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A Novel Optimization Method for Parameter Extraction of Industrial Solar Cells

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***Abstract*—Triple diode model is used in the present work for making a lumped parameter equivalent circuit for solar photovoltaic (PV) model. Flower pollination optimization algorithm (FPOA) is used for finding out various parameters of the solar cell. The theoretical values considering the estimation are not the same as the industrial samples of double diode model. Many current components of solar cells were not found by the two diode model correctly whereas a triple diode model can extract the data accurately. The FPOA is being used to extract different parameters of the given triple diode model. The success of the FPOA optimization process is that it performs the local and global search within the single stage to extract the parameters. Simulation is carried out and the performance of the FPOA is compared with two other optimization techniques such as differential evolution (DE) method and particle swarm optimization (PSO) method. Comparison result shows that the triple diode model including FPOA provides superior performance than the double and single diode model. Moreover, huge silicon solar cells could be explained easily by the triple diode model.**

Keywords—photovoltaic array, parameter extraction, optimization algorithm, solar cell, diode model

I. Introduction

Solar cell characteristics were needed to be known to generate the characteristics curves of power, voltage, and current. The electrical circuit which is used converts the dc current generated by the solar cell into ac for commercial use. Handful models were found for simulating systems of complete PV or a single solar cell. Shading effect has been studied using various models. Two diode model and one diode model were vastly used for equivalent circuit model. A current source is used to denote the photovoltaic current (I_{ph}) of an ideal solar cell and the radiations of solar are proportional to it. I_{ph} gets misguided from normal behavior due to loss of electrical and optical in solar cells. A single diode model consists of series resistance (R_{ser}), connected with the parallel combination of I_{ph}, a diode (D), and a shunt resistance (R_{sh}) [1, 2]. Quasi-neutral regions have some currents due to the recombination and diffusion which is generally denoted by I. R_{ser} and R_{sh} denotes resistance in the current path and leakage of current in PN junction respectively [3]. R_{sh} is connected to the equivalent circuit in parallel with the diode. Figure 1 shows the single diode model of a solar cell. The figure shows the equivalent circuit of a solar cell with all the components including the diode current (I_d) and shunt current (I_{sh}) [4].

Double diode model contains both the recombination current of space charge regions and the diffusion current of the diode. The resistances R_{ser} and R_{sh} are same as the single diode model [5]. The ideality factor (I_{df}) of single diode model is between 1-2 and for double diode model, I_{df2} should be 2 and I_{df1} should be 1. One diode model consists of five different parameters and the double diode model has 7 parameters. The diode ideality factor and the reverse of saturation current for the second diode are extra in the double diode model compared to single diode model [6, 7]. To carry out the estimations of double diode model and single diode model many methods like numerical and analytic have been introduced. Some other methods like the pattern search algorithm and genetic algorithms have also been suggested [8]. These methods often show better accuracy and they are also much more efficient for solar cell parameters. The swarm optimization methods have different advantages such as 1) eliminating convergence toward local minima, 2) starts with random search, and 3) easy implementation. The particle swarm optimization method [9] is the first successful method, which was introduced recently in many fields of the power system.

The conventional methods suffer due to insufficient randomness even reaching the local minima, fixed step size, and the complexity is more in the case of two-stage adaptive methods [10, 11]. As a challenge to handle the above mentioned disadvantages, a novel optimization method, FPOA is proposed to extract different parameters of solar PV module [12]. This method has a number of advantages such as 1) few control parameters are used so less complexity, 2) easy to write the program and occupies less memory space, and 3) parameter tuning can be done easily [13]. The above-mentioned advantages of the FPOA method motivate the author to utilize this method for extracting different parameters of the solar PV module. Three different test patterns with a different environmental condition are evaluated through simulation software. The obtained result is compared with the single diode and double diode models. To describe the superiority of the proposed FPOA, a comparative analysis has been done for various parameters such as parameter tuning, efficiency, and tracking speed of the proposed method. The remaining part of the paper is structured as follows. Section II describes different modeling of the solar cell, Section III explains the proposed FPOA with detailed steps. In Section IV, simulation studies include MAE, IAE, and comparison of the proposed method with two other optimization techniques such as DE and PSO. Finally, conclusions are presented at the end.

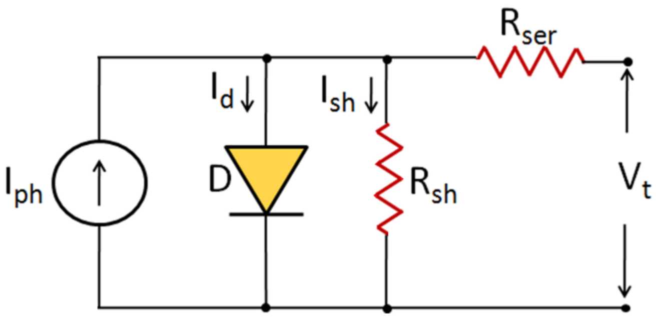

Fig. 1. Solar cell model using single diode.

II. Estimation Method

A. Single Diode Model

The schematic of the single diode model for a solar cell is shown in Fig.1. Various parameters such as R_{ser}, R_{sh}, I_{ph}, I_d, and the reverse saturation current (I_{sd}) are considered for estimation. In the single diode model, the other two parameters such as the diffusion current and the recombination currents are combined together. The output current I_t of a solar cell using a single diode model can be expressed by applying Kirchoff's current law, and it is given as:

$$I_t = I_{ph} - I_d - I_{sh} \tag{1}$$

The value of I_d can be modeled using Shockley equation, $I_d = I_{sd}[\exp(V_t + I_t R_{ser})/mV_T] - 1$, shunt current $I_{sh} = (V_t + I_t R_{ser})/R_{sh}$, and the thermal voltage $V_T = kT_c/q$.

Now (1) can be written based on [14] as:

$$I_t = I_{ph} - I_{sd}\left[\exp\left(\frac{q(V_t+R_{ser}I_t)}{I_{df}kT_c}\right) - 1\right] - \left(\frac{V_t+R_{ser}I_t}{R_{sh}}\right) \tag{2}$$

The solar PV cell parameters such as R_{sh}, R_{ser}, I_{ph}, I_{sd}, and I_{df} can be estimated from the current voltage (I-V) data set.

B. Double Diode Model

The schematic of a double diode model for a solar PV cell is shown in Fig. 2. The output current I_t of a solar cell using a double diode model can be expressed by applying Kirchoff's current law, and it is given as:

$$I_t = I_{ph} - I_{d1} - I_{d2} - I_{sh} \tag{3}$$

The value of both the diode current of double diode model can be represented using the Shockley equation as,

$$I_{d1} = I_{sd1}\left[\exp\left(\frac{V_t+I_tR_{ser}}{I_{df1}V_T}\right) - 1\right] \tag{4}$$

$$I_{d2} = I_{sd2}\left[\exp\left(\frac{V_t+I_tR_{ser}}{m_2V_T}\right) - 1\right] \tag{5}$$

Now substitute (4) and (5) in (3) and the total current I_t can be written based on [14] as:

$$I_t = I_{ph} - I_{sd1}\left[\exp\left(\frac{q(V_t+R_{ser}I_t)}{I_{df1}kT_c}\right) - 1\right] - I_{sd2}\left[\exp\left(\frac{q(V_t+R_{ser}I_t)}{I_{df2}kT_c}\right) - 1\right] - \left(\frac{V_t+R_{ser}I_t}{R_{sh}}\right) \tag{6}$$

The five parameters such as R_{ser}, R_{sh}, I_{ph}, I_{df}, and I_{sd} are same as the single diode model. The other two parameters such as the diode ideality factor and reverse saturation current for the second diode are included in the double diode model.

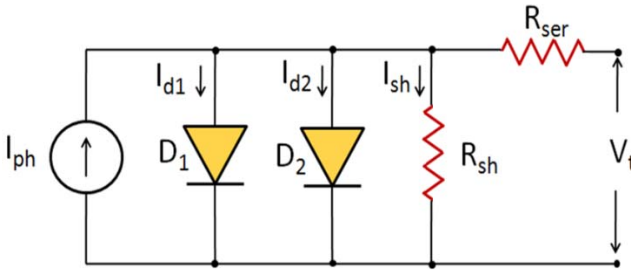

Fig. 2. Solar cell model using a double diode.

C. Triple Diode Model

Generally, in a double diode model the value of ideality factors I_{d1} and I_{d2} are assumed that 1 and 2 respectively. In practice, the size of industrial samples is bigger than 155.2 cm^2 with an efficiency of 17.1% for the estimated value of I_{d1} between 1.1 and 1.7 and I_{d2} was between 2 and 4.5. These values are not sufficient to represent various parameters of solar PV module clearly. In this work, to overcome the above problem triple-diode model has been introduced. The schematic of a triple diode model for a solar cell is shown in Fig. 3. In Fig. 3, the first diode represents the diode current (I_{d1}) due to diffusion of the emitter and bulk regions with the value 1. The second diode represents the diode current (I_{d2}) due to recombination in the space charge region with the value 2. In the triple diode model, the third diode (I_{d3}) is included in across with the second diode. I_{d3} is included for the current due to recombination in the defect regions, grain sites, etc. with the value taken between 2 and 5 [15].

The simulation and experimental work have been done by Steingrube et al. [15] and he proved that if the thickness of the defect of solar cell increases, I_{df} will increase. The value of I_{df} in the range between 2 and 5 for industrially fabricated solar PV cells. However, the value of the ideality factor of the double diode model, I_{d2} and I_{d2} is 1 and 2 respectively.

$$I_t = I_{ph} - I_{sd1}\left[\exp\left(\frac{q(V_t+R_{ser}I_t)}{I_{df1}kT_c}\right) - 1\right] - I_{sd2}\left[\exp\left(\frac{q(V_t+R_{ser}I_t)}{I_{df2}kT_c}\right) - 1\right] - I_{sd3}\left[\exp\left(\frac{q(V_t+R_{ser}I_t)}{I_{df3}kT_c}\right) - 1\right] - \left(\frac{V_t+R_{ser}I_t}{R_{sh}}\right) \tag{7}$$

III. Flower Pollination Algorithm

Xin She Yang developed Flower Pollination optimization Algorithm (FPOA) in 2012. It is a simple and efficient optimization algorithm for the global optimization problem. FPOA helps the flower to emerge the new species.

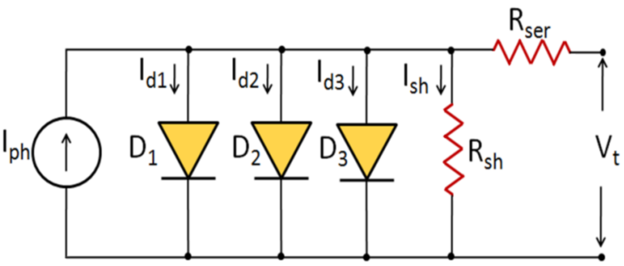

Fig. 3. Triple-diode model of a solar cell.

Pollination is an action that represents the movement of pollen from one group to another. The pollination can be divided based on the pollens 1) self-pollination and 2) cross-pollination. The self pollination is an abiotic process i.e. it contains the same type of species. In this type, the wind acts as a pollinating agent to emerge a new species under all the pollen belong to the same plant. On the other hand, the cross-pollination abiotic process i.e. it contains different types of species and the transfer of pollens between them. Here the birds, bees, and bats are acts as a pollinating agent (pollinator). It is important to note that in practice the first type (self pollination) of FPOA is used 10% and the second type (cross-pollination) is used remaining 90% [13].

For example, the self-pollination occurs in same type flower whereas cross-pollination occurs between different plants. In both the cases, the pollinators can travel a long distance to measure the global pollination. A probability control variable K϶[0,1] is used to maintain control between self and cross-pollinations. The optimal value of K is 0.8 in most of the practical cases [16]. In some case, the insects move from one to other at the same time and avoid other species. This phenomenon is known as flower constancy (FC). Each flower has its own FC even it should have the assurance that to produce optimal output. Further, the value of FC depends on the number of flowers entailed in the pollination. One of the important advantages of FPOA is it uses fewer parameters thereby decrease the computation time and the complexity of the process.
To implement FPOA, there are four different steps of flower pollination algorithm to be followed:

- Global pollination is mainly due to biotic and cross-pollination.
- local pollination is mainly due to self and abiotic pollination.
- FC is considered as the reproduction probability.
- The probability control variable K϶[0,1] is used to control the switch between local and global pollination.

Now implementing FPA for the triple diode model for extracting different parameters, the cross pollination and levy flight represents the global pollination process and transfer of pollens respectively. For the t^{th} iteration, the i^{th} pollen updated through biotic pollination based on [14] as:

$$K_i^{t+1} = K_i^t + L(G_{best} - K_i^t) \quad (8)$$

Where K_i^t represents the set of pollens, G_{best}, L represents the present best solution in the K_i^t set and the levy factor respectively. The transfer of pollen will follow the levy distribution and it can be expressed based on [14] as:

$$L = \frac{\gamma\Gamma(\gamma)\sin(\pi\gamma/2)}{\pi}\frac{1}{M^{\gamma+1}}\ (M \gg M^0 > 0) \quad (9)$$

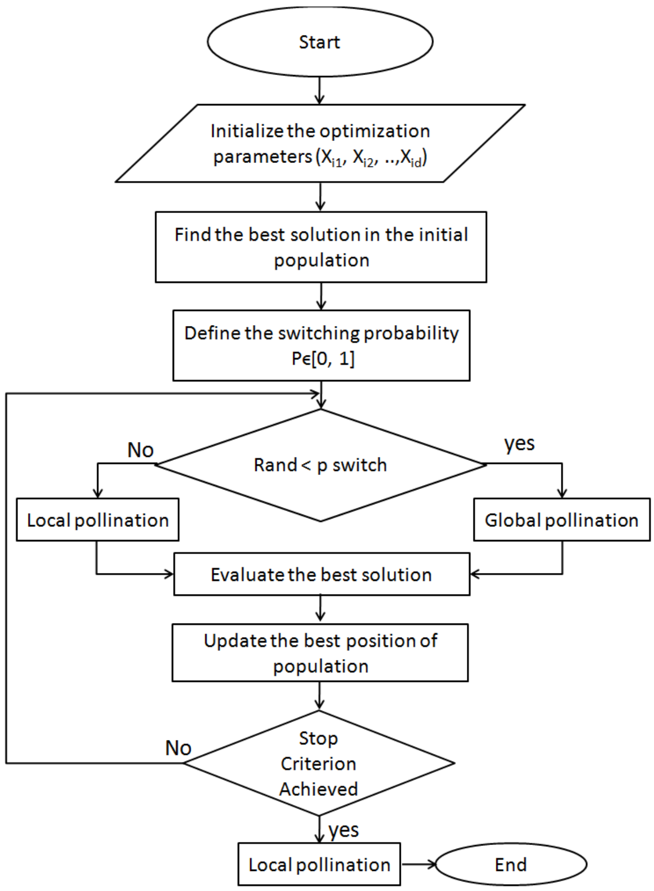

Fig. 4. Flow diagram of FPOA algorithm.

Where $\Gamma(\gamma)$ and γ represents the standard gamma function and the scaling factor to control the step size respectively. The trial and error method is followed and fixes the value of γ and is 1.4 in this case. The following equation shows the local pollination process and it can be expressed as:

$$K_i^{t+1} = K_i^t + \varepsilon(K_m^t - K_j^t) \quad (10)$$

Here K_i^t and K_m^t are pollens from the different flowers of the same plant and ε is uniform distribution with values (0, 1). In this simulation, ε is assumed as (our threshold) and kept the optimal value of 0.85.

The FPOA technique is used to match the I-V characteristics of the solar cell models such as a single diode, double diode, and triple diode models. The flow diagram of FPOA is shown in Fig. 4. In this work, double diode and triple diode model were taken for investigation. In this work, the below two cases have been investigated:

case 1) The R_{ser} of the double diode model is assumed to be fixed: Hence the other parameters such as R_{sh}, I_{df1}, I_{df2}, I_{sd1}, and I_{sd2} can be calculated. In this case, the short circuit current (I_{sh}) is equal to I_{ph}.

case 2) The triple-diode model with variable R_{ser}: From the ten parameters of triple diode model, the value of I_{df1} and I_{df2} are assumed to 1 and 2; the short circuit current is equal to $I_{ph.}$ Hence the other parameters such as R_{sh}, I_{df1}, I_{df2}, I_{df3}, I_{sd3}, K and I_{sd2} can be calculated.

An optimized solution is achieved using a random approach under different iterations in the FPOA algorithm.

Inspired by the random nature of FPOA, the same set of data (I-V) was used for a different number of iterations. The same procedure is followed in all the solar PV models and estimates the variations. A sample value (I_{sc}=5.62893 A) has been taken and run for different iterations for the double diode model is shown in Table I. From Table I, one can easily understand that the standard deviation of various assumed parameters can be taken by the FPOA algorithm and multiple runs have been carried out to get the result.

TABLE I. THE ESTIMATED PARAMETER VALUES OF DOUBLE DIODE MODEL UNDER MULTIPLE RUNS USING FPOA.

Samples	I_{sd1} (nA)	I_{df1}	I_{sd2} (µA)	I_{df2}	Rsh (Ω)	Rser (mΩ)	MAE (A)
1	6.03	1.301	23.02	2.673	21.19	8.94	0.00583
2	4.83	1.204	09.62	2.483	21.42	8.86	0.00589
3	7.49	1.239	11.05	2.429	21.37	8.73	0.00591
4	7.47	1.198	28.93	2.937	21.62	8.83	0.00595
5	5.03	1.302	09.37	2.294	21.28	8.91	0.00591
6	7.42	1.289	17.37	2.639	22.67	8.69	0.00589
7	5.23	1.203	23.82	2.717	22.59	8.73	0.00600
8	8.89	1.241	12.03	2.482	21.29	8.84	0.00594
9	5.16	1.201	20.19	2.638	20.63	8.39	0.00596
Std. Deviation	1.43	0.0138	7.38	0.152	0.0662	0.642	3.36E-05

IV. RESULTS AND DISCUSSION

The simulation is carried out using Matlab 2017, Intel i7 Processor with 4-GB RAM for both the double diode and triple diode model. In this study, nine industrial samples have been taken and the test has been performed for the proposed FPOA algorithm. The performance of FPOA is compared with two other optimization techniques such as DE and PSO. Various parameters of the different algorithm used in this study are listed in Table II. The FPOA used two parameters such as the scaling factor (β) and switching probability (S_p). The PSO uses six parameters: the velocity boundaries are represented as K_1, $K_{1\ min}$, K_2, $K_{2\ min}$, and the inertia weights are represented as IW_{min} and IW_{max}. DE consists of different parameters such as PS, G_{max}, SZ are the population size, maximum number of generation, the step size respectively. CP is the crossover probability, TC is the termination criteria and MR is the merging generation rate.

TABLE II. PARAMETERS USED IN VARIOUS OPTIMIZATION TECHNIQUES.

FPOA	PSO	DE
β=1.45 S_p=0.85	K_1=1.5 $K_{1\ min}$=1	PS=150, G_{max}=500
-	K_2=1.9	SZ=0.5
-	$K_{2\ min}$=1	CP=0.5
-	IW_{min}=0.35	TC=1xe^{-06}
-	IW_{max}=1	MR=0.5

Firstly, the performance of the double diode model using FPOA has been studied with the nine industrial samples. The I-V characteristics of the double diode model for the sample 2 are shown in Fig. 5. The estimated I-V curve using the parameter values should be matched with the measured I-V curve. The value of MAE should be very less. From Fig. 5 one can easily understand that the estimated and measured curves for the double diode model are exactly matched with each other. For example, the second sample contains the MAE value of 0.00626 A which is 0.11 % of I_{sc}. In the same way, for sample five, the MAE value of 0.00603 A, which is 0.107% of I_{sc}. From all the nine tests the highest and lowest value of MAE values using the FPOA algorithm is 0.092% and 0.15% of I_{SC} respectively.

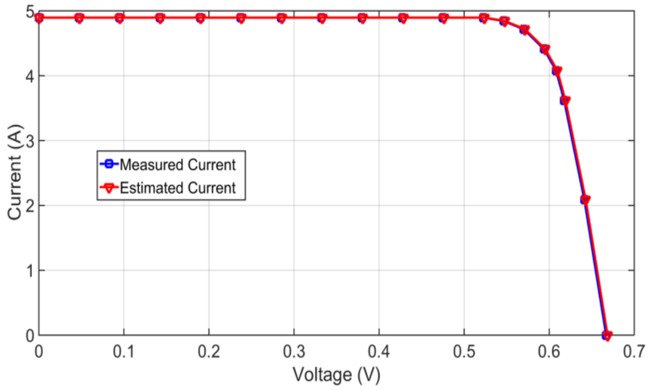

Fig. 5. Estimated and measured I-V curve of double diode model for Sample 2.

To study the performance of the double diode model the estimated and measured current and the individual absolute error (IAE) are shown in Fig. 6. The measured current, calculated current, and the IAE of the double diode model for the second sample are shown in Fig. 6(a). The plot is taken for the best value of MAE with 0.132%. From Fig. 6(a) one can easily understand that the IAE is less at maximum power point (MPP). Fig. 6(b) shows that the calculated and measured current and IAE for the fifth sample. The plot is taken for the best value of MAE with 0.093%. From Fig. 6(a) and (b) one can understand that IAE is very less at MPP.

The various parameter of the double diode model is estimated using the FPOA method for the nine industrial samples is listed in Table III. To estimate these parameters the I_{df1}value is fixed (1.25) for all the samples and I_{df1} is taken between 2.4 and 2.9 for all the nine samples. Different iteration has been performed (13-15) for FPOA and the parameter values have been chosen for the least value of MAE. From Table III it is observed that the shunt resistance is varying from 14 to 98 Ω for all the nine samples whereas the series resistance varies from 9 to 23 mΩ.

TABLE III. ESTIMATED PARAMETER VALUES USING FPOA FOR THE DOUBLE DIODE MODEL.

Samples	I_{sd1} (nA)	I_{df1}	I_{sd2} (µA)	I_{df2}	R_{sh} (Ω)	R_{ser} (mΩ)	MAE (A)
1	7.28	1.479	32.73	2.743	39.59	11.49	0.00629
2	5.51	1.289	14.18	2.521	31.39	14.29	0.00602
3	7.93	1.318	21.28	2.528	28.83	15.31	0.00611
4	7.88	1.215	32.23	2.963	14.28	21.21	0.00616
5	6.39	1.312	15.25	2.329	24.28	22.90	0.00606
6	8.58	1.294	22.16	2.723	28.51	11.28	0.00598
7	6.63	1.217	28.19	2.749	29.26	17.29	0.00620
8	8.31	1.258	19.26	2.521	98.49	9.13	0.00613
9	6.47	1.280	26.25	2.683	32.18	9.83	0.00503

The values of I_{df1} and I_{df2} are having a negligible variation for all the samples. The range of value of I_{df1} and

TABLE IV. COMPARISON BETWEEN PSO, DE, AND FPOA.

Sample	Algorithm	I_{sd1} (nA)	I_{df1}	I_{sd2} (μA)	I_{df2}	R_{sh} (Ω)	R_{ser} (mΩ)	MAE (A)
1	DE	6.283	1.393	38.27	2.173	68.37	18.35	0.00582
	PSO	7.382	1.298	57.28	2.394	66.19	13.36	0.00518
	FPOA	9.216	1.284	62.36	2.294	65.37	13.61	0.00504
2	DE	5.376	1.193	62.46	2.639	19.36	17.36	0.00537
	PSO	4.741	1.218	71.42	2.836	18.33	12.89	0.00521
	FPOA	8.372	1.392	79.35	2.935	18.16	12.34	0.00512

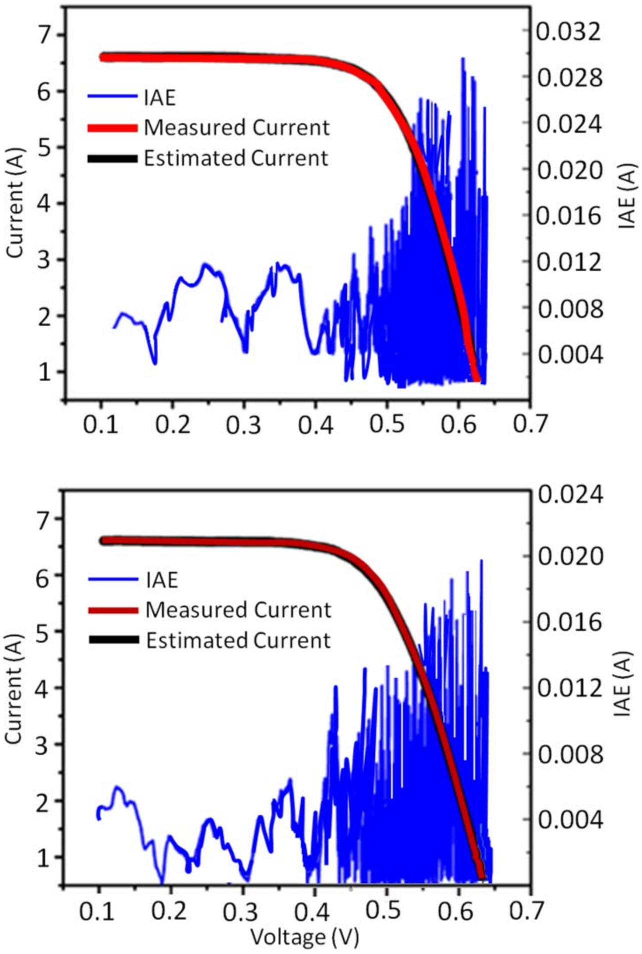

Fig. 6. Measured and estimated I-V curve and the value of IAE (a) for sample-2 (b) for sample-5.

I_{df2} are less than 0.0015 A and 0.003 A respectively. From this, we can say that both the estimated and measured I-V characteristics are matched perfectly with each other.

Finally, it is observed that the value of $I_{df1}>1$ and $I_{df2}>2$ but the theoretical values are 1 and 2 respectively. The performance of the proposed FPOA has been compared with two other optimization techniques such as PSO and DE. The comparison result for two different cases is listed in Table IV. The shunt and series resistance values have been measured from the I-V characteristics slope at the short circuit and open circuit conditions respectively. From Table IV it is observed that the proposed FPOA provides less MAE compared to other two techniques such as DE and PSO for the two sample cases.

It could be expected since the slope method assumes a single diode model is applicable R_{sh} values which were noted from the slope method matched well with those estimated from the FPOA method .the parameters 1 and 2 of solar cell samples were also estimated by using differential evolution (DE) algorithm [17-19] for the sake of comparison the estimated parameters of samples 1 and 2 for double diode model are tabulated in Table IV for DE and FPOA algorithms. The different values of solar cell parameters estimated by 2 algorithms are comparable; hence it confirms the sanctity of our results using the FPOA algorithms.

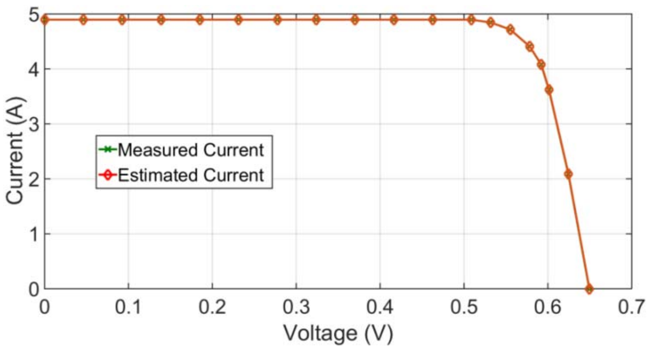

Fig. 7. The measured and estimated I-V curve of triple diode model.

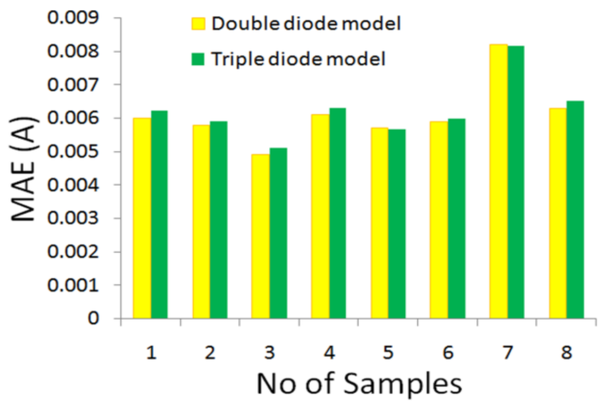

Fig. 8. Comparison of mean absolute error value for both the double and triple diode model.

The MAE value for the double diode and triple diode model for eight solar PV cell sample has been performed and shown in Fig. 8. From Fig. 8 one can easily understand that the MAE values are little higher in the triple diode model compared to double diode model. In a few cases, the MAE values are lower in triple diode model. It is observed that a little higher MAE values in the triple diode model do not have an observable effect on both the measure and estimated curve.

V. CONCLUSION

In the current work, the triple diode model is being utilized for making a lumped parameter circuit model and in this model three diodes are used for solar cell parameter extraction. This model would be a better option because the industrial solar silicon crystalline cell has huge area. This work is aimed for getting better models for the large size industrial solar cells compared to the two familiar models exists. The aim is to fit calculated curves of I-V into measured I-V curves by utilizing flower pollination optimization algorithm. The series resistance and the load current under open and short circuit conditions are proportional to each other. We can conclude from this work that the triple diode model is a better fit for the industry solar modules than the double diode model. The triple diode model can give a complete picture about the I-V characteristics of huge solar cells. FPOA plays a pivotal role for getting the I-V characteristics.

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