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Particle swarm optimization for enhanced maximum power point tracking: design and implementation in Proteus

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ABSTRACT

This study introduces a photovoltaic (PV) system model tailored for PV design, incorporating a particle swarm optimization (PSO) MPPT technique to achieve optimal efficiency, swift responsiveness, and cost-effectiveness. To initiate, a PV module model is formulated within Proteus using SPICE coding. Subsequently, an experimental test setup is deployed to authenticate and validate the model. Following this, a PSO-based MPPT algorithm is proposed, which overcomes the limitations of conventional perturb and observe (P&O) and incremental conductance MPPT methods, notably reducing the reliance on mathematical divisions. To substantiate the effectiveness of the proposed approach, both methodologies are implemented on an affordable Arduino Uno platform utilizing the simulated PV module model. The outcomes highlight that the PSO-based MPPT algorithm excels in terms of rapid response (0.09 s), minimal steady-state oscillation, and an impressive 99 percent efficiency.

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1. INTRODUCTION

The utilization of non-conventional fossil power resources like petroleum and natural gas is widely recognized as unsustainable. In response, sustainable and renewable energy sources are emerging as the viable alternatives to fulfill upcoming energy needs [1]. Among these, solar energy holds significant promise due to its abundant and reliable nature. Notably, photovoltaic (PV) technology stands out as a means to generate clean energy [2]. Nonetheless, the efficiency of PV systems remains suboptimal, and their cost remains relatively high. Researchers have dedicated substantial efforts to enhance PV converters, striving to elevate efficiency while simultaneously reducing manufacturing expenses. Moreover, the intricate non-linear behavior of PV panels, coupled with their strong reliance on external weather conditions and load profiles, presents a formidable challenge in maximizing PV energy generation. One strategy proposed to alleviate the problem in existing methods and to address this problem of operating PV panels at their maximum power point (MPP) [3]. Consequently, several algorithms for maximum power point tracking (MPPT) have been introduced. To assess the efficacy of MPPT algorithms, subjecting them to controlled weather conditions becomes an apparent approach for evaluation. Due to the random nature of ambient meteorological data, such circumstances are difficult to achieve. PV emulators, rather than PV panels, are commonly employed for this PV emulators, on the other hand, are not always accessible and are expensive, especially in underdeveloped nations [4].

To build and validate the performance of MPPT algorithms, researchers employ PSIM or MATLAB/Simulink environments [5]. However, these software tools lack the inclusion of integrated boards or processors chips (such as FPGA, Arduino, PIC, or DSP) suitable for the implementation and real-world testing of MPPT algorithms as physical prototypes [6]. In this context, Proteus stands out as a unique solution, offering the capability to replicate electrical systems utilizing hardware elements like microcontrollers, FPGA, DSP, embedded boards (including Arduino), sensors, and actuators. This distinct feature permits simulation and debugging of the system with hardware components, minimizing the potential for errors. Notably, Proteus has been notably absent of a PV panel model [7]. Significantly, this study introduces the integration of the one-diode PV model into Proteus for the first time in the available literature. An empirical setup has been constructed to validate the proposed model. Consequently, the MPPT technique can be effectively executed utilizing Proteus' array of experimental blocks. This approach thus serves as a cost-effective PV emulator, particularly when a physical prototype is unfeasible [8].

Conversely, a multitude of MPPT algorithms have been put forth in scholarly works by researchers. The selection of an appropriate MPPT algorithm warrants considerations of response time, stability in steady-state operation, implementation intricacy, and sensor requisites. Notably prominent MPPT techniques encompass fuzzy logic control (FLC) [9], artificial neural network (ANN) [10], perturb and observe (P&O) [11], and incremental conductance (INC) [9]. The distinct advantage of FLC and ANN methodologies lies in their adeptness at managing the non-linear characteristics of PV panels, thereby yielding consistent MPPT outcomes. For instance, an FLC-based MPPT was meticulously designed and realized on an FPGA platform, attaining a commendable efficiency rating of 98 percent. Additionally, an adjustable step size ANN-MPPT was conceptualized and implemented on a DSP board, showcasing favorable tracking precision and response time [12]. Notably, the intricacy associated with PV systems founded on artificial intelligence paradigms like FLC and ANN poses significant challenges to successful implementation [13].

Rule implementation and training of these methods demand substantial memory capacity, along with high-speed processing capabilities and proficiency in high-level programming languages. Consequently, the utilization of costly integrated boards, such as FPGA or DSP, becomes a significant contributor to escalated expenses within a PV system. Conversely, P&O and INC stand out as the prominently adopted MPPT algorithms in the market [14]. Notably, owing to its simplicity, the P&O technique finds widespread application in PV standalone setups. In the context of such PV systems, a pragmatic approach to cost reduction involves the implementation of MPPT algorithms through economical microcontrollers [15]. However, it's noteworthy that the effective deployment of INC MPPT is comparatively more intricate than P&O, owing to the numerous division computations intrinsic to its operation. This mandates a swifter calculation mechanism and the use of more potent microcontrollers [16]. It's crucial to highlight that P&O may occasionally yield inaccurate responses, leading to system fluctuations around the MPP and consequential power losses. For instance, a customized P&O algorithm was adopted on the budget-friendly FRDM-KL25Z Freescale development processor chip, yielding an extreme efficiency of 96 percent—though still insufficient for optimal PV system performance. In contrast, INC MPPT demonstrates swift MPP tracking with minimal steady-state oscillations, especially in the face of rapid fluctuations in solar irradiation [17].

This study aims to introduce a PSO algorithm-based MPPT technique characterized by its simplicity and exceptional performance. This methodology eliminates the need for division operations, enhancing comprehensibility and facilitating decreases on line conversions demands, thus accommodating the utilization of cost-effective processor chips. A comprehensive assessment of its technical viability and comparative advantages against conventional methods is undertaken through both system-level simulation and practical validation. This innovation holds particular promise for compact or portable PV systems where cost-effectiveness is pivotal for widespread adoption, especially in economically challenged regions. The ensuing structure of this article unfolds as follows: i) Section 2 describes the development of photovoltaic panel model using spice in Proteus; ii) Section 3 delineates the PSO technique for MPPT; iii) Moving on, section 4 offers insight into the implementation and outcomes of the proposed system, subject to detailed analysis; and iv) Ultimately, section 5 encapsulates the key findings derived from this simulation.

2. DEVELOPMENT OF PHOTOVOLTAIC PANEL MODEL USING SPICE IN PROTEUS

The photovoltaic phenomenon facilitates the conversion of sunlight into electrical energy within the PV panel. Illustrated in Figure 1 is the single-diode model characterizing the PV panel. While more intricate and accurate models have been introduced in existing literature, the choice of employing the single-diode model in this study stems from its inherent simplicity [18]. This model strikes a harmonious balance between precision and straightforwardness, finding utilization across various studies with varying degrees of simplification while consistently maintaining the core elements of a current source and a parallel diode. For power electronics practitioners seeking an uncomplicated yet efficient model for PV panel simulations alongside power converters, the single-diode model proves advantageous. Essential constituents of this model encompass a photon current source (Is) interconnected with a diode that emulates the P-N junction, supplemented by a shunt resistor (Rsh) and a series resistor (Rs), depicted in Figure 1. Consequently, the (1) serves as a representative formulation for PV current [19].

$$I_{pv} = I_s - I_d\left(e^{\left(\frac{V_{pv}+I_{pv}R_{se}}{\alpha\times K\times N_n\times T}\right)} - 1\right) - \left(\frac{V_{pv}+I_{pv}R_{se}}{R_s}\right) \quad (1)$$

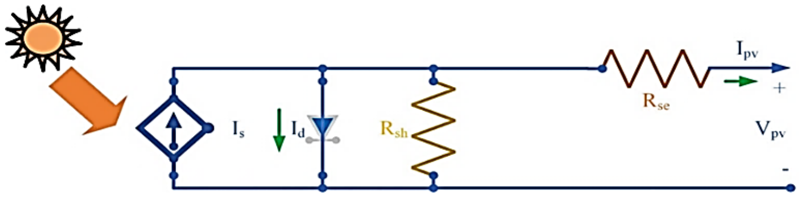

Figure 1. Equivalent circuit of the PV cell in single diode model

For this study, the TDC-M20-36 panel was employed, with its specifications outlined in Table 1. It's important to highlight that any absent datasheet parameters were derived through the utilization of MathWorks' "PV array" tool, as elucidated in [20]. The electrical configuration for the photovoltaic panel within Proteus is structured as follows: an interconnected voltage-controlled current source and diode arrangement (the SPICE code tailored according to the PV panel's specifics), accompanied by a pair of resistors in parallel and series to simulate the series and shunt resistors [21]–[23]. Figure 2 provides a depiction of the Proteus model alongside the corresponding SPICE code.

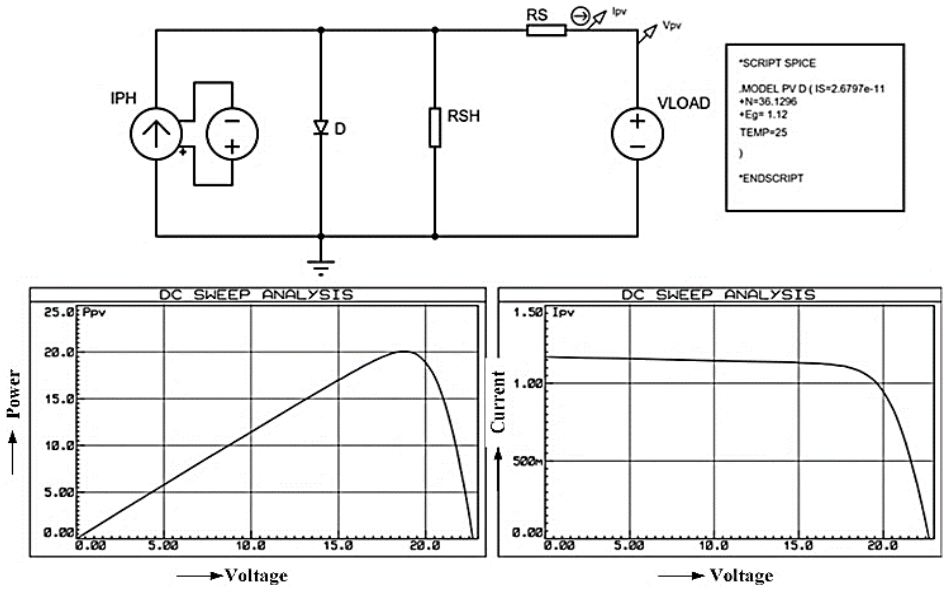

Figure 2. Proteus model of PV cell and corresponding PV and IV characteristics

Table 1. Specification of TDC-M20-36 PV panel

S. No	Description	Values	Unit
1	Open circuit voltage	22.6	V
2	Short circuit current	1.17	A
3	Voltage at peak power	18.76	V
4	Current at peak power	1.07	A
5	Voltage temperature coefficient	-0.35	%/°C
6	Current temperature coefficient	0.043	%/°C
7	Reverse saturation current of diode	2.6797×10^{-11}	A
8	Resistance in shunt	405.96	Ω
9	Resistance in series	1.0547	Ω
10	Number of PV cells	36	-
11	Ideality factor	1.0036	-

3. PARTICLE SWARM OPTIMIZATION MPPT

The concept of PSO was introduced by Eberhart and Kennedy in 1995 as a form of intelligent optimization theory [24]. This algorithm drew inspiration from the collective behavior of birds and fish schooling, applying their principles to search and optimization processes. Similar to birds, each particle in the algorithm possesses a distinct fitness value evaluated by an objective function and a velocity component that dictates its movement relative to other particles in the given space. Crucially, information from each particle's individual search journey is exchanged with others within the swarm as shown Figure 3. The movement of particles is governed by two key variables: Pbest, which stores the best position for each particle as an individual's optimal state, and Gbest, determined by comparing the individual positions of the particle swarm and signifying the collective best position. As particles in the swarm gravitate towards the optimal position, their direction and velocity continually adjust, facilitating rapid convergence toward a local or global optimum. The standard PSO method is governed by (2) and (3) [25], [26].

$$V_i(k+1) = \omega \times \left(V_i(k) + C_1 \times rand \times \left(P_{best,i} - X_i(k)\right) + C_2 \times rand \times (G_{best} - X_i(k))\right) \quad (2)$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \quad (3)$$

This section explains how to use the PSO method to solve the MPPT controller problem in a PV system. Figure 4 illustrates how the proposed PSO-based MPPT algorithm works, the main blocks of this algorithm are as follows: i) All particles were seeded with a random position and velocity in a uniform distribution across the search space in order to generate a random duty cycle and a random fitness value evaluation function for the proposed MPPT algorithm. ii) After the controller has sent the duty cycle command, which represents particle position, the fitness value of particle is computed. iii) Recalculate each particle's fitness values, as well as its individual and global best positions, and replace the P_{best} and G_{best} values corresponding to those positions as necessary, using the newly calculated fitness values. iv) Update the velocities and positions of each particle in the swarm using the PSO formulas (2) and (3) after evaluating all of the particles in the system. v) The criterion for convergence is either finding the best solution or completing the maximum number of iterations possible. In this case, the process would end if all of Steps 2 through 5 were completed; if not, repeat them.

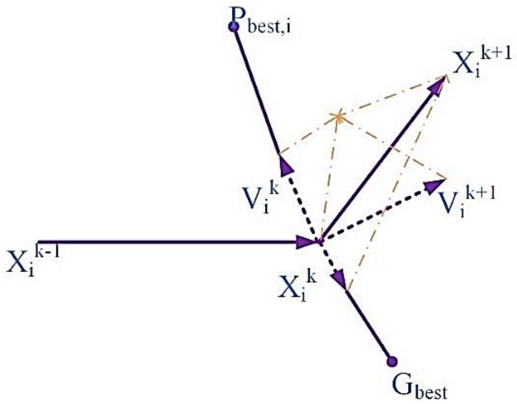

Figure 3. Particle movement in PSO algorithm

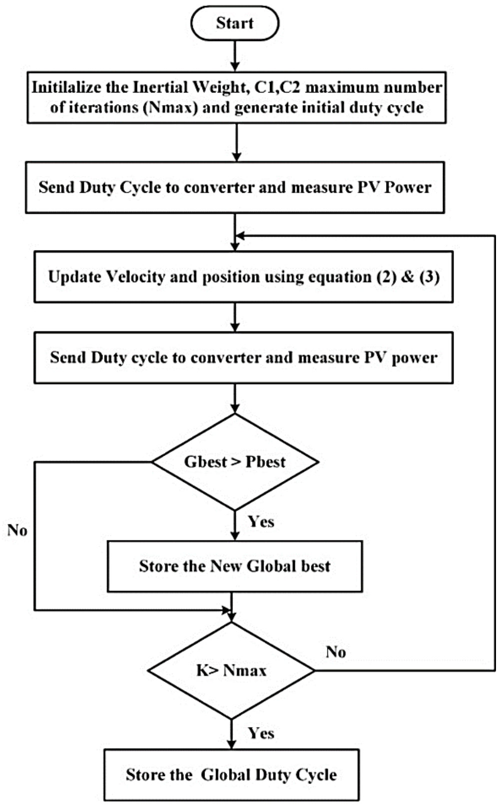

Figure 4. Flowchart of PSO algorithm

4. SIMULATION AND RESULTS DISCUSSION

The implementation of the MPPT algorithm involves the integration of various hardware components, encompassing current and voltage sensors, an integrated board, a drive and converter, r. Proteus furnishes all these essential experimental elements. Integrated Board: To fulfill the goal of constructing an economical PV system, the study employs the UNO Arduino board, which is centered around the budget-friendly ATMega328 microprocessor. Voltage Sensor: Facilitating the conversion of PV high voltage to the 5 V input analog of the Arduino, a voltage sensor is indispensable. The "B25 Voltage Sensor Module" ("Voltage Sensor Module-Arduino Compatible," n.d.) was selected as the sensor of choice for this project. Current Sensor: Essential for detecting PV current, the study mandates the use of a current sensor. The "INA169 Analog DC Current Sensor" was the selected current sensor, with its output voltage directly reflecting the flowing current through it ("INA1×9 Datasheet," 2017). Modulator: For mitigating the disparity between the load and panel, ensuring operation at the MPP, the step-up converter is adopted. This functional aspect is illustrated in Figure 5.

The step-up converter configuration is as follows: Fs = 1000 Hz, Cin = 220 micro–Farad, L = 20 milli Hendry, Co = 470 micro-Farad, and the load impedance R equals 70 Ω. It is important to emphasize that the selection of the IRFP250N transistor for the planned Boost converter is motivated by its low Rds (on) value of 0.075 Ω, effectively minimizing power losses associated with this switch. Furthermore, the inclusion of a Schottky diode is justified due to its low forward voltage drop and swift recovery time, contributing to enhanced overall efficiency of the Boost converter. Driving the MOSFET transistor, the processor chip interfaces with the driver. In this study, the TC4420 driver is employed, leveraging its CMOS design for reduced power consumption and improved efficiency compared to bipolar drivers. For enhanced clarity, the PV Proteus panel model is encapsulated within a "Subcircuit," subsequently linked to the load through the Boost converter arrangement, as depicted in Figure 5. The embedded board (Arduino) integrates current and voltage sensors, thereby detecting PV voltage and current. These acquired data are then utilized by the embedded board's MPPT algorithm to regulate the Boost converter via the driver, employing the calculated duty cycle to achieve the MPP. Additionally, the LCD panel provides a visual display of PV power, voltage, and current.

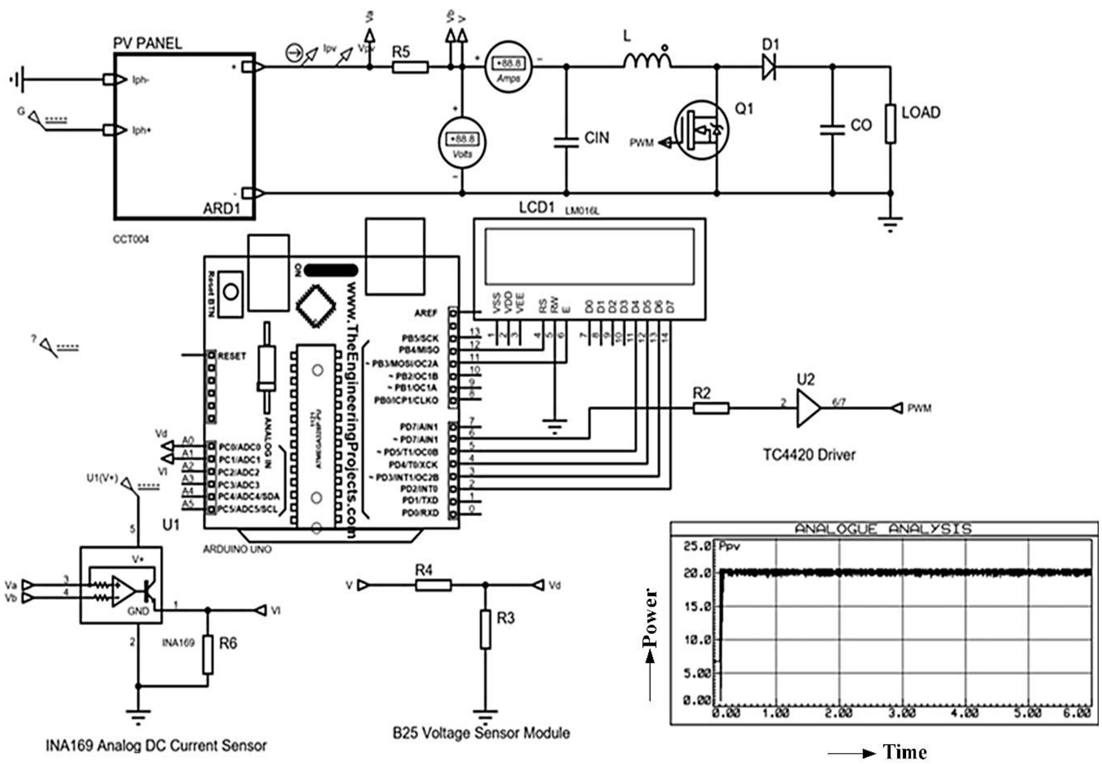

Figure 5. Proteus simulation of PSO MPPT for PV Panel

In this simulation, an assessment of the PSO MPPT strategies encompassed both dynamic and steady-state performance considerations. As depicted in Figure 6, the simulation results for the PV panel operating at 1000 W/m² are presented. Similarly, Figure 7 illustrates the PV panel's performance in response to an irradiance transition from 1000 W/m² to 500 W/m². Notably, the adoption of the enhanced method is evidenced to curtail steady-state oscillations, as discerned from these graphical representations. This outcome underscores how the PSO MPPT technique, by eliminating all division computations, contributes to an improved performance marked by diminished steady-state oscillations and heightened tracking speed.

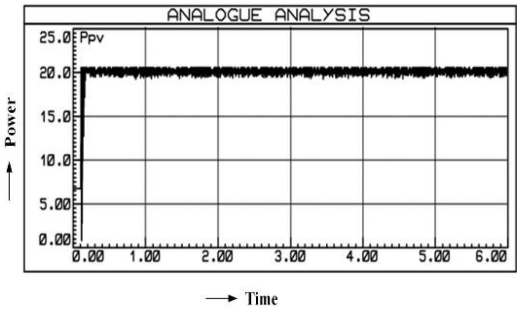

Figure 6. The results of PV panel at 1000 W/m^2

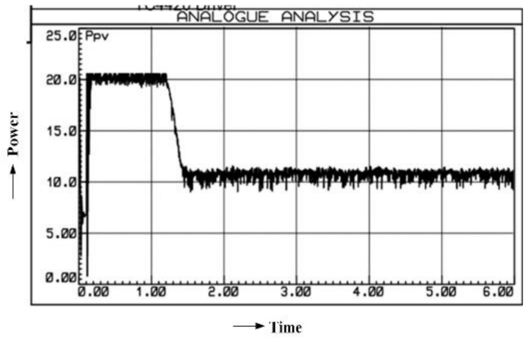

Figure 7. The results of PV panel for change in Irradiance from 1000 W/m^2 to 500 W/m^2

5. CONCLUSION

This research introduces and validates the inaugural Proteus PV panel model, serving as a foundational achievement. In cases where a tangible prototype is absent, this PV model coupled with the available hardware elements in Proteus assumes the role of a cost-effective PV simulator, facilitating the construction and validation of MPPT algorithm performances. This simulator is poised to substantially ease future system enhancements. Additionally, a noteworthy contribution is the presentation of a PSO MPPT algorithm achieved by the elimination of all division operations from the traditional MPPT methodology. This streamlined framework not only permits straightforward implementation utilizing low-cost microcontrollers but also translates to reduced system expenses. Drawing insights from the modeling and simulation outcomes, it is evident that the PSO MPPT approach, relative to conventional MPPT techniques, excels in achieving precise MPP tracking, characterized by swifter response times and minimized steady-state oscillations during abrupt changes. Consequently, the proposed system emerges as a pragmatic and economical avenue for PV power generation.

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