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A Hybrid Particle Swarm Optimization Algorithm for Maximum Power Point Tracking of Solar Photovoltaic Systems

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Abstract

In this paper, we investigated a maximum power point tracking (MPPT) technique based on a hybrid particle swarm optimization (PSO) algorithm to harvest maximum energy from a solar photovoltaic (PV) module. The hybrid PSO algorithm was designed to search and locate the maximum power point (MPP) on the power-voltage curve for abrupt changes in solar irradiance, and automatically switch to perturb and observe (P&O) mode to keep track of the MPP under steady state operation. The designed hardware consisted of a buck-boost converter operating at 100 kHz. 16-bit analog-to-digital (ADC) converters were used to accurately measure the voltages and currents at the load side, which was then read by an Arduino microcontroller to implement the hybrid PSO algorithm. The MPPT algorithm was executed on the microcontroller, which controls the MOSFET switches of the power converter by varying the duty cycle to achieve MPP tracking. MATLAB simulations were performed to find the maximum power and the corresponding optimum duty cycle under various irradiance conditions. Simulated results were verified by experiments using a 40 watt solar module and the experimental results closely agree with the values obtained by simulation. We are currently investigating the effects of several key operating parameters of the PSO technique, such as the particle count, PSO search space, and processor clock speed to further optimize the algorithm and achieve highest possible efficiency. The detailed description of the developed algorithm, the MATLAB simulation, and design of the experimental hardware platform with the results are presented here.

Keywords: Maximum Power Point Tracking, PSO, Photovoltaic Renewable Energy

1. Introduction

Maximum Power Point Tracking (MPPT) is a technique to extract the maximum power out of a photovoltaic (PV) solar panel or array and optimize the energy harvesting capacity of the system. For maximum power point tracking, the solar panel or array is connected to a DC-DC converter, which transfers extracted power from the panel/array to the load. The operating point corresponding to the maximum output power is known as the maximum power point (MPP) of the PV panel, which is attained by adjusting the duty cycle of the MOSFET switches driving the DC-DC power converter. The MPP on the power curve of a solar panel/array changes with varying ambient conditions, such as the solar irradiance, temperature, and connected load. Hence, continuous monitoring and adjustment of the duty cycle driving the MOSFET switches of the DC-DC converter is necessary to track the MPP[1]. This is achieved by implementing an algorithm using a microcontroller.

The simulated current-voltage (I-V) and power-voltage (P-V) curves of a 40W solar module for three different irradiance levels (at 25°C) are shown in Fig. 1. The MPPs under these three irradiance conditions (250W/m^2, 500W/m^2, and 1000W/m^2) are marked as P_{m1}, P_{m2}, and P_{m3}, respectively. As irradiance changes, operating point shifts on the corresponding power curve associated with the irradiance. The goal is to adjust the duty cycle of the MOSFET switch in the power converter to operate the circuit at the global maximum of the power curve.

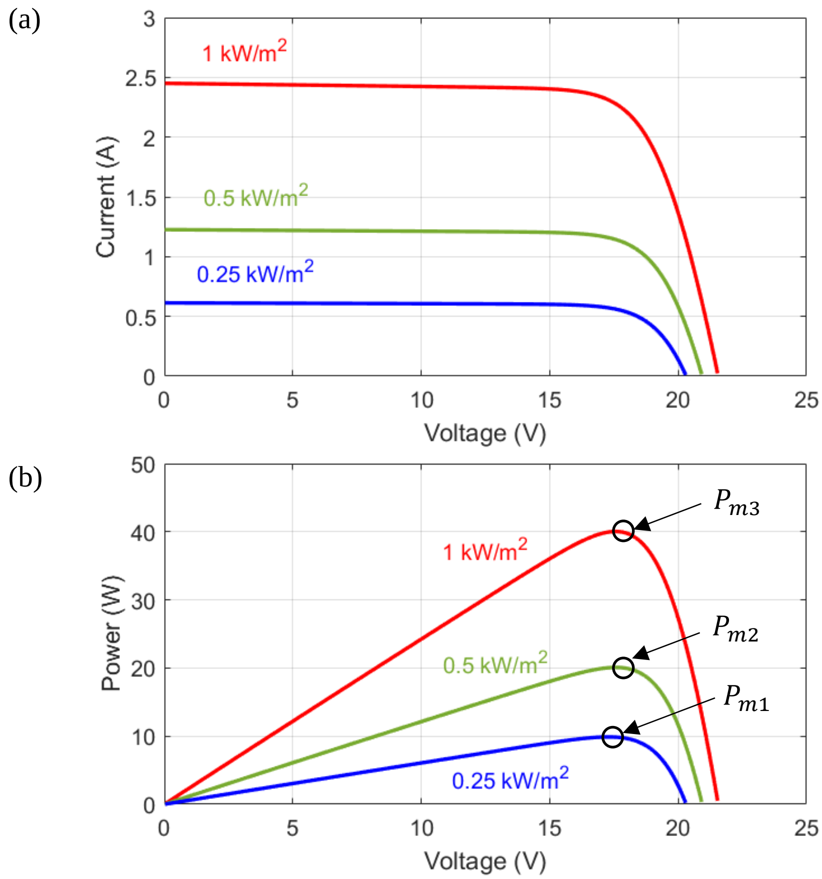

Figure 1. (a) Current-Voltage curves and (b) Power-Voltage curves for a 40W module.

Our algorithm is a hybrid, combining the perturb and observe (P&O) method and particle swarm optimization (PSO) technique. The P&O method is simple and one of the most widely used MPPT algorithms[2]. Although the P&O technique is easy to implement, it has many drawbacks. For example, if the power curve has multiple maxima (e.g. during partial shading), the P&O method cannot discern the difference between a local maximum of the power curve and the global maximum[2, 3]. Thus, more intelligent and efficient methods are required for MPPT. The particle swarm optimization (PSO) algorithm aims to mimic the behavior of swarms of bees, flocks of birds, or schools of fish[2]. Our hybrid algorithm is expected to be more flexible, faster, and efficient than the P&O technique.

2. Algorithm Development

Our algorithm begins by calculating the range of possible duty cycles. The converter then tests several duty cycles and calculates the power corresponding to each point. If partial shading is not detected, the algorithm sets the duty cycle to the optimum point, and then switches to local mode (P&O). If partial shading is detected, the algorithm switches to global mode, using the PSO technique to find the global maximum power point. After finding the MPP, the algorithm switches to local mode to stay at the MPP through small changes to the power curve. When large changes are detected, the algorithm restarts and PSO is employed to detect the power curve maxima. The algorithm block diagram is shown in Fig. 2.

To implement the PSO algorithm, many "particles" are created along the power curve. The location of each particle is a potential MPP[2]. The system tests the power output at the location of each particle. The particles then communicate with each other to identify which location has the best power output. Each particle's movement along the power curve is then determined by the swarm's previous locations. As the particles continue to move, they eventually converge on the MPP[4]. Every time our system finds an MPP, a data point is created in a table that is saved in the microcontroller memory. Thus, the system remembers the MPP for a specific operating or irradiance condition. Over time, our algorithm builds a database and uses the previously saved information to predict the location of the MPP[5]. This technique is known as memetic machine learning[6]. This is expected to expedite the MPP searching process and make it more efficient. This is also expected to significantly reduce the PSO algorithm search space, thus saving time and improving efficiency during execution[7].

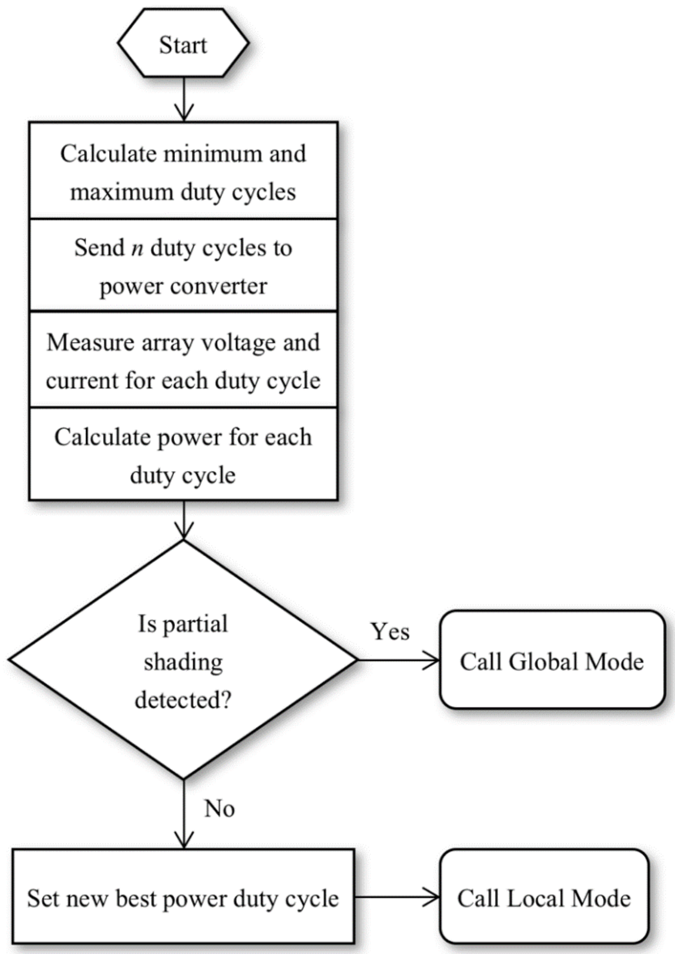

Figure 2. Block diagram of the developed hybrid PSO algorithm

If partial shading is not detected, the algorithm operates in local mode. Alternatively, the algorithm will also go to local mode after the MPP is found by global mode. Local mode is implemented by the P&O method. In this process, the duty cycle is perturbed, either up or down. If the power output increases, the duty cycle is adjusted in the same direction again. If the power output decreases, the duty cycle is adjusted in the opposite direction[2]. This allows the system to track the MPP reliably for small changes in the power curve. If a large change in power output is detected, the system will assume that the power curve may have changed dramatically, and the algorithm will restart, checking for partial shading and potentially going into global mode again. One of the major problems with the standalone P&O algorithm is that it oscillates near the MPP and takes long time to find the MPP for abrupt change in irradiance[8]. In our hybrid algorithm, such oscillation can be reduced by decreasing the duty cycle increment or decrement step size, and the time required to search for the MPP can be reduced with the assistance of the PSO method[9]. Thus, the system is expected to be more flexible and efficient.

3. Experimental Setup and Circuits

The block diagram for the experimental setup is presented in Fig. 3. The PV module was connected to a buck-boost DC-DC converter. A buck-boost converter can step the voltage up or down. The power going into and out of the converter was calculated by multiplying the voltage and current measured at each point. This was done using a four channel analog-to-digital converter (ADC), ADS1115. The ADC allowed the microcontroller to read voltage and current, as well as to calculate power. The buck-boost converter is driven by a PWM signal at 100 kHz frequency. A PWM circuit was designed employing LM741 op-amp and a MAX9072 comparator chip.

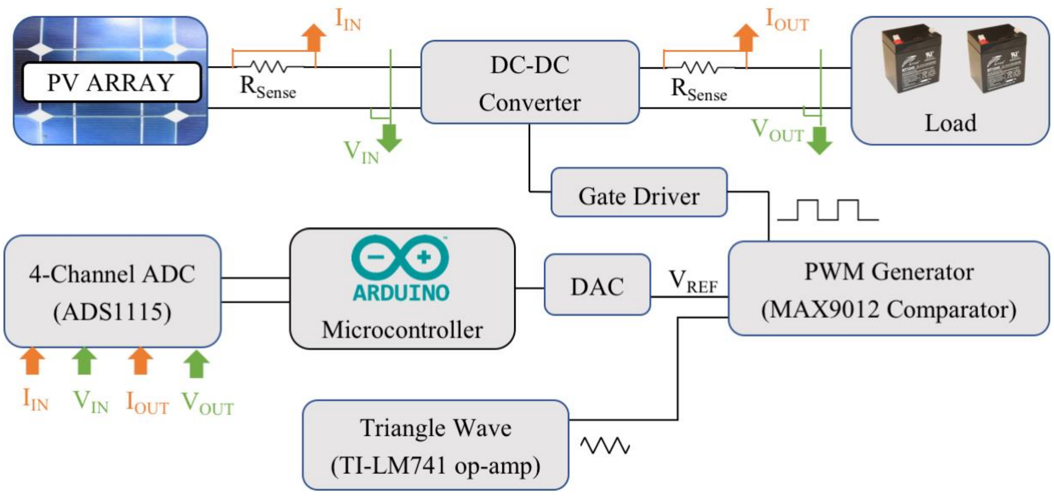

Figure 3. Block diagram showing various major components of the MPPT experimental setup.

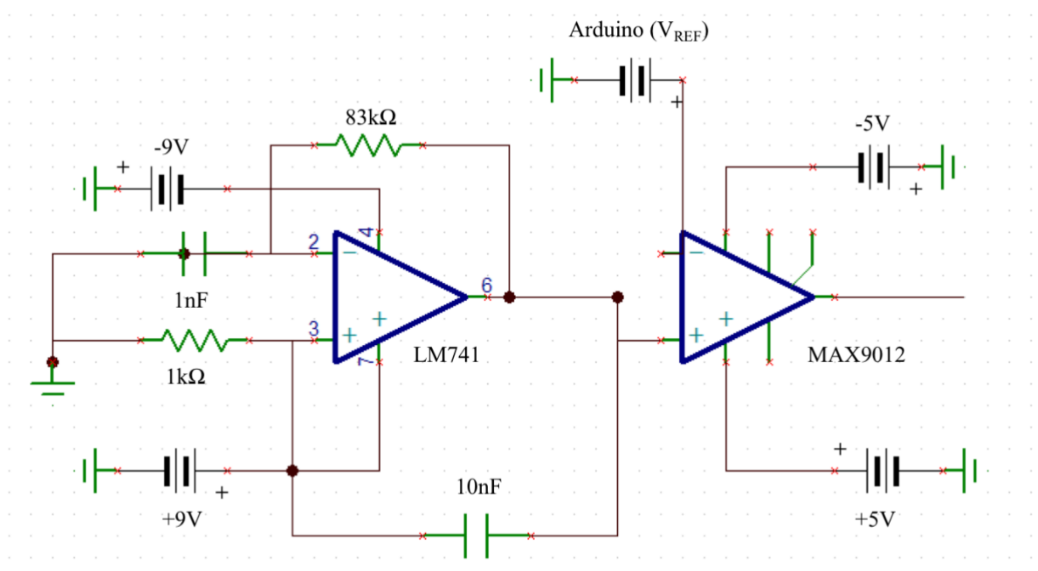

Figure 4. PWM Generation and Control Circuit

Duty cycle adjustment of the PWM signal was achieved using the comparator which compares the triangular wave output from the LM741 op-amp to a reference DC voltage (V_{Ref}) produced by the microcontroller through a digital-to-analog (DAC) converter. A 12-bit buffered voltage output DAC (MCP4725) was used in our circuit. When the magnitude of the triangular wave is higher than V_{Ref}, the comparator chip outputs a high (+5V) and when V_{Ref} is higher than the triangular wave, the comparator outputs a low (0V). As V_{Ref} changes, the output pulse width changes

– thus producing the PWM signal[10]. The PWM circuit is shown in Fig. 4. This PWM signal was then fed through a gate driver circuit to switch the MOSFET of the DC-DC converter. The program (algorithm) running on the Arduino essentially changes the DAC output voltage to control the PWM duty cycle. The prototype experimental setup is shown in Fig. 5.

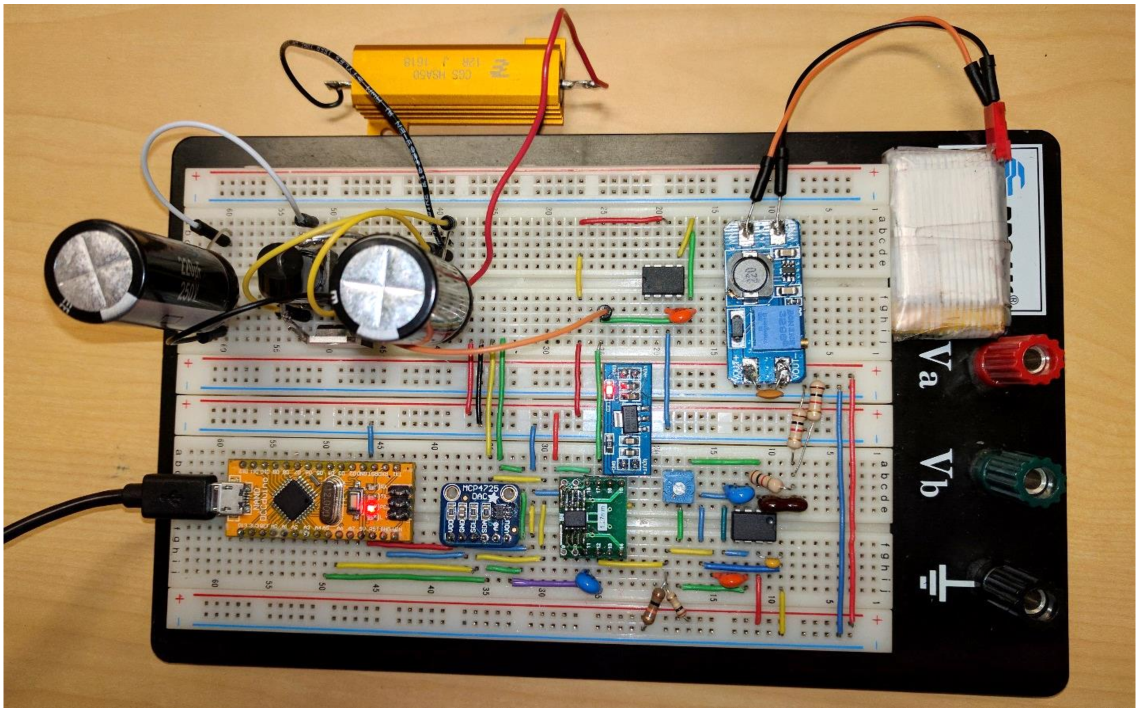

Figure 5. Photograph of the experimental MPPT prototype setup.

4. Modeling and Simulation

The DC-DC buck-boost converter with the 40W solar module was modeled in MATLAB Simulink. The Simulink model is shown in Fig. 6.

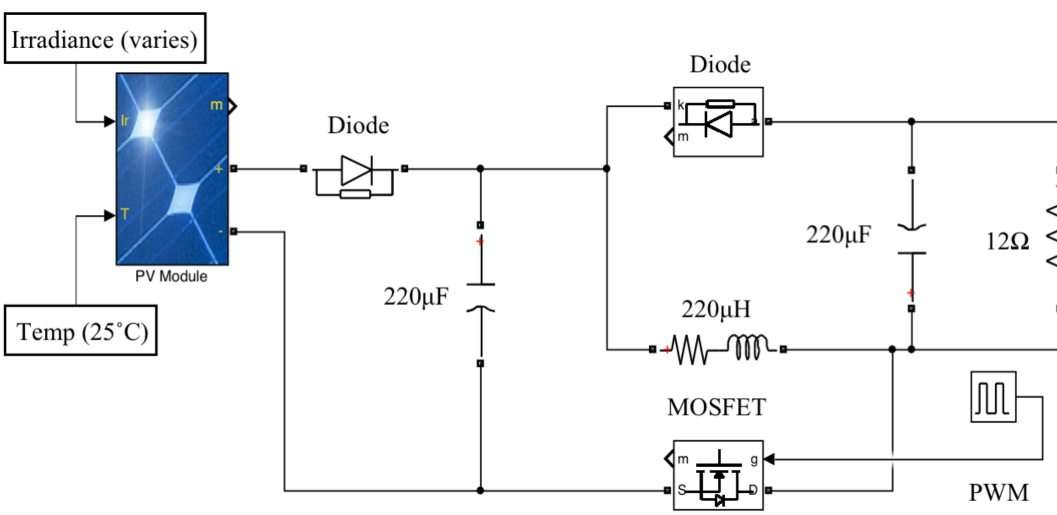

Figure 6. MATLAB Simulink model of the buck-boost converter with the solar module for MPPT.

We used a 12Ω fixed resistor (50W) as the load. In the simulation model, we have varied the duty cycle of the PWM signal manually to find out the optimum duty cycle at different irradiance levels. The polycrystalline Si solar module used in our study consisted of 36 cells connected in series. The module parameters are summarized in Table 1.

Table 1. Parameters of the solar module used.

Open-circuit voltage (V_{OC})	Short-circuit current (I_{SC})	Rated Power (P_{Out})	Voltage at Max. power (V_{mp})	Current at Max. power (I_{mp})	Fill Factor (FF)	Efficiency (η)
21.56 V	2.45 A	40 W	17.56 V	2.28 A	75.8%	~16%

5. Results and Discussion

Output waveforms of the MOSFET gate driver circuit at various points are shown in Fig. 7. The top (yellow) waveform represents the triangular wave generated by the LM741 op-amp circuit. The green waveform is the output of the comparator chip. The purple waveform is the output of the MOSFET gate driver used in the circuit. Finally, the red waveform at the bottom is the drain to source voltage across the MOSFET with the gate driver output applied to the MOSFET gate.

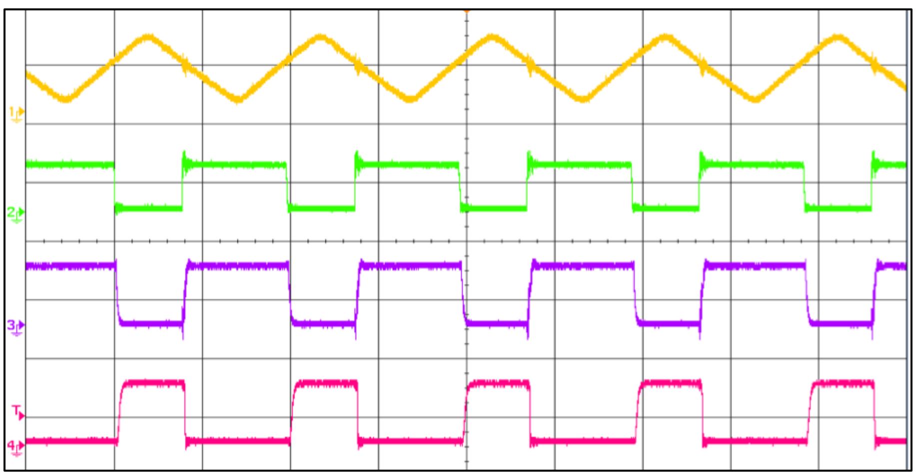

Figure 7. Output waveform of the PWM generator and the gate driver circuit at various points.

Using the Simulink model, we have estimated the optimum duty cycles to track the maximum power point at various irradiance conditions. The theoretical values matched closely with the actual values. The results are summarized in Table 2.

Table 2. Summary of the Maximum Power Point Tracking results.

Irradiance (W/m^2)	Theoretical Max. Power (W)	Actual Max. Power (W)	Optimum Duty Cycle (%)	Converter Efficiency (%)
300	11.7	11.2	50.0	96.2
400	15.7	15.2	46.5	96.6
500	19.8	19.1	44.0	97.0
600	23.8	23.0	42.0	97.2
700	27.9	26.9	40.1	97.4
800	32.0	30.8	38.7	97.6

From the results, it is obvious that the maximum power output increased as the irradiance increased. Also, the converter's efficiency increased slightly as the power level increased which confirms the appropriate design of the converter circuit. A rigorous field testing is currently underway to compare our results with standalone P&O algorithm and other competing MPPT systems.

6. Conclusions and Future Work

We have successfully designed and built a prototype of a photovoltaic maximum power point tracking system implementing a hybrid PSO algorithm. Simulation and experiments were performed using a 40W polycrystalline solar module and our results show close match with the theoretical predicted values. We expect this MPPT system to be more flexible, faster, lower-cost, and more reliable compared to the standalone P&O algorithm-based MPPT systems currently available in the market[11].

Currently, we are testing several important parameters, such as the optimum number of particles to use in the PSO algorithm to attain the best balance of speed and accuracy. We are investigating the effects of microcontroller clock speed on the system's efficiency. In addition, we also plan to test our algorithm using multiple solar modules under partial shading conditions. For easy comparison, we will test one system with the hybrid PSO algorithm and the other with the commonly used P&O algorithm. Our planned future work will help us to further assess the algorithm's capabilities and limitations.

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