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EXPERIMENTAL TESTING OF TWO SOLAR PANEL SIMULATIONS

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Abstract.

This paper focuses on verifying two simulation models by experimental [1]. Two models for silicon polycrystalline photovoltaic solar cells [2], [3] were analysed. Comparison between the Power vs. Voltage and Current vs. Voltage curves obtained from the simulation to those obtained experimentally was made.

The goal is to identify if a simulation model gives correct information about the behaviour of one single solar panel for varying temperature and irradiance. Final validation was done by comparing experimental and simulation results. The single panel model was integrated into array of 16 elements. This can be used a simulation of an isolated micro grid or in a hybrid energy system [4], [5].

By comparing simulation results from both models with experimental results, we can conclude that model 2 is the most reliable one.

Key words: *photovoltaic, solar cells, renewable energy, simulation, model.*

1. Introduction

Solar cells are a renewable, non-polluting source of energy that are increasingly used for hybrid (solar panels and grid) or stand-alone applications [4], [5] and [6]. In order to have an idea about the performance and behaviour of the solar micro-grid, a simulation model of the photovoltaic array should de made. For this purpose, the simulation of a single solar cell must give accurate information of the output voltage with respect to the inputted ambient temperature and irradiance.

To determine the characteristics of the solar cell, the power vs. voltage (PV) and current vs. voltage (IV) curves must be constructed. Current is measured at the output when the cell is short-circuited [7]. From these curves the maximum power point (MPP) can be ascertained [8].

Data sheet values specify typical PV and IV curves obtained under standard test conditions, STC (ambient temperature of 25 °C and irradiance of 1000 $W \cdot m^{-2}$) [3].

The goal of this work is to identify if the simulation models give correct information about the behaviour of a single solar panel for varying temperature and irradiance. Models were validated by comparing experimental and simulation results. The single panel model was integrated into an array of 16 elements. As an example, this may be useful in the simulation of an isolated micro grid or in a hybrid energy system [4], [5].

In addition to comparing simulation results with experimental results, the implemented models were tested by observing the response to standard test condition input values. Both simulated models were tuned using datasheet values and measured standard test condition values for temperature and irradiance.

2. Photovoltaic panel models

2.1. First PV Model

The equivalent circuit of the first model proposed by Altas, and Sharaf, [2] is presented in Figure 1.

The solar cell is modelled as a current source. I_{ph}, the photovoltaic current is proportional to the ambient irradiance level and to the temperature of the panel. To allow for losses, a series (R_s) and parallel resistance (R_p) are commonly included in the circuit. In this model, the parallel resistance was neglected in order to simplify the model [2], [3].

The diode, D represents the PN junction of the PV solar cells with I_0 reverse saturation current of the diode [2].

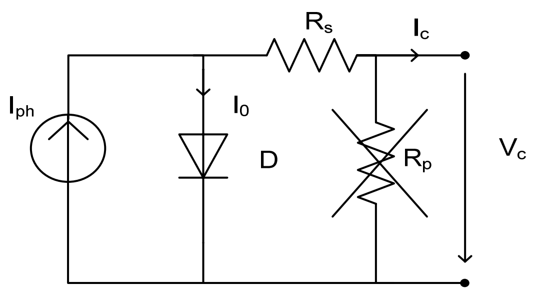


Figure 1: PV Model 1 – Solar panel equivalent circuit

The output voltage of the PV panel is given by:

$$V_C = \frac{AkT_c}{e}\ln\left(\frac{I_{ph} + I_0 - I_c}{I_0}\right) - R_s I_c \qquad (1)$$

The curve fitting factor, A, was adjusted so that at rated input values of temperature and irradiance the datasheet values of output were obtained as model outputs. The same approach was taken to obtain the temperature and irradiance correction coefficients. In this way, the model was tuned to give the datasheet values at STC(equations (2) to (4)).

Correction coefficients used to adjust the voltage V_c and current I_{ph} for various values of ambient temperature and irradiance are as follows:

- Temperature correction factors for voltage and current respectively:

$$C_{TV} = 1 + \beta_T (Tc - T_x) \qquad (2)$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_C}\beta_T (T_C - T_x) \qquad (3)$$

- Irradiance correction factors for voltage and current respectively:

$$C_{SV} = 1 + \beta_T \alpha_T (S_x - S_C) \qquad (4)$$

$$C_{SI} = 1 + \frac{1}{S_C}(S_x - S_C) \qquad (5)$$

- Applying the correction factors to I_{ph} and V_c the temperature-irradiance relationship was obtained.

$$V_{cx} = V_c C_{TV} C_{SV} \qquad (6)$$

$$I_{phx} = I_{ph} C_{TI} C_{SI} \qquad (7)$$

where:

V_c - cell output voltage - [V]
A- curve fitting factor [-]
k - Boltzmann constant [J/K]
e - electron charge [C]
T_c- STC temperature [K]
T_x- ambient temperature [K]
S_c- STC irradiance [W/m^2]
S_x- variable irradiance [W/m^2]
I_{ph}- photocurrent [A]
I_0- reverse saturation current of the diode [A]
R_s - series resistance of one cell [Ω]
C_{TV} - temperature voltage correction factor [-]
C_{TI} - temperature current correction factor [-]
C_{SV} - irradiance voltage correction factor [-]
C_{SI} - irradiance current correction factor [-]
β_T - correction coefficient [1/K]
γ_T - correction coefficient [W/Km^2]
α_s - slope of change in the cell operating temperature due to a change in the solar irradiation level [Km^2 /W]

2.2. Second PV Model

The second model to be studied, proposed by Sera, Teodorescu, and Rodriguez, [3], requires active compensation (at every moment) of R_s, V_c, and I_{ph} ((10) to (19)) as functions of temperature and irradiance. The equivalent circuit for this model is that of Figure 1. In [3] the effect of the shunt resistor was considered, but in order to obtain a valid comparison between models 1 and 2, this was not done in this paper.

- Thermal voltage for variable temperature T_x:

$$V_t = \frac{A_D k T_x n_c}{e} \qquad (8)$$

- Diode ideality factor:

$$A_D = \frac{-(I_{mpp} - I_{sc})V_{mpp}}{e} \qquad (9)$$

- Series resistance calculation using datasheet values:

$$R_S = \frac{V_{mmp} - \ln\left(\frac{-I_{mmp}+I_{sc}}{I_{sc}}\right)(I_{mpp} - I_{sc})\frac{V_{mpp}}{I_{mpp}} + V_{oc}}{I_{mpp}} \qquad (10)$$

- Open circuit voltage :

$$V_{oc} = \ln\left(\frac{I_{sc}}{I_o}\right)V_t \qquad (11)$$

- Temperature dependence of voltage:

$$V_{ocT} = V_{oc} + k_v (T_x - T_c) \qquad (12)$$

- The short-circuit current and photo-current were considered to be proportional to the value of irradiation.

$$I_{scG} = I_{sc} S_x$$
$$I_{phG} = I_{ph} S_x \qquad (13)$$

- Dark saturation current:

$$I_o = \frac{-I_{scT}}{-e^{\frac{V_{oc}}{V_t}} + e^{\frac{I_{ocT} R_s}{V_t}} - 0.001} \qquad (14)$$

- The output voltage of the PV panel, compensated for irradiance and temperature :

$$V_x = \frac{-I_x R_s + \ln\left(-I_x e^{\left(\frac{V_{oc}}{V_t}\right)} - I_x e^{\left(\frac{I_{sc} R_s}{V_t}\right)} - I_{sc} e^{\left(\frac{V_{oc}}{V_t}\right)}\right)}{I_{sc}} \quad (15)$$

The influence of irradiance is modelled indirectly by (14) and (17) introduced into (16).

$$I_x = I_{scT} S_x \quad (16)$$

Equations were implemented in MATLAB script language.

V_{mpp}-voltage at the Maximum Power Point (MPP) in STC
V_{oc} - open-circuit voltage in STC [V]
V_{ocT} - open circuit voltage as a function of temperature [V]
V_t - junction thermal voltage [V]
V_x - PV voltage (with T and S) [V]
I_{mpp} - current at the MPP in STC [A]
I_{sc} - short-circuit current in STC [A]
I_o - dark saturation current [A]
I_x - PV current (with T and S) [A]
I_c - cell output current [A]
I_{ocT} - short-circuit current as a function of temperature [A]
A_D - diode ideality factor [-]
n_c - number of panels in the array [-]
n_s - number of cells in the panel connected in series [-]
k_i - temperature coefficient of the short-circuit current [-]
k_v - temperature coefficient of the open-circuit voltage [-]

3. PV simulation

Models 1 and 2 were implemented and simulated in MATLAB-Simulink.[9] ,[10]. An array of 16 cells was studied using the two models. Results from the two simulations were compared to each other and to experimental measurements.

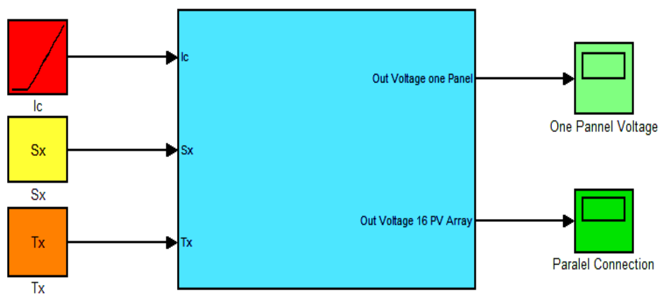


Figure 2: PV Model – Simulation System Block

Inputs and outputs (Figure 2) to the two models were the same:

4. a current ramp I_c (varying from zero to the data sheet short circuit to simulate the varying current of the panel)
5. T_x-the variable ambient temperature
6. S_x- the variable irradiance
7. single panel and array output voltage.

Care was taken to avoid windup effects caused by the I_c ramp signal block [10].

Simulation results from the first model are presented in Figures 3 a and 3 b. STC curves are displayed using thicker lines. Various temperature and irradiance values were applied.

The same approach was taken to model 2. The results can be viewed in Figures 4, 5 and 6.

It may be observed, that with rising temperature, the output voltage of the panel, and implicitly the output power, decreases. The value of the current is not greatly affected by changes of temperature.

Irradiance lower than STC irradiance causes the output voltage, current and power to fall.

4. Experiments

4.1 Experimental layout

Experiments were carried out on two arrays of eight polycrystalline solar panels connected in series (Figures 5 and 7).

Five sets of measurements were made at 20 minutes intervals. The results are presented in Figures 8 and 9.

For measurements a model PVPM 1000C meter and a PVPM_LST1000 protection switch were used. With this device the photovoltaic voltage, current and power may be measured.

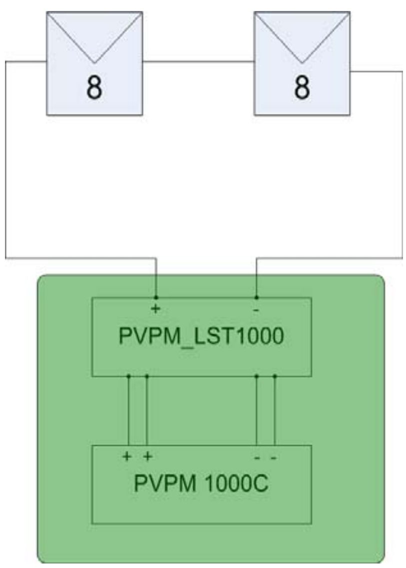
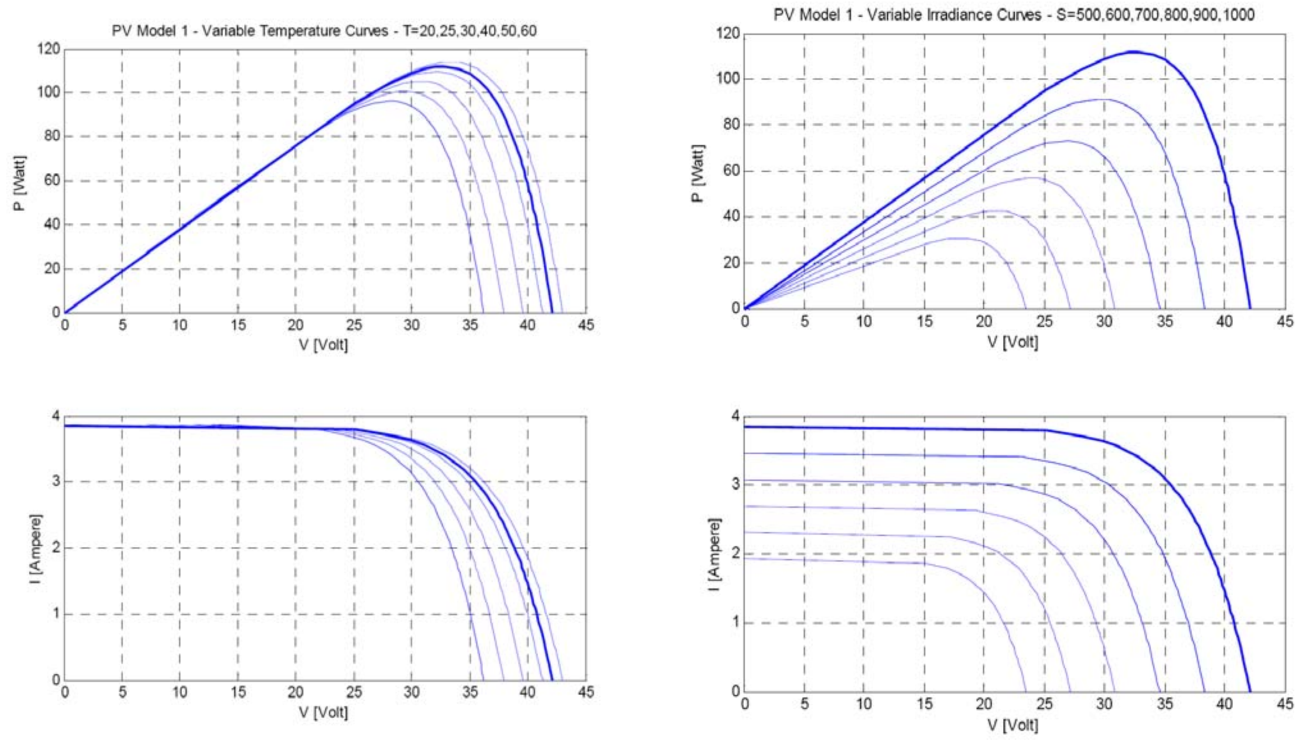
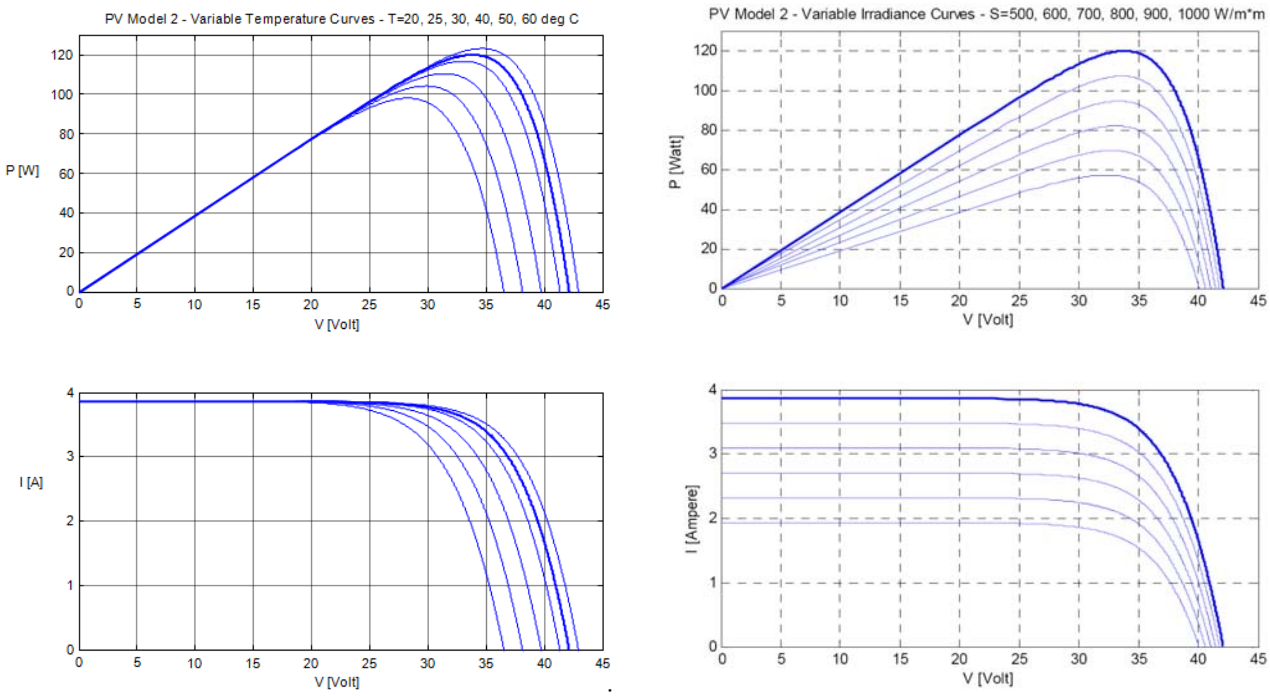


Figure 7: Experimental Arrangement



a *b*

Figure 3: PV Model 1 – One cell PV and IV simulated curves at variable temperature (a) and irradiance (b)



a ***b***

Figure 4: PV Model 2 – One cell PV and IV simulated curves at variable temperature (a) and irradiance (b)

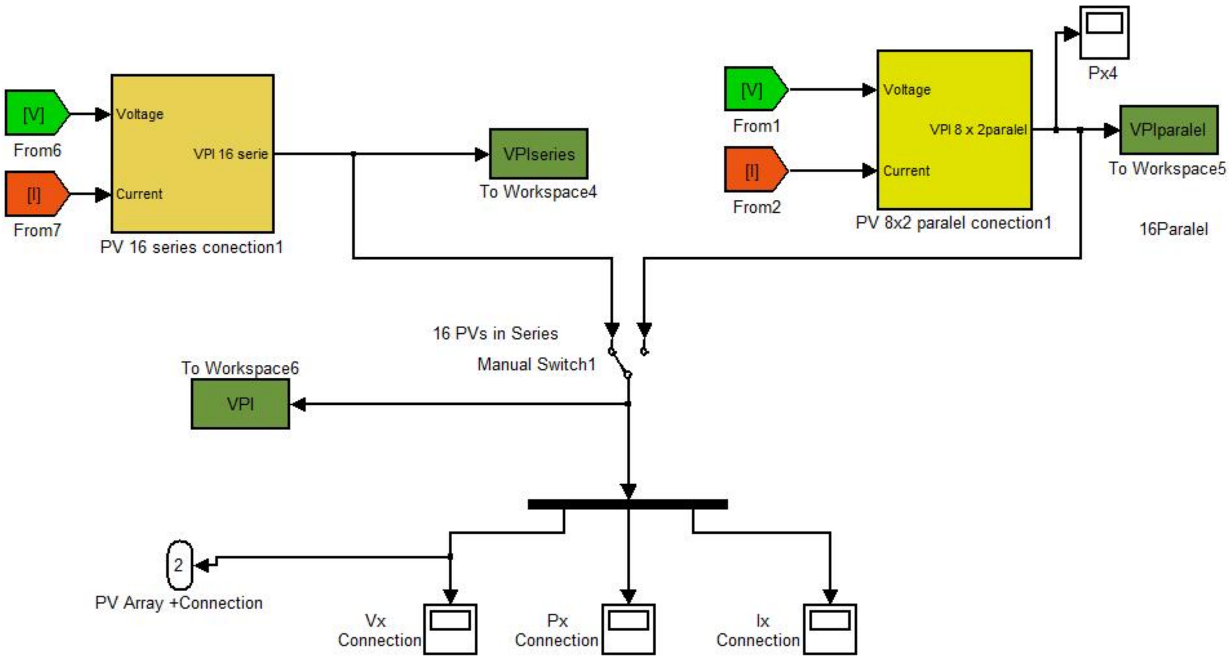


Figure 5: PV Model 2 – Series connection-simulation

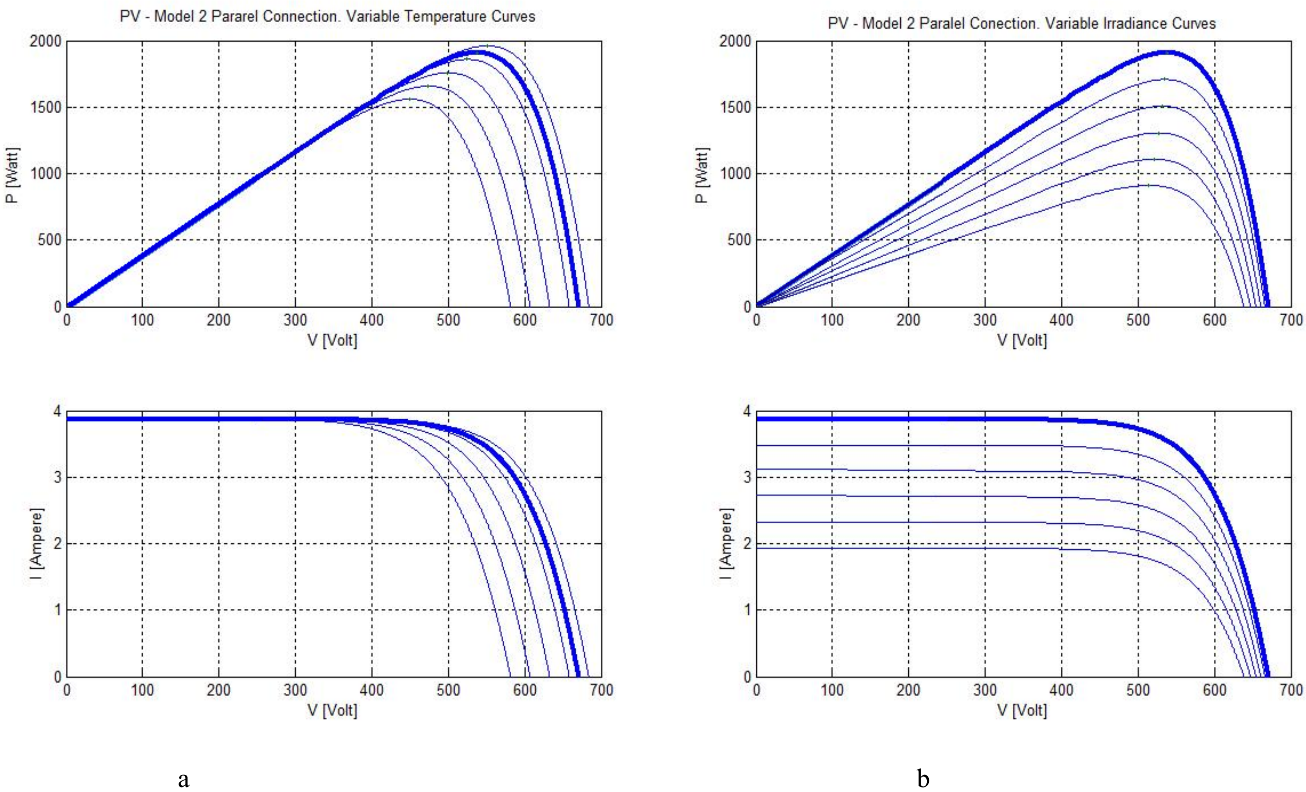


*Figure 6: PV Model 2 – Series array simulation curves at variable temperature (*a*) and irradiance* (b)

4.2 Experimental results

Measured PV and IV curves were recorded at 19.5°C and 695 W/cm^2 are presented in Figure 8. In Figure 9 experimental IV curves for ambient temperatures between 25.2 and 28 °C and for irradiance between 635 and 693 W/cm^2 are shown.

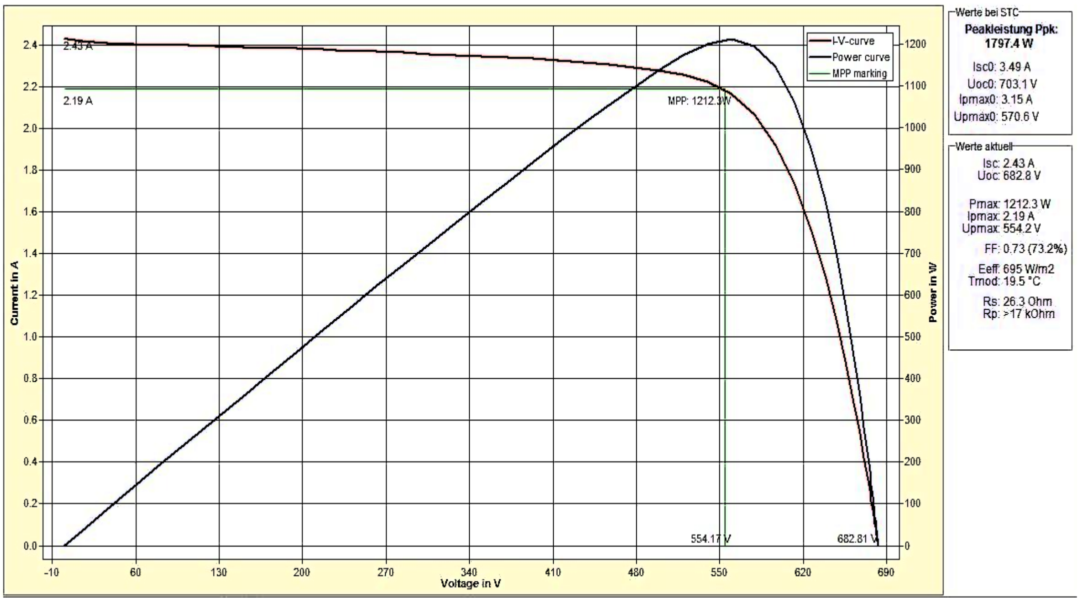


Figure 8: Experimental IV and PV Curves

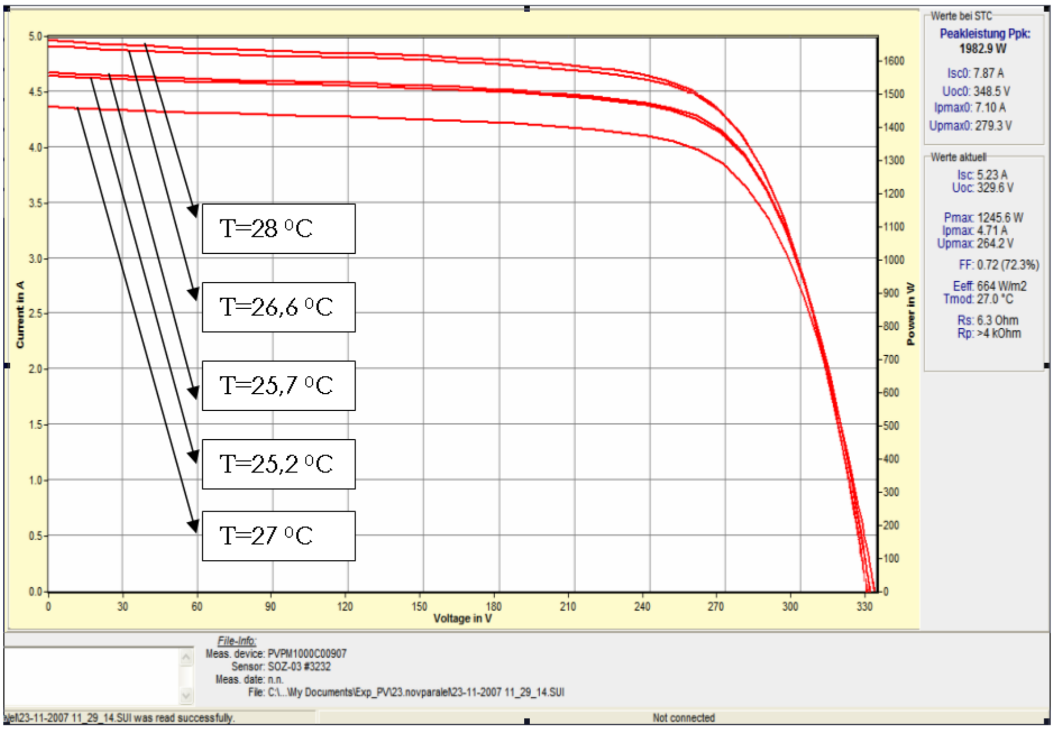


Figure 9: Temperature and irradiance variation curves (experimental results)

5. Discussion of results

Since temperature curves given by both models are similar in shape, the irradiance curves must be studied in detail. The information needed from the simulation is the voltage variation with irradiance.

As may be seen from Figure 9, the shapes of the curves prove that model 1 does not output valid information at variable ambient irradiance (Figure 3). Reason for this lies in the compensation method used in [2]. Also correction coefficients α_T, β_T and γ_T could not be assigned precise values due to their empiric origins.

Actively compensating equivalent circuit parameters of model 2 make a more reliable output than model 1.

In the time that the test where carried out (~2 hours), ambient temperature remained approximately constant, irradiance however varied so curves from Figure 8 can be considered irradiance curves. Variation of panel voltage was under 10V. This fact was reflected by model 2, but not by model 1.

I. CONCLUSIONS

By comparing simulation results from both models with experimental results we can conclude that model 2 is the most reliable one. Model 1 has a correct varying input temperature response, but irradiation dependences could not be correctly set. In the preferred model, active compensation of parameters has made the simulation less susceptible for errors.

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