm{s}}I}{AN_{\mathrm{s}}kT/q}} - 1\right) - \frac{U + R_{\mathrm{s}}I}{R_{\mathrm{sh}}}. \qquad (1)$$

The parameters of this model are the light-generated current I_{ph}, the dark saturation current I_{o}, the series resistance R_{s}, the ideality factor A, the temperature T and the shunt resistance R_{sh}. N_{s} is the number of PV cells in the module, k the Boltzmann constant and q the elementary charge. In this study, the bypass diodes of the module were modelled using (1) with the assumptions that I_{ph} is zero, R_{sh} is infinite and the bypass diode temperature is equal to the temperature of the PV cells.

In Figs. 1 and 2, the measured and simulated *I–U* and *P–U* curves are presented under various operating conditions. The one-diode model was fitted to the measured *I–U* curves of a NAPS NP190GKg PV module. The simulated curves were obtained using the one-diode model and measured module irradiance and temperature at the time of curve measurement as input values. The black curves represent closely standard test conditions (STC) (1000 W/m^2 and 25 °C), the red curves lower temperature with the STC irradiance and the blue and green curves lower irradiances with the STC temperature. The differences in the short-circuit (SC) current and open-circuit (OC) voltage and in the MPP power, voltage and current between the measured and simulated curves of Figs. 1 and 2 are compiled into Tab. 1.

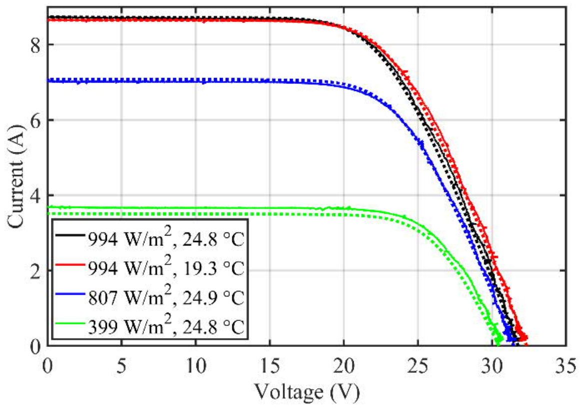

Fig. 1 Measured (solid lines) and simulated (dashed lines) *I–U* curves under various operating conditions.

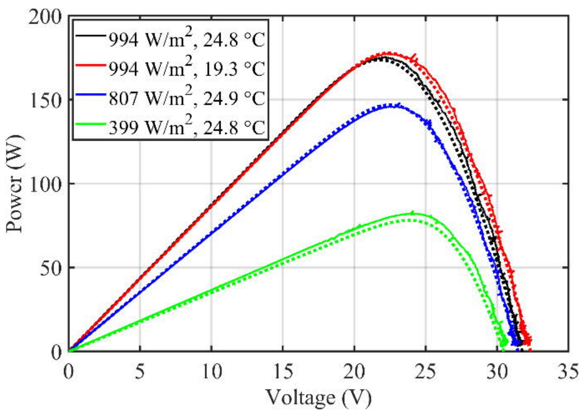

Fig. 2 Measured (solid lines) and simulated (dashed lines) *P–U* curves under various operating conditions.

Table 1 Accuracy of the simulation model in the cases of Figs. 1 and 2 with respect to the measured *I–U* curves.

Case	1	2	3	4
Irradiance (W/m^2)	994.4	994.5	806.7	399.4
Temperature (°C)	24.83	19.34	24.88	24.80
Difference in U_{OC} (%)	0.156	0.188	0.266	0.840
Difference in I_{SC} (%)	0.100	0.002	0.853	4.632
Difference in P_{MPP} (%)	0.915	0.252	0.519	5.176
Difference in U_{MPP} (%)	1.420	0.612	1.405	0.551
Difference in I_{MPP} (%)	0.496	0.228	2.305	4.415

Although the simulation model is quite accurate under good irradiance conditions, the accuracy is lower on low irradiance levels. This is a known feature of the one-diode model. The inaccuracy on low irradiance levels appears especially as a difference in current and, thereby, in power.

It is worth noting that the experimental measurements of the PV module were not performed at the terminals of the module. Thus, the measurements include the resistance of quite long cables (0.363 Ω), which is taken into account in the adjusting of the simulation model. Measurements also reveal that the actual module SC current is larger and the OC voltage is smaller in STC than declared by the manufacturer.

2.2. Irradiance transitions

Measurements done at the solar PV power station research plant of Tampere University has been used in this study. 201 decreasing and 199 increasing irradiance transitions were identified in four days (June 22nd–25th 2018) of data measured with a single irradiance sensor attached to the studied PV module by utilising the method described in [11]. The median duration of these transitions was 12.4 s.

The mathematical model based on the modified sigmoid function was used to model irradiance transitions caused by cloud edges [11]. The model gives irradiance G during a transition as

$$G(t) = \frac{G_{\mathrm{us}} - G_{\mathrm{s}}}{1 + e^{(t-t_0)/b}} + G_{\mathrm{s}}, \qquad (2)$$

where G_{us} and G_{s} are the irradiances of an unshaded and a fully shaded situation, respectively, and t is the time. Parameter t_0 defines the midpoint of the transition. Parameter b is related to transition steepness and its sign defines whether the transition is decreasing or increasing. The operation of the mathematical model has been validated with around 43,000 measured irradiance transitions in [12].

The average of the normalised root-mean-square deviation (NRMSD) between the curve fits and the measured irradiance transitions, normalised to the irradiance change during the transition, was 2.7%.

By using the mathematical model, irradiance transitions can be defined by four independent variables: *b*, shading strength, i.e., the irradiance attenuation due to shading, and apparent speed and direction of movement [12]. The combined use of the mathematical model and the simulation model of the PV module enables realistic simulations of the electrical behaviour of PV generators during partial shadings caused by clouds using measurements of only three irradiance sensors [12].

The irradiance given by the curve fit of the modified sigmoid function (2) to the measured irradiance data was used as an input for the simulation model. The temperature of the PV module was assumed to stay constant during an irradiance transition and the temperature at the beginning of the transition was used as an input for the simulation model. As a theoretically ideal reference case, the same one diode model of the PV module was applied by using the measured irradiance and temperature during the transition as inputs.

3 Results

First, the accuracy of the used one-diode model was studied utilising the measurements of four days. Daily measurement time was from 9 a.m. to 6 p.m. (UTC+2). The simulation results, obtained using the measured irradiance and temperature, were compared to the measured *I–U* curves. The results of this analysis are presented in Section 3.1.

In Section 3.2, the operation of the PV module during the identified irradiance transitions was studied. The simulation results obtained by utilising the measured irradiance and temperature values and by using the mathematical irradiance transition model were compared to the measured *I–U* curves. The results are further discussed in Section 3.3.

3.1 Accuracy of the one-diode model

The measured irradiance and the MPP power of the PV module for a 24 min period on June 23rd 2018 are presented in Fig. 3. The chosen period contained many irradiance transitions caused by moving clouds and is therefore a good example of partly clouded conditions. As can be seen in the figure, the irradiance transitions can be very deep and steep. The measured power follows the irradiance closely but the amplitude of the changes is smaller. The reason for this is that the efficiency of PV cells decrease with increasing cell temperature, which is caused by increasing irradiance.

The measured and simulated MPP power, voltage and current during a 5 min period on June 23rd 2018 are presented in Fig. 4. The differences between the simulation results and measurements were reasonably small. It can be seen in Fig. 4 that the simulation model somewhat smooths the fastest fluctuation spikes in the measurements. By

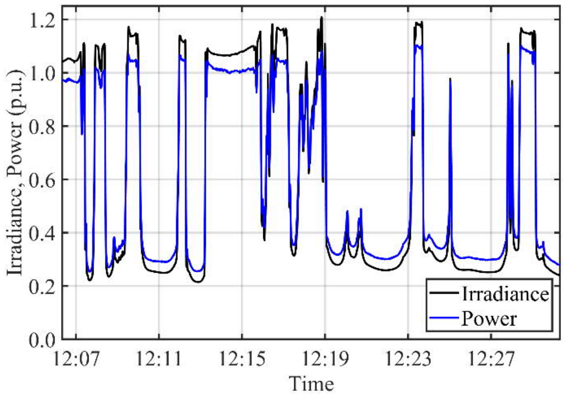

Fig. 3 Measured irradiance and PV module power during a 24 min period on June 23rd 2018. The irradiance is shown relative to the STC irradiance and the power relative to the nominal MPP power in STC.

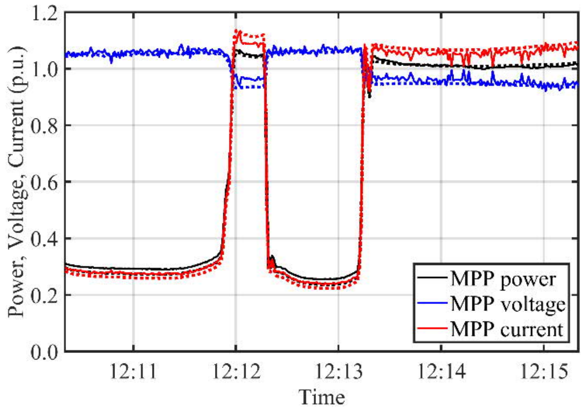

Fig. 4 Measured (solid lines) and simulated (dashed lines) MPP power, voltage and current during a 5 min period on June 23rd 2018.

comparing Figs. 3 and 4, it can be noticed that the MPP power and current increase with the increasing irradiance whereas the MPP voltage behaves in reverse. The decrease of the MPP voltage with the increasing irradiance is caused by the increase of the operating temperature of the PV cells.

The NRMSDs between the simulated and measured MPP power, voltage and current during the period of four days are compiled into Tab. 2. The NRMSD value of each quantity was normalised to the average of the measured values of the quantity. The NRMSD of the MPP voltage was clearly smaller than the NRMSD of the MPP power and current. The reason for this is that, as illustrated in Fig. 4, the changes in the MPP power and current during the studied period were much larger than in the MPP voltage,

Table 2 NRMSD values of the MPP power, voltage and current between the measurements and simulations during the period of four days.

Level of irradiance	P_{MPP} (%)	U_{MPP} (%)	I_{MPP} (%)
All irradiances	4.26	1.26	4.54
Below 400 W/m^2	5.93	1.25	5.83
Above 700 W/m^2	2.02	1.54	2.91

which is almost constant with irradiance values higher than 400 W/m^2 [12].

As stated earlier, the accuracy of the simulation model is worse with low irradiances than with high irradiances. Thus, the NRMSDs of the MPP power, voltage and current have been presented separately for low and high irradiances in Tab. 2. The NRMSD values of the MPP power and current were about three and two times, respectively, as large as at low irradiances than at high irradiances. On the contrary, the NRMSD of the MPP voltage actually decreased with the decreasing irradiance. During the studied period, the low irradiance values below 400 W/m^2 appeared 80% of the time leading to large overall NRMSD values of the MPP power and current. Only 10% of the time irradiance was more than 700 W/m^2.

3.2 Accuracy of the irradiance transition model

An example of the behaviour of the MPP power of the PV module during a typical irradiance transition is presented in Fig. 5. As can be seen the simulated power, obtained by using the measured irradiance and temperature as inputs, follows the measured power very well. Also the simulated power, obtained with the curve fit, matches well to the measured power with an NRMSD of 3.3%. In general, the largest differences between the simulated MPP power using the curve fit and the experimental MPP power appear during fluctuation spikes occurring during the transitions (such as around 1.5 s in Fig. 5) and during clearly asymmetrical transitions since the fitted function is symmetrical.

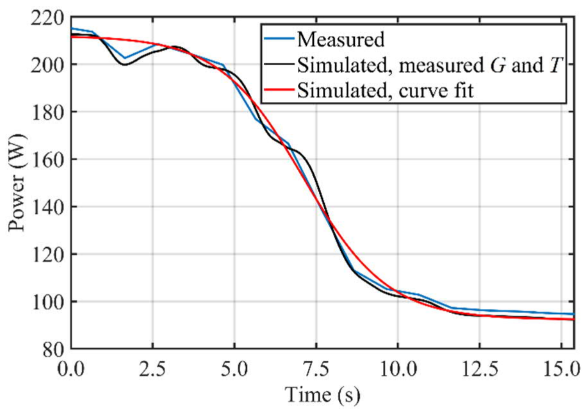

Fig. 5 Measured and simulated MPP power of the PV module during an identified irradiance transition.

The NRMSDs between the two simulated and the measured MPP power, voltage and current during the identified irradiance transitions are presented in Tab. 3. The NRMSD values between the simulated MPP power and current using the measured G and T and the measured ones were only somewhat higher than during the whole period of four days (Tab. 2), while the NRMSD of the MPP voltage was even a bit lower. This demonstrates that the one diode simulation model works well also during the transitions. The NRMSD values between the simulated MPP power and current using the curve fit and the measured ones were only around 50% larger that when using the measured G and T, whereas there was only negligible difference in the NRMSD of the MPP voltage between the two simulation methods. The small difference between the NRMSD values of the two simulation approaches confirms that the mathematical model based on the modified sigmoid function describes the irradiance transitions caused by cloud edges very well.

Table 3 NRMSD values between the two simulated and the measured MPP power, voltage and current during the identified irradiance transitions.

Simulation method	P_{MPP} (%)	U_{MPP} (%)	I_{MPP} (%)
Measured G and T	4.68	1.25	5.19
Curve fit	7.18	1.31	7.72

3.3 Discussion

The differences between the simulation results based on the one-diode model and the measured *I–U* curves are caused partly by the simplifications made in the used PV cell model but result also from other sources. The temperature used in the simulations was measured from the backside of the module. This temperature, naturally, can be up to 1 ºC lower that the actual operating temperature of the PV cells in the module. Moreover, the operating conditions of all the cells were assumed to be identical with each other. In practice, there are always some differences in the operating conditions of the cells. Especially during sharp irradiance transitions, irradiance and temperature differences can be notable. Also, when the mathematical irradiance transition model was applied, the temperature of the PV module was assumed to stay constant during an irradiance transition which causes some error to the results. Anyway, the differences between the simulation results and the measured *I–U* curves were relatively small.

4 Conclusions

An experimental verification of a method to model the operation of PV modules during irradiance transitions caused by cloud shadows was presented in this paper. The method uses the one-diode model for PV modules and a mathematical model based on the modified sigmoid function for irradiance transition. The one-diode model was shown to be accurate enough for most of the PV module and system analyses under highly varying climatic conditions. The modified sigmoid function has been used earlier to study irradiance transitions caused by moving clouds in a systematic way. It was verified experimentally in this study that irradiance transitions can be modelled accurately enough with the modified sigmoid function to study the irradiance transitions caused by moving clouds and their impact on the operation of PV systems.

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