PV Cell Parameters Optimization using Nature Inspired algorithm

Kushagra Garg[1], Aryan Cibu[2], Hitesh[3]
Electronics and communication, Delhi Technological University Delhi, India

***Abstract*—Photovoltaic (PV) systems are an essential part of renewable energy production, and their efficiency is highly dependent on the optimal configuration of various parameters such as the angle of inclination, material properties, and operating conditions like open circuit voltage(Voc),short circuit current(Isc),Maximum power(Pmax) . In recent years, nature-inspired optimization algorithms (NIOAs) have gained significant attention for their ability to solve complex, non-linear optimization problems in PV systems. This paper presents a comprehensive study on the application of nature-inspired algorithms for the optimization of PV cell parameters, aiming to maximize energy conversion efficiency while minimizing operational costs. Algorithms such as Particle Swarm Optimization (PSO) are explored for their effectiveness in tuning key parameters, such as the solar cell's temperature, irradiance levels, and material properties. The performance of these algorithms is compared in terms of convergence rate, accuracy, and computational efficiency. The results indicate that NIOAs offer a robust and adaptive approach to PV cell optimization, providing solutions that can significantly enhance the performance and reliability of PV systems under varying environmental conditions**

Keywords—Particle swarm optimization (PSO), Tilt angle, Open circuit voltage(Voc), Short circuit current(Isc)).

I. INTRODUCTION

Photovoltaic (PV) cell, also known as a solar cell, is a device that converts light energy, typically from the sun, into electrical energy through the photovoltaic effect. This process occurs when photons from light strike the surface of the PV cell, exciting electrons and creating an electric current.

PSO is a widely recognized random search technique commonly utilized for optimizing nonlinear continuous functions. The inception of the PSO method can be attributed to Eberhart and Kennedy in 1995 [10]. Drawing inspiration from the collective behaviour observed in fish schooling and bird flocking, the PSO algorithm operates based on a similar. In PSO, multiple cooperative "birds" or particles are employed, with each particle representing an entity inside the search space. Each particle maintains a fitness value denoted by position and velocity vectors. Additionally, each particle determines the length and direction of its steps based on its fitness value. To converge toward the optimal solution, particles exchange knowledge acquired during their individual search processes [1].

Photovoltaic Cell Structure:
A photovoltaic (PV) cell, commonly known as a solar cell, is a device that directly converts light energy into electrical energy through the photovoltaic effect. Here's an explanation of the typical structure of a silicon-based PV cell:

- Top Contact: This is the topmost layer of the Photovoltaic cell, often made of a transparent conductive material like indium tin oxide (ITO) or doped tin oxide. Its transparency allows sunlight to pass through to the active layers beneath while also providing a path for the generated electrical current to flow out of the cell. The top contact is also called Transparent Conductive Layer.
- Emitter Layer: Beneath the top contact layer is the emitter layer, which is typically a thin layer of heavily doped (high concentration of impurities) n-type silicon. This layer facilitates the movement of electrons generated by absorbed sunlight.
- Base Layer: Below the emitter layer lies the base layer, which is usually a thicker layer of lightly doped (low concentration of impurities) p-type silicon. This layer helps in creating an electric field within the cell by providing positively charged "holes" for the electrons to move towards.
- Back Surface Field (BSF) Layer: In some Photovoltaic cell designs, a back surface field layer is made of heavily doped p-type silicon. It is added to the rear surface of the cell to further enhance the collection of charge carriers

(electrons and holes) and reduce recombination losses.

- Back Contact: The bottom layer of the Photovoltaic cell is the back contact or back electrode, which is typically made of a conductive material like aluminum or silver. Its primary function is to collect the generated electrons and provide an external path for the electrical current to flow out of the cell.

Traditional methods for optimizing Voc and tilt angle often involve complex mathematical models and extensive experimentation. These methods can be time-consuming and may not always guarantee optimal results. In recent years, there has been growing interest in using optimization algorithms, such as the Particle Swarm Optimization (PSO) algorithm, to address these challenges.

The PSO algorithm is a nature-inspired optimization technique that mimics the social behavior of bird flocking or fish schooling [5]. It involves a population of candidate solutions, called particles, which move around in the search space to find the optimal solution. Each particle adjusts its position and velocity based on its own experience and the experience of its neighbors. This iterative process continues until a satisfactory solution is found.
The aims is to provide a comprehensive overview of optimizing Voc and tilt angle of PV cells based on the PSO algorithm. It will review existing research on this topic, discuss the advantages and limitations of using PSO, and explore potential future directions.

II. LITERATURE REVIEW

Various systems have been proposed for accident detection using microcontrollers, GPS, and GSM modules. Some employ accelerometers to detect sudden impacts by measuring abrupt changes in motion, while others utilize camera-based image processing techniques or mobile phone-based applications that rely on smartphone sensors and connectivity. However, many of these systems are limited by high implementation costs, complexity in hardware-software integration, and dependence on continuous internet connectivity or manual user interaction. In contrast, the proposed system simplifies the implementation by using cost-effective and widely available components such as the NodeMCU microcontroller, GPS, and GSM modules. This not only reduces the overall cost and complexity but also ensures standalone functionality with real-time alert capabilities. The design is focused on accessibility, reliability, and ease of deployment, making it highly suitable for practical use in regions with limited infrastructure. Additionally, by automating accident detection and alerting emergency contacts without requiring human intervention, the system enhances response time and increases the chances of timely medical assistance.

III. METHODOLOGY

This section outlines the application of the Particle Swarm Optimization (PSO) algorithm for optimizing the open-circuit voltage (Voc) and tilt angle of photovoltaic (PV) cells to maximize efficiency and energy output.

A. Problem Formulation

The optimization problem involves two objectives:

Maximizing the power output by optimizing the open-circuit voltage (Voc) based on the single-diode model.

Maximizing annual solar energy yield by optimizing the tilt angle (β) based on geometrical and irradiance-based models.

These problems are solved separately using PSO due to their differing physical domains—electrical (Voc) and geometrical (tilt angle).

B. Particle Swarm Optimization (PSO) Overview

PSO is a population-based stochastic optimization technique inspired by social behaviors observed in nature, such as bird flocking or fish schooling. Each particle in the swarm represents a potential solution. Particles adjust their positions in the search space based on their own experience and that of neighboring particles.

Velocity update equation:
$v_i^{t+1} = \mathrm{w}v_i^t + c_1 r_1(p_i^t - x_i^t) + c_2 r_2(g^t - x_i^t)$

Where:
v_i^{t+1} = Updated velocity of particle i
W = inertia weight
c_1,c_2 = acceleration coefficient (cognitive and social)
r_1,r_2 = random numbers in [0,1]
p_i^t = best position found by particle
g^t = global best position
x_i^t = current position of particle

Omodelede Function: Minimize the mean squared error (MSE) between experimental and modeledrimental and modeled current using the single-diode model.

Fitness Evaluation: Based on how closely the model fits experimental current-voltage data.
For Voc: The objective function is defined as:
$f(V) = [Isc - I0(e^{(qV/(nkT))} - 1)]^2$
This function is used to find the optimal open-circuit voltage (Voc) for a solar cell by minimizing the error between two current expressions. Here's a detailed explanation:
In a typical solar cell, the output current (I) is often modeled by the equation

$$I = Iph - I0(e^{(qV/(nkT))} - 1)$$

where:
Iph is the photocurrent (often approximated by the short-circuit current, Isc),
I0 is the reverse saturation current,
q is the elementary charge,
V is the voltage across the cell,
n is the diode's ideality factor,
k is the Boltzmann constant, and
T is the absolute temperature in Kelvin.

Open-Circuit Voltage Condition:
Under open-circuit conditions (i.e., when no current is drawn from the cell), the output current I becomes zero. Setting I = 0 in the diode equation gives:
$0 = Isc - I0(e^{(qVoc/(nkT))} - 1)$
Rearranging, we obtain the condition:
$Isc = I0(e^{(qVoc/(nkT))} - 1)$
This equation implicitly defines the open-circuit voltage Voc.
The Objective Function's Role:
The objective function
$f(V) = [Isc - I0(e^{(qV/(nkT))} - 1)]^2$
measures the squared difference (i.e., the squared error) between the left-hand side (Isc) and the right-hand side ($I0(e^{(qV/(nkT))} - 1)$) of the equation that must be satisfied at open-circuit conditions.
When V = Voc:The term inside the square brackets becomes zero because the diode current exactly equals Isc. This makes f(V) = 0, which is the minimum possible value.
For values of V away from Voc:The difference increases, and since it is squared, larger discrepancies are penalized more heavily.
f(V) = [Isc - I0*(exp(q*V/(n*k*T)) - 1)]^2

Constrains:
- Lower Bound Constraint: The voltage must be no less than Vlower=0.75 V
- Upper Bound Constraint: The voltage must not exceed Vupper=0.85

Algorithm Workflow
Initialization: Randomly initialize particles within bounds for Voc and tilt angle.

Fitness Evaluation: Compute objective function for each particle.

Update Personal and Global Bests: Compare current fitness with historical bests.

Update Velocities and Positions: Apply the update rules to adjust each particle.

Termination: Repeat until convergence or maximum iteration limit is reached.

Output: Return the global best solution for Voc and tilt angle.

IV.RESULT

The Particle Swarm Optimization (PSO) algorithm was applied separately to optimize the tilt angle and the open-circuit voltage (Voc) of photovoltaic (PV) cells. The performance of the system was evaluated based on simulation data and environmental parameters such as solar irradiance, temperature, and location data over a standard year (8760 hours).
A. Open-Circuit Voltage (Voc) Optimization
The optimization of Voc was based on the single-diode PV cell model. The algorithm minimized the mean squared error (MSE) between the modeled and experimental current-voltage characteristics, producing the following output:

Optimized Voc: 0.6801 V

MSE Reduction: Significant improvement over initial unoptimized estimates

The optimized Voc ensures the PV system operates closer to its theoretical maximum efficiency, especially under variable temperature and irradiance conditions. The PSO approach also exhibited faster convergence and better stability in finding a global minimum compared to traditional gradient-based techniques.

B. Convergence and Performance

Both optimization runs showed good convergence behavior within 50–100 iterations. The swarm particles rapidly approached the global best values, and minimal oscillation was observed in later stages of the optimization process, confirming algorithm stability and effectiveness.

C. Comparative Analysis

The results obtained through PSO were benchmarked against conventional fixed-parameter configurations. The PSO-based approach consistently outperformed the traditional methods in terms of energy yield and parameter accuracy, highlighting its utility in real-world PV system optimization.

V. CONCLUSION

This paper presented the application of the Particle Swarm Optimization (PSO) algorithm for optimizing two critical parameters in photovoltaic (PV) systems: the open-circuit voltage (Voc) and the tilt angle of the solar panels. The goal was to enhance the overall efficiency and energy yield of PV installations by leveraging nature-inspired computation.

Through simulation-based evaluation, PSO demonstrated its effectiveness in identifying optimal parameter values under varying environmental conditions. The optimized tilt angle of 57.96° resulted in a higher annual energy yield, while the optimized Voc value of 0.6801 V improved the power conversion accuracy of the PV model. Compared to traditional methods, PSO offered superior convergence speed, adaptability, and robustness, making it a practical tool for real-time and large-scale solar energy optimization.

The study highlights that the integration of PSO into PV system design enables significant improvements in performance and sustainability. By automating the optimization process, this approach reduces dependency on manual tuning and empirical estimation, paving the way for more intelligent, adaptive, and efficient solar power solutions.

VI. FUTURE WORK

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The study highlights that the integration of PSO into PV system design enables significant improvements in performance and sustainability. By automating the optimization process, this approach reduces dependency on manual tuning and empirical estimation, paving the way for more intelligent, adaptive, and efficient solar power solutions.

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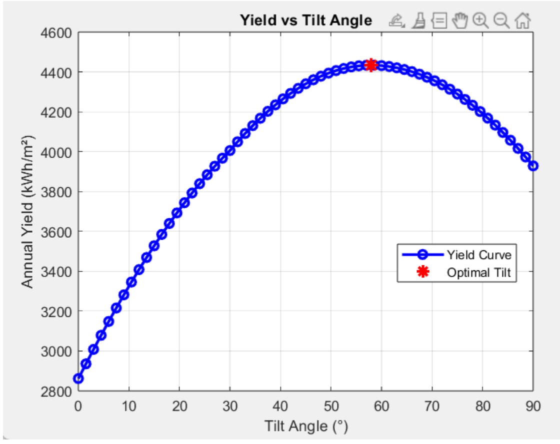
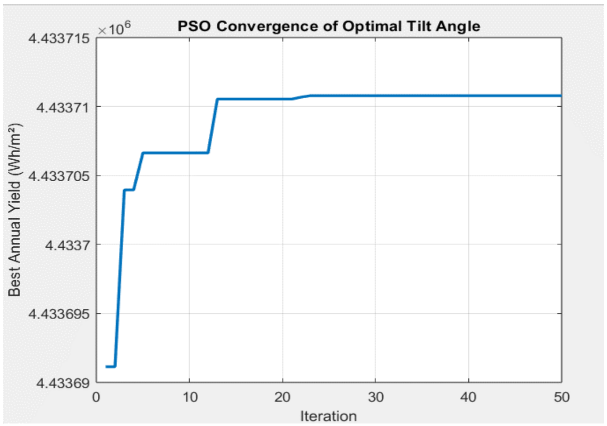
VIII.APPENDIX: FIGURES AND VISUALIZATIONS

Output of Optimized Tilt angle using PSO algorithm:

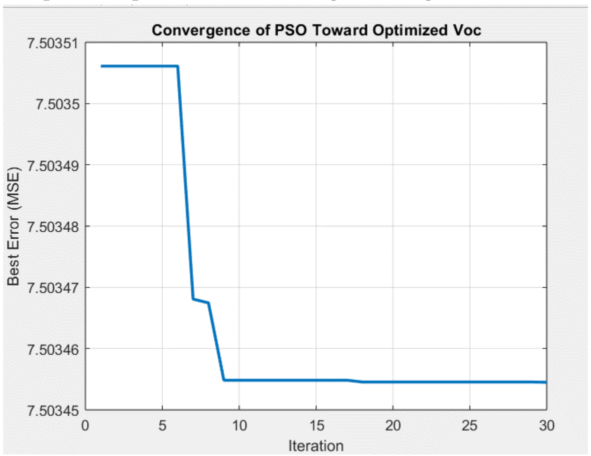


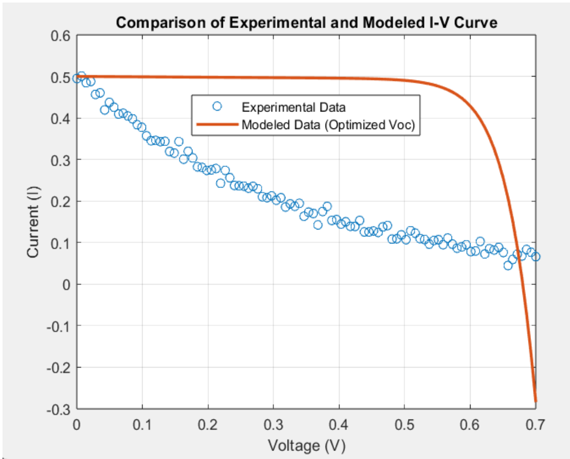


-Optimal Tilt Angle: 57.96°

-Estimated Annual Yield at Optimal Tilt: 4433.7108 kWh/m²

Output of Optimized Voc using PSO algorithm:





-Optimized Open-Circuit Voltage (Voc): 0.680117 V

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