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RESEARCH ARTICLE

Systems Engineering Methodology for Verification of PV Module Parameter Solutions

PETER R. MICHAEL[1], (Senior Member, IEEE), DANVERS E. JOHNSTON[2], AND WILFRIDO A. MORENO[1]
[1]Electrical Engineering Department, University of South Florida, Tampa, FL 33620, USA
[2]Department of Civil and Environmental Engineering, Florida Gulf Coast University, Fort Myers, FL 33956, USA
Corresponding author: Peter R. Michael (prm@usf.edu)

ABSTRACT Numerous sources provide methods to extract photovoltaic (PV) parameters from PV module datasheet values. The inputs are the number of series cells N_s, open circuit voltage V_{oc}, maximum power voltage V_{mp}, maximum power current I_{mp}, and short circuit current I_{sc}. The 5 Parameter Model solutions outputs are diode ideality factor η, series resistance R_s, parallel resistance R_p, photon light current I_L, and diode reverse saturation current I_o. The parameter solution requires solving three simultaneous transcendental equations for η, R_s, and R_p and additional calculations for I_L and I_o. One of the primary tenants of Systems Engineering, verification, was applied to parameter solution results to check for physical and model fitness. This manuscript provides novel methods to verify parameter results and applies them to available solutions.

INDEX TERMS PV model check, PV 5 parameter model, PV parameter extraction, PV systems engineering.

I. INTRODUCTION

Typically, the analysis of a PV system uses the 5 Parameter Model [1]. A notional diagram is shown in Fig 1.

Photon light input Φ generates the light current I_L. The generated light current conducts through the diode as I_d, the parallel resistance as I_p, and the external load as I_e. Using Kirchhoff's Current Law, Equation (1) was derived.

$$I_L = I_d + I_p + I_e \tag{1}$$

Equation (1) is modified to a format with the external current on the left, the diode current I_d, replaced with the Shockley diode equation, and the parallel current I_p shown in terms of the circuit parameters. This yields a PV module primary 5 Parameter Equation (2).

$$I_e = I_L - I_o\left(e^{\frac{V_e+I_eR_s}{\Upsilon}} - 1\right) - \frac{V_e + I_eR_s}{R_p} \tag{2}$$

- I_e is the external current.
- I_L is the photon light current.
- I_o is the diode reverse saturation current.
- V_e is the external voltage.

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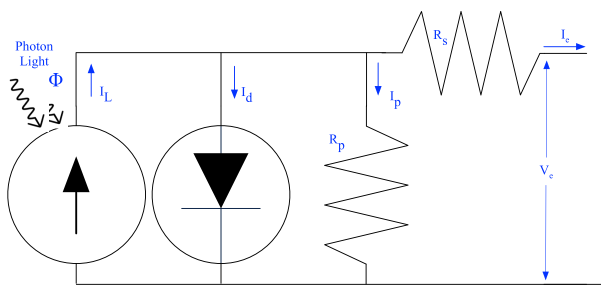

FIGURE 1. 5 parameter PV model.

- R_s is the series resistance.
- Υ is the PV module's thermal voltage ($\Upsilon = N_s\ \eta\ v_t$) (The number of series PV cells N_s, the diode ideality factor η, and thermal voltage v_t.)
- R_p is the parallel resistance.

II. MODULE CONDITIONS

PV module datasheets provide five characteristics, N_s, the number of series PV cells in the module, the open circuit voltage V_{oc}, the voltage at maximum power V_{mp}, the current at maximum power I_{mp}, and the current at short circuit I_{sc}. The last four parameters were obtained from testing under standard test conditions (STC) of AM1.5G sunlight, 25° C,

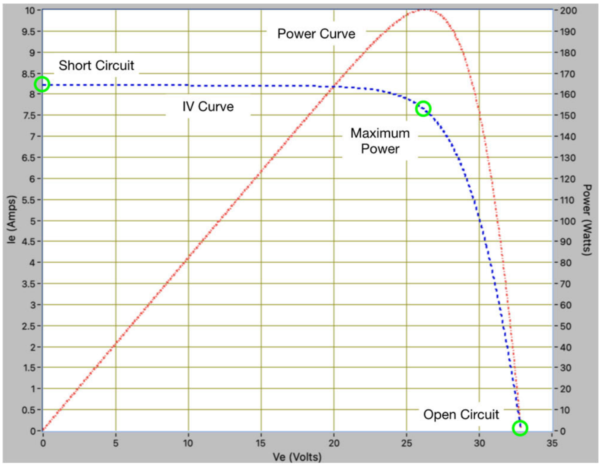

FIGURE 2. PV I-V and power curves for KG200GT PV module.

with an irradiance of 1,000 W/m^2 [2]. At STC, the characteristic values are fixed and static.

Fig 2, which plots Equation (2), shows the locations of the open circuit, short circuit, and maximum power point conditions on the PV I-V (current-voltage) curve. In addition, the power curve, P=IV, was plotted.

Manipulation of the PV equation under open circuit, short circuit, and maximum power conditions result in the following equations in terms of the photon current I_L. Following the methods established in [3], the simplified Equations for short circuit, Equation (3), open circuit Equation (4), and maximum power Equation (5) were derived.

$$I_L = \frac{I_{sc}R_s}{R_p} + I_{sc} \tag{3}$$

$$I_L = I_o\left(e^{\frac{V_{oc}}{\Upsilon}}\right) + \frac{V_{oc}}{R_p} \tag{4}$$

$$I_L = I_o\left(e^{\frac{V_{mp}+I_{mp}R_s}{\Upsilon}}\right) + \frac{V_{mp}+I_{mp}R_s}{R_p} + I_{mp} \tag{5}$$

III. SOLUTION EQUATIONS FOR 5 PV PARAMETERS

The 5 Parameter Model contains five unknowns, η, R_s, R_p, I_L, and I_o. Note that finding Υ enables a solution for η. Equation (6), utilizing equations (3) and (4), derives a solution for I_o in terms of datasheet characteristics and unknown parameters R_s, R_p, and Υ.

$$I_o = (I_{sc} + \frac{I_{sc}R_s}{R_p} - \frac{V_{oc}}{R_p}) / \left(e^{\frac{V_{oc}}{\Upsilon}}\right) \tag{6}$$

With Equation (3) to find I_L and Equation (6) solving for I_o, the three remaining unknowns, Rs, Rp, and Υ, require three additional equations. Following the method described in [4] and combining Equations (3), (4), (5), and (6), a solution for I_{mp} shown in Equation (7) was derived. The transcendental equation is in terms of unknowns R_s, R_p, and Υ and known datasheet characteristic values of N_s, V_{oc} V_{mp}, I_{mp}, and I_{sc}.

$$I_{mp} = I_{sc} - \frac{V_{mp} + R_s\left(I_{mp} - I_{sc}\right)}{R_p} - \frac{I_{sc}\left(R_p + R_s\right) - V_{oc}}{R_p}\left(e^{\frac{V_{mp}+I_{mp}R_s-V_{oc}}{\Upsilon}}\right) \tag{7}$$

TABLE 1. KC200GT datasheet parameters.

Parameter	Term	Information from Datasheet
54	N_s	Number of series PV cells
32.9	V_{oc}	Open circuit voltage
26.3	V_{mp}	Maximum power voltage
7.61	I_{mp}	Maximum power current
8.21	I_{sc}	Short circuit current

Two more equations were derived by using the characteristic of the PV I-V and Power curves. The two locations chosen are at the short circuit and the maximum power points, identified in Fig 2.

Taking the derivative of the PV equation at short circuit, manipulating, and simplifying, Equation (8), another transcendental was derived. This is the second equation.

$$R_p = \frac{\left(1 + \frac{R_s}{R_p} + \frac{I_{sc}(R_p+R_s)-V_{oc}}{R_p\Upsilon}R_s e^{\frac{I_{sc}R_s-V_{oc}}{\Upsilon}}\right)}{\left(\frac{1}{R_p} + \frac{I_{sc}(R_p+R_s)-V_{oc}}{R_p\Upsilon}e^{\frac{I_{sc}R_s-V_{oc}}{\Upsilon}}\right)} \tag{8}$$

The third equation uses the power curve, where the derivative is zero at maximum power. Equation (9), also transcendental, provides the required third for the solutions.

$$0 = I_{mp} - V_{mp}\frac{\left(\frac{1}{R_p} + \frac{I_{sc}(R_p+R_s)-V_{oc}}{R_p\Upsilon}e^{\frac{V_{mp}+I_{sc}R_s-V_{oc}}{\Upsilon}}\right)}{\left(1 + \frac{R_s}{R_p} + \frac{I_{sc}(R_p+R_s)-V_{oc}}{R_p\Upsilon}R_s e^{\frac{V_{mp}+I_{sc}R_s-V_{oc}}{\Upsilon}}\right)} \tag{9}$$

By solving the three simultaneous transcendental equations (7), (8), and (9), parameter solutions for the values of R_s, R_p, and Υ were found. The solutions for η, I_L, and I_o, were then obtained by simple calculations. The diode ideality factor η was found using Υ and solving equation (10). The factors are k Boltzmann's constant, the temperature T in Kelvin, the charge of an electron q, and the number of series PV cells N_s. Equation (3) calculates I_L, and Equation (6) I_o.

$$\eta = \frac{\Upsilon}{N_s v_t}(v_t = \frac{kT}{q}) \tag{10}$$

IV. SOLVING FOR 5 PV PARAMETERS

A. DATASHEET VALUES

Various sources utilized different methods to solve these three simultaneous transcendental equations. The Kyocera KC200GT PV module data was utilized to demonstrate this error analysis. Table 1 provides datasheet characteristics for the KC200GT PV module [5]. The fixed characteristics are N_s, the count of the number of series connection PV cells, and the others obtained from testing at STC.

B. SOLUTION METHODS AND SOURCES

Table 2 summarizes the solution set, the methods used to solve for the 5 parameters, and the source of the solutions. The

TABLE 2. Solution set methods and source.

Set #	Method	Source
1	TK Solver Newton-Raphson	Configured by Authors [6]
2	MATLAB "PV_Array.slx" v 1.4	MATLAB R2022b [7]
3	Laplacian Nelder-Mead spherical	Weng X., et all, [8]
4	De Soto	Lun, S., et all, [9]
5	Pade' approximants	"
6	Basic Taylor model	Lun, S., et all, [10]
7	Five Parameter model	"
8	MATLAB S-function	Yildiran, N, Tacer E. [11]
9	Novel iterative method	Wang, G, et al. l [12]
10	Villalva's method	"
11	Adaptive Harris hawks	Song, S. et all [13]
12	Simple iterative	Chaibi, Y., et all [14]
13	New explicit mathematical	Pindado, S, Cubas, J., [15]
14	Whippy Harris Hawks	Naeijian, M., [16]
15	Analytical-numerical approach	Hejri, M., et all [17]

TABLE 3. Parameter solutions.

#	η	R_S, Ω	R_P, Ω	I_O, AMPS	I_L, Amps
1	1.340996014	0.2171524429	951.9318193	1.710643752E-7	8.211872846
2	0.60957	0.49485	80.0174	9.9924E-17	8.2608
3	1.076405798	0.34381505	763.5403341	2.24175E-9	8.216891354
4	1.391	0.3355	160.1	4.255571E-10	8.22721
5	1.391	0.3405	155.7	4.254766E-10	8.22795
6	1.391	0.3596	153.2	4.254686E-10	8.22927
7	1.391	0.3355	160.1	4.255571E-10	8.22721
8	1.3	0.222	462	9.8252E-8	8.21
9	1.3	0.226	508.99	9.83E-8	8.2136
10	1.3	0.229	593.24	9.83E-8	8.2132
11	1.0748	0.40909	775.03	1.5524E-9	8.2174
12	1.22	0.2555	358	3.26E-8	*8.215859
13	1	0.336	159	4.03E-10	8.123
14	1.05528589	0.24093983	774.212315	1.43601E-9	8.21860582
15	1.34	0.217	951.932	1.71E-7	8.212
16	1.41	0.194	640.771	4.1E-7	8.21
17	1.277	0.239	490.218	6.9127E-9	8.214
18	1.3	0.221	415.405	9.825E-8	8.214
19	1.235	0.247	414.89	4.812E-8	8.215
20	1.192	0.212	388.6	1.675E-8	8.184

* I_L was not provided in Set #12. A calculated solution using Equation (3) was inserted.

authors analyzed the first two, and the following were from a collection of 13 different sources. A total of 20 parameter solution sets were analyzed.

C. SOLUTION PARAMETER SETS

With PV data from the KC200GT PV module listed in Table 1 and the solutions provided by the sources listed in Table 2, sets of the 5 parameter solution values were copied into Table 3. The table lists the solutions of the 5 parameters η, R_s, R_p, I_L, and I_o. The parameter digits listed were those provided from each source solution method and subsequently used in the error calculations.

D. REPORTED SOLUTION ERRORS

Many of the sources reported solution error results. Table 4 summarizes the source set #, error calculation methods, and the reported errors. For consistency, all errors were, when required, converted and presented in percent. RMS is Root Mean Square, and RMSE is Root Mean Square Error. When "Graph" was listed, the error referenced a graph in the source, which reported different error values depending on conditions.

TABLE 4. Solution set error reporting.

#	Error Determination Method	Reported Error
1	RMS 5 Error method from this manuscript	0.00%
2	RMS 5 Error method from this manuscript	5.64%
3	Table A7: RMSE calculated model to its experimental value	0.15390%
4	Fig 6: I-V Graph Model value versus De Soto measured	Graph
5	Fig 6: I-V Graph Model value versus proposed measured	Graph
6	Table 2: RMSE Explicit Method for Basic Taylor model	2.90%
7	Table 2: RMSE Explicit Method for Five Parameter model	1.56%
8	No error calculation included	Not reported
9	Appendix B: Relative RMSE calculated versus experimental	1.6212%
10	Villalva's method	Not reported
11	Table A.9: RSME simulated versus measured	0.12294%
12	Table 3: Datasheet versus proposed method	1.73%
13	Table 4: RMSE Normalized at set points	1.62% & 1.21%
14	Table 13: RMSE Datasheet versus proposed	1.822%
15	Table 4: Normalized RSME measured versus approach	4.65%

V. SOLUTION VERIFICATION

Two general methods are recommended for a systems engineer solution verification.

- Physical Parameter
- RMS 5 Error Equation

A. PHYSICAL PARAMETER VERIFICATIONS

This check involves physical parameter verification. Even if an equation provides a valid mathematical solution, the solved values may not provide a physically reasonable answer. An example is optimizing a fence length problem, where the negative root solutions are ignored. The checks verify parameters determined by transcendental equation solutions for η, Rs, and R_p. All the parameter solutions listed in Table 2, except for the value of diode ideality factor η solved by method #2, passed these physical parameter checks.

1) DIODE IDEALITY FACTOR

An ideal diode has a value of 1.0, and for silicon devices, a reasonable number is 1.2 to 1.3 [8]. To enable support for a wider range of solutions, the diode factor limit was set from 1.0 to 1.6. For example, in set #2, the MATLAB "PV_Array.slx" provided a relatively low error solution, but the solved diode ideality factor of 0.60957 is not physically reasonable.

2) SERIES RESISTANCE

The series resistance R_s is the contributions of the PV cell material, contact between the PV cell to metal, and the metal contact path resistances. Values for R_s are bound by the ideal, but not physically possible 0 Ω on the low end, and the slope of the I-V curve from V_{oc} to the maximum power point on the high end. For the KC200GT, the slope from V_{oc} to the maximum power point (V_{oc}-V_{mp})/I_{mp} establishes the maximum series resistance of 0.867 Ω for R_s. Typical PV modules have external 2.6 mm (#10 AWG) copper cables with a resistance of about.006 Ω per meter. One meter of the connecting cable has a resistance of 0.006 Ω. Other resistance, such as the PV cell material, interfaces, and conductive traces, increase this resistance. The calculated lower limit was set to 1/50 of the R_s maximum or an R_s minimum of 0.017 Ω.

3) PARALLEL RESISTANCE

The parallel resistance R_p sources include manufacturing defects and leakage paths around the PV cells. From Fig 2, the minimum resistance R_p is the inverse slope of the IV curve at short circuit. For the KC200GT, the slope from the I_{sc} to the maximum power point V_{mp}, I_{mp} is calculated as V_{mp}/(I_{sc}-I_{mp}) or 43.8 Ω. This calculation set the lower bound for R_p. The upper limit is controlled by parallel resistance paths. Using the ratio determined for R_s, the R_p upper limit was set at 50 times for an R_p maximum of 2,190 Ω.

B. RMS 5 ERROR EQUATION VERIFICATIONS

The verification checks model fit by calculating errors on the three primary points of the I-V curve defined by Equation (2), short circuit, open circuit, and maximum power. The equation checks involve taking the solved solution parameters, plugging them into the set of 5 check equations, and calculating each error. The error is the absolute difference in the provided solution versus the value calculated from the check equations. For comparison, the absolute error is converted to percent.

The merit of the solution parameters was judged by the RMS of the 5 calculated errors. The N_s, V_{oc}, V_{mp}, I_{mp}, and I_{sc} factors are from the PV module datasheet. The values of η (embedded in the module thermal voltage Υ), R_s, R_p, I_L, and I_o are from the solved parameter solutions. Equation (11) checks the current at short circuit, Equation (12) the current at open circuit, and Equation (13) the current at maximum power. These three equations check the fit of I_L solved versus I_d, I_p, and I_e under short circuit, open circuit, and maximum power conditions. Equations (14) compares the datasheet V_{oc} with solved V_{ocs} using I_L, I_o, R_p, and Υ. Equations (15) compares the datasheet V_{mp} with a solved V_{mps} using the datasheet I_{mp} and solved parameters I_L, I_o, R_s, R_p, and Υ. Finding V_{ocs} and V_{mps} require finding solutions for transcendental Equation 14_s and Equation 15_s, which were found using a MATLAB solver.

$$error_{sc} = I_L - \frac{I_{sc}R_s}{R_p} - I_{sc} \tag{11}$$

TABLE 5. Solution sets calculated errors.

#	ERROR$_{SC}$	ERROR$_{OC}$	ERROR$_{MP}$	ERROR$_{VOC}$	ERROR$_{VMP}$	RMS$_{5\ error}$
1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.00%	-0.54%	-11.9%	-0.07%	-0.03%	5.33%
3	-0.32%	10.9%	-9.15%	1.99%	1.73%	6.48%
4	0.00%	-801%	43.4%	-1,274%	-1,087%	830%
5	0.00%	-801%	43.0%	-1,274%	-1080%	828%
6	0.00%	-800%	42.7%	-1,274%	-1064%	824%
7	0.00%	-801%	43.4%	-1,274%	-1087%	830%
8	0.39%	-806%	53.3%	-829%	-824%	635%
9	0.00%	6.52%	-4.34%	1.44%	0.01%	3.56%
10	0.00%	5.64%	-4.42%	1.24%	-0.02%	3.25%
11	-0.31%	-225%	-10.5%	-47.9%	0.65%	103%
12	0.00%	88.6%	-10.4%	17.5%	14.8%	41.2%
13	-0.27%	-0.78%	-6.56%	-0.14%	-1.14%	3.00%
14	-0.61%	6.97%	22.1%	1.24%	-85.8%	39.7%
15	-0.01%	11.2%	-4.83%	2.53%	1.98%	5.64%
16	0.25%	9.73%	-8.20%	2.32%	15.1%	8.89%
17	0.00%	-734%	48.8%	405%	403%	417%
18	0.04%	7.52%	-4.18%	1.66%	0.17%	3.92%
19	-0.01%	237%	-19.2%	43.7%	37.1%	109%
20	3.05%	-79.2%	11.5%	-14.5%	-34.4%	39.5%

$$error_{oc} = I_L - I_o\left(e^{\frac{V_{oc}}{\Upsilon}}\right) - \frac{V_{oc}}{R_p} \tag{12}$$

$$error_{mp} = I_L - I_o\left(e^{\frac{V_{mp}+I_{mp}R_s}{\Upsilon}}\right) - \frac{V_{mp}+I_{mp}R_s}{R_p} - I_{mp} \tag{13}$$

$$I_L = I_o\left(e^{\frac{V_{ocs}}{\Upsilon}}\right) + \frac{V_{ocs}}{R_p} \tag{14s}$$

$$error_{V_{oc}} = V_{oc} - V_{ocs} \tag{14}$$

$$I_L = I_o\left(e^{\frac{V_{mps}+I_{mp}R_s}{\Upsilon}}\right) + \frac{V_{mps}+I_{mp}R_s}{R_p} + I_{mp} \tag{15s}$$

$$error_{V_{mp}} = V_{mp} - V_{mps} \tag{15}$$

The overall merit of the solution set was judged by the RMS error of the results of the 5 error equations. The 'RMS 5 Error' calculation treated all five error results with equal weights, as shown in RMS_{5error} Equation (16), as shown at the bottom of the page. Table 5 shows the method # from Table 2, the 5 absolute error calculations in percent for Equations (11), (12), (13), (14), and (15), and the overall absolute RMS 5 Error in percent from Equation (16).

VI. DISCUSSION OF ERRORS

A. CURRENT CHECK AT SHORT CIRCUIT

The first check compares the solved I_L parameter versus the I_L calculated with Equation (11). This is an easy check, and generally, the errors were low since the controlling factor is the ratio of R_s to R_p. Any reasonable solution should have a very low error for this check. Except for parameter set #20, with an error of 3.05%, all errors were under 1%, with an average of 0.11% and several 0.00%.

$$RMS_{5error} = \sqrt{\frac{((error_{sc})^2 + ((error_{oc})^2 + ((error_{mp})^2 + ((error_{Voc})^2 + ((error_{Vmp})^2}{5}} \tag{16}$$

B. CURRENT CHECK AT OPEN CIRCUIT

The check for current at open circuit uses Equation (12) which includes an exponential function. Because of the exponential, any error in the solution for η will significantly impact the results. The exponential result is then multiplied by the diode reverse saturation current I_o to determine the diode current I_d. This means a low error solution must include accurate values of both η and I_o. These calculations showed that several solution sets contained significant errors for this verification test. For set #17, the diode factor η of 1.277 is a reasonable value but, combined with an I_o of 6.9127 nA, produces an unreasonable diode current I_d of only 802 mA.

C. CURRENT CHECK AT MAXIMUM POWER

The third check utilized Equation (13), which also includes an exponential factor. In the case of maximum power, the diode current I_d, calculated with the exponential function and I_o, was a smaller part of the overall current compared to the open circuit case. This was reflected, for example, in set #8, where the current error at maximum power was 53.3% versus -806% for the open circuit current error.

D. VOLTAGE CHECK AT OPEN CIRCUIT

The influence of the exponent, diode ideality factor η, and reverse saturation current is also important in this error verification. In the worst cases, sets #4, #5, #6, and #7 contain errors of almost $-1{,}300\%$.

E. VOLTAGE CHECK AT MAXIMUM POWER

The fifth check includes the influence of the exponent but with a lower effect than in the open circuit check. The worst cases are again in sets #4, #5, #6, and #7, with errors of almost -1,100%.

F. OVERALL RMS 5 ERROR

Set #1 shows the lowest error, which to 3 decimals was 0.00%. The worst cases were sets #4 and #7, with an error of 830%. Table 5 shows that solutions with a high error have solved for an inferior value for the diode current I_d, found from the diode ideality factor η and the diode reverse saturation current I_o.

VII. ANALYSIS OF ERROR SENSITIVITY

Solution sets #1 and #15 parameters are similar, with the only difference in the number of digits provided by each. In set #1, all the solved values were calculated and presented with 10 digits. In set #15, the values of η, R_s, and I_o were stated to 3 digits, R_p to 6 digits, and I_L to 4 digits. This difference led to the question of how the number of digits used in a solution affects the error calculation results.

For solution set #1, Table 6 shows the number of solution digits starting with 10. Subsequent rows rounded the solution to 7, 6, 5, 4, 3, and 2 digits for each parameter.

Table 7 shows the resulting errors found by equations (11) to (16) using the input parameter values from the original 10 to 2 digits. Using all 10 digits resulted in calculated errors of 0.000% for all equations. Rounding the solution to 4 digits calculated, for example, an Error_{oc} of 0.817% and an overall RMS 5 error of 0.731%.

For set #1, an analysis of Table 7 data shows little error difference between 10 and 6 digits. Five digits provide a high precision result of under 0.2% for the RMS_{5error} calculation. The IEC test standard for PV Modules specifies 0.2% measurement accuracy [22]. Four digits provide a reasonable solution with an error of under 1%.

VIII. RECOMMENDATIONS

It is recommended that any solution in calculating values for the 5 Parameter model (η, R_s, R_p, I_L, and I_o) should include verification checks. A solution that results in unreasonable physical values or high RMS 5 Error should be re-evaluated. Any solution with less than 4 digits can provide unreliable results and should not be used.

TABLE 6. Parameter solutions set #1 with fewer digits.

# Digits	η	R_S, Ω	R_P, Ω	I_O, AMPS	I_L, Amps
10	1.340996014	0.2171524429	951.9318193	1.710643752E-7	8.211872846
7	1.340996	0.2171524	951.9318	1.710644E-7	8.211873
6	1.34100	0.217152	*951.932	1.71064E-7	8.21187
5	1.3410	0.21715	951.93	1.7106E-7	8.2119
4	1.341	0.2171	951.9	1.711E-7	*8.212
3	*1.34	*0.217	952	*1.71E-7	8.21
2	1.3	0.22	950	1.7E-7	8.2

* Matched solution parameters from set #15

TABLE 7. Calculated error with fewer digits.

# Digits	ERROR_{SC}	ERROR_{OC}	ERROR_{MP}	ERROR_{VOC}	Error_{Vmp}	RMS_{5error}
10	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
7	0.000%	0.002%	0.000%	0.000%	0.000%	0.001%
6	0.000%	0.011%	-0.001%	0.000%	0.000%	0.005%
5	-0.003%	-0.443%	0.030%	0.000%	0.000%	0.198%
4	-0.013%	0.817%	-0.026%	0.000%	0.000%	0.731%
3	0.187%	11.41%	-0.814%	0.00%	0.000%	5.11%
2	1.190%	604%	-36.5%	-110.0%	-70.0%	277%

TABLE 8. Source, RMS 3 and RMS 5 calculation errors.

#	SOURCE	$\text{RMS}_{3\ ERROR}$	$\text{RMS}_{5\ ERROR}$
1	0.00%	0.00%	0.00%
2	5.33%	6.89%	5.33%
3	0.154%	8.22%	6.48%
4	Graph	463%	830%
5	Graph	463%	828%
6	2.90%	463%	824%
7	1.56%	463%	830%
8	Not reported	466%	635%
9	1.6212%	4.52%	3.56%
10	Not reported	4.14%	3.25%
11	0.12294%	130%	103%
12	1.73%	51.5%	41.2%
13	1.62% & 1.21%	3.82%	3.00%
14	1.822%	13.4%	39.7%
15	4.65%	7.05%	5.64%
16	Not reported	7.35%	8.89%
17	Graph	425%	417%
18	Not Reported	5.00%	3.92%
19	Not Reported	137%	109%
20	1.87%	46.2%	39.5%

Since the solution to the RMS 5 Error method requires solving the transcendental equations (14s) and (15s) to find the voltage errors at open circuit and maximum power point, an alternative RMS 3 Error method can be used. This method only checks the RMS errors from Equations (11), (12), and (13). The error calculation is Equation (17). Table 8 summarizes the results of the reported source, and from the RMS_{3error}, and RMS_{5error} equations.

$$RMS_{3error} = \sqrt{\frac{((error_{sc})^2 + ((error_{oc})^2 + ((error_{mp})^2}{3}} \quad (17)$$

IX. CONCLUSION

A new method was presented to verify the solved values for the 5 Parameter PV model solution of η, R_s, R_p, I_L, and I_o. Using parameter values for the KG200GT PV module, this manuscript showed that all but a single solved parameter passed the Physical Parameter Verification test. When the solutions were verified with the PV 5 parameter equations at short circuit, open circuit, and maximum power, most published solutions have significantly high calculated errors found by both the RMS 5 Error and RMS 3 Error verification methods.

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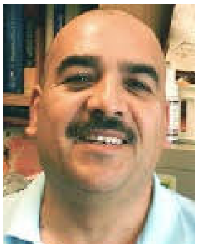
PETER R. MICHAEL (Senior Member, IEEE) received the B.S. degree in electrical engineering from the University of Colorado, USA, and the master's degree in systems engineering from Arizona State University, USA. He is currently pursuing the Ph.D. degree with the University of South Florida, USA. He has more than 30 years of industry experience in systems integration. This work is in support of his dissertation.

DANVERS E. JOHNSTON received the Ph.D. degree in physics from the University of Pennsylvania, USA. He is currently an Assistant Professor with Florida Gulf Coast University. His research interests include electronic nanomaterials and device physics, low-cost thin-film solar cells, and scalable nanomanufacturing.



WILFRIDO A. MORENO received the Ph.D. degree in electrical engineering from the University of South Florida (USF), USA. He is currently a Full Professor with USF. His research interests include energy, power electronics, controls option supervisor, and system integration for industrial applications in the areas of industrial controls and instrumentation.