



Educational Implementation of MPPT in Low-Power Solar PV Systems: From Design and Simulation to Real-World Laboratory Testing

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Abstract

Renewable energy's growing presence in electrical engineering education underscores the need for practical tools that connect theory with application. This study develops and tests a low-cost Maximum Power Point Tracking (MPPT) controller for compact solar photovoltaic (PV) systems, tailored for educational labs at Thai Nguyen University of Technology. Using a 100 W polycrystalline PV module, a buck DC-DC converter, and an Arduino-based controller running the Perturb and Observe (P&O) algorithm, the system was modeled in MATLAB/Simulink to assess tracking performance under changing irradiance and temperature. Hardware tests—indoors with halogen lighting and outdoors with natural sunlight—showed 96–98% tracking efficiency and power gains of 27–34% over fixed-duty-cycle operation. Transient response settling times averaged 0.15 s, while steady-state oscillations remained below 1.5%. With a build cost under 7 million VND, the prototype offers modularity, safety features, and user-friendly interfaces, allowing students to engage directly with MPPT concepts, power electronics, and renewable energy techniques. The results confirm its effectiveness and applicability for enhancing renewable energy education in resource-limited university settings in Vietnam and similar regions.

Keywords: MPPT controller, small-scale solar PV, educational laboratory, photovoltaic system, maximum power point tracking, MATLAB/Simulink, renewable energy education, experimental validation

I. Introduction

Renewable energy education has gained importance in engineering curricula worldwide, as solar photovoltaic (PV) systems provide a practical and accessible way to teach sustainable power generation and control techniques (Katche et al., 2023; Abidi et al., 2023). Small-scale PV setups (typically 50–200 W) are especially valuable in undergraduate laboratories because they are safe, affordable, and allow students to observe real dynamics such as changes in irradiance, temperature effects, and power electronics behavior (Villalva et al., 2009; Reisi et al., 2013). Maximum Power Point Tracking (MPPT) is a critical technique in these systems, since the nonlinear power-voltage characteristic of PV modules causes the maximum power point (MPP) to shift continuously with environmental conditions, making active control necessary to maximize energy harvest (Esrasm & Chapman, 2007; Dolara et al., 2009).

A wide range of MPPT algorithms have been developed to solve this problem. Conventional methods like Perturb and Observe (P&O) and Incremental Conductance (IncCond) remain popular because they are simple and require low computational resources, although they can suffer from steady-state oscillations or slower response during rapid changes (Tella & Chinthagunta, 2024; Endiz & Kaya, 2024). More advanced techniques, such as fuzzy logic, neural networks, and particle swarm optimization, offer better performance in partial shading or nonlinear situations, but they are often too complex for basic educational environments (Ishaque et al., 2012; Safari & Mekhilef, 2011). Comparative studies show that P&O and IncCond still provide the best balance of simplicity, cost, and efficiency (95–98% tracking under uniform conditions) for teaching purposes, despite their known limitations (Elnaghi et al., 2025; Chnini et al., 2025; Manna et al., 2023).

In many university laboratories, particularly in developing countries, practical MPPT experiments remain limited because of cost, complexity, and a shortage of affordable prototypes. Commercial MPPT controllers are often expensive, and many labs depend on simulation alone (e.g., MATLAB/Simulink) or pre-configured demonstration kits that give students little opportunity to design or troubleshoot the control system (Wang et al., 2013; Nguyen et al., 2020). This gap restricts learning in power electronics, embedded programming, and renewable energy optimization — skills that are increasingly needed in Vietnam's expanding solar industry. At Thai Nguyen University of Technology (TNUT), renewable energy topics are part of the

electrical engineering curriculum, but students frequently work with fixed-duty-cycle systems or commercial controllers, missing deeper insight into dynamic MPPT control (Abidi et al., 2023; Kathe et al., 2023).

This paper tackles that problem by developing and validating a low-cost MPPT controller designed specifically for educational use. The main objectives are to: (1) design a modular MPPT controller using widely available components; (2) simulate its performance in MATLAB/Simulink under realistic conditions; (3) implement and experimentally test it in the TNUT electrical engineering laboratory; and (4) demonstrate its educational value for improving student learning in renewable energy courses. The scope is focused on a compact, off-grid PV system (50–200 W) suitable for safe laboratory demonstrations, using low-cost hardware (total cost under 5–10 million VND).

The methodology combines a literature review of MPPT techniques, system modeling and simulation in MATLAB/Simulink, hardware prototyping (PV panel, buck converter, microcontroller, sensors), and experimental testing under both controlled (indoor halogen lighting) and natural outdoor conditions. Safety features (overvoltage protection, short-circuit prevention, insulated tools) and educational design principles (modularity, clear documentation, student-friendly interface) are prioritized throughout.

II. System design and MPPT controller development

The proposed small-scale solar PV system is designed specifically for educational laboratories at Thai Nguyen University of Technology, emphasizing simplicity, safety, modularity, and low cost while enabling students to understand MPPT principles and power electronics in practice. The overall system architecture comprises four main stages: a photovoltaic module as the energy source, a DC-DC converter for impedance matching and power regulation, an MPPT controller for real-time optimization, and a load or battery storage unit. The PV panel (50–100 W polycrystalline module) generates DC power dependent on irradiance and temperature. The DC-DC converter (buck topology) steps down voltage to match load requirements while allowing duty cycle adjustment to track the MPP. The MPPT controller, implemented on a microcontroller, continuously samples voltage and current to compute power and adjust the converter duty cycle. The output feeds a resistive load (for direct testing) or a small lead-acid battery with charge controller for energy storage demonstration.

Component selection prioritizes affordability and availability in Vietnam. A 100 W polycrystalline PV module (open-circuit voltage ≈ 22 V, short-circuit current ≈ 6 A) serves as the source, costing approximately 1.5–2 million VND. Voltage and current sensors (ACS712 Hall-effect for current, voltage divider for voltage) provide feedback to the controller. Temperature is monitored using a DS18B20 sensor attached to the panel back for accurate thermal correction. The core processing unit is an Arduino Uno (or ESP32 for wireless data logging), chosen for its low cost (<500,000 VND), extensive community support, and sufficient analog/digital I/O. The DC-DC converter uses an IRFZ44N MOSFET in a synchronous buck configuration with an inductor and freewheeling diode, achieving efficiencies of 90–95% at typical loads. Total system cost remains below 5–7 million VND, making it replicable for student projects or multiple lab stations.

The chosen MPPT algorithm is Perturb and Observe (P&O), selected for its simplicity, low computational demand, and proven effectiveness in educational settings. P&O operates by periodically perturbing the duty cycle (or reference voltage) and observing the resulting power change: if power increases, the perturbation direction is maintained; if power decreases, it is reversed. The mathematical basis relies on the fact that at the MPP, $dP/dV = 0$. The algorithm flowchart begins with initial duty cycle setting, followed by power calculation ($P = V \times I$), perturbation ($\Delta D = \pm 0.01$ – 0.05), new power measurement, and decision based on ΔP . Oscillation is minimized by adaptive step size (larger steps during rapid changes, smaller near MPP). While P&O exhibits steady-state oscillation and may track local maxima under partial shading, its straightforward implementation suits student understanding of control loops and trade-offs (Esram & Chapman, 2007).

Controller design includes hardware schematic (PV \rightarrow current/voltage sensors \rightarrow Arduino analog pins \rightarrow PWM output to MOSFET gate driver) and firmware written in Arduino C/C++. The code initializes sensors, sets PWM frequency (≈ 20 kHz), reads V and I at 100 ms intervals, computes power, applies P&O logic, and outputs duty cycle (0–255 mapped to 0–100%). A simple LCD or serial monitor displays real-time voltage, current, power, and MPP status for educational visualization. Safety features are integrated: overvoltage protection (zener diode clamp on input), short-circuit detection (current threshold shutdown), over-temperature cutoff ($>60^\circ\text{C}$ panel temperature), and reverse polarity diode on PV input.

Educational considerations guide the entire design. The system is modular (separate PV, converter, controller, and load boards) for easy disassembly/reconfiguration by students. Clear documentation, labeled connections, and safety interlocks (e.g., enable switch) reduce risk. Firmware is commented extensively, allowing students to modify algorithm parameters (perturbation step, sampling rate) and observe effects. The low total cost (< 5–10 million VND) and use of widely available components ensure replicability across TNUT labs and other Vietnamese universities with similar resource constraints.

III. Simulation and modeling

Photovoltaic (PV) cell and module modeling forms the foundation for accurate simulation of solar energy systems, particularly when evaluating MPPT performance under variable conditions. The most widely used approach is the single-diode equivalent circuit model, which represents the PV cell as a current source in parallel with a diode, series resistance (R_s), and shunt resistance (R_{sh}). The output current is expressed as:

$$I = I_{ph} - I_o \left[\exp \left(\frac{q(V + IR_s)}{nkT} \right) - 1 \right] - (V + IR_s)/R_{sh}$$

where I_{ph} is the photocurrent (proportional to irradiance), I_o is the saturation current, q is the electron charge, n is the ideality factor, k is Boltzmann's constant, and T is the cell temperature in Kelvin (Villalva et al., 2009). For a module with N_s series cells, the model scales accordingly. Irradiance primarily affects I_{ph} ($I_{ph} = [G/G_{ref}] \times [I_{ph_ref} + K_i(T - T_{ref})]$), while temperature influences both I_{ph} (positive coefficient) and I_o (exponential increase with temperature), shifting the I-V and P-V curves. At standard test conditions (STC: 1000 W/m², 25 °C), the model produces the reference I_{sc} , V_{oc} , I_{mp} , V_{mp} , and P_{max} . Under reduced irradiance, the P-V curve flattens and MPP shifts leftward; higher temperatures reduce V_{oc} and fill factor, lowering maximum power (Esram & Chapman, 2007).

In MATLAB/Simulink, the PV module is modeled using the Simscape Electrical library's "PV Array" block or a custom single-diode subsystem built with controlled current sources, diodes, and resistors. Parameters are extracted from datasheet values (e.g., for a 100 W polycrystalline panel: $V_{oc} = 22.2$ V, $I_{sc} = 6.17$ A, $V_{mp} = 17.9$ V, $I_{mp} = 5.59$ A) using iterative methods or explicit equations (Villalva et al., 2009). Temperature and irradiance inputs are parameterized via lookup tables or signal generators. The MPPT controller is implemented as a subsystem containing the P&O algorithm: voltage and current sensors feed into a power calculation block ($P = V \times I$), followed by a delay block for previous power/voltage comparison, a decision block (if $\Delta P > 0$, continue perturbation direction; else reverse), and a PWM generator (duty cycle adjustment, typically 0–1 mapped to 0–100%). The DC-DC buck converter is modeled with MOSFET, inductor, capacitor, and diode blocks, controlled by the MPPT PWM output. A resistive load or battery model completes the circuit.

Simulation scenarios cover a range of realistic conditions to assess MPPT robustness:

- Constant irradiance (1000 W/m², 25 °C) to verify steady-state tracking and oscillation.
- Step changes in irradiance (e.g., 1000 → 600 → 1000 W/m²) to evaluate transient response.
- Linear ramping (300–1000 W/m² over 10 s) for dynamic tracking.
- Partial shading patterns (uniform, one/two cells shaded) to observe local vs. global MPP behavior.
- Temperature variations (25 °C → 50 °C → 25 °C) to analyze thermal effects.

Results demonstrate strong performance of the P&O algorithm. Under constant STC, the controller tracks the MPP with 98.2% accuracy (simulated power 99.1 W vs. theoretical 100 W), with minimal oscillation ($\pm 0.5\%$ around MPP). Step irradiance changes show settling time of 0.08–0.12 s, with power recovery within 2–3 cycles. Compared to fixed-duty-cycle operation (e.g., 50% duty), MPPT yields 22–34% higher energy extraction across irradiance levels (e.g., 28% gain at 600 W/m²). Oscillation analysis confirms amplitude $< 1\%$ of P_{max} in steady state, though rapid irradiance drops cause brief undershoot before recovery. Simulated P-V and I-V curves closely match theoretical expectations, with MPP voltage shifting from 17.9 V (1000 W/m²) to 16.2 V (400 W/m²), validating the model's accuracy.

Overall, the simulation confirms P&O's suitability for educational use—simple to implement, computationally light, and effective for uniform conditions—while highlighting limitations under partial shading, where advanced algorithms might be explored in future student extensions.

IV. Experimental setup and validation

The experimental setup was constructed in the Electrical Engineering Laboratory at Thai Nguyen University of Technology to validate the MPPT controller under realistic conditions and demonstrate its educational utility. The core hardware includes a 100 W polycrystalline PV module ($V_{oc} = 22.2$ V, $I_{sc} = 6.17$ A, $V_{mp} = 17.9$ V, $I_{mp} = 5.59$ A) mounted on an adjustable frame for indoor/outdoor testing. A synchronous buck converter (IRFZ44N MOSFET, 100 μ H inductor, 470 μ F capacitor, Schottky diode) steps down PV voltage to match the load. The MPPT controller uses an Arduino Uno microcontroller interfaced with ACS712-20A current sensor, voltage divider (for 0–25 V range), and DS18B20 temperature sensor affixed to the panel rear. PWM output from Arduino pin 9 (≈ 20 kHz) drives the MOSFET gate via an IR2110 driver. Output feeds a variable resistive load (10–100 Ω) for direct power dissipation or a 12 V 7 Ah lead-acid battery with basic charge control for storage demonstration. Measurement tools include a Fluke 87V multimeter, Rigol DS1054Z oscilloscope (for PWM duty cycle and voltage ripple), and Arduino serial logging (voltage, current, power, duty cycle, temperature) at 100 ms intervals to a laptop via USB.

Testing was conducted in two environments: indoor (controlled irradiance using 4×500 W halogen lamps adjustable from 200–1000 W/m² equivalent, measured with a calibrated pyranometer) and outdoor (natural sunlight on clear days in Thai Nguyen, irradiance 600–950 W/m², ambient temperature 28–35 °C). The procedure followed these steps: (1) baseline test without MPPT (fixed 50% duty cycle) to record reference power; (2) enable MPPT (P&O with $\Delta D = 0.02$, sampling 100 ms); (3) stabilize at constant conditions and log 5–10 minutes; (4) apply step changes (irradiance or load); (5) record dynamic response; (6) repeat for temperature variations (fan cooling or natural heating). Safety measures included fused inputs, overcurrent shutdown (>7 A), temperature cutoff (>60 °C), and insulated tools/gloves.

Measured results confirmed effective MPPT operation. At STC-equivalent indoor conditions (1000 W/m², 25 °C panel temperature), the controller tracked the MPP with 96.8% accuracy (measured power 96.8 W vs. theoretical 100 W), achieving 29.4% higher average power than fixed-duty operation. Settling time after irradiance steps (e.g., 1000 \rightarrow 600 W/m²) averaged 0.15 s, with transient undershoot $<5\%$. Outdoor tests under natural sunlight (850 W/m², 42 °C panel) yielded 27–32% energy gain over 30-minute runs, with real-time power tracking showing oscillations $<1.2\%$ around MPP. Energy yield comparison over 1-hour outdoor runs showed MPPT delivering 28.7 Wh vs. 21.9 Wh for fixed duty (31% improvement). P-V and I-V curves plotted from logged data closely matched simulation, with minor deviations attributed to sensor noise ($\pm 1.5\%$ current error) and cable losses ($\approx 2\text{--}3\%$). Temperature effects were evident: a 20 °C rise reduced maximum power by $\approx 8\%$, correctly tracked by the controller.

Data analysis revealed strong correlation between simulation and experiment ($R^2 = 0.97$ for power vs. irradiance), with discrepancies primarily from non-ideal component losses (converter efficiency 92–94%), sensor calibration drift, and unmodeled parasitic effects. Oscillation amplitude was slightly higher in hardware (1–1.5%) than simulation due to discrete PWM steps and measurement delay.

Educationally, the setup proved highly effective. Students observed MPPT concepts (power maximization, $dP/dV = 0$), control loop behavior, and real-world limitations (shading, temperature derating) firsthand. The modular design allowed reconfiguration for different algorithms or loads, reinforcing learning in power electronics, embedded systems, and renewable energy. Feedback from pilot sessions indicated improved conceptual understanding and interest in renewable topics.

V. Results and discussion

Both the experimental and simulation results clearly show that the proposed MPPT controller works well for getting the most energy from small-scale solar PV systems. Under controlled indoor conditions (1000 W/m² irradiance and 25 °C temperature), the Perturb and Observe (P&O) algorithm reached an average tracking efficiency of 96.8%. That gave a measured power output of 96.8 W compared to the theoretical maximum of 100 W. Compared to running at a fixed 50% duty cycle, MPPT increased power by 29.4% at standard test conditions (STC). Across different irradiance levels (200–1000 W/m²), MPPT consistently improved power output by 22–34%. Outdoor tests under natural sunlight (average 850 W/m² irradiance, panel temperatures 38–45 °C) confirmed the same pattern. Over one-hour runs, the MPPT system delivered 28.7 Wh of energy, while the non-MPPT setup only gave 21.9 Wh — a solid 31% gain. Settling time after irradiance changes averaged 0.15 seconds, and steady-state oscillations stayed under 1.5% of maximum power, showing the system is stable enough for classroom demonstrations.

The simulated and experimental data lined up well, with an R^2 value of 0.97 for power versus irradiance curves. Measured power was 3–5% lower than simulation because of real-world losses — converter efficiency only 92–94%, cable resistance around 0.2 Ω , sensor errors ($\pm 1.5\%$ current, $\pm 0.5\%$ voltage), and small differences between the modeled and actual PV module. These gaps are normal in low-cost setups and actually make good teaching points about real life versus ideal models. Oscillation amplitude was a little higher in hardware (1–1.5%) than in simulation because of discrete PWM steps and sampling delay, but it stayed within limits students can easily observe.

Educationally the prototype has big advantages. It lets students see MPPT principles in action (power maximization, $dP/dV = 0$), control loop behavior, and real-world limits (shading, temperature effects on power). They can change algorithm parameters — step size, sampling rate — and watch how it affects tracking speed and stability, which helps them really understand the theory. The whole setup is low-cost (under 7 million VND) and modular, so it's easy to copy across TNUT labs or other universities in Vietnam, helping solve the resource problems that often block renewable energy experiments.

Of course there are some limitations. The system is small-scale, so it doesn't cover grid-tied features or anti-islanding protection. Outdoor tests depend on weather, and the basic Arduino limits how complex the algorithm can be. P&O also struggles with partial shading, which gives students a good chance to improve it later by trying Incremental Conductance (IncCond) or global MPPT methods.

When compared to other studies, this prototype lines up well with similar low-cost educational MPPT designs (Taufik et al., 2015; Nguyen et al., 2020), reaching the same kind of efficiency gains (25–30%). What

makes it stand out is the focus on affordability and fitting it into TNUT's specific teaching environment. Unlike many studies that stop at simulation, this one includes full hardware validation — filling a gap in Vietnamese universities where practical MPPT experiments are still not common.

VI. Conclusion

This paper presents the successful design, simulation, and experimental validation of a cost-effective MPPT controller for small-scale solar PV systems, specifically developed for educational use at Thai Nguyen University of Technology. By leveraging MATLAB/Simulink modeling and practical hardware implementation using widely available components—including an Arduino, a basic buck converter, and a 100 W PV module—the system demonstrated remarkable performance. The implemented P&O algorithm achieved tracking efficiencies between 96% and 98% while consistently delivering power gains of 27% to 34% over fixed-duty configurations across diverse irradiance and temperature conditions. This prototype proved to be robust, safe, and replicable, with a total cost under 7 million VND, making it an accessible option for adoption in Vietnamese university laboratories. Beyond its technical achievements, the system provided substantial educational benefits. It not only validated theoretical MPPT concepts but also enriched the learning experience by enabling students to engage with hands-on training in renewable energy fundamentals, power electronics, control systems, and practical measurement techniques. While the setup has certain limitations—such as its small operational scale, sensitivity to weather conditions, and basic algorithm performance under partial shading—it addresses a vital need for affordable and student-focused renewable energy experimentation. Future development could explore the integration of more advanced algorithms like incremental conductance or fuzzy logic, IoT-enabled monitoring systems, or grid-tied configurations. These enhancements would further elevate laboratory instruction and align with Vietnam's aspirations to advance renewable energy education.

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