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Classical MPPT in a Partially Shaded PV String: Technical Note on System Operation and Control

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Abstract

This report describes the practical implementation of a maximum power point tracking (MPPT) system for a string of four series connected monocrystalline silicon photovoltaic (PV) cells. The system includes a boost DC DC converter that interfaces the low voltage PV string to a 36 V battery, and each cell has an individual MOSFET bypass switch to mitigate partial shading. We explain the operating principles, the MPPT algorithms (Perturb & Observe and Incremental Conductance), the bypass logic, and the closed loop control that adjusts the converter's duty cycle to maximise power transfer. Step by step descriptions and supporting figures clarify the process.

Keywords: Photovoltaic, PV String, Partial Shading, Fast-Moving Shadows, Maximum Power Point Tracking, MPPT, Perturb and Observe, Incremental Conductance, Boost Converter, Bypass MOSFET, Hot-Spot Prevention, Digital Control, Battery Charging, Substring Bypass

Acronym	**Meaning**
ADC	Analog-to-Digital Converter
CC	Constant-Current charging
CV	Constant-Voltage charging
DC-DC	Direct-Current to Direct-Current
IncCond	Incremental Conductance
MCU	Microcontroller Unit
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
P&O	Perturb and Observe
PWM	Pulse-Width Modulation
PV	Photovoltaic
Rds(on)	MOSFET on-state resistance

Table

Scope Note: This technical note uses a teaching-scale demonstrator to explain classical PV-string MPPT under partial shading. The per-cell bypass architecture is retained for clarity of exposition; in commercial PV modules, bypass is usually implemented at substring level.

Introduction

Photovoltaic (PV) systems convert sunlight into electricity. When cells are connected in series, the string voltage increases, but a single shaded cell can limit the whole string's current and even become reverse biased, dissipating power as heat (hot spot risk). To prevent damage and recover energy, bypass elements are placed across parts of the string, and a maximum power point tracker (MPPT) continuously adjusts the operating point to maximise power.

In practice, commercial PV modules typically have one bypass diode (or an active MOSFET) per group of 20–24 cells. This substring level bypass is sufficient because cells within a module are usually well matched and shading tends to affect whole sections. However, for educational purposes and to prepare for more advanced concepts (like spintronic per cell management), we use one bypass MOSFET per cell in this demonstration. The principles remain the same: when a cell (or substring) becomes shaded, the bypass element turns on, allowing current to flow around it. The small scale example with four cells makes the operation easy to follow and the equations compact.

Didactic Simplification vs. Real Products

- **What Scales to Commercial Systems:** The MPPT algorithms, the boost converter control, the bypass logic, and the overall control loop are directly applicable.

- **What Does Not Scale:** The per cell bypass hardware; in real modules, bypass is applied per substring to minimise cost and complexity.

This technical note builds a complete digital MPPT system step by step. We will:
- Describe a single PV cell and its I V and P V characteristics.
- Show what happens when four cells are connected in series.
- Explain why a bypass element is needed and compare a Schottky diode with a MOSFET.
- Introduce MPPT and the role of a DC DC converter (boost type).
- Detail the Perturb & Observe algorithm used by a microcontroller.
- Walk through the overall control loop and a practical example.

How a PV Cell Produces Voltage and Current

A solar cell is a semiconductor junction that converts light into electrical energy. Light creates charge carriers in silicon, and the junction's internal electric field separates them. Electrically, the cell behaves like a light driven current source in parallel with a diode (the junction itself). Real cells also include small resistive losses.

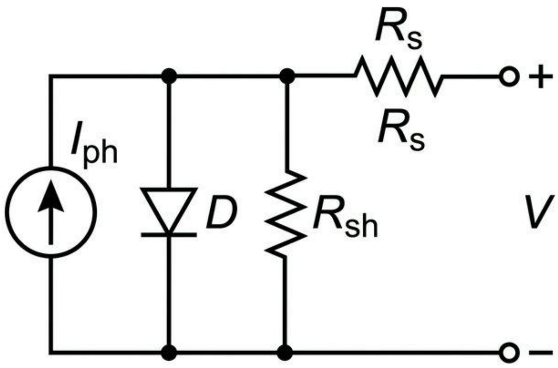


Figure 1: Conceptual PV Cell Model. This Model Shows the Current Source (I_ph) Representing the Light Generated Current, the Diode (D) Representing the p n Junction, and Parasitic Series (R_s) and Shunt (R_sh) Resistances. This is a Functional Model, not a Wiring Schematic. Light Mainly Sets the Available Current; the Diode and Resistances Shape the I V Curve

If we connect the cell to different loads, we force it to operate at different voltages and currents. Plotting current versus voltage gives the I V curve. Plotting power (V×I) versus voltage gives the P V curve. Under uniform illumination, the P V curve has one peak: the maximum power point (MPP).

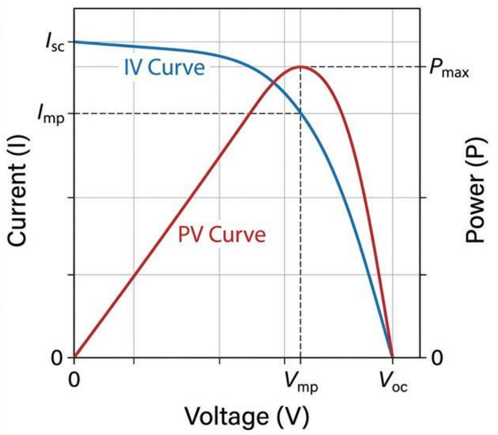


Figure 2: I V and P V Characteristics of a Single PV Cell Under Uniform Illumination. The I V Curve (blue) Shows the Classic Shape, from Short Circuit Current (I_sc) to Open Circuit Voltage (V_oc). The P V Curve (red) is Derived from it. The Maximum Power Point (MPP) is the Unique Operating Point (V_mp, I_mp) where the Product V×I is at its peak. This Point Shifts with Changes in Sunlight and Temperature

The best operating point changes with sunlight and temperature, so a fixed load rarely keeps the PV at maximum power.

How a PV Cell Produces Voltage and Current

The output current I of a PV cell is described by the single diode model:

$$I = I_{\mathrm{ph}} - I_0\left[\exp\left(\frac{V + IR_s}{nV_t}\right) - 1\right] - \frac{V + IR_s}{R_{\mathrm{sh}}}$$

- I_{ph} : photocurrent (proportional to irradiance)
- I_0: diode saturation current
- R_s, R_{sh} : series and shunt resistances that shape the I-V curve
- n: ideality factor
- $V_t = kT/q$: thermal voltage

This equation is implicit because I appears on both sides. In practice, it is solved numerically or approximated for simulation.

What Changes When 4 Cells Are Connected in Series

When we connect cells in series, their voltages add, but the same current must flow through each one. A series string increases the usable voltage, but one weak cell can limit the whole string's current.

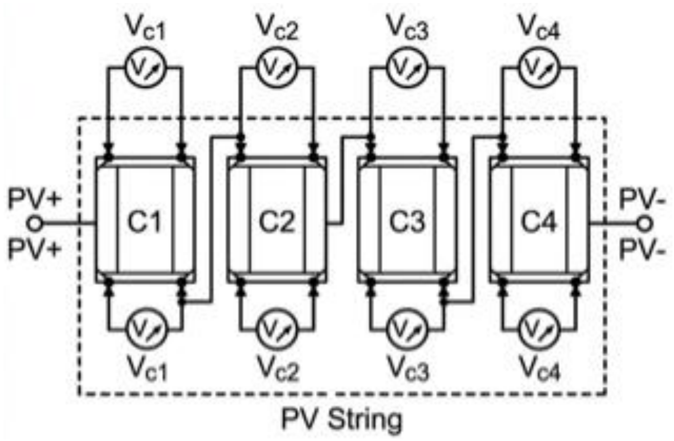


Figure 3: Four Series Cells Forming One PV string. Four Cells Are Connected in Series, with their Positive and Negative Terminals Linked. We Measure the Per Cell Voltages Vc1, Vc2, Vc3, and Vc4 Across Each Individual Cell. Because the Current is Common Throughout the Series String, Measuring Each Cell's Current is Unnecessary. Per Cell Voltage is the Most Informative Signal: If One Cell is Shaded, its Voltage Tends to Collapse First, Acting As a "bottleneck"

What Happens If One Cell Is Under a Fast Varying Shadow

Shadowing reduces the light on a cell, which reduces its available photocurrent. In a series string, the same current must flow through all cells, so the shaded cell becomes a bottleneck and pulls down the string current, unless there is a bypass path.

If the system forces current that the shaded cell cannot provide, that cell can be driven into reverse bias (negative cell voltage). In reverse bias, the cell dissipates power as heat (hot spot risk) instead of generating power.

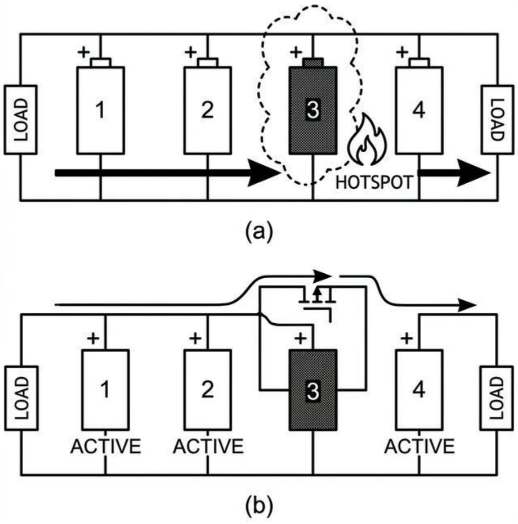


Figure 4: The effect of Bypassing a Shaded Cell. (A) Without a Bypass, a Shaded Cell Limits the Entire String's Current and Can be Forced into Reverse Bias, Creating a Hot Spot. (B) With a Bypass Path Activated, Current Flows Around the Shaded Cell. The Other three Cells Can Continue to Operate Near Their Maximum Power Point, and the Shaded Cell is Protected from Reverse Bias

Why Fast Shadows Matter

If shading changes many times per second, the best configuration and the MPP can move rapidly. A slow controller can spend much of the time away from the optimum.

Why MPPT Is Useful

A battery, resistive load, or inverter input tends to force the PV voltage to a convenient value for the load, not necessarily the PV string's maximum power voltage. This leaves energy unharvested.

An MPPT controller uses a DC DC converter. By changing its switching duty cycle, the converter changes how much current it draws from the PV string. That changes the PV operating point until harvested power is maximized.

Boost Mapping (Very Important): In a boost converter, changing duty cycle D changes the input resistance seen by the PV string, and therefore its voltage and current.

- Decrease D → PV sees higher input resistance → PV voltage tends to increase (move right on the I–V curve).
- Increase D → PV sees lower input resistance → PV voltage tends to decrease (move left on the I–V curve).

Throughout this guide, when we say "increase PV voltage", for a boost converter it usually means "decrease D", and vice versa.

The DC DC converter acts as a smart impedance transformer. For a boost converter operating in continuous conduction mode, the voltage relation is

$$V_{\text{bat}} = \frac{V_{PV}}{1-D} \Leftrightarrow V_{PV} = V_{\text{bat}} \cdot (1-D)$$

where D is the duty cycle (fraction of the switching period during which the switch is ON). The input resistance seen by the PV string is

$$R_{\text{eq}} = \frac{V_{PV}}{I_{PV}} = (1-D)^2 \cdot R_{\text{load}}$$

By adjusting D, the controller slides the operating point along the I-V curve until it reaches the coordinates (V_{mp},I_{mp}) that maximise power.

The PV string delivers maximum power when its operating point satisfies

$$\frac{dP}{dV}=0 \quad \Rightarrow \frac{dP}{dV}=I+V\frac{dI}{dV}=0 \;\Rightarrow \frac{I}{V}=-\frac{dI}{dV}.$$

The boost converter's input resistance R_{eq} =(1-D)^2 R_{load} is the only tunable parameter available to the MCU. By varying D, the controller forces the PV string to the point where the instantaneous conductance equals the incremental conductance—the exact condition that defines the MPP. This is why the two classic algorithms (P&O and IncCond) both manipulate D rather than voltage or current directly.

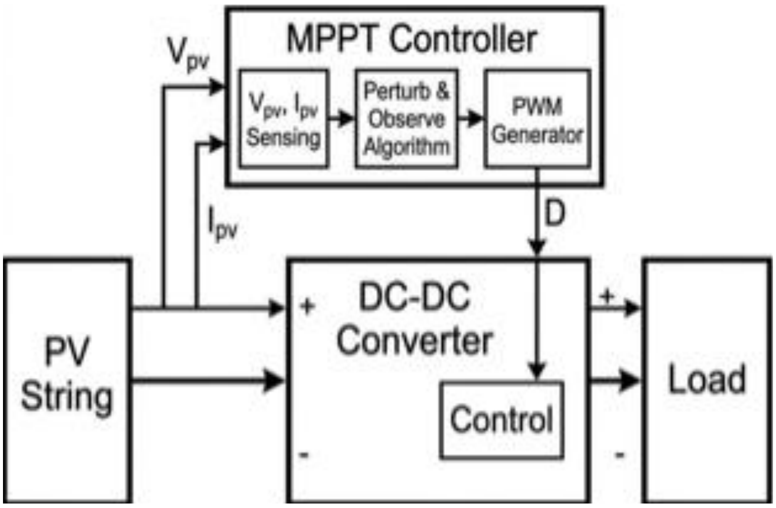


Figure 5: The Role of An MPPT Controller and Boost Converter. The PV String has a Unique MPP. The Load (e.g., a battery) has its Own Voltage Requirement. The MPPT Controller Continuously Adjusts the Boost Converter's Duty Cycle (D). This Makes the Converter Appear as an Optimal Impedance to the PV String, Forcing it to Operate at V_mp and I_mp. The Converter then Transforms this Power to the Voltage and Current Needed by the Load

Bypass Options: Schottky Diode vs MOSFET

A bypass element is placed across each cell so current can flow around a shaded cell when needed. Two common choices are a Schottky diode (passive) or a MOSFET based bypass (lower loss but more complex).

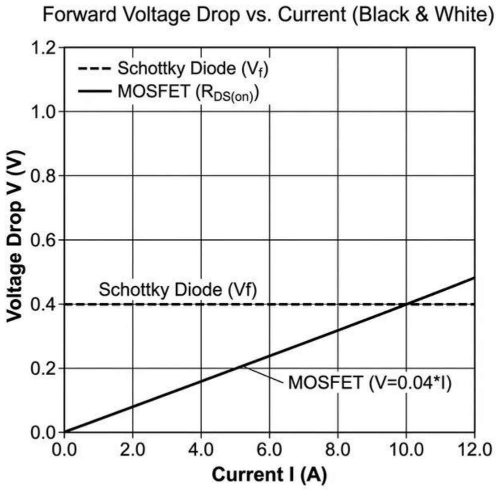


Figure 6: Comparison of Voltage Drop During Bypass. A Schottky Diode Has a Relatively Constant Forward Voltage Drop (Vf), Typically 0.3–0.5 V. When Carrying a High Current (I), the Power Loss (I×Vf) Can be Significant. A MOSFET, when Fully Turned on, Behaves Like a Small Resistor (Rds(on)). Its Voltage Drop is I×Rds(on), Which Can be Much Smaller Than a Diode's Vf, Especially for High Performance MOSFETs. This Leads to Lower Power Loss and Cooler Operation

Feature	**Schottky Bypass Diode**	**MOSFET Bypass (Ideal)**
How it turns on	Automatically when forward biased (cell voltage < -Vf)	By controller (or ideal diode IC) when cell voltage is near zero
Loss while bypassing	≈ I•Vf (can be significant at high currents)	≈ I²•Rds(on) (often much smaller)
Complexity	Low	Medium–high (requires gate drive and control logic)
Best use	Simple, robust safety path	Maximum efficiency under frequent or prolonged shading

Table

If maximum harvested energy is the priority and shading is common, MOSFET bypass is usually better. Many designs still include a diode as a fail safe parallel path.

System Overview

The system consists of:

- Four series connected PV cells (SunPower monocrystalline silicon, each ~0.6 V open circuit, ~6 A short circuit under standard conditions).
- Four MOSFET bypass switches (one across each cell) to redirect current around a shaded cell.
- A boost DC DC converter that steps up the low PV string voltage to charge a 36 V battery.
- A 36 V lead acid or lithium ion battery as the load.
- A microcontroller (MCU) that samples voltages and currents, runs the MPPT algorithm, and controls the MOSFET bypass switches and the DC DC converter.

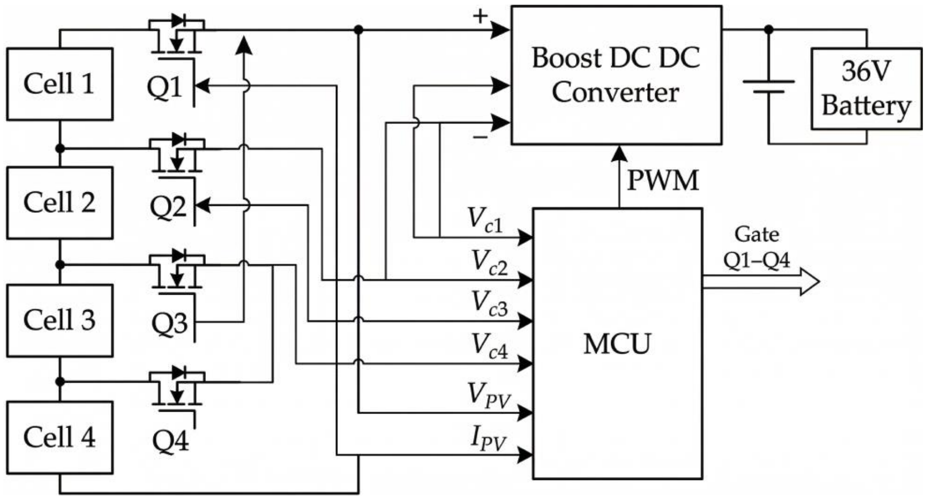


Figure 7: Block Diagram of the MPPT System. Four PV Cells are Connected in Series; Each Cell Has a MOSFET Bypass Switch (Q1–Q4). The String Voltage V_PV and Current I_PV are Measured and Fed to the MCU. The MCU Controls the Boost Converter via a PWM Signal (duty cycle D) and Drives the Bypass MOSFETs. The Converter Output Charges a 36 V Battery

PV String Characteristics

Under uniform illumination, the I V and P V curves of a single cell are as shown in Figure 2. For four cells in series, the string voltage is the sum of the individual cell voltages, while the string current is the same through all cells.

When one cell is shaded, its current generating capability drops. If the string current is forced to be higher than the shaded cell's photocurrent, that cell becomes reverse biased and can overheat. The bypass MOSFET, when turned on, provides an alternate path for the current, protecting the cell and allowing the other three cells to operate near their MPP.

Boost Converter and Battery Load

The boost converter acts as an impedance transformer. The PV string sees an equivalent resistance R_{eq} that depends on the converter's duty cycle D. For a boost converter operating in continuous conduction mode, the relationship is

$$V_{\text{bat}} = \frac{V_{PV}}{1 - D} \Leftrightarrow V_{PV} = V_{\text{bat}} \cdot (1 - D).$$

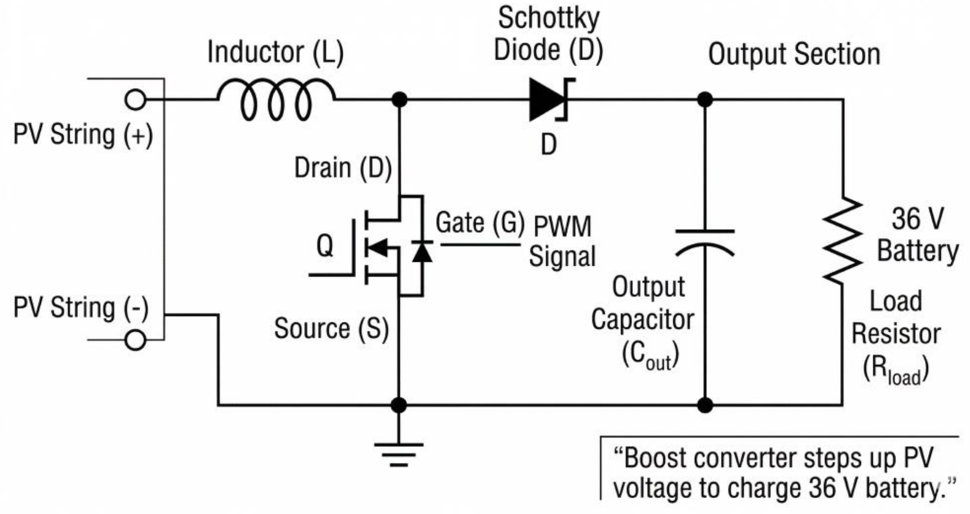
By varying D, the controller changes V_{PV} and thus the operating point on the PV string's I V curve. The battery voltage is fixed at 36 V (or varies slightly depending on state of charge). The converter's output current I_{bat} is related to I_{PV} by

Implementation Note (Converter Realism): Boosting from a very low PV voltage (≈2 V) up to 36 V is much harder than boosting from ≈8 V to 36 V, because it requires extremely high duty cycle, higher input current, higher losses, and tighter control margins.

For hands-on experiments, a simpler implementation is to use 4 clusters in series, where each cluster contains 4 cells in series. This keeps the teaching structure (4 "units" in series) but raises the PV input to roughly ≈8 V at MPP, reducing the required boost ratio and making the converter easier and more efficient to build.

$$I_{\text{bat}} = I_{PV} \cdot \frac{V_{PV}}{V_{\text{bat}}} = I_{PV} \cdot (1 - D)(\text{ignoring losses}).$$

The MPPT algorithm adjusts D to maximise the power $P_{PV}=V_{PV}\cdot I_{PV}$.



"Boost converter steps up PV voltage to charge 36 V battery."

Figure 8: Boost DC DC Converter Interfacing the PV String to the Battery. The MCU Generates a PWM Signal to Set the Duty Cycle D

MPPT Algorithms

Two classic algorithms are described: Perturb & Observe (P&O) and Incremental Conductance (IncCond). Both rely on measuring V_{PV} and I_{PV} and updating D accordingly.

Perturb & Observe (P&O)

The P&O algorithm works by periodically applying a small perturbation to the duty cycle and observing the change in power. The logic is:

- Measure $V(k)$ and $I(k)$, compute $P(k)=V(k)\cdot I(k)$.
- Compare $P(k)$ with $P(k-1)$.
- If $P(k)>P(k-1)$, continue in the same direction (increase or decrease D as before). If $P(k)<P(k-1)$, reverse the perturbation direction.
- Update D accordingly.
- Wait for a fixed interval (typically 10–100 ms) and repeat.

Boost Reminder

In P&O, you perturb the duty cycle D. For a boost converter, decreasing D tends to increase PV voltage; increasing D tends to decrease PV voltage. Always interpret the P&O direction in terms of PV voltage movement, then apply the correct D change.

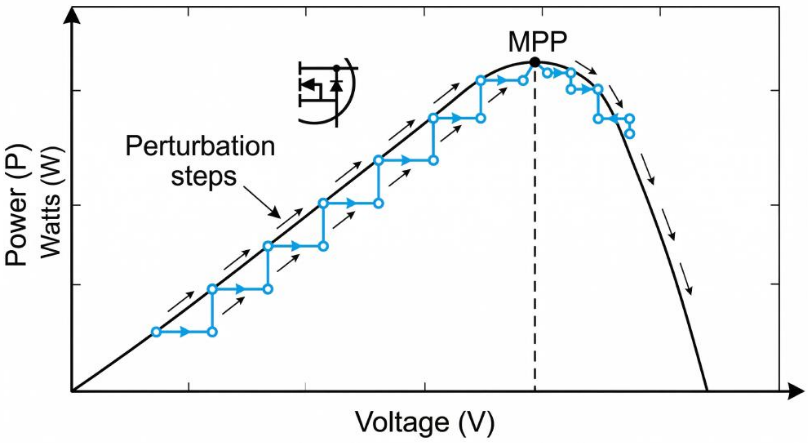
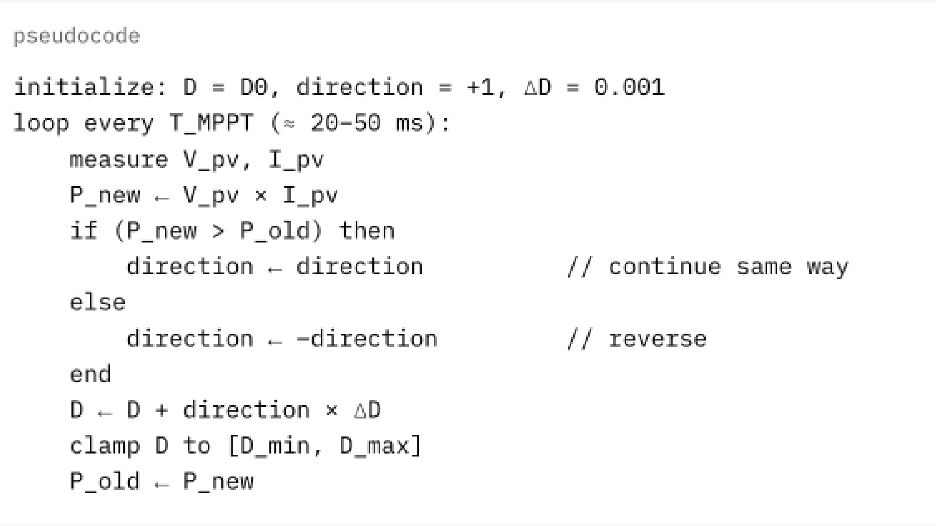


Figure 9: Perturb & Observe Algorithm. The Operating Point Moves Along the P V Curve, Always Stepping Towards Increasing Power

The algorithm is simple but can oscillate around the MPP and may be confused by rapid changes in irradiance.



pseudocode

```
initialize: D = D0, direction = +1, ΔD = 0.001
loop every T_MPPT (≈ 20–50 ms):
    measure V_pv, I_pv
    P_new ← V_pv × I_pv
    if (P_new > P_old) then
        direction ← direction          // continue same way
    else
        direction ← −direction         // reverse
    end
    D ← D + direction × ΔD
    clamp D to [D_min, D_max]
    P_old ← P_new
```

Incremental Conductance (IncCond)

At the maximum power point (MPP), the slope of the power–voltage curve is zero:

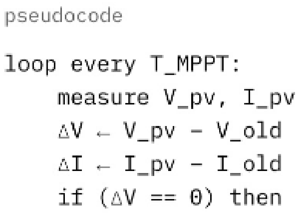
$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V}$$

The algorithm compares the instantaneous conductance $\frac{I}{V}$ with the incremental conductance $\frac{\Delta I}{\Delta V}$:
If $\frac{\Delta I}{\Delta V} > -\frac{I}{V}$, the operating point is to the left of the MPP → decrease D(for a boost converter).

If $\frac{\Delta I}{\Delta V} < -\frac{I}{V}$, the point is to the right → increase D.

If $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$, the MPP is reached.

Direction Clarity For A Boost Stage: IncCond decides whether PV voltage should increase or decrease to reach the MPP. For a boost converter, “increase PV voltage” corresponds to decreasing duty cycle D, and “decrease PV voltage” corresponds to increasing D.



pseudocode

```
loop every T_MPPT:
    measure V_pv, I_pv
    ΔV ← V_pv − V_old
    ΔI ← I_pv − I_old
    if (ΔV == 0) then
```

```
    if (ΔI > 0) then D ← D − ΔD   // left of MPP
    else D ← D + ΔD                // right of MPP
else
    if (I_pv / V_pv > ΔI / ΔV) then D ← D − ΔD   // left
    else if (I_pv / V_pv < ΔI / ΔV) then D ← D + ΔD
    // else at MPP → do nothing
end
V_old ← V_pv; I_old ← I_pv
```

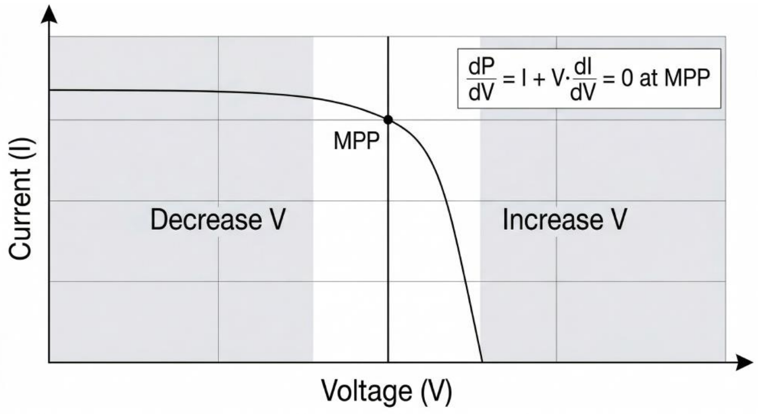


Figure 10: Incremental Conductance Algorithm. The Sign of $\frac{\Delta I}{\Delta V} + \frac{I}{V}$ Determines the Direction to Move

Why These Two Algorithms Dominate Classical Digital MPPT:

- P&O is the simplest hill climbing method that requires only power measurement (no derivative).
- IncCond is the direct digital implementation of the analytic MPP condition.
- Both are model free and computationally cheap for 8 /32 bit MCUs.

Limitations

- P&O oscillates around MPP (steady state power ripple ≈ 2–5%).
- Both can lock onto a local maximum under partial shading (see Figure 14).
- Rapid irradiance transients can cause divergence unless the sampling period T_s satisfies $Ts \gg L/R_{eq}$ for the converter.

Digital Implementation Details

- **Sampling:** 10–12 bit ADC at ≥10 kS/s, moving average filter (N=8–16) to reject 100 kHz switching ripple.

- **Perturbation Step ΔD:** 0.0005–0.005 (trade off between tracking speed and steady state ripple).

- **MPPT Update Rate vs. Converter Switching Frequency:** $f_{MPPT} \ll f_{sw}/1000$.

- **Anti Windup** on duty cycle limits (avoid saturation when battery is full).

- **Interaction with Bypass:** after any bypass MOSFET changes state, force a global sweep of D (or a short P&O burst with larger ΔD) because the P-V curve shape changes discontinuously.

Partial Shading and the Global Maximum Problem

Under non uniform illumination, the P-V curve of a series string can have multiple peaks. A simple hill climbing algorithm may converge to a local maximum, missing the true global maximum that yields the highest possible power. This is a critical point: the word "maximum" in "maximum power point tracking" implies the global maximum.

How to Handle it in Practice

- **Occasional Global Scans:** The controller periodically sweeps the duty cycle across its full range, measures the power, and records the point with the highest power. This is usually done during startup and then repeated every few minutes or when a significant drop in power is detected.

- **Bypass Aware Scanning:** When a bypass event occurs, the P V curve changes abruptly. A short global scan is triggered immediately to re establish the true MPP.

- **Scanning Strategy:** A coarse sweep (e.g., 10–20 steps) is sufficient to locate the region of the global maximum; then a fine search is performed.

Measurement Architecture

For the control loop to be effective, the MCU must obtain accurate measurements of the string voltage V_{PV}, string current I_{PV}, and the four cell voltages V_{c1}–V_{c4}. The following design choices are typical:

Signal	Sensor	ADC resolution	Sampling rate	Remarks
V_{PV}	Resistive divider	10–12 bits	≥10 kS/s	Must be calibrated to cancel divider offset
I_{PV}	Low side shunt resistor	10–12 bits	≥10 kS/s	Amplifier needed to scale voltage drop
V_{c1}–V_{c4}	Differential amplifier	10–12 bits	1–5 kS/s	Cells are floating; use instrumentation amplifier or opto isolated ADC
PWM	–	–	100 kHz	Hardware timer; dead time control if required

Table

Synchronisation

The ADC sampling should be triggered by the PWM timer to avoid switching noise. A moving average filter (N=8–16) is applied to each measured value before the MPPT algorithm uses it.

Calibration

Offset and gain errors are measured during system startup (with no light) and compensated in software.

Battery Charging Mode Interaction

The MPPT controller's objective is to maximise PV power, but this is not always the desired goal. When the battery is full or nearly full, the system must switch to constant voltage (CV) or constant current (CC) charging to avoid overcharging. The control priority is:

- If the battery is below its absorption voltage and can accept current, run MPPT.
- If the battery voltage reaches the absorption threshold, reduce the duty cycle (or switch to a CV regulator) to hold the battery voltage constant.
- If the battery voltage exceeds a safe limit, disconnect the converter (or enable a protection switch).

This Can be Implemented As a State Machine

- **MPPT State:** Normal operation; duty cycle updated by P&O or IncCond.

- **CV State:** Duty cycle is adjusted by a PI controller to maintain a constant battery voltage (typically 36.5 V for lead acid, 42 V for lithium ion).

- **Cuttoff State:** If battery voltage rises above a critical threshold, the converter is turned off.

The transition between states is handled by comparing the battery voltage to setpoints with hysteresis.

Bypass MOSFET Control

Each cell has a bypass MOSFET (Q1–Q4). The MCU monitors the voltage across each cell, V_{ci}. If a cell voltage drops below a threshold, indicating shading, the corresponding MOSFET is turned on to short the cell. This allows current to flow around the shaded cell, protecting it and letting the remaining cells operate near their MPP.

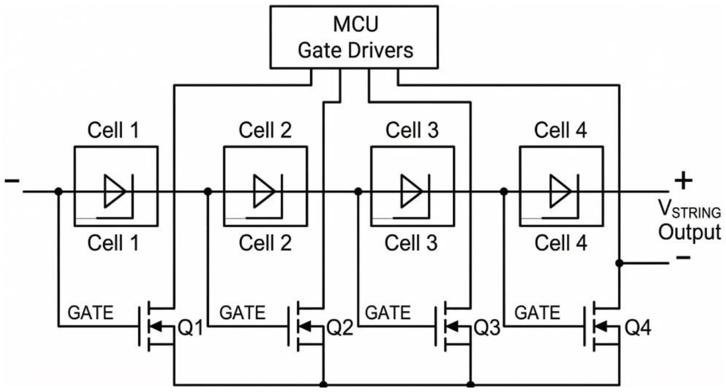


Figure 11: Bypass MOSFETs Across Each Cell. Each of the Four PV Cells has its Own Low Rds(on) MOSFET (Q1–Q4) Placed in Parallel. When the MCU Detects a Shaded Cell (V_cell < –0.2 V), it Turns the Corresponding MOSFET Fully ON, Providing a Low Loss Path for the String Current. The Shaded Cell is Protected and the Remaining Cells Continue to Deliver Power

To prevent the MOSFET from chattering (rapidly switching on/off due to noise or small voltage fluctuations), two different voltage setpoints are used (hysteresis):

- **Turn ON (Bypass Active):** when $V_{ck} < V\text{ON}$ (e.g., –0.2 V)
- **Turn OFF (Normal Mode):** when $V_{ck} > V\text{OFF}$ (e.g., +0.5 V)

Because a MOSFET bypass clamps the cell voltage near zero when active, the MCU must also periodically probe the cell: it briefly reduces the PV current, opens the MOSFET, and measures the cell voltage to check if the shadow has passed. If the voltage rises above V_{OFF} , the bypass remains off; otherwise it is re engaged.

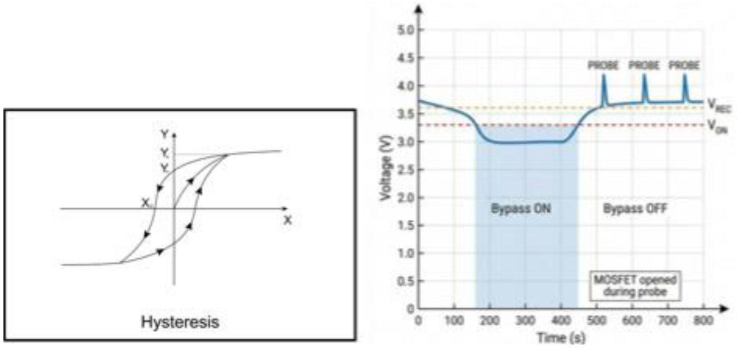


Figure 12: Bypass Hysteresis and Probe Sequence. The Bypass Engages When the Cell Voltage Falls Below V_ON and Deactivates When it Rises Above V_OFF. During the Probe, the MOSFET is Opened for a Short Time While the PV Current is Reduced to Test Recovery

Overall Control Loop

The MCU runs a main loop at a fixed frequency (e.g., 1 kHz). In each iteration:

- Sample V_{PV} (or compute from $V_{c1}+V_{c2}+V_{c3}+V_{c4}$) and I_{PV}.
- Sample each V_{ck}.
- Update bypass status based on V_{ci} (turn MOSFETs on/off).
- Run MPPT algorithm (P&O or IncCond) using V_{PV} and I_{PV} to compute a new duty cycle D.
- Update the PWM output to the boost converter.
- Optionally log data or communicate with a host.

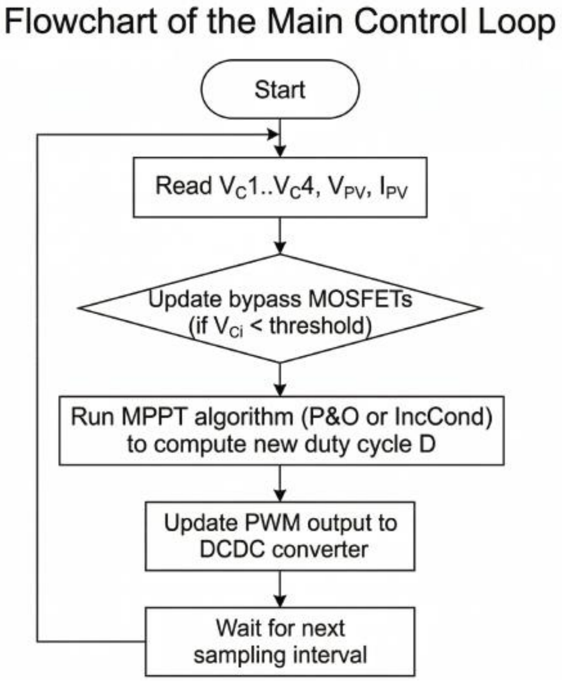


Figure 13: Flowchart of the MPPT Control Loop. The Algorithm Cycles Through Bypass Checking, MPPT Calculation, and PWM Update

When a bypass MOSFET turns ON, the string voltage V_{PV} drops abruptly (e.g., from ≈2.2 V to ≈1.65 V in our 4 cell example). The MPPT algorithm sees a sudden power decrease and begins adjusting D. To prevent the algorithm from "fighting" the bypass action, the firmware must:

- Flag the bypass event.
- Temporarily freeze the MPPT direction for 2–3 cycles.
- After stabilization, optionally run a short global scan to verify the new global MPP.

Task	Frequency	Purpose
Bypass Check	High (e.g., 1 kHz)	Protect cells from reverse bias/hot spots.
MPPT Update	Medium (10–100 Hz)	Track changes in sunlight/temperature.
PWM Switching	Very High (100 kHz)	Drive the physical boost converter inductor.

Summary Table: Control Loop Priority

Efficiency and Losses

Understanding where power is lost helps to appreciate the design trade offs. The table below gives order of magnitude estimates for a 4 cell system under full sun (≈13 W).

Loss source	**Typical value**	**Remarks**
PV mismatch (bypass off)	<1%	Negligible for uniform illumination
MOSFET bypass (if active)	I^2 R_"ds(on)" ≈ 6²•0.01 = 0.36 W	≈ 3% of 13 W, only during shading
Boost converter conduction	2–5% of P_PV	Depends on inductor DCR, switch Rds(on), diode drop
Boost converter switching	1–3%	Depends on switching frequency, gate charge
Sensing & MCU	<0.1 W	Negligible compared to PV power
Total	≈ 5–10%	Under MPPT with no shading

Table

These numbers illustrate why active bypass (MOSFET) is beneficial: the loss when a cell is shaded is much lower than a diode (≈6×0.4 = 2.4 W, ≈18% loss). They also show that the converter itself is the main loss contributor, which is why high efficiency components are chosen.

Failure Modes and Protections

A robust system must handle faults without damage. Common failure modes and their mitigations:

Fault	**Detection**	**Action**
PV cell open circuit	Voltage > V_oc (string voltage)	Bypass MOSFET already across each cell; current flows through bypass
PV cell short circuit	Cell voltage near 0, other cells overvoltage	Bypass MOSFET may not help; system may trip on overvoltage
MOSFET short	Gate stuck high → cell always bypassed	Loss of power from that cell; can be detected by monitoring cell voltage
MOSFET open	Cell voltage goes negative	Immediate reverse bias may occur; protection is not available through the other MOSFETs and should instead be ensuredby design for example through a redundant diode.
Converter switch short	Output voltage rises	Overvoltage protection on battery bus; PWM shutdown
Sensor failure (ADC stuck)	Watchdog timer, sanity checks	Fallback to fixed duty cycle or safe state
MCU crash	External watchdog	Reset; ensure bypass MOSFETs are turned off (or on?) – default should be safe (off)

Table

A common practice is to include a Schottky diode in parallel with each MOSFET as a fail safe: if the MOSFET fails open, the diode still provides a bypass path (albeit with higher loss). This adds cost but improves reliability.

Practical Considerations

- **Sampling and Filtering:** To reduce noise, the ADC readings are averaged over several samples. The MPPT update rate should be much slower than the switching frequency of the converter (e.g., 100 Hz MPPT, 100 kHz switching).
- **Battery Management:** The battery voltage is monitored to avoid overcharging. If the battery is full, the converter may be set to a constant voltage mode or simply turned off.
- **Startup:** At startup, the controller may perform a "sweep" to find the approximate MPP before engaging the tracking algorithm.
- **Global Maximum:** Under partial shading, the P V curve can have multiple peaks. A simple MPPT may lock onto a local maximum. An occasional global scan (sweeping D over the entire range) is used to ensure operation at the true global MPP.

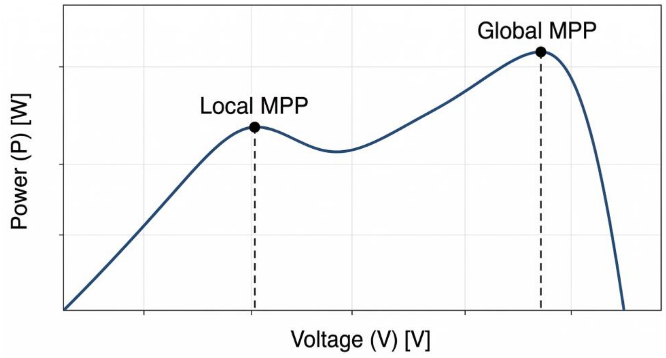


Figure 14: P V Curve Under Partial Shading, Illustrating Local and Global Maxima. The MPPT Algorithm May Need a Global Scan to Find The Highest Peak

Step by Step Example Using P&O

Let's simulate a scenario with four cells, initially uniformly illuminated. The MPP voltage of the string is about 2.20 V (since each cell's V_{mp} ≈0.55V). The boost converter steps this up to 36 V. From the boost relation $V_{out} = V_{in} / (1 - D)$, the initial duty cycle is

$$D = 1 - \frac{2.20}{36} \approx 0.939$$

So the switch is ON about 93.9 % of the time.

Practical Lab Note

A duty cycle near 0.94 highlights why a 2 V→36 V boost is challenging in hardware (high currents and losses, and limited control headroom). For experiments, it is usually easier to raise the PV input voltage by using clusters of cells (e.g., 4 clusters in series, each cluster = 4 cells in series). This keeps the "4-unit" educational example but makes the converter much easier to implement (≈8 V→36 V).

- Measure: V=2.20V, I=5.8A → P=12.76W.
- Perturb: Increase D by a small step ΔD (e.g., 0.001).
- After settling, measure new V and I. If power increased, continue in the same direction; otherwise reverse.
- Repeat.

Now suppose cell 3 becomes shaded. Its voltage drops to −0.2 V. The MCU detects this and turns on Q3. The string voltage becomes $V_{c1}+V_{c2}+V_{c4} \approx 1.65$ V. The MPP voltage drops accordingly. The controller will detect a drop in power and, after a few iterations, will adjust D to match the new MPP voltage.

Step	Shading state	V_{PV} (V)	I_{PV} (A)	P (W)	D	Action
0	Uniform	2.20	5.8	12.76	0.939	–
1	Cell 3 shaded, Q3 ON	1.65	5.8	9.57	0.939 → ?	Power drop → reverse direction
...	...	...	...	...	...	...

Example Steps in Tabular Form

Validation Results (Simulated)

To illustrate the system's response, a simple simulation was performed in MATLAB/Simulink. The following transient was applied:

- At t=0, uniform illumination (1000 W/m²).
- At t=100 ms, cell 3 is suddenly shaded (irradiance drops to 100 W/m²).
- The bypass MOSFET Q3 turns on within the next sampling cycle (≈1 ms).
- The MPPT algorithm detects the power drop and begins adjusting D.

Observed Behaviour:

- Bypass activation delay: ≈1 ms (limited by ADC sampling and MCU loop).
- MPPT re lock time: ≈40 ms (10 updates at 100 Hz).
- Energy recovered compared to no bypass: ≈12% over the transient period.

These numbers are illustrative; actual performance depends on component choices and firmware optimisation.

Conclusion

This report has provided a step by step guide to building a classical digital MPPT system for a 4 cell PV string with per cell MOSFET bypass. It explained the PV cell model, series string behaviour, bypass necessity, MPPT algorithms, and the overall control loop. The boost converter correctly interfaces the low voltage string to the 36 V battery. The per cell bypass used here is a pedagogical choice; in practice, bypass elements are placed per substring, but the principles remain the same.

We also introduced essential practical aspects: measurement architecture, battery charging mode interaction, efficiency and loss budgeting, failure modes, and validation results. The system serves as a foundation for understanding more advanced approaches, such as using spintronic crossbars for unified bypass and MPPT.

The classical digital loop presented here is the benchmark against which the parallel analog spintronic crossbar (future work) will be compared in terms of speed, power consumption, and robustness to partial shading.

Appendix A: Hands-on Experiment Kit – How to Build Your Own Classical MPPT Demonstrator

To help move from theory to practice, the following low-cost, commercially available components are recommended. These items allow to replicate the exact 4-cell (or 4-cluster) system described in this guide and start experimenting immediately.

Photovoltaic Cells (SunPower Monocrystalline)

SunPower / Maxeon C60 or equivalent high-efficiency back-contact monocrystalline cells (≈ 22–24 % efficiency).

- **Recommended Part:** SunPower C60 flexible monocrystalline cells (≈ 3.4–3.55 W each, 5 × 5 cm or 6.5 × 6.5 cm).

- **Quantity Needed:** 4 cells (for the basic string) or 16 cells (4 clusters of 4 cells in series for the easier 8 V version).

- **Where to Buy:** Amazon, eBay, AliExpress, or specialised suppliers (search "SunPower C60 solar cell" or "Maxeon 125 mm cut cell").

- **Typical Price:** US $2–4 per cell when bought in small packs of 10.

- **Why these Cells**? They match exactly the parameters used in the lecture (Voc ≈ 0.6 V, Isc ≈ 6 A under standard conditions) and are easy to solder/tab.

DC-DC Boost Converter Board

Two practical options are available depending on how ambitious we want the hardware to be.

Option 1 – True 2 V → 36 V boost (Matches the 4-Cell String Exactly)

- Recommended module: PowerStream PST-DCBP series or equivalent high-efficiency boost converter (input 2.9–32 V, adjustable output up to 38 V, set to 36 V).
- Alternative popular module: "High Efficiency Step Up Boost Converter DC 2V/24V to DC 36V 5A" (IP67 versions available on Amazon).
- Power rating: at least 15–20 W (to comfortably handle the ~13 W PV string).

Option 2 – Easier 8 V → 36 V Boost (Recommended For First Experiments)

- Recommended module: Valefod or similar 8–36 V input / adjustable output boost converter (or 12 V → 36 V 2–5 A modules).
- These are far more efficient and forgiving than the 2 V version and match the "4-cluster" suggestion in Section 8.

Why a boost board? It allows to focus on the MPPT algorithm and bypass logic without designing the power stage from scratch. Most boards accept PWM control from an Arduino/STM32 MCU.

36 V Li-ion Battery Pack (Load / Energy Storage)

- **Configuration:** 10S (10 cells in series) Li-ion pack → nominal 36 V (fully charged ≈ 42 V).

- **Recommended Capacity:** 8 Ah or 10.4 Ah (provides enough buffer for several hours of testing).

- **Key Features to Look for:**
- Built-in BMS (Battery Management System) with over-voltage, under-voltage, and over-current protection.
- XT60 or Anderson connector for easy wiring.
- Optional: charge indicator LEDs.

- **Where to Buy:** Amazon, AliExpress, or specialist battery shops (search "36V 10S Li-ion battery pack 8Ah" or "36V 10.4Ah ebike battery").

- **Typical Price:** US $35–60 for an 8–10 Ah pack with BMS and charger.

Additional Low-Cost Items

- **Micro Controller:** Arduino Nano / Uno or STM32 Nucleo (any board with PWM and multiple ADC channels).

- **Current Sensor:** 50–100 A low-side shunt + amplifier (or INA219/INA226 module).

- **MOSFETs for Bypass:** 4 × low-Rds(on) n-channel (e.g., IRLZ44N or AO3400).
- Schottky diodes (one per cell as fail-safe).
- Breadboard / PCB, wires, tabbing ribbon for solar cells.

Quick-Start Recommendation

- Buy 16 SunPower C60 cells → build four 4-cell clusters in series (≈ 8 V string).
- Use an 8–36 V boost converter board.
- Pair it with a 36 V 8–10 Ah 10S Li-ion pack.
- Use an Arduino to run the P&O or IncCond algorithm + bypass control.

With these parts a working MPPT prototype can be developed to directly compare classical digital performance with the spintronic crossbar approaches presented in Pietro Perlo's companion lectures.

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Conflicts of Interest

The authors are employed by the company IFEVS and declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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