

An Efficient War Strategy Optimization Algorithm For Parameter Estimation And Modelling of Photovoltaic Cell

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Abstract

The increasing demand for electricity, environmental pollution, climate change, and depletion of conventional energy resources have accelerated the adoption of renewable energy sources. Among these, solar photovoltaic (PV) technology has gained significant importance due to its clean, abundant, and sustainable nature. Accurate parameter estimation of PV cells and modules is essential for reliable modeling, performance analysis, and system optimization. However, the nonlinear and multimodal characteristics of PV models make parameter identification a challenging optimization problem. This research investigates the War Strategy Optimization (WSO) algorithm for parameter estimation in three cases: the single-diode model, double-diode model, and practical PV module model. The performance of WSO is compared with the Chaotic Whale Optimization Algorithm (CWOA) and other metaheuristic algorithms using RMSE, convergence characteristics, estimation accuracy, and robustness. The study aims to improve PV model accuracy and support the efficient design, simulation, and optimization of solar energy systems.

Keywords— Photovoltaic (PV) System,; War Strategy Optimization (WSO); Single-Diode Model (SDM); Double-Diode Model (DDM); PV Module Parameter Estimation; Chaotic Whale Optimization Algorithm (CWOA); Root Mean Square Error (RMSE).

1.Introduction

The increasing demand for electrical energy, environmental pollution, climate change, and depletion of conventional energy resources have encouraged the development of renewable energy technologies[3]. Among various renewable energy sources, solar photovoltaic (PV) technology has gained significant attention due to its clean, abundant, and sustainable nature. The efficient utilization of solar energy requires accurate mathematical modeling of PV cells and modules to analyze their electrical characteristics and improve overall system performance. Accurate parameter estimation is a crucial aspect of PV modeling because the nonlinear current-voltage (I-V) characteristics of photovoltaic devices make the identification of unknown parameters a complex optimization problem[5]. Conventional optimization techniques may face difficulties in achieving accurate solutions due to local optima and complex search spaces. Therefore, metaheuristic optimization algorithms have emerged as effective approaches for estimating PV model parameters with improved accuracy and convergence performance[6].

In this paper, the War Strategy Optimization (WSO) algorithm is investigated for parameter estimation in three cases: the single-diode model (SDM), double-diode model (DDM), and practical PV module model. The objective is to determine the optimal model parameters by minimizing the error between measured and estimated current values using the root mean square error (RMSE) as the objective function. Furthermore, the performance

of WSO is compared with the Chaotic Whale Optimization Algorithm (CWOA) and other established metaheuristic algorithms in terms of estimation accuracy, convergence characteristics, and robustness. This comparative investigation aims to evaluate the effectiveness of WSO for different PV modeling configurations and contribute to the development of accurate and reliable photovoltaic models for solar energy system simulation, analysis, and optimization[10].

1.1 Objective Function

In the parameter estimation of photovoltaic (PV) models, the primary objective is to determine the optimal model parameters by minimizing the deviation between experimentally measured and model-predicted data. The estimation accuracy is quantified using the root mean square error (RMSE), which serves as the objective function for evaluating the performance of the optimization algorithm. The objective function is mathematically expressed as follows[11]:

$$RMSE(x) = \sqrt{\frac{1}{N} \sum_{k=1}^N f(V_L, I_L, x)^2} \quad (1)$$

Where N is the no. of experimental data.

2. Explanation of Block Diagram of Solar PV Estimation Models

Fig.1 illustrates three mathematical models used for solar photovoltaic (PV) parameter estimation: the Single Diode Model (SDM), Double Diode Model (DDM), and PV Module Model. These models describe how solar energy is converted into electrical energy and help estimate the electrical characteristics of solar cells and modules[8].

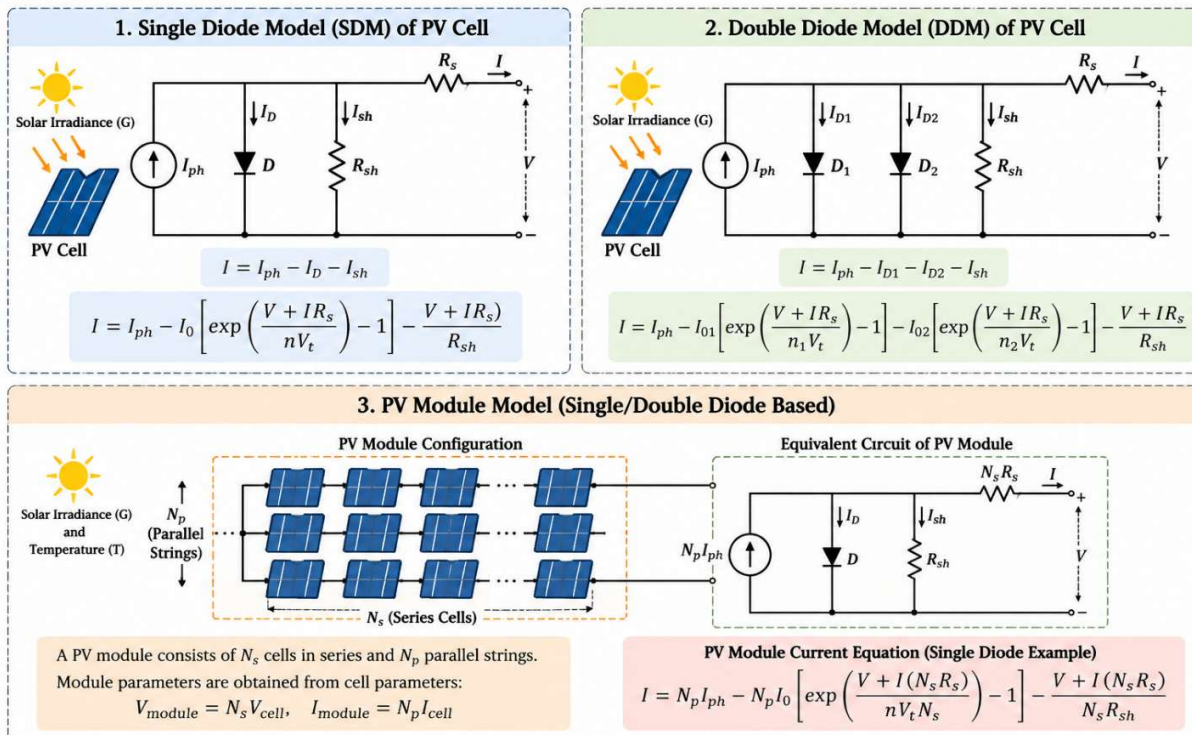


Fig.1 Block Diagram of Solar PV Estimation Models[9]

2.1 Single Diode Model (SDM)

The Single Diode Model consists of a photocurrent source, one diode, series resistance, and shunt resistance. Solar irradiance generates photocurrent, while the diode represents the nonlinear electrical behavior of the PV cell. This model is simple and widely used for estimating solar cell parameters. The various parameters of single diode are I_{ph} , I_{sd} , R_s , R_{sh} , and n represent the electrical characteristics of the PV cell[10].

2.2 Double Diode Model (DDM)

The Double Diode Model contains two diodes instead of one. The first diode primarily represents diffusion current, while the second accounts for recombination effects. It can provide a more detailed representation of solar cell behavior, particularly under low irradiance conditions. The Various parameters of double diode model are the photocurrent (I_{ph}), I_{s1} and I_{s2} are the saturation currents of the two diodes, The ideality factors (n_1 and n_2) The series resistance (R_s) and the shunt resistance (R_{sh})[12].

2.3 PV Module Model

A PV module consists of several solar cells connected in series and parallel. The diagram shows the physical arrangement of the cells and their equivalent electrical circuit. Series-connected cells increase voltage, whereas parallel-connected strings increase current. The main parameters used in PV module are I_{ph} =Photocurrent generated by solar radiation, I_{sd} =Diode reverse saturation current, R_s =Series resistance, which affects the voltage drop and power output, R_{sh} =Shunt resistance, which represents internal leakage current, n =Diode ideality factor, which influences the nonlinear I-V relationship[16].

3. War Strategy Optimization (WSO) Algorithm for Solar PV Parameter Estimation

The War Strategy Optimization (WSO) Algorithm is a population-based metaheuristic optimization technique inspired by war strategies and military operations. It uses search mechanisms such as attack, defense, reinforcement, and adaptation to explore the search space and identify optimal solutions[15].

In Solar PV parameter estimation, WSO optimizes unknown parameters such as photocurrent, diode saturation current, series resistance, shunt resistance, and diode ideality factor. The algorithm minimizes the Root Mean Square Error (RMSE) between measured and calculated PV current values to obtain accurate model parameters for Single Diode, Double Diode, and PV Module models[1].

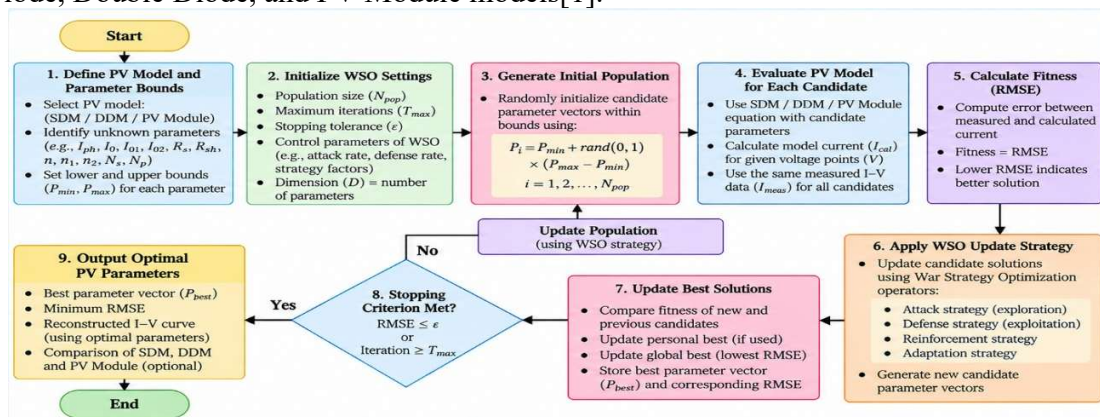


Fig.2 War Strategy optimization algorithm for solar PV parameter Estimation[15]

Fig.2 illustrates the complete procedure of Solar PV Parameter Estimation using the War Strategy Optimization (WSO) Algorithm. The proposed approach is applied to three photovoltaic models: the Single Diode Model (SDM), Double Diode Model (DDM), and PV Module Model. Initially, the unknown PV parameters and their lower and upper bounds are defined, followed by the initialization of WSO control settings and the generation of an initial population of candidate solutions[1].

Each candidate solution is evaluated using the corresponding PV model to calculate the output current for given voltage values. The Root Mean Square Error (RMSE) is then employed as the fitness function to measure the difference between experimentally measured and model-calculated current values. The WSO algorithm updates candidate solutions using its optimization strategies, including attack, defense, reinforcement, and adaptation, to explore the search space and refine promising solutions[4].

The algorithm continuously updates the best parameter set and checks the stopping criteria based on the predefined error tolerance or maximum number of iterations. Once the stopping condition is satisfied, the algorithm provides the optimal PV parameters with the minimum RMSE. This approach facilitates accurate parameter estimation and enables a comparative performance analysis of SDM, DDM, and PV Module models under different solar irradiance and temperature conditions[17].

4.RESULT AND DISCUSSIONS

In this paper, the proposed War Strategy Optimization (WSO) algorithm is evaluated using three PV parameter estimation cases: the Single-Diode (SD) model, Double-Diode (DD) model, and practical PV module model. The algorithm estimates the unknown parameters by minimizing the error between measured and calculated current values. Its performance is assessed using RMSE and the corresponding I–V and P–V characteristics to evaluate estimation accuracy across different model complexities.

Furthermore, the obtained results can be compared with existing optimization algorithms to validate the effectiveness of WSO. The convergence behavior and computational performance are also analyzed to assess the reliability of the proposed approach. These investigations help establish the suitability of WSO for accurate and efficient solar PV parameter estimation.

Table 1Different Analysis Model

S.NO.	Different Test Cases
1	Test Case 1: Performance Evaluation of WSO for Single-Diode PV Model
2	Test Case 2: Performance Evaluation of WSO for Double-Diode PV Model
3	Test Case 3: Performance Evaluation of WSO for PV Module PV Model

The table-1 presents three test cases for evaluating the performance of the proposed War Strategy Optimization (WSO) algorithm in solar photovoltaic (PV) parameter estimation. The first test case focuses on the Single-Diode (SD) PV model, the second on the Double-Diode (DD) PV model, and the third on the practical PV Module model. In each case, WSO is employed to estimate the optimal model parameters by minimizing the error between measured and calculated current values.

4.1 Test Case 1: Performance Evaluation of WSO for Single-Diode PV Model

The Fig.3 I–V graph shows that the PV cell current remains nearly constant at 0.76 A before decreasing rapidly near the open-circuit voltage. Fig.4 P–V graph indicates that the maximum power is approximately 0.31 W at 0.45–0.46 V. The close agreement between the manufacturer and estimated values demonstrates the effectiveness of the parameter estimation method in reproducing the PV cell characteristics. These results confirm that the estimated parameters accurately represent the nonlinear electrical behavior of the PV cell. The proposed approach can therefore be used to evaluate PV model performance under different operating conditions.

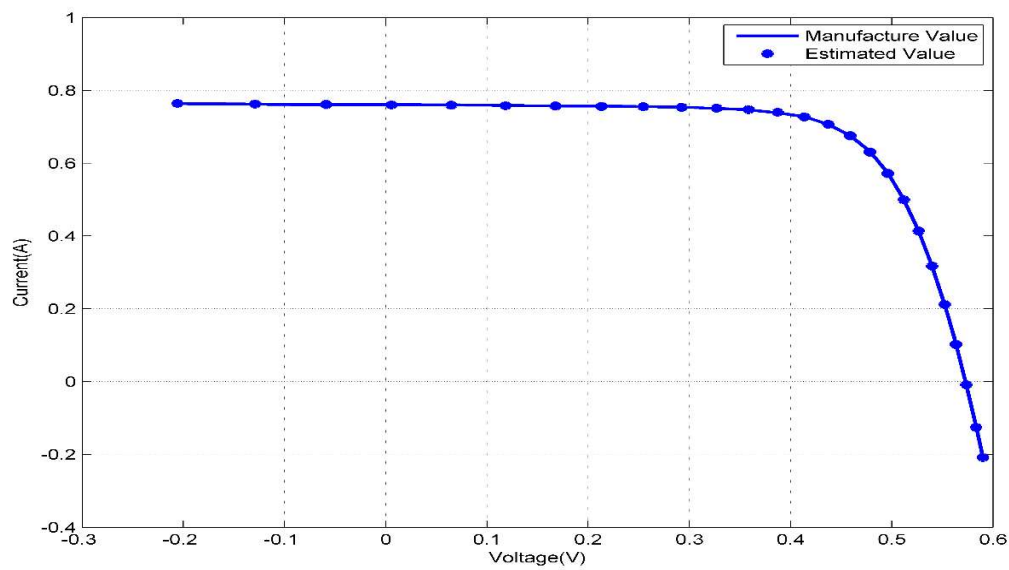


Fig.3 I-V Graph of PV Cell Single Diode Model

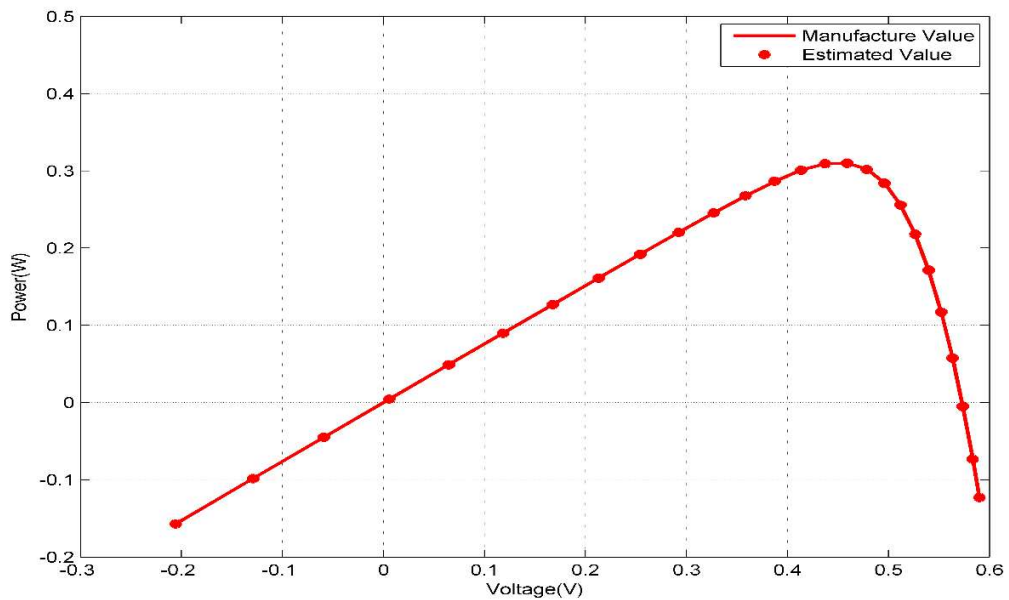


Fig.3 P-V Graph of PV Cell Single Diode Model

Table 2 exact RMSE values reported in the table are 0.0009860219 for WSO and 0.0009860200 for CWOA. The absolute difference is 0.0000000019 (1.9×10^{-9}). Therefore, WSO achieves a marginally lower RMSE than CWOA, indicating slightly better fitting accuracy for this test case. Both algorithms demonstrate nearly identical parameter estimation accuracy for the Single-Diode PV model.

Algorithm	I _{ph} (A)	I _{sd} (uA)	R _s (Ohm)	R _{sh} (Ohm)	a	RMSE
WSO	0.7607755303	0.3230208155	0.0363770927	53.7185258792	1.4811835917	0.0009860219
CWOA [18]	0.7607700000	0.3239000000	0.0363600000	53.7987000000	1.4812000000	0.0009860200

Table 2: Comparison Parameters of SD Model at WSO & CWOA Algorithm

4.2 Test Case 2: Performance Evaluation of WSO for Double-Diode PV Model

Fig. 4 I–V graph of the Double-Diode Model (DDM) shows that the PV cell current remains nearly constant at 0.76 A before decreasing rapidly near the knee point. Fig.5 P–V graph indicates that the maximum output power is approximately 0.31 W at 0.45–0.46 V. The close agreement between the manufacturer and estimated curves demonstrates the accuracy of the parameter estimation method. The Double-Diode Model considers both diffusion and recombination effects, providing a more detailed representation of solar cell behavior and reliable prediction of its electrical characteristics.

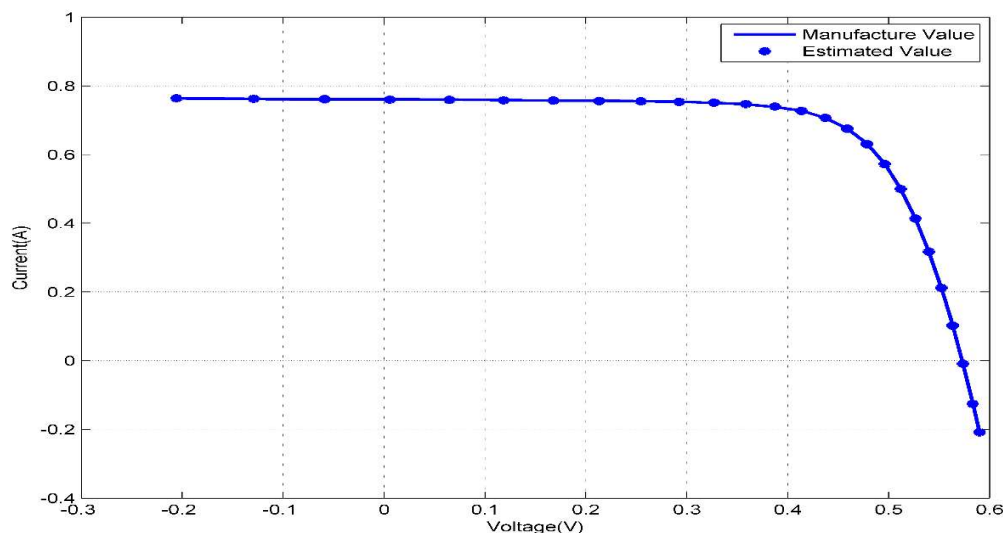


Fig.4 I-V Graph of PV Cell Double Diode Model

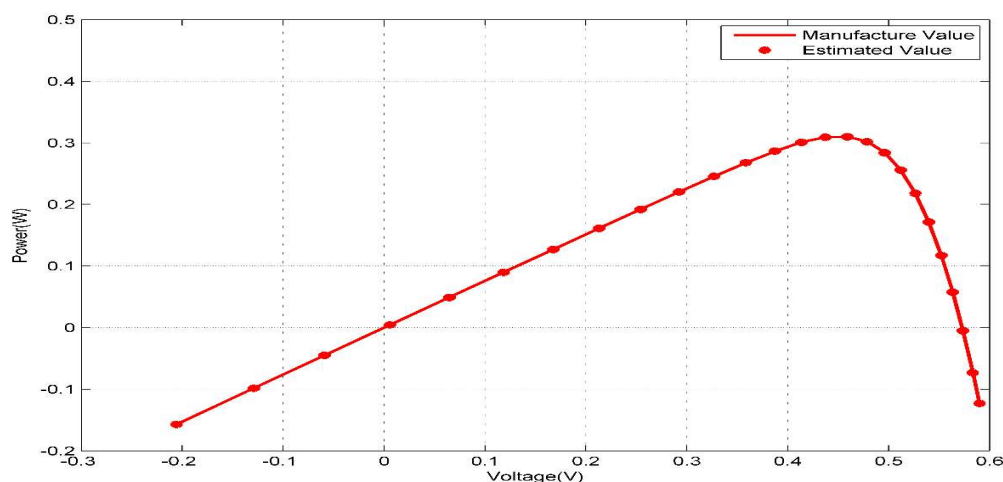


Fig.5 P-V Graph of PV Cell Double Diode Model

Table 3 shows the WSO algorithm achieves an RMSE of 0.0009824849, compared with 0.0010069200 for TLBO and 0.0009827200 for CWOA. Thus, WSO provides the lowest RMSE among the three algorithms, indicating the best fitting accuracy for this reported test case. Its RMSE is approximately 2.43% lower than TLBO and 0.024% lower than CWOA. These results suggest that WSO can estimate the DD model parameters with high accuracy, although further comparisons of convergence speed, computational time, and robustness are needed to establish its overall performance advantage.

Table3 : Comparison Parameters of DD Model at Different Algorithm

Algorithm	$I_{ph}(A)$	$I_{s1}(\mu A)$	$R_s (Ohm)$	$R_{sh} (Ohm)$	n_1	$I_{s2}(\mu A)$	n_2	RMSE
WSO	0.76078107 95	0.74934985 22	0.03674043 06	55.48544769 52	2.00000000 00	0.22597403 14	1.45101668 12	0.00098248 49
TLBO	0.76099000 00	0.29465000 00	0.03661000 00	53.12099000 00	1.47295000 00	0.13727000 00	1.99375000 00	0.00100692 00
CWOA [18]	0.76077000 00	0.24150000 00	0.03666000 00	55.20160000 00	1.45651000 00	0.60000000 00	1.98990000 00	0.00098272 00

4.3 Test Case 1: Performance Evaluation of WSO for PV Module PV Model

Fig. 6 the I–V characteristic graph of the PV module shows that the output current remains nearly constant at approximately 1.66 A as the voltage increases, followed by a rapid decline near the open-circuit voltage. Fig.7 the P–V characteristic graph indicates that the output power increases with voltage and reaches a maximum power point (MPP) of approximately 25.5 W at 16.5–17 V, after which the power decreases. The close agreement between the manufacturer and estimated values demonstrates the effectiveness of the parameter estimation method in reproducing the electrical characteristics of the PV module. These results indicate that the estimated parameters can accurately represent module performance and help identify its maximum power operating point.

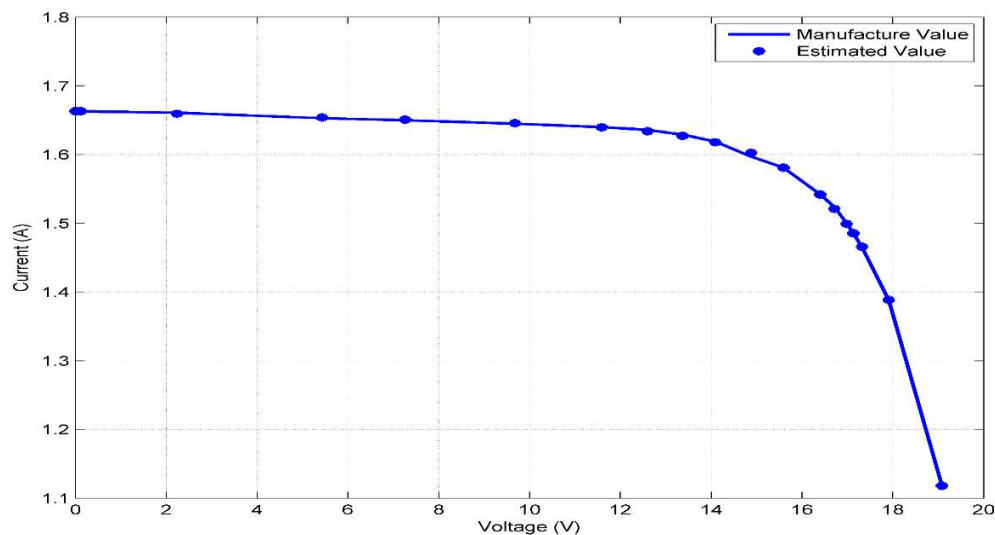


Fig.6 : I-V Curve of PV Module

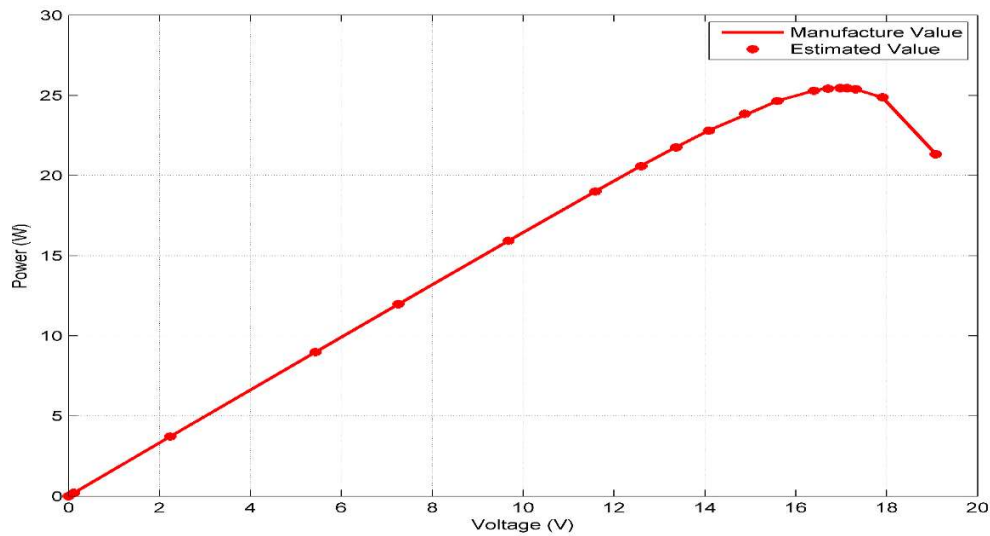


Fig.7: P-V Curve of PV Module

The table 4 presents a comparative analysis of the proposed War Strategy Optimization (WSO) algorithm and the CWOA algorithm for PV module parameter estimation. WSO achieves lower values of MAE (0.0011353947) and RMSE (0.0017261704) compared with CWOA, which reports MAE of 0.0012200300 and RMSE of 0.0018000000. WSO also provides lower NRMSE (0.0031653955) and a nearly zero MBE ($2.6823946573 \times 10^{-11}$), indicating high estimation accuracy and negligible systematic bias. Although the estimated parameters differ between the algorithms, the error metrics suggest that WSO provides a better fit to the measured PV module characteristics for this test case.

Table 4: Comparison Parameters of PV Module at Different Algorithm

Algorithm	R_s (m Ohm)	R_{sh} (Ohm)	I_{ph} (A)	I_{sd} (uA)	n	MAE	RMSE	NMAE	NRMSE	MBE
CWOA[18]	5.0000000000	15.4000000000	1.7000000000	1.6338000000	1.5000000000	0.0012200300	0.0018000000	0.0007696300	0.0032996700	-0.0000002180
WSO	3.2100000000	16.7656318496	1.6632262093	2.9128930840	1.5706504095	0.0011353947	0.0017261704	0.0007171094	0.0031653955	-2.6823946573E-11

5.CONCLUSIONS

This paper evaluates the War Strategy Optimization (WSO) algorithm for parameter estimation of the Single-Diode Model (SDM), Double-Diode Model (DDM), and practical PV module. Its performance is assessed using I–V and P–V characteristics, convergence behaviour, and statistical error indices such as RMSE and MAE. The DDM achieves an RMSE of approximately 0.00098248, indicating good estimation accuracy. The PV module produces a maximum power of approximately 25.5 W at 16.5–17 V, with good agreement between estimated and manufacturer characteristics. The convergence curve indicates stabilization after approximately 250–300 iterations. Overall, WSO is a promising technique for solar PV parameter estimation, although further testing is required to validate its robustness and reliability.

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