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Simplified Method of Classification and Extraction of Physical Parameters of Dye-sensitized Solar Cells

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ABSTRACT
Dye-Sensitized solar cells (DSSCs) are a promising alternative to traditional silicon-based photovoltaics due to their cost-effectiveness and efficiency under low-light conditions. In this paper, a simplified non-iterative analytical method hinged on 1-diode/2-resistors electric equivalent circuit model neglecting either series or parallel resistor is employed to extract model coefficients/parameters of a total of 15 fabricated dye-sensitized solar cells. This method despite its simplicity reveals model coefficients extracted from experimental characteristic points were used to calculate the model parameters required to describe the behaviour of PV modules. In addition, a series to parallel ratio (SPR) criterion is used to classify 15 DSSCs into two classes namely class SPR ≥1 and class SPR<1. According to the SPR classification, the results show that 11 (73%) of the DSSCs belong to the class SPR≥1 and 4 (27 %) to the class SPR<1.

Keywords:
Single-diode circuit model,
SPR classification,
Model coefficients/ parameters,
Extraction of model parameters,
DSSCs.

INTRODUCTION

Energy is vital for sustainable development, impacting livelihoods, agriculture, health, and education. Fossil fuels currently dominate energy production but contribute significantly to global warming, driving the transition to renewable energy sources like solar, wind, hydro, and biomass. Among these, photovoltaic (PV) solar cells efficiently convert sunlight into electricity, with dye-sensitized solar cells (DSSCs) emerging as a promising third-generation solar technology (0ladosu *et al.,* 2024).

Non-iterative analytical models of PV systems are commonly used to define the electrical characteristics of a PV source for varying input and environmental effects. Furthermore, these models have been found useful tools to study the PV source behavior for any working condition such as irradiance, nature of PV source, temperature to mention a few. Also, suitable possible PV models are important when working on dynamic analysis of energy converters, determining the most preferred maximum power point tracking (MPPT) algorithms and during preparing simulation techniques for PV systems (Sera *et al.,* 2007; Chatterjee *et al.,* 2011; Vilallva *et al.,* 2009; Gow and Minning, 1999; Liu and Dougal, 2002; Di Piazza *et al.,* 2013a; Xiao *et al.,* 2004; Di Piazza and Vitale, 2013).

Different stable PV models are readily obtainable in published scholarly journals, letters, books and articles (Sera *et al.,* 2007; Chatterjee *et al.,* 2011; Vilallva *et al.,* 2009; Gow and Minning, 1999; Liu and Dougal, 2002). For example, the single-diode five-parameter model has been explained in detail when handling electric power generation. This method is obtained from the double-diode model, remembering that the recombination diode phenomenon is applicable only at low voltage bias. It gives a better mutual agreement between robustness and correctness (Liu and Dougal, 2002; Xiao *et al.,* 2004; Mahmoud et al., 2013; Di Piazza *et al.,* 2013b). The extraction of the model parameters of the single-diode model is done beginning from manufacturer's datasheet values or from experimental values and it is related to equations which can only be handled via iterative algorithms (Sera *et al.,* 2007; Chatterjee *et al.,* 2011).

Nevertheless, it has frequently been demonstrated that iterative methods are not fast and that they do not assure that the solution obtained is the true one, nor that a solution is determined at all (Chatterjee *et al.,* 2011; Di Piazza et al., 2013b). For example, the convergence to the correct answer relies on the first academic guess on the pattern the algorithm takes during the time it examines the surfaces and on the acceptance of the zero-value of each surface. However, if the algorithm fails to converge, the first guess must be replaced randomly as suggested by (Chatterjee *et al.,* 2011), and the algorithm must be done repeatedly. Consequently, iterative methods are not sufficient to be relevant on-line, for example to propose a maximum power point tracking (MPPT).

A robust parameter extraction method is important to appropriately execute PV models within actual time of modeling. For instance, a non-iterative PV model extraction method enhances and simplifies the understanding of the PV system behavior, from which the coordinates of the maximum power point are determined. In this case, an actual time simulation of MPPT computational procedures is feasible (Varnham *et al.,* 2007; Di Piazza *et al.,* 2010). Likewise, a single PV model parameter extraction, is useful for the real time simulation within PV simulators, that is, electronic power converters governed on the condition of given PV characteristics to regenerate the behavior of a PV system in the laboratory (Di Piazza and Vitale, 2013; Anderson, 1996).

For this purpose, ignoring one of the resistances of the single-diode equivalent circuit model, is a common trick, which simplifies the model and parameter extraction. This is the way simplified single-diode models are generated. For example, a host of researchers (Vilallva *et al.,* 2009; Di Piazza *et al.,* 2013c; Xiao *et al.,* 2004; Mahmoud *et al.,* 2013; Di Piazza *et al.,* 2013b; Cannizzaro *et al.,* 2013c) have reported that either the series resistor (R_s) or the shunt resistor (R_{sh}) is neglected. Regardless in all cases, only measured data have been used to satisfy both options. On the other hand, an analytical evaluation justifying the reliability of simplified single-diode models has been reported. To a great extent, in (Mahmoud *et al.,* 2013) the entire range of R_{sh} values is calculated, which generate a non-singular solution of the equations in question, so that for each value within that range, a particular parameter is determined, which is a measure of the entire curve fit.

In the same manner, no suitable tests have been suggested in academic literature to decide which resistance can be rejected. In particular (Mahmoud *et al.,* 2013) proposes to try rejecting R_{sh} and solving the appropriate transcendental equations to get R_S and the ideal diode factor. If the equations yield no solution, then the equations must be solved again setting R_s=0. Anyway, an analytical study been proposed by a host of authors (Cannizzaro *et al.*,2013; Cannizzaro *et al.*, 2014; Saleem and Karmalkar, 2009; Toledo *et al.,* 2012) that it is always reasonable to neglect one unknown resistance in the circuit model without risking its accuracy. Furthermore, they provided a criterion to classify PV modules using the possibility to model with (R_s=0, $R_{sh}\neq 0$) and with ($R_s\neq 0$, $R_{sh}=\infty$). This criterion is connected to the definition of a new parameter known as the series/parallel ratio (SPR) of the PV cell/panel.

In this paper, some analytical methods (Sera *et al.*,2007; Caanizzaro *et al.*, 2013c; Phang *et al.*, 1984; Saleem and Karmalkar, 2009; Khan et al., 2013; Babangida *et al.*, 2022; Petrone *et al.*, 2017) based on the 1 diode/ 2 resistors electric circuit model in conjunction with the SPR criterion are used to study the behavior and classification of fifteen dye-sensitized solar cells (DSSCs) (Yerima *et al.*, 2022; Cubas *et al.*, 2014) made up of different dyes.

MATERIALS AND METHODS

Solar cell modeling, the 1-diode/2-resistors model

The model equivalent circuit of the single-diode/double resistors solar cell is depicted in Figure 1 which is made up of a set of five model parameters namely the photocurrent I_{ph}, the diode saturation current I_o, the diode ideality factor n (or its modified version, a), the series resistance R_s, and the shunt resistance R_{sh}.

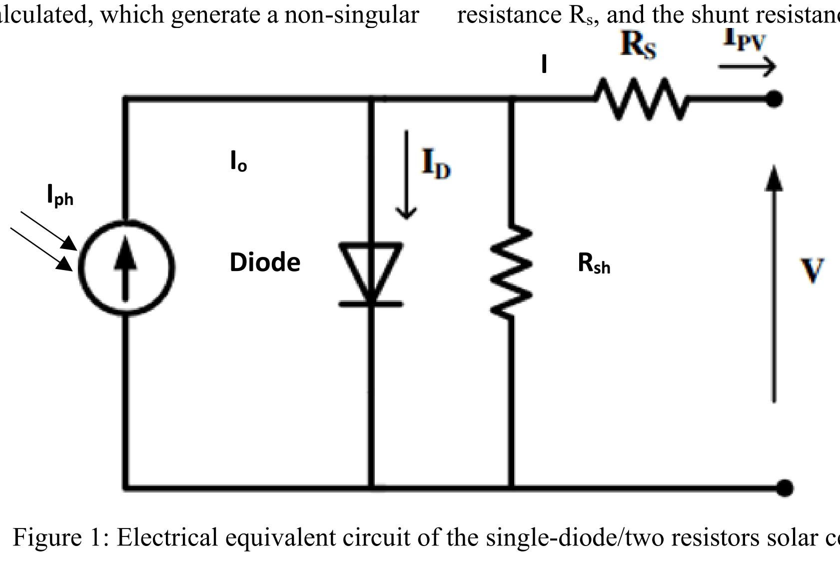


Figure 1: Electrical equivalent circuit of the single-diode/two resistors solar cell

Most of the time, the modified diode ideality factor 'a' is usually written in the literature as equation (1)

$$a = N_s n V_T \tag{1}$$

where N_s is the number of series-connected cells, n the ideal diode factor, and V_T is the thermal voltage given by

$$V_T = \frac{kT}{q} \tag{2}$$

where k=1.381×10⁻²³ J/K is the Boltzmann constant, T=300 K is the temperature in Kelvin and q=1.602×10⁻¹⁹ C the electron charge.

It is worth noting that the power is obtained by the product of voltage V and current I at different loads. The P-V graph can be plotted and the peak of the graph corresponds to maximum power which is given by equation (3);

$$P_{max} = V_{max} I_{max} \tag{3}$$

The fill factor (FF) of a cell being essentially a measure of the quality of the solar cell, it is the ratio of maximum power ($V_{max}I_{max}$) output referring to equation (3) to the product of the open-circuit voltage (V_oI_{sc}) and short circuit current is defined by equation (4)

$$FF = \frac{V_{max}\, I_{max}}{V_{oc}\, I_{sc}} \tag{4}$$

The conversion efficiency of a cell which determines utmost the reliability of the cell is defined as the ratio of electrical energy output to the light energy input which is represented by equation (5)

$$\eta = \frac{V_{mp} I_{mp}}{P_i A} \times 100\ \% \tag{5}$$

where P_i=1000 is the identical optical power in watts/m^2 at average solar spectrum at AM 1.5 and A is the illuminated area in cm^2.

The current-voltage equation is generally given implicitly by equation (6)

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{a}} - 1\right) - \frac{V+IR_s}{R_{sh}} \tag{6}$$

where all symbols have their usual meanings. This is an implicit equation that cannot be solved explicitly and requires numerical solution, which usually leads to some difficulties during the computation. Nevertheless, an equivalent explicit formulation can be achieved by employing the principal branch of the Lambert W function W_o (Cubas *et al.*, 2014; Petrone *et al.,* 2017; Mahmoud and El-Saadnany, 2016; Toledo *et al.*, 2012).

$$I = \frac{R_{sh}(I_{ph}+I_o)-V}{R_{sh}+R_s} - \frac{a}{R_s} W_o\left(\frac{R_{sh}R_sI_o}{aV_T(R_{sh}+R_s)} e^{\left(\frac{R_{sh}R_s(I_{ph}+I_o)+VR_{sh}}{a(R_{sh}+R_s)}\right)}\right) \tag{7}$$

$$V = R_{sh}(I_{ph}+I_o) - (R_s+R_{sh})I - aW_o\left\{\frac{R_{sh}I_o}{a} e^{R_{sh}\left(\frac{I_{ph}+I_o-I}{a}\right)}\right\} \tag{8}$$

It is obvious; one can directly find the current for a given value of voltage using equation (7) or the voltage via equation (8), which makes the computation easy and robust, in contrast to equation (6). The Lambert W function is readily available for readers of interest in all calculation procedures (Cubas *et al.*, 2014).

Now applying conditions of the simplified single-diode model that either (i) $R_s \neq 0$ and $R_{sh}=\infty$ to equation (7) and (ii) $R_s=0$ and $R_{sh} \neq 0$ to equation (8) leads to equations (9) and (10) respectively.

$$I = A - \frac{1}{C} W_o\left(BCe^{AC}\right),\ where\ A = I_{ph}+I_o, B = I_o e^{\frac{V}{a}}, C = \frac{R_s}{a} \tag{9}$$

$$V = D - R_{sh}I - aW_o\{Ee^{-FI}\},\ where\ D = AR_{sh},\ E = FI_o e^{\frac{D}{a}},\ F = \frac{R_{sh}}{a} \tag{10}$$

It is worth noting both equations (9) and (10) represent the simplified form of a four-parameter single-diode model with model parameters a, I_o, I_{ph}, R_s and a, I_o, I_{ph}, R_{sh} respectively.

Non-iterative equations generated for parameter extraction

In this paper, Cannizzaro et al., method (Varnham *et al.*, 2007; Petrone *et al.,* 2017) in conjunction with other analytical methods (Sera *et al.*, 2007: Cannizzaro *et al.*, 2013c; Cannizzaro *et al.*, 2014; Phang *et al.*, 1984; Saleem and Karmalkar, 2009; Khan *et al.*, 2013; Cubas *et al.*, 2014) of classifying and extraction of the model parameters of a solar cell is adopted. Thus, the present technique is based on the idea that the five-parameter model can always be reduced to a four-parameter model, neglecting either R_s or R_{sh} in agreement with the series to parallel ratio (SPR) conditions

$$SPR = \frac{1-\gamma_i}{e^{-r}}, where\ \gamma_i = \frac{I_{mp}}{I_{sc}},\ \gamma_v = \frac{V_{mp}}{V_{oc}},\ r = \frac{\gamma_i(1-\gamma_v)}{\gamma_v(1-\gamma_i)} \tag{11}$$

If $SPR \geq 1$, the shunt resistance is neglected, and the series resistance is given by

$$R_s = \frac{V_{oc}}{I_{sc}} \frac{\gamma_v(1-\gamma_i)ln(1-\gamma_i)+(1-\gamma_v)}{\gamma_i(1-\gamma_i)ln(1-\gamma_i)+\gamma_i}, \quad R_{sh} = \infty \tag{12}$$

Otherwise, if SPR<1,

$$R_s = 0, \quad R_{sh} = \frac{V_{oc}}{I_{sc}} \frac{\lambda_2 w+\lambda_1}{w+\lambda_1} \tag{13}$$

$$where\ \lambda_1 = \frac{1-\gamma_v}{1-\gamma_i}\frac{2\gamma_i-1}{\gamma_i+\gamma_v-1}, \quad \lambda_2 = \frac{\gamma_v}{1-\gamma_i},\ w = W_{-1}\left(-SPR\lambda_1 e^{-\lambda_1}\right) \tag{14}$$

The term $W_{-1}(\bullet)$ is the lower branch of the Lambert W function. Thus, having the two resistances allows the calculation of the modified ideality factor a via (15)

$$a = \frac{V_{mp}-V_{oc}+I_{mp}R_s}{ln\left[\frac{(I_{sc}-I_{mp})\left(1+\frac{R_s}{R_{sh}}\right)-\frac{V_{mp}}{R_{sh}}}{I_{sc}\left(1+\frac{R_s}{R_{sh}}\right)-\frac{V_{oc}}{R_{sh}}}\right]} \tag{15}$$

Obviously, equation (15) reduces to Khan's equation (16) when SPR>1 ($R_{sh}=\infty$) and to equation (17) when SPR<1 (R_s=0).

$$a = \frac{V_{mp}-V_{oc}+I_{mp}R_s}{ln\left(1-\frac{I_{mp}}{I_{sc}}\right)} \tag{16}$$

$$a = \frac{V_{mp} - V_{oc}}{ln\left(\frac{(I_{sc} - I_{mp}) - \frac{V_{mp}}{R_{sh}}}{I_{sc} - \frac{V_{oc}}{R_{sh}}}\right)} \quad (17)$$

Similarly, I_{ph} is calculated through Saleem's equation (18) and I_o via Phang's equation (19) respectively

$$I_{ph} = I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) \quad (18)$$

$$I_o = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) e^{\frac{-V_{oc}}{a}} \quad (19)$$

Evidently, applying the SPR conditions, equation (18) reduces to (20) only for both $SPR \geq 1$ and SPR<1

$$I_{ph} = I_{sc} \quad (20)$$

Similarly, equation (19) reduces to (21) when $SPR \geq 1$ and remain the same when SPR<1

$$I_o = I_{sc} e^{\frac{-V_{oc}}{a}} \quad (21)$$

It is crystal clear to note that the coefficients (γ_i, γ_v, r, SPR, λ_1, λ_2, w) in equations (11, 14) depend on the characteristic parameters (V_{oc},V_{mp}, I_{sc}, I_{mp}) while the model parameters (R_s, R_{sh}, I_o, I_{ph}, a) in equations (12, 13, 18, 19) depend on both the coefficients and characteristic parameters. Therefore, in this paper, for $SPR \geq 1$ ($R_{sh} = \infty$), the four model parameters R_s, a, I_{ph}, and I_o are calculated from equations (12), (16), (20) and (21) respectively whereas for SPR<1 (R_s=0), the parameters R_{sh}, a, I_o and I_{ph} are obtained via equations (13), (17), (19), and (20) respectively. Finally, the values of the calculated model parameters can be substituted in equations (9) and (10) to obtain the current and voltage that describe the behavior of a photovoltaic or solar cell.

In another vein, the measured data and those based on the 1-diode/2-resistor equivalent circuit model are usually presented in graphs related to the I-V curves. The absolute percentage difference (ξ_{av}) between the output current calculated (I_{cal}) via the model equation and the measured current (I_{exp}), related to the short-circuit current (I_{sc}) is given by equation (22)

$$\xi_{av} = \frac{1}{NI_{sc}} \sum_{i=0}^{N} \left(|I_{cal,i} - I_{exp,i}|\right) \times 100\% \quad (22)$$

where N is the number of points on the I-V curve.

Similarly, the average absolute difference between the output power calculated (P_{cal}) via model and the measured data (P_{exp}), is given by equation (23)

$$\xi_{av}^{*} = \frac{1}{M} \sum_{i=0}^{M} \left(|P_{cal,i} - P_{exp,i}|\right) \quad (23)$$

where M is the number of points on the P-V curve.

RESULTS AND DISCUSSION

Table 1 The measured I-V data (short circuit-V=0,I=I_{sc}, - open circuit-V=V_{oc}, I=0, - and the maximum power-V= V_{mp}, I= I_{mp}-points at the open circuit and short circuit points), the maximum power P_{max}, fill factor FF, and efficiency η of various DSSCs studied.

Table 1: Measured I-V data

Source of Natural Dye		Photovoltaic Parameters						
English Name	**Scientific Name**	**I_{sc} (mA)**	**I_{mp} (mA)**	**V_{mp} (V)**	**V_{oc} (V)**	**P_{max} (mW)**	**FF**	**η %**
Control	TiO_2/N719	9.355	7.574	0.4	0.590	3.028	0.54	3.02
Witch seed flower	Striga hermonthica	1.970	1.379	0.4	0.639	0.551	0.43	0.55
Bitter gourd	Momordica charantia	9.244	6.450	0.4	0.536	2.580	0.51	2.57
Bougainvillea	Bougainvillea	3.450	2.783	0.3	0.484	0.834	0.50	0.83
Flamboyant	Delonix regia	1.717	1.442	0.4	0.610	0.576	0.55	0.57
Wild marigold	Calendula arvensis	1.600	0.957	0.3	0.504	0.287	0.35	0.28
Red cockscomb	Celosia cristata	1.580	1.290	0.3	0.490	0.387	0.49	0.38
Lantana	Lantana camera	1.530	1.262	0.4	0.600	0.504	0.54	0.50
Hibiscus	Hibiscus rosa sinensis	1.480	1.090	0.3	0.450	0.327	0.49	0.32
Sun flower	Helianthus	1.590	1.081	0.4	0.530	0.432	0.51	0.43
Rose flower	Rosa	1.690	1.283	0.4	0.563	0.512	0.53	0.51
Orange peel	Citrus aurantium	1.400	1.121	0.2	0.370	0.224	0.43	0.22
Tomato	Lycopersicon esculentum	0.230	0.135	0.2	0.290	0.027	0.40	0.03
Mango peel	Mongifera indica	2.51	2.130	0.4	0.618	0.852	0.55	1.00
Guava peel	Psidium guajava	0.900	0.669	0.3	0.452	0.201	0.49	0.20

Table 1 contains the experimental data of 15 DSSCs made up of different dyes/photosensitizers. The model parameters for the solar cells were measured at 30 °C and A.M1.5 (1000 Wm^{-2}). The results show that the model parameters are independent of each other. This implies that the model parameters depend on the light absorbers (dyes/pigments) in the DSSCs because they have different chemical compositions and hence, they absorb light at different rate. For example, this fact is reflected in the variation of conversion efficiency with dye type in the range 0.03≤η≤2.57 % such that fabricated DSSCs with bitter gourd dye has the highest conversion efficiency 2.57% and that of mango peel 1 %. In terms of classification of PV modules based on the SPR criterion, the result shows that 11 of the DSSCs belong to the class with SPR≥1 and 4 belong to the class with SPR<1

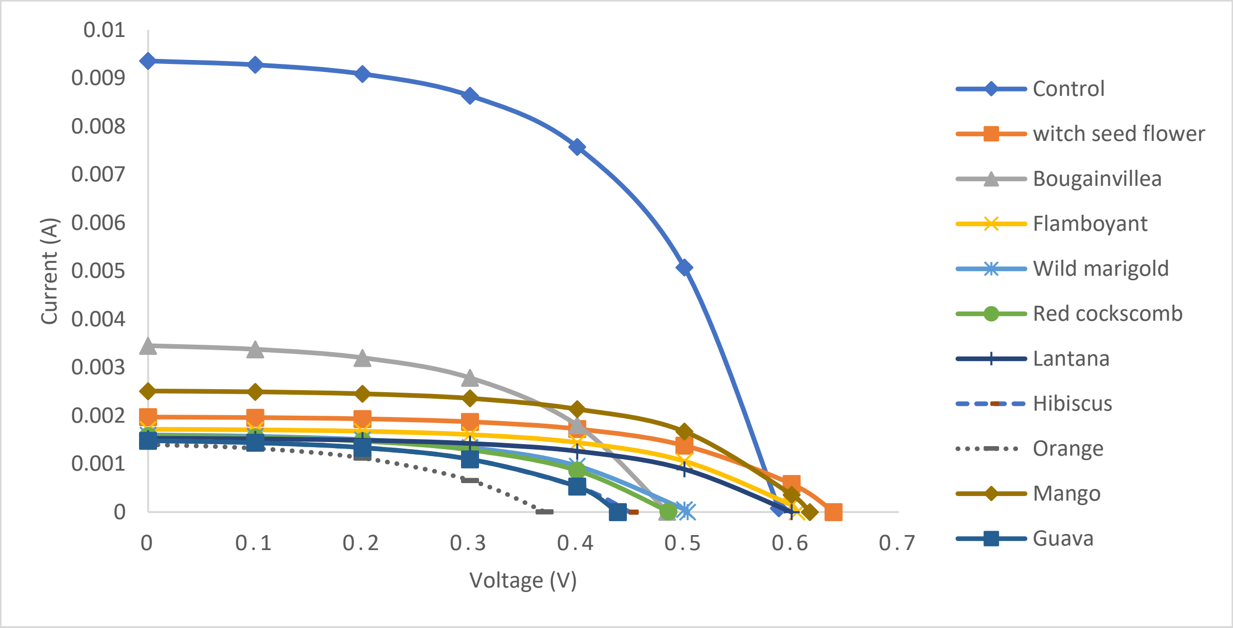
(Tables 2 & 3). In this paper, the procedures followed for the present simplified calculations of the model parameters in conjunction with SPR method of classification of PV modules are summarized as follows:
Estimate the coefficients and SPR from equation (11)
Identify the class: $SPR \geq 1$, (R_{sh}=∞) or SPR<1, (R_s=0)
If $SPR \geq 1$, (R_{sh}=∞) calculate R_s, a, I_{ph}, and I_o from equations (12), (16), (20) and (21) respectively
If SPR<1, (R_s=0) calculate R_{sh}, a, I_{ph}, and I_o from equations (13), (17), (20) and (19) respectively
Obtain the current-voltage values by plugging the calculated model parameters in equations (9) and (10)
Finally obtain the I-V and P-V curve fits

Table 2: Model coefficients and parameters of 11 fabricated DSSCs with $SPR \geq 1$, (R_{sh}=∞)

Source of dye	Four model coefficients				Four model parameters			
English Name	γ_i	γ_v	R	SPR	R_s (Ω)	A	I_o (A)	I_{ph} (mA)
Control	0.8096	0.6780	2.0200	1.4352	12.3	0.0584	3.8536E-7	9.355
Witch seed flower	0.7000	0.6260	1.3942	1.2095	107.3	0.0756	4.2083E-7	1.970
Bougainvillea	0.8067	0.6198	2.5591	2.4986	46.7	0.0329	1.3898E-9	3.450
Flamboyant	0.8398	0.6557	2.7529	2.5127	90.9	0.0431	1.2105E-9	1.717
Wild marigold	0.5981	0.5952	1.0121	1.1057	155.2	0.0609	4.0656E-7	1.600
Red cockscomb	0.8165	0.6122	2.8172	3.0708	108.8	0.0293	8.6737E-11	1.580
Lantana	0.8248	0.6667	2.3545	1.8449	88.9	0.0504	1.0382E-8	1.530
Hibiscus	0.7365	0.6667	1.3974	1.0659	63.0	0.0609	9.1955E-7	1.480
Orange peel	0.8007	0.5405	3.4152	6.0631	139.0	0.0088	8.0991E-22	1.400
Mango peel	0.8486	0.6472	3.0549	3.2123	68.2	0.0386	2.7731E-10	2.510
Guava peel	0.7433	0.6637	1.4674	1.1134	108.6	0.0584	3.8943E-7	0.900

Table 2 presents the values of model coefficients and parameters for eleven (11) DSSCs class SPR ≥1. The results show that this class requires only four coefficients to calculate the four model parameters of the DSSCs in question. Furthermore, the result reveals that both the model coefficients and parameters are independent of each other. This means these quantities depend largely only the nature of the dyes used in the fabrication of the DSSCs.

(a)



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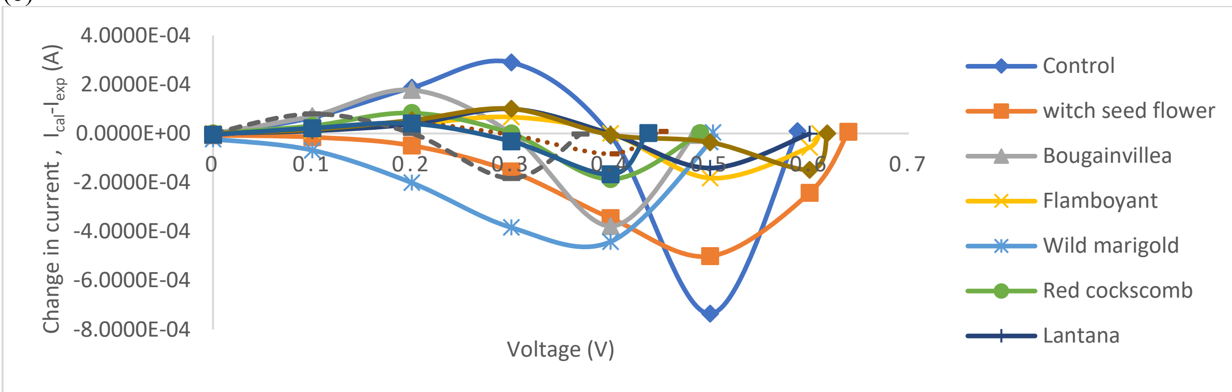

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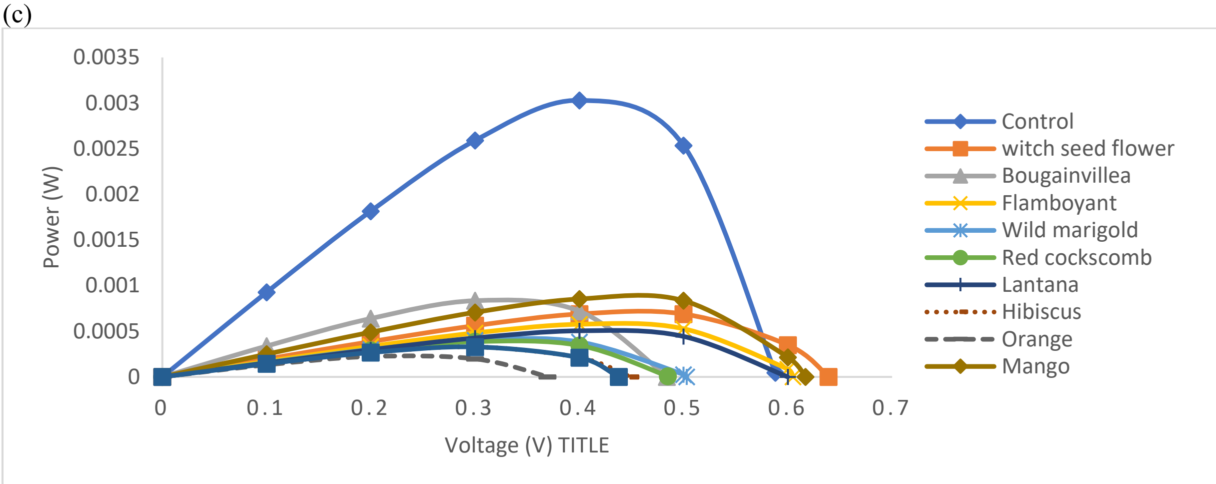

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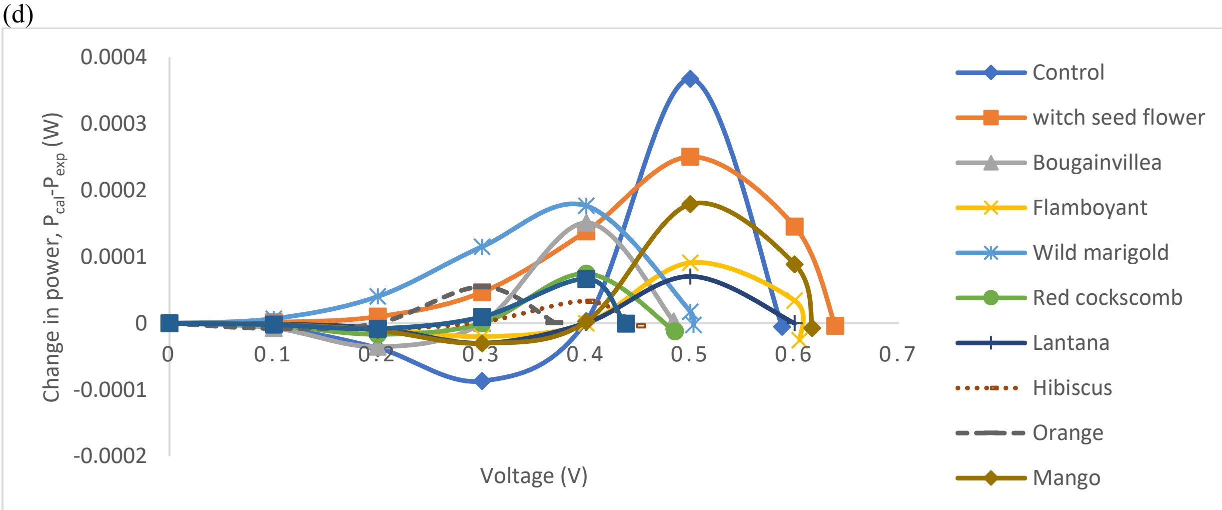
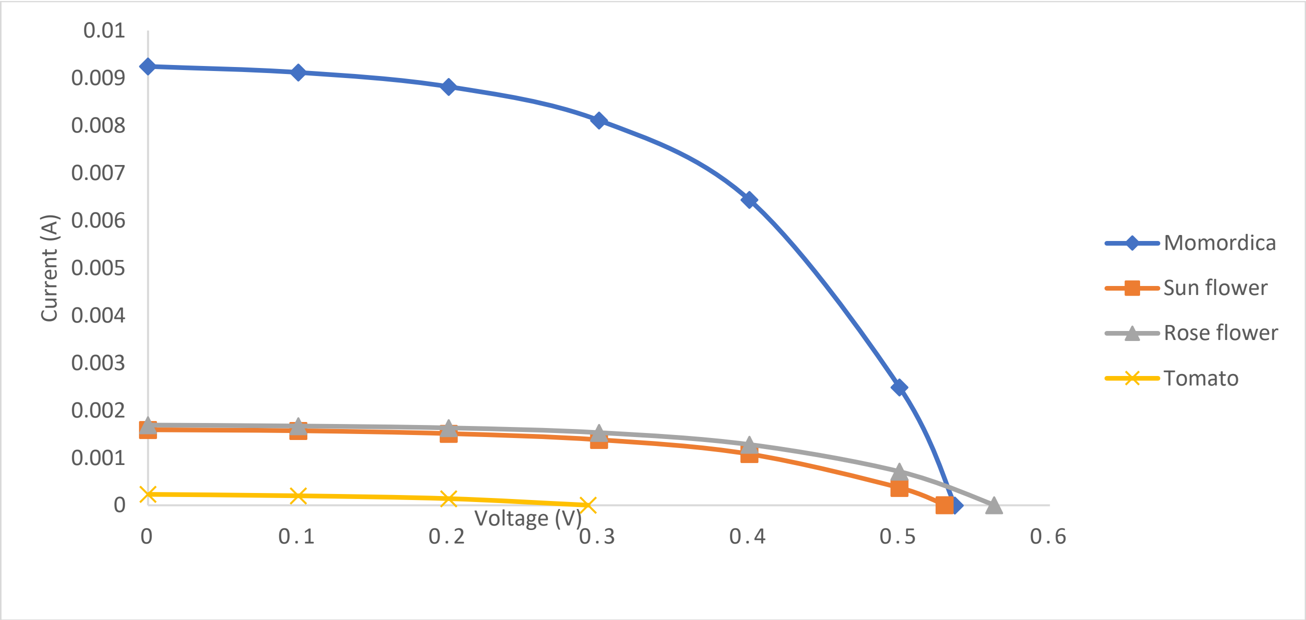


Figure 2: The pattern of I-V/P-V curves including error distributions (a) I-V characteristic curves, (b) error in current, (c) P-V curves, and (d) error in power, fitted for 11 DSSCs (class SPR≥1)

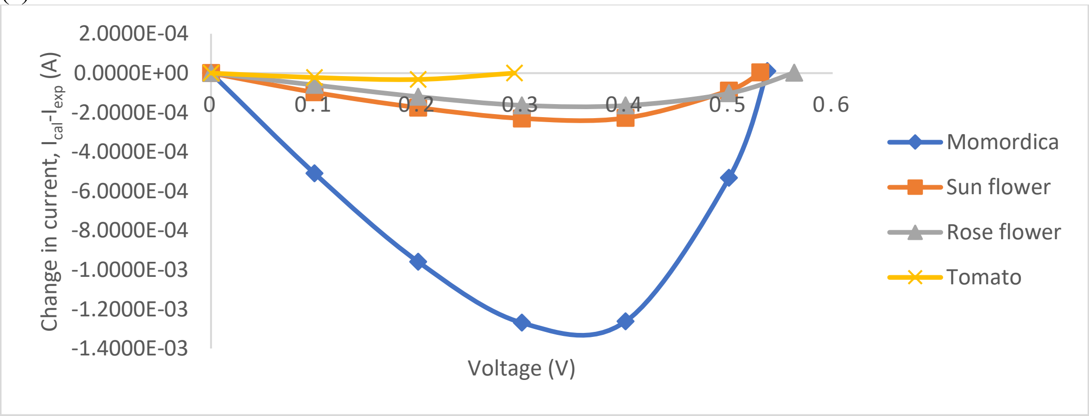
Table 3 Model coefficients and parameters of 4 DSSCs with SPR<1, (R_s=0)

Dye name	Model coefficients							Model parameters			
English	γ_i	γ_v	**R**	**SPR**	**w**	λ_1	λ_2	R_{sh} (Ω)	**A**	I_o (μA)	I_{ph} (mA)
Bitter gourd	0.6961	0.7463	0.7789	0.6622	-1.2264	0.7404	2.4559	179.6	0.1142	57.247	9.244
Sun flower	0.6799	0.7547	0.6902	0.6384	-2.4236	0.6343	2.3576	962.3	0.1141	9.9987	1.590
Rose flower	0.7592	0.7105	1.2846	0.8701	-1.7330	1.3268	2.9501	1489.3	0.1145	9.6017	1.690
Tomato	0.5870	0.6897	0.6395	0.7829	-2.3000	0.4724	1.6697	2394.6	0.1018	6.3046	0.230

Table 3 presents the values of seven coefficients (γ_i, γ_v, r, SPR, w, λ_1, λ_2) and four model parameters (a, R_{sh}, I_o, I_{ph}) of 4 DSSCs with SPR<1. This implies that neglecting series resistance requires more model coefficients to calculate the model parameters. The results show that two of the coefficients (λ_1, λ_2) and the modified ideality factor (a) are directly proportional to each other. This implies that these quantities are dependent on the nature or composition of the photo-absorbers used in the fabrication of the DSSCs. Nevertheless, this can only be one possibility if and only if the dyes have similar chemical composition of pigments (chlorophyl, anthocyanin, etc.) responsible for the absorption of light. To ascertain this assertion, the effects of chemical composition of pigments responsible for light absorption of light is required. On the other hand, the rest of the quantities do not depend on each other and neither the type of dye.



(a)



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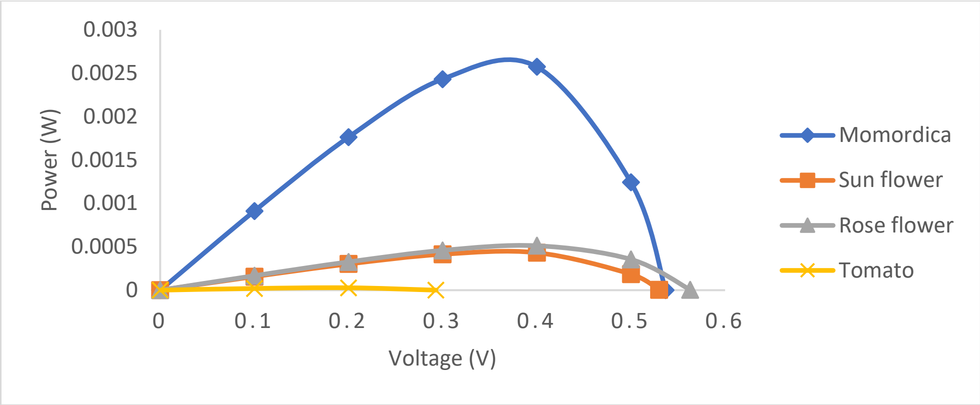
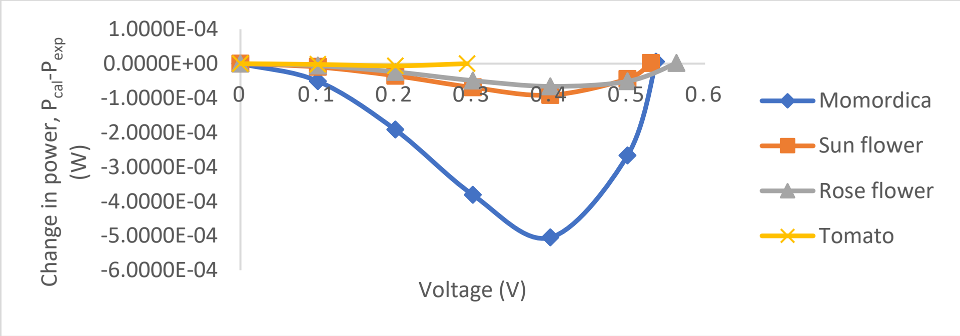


(c)



(d)

Figure 3: Shows the pattern of I-V/P-V curves including error distributions (a) I-V characteristic curves (b) error in current, (c) P-V curves, and (d) error in power, fitted for 4 DSSCs (class SPR<1)

Table 4: Non-dimensional average absolute percentage difference ξ_{av}% and the average absolute difference ξ_{av}^{*} calculated using the proposed model, with respect to the experimental values of the I-V curves and P-V curves of the DSSCs studied respectively

Source of natural dye		ξ_{av} %	ξ_{av}^{*}
English Name	**Scientific Name**		
Control	TiO_2/N719	0.36	3.36×10^{-5}
Witch seed flower	Striga hermonthica	3.73	7.35×10^{-5}
Bougainvillea	Bougainvillea	0.54	1.86×10^{-5}
Flamboyant	Delonix regia	0.51	8.81×10^{-6}
Wild marigold	Calendula arvensis	3.16	5.06×10^{-5}
Red cockscomb	Celosia cristata	0.45	7.10×10^{-6}
Lantana	Lantana camera	0.30	4.57×10^{-6}
Hibiscus	Hibiscus rosa sinensis	0.23	3.42×10^{-6}
Orange peel	Citrus aurantium	0.68	9.57×10^{-6}
Mango peel	Mongifera indica	1.09	2.75×10^{-5}
Guava peel	Psidium guajava	1.21	1.09×10^{-5}
Bitter gourd	Momordica charantia	2.15	5.22×10^{-6}
Sun flower	Helianthus	2.23	3.54×10^{-5}
Rose flower	Rosa	1.65	2.79×10^{-5}
Tomato	Lycopersicon esculentum	0.13	2.16×10^{-6}

To universally compare results, some authors have employed the dimensionless standard deviation (SD) proposed by Easwarakhanthan *et al.,* (1986)

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{I_{cal,i}}{I_{exp,i}} - 1\right)^2} \qquad (24)$$

where $I_{cal,I}$ is the current calculated with the electric circuit model and $I_{exp,i}$ is the measured current at a certain point, i, of the I-V curve, and N is the number of points on the curve. This parameter can compare results from different I-V curves. Nevertheless, its disadvantage is that it largely includes the errors around the open circuit point. As a remedy, it appears better to define two non-dimensional quantities ξ_{av} *and* ξ_{av}^* given in equations (22) and (23) respectively.

In Table 4, the values of the comparison parameters, ξ_{av} *and* ξ_{av}^* are included for the DSSCs studied. Fig. 4 depicts the graphically representation of the dimensionless parameter ξ_{av} obtained from the calculated and experimental I-V curves of all the DSSCs studied. Similarly, Fig. 5 presents the graphically relation between the parameter ξ_{av}^* obtained from the calculated and experimental P-V curves with regard to all the DSSCs studied. It is obvious that with the proposed analytical method adopted in this work based on the experimental data, it is possible to derive the 1-diode/2-resistors circuit model parameters of the aforementioned DSSCs.

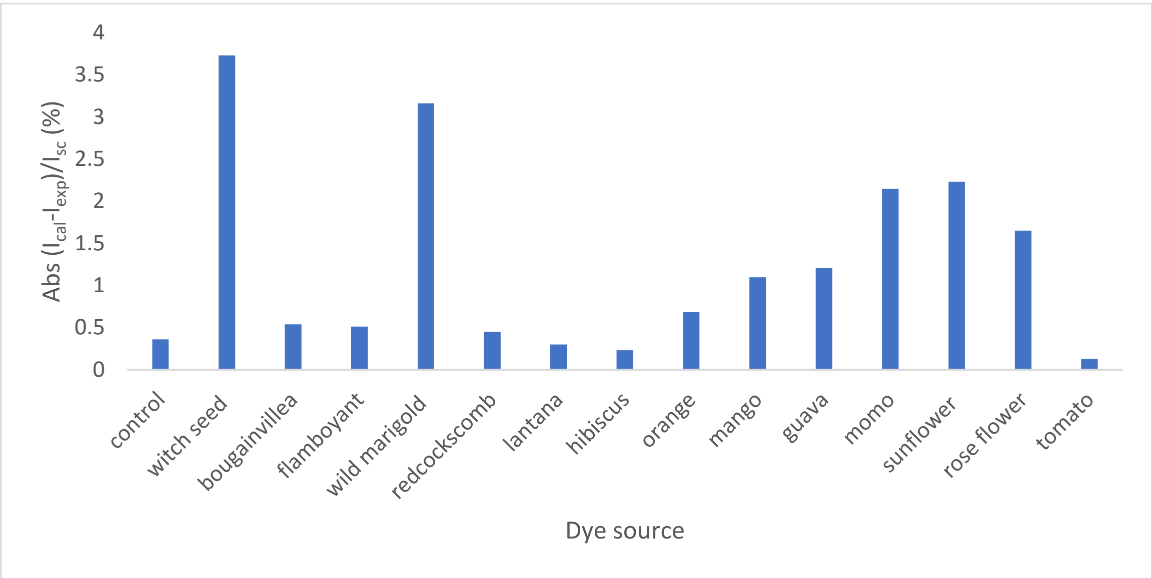


Figure 4: Average percentage absolute difference between the calculated and experimental I-V curves with regard to all the DSSCs studied

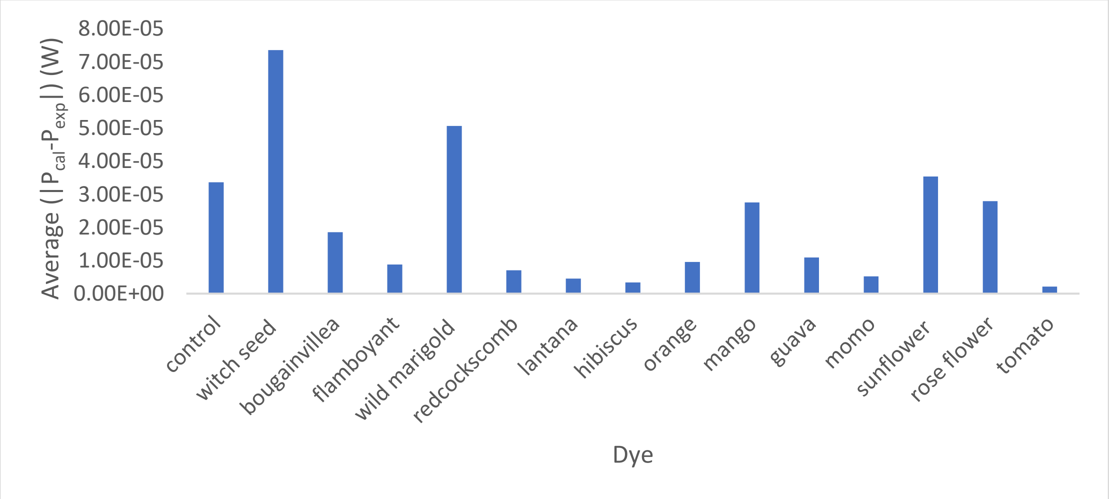


Figure 5: Average absolute difference between the calculated and experimental P-V curves with regard to all the DSSCs studied

CONCLUSION

In this study, an analytical method for classifying and extracting the parameters of a 1-diode/2-resistor equivalent electric circuit model for a solar cell has been presented. The method relies on experimental data from dye-sensitized solar cells (DSSCs), specifically short-circuit current, maximum power point, and open-circuit voltage. The proposed explicit equations, once suitably modified, accurately replicate the behavior of the solar cell and its corresponding 1-diode/2-resistor circuit model. This approach simplifies earlier methods by neglecting either the series or the shunt resistor, with the value of the chosen resistor determined through special coefficients related to the cell's characteristic points. Additionally, the approach employs the SPR (short-circuit to power ratio) conditions to identify and classify the fabricated DSSCs into two categories: those with SPR ≥ 1 and those with SPR < 1. Overall, the method has demonstrated effective curve fitting for both modeled and experimental data, confirming its applicability and reliability.

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