A New Parameter Estimation Method of Solar Photovoltaic

Utkarsh Jadli, Padmanabh Thakur, and Rishabh Dev Shukla

***Abstract*—The accuracy in electrical model parameters of solar photovoltaic (PV), such as photon current, the diode dark saturation current, series resistance, shunt resistance, and diode ideality factor, are desirable to predict the real performance characteristics of solar PV under varying environment conditions. First, this paper derives mathematical model of solar PV, in terms of two unknown, namely, series resistance and ideality factor. Then, using combination of analytical method, simulated annealing method, and derived model, a new parameter estimation technique has been proposed. Finally, performance indices, such as PV characteristics curve, relative maximum power error, root mean square deviation, and normalized root mean square deviation are estimated for the various solar PV panels, using proposed and existing methods, to reveal the effectiveness of the proposed method. Also, experimental data have been considered for the validation. Finally, through the comparative analysis of the results, it is revealed that the proposed method offers solar PV characteristics more closer to the real characteristics than the other existing methods.**

***Index Terms*—Newton–Raphson (NR), parameter estimation, root mean square deviation (RMSD), search algorithm, simulated annealing (SA), solar photovoltaic (PV).**

I. Introduction

NOWADAYS solar photovoltaic (PV) parameter estimation techniques have received significant research attention to enhance its utilization in order to fulfill the increasing demands of electrical power. Over the past decades, myriads of research contributions were carried out for the accurate estimation of unknown parameters of solar PV. Usually, analytical, numerical, and metaheuristic-based methods have been implemented to obtain accurate values of electrical model parameters of solar PV.

In analytical method [1]–[4], the accuracy of estimation is greatly dependent on the exact placement of data, as given on manufacturers data sheet, on nonlinear characteristics curve of solar PV. Though the analytical methods have numbers of attributes, such as provide rapid solution, accurate results, less computational time, etc., but on the other hand, it gives erroneous results with large numbers of unknown parameters, such as in the case of solar PV [5]. In addition, the large numbers of unknown variables result in high computation.

In contrast with the analytical method, numerical method considers all the sample points on the output characteristics curve of the solar PV. Therefore, the numerical methods provide more accurate results than the analytical methods [5], [6]. The numerical methods, based on Newton–Raphson (NR) [7], [8] and Gauss–Seidel [1], [9], were often used by the researchers to estimate electrical model parameters of solar PV. However, numerical methods offer a high degree of accuracy, but the prediction of initial guess for the large numbers of unknown parameters, such as five unknown parameters in single-diode model, has been found difficult [10], [11]. Any wrong in initial guess results in the solution convergence to local minima instead of global minima. Furthermore, the large numbers of unknown parameters make computational time high [10].

Additionally, in order to resolve the issues, as existing in numerical and analytical methods, several metaheuristic algorithms (MAs)-based approaches, such as, genetic algorithm [12], particle swarm algorithm [13], [14], simulated annealing (SA) algorithm [15], differential evolution algorithm [16], teaching-learning algorithm [17], etc., were recommended. However, these Mas-based approaches were found more proficient in estimating the electrical model parameters of solar PV than the numerical and analytical methods, but at the same time, the large numbers of unknown parameters, existing in solar PV model, result in slow speed of convergence and incapability in tracking actual characteristics [5], [6]. Recently, cost minimization, using search algorithm, has also been tested to enhance the accuracy in electrical model parameter [18].

Furthermore, in some of the research works, computational efforts have been reduced by neglecting series resistance "R_s" [19], [20], shunt resistance "R_{sh}" [21], [22], and assuming the value of diode ideality factor "n" [5]. These approaches lead to an error in estimating the maximum power point (MPP) [11], [23].

In this paper, all five unknown electrical model parameters have been considered to improve the accuracy of the results. Furthermore, to reduce the computational efforts, only two unknowns electrical model parameters of solar PV have been estimated through MA, namely, SA, and remaining three are evaluated through the analytical method.

The contributions of the proposed work are summarized in the following points.

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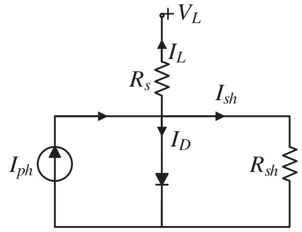

Fig. 1. Single-diode model of a solar cell.

1) First, the characteristics equation or mathematical model of solar PV has been derived in terms of two unknown, namely series resistance ("R_s") and modified diode ideality factor ("V_t").
2) Then, the derived equation has been applied using the SA method to estimate the unknown parameters "R_s" and "V_t."
3) Afterward, the remaining three unknown parameters, namely photon current I_{ph}, saturation current I_o, and shunt resistance R_{sh}, have been estimated with the help of analytical method.
4) Finally, eight different solar PV panels have been considered to check the effectiveness of the proposed method. Performance indices of solar PV, such as PV characteristics curve, maximum power error, root mean square deviation (RMSD), and normalized RMSD have been estimated for these panels using various existing and proposed parameter estimation method. Through the comparative analysis, it is revealed that the proposed method provides more accurate characteristics than the existing methods.

II. Mathematical Modeling of Solar PV and Parameter Estimation Using NR and SA

In most of the studies, single-diode model has been considered for the estimation of electrical model parameters due to its accuracy and simplicity [24]–[26]. Typically, a solar PV is modeled as current source with inverted diode as shown in Fig. 1.

Resistance R_s, as shown in Fig. 1, represents the resistance between the bulk material and the metal contact, whereas R_{sh} represents the recombination of electron-hole pairs. The relationship between the output current I_L and voltage V_L for the single-diode model is given as follows:

$$I_L = I_{\mathrm{ph}} - I_o \left[\exp\left(\frac{V_L + I_L R_s}{V_t}\right) - 1\right] - \frac{V_L + I_L R_s}{R_{\mathrm{sh}}} \quad (1)$$

where $V_t = nKTN_s/q$ is the modified diode ideality factor.

Here, n is the diode ideality factor, T is the solar cell temperature (in Kelvin), K is the Boltzmann constant (1.3806×10^{-23} J/K), q is the charge of an electron (1.6021×10^{-19} C), I_o is the diode dark saturation current (in Ampere), I_{ph} is the photon current (in Ampere), and N_s is the numbers of series-connected cells.

The five unknown electrical model parameters, which are not specified in manufacturer data sheet, are as I_{ph}, I_o, R_s, R_{sh}, and V_t. From (1), it is apparent that the characteristics curve of solar PV is greatly dependent on these five unknown parameters. Therefore, precise estimations of these five unknown parameters are vital to achieve characteristics closer to the real characteristics.

The five equations, as given in (2), (3), (4), (7), and (9), are required for the estimation of these five unknown electrical model parameters, using the NR method, are obtained in the following steps.

1) Short circuit is placed at the load terminal of solar PV and corresponding short-circuit current (I_{sc}) is obtained by substituting $V_L = 0$ in (1) and is given as follows:

$$I_{\mathrm{sc}} = I_{\mathrm{ph}} - I_o \left[\exp\left(\frac{I_{\mathrm{sc}} R_s}{V_t}\right) - 1\right] - \frac{I_{\mathrm{sc}} R_s}{R_{\mathrm{sh}}}. \quad (2)$$

2) Open circuit is placed at the load terminal of solar PV, i.e., substituting $I_L = 0$ in (1), and corresponding equation is given as follows:

$$I_{\mathrm{ph}} - I_o \left[\exp\left(\frac{V_{\mathrm{oc}}}{V_t}\right) - 1\right] - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}}} = 0. \quad (3)$$

3) Voltage V_{mp} and current I_{mp} at MPP are usually available with manufacturer data sheet. Third expression is obtained by substituting V_{mp} and I_{mp} in (1) as follows:

$$I_{\mathrm{mp}} = I_{\mathrm{ph}} - I_o \left[\exp\left(\frac{V_{\mathrm{mp}} + I_{\mathrm{mp}} R_s}{V_t}\right) - 1\right] - \frac{V_{\mathrm{mp}} + I_{\mathrm{mp}} R_s}{R_{\mathrm{sh}}}. \quad (4)$$

4) Tangent at MPP of PV characteristics curve or PV curve will be parallel to the voltage axis. Therefore

$$\left.\frac{dP}{dV}\right|_{\mathrm{MPP}} = 0. \quad (5)$$

On solving (5), it is found as follows:

$$\left.\frac{dI_L}{dV_L}\right|_{\mathrm{MPP}} = -\frac{I_{\mathrm{mp}}}{V_{\mathrm{mp}}}. \quad (6)$$

Using (6) and (1), the fourth equation can be derived as follows:

$$I_{\mathrm{mp}} = (V_{\mathrm{mp}} - I_{\mathrm{mp}} R_s) \times \left(\frac{I_o}{V_t}\left[\exp\left(\frac{V_{\mathrm{mp}} + I_{\mathrm{mp}} R_s}{V_t}\right)\right] + \frac{1}{R_{\mathrm{sh}}}\right). \quad (7)$$

5) During short-circuit condition, the slope of the *I–V* characteristics curve of solar PV, near short-circuit region, is calculated by differentiating current with respect to voltage and is given as [7], [9], [26] follows:

$$\left.\frac{dI_L}{dV_L}\right|_{I=I_{\mathrm{sc}}} = -\frac{1}{R_{\mathrm{sh}}}. \quad (8)$$

So, the final equation is derived by solving (8) and is given as follows:

$$\frac{I_o}{V_t}\left[\exp\left(\frac{I_{\mathrm{sc}} R_s}{V_t}\right)\right][R_{\mathrm{sh}} - R_s] = \frac{R_s}{R_{\mathrm{sh}}}. \quad (9)$$

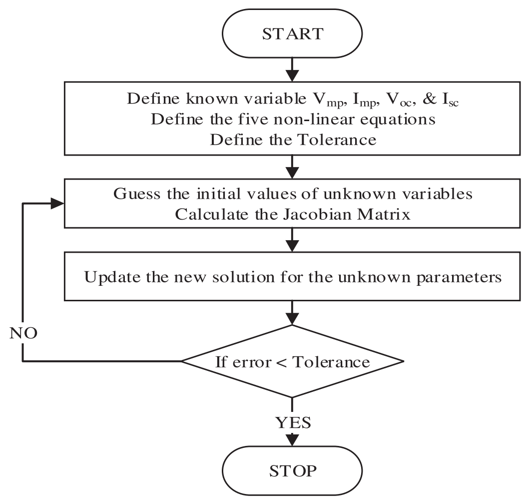

Fig. 2. Flowchart of NR method.

A. Parameter Extraction Using Newton-Raphson Method

NR method has been adopted widely for obtaining the roots of transcendental or nonlinear equation because of its simplicity and fast convergence [7]. The expression, used to solve the nonlinear equation, with the NR method is given as follows:

$$I_{L_{k+1}} = I_{L_k} - \frac{f\left(I_{L_k}\right)}{f'\left(I_{L_k}\right)},\ k \geq 0. \tag{10}$$

Here, $I_{L_{k+1}}$ and I_{L_k} represent the value of I_L in the $k\mathrm{th}$ and $k + 1\mathrm{th}$ iteration. The expression for the $f(I_{L_k})$ and $f'(I_{L_k})$ are given as follows:

$$f\left(I_{L_k}\right) = I_{L_k} - I_{\mathrm{ph}} + I_o\left[\exp\left(\frac{V_L + I_{L_k}R_s}{V_t}\right) - 1\right] + \frac{V_L + I_{L_k}R_s}{R_{\mathrm{sh}}} = 0 \tag{11}$$

$$f'\left(I_{L_k}\right) = 1 + \frac{I_oR_s}{V_t}\left[\exp\left(\frac{V_L + I_{L_k}R_s}{V_t}\right)\right] + \frac{R_s}{R_{\mathrm{sh}}} = 0. \tag{12}$$

Furthermore, the steps, as shown in Fig. 2, are used to extract unknown variable with the NR method.

However, the NR method being simple in application and gives fast convergence, but is found inapt to estimate large number of unknown variables. The assumption of initial guesses to initiate this method for large number of unknown variable is a big challenge. Wrong initial guess may lead to erroneous estimation.

In this paper, the NR method has been tested on six different solar PV panels, three monocrystalline and three polycrystalline, to reveal its accuracy. The results, obtained with this method, are shown in Section IV of this paper.

B. Parameters Extraction Using Simulated Annealing Method

Annealing is the process to cool and freeze the metal in crystalline state with minimum energy to produce high quality crystals. This process involves the careful control of cooling rate and temperature. The SA method of parameter estimation is motivated from this process. Furthermore, in contrast with the NR method, the SA method avoids the trapping of unknown parameters in local minima [15]. The steps, as shown in Fig. 3, have been used to extract the unknown electrical model parameters of solar PV [15]. The objective function used for estimating five unknown parameters through SA is given in (11). However, the SA method provides more accurate results than the NR method but at the same time gives erroneous results for large numbers of unknown parameters. In this paper, the SA method is also tested on six different, monocrystalline and polycrystalline, solar PV panels to reveal its accuracy. It is shown that this method alone is not proficient to get accurate electrical model parameters of solar PV. Therefore, combination of this method with the analytical method is desirable to get accurate results. In this paper, number of cycle, probability of acceptance at start, end, and cooling factor are considered as 50, 0.7, 0.001, 0.95, respectively, for implementation of SA-based method for parameter estimation.

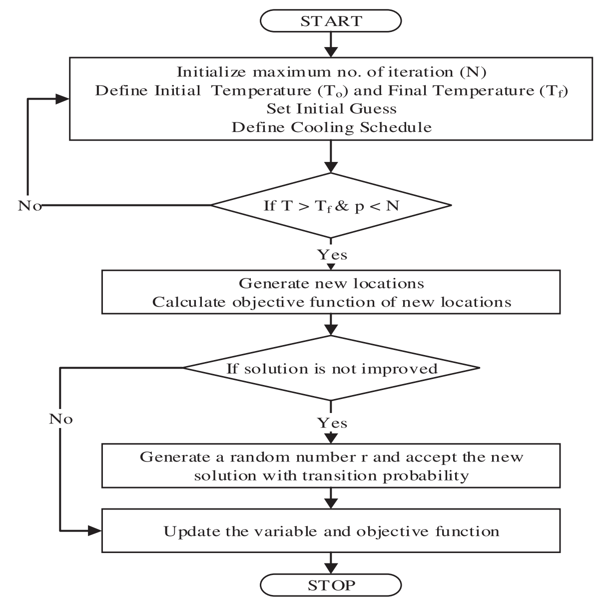

Fig. 3. Flowchart of SA method.

In Fig. 3, "*N*" and "*p*" represent the maximum number of iteration and the values of iteration set by the users, respectively. Here, the range of *p* lies between 0 to *N*.

III. Proposed Mathematical Model of Solar PV and Determination of Objective Function

In this section, the characteristics equation or mathematical model of solar PV has been derived, in terms of two unknown, namely R_s and V_t. Then, the SA method has been applied to the derived characteristic equation to achieve their values. As the proposed characteristics equation has two unknowns, only, so the SA method converges faster and provides more accurate results than the results with the five unknown.

The proposed characteristics equation of solar PV model is derived as follows.

TABLE I
SOLAR PV PANELS PARAMETERS AVAILABLE WITH DATA SHEET

S. No.	Solar PV Panels	Given Parameters taken from datasheet					
		$V_{\rm mp}$ (V)	$I_{\rm mp}$ (A)	$V_{\rm oc}$ (V)	$I_{\rm sc}$ (A)	N_s	T (°C)
1.	Schutten Solar, STM6 40-36 (Monocrystalline)	16.98	1.50	21.02	1.663	36	51
2.	H&T GmbH, TS265D60 (Monocrystalline)	30.90	8.58	38.10	9.19	60	25
3.	Nemy, JP270M60 (Monocrystalline)	31.10	8.68	38.60	9.20	60	25
4.	Schutten Solar, STP6 120-36 (Polycrystalline)	14.93	6.83	19.21	7.48	36	55
5.	Solarworld, Pro. SW255 (Polycrystalline)	30.90	8.32	38.00	8.88	60	25
6.	Solarworld, SW80RNA (Polycrystalline)	17.90	4.49	21.90	4.78	36	25

First, the value of $I_{\rm ph}$ from (3) has been substituted in (2) and (4) to obtain the expression for $I_{\rm sc}$ and $I_{\rm mp}$ as follows:

$$I_{\rm sc} = (B - A)\, I_o + \frac{V_{\rm oc} - I_{\rm sc} R_s}{R_{\rm sh}} \tag{13}$$

$$I_{\rm mp} = (B - C)\, I_o + \frac{V_{\rm oc} - V_{\rm mp} - I_{\rm mp} R_s}{R_{\rm sh}} \tag{14}$$

where $A = \exp(\frac{I_{\rm sc} R_s}{V_t}) - 1$, $B = \exp(\frac{V_{\rm oc}}{V_t}) - 1$, and $C = \exp(\frac{V_{\rm mp} + I_{\rm mp} R_s}{V_t}) - 1$.

Then, the value of I_o from (9) is substituted in (7), (13), and (14) to achieve $I_{\rm sc}$ and $I_{\rm mp}$ in terms of R_s, $R_{\rm sh}$, and V_t as follows:

$$I_{\rm sc} = \frac{(B - A)\, V_t R_s}{R_{\rm sh}(1 + A)\,(R_{\rm sh} - R_s)} + \frac{V_{\rm oc} - I_{\rm sc} R_s}{R_{\rm sh}} \tag{15}$$

$$I_{\rm mp} = \frac{(B - C)\, V_t R_s}{R_{\rm sh}(1 + A)\,(R_{\rm sh} - R_s)} + \frac{V_{\rm oc} - V_{\rm mp} - I_{\rm mp} R_s}{R_{\rm sh}} \tag{16}$$

$$I_{\rm mp} = (V_{\rm mp} - I_{\rm mp} R_s)\left(\frac{R_s\,(1 + C)}{R_{\rm sh}(1 + A)\,(R_{\rm sh} - R_s)} + \frac{1}{R_{\rm sh}}\right). \tag{17}$$

Furthermore, equating (16) and (17) to obtain the value of $R_{\rm sh}$ as follows:

$$R_{\rm sh} = R_s + \frac{R_s}{(2V_{\rm mp} - V_{\rm oc})} \times \left(\frac{V_t\,(B - C) - (1 + C)\,(V_{\rm mp} - I_{\rm mp} R_s)}{1 + A}\right). \tag{18}$$

The value of $R_{\rm sh}$ can also be obtained by solving (15) and (16) as follows:

$$R_{\rm sh} = \frac{V_{\rm oc}\,(A - C) + I_{\rm sc} R_s\,(C - B) + (V_{\rm mp} + I_{\rm mp} R_s)\,(B - A)}{I_{\rm sc}\,(B - C) + I_{\rm mp}\,(A - B)}. \tag{19}$$

Finally, the proposed characteristic equation is derived by equating (18) and (19) as follows:

$$f\,(R_s, V_t) = \left(R_s + \frac{R_s}{(2V_{\rm mp} - V_{\rm oc})} \times \left(\frac{V_t\,(B - C) - (1 + C)\,(V_{\rm mp} - I_{\rm mp} R_s)}{1 + A}\right)\right) - \left(\frac{V_{oc}\,(A - C) + I_{\rm sc} R_s\,(C - B) + (V_{\rm mp} + I_{\rm mp} R_s)\,(B - A)}{I_{\rm sc}\,(B - C) + I_{\rm mp}\,(A - B)}\right) = 0. \tag{20}$$

It is obvious from (20) that the proposed characteristics equation is function of R_s and V_t, only. Hence, in contrast with the characteristics equation with five unknown, the SA method converges much faster and provide more accurate results with the proposed characteristics equation. This paper considers (20) as a single objective nonlinear optimization function, which must be minimized with the help of SA algorithm as discussed in Section II.

R_s and V_t are obtained by SA algorithm while the remaining three unknown electrical model parameters are extracted analytically by substituting the values of R_s and V_t in (19), (9), and (2), respectively.

IV. RESULTS AND DISCUSSIONS

A. *Estimation of PV Characteristics Curve With the Proposed, NR, SA, and Search Algorithm Methods*

Six different solar PV panels, three of which monocrystalline and remaining three are polycrystalline material, have been considered, from [18] and summarized in Table I, to check the effectiveness of the proposed method as well as the methods based on SA, NR, search algorithm. Proposed, SA, NR, and search algorithm methods [18] are applied on these datasets and results obtained are summarized in Table II.

Using the results, as summarized in Table II, the *P–V* characteristics curves are obtained and are shown in Figs. 4–9. It is noticeable from Figs. 4–9 that the proposed approach is more closer to MPP than the NR, SA, and search algorithm. It is also worthwhile to note that the boundary condition for SA and proposed methods are kept same. Thus, the proposed method gives more realistic characteristics than the NR, SA, and search algorithm-based approaches, wherein five unknown parameters have been considered for evaluation, simultaneously.

TABLE II
ESTIMATED PARAMETERS WITH THE PROPOSED, NR, SA AND SEARCH ALGORITHM METHODS

S. No.	Solar PV Panel	Parameters to be extracted	NR on 5 equations		Extraction using SA			Search Algorithm	Proposed Technique		
			Initial Values	Estimated Parameter	Lower bound	Upper Bound	Estimated Parameter		Lower bound	Upper Bound	Estimated Parameter
1.	Schutten Solar, STM6 40-36 (Monocrystalline)	I_{ph} (A)	1.6	1.664	1.5	1.7	1.66340	1.6635	–	–	1.6637
		I_o (A)	1e–6	9.853e–7	9.6e–7	9.9e–7	9.8464e–7	1.4142e–6	–	–	9.8441e–7
		R_s (Ω)	0.2	0.2176	0.2	0.3	0.21631	4.879e–3	0.2	0.3	0.21695
		R_{sh} (Ω)	500	503.6	500	550	506.0718	15.419	–	–	502.9332
		V_t	1.4	1.468	1.3	1.5	1.46832	$n = 1.4986$	1.3	1.5	1.46880
2.	H&T GmbH, TS265D60 (Monocrystalline)	I_{ph} (A)	9.0	9.191	9.0	9.2	9.19053	9.1908	–	–	9.1911
		I_o (A)	1e–7	5.873e–8	5.7e–8	5.9e–8	5.8776e–8	6.84e–8	–	–	5.7748e–8
		R_s (Ω)	0.1	0.1940	0.1	0.2	0.19799	3.174e–3	0.1	0.2	0.19421
		R_{sh} (Ω)	1000	1661	1500	1700	1661.2057	36.45	–	–	1675.1
		V_t	1.8	2.019	2.0	2.1	2.0221	$n = 1.3213$	2.0	2.1	2.01912
3.	Nemy, JP270M60 (Monocrystalline)	I_{ph} (A)	9.0	9.2	9.1	9.3	9.20681	9.2002	–	–	9.2003
		I_o (A)	1e–7	1.197e–9	1.0e–9	1.2e–9	1.1918e–9	1.3e–9	–	–	1.1930e–9
		R_s (Ω)	0.3	0.3015	0.2	0.4	0.30156	5.013e–3	0.2	0.4	0.30145
		R_{sh} (Ω)	9000	9121	9100	9200	9138.7469	207.73	–	–	9139.9
		V_t	1.6	1.696	1.5	1.7	1.69491	$n = 1.1027$	1.5	1.7	1.69608
4.	Schutten Solar, STP6 120-36 (Polycrystalline)	I_{ph} (A)	7.4	7.485	7.3	7.5	7.48442	7.4838	–	–	7.4848
		I_o (A)	1e–6	8.944e–7	8.7e–7	9.0e–7	8.9165e–7	1.2e–6	–	–	8.9391e–7
		R_s (Ω)	0.1	0.1819	0.1	0.2	0.18213	4.9e–3	0.1	0.2	0.18168
		R_{sh} (Ω)	200	281.8	200	300	282.7375	9.745	–	–	282.0717
		V_t	1.3	1.206	1.1	1.3	1.20634	$n = 1.2072$	1.1	1.3	1.2066
5.	Solarworld, Pro. SW255 (Polycrystalline)	I_{ph} (A)	8.8	8.881	8.7	8.9	8.88080	8.8805	–	–	8.8807
		I_o (A)	1e–8	2.318e–8	2.2e–8	2.4e–8	2.3178e–8	2.61e–8	–	–	2.3129e-8
		R_s (Ω)	0.2	0.21	0.1	0.3	0.21018	3.457e–3	0.1	0.3	0.20952
		R_{sh} (Ω)	2000	2570	2500	2600	2571.7304	57.40	–	–	2574.9
		V_t	1.7	1.923	1.8	2.0	1.92380	$n = 1.2554$	1.8	2.0	1.92440
6.	Solarworld, SW80RNA (Polycrystalline)	I_{ph} (A)	4.7	4.78	4.6	4.8	4.78149	4.7802	–	–	4.7803
		I_o (A)	1e–7	6.916e–9	6.7e–9	7.1e–9	7.0786e–9	7.6e–9	–	–	6.8650e–9
		R_s (Ω)	0.2	0.2154	0.1	0.3	0.22221	5.921e–3	0.1	0.3	0.21553
		R_{sh} (Ω)	3000	3588	3550	3650	3586.4076	134.63	–	–	3600.9
		V_t	1.0	1.076	1.0	1.1	1.07900	$n = 1.1696$	1.0	1.1	1.07591

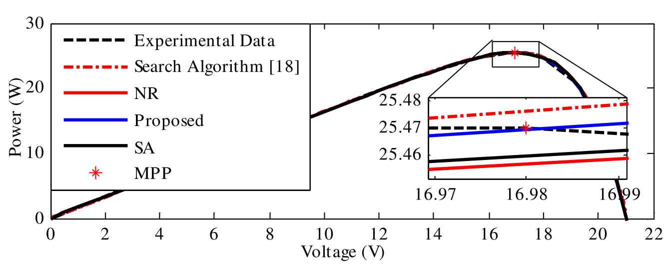

Fig. 4. $P-V$ characteristics for Schutten Solar, STM6 40-36 panel.

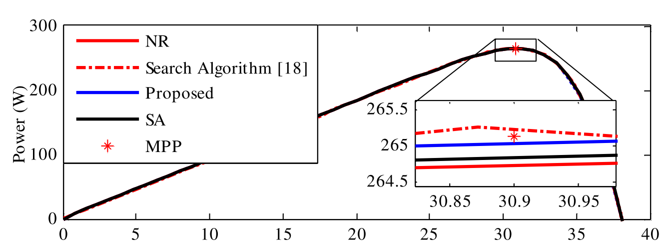

Fig. 5. $P-V$ characteristics for H&T GmbH, TS265D60 panel.

Furthermore, it is obvious from Figs. 4–9, the PV curve, obtained with the proposed method, is more closer to the experimental curve. Therefore, it can be said that the parameters, estimated with the proposed method, are more accurate than the parameters estimated with NR, SA, and search algorithm-based approaches.

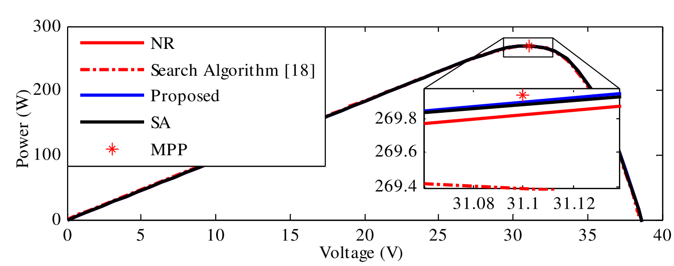

Fig. 6. $P-V$ characteristics for Nemy, JP270M60 panel.

B. Estimation of Maximum Power Error With the Proposed, NR, SA, and Search Algorithm Methods

The maximum power error or relative error, i.e., the difference between the actual power and the calculated power, are estimated for different methods and summarized in Table III. It is obvious from Table III that the maximum power error, ob-

TABLE III
RELATIVE ERROR FOR DIFFERENT TECHNIQUES IN EXTRACTION FOR DIFFERENT SOLAR PV PANELS

S. No.	Solar PV Panel	Extraction Techniques Used	Actual Maximum Power P_a (W)	Calculated Maximum Power P_c (W)	Relative Error $E = \frac{P_a - P_c}{P_a} \times 100(\%)$
1.	Schutten Solar, STM6 40-36 (Monocrystalline)	NR on 5 equations	25.4700	25.4573	4.9862×10^{-2}
		SA	25.4700	25.4600	3.9261×10^{-2}
		Proposed Technique	25.4700	25.4693	2.7483×10^{-3}
		Search Algorithm	25.4700	25.4760	-2.3357×10^{-2}
2.	H&T GmbH, TS265D60 (Monocrystalline)	NR on 5 equations	265.1220	264.7340	1.4635×10^{-1}
		SA	265.1220	264.8446	1.0463×10^{-1}
		Proposed Technique	265.1220	265.0377	3.1797×10^{-2}
		Search Algorithm	265.1220	265.2214	-3.7492×10^{-2}
3.	Nemy, JP270M60 (Monocrystalline)	NR on 5 equations	269.9480	269.8232	4.6231×10^{-2}
		SA	269.9480	269.8873	2.2486×10^{-2}
		Proposed Technique	269.9480	269.8991	1.8115×10^{-2}
		Search Algorithm	269.9480	269.4993	1.6622×10^{-1}
4.	Schutten Solar, STP6 120-36 (Polycrystalline)	NR on 5 equations	101.9719	101.8691	1.0081×10^{-1}
		SA	101.9719	101.9095	6.1193×10^{-2}
		Proposed Technique	101.9719	101.9368	3.4421×10^{-2}
		Search Algorithm	101.9719	101.9340	3.7167×10^{-2}
5.	Solarworld, Pro. SW255 (Polycrystalline)	NR on 5 equations	257.0880	256.7974	1.1304×10^{-1}
		SA	257.0880	256.8950	7.5072×10^{-2}
		Proposed Technique	257.0880	257.0574	1.1903×10^{-2}
		Search Algorithm	257.0880	257.0315	2.1977×10^{-2}
6.	Solarworld, SW80RNA (Polycrystalline)	NR on 5 equations	80.3710	80.3327	4.7654×10^{-2}
		SA	80.3710	80.3441	3.3470×10^{-2}
		Proposed Technique	80.3710	80.3642	8.4608×10^{-3}
		Search Algorithm	80.3710	80.4171	-5.7359×10^{-2}

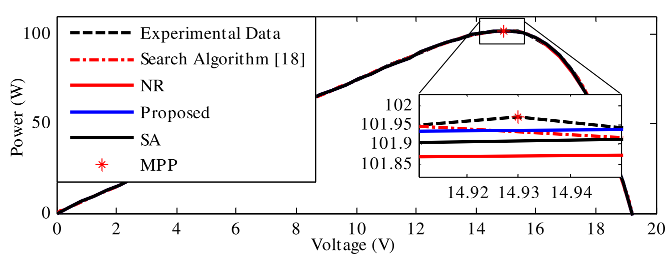

Fig. 7. $P - V$ characteristics for Schutten Solar, STP6 120-36 panel.

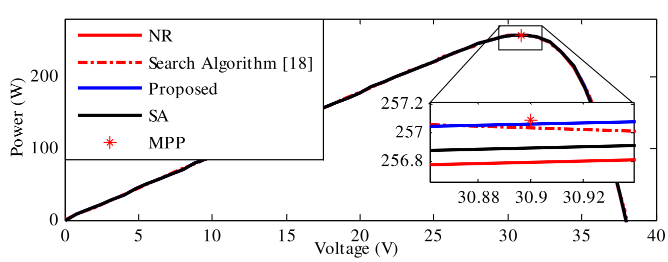

Fig. 8. $P - V$ characteristics for Solarworld, Pro. SW255 panel.

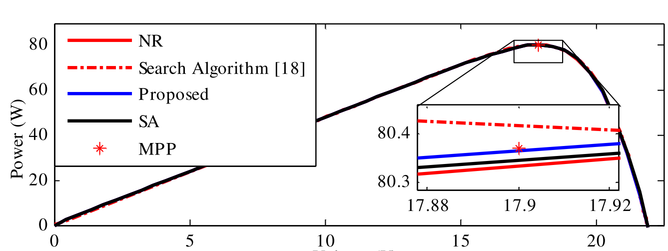

Fig. 9. $P - V$ characteristics for Solarworld, SW80RNA panel.

TABLE IV
COMPARISON BASED ON RMSD

S. No.	Solar Panel	Evaluating Criteria	NR	SA	Search Algorithm [18]	Proposed
1.	X	RMSD	0.0029	0.0027	0.0022	0.0020
		NRMSD (%)	0.1744	0.1624	0.1323	0.1203
2.	Y	RMSD	0.0176	0.0158	0.0179	0.0156
		NRMSD (%)	0.2353	0.2112	0.2393	0.2086

tained with the proposed method, is minimum for all six solar PV panels.

C. Estimation of Root Mean Square Deviation With the Proposed, NR, SA, and Search Algorithm Methods

Furthermore, RMSD of current is estimated with the proposed as well as the methods, based on NR, SA, and search algorithm, to reveal the superiority of the proposed method over NR, SA, and search algorithm method. RMSD represents the difference between the experimental values of current ($\tilde{I}_L$) and the current generated with model (I_L) [26]. Mathematically, RMSD is defined as follows:

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{j=1}^{N_{\mathrm{curve}}} \left[\left(\tilde{I}_L\right)_j - \left(I_L\right)_j\right]^2}{N_{\mathrm{curve}}}}. \tag{21}$$

The normalized RMSD (NRMSD) is given as follows:

$$\mathrm{NRMSD} = \frac{\mathrm{RMSD}}{I_{\mathrm{sc}}} \times 100\%. \tag{22}$$

TABLE V
COMPARISON BETWEEN NR, SA, AND PROPOSED METHOD

Known parameters [7] (KC200GT)	Known parameters [15] (Photowatt-PWP201)	Estimated parameters	Estimated through		Estimated through proposed method	
			SA [15] (Photowatt-PWP201)	NR [7] (KC200GT)	(Photowatt-PWP201)	(KC200GT)
$V_{\rm mp} = 26.3$ V	$V_{\rm mp} = 12.64$ V	$I_{\rm ph}$(A)	1.0331	8.211873	1.0322	8.2119
$I_{\rm mp} = 7.61$ A	$I_{\rm mp} = 0.913$ A	I_o(A)	3.6642e–6	1.711e–7	1.4586e–6	1.9606e–7
$V_{\rm oc} = 32.9$ V	$V_{\rm oc} = 16.78$ V	$R_s\,(\Omega)$	1.1989	0.2171521	1.338	0.21089
$I_{\rm sc} = 8.21$ A	$I_{\rm sc} = 1.031$ A	$R_{\rm sh}\,(\Omega)$	833.333	951.927	616.751	895.7971
$N_s = 54$	$N_s = 36$	V_t	1.3379	1.8605	1.2482	1.87656

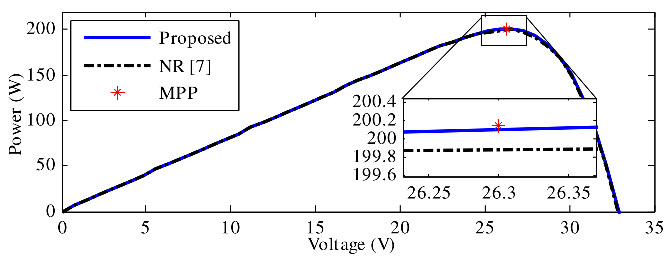

Fig. 10. $P - V$ characteristics for KC200GT polycrystalline panel.

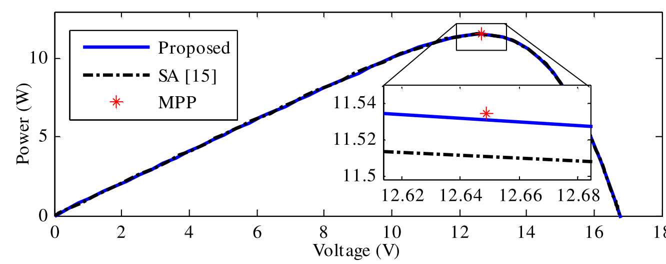

Fig. 11. $P - V$ characteristics for Photowatt-PW201 polycrystalline panel.

The values of I_L, generated with the proposed, NR, SA, and search algorithm, are subtracted from experimental values of current, i.e., $\tilde{I}_L$, to achieve the values of RMSD and NRMSD, as defined in (21) and (22), respectively, for STM6 40-36 (X) and STP6 120-36 (Y) panels. The results, obtained with these methods, are summarized in Table IV. It is evident from the results that the proposed method offers lesser value of RMSD and NRMSD for these two cases.

D. Estimation of PV Characteristics Curve for KC200GT and Photowatt-PWP201Panels

Furthermore, two new solar PV panels, namely, KC200GT [7] and Photowatt-PWP201 [15], as summarized in Table V, have been considered to check the efficiency of the proposed method.

The NR [3], SA [15], and the proposed method are applied on these panels to estimate the values of unknown electrical model parameters of solar PV. In addition, the comparative analysis of the results, obtained with these methods, is summarized in Table V to check the effectiveness of the proposed method. Moreover, the characteristics curves have been estimated from the results, as summarized in Table V, and are shown in Figs. 10 and 11. It is obvious from the Figs. 10 and 11 that the characteristics curves, obtained with the proposed method, is closer to MPP than the method suggested in [7] and [15].

E. Comparative Analysis of the Proposed Method With Existing Various Existing Methods

In this section, various existing electrical model parameter estimation methods, such as Accarino's method or explicit method [10], Villalva's method [5], iterative method [27], Lambert function [27], Silva's method [26], as summarized in Table VI, have been considered to check the effectiveness of the proposed as well as these existing parameter estimation methods. The results, as obtained with these methods and the proposed method, are summarized in Table VI. The PV curves, as obtained with these existing methods and the proposed method, are shown in Fig. 12. It is obvious from Fig. 12 that the MPP is more closer to the PV curve, obtained with the proposed method, than the other existing methods. Here, estimated parameters of the existing methods [5], [10], [26]–[27] are directly considered from the references.

Also, the accuracy of the proposed method is revealed by comparing maximum power error obtained with the proposed method and the method as suggested in [5], [10], [26], and [27]. The results of maximum power error, as summarized in Table VII, indicate that the proposed method offers more real characteristics than the methods as suggested in [5], [10], [26], and [27]. It is evident from the results that the maximum power error is smallest for the proposed method and highest for Silva's method [26]. It is noticeable that the characteristics of solar PV, as predicted by the proposed method, are very close to the real characteristics. Therefore, the proposed mathematical model, in terms of "R_s" and "V_t," as well as the parameter estimation method, as suggested in this paper, using combinations of analytical and SA, could be used for the precise estimation of unknown electrical model parameters of solar PV.

V. CONCLUSION

In this paper, first, characteristics equation of solar PV has been derived in terms of two unknown parameters of solar PV, namely series resistance and modified diode ideality factor, respectively. Then, the proposed characteristics equation is used

TABLE VI
COMPARISON OF PARAMETERS OF SOLAR PV ESTIMATED WITH VARIOUS EXISTING AND PROPOSED METHODS

Known parameters for Kyocera (KC200GT)	Estimated parameters	Estimated By					
		Accarino [10]	Villalva [5]	Iterative Method [27]	Lambert-W Function [27]	Silva [26]	Proposed
$V_{\rm mp} = 26.3$ V	$I_{\rm ph}$ (A)	8.21	8.214	8.2233	8.21	8.193	8.2119
$I_{\rm mp} = 7.61$ A	I_o (A)	2.1546e–9	9.825e–8	2.1523e–9	2.1954e–9	0.3e–9	1.9606e–7
$V_{\rm oc} = 32.9$ V	R_s (Ω)	0.2844	0.221	0.308	0.28405	0.271	0.21089
$I_{\rm sc} = 8.21$ A	$R_{\rm sh}$ (Ω)	157.536	415.405	193.0493	157.8532	171.2	895.7971
$N_s = 54$	V_t	1.4922	1.8036	1.4926	1.4926	1.3874	1.87656

TABLE VII
COMPARISONS OF RELATIVE POWER ERROR

S. No.	Extraction Techniques Used	Actual Maximum Power $P_{\rm a}$ (W)	Calculated Maximum Power $P_{\rm c}$ (W)	Relative Error $E = \frac{P_a - P_c}{P_a} \times 100(\%)$
1.	Accarino's Method [27]	200.1430	199.9727	8.5089×10^{-2}
2.	Villalva's Method [5]	200.1430	199.8832	1.2981×10^{-1}
3.	Lambert Method [28]	200.1430	199.8823	1.3026×10^{-1}
4.	Iterative Method [28]	200.1430	199.8664	1.3820×10^{-1}
5.	Silva's Mehod [26]	200.1430	204.7336	-2.2937×10^{-0}
6.	Proposed technique	200.1430	200.0960	2.3483×10^{-2}

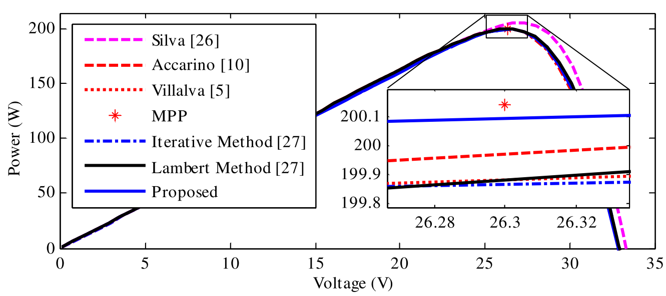

Fig. 12. PV curves for existing and proposed methods.

with the SA method to estimate these two unknown parameters. Rest of the three unknown parameters, namely photon current, saturation current, and shunt resistance, have been estimated analytically. Furthermore, the eight different solar PV panels have been considered to check the effectiveness of the proposed method. The various characteristics of solar PV, such as PV curve, MPP, RMSD, NRMSD, MPP error, etc., are estimated with the proposed method as well as with various existing methods. It is revealed through the comparative analysis that the proposed method offers the solar PV characteristics more closer to the real characteristics than the other existing parameter estimation methods. Maximum power error, RMSD, and NRMSD are found smaller with the proposed method.

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