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A Method for Predicting Solar Cell Current-Voltage Curve Characteristics as a Function of Incident Solar Intensity and Cell Temperature

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Abstract

A computer program for extrapolating an arbitrary point on a photovoltaic curve characteristic, whose voltage and current coordinates V and I, respectively, are known, has been developed to predict solar cell electrical parameters as a function of cell temperature and incident light intensity. The program utilizes a current-voltage curve obtained at a reference temperature and solar intensity which is subsequently projected over a wide range of cell temperatures and tungsten light intensities. The degree of correlation between empirical and predicted data for short-circuit current, open-circuit voltage, maximum power, and maximum power voltage is presented.

A Method for Predicting Solar Cell Current-Voltage Curve Characteristics as a Function of Incident Solar Intensity and Cell Temperature

I. Introduction

This paper reports the work done at Jet Propulsion Laboratory (JPL) to refine an existing computer program in order to predict the performance characteristics of silicon solar cells over the heliocentric distances equivalent to Mars/Venus missions.

The computer program has been developed from linear equations which are representative of solar energy conversion device behavior as a function of incident light intensity and cell temperature. The equations utilize a point-by-point extrapolation technique of an arbitrary number of current-voltage coordinates, I and V, respectively, taken from a reference solar cell curve characteristic whose temperature and incident solar intensity are known.

The reference photovoltaic curve characteristic for each cell investigated in this program was established empirically at a solar intensity of 300 mW/cm^2 and a cell temperature of 20°C. The computer predicted current-voltage I-V curves have been generated from these reference characteristics by translating the original curve in a manner commensurate with changes in temperature or solar intensity from the reference values. This paper presents correlative results between experimental measurements and predicted digital data over a cell temperature range from 20°C to 130°C, and over an incident light level range from 50 mW/cm^2 to 300 mW/cm^2.

Ten unfiltered p on n, 1×2 cm silicon solar cells were employed as the subject of this test program and evaluation. The cells were irradiated with a tungsten light source at a color temperature of 2800°K. A JPL secondary standard was used to establish the equivalent solar intensities.

Review of experimental data indicated that test measurements were repeatable over a period of time. Short circuit current could be duplicated to better than 1%, while open circuit voltage variations averaged 1.4% and maximum power and maximum power voltage to within 2%.

II. A Description of the Method for Predicting Performance Characteristic of Silicon Solar Cells as a Function of Temperature and Intensity

The method used to predict the photovoltaic curve characteristic for various cell temperatures and light levels is essentially a refinement of a technique described in a paper by Wolf and Rauschenbach.[1] This prior work dealt in part with the photovoltaic curve characteristic as a function of intensity, and the ability to calculate cell series resistance from two or more different light levels. The method is valid for extrapolating an *I-V* curve characteristic over incident intensity ranges, at a fixed cell temperature, where the cell short circuit current, I_{sc}, is proportional to the light level. The test program conducted at JPL also found that in addition to the change in the photovoltaic output characteristic as a function of the change in incident light level, which is a simple transformation of the voltage and current axes in a direction normal to one another, there are subsequent transformations to the *I-V* curve which are dependent upon variations in cell temperature.

There appear to be three alterations which occur to a photovoltaic curve characteristic as a function of cell temperature and incident light level, which are described as follows:

(1) A translation of current, proportional to the change in light level and in cell temperature.

(2) A voltage transformation related to the voltage drop across the cell series resistance and a transformation proportional to the change in open circuit voltage with changes in cell temperature.

(3) The knee of the *I-V* curve becomes characteristically more rounded with increasing temperature.

The typical transformations which take place to an *I-V* curve with changing light level and cell temperature are illustrated in Fig. 1. The preceding transformations described are accomplished with the JPL computer program as a point-by-point translation of a photovoltaic curve characteristic, whose voltage and current coordinates, V_1 and I_1, respectively, are known at a reference temperature and solar intensity. The general equations

[1] Wolf, Martin, and Rauschenback, Hans, "Series Resistance Effects on Solar Cell Measurements," *Advanced Energy Conversion*, Vol. 3, pp. 455, 479, 1963.

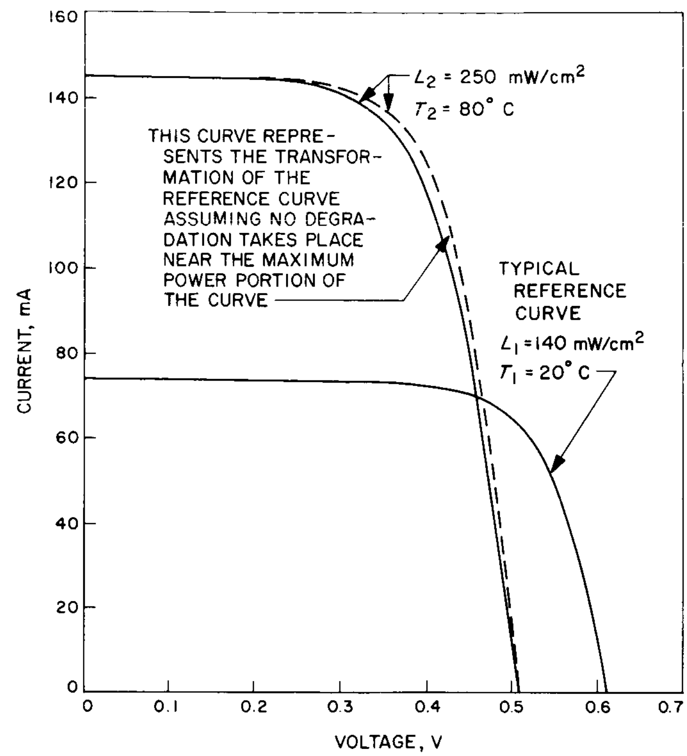

Fig. 1. The transformations an *I-V* curve experiences as a function of solar intensity and cell temperature

for extrapolating these reference coordinates are of the form:

$$I_2 = I_1 + I_{sc_1}\left(\frac{L_2}{L_1} - 1\right) + \alpha(T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - \beta(T_2 - T_1) - \Delta I_{sc} R_s - K(T_2 - T_1)I_2 \quad (2)$$

$$\Delta I = \Delta I_{sc} = I_{sc_1}\left(\frac{L_2}{L_1} - 1\right) + \alpha(T_2 - T_1) \quad (3)$$

$$P_2 = I_2 V_2 \quad (4)$$

In reference again to Fig. 1, the first transformation described in the preceding as a translation of current proportional to the change in light level or temperature is performed by Eq. (1). The second transformation is accomplished by the second and third terms of Eq. (2). The last transformation, as noted and seen as the solid line displaced from the dashed curve, is performed by the last term in Eq. (2).

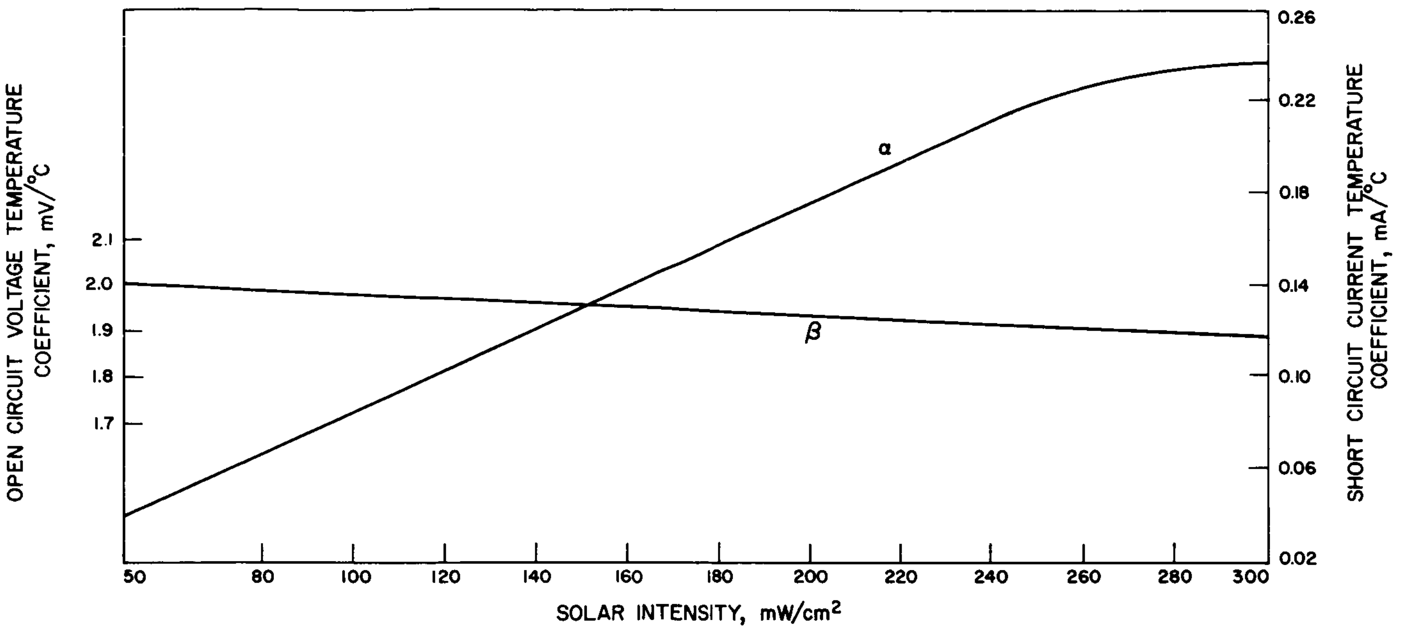

Fig. 2. Cell temperature coefficients as a function of solar intensity

In order to perform the preceding transformations, it was found that it was necessary to treat α and β, the temperature coefficients for current and voltage, respectively, as variables with solar intensity. Figure 2 is a plot of the short circuit current temperature coefficient, α, and the open circuit voltage temperature coefficient β, vs incident (2800°K tungsten) light intensity. The short circuit current temperature coefficient and open circuit voltage temperature coefficient are defined as the magnitude of the slope of the curves which express I_{sc} and V_{oc}, respectively, as a function of temperature at a given intensity. That is

$$\alpha \equiv \left. \frac{dI_{sc}}{dT} \right| \text{intensity constant}$$

$$\beta \equiv \left. \frac{dV_{oc}}{dT} \right| \text{intensity constant}$$

Based upon empirically observed silicon solar cell behavior near the maximum power portions of the *I-V* curve, a curve factor temperature coefficient, *K*, has been developed. Apparent changes in cell resistance as a function of temperature are compensated for by this additional correction factor. The curve correction coefficient is assumed invariant to intensity, over the range of light levels investigated here.

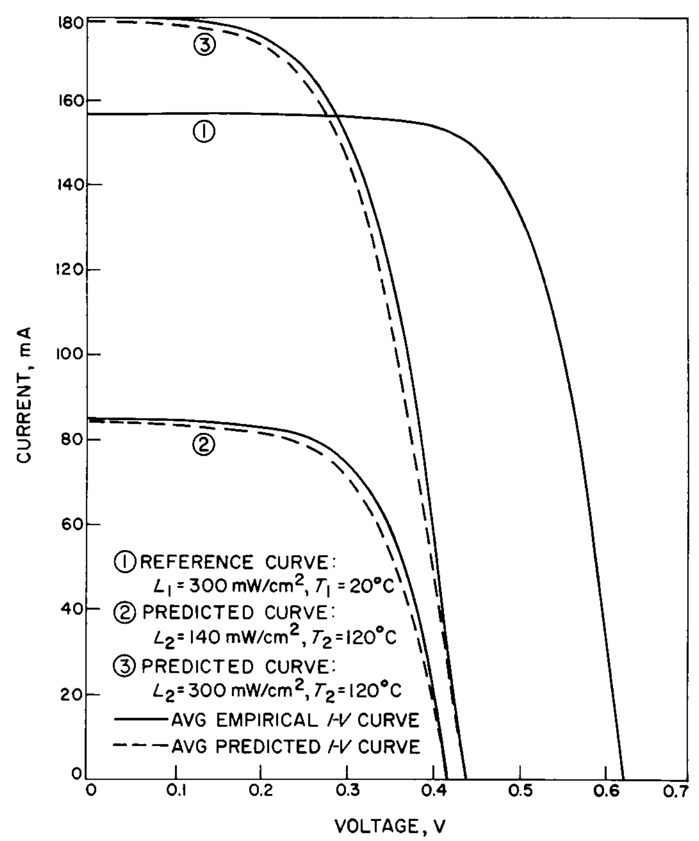

Fig. 3. The correlation between the average empirical photovoltaic curve characteristic of several cells and the mean computer-predicted *I-V* curves

III. A Comparison of Empirical Data With Computer Predicted Data

Typical predicted vs empirical photovoltaic curve characteristics are presented in Fig. 3. Curve 1 is the experimentally derived reference *I-V* characteristic obtained at a cell temperature of 20°C, and a solar intensity of 300 mW/cm². The dashed curves 2 and 3, are computer predicted *I-V* characteristics corresponding to a cell temperature of 120°C, and solar intensities of 140 mW/cm² and 300 mW/cm², respectively. Both of these latter curves were obtained by applying the extrapolation equations previously described to the reference characteristic (curve 1). The experimentally obtained *I-V* characteristics are presented as the solid lines in curves 2 and 3 to show the close correlation of the predictions.

The average predicted short circuit current, open circuit voltage, maximum power, and maximum power voltage as a function temperature, at a solar intensity of 140 mW/cm² is presented in Fig. 4 with corresponding empirical data. The same parameters are shown in Fig. 5 at a solar intensity of 300 mW/cm². The extremely good correlation of predicted short circuit current to empirical data is readily seen. Both the average and standard deviation from the mean experimental I_{sc} are found to be within 1.5%. Furthermore, there is very good agreement between predicted open circuit voltage (V_{oc}) and empirical values. Note that the ordinate has been expanded to show the deviation of predicted V_{oc} from empirical open circuit voltage more clearly. The average deviation of predicted V_{oc} from empirical values is less than 1%. Good agreement can be seen between predicted and empirical voltage at maximum power (V_{mp}). The predicted maximum power voltage averages approximately 2% less than corresponding empirical V_{mp} data. The average predicted maximum power output of the ten cells as a function of temperature is within 2% of the mean empirical maximum power.

Again, these same parameters are presented in Fig. 6, at a cell temperature of 40°C, as a function of incident intensity. The very good correlation between experimental data and predicted digital data is readily seen.

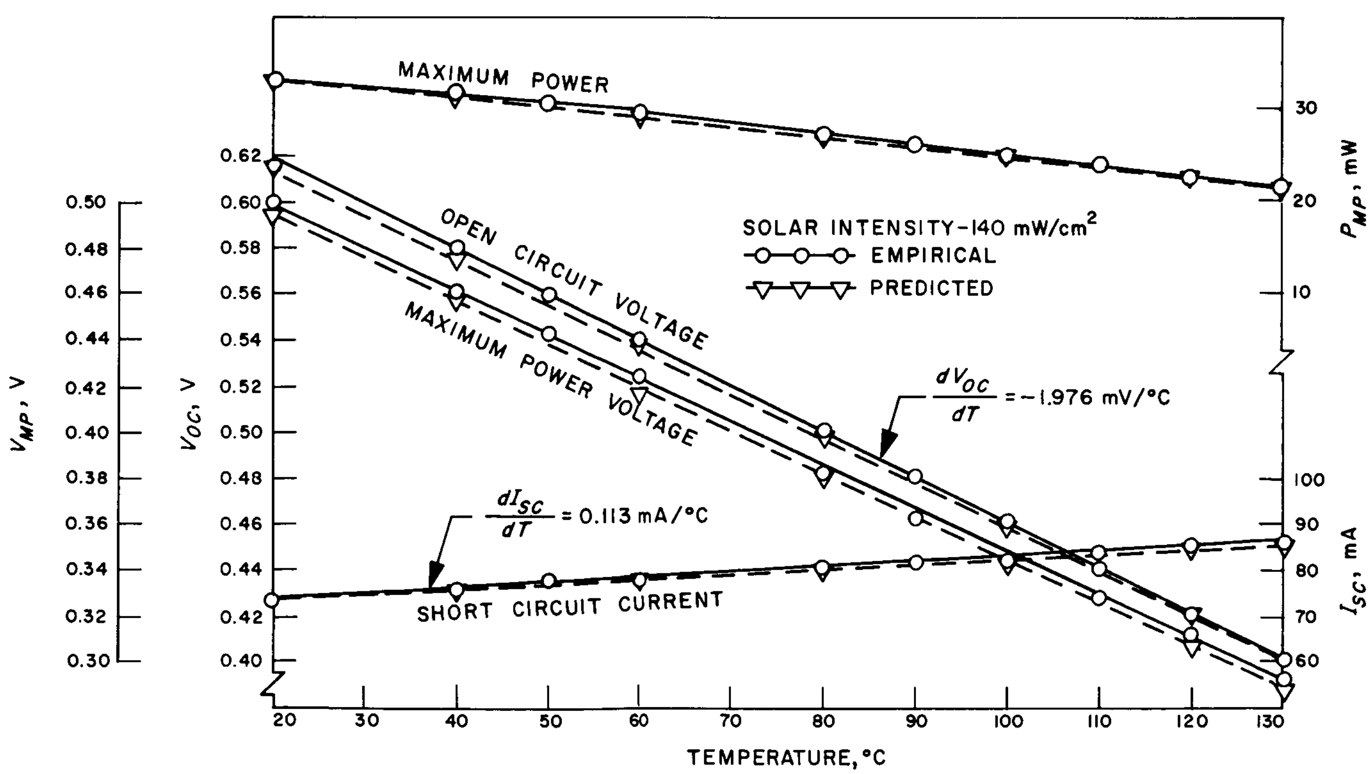

Fig. 4. A comparison between empirical and predicted digital data at a solar intensity of 140 mW/cm², as a function of temperature

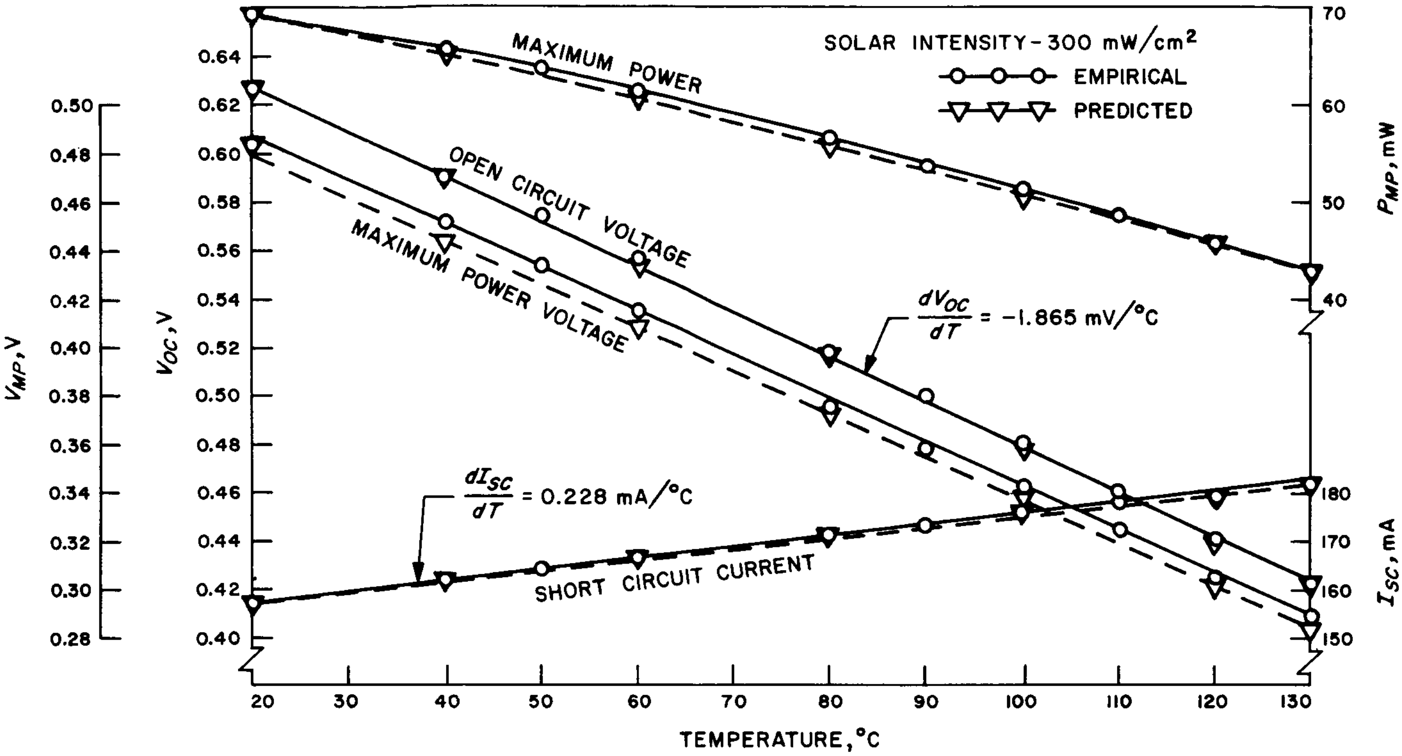

Fig. 5. A comparison between empirical and predicted digital data at a solar intensity of 300 mW/cm², as a function of temperature

IV. Conclusions

Very good correlation to empirical solar cell curve characteristics has been achieved with the computer-oriented method outlined in this paper. It appears possible to predict photovoltaic curve characteristics over wide variations of solar intensity and cell temperature, if one knows the values for α, β, and K and applies them to the equations described. The computer-programmed equations are a mathematical representation of various points on an *I-V* curve which will experience a shift in coordinates (current and voltage) as a function of cell temperature and incident light intensity. Further work is currently in progress to validate the computer program's prediction capabilities over much wider temperature and intensity ranges than were investigated here. In addition, efforts are being initiated to further refine the computer program to show the effects of solar panel performance as a function of temperature, solar intensity, and particulate irradiation.

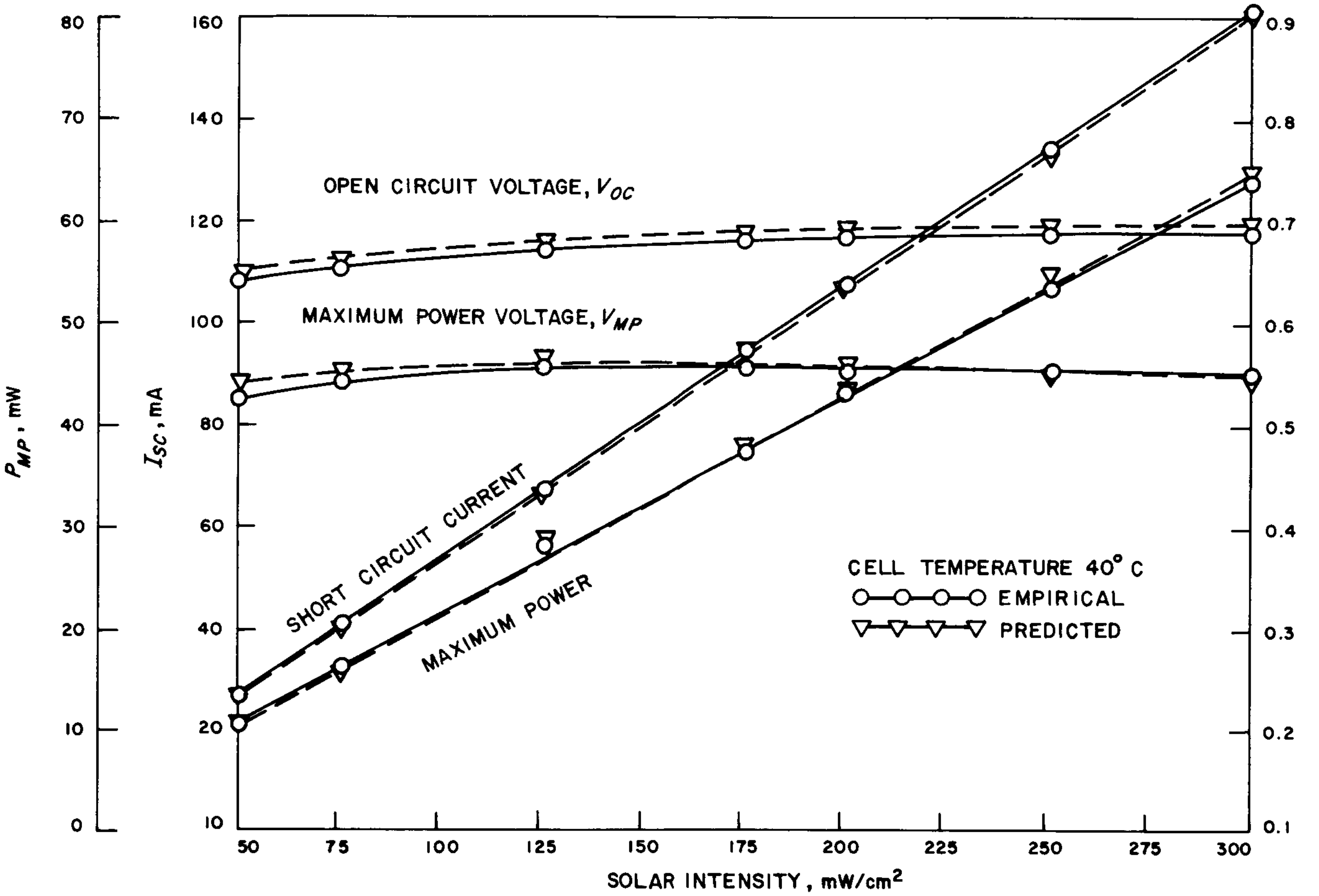

Fig. 6. A comparison between empirical and predicted digital data at a cell temperature of 40°C, as a function of solar intensity

Nomenclature

I_1 reference current coordinate

I_2 extrapolated current coordinate

I_{sc} short circuit current

I_{sc_1} short circuit current of the reference data

I-V current-voltage

K curve correction coefficient; 1.25×10^{-3} Ω/°C

L_1 reference incident solar intensity

L_2 equivalent solar intensity to be investigated

P_{mp} maximum power

P_2 predicted power output

R_s cell series resistance; 0.5 Ω nominal

T_1 reference cell temperature

T_2 cell temperature to be investigated

V_1 reference voltage coordinate

V_2 extrapolated voltage coordinate

V_{oc} open circuit voltage

V_{mp} voltage at maximum power

α short circuit current temperature coefficient

β open circuit voltage temperature coefficient