Power Electronics and Control in Grid-Connected PV Systems

ECEN 2060

Spring 2008

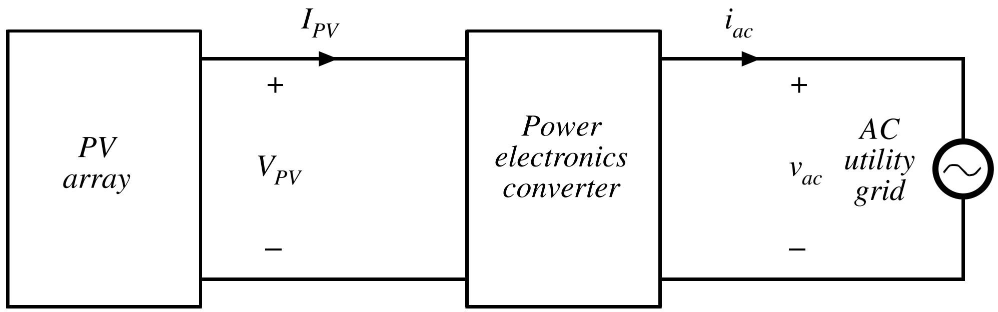
Grid-Connected PV System

One possible grid-connected PV system architecture

DC input

$$V_{PV},\ I_{PV}$$

$$P_{PV} = V_{PV} I_{PV}$$



AC output

$$v_{ac}(t) = \sqrt{2} V_{RMS} \sin(\omega t)$$

$$i_{ac}(t) = \sqrt{2} I_{RMS} \sin(\omega t)$$

$$P_{ac} = V_{RMS} I_{RMS}$$

$$p_{ac}(t) = v_{ac} i_{ac} = V_{RMS} I_{RMS} \left(1 - \cos(2\omega t)\right)$$

Functions of the power electronics converter

- Operate PV array at the maximum power point (MPP) under all conditions
- Generate AC output current in phase with the AC utility grid voltage
- Achieve power conversion efficiency close to 100%

$$\eta_{converter} = \frac{P_{ac}}{P_{PV}} = \frac{V_{RMS} I_{RMS}}{V_{PV} I_{PV}}$$

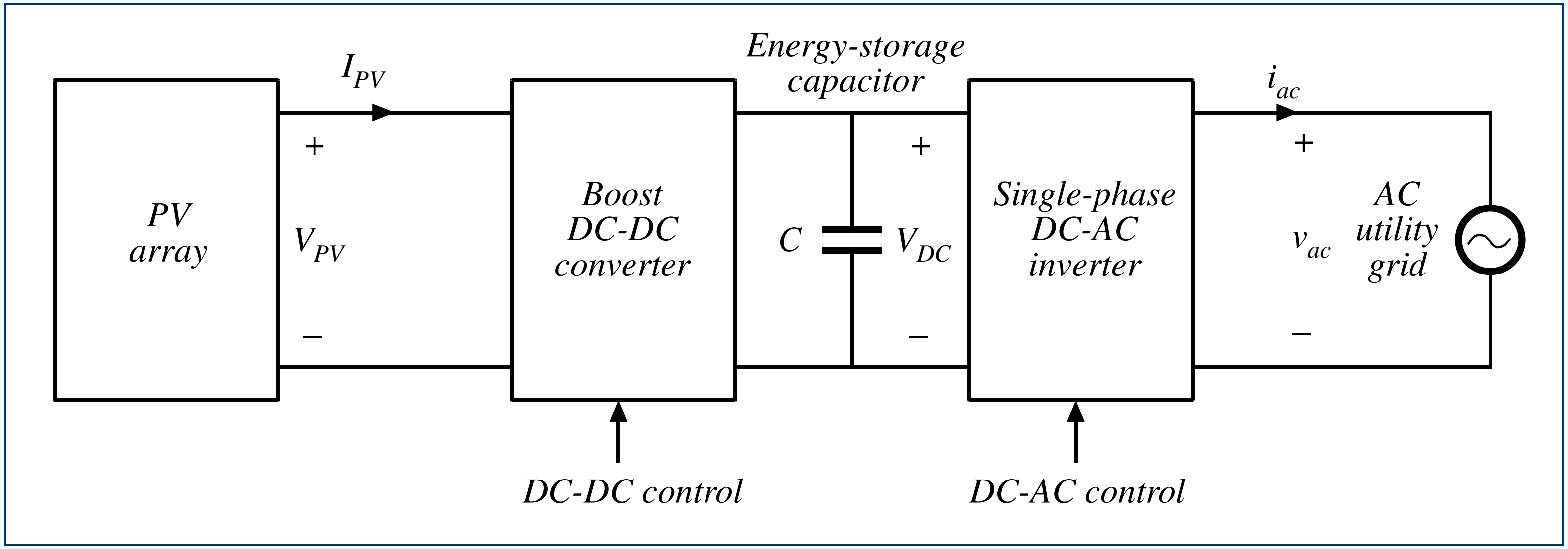
- Provide energy storage to balance the difference between P_{PV} and $p_{ac}(t)$

Desirable features

- Minimum weight, size, cost
- High reliability

Power Electronics for Grid-Connected PV System

One possible realization:



Boost DC-DC converter

- Set the PV operating point (V_{PV}, I_{PV}) to MPP
- Efficiently step up V_{PV} to a higher DC voltage V_{DC}

DC-AC inverter

- Efficiently generate AC output current i_{ac} in phase with the AC grid voltage v_{ac}
- Balance the average power delivery from the PV array to the grid, $P_{ac} = P_{pv} * \eta_{DC\text{-}DC} * \eta_{DC\text{-}AC}$

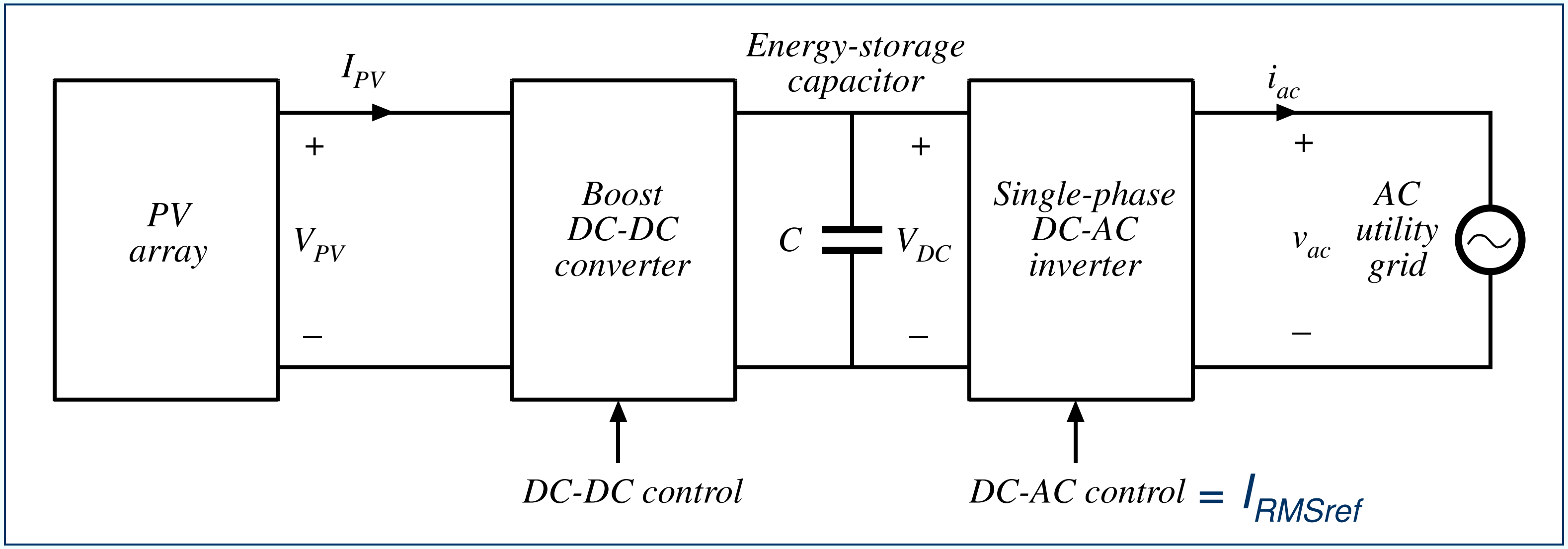
Energy storage capacitor *C*

- Balance the difference between the instantaneous power $p_{ac}(t)$ and the average power

The system must be disconnected from the grid if the utility loses power

DC-AC Inverter Control

One possible realization:

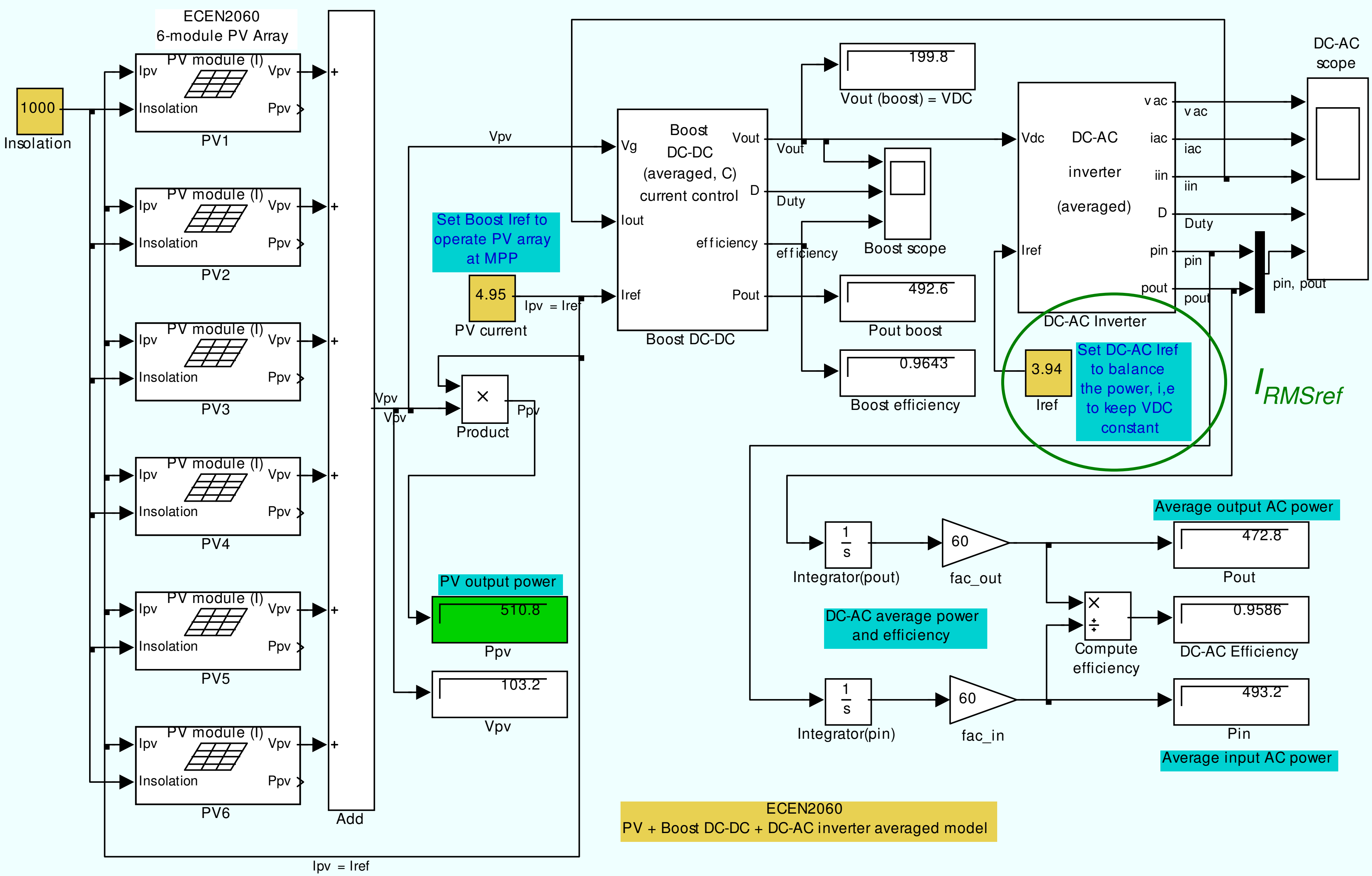


- The control variable for the DC-AC inverter is the RMS current reference I_{RMSref}
- The inverter output current $i_{ac}(t)$ is controlled so that it is in phase with the grid voltage $v_{ac}(t)$ and so that it's RMS value equals the reference:

$$I_{RMS} = I_{RMSref}$$

One possible current control approach, based on a comparator with hysteresis, has been discussed in class, see Intro to Power Electronics notes

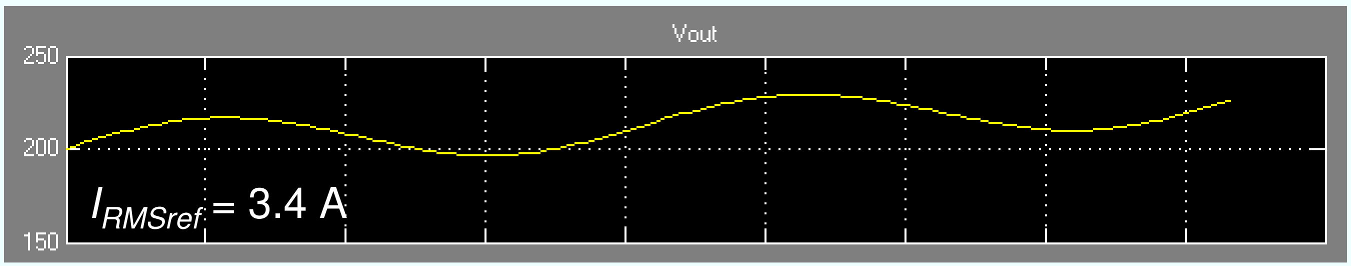
Simulation model: pv_boost_dcac_averaged.mdl



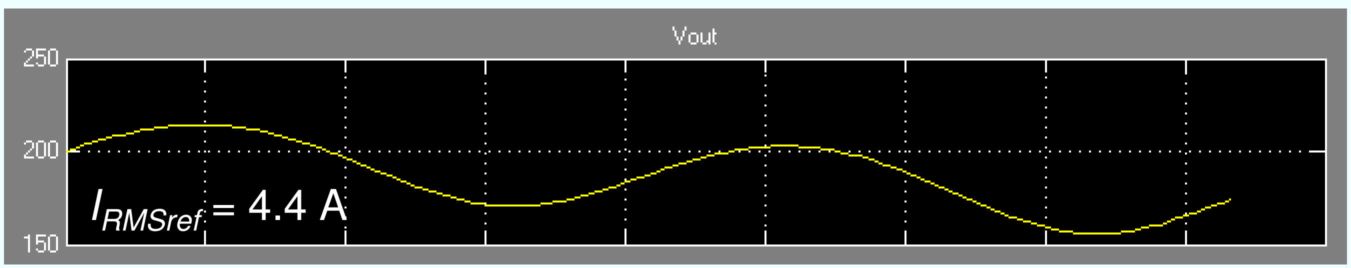
How to achieve average power balance?

Simulation example:

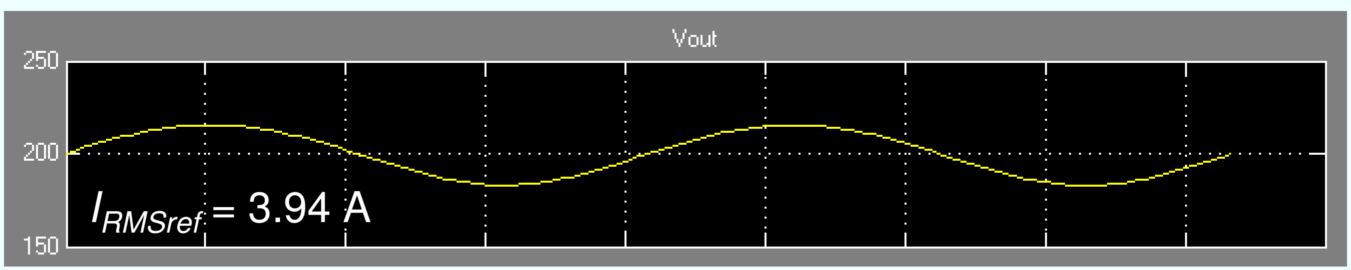
- 6-module (85 W each) PV array with full sun (1,000 W/m^2 insolation)
- PV array operates at MPP: P_{pv} = 6*85 W = 510 W
- AC grid RMS voltage: 120 V
- Run simulations for 3 different values of I_{RMSref} and observe boost output voltage $V_{out}(t) = V_{DC}(t)$



I_{RMSref} is too low
$P_{ac} < P_{pv}$
V_{DC} increases



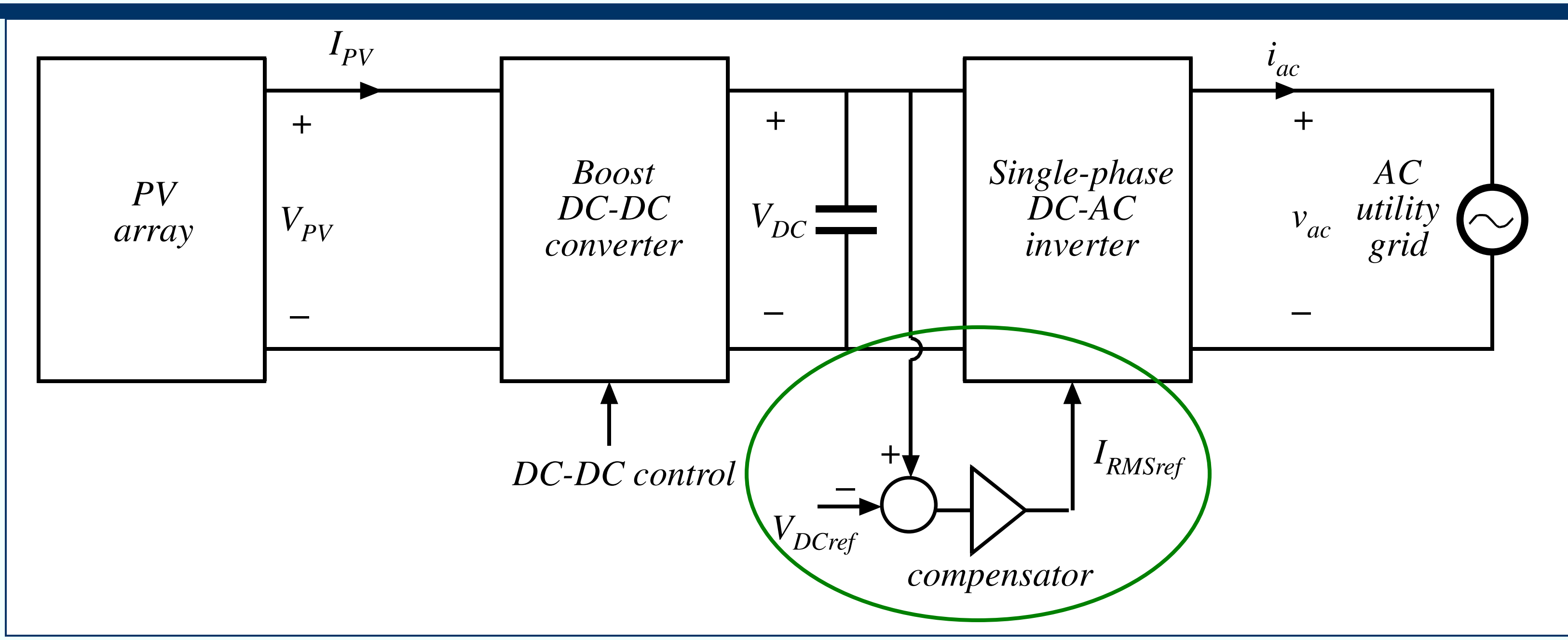
I_{RMSref} is too high
$P_{ac} > P_{pv}$
V_{DC} decreases



I_{RMSref} is just right
$P_{ac} \approx P_{pv}$
V_{DC} starts at 200 V and returns to 200 V

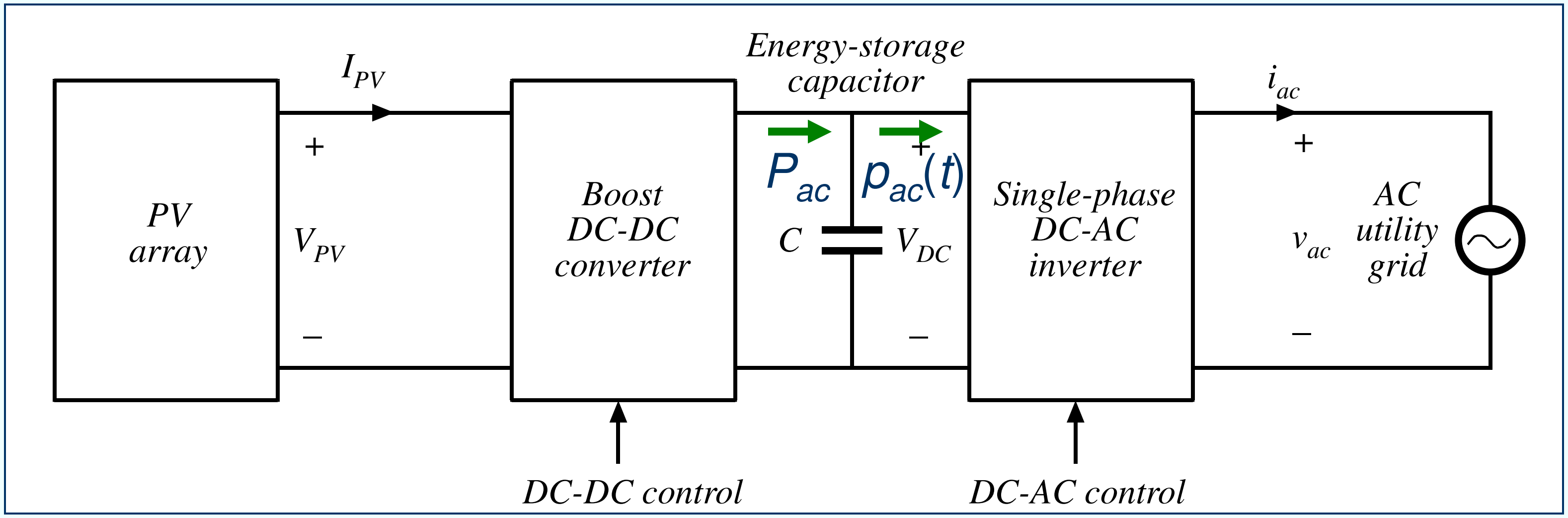
T_{ac} = AC line period (1/60 seconds)

Average Power Balance by Automatic Feedback Control

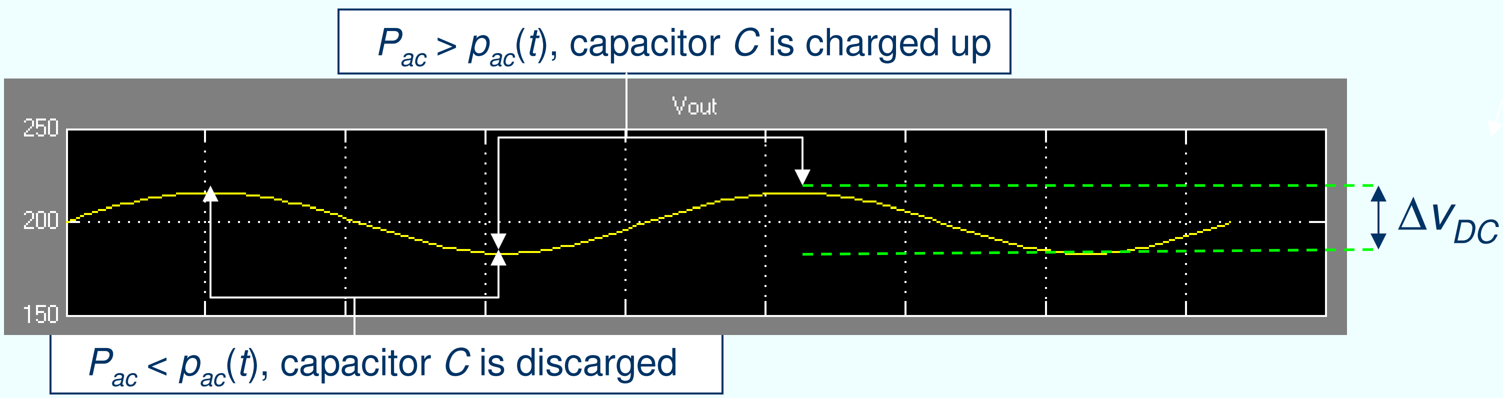


- Voltage V_{DC} is sensed and compared to a reference value V_{DCref} (e.g. V_{DCref} = 200 V)
- The difference $V_{DC} - V_{DCref}$ is the error signal for the feedback controller
- If the error is positive, i.e. if V_{DC} is greater than V_{DCref}, the compensator increses I_{RMSref}
- If the error is negative, i.e. if V_{DC} is less than V_{DCref}, the compensator decreases I_{RMSref}
- In steady-state, I_{RMSref} adjusted by the automatic feedback controller is just right so that $V_{DC} = V_{DCref}$, error signal is zero, and the average power P_{ac} delivered to the AC grid matches the power generated by the PV array
- Stability, dynamic responses and realizations of feedback controllers are topics beyond the scope of this class. These topics are addressed in Circuits, and more advanced Control and Power Electronics courses

Energy storage



$$P_{ac} - p_{ac}(t) = P_{ac} - P_{ac}(1 - \cos 2\omega t) = P_{ac} \cos 2\omega t$$

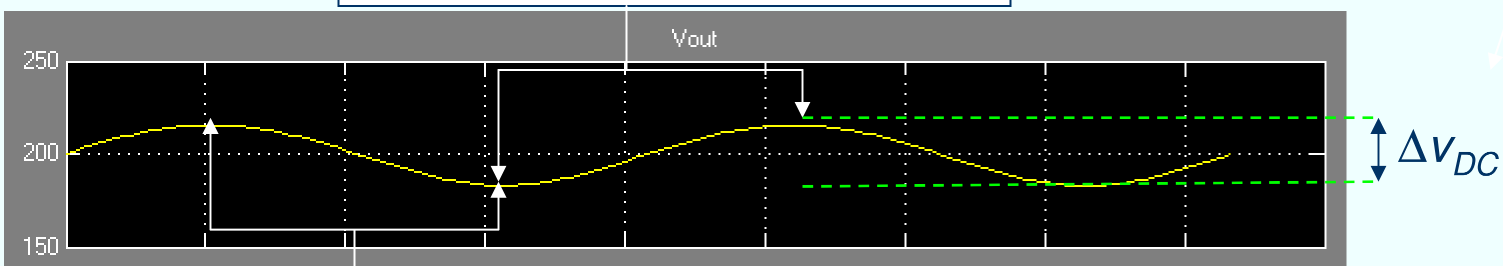


- Capacitor C provides energy storage necessary to balance instantaneous power delivered to the grid
- Magnitude of the resulting voltage ripple ΔV_{DC} at twice the line frequency (2 x 60 = 120 Hz) depends on the average power P_{ac} and capacitance C

Energy storage capacitor C

$$P_{ac} - p_{ac}(t) = P_{ac} - P_{ac}(1 - \cos 2\omega t) = P_{ac}\cos 2\omega t$$

$P_{ac} > p_{ac}(t)$, capacitor C is charged up



$P_{ac} < p_{ac}(t)$, capacitor C is discarged

- Energy supplied to the capacitor during the time when $P_{ac} > p_{ac}(t)$, i.e. when the capacitor is charged from V_{DCmin} to V_{DCmax}

$$\Delta E_C = \int_{-T_{ac}/8}^{T_{ac}/8} P_{ac}\cos 2\omega t\, dt = \frac{P_{ac}}{2\omega}\int_{-\pi/2}^{\pi/2}\cos\theta\, d\theta = \frac{P_{ac}}{\omega}$$

- This energy must match the change in energy stored on the capacitor:

$$\Delta E_C = \frac{1}{2}CV_{DC\max}^2 - \frac{1}{2}CV_{DC\min}^2 = C\left(V_{DC\max} - V_{DC\min}\right)\frac{V_{DC\max} + V_{DC\min}}{2} \approx CV_{DC}\Delta V_{DC}$$

- Solve for the ripple voltage:

$$CV_{DC}\Delta V_{DC} = \frac{P_{ac}}{\omega} \qquad \boxed{\Delta V_{DC} = \frac{P_{ac}}{CV_{DC}\omega}}$$

Energy storage analysis example

- DC-AC inverter input voltage: V_{DC} = 200 V
- Average power delivered to the grid: P_{ac} = 600 W
- Find C so that ΔV_{DC} = 40 V (i.e. +/-10% of the DC voltage at the input of the DC-AC inverter)
- Solution:

$$CV_{DC}\Delta V_{DC} = \frac{P_{ac}}{\omega}$$

$$C = \frac{P_{ac}}{\Delta V_{DC} V_{DC} \omega} = \frac{600 \text{ W}}{40 \text{ V} * 200 \text{ V} * 2\pi 60 \text{ Hz}} = 200\ \mu\text{F}$$

- Note that the energy supplied (or absorbed) by the capacitor is relatively small:

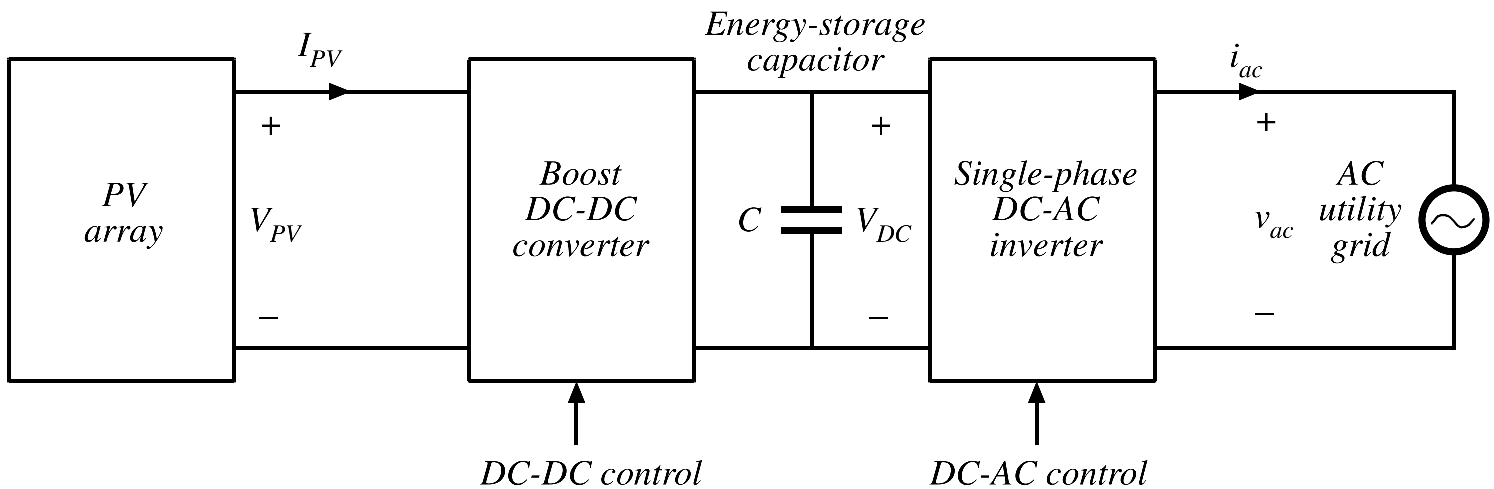
$$\Delta E_C = \frac{P_{ac}}{\omega} = \frac{600}{2\pi 60} = 1.6 \text{ J}$$

- The total energy stored on the capacitor is also small

$$E_C = \frac{1}{2} C V_{DC}^2 = 4 \text{ J}$$

- This example illustrates the need for only relatively small energy storage in a grid-connected system, easily accomplished by a capacitor, in sharp contrast to stand-alone PV systems that require very significant energy storage (e.g. batteries)

Maximum Power Point (MPP) Tracking



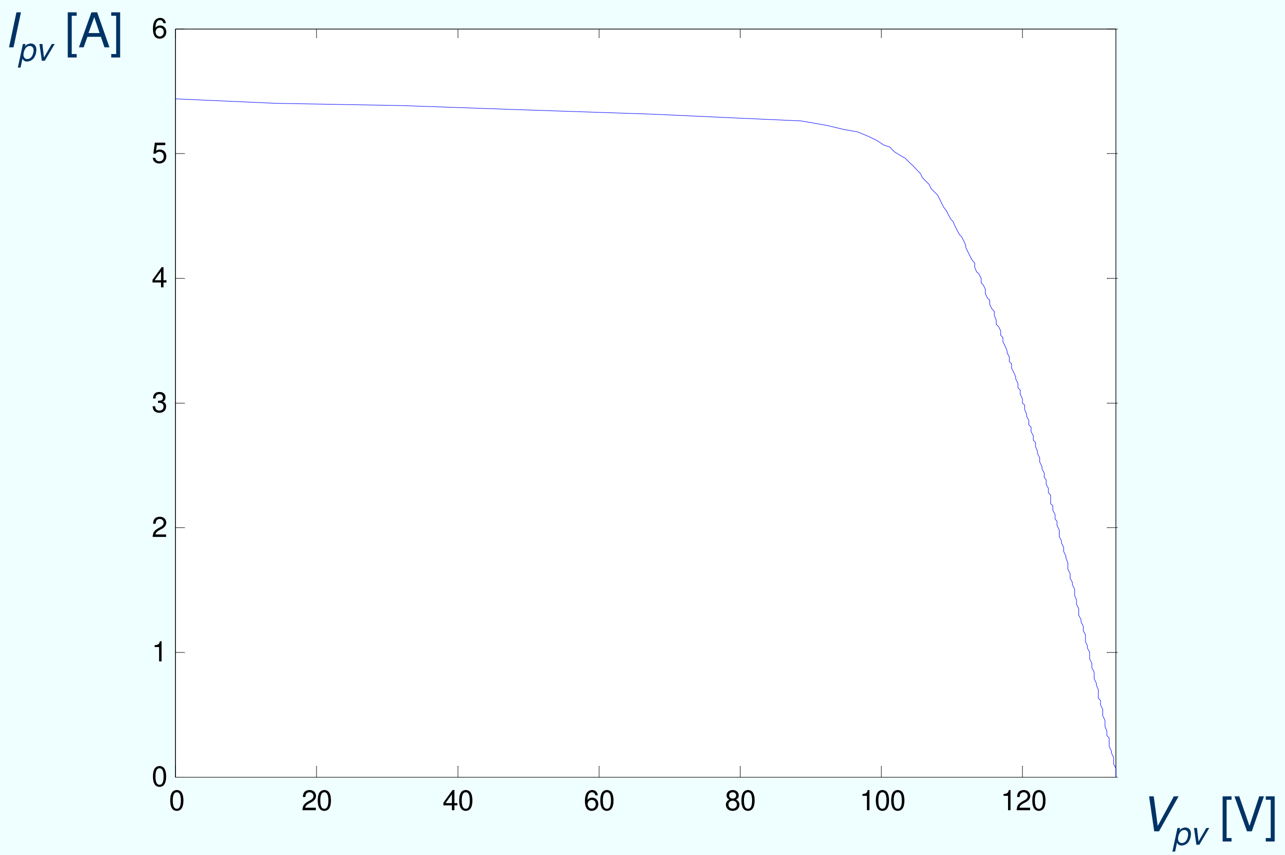
Choices for the Boost DC-DC control variable:

- Duty cycle D
- Input current reference I_{ref}
- Input voltage reference V_{ref}

- The objective of the MPP tracking algorithm is to adjust the DC-DC control variable so that the PV array operates at the maximum power point
- In the example discussed here:
  - It is assumed that the Boost output voltage $V_{out} = V_{DC}$ is constant
  - I_{ref} is used as the control variable for the Boost DC-DC converter
  - PV array current ideally tracks the Boost input current reference: $I_{PV} = I_{ref}$

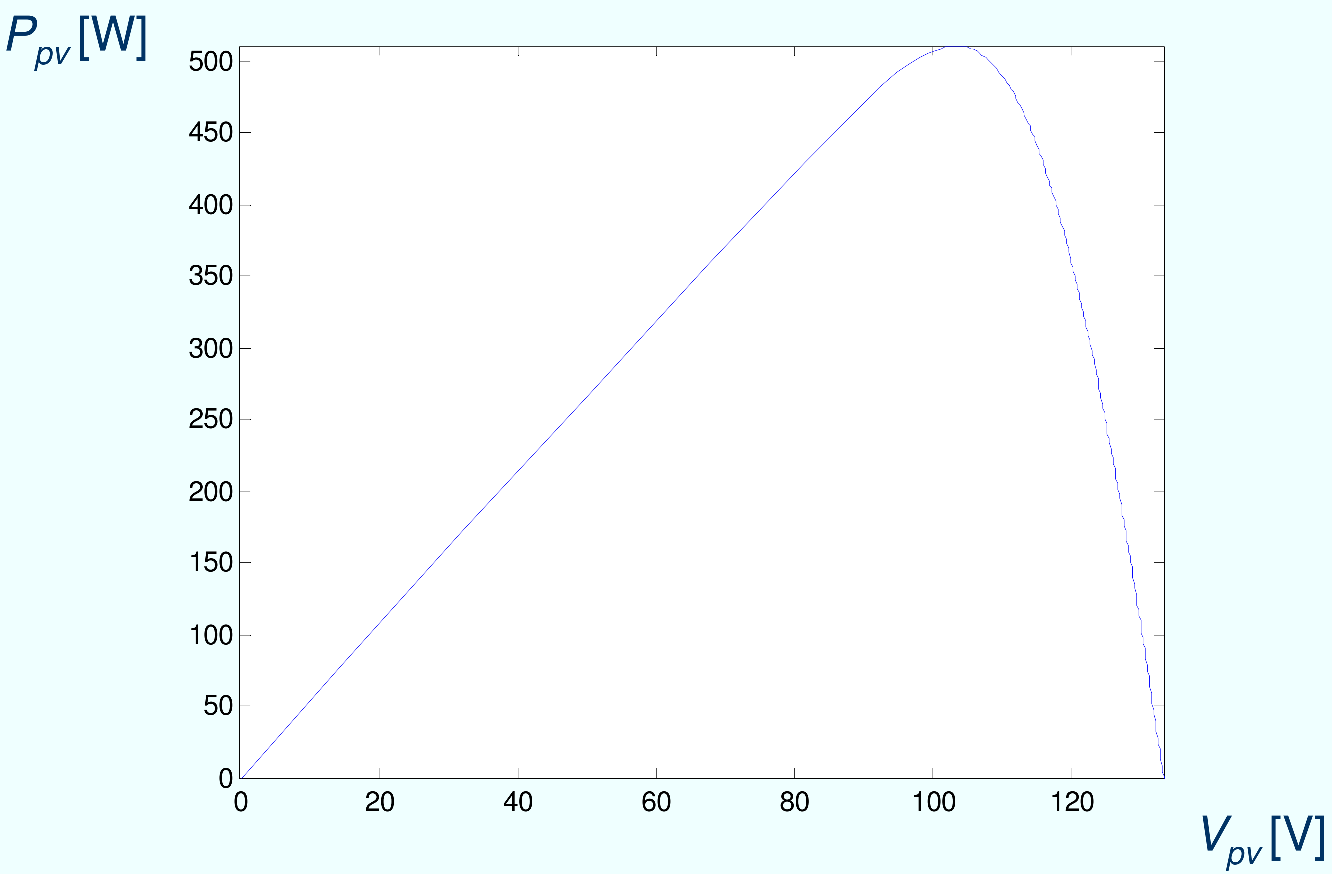
Reminder: PV array characteristic

- Example: six 85 W modules in series, full sun



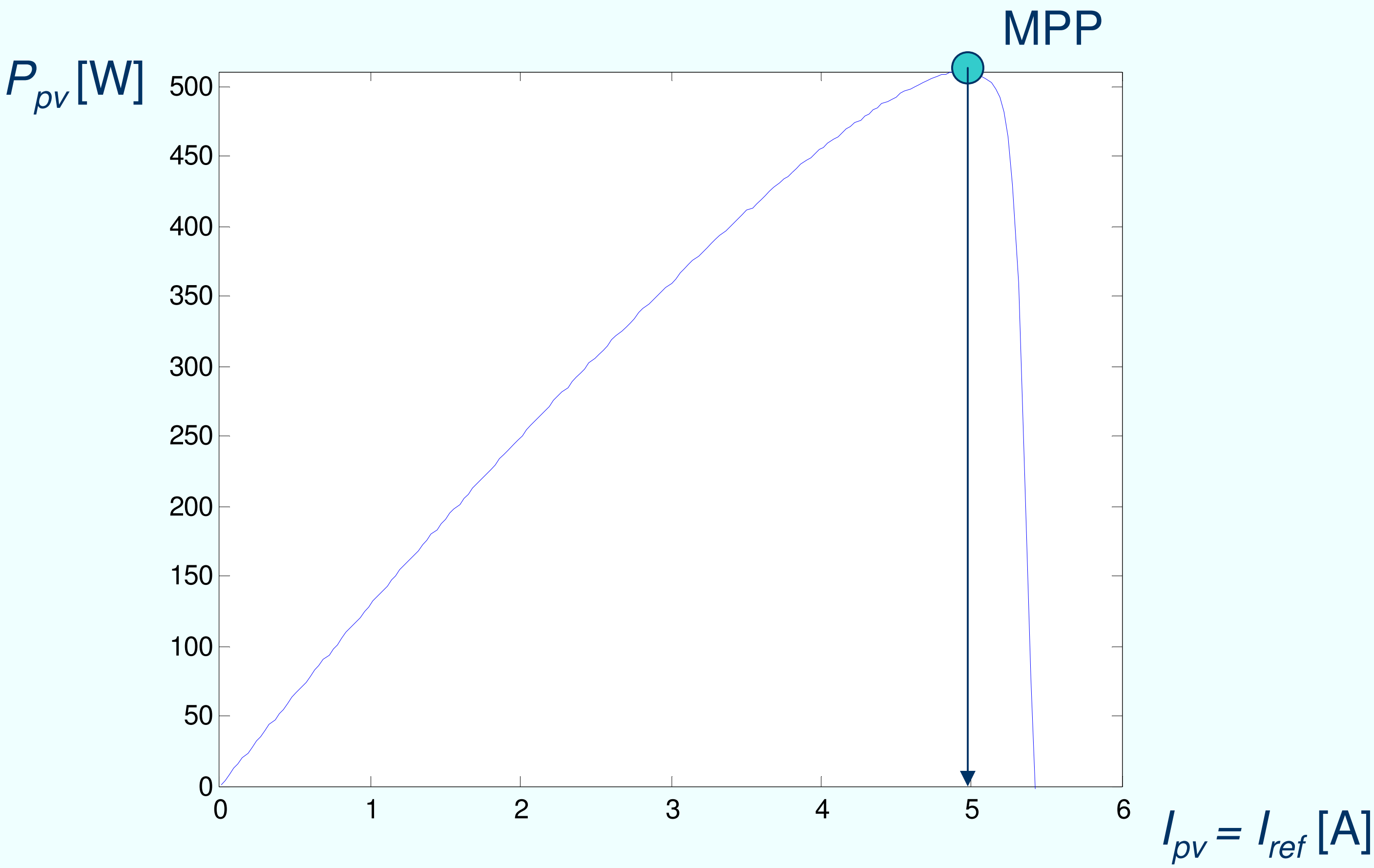
P_{pv} as a function of V_{pv}

- Example: six 85 W modules in series, full sun



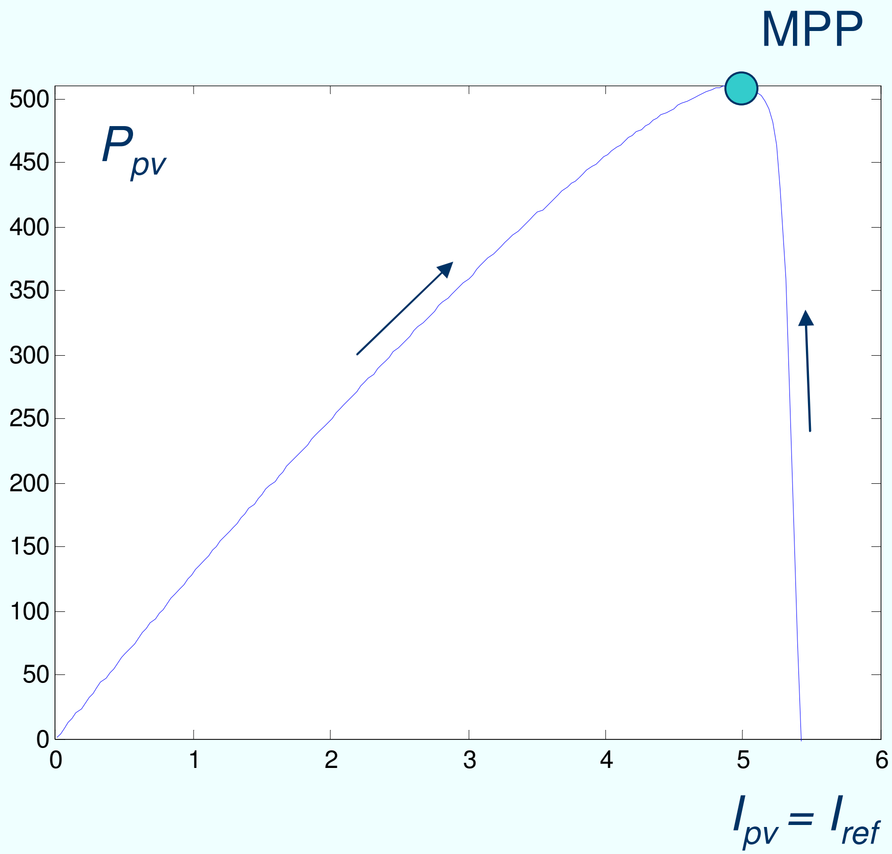
P_{pv} as a function of $I_{pv} = I_{ref}$

- Example: six 85 W modules in series, full sun

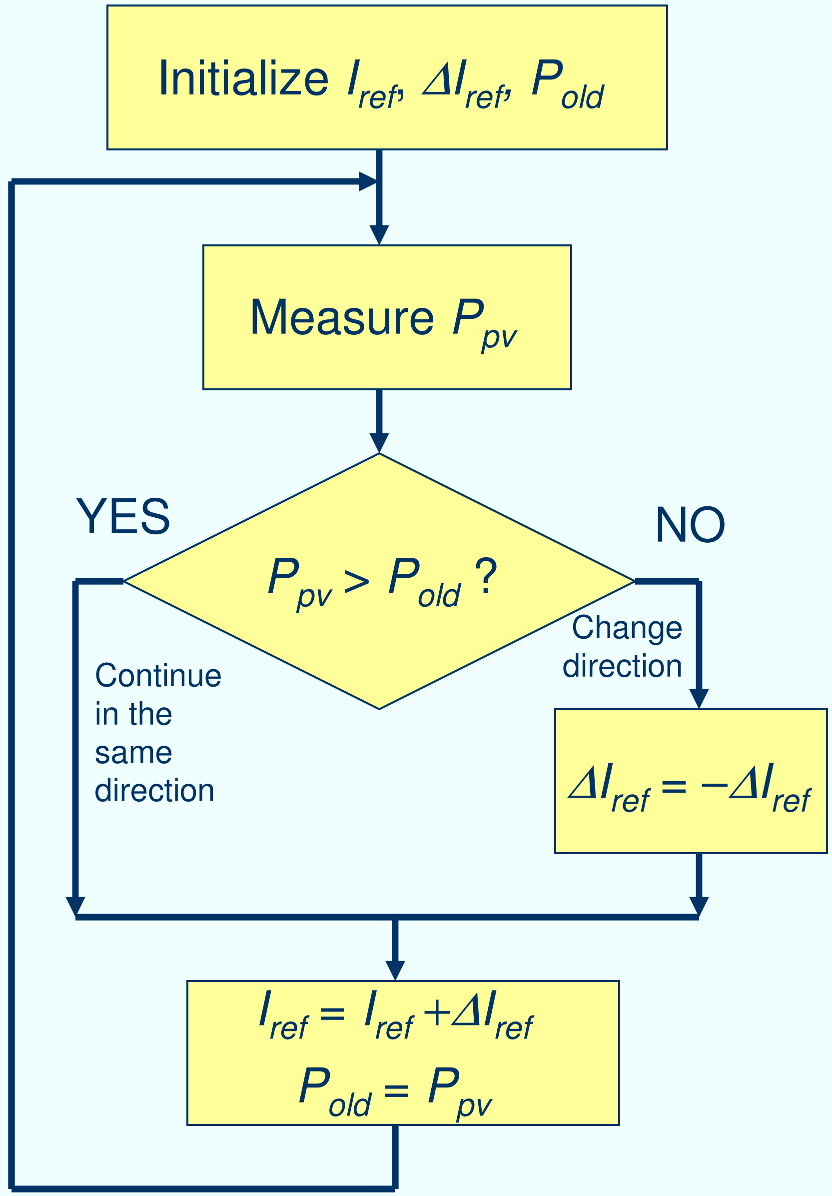


Objective: adjust $I_{pv} = I_{ref}$ to operate at MPP

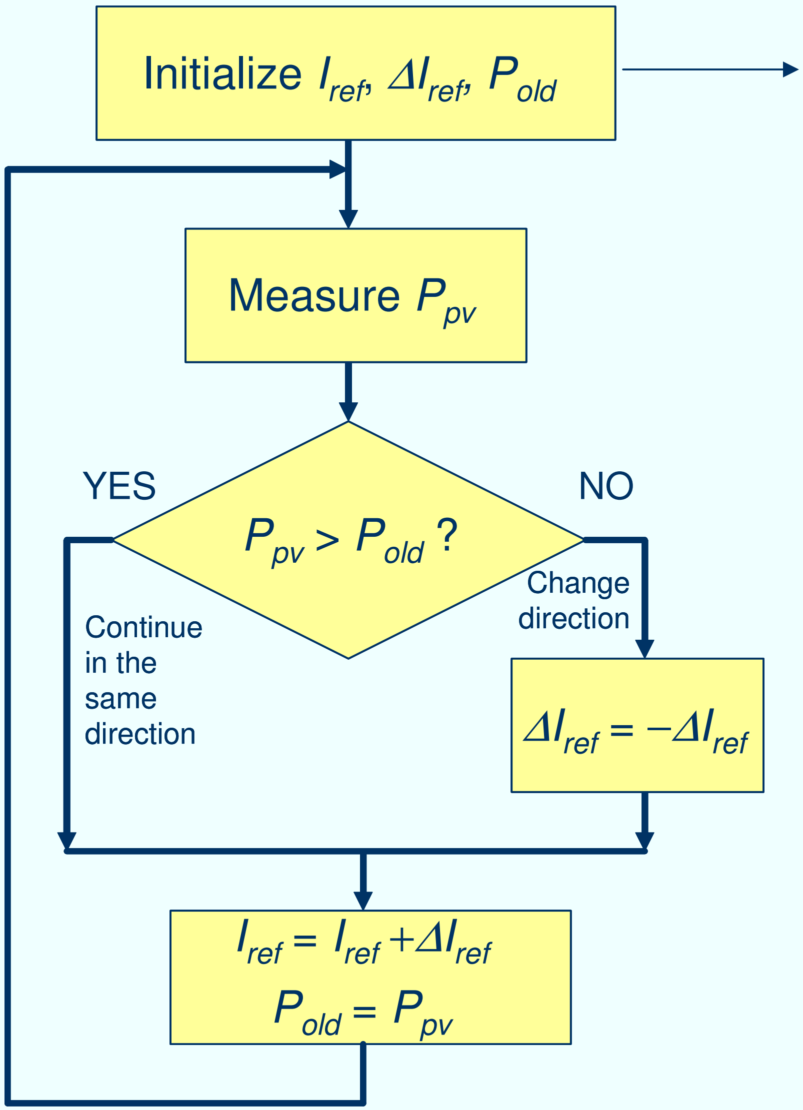
Simple "perturb and observe" MPP tracking algorithm



Always step I_{ref} in the direction of increasing P_{pv}

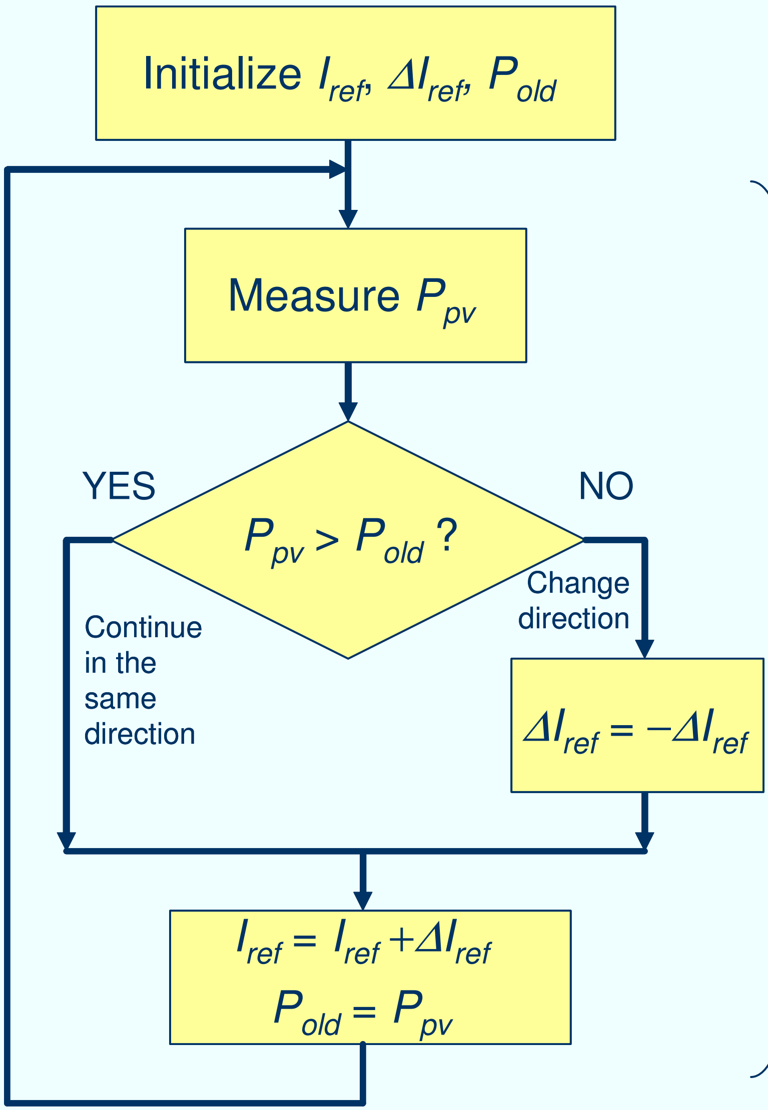


MATLAB code: MPP tracking algorithm initialization



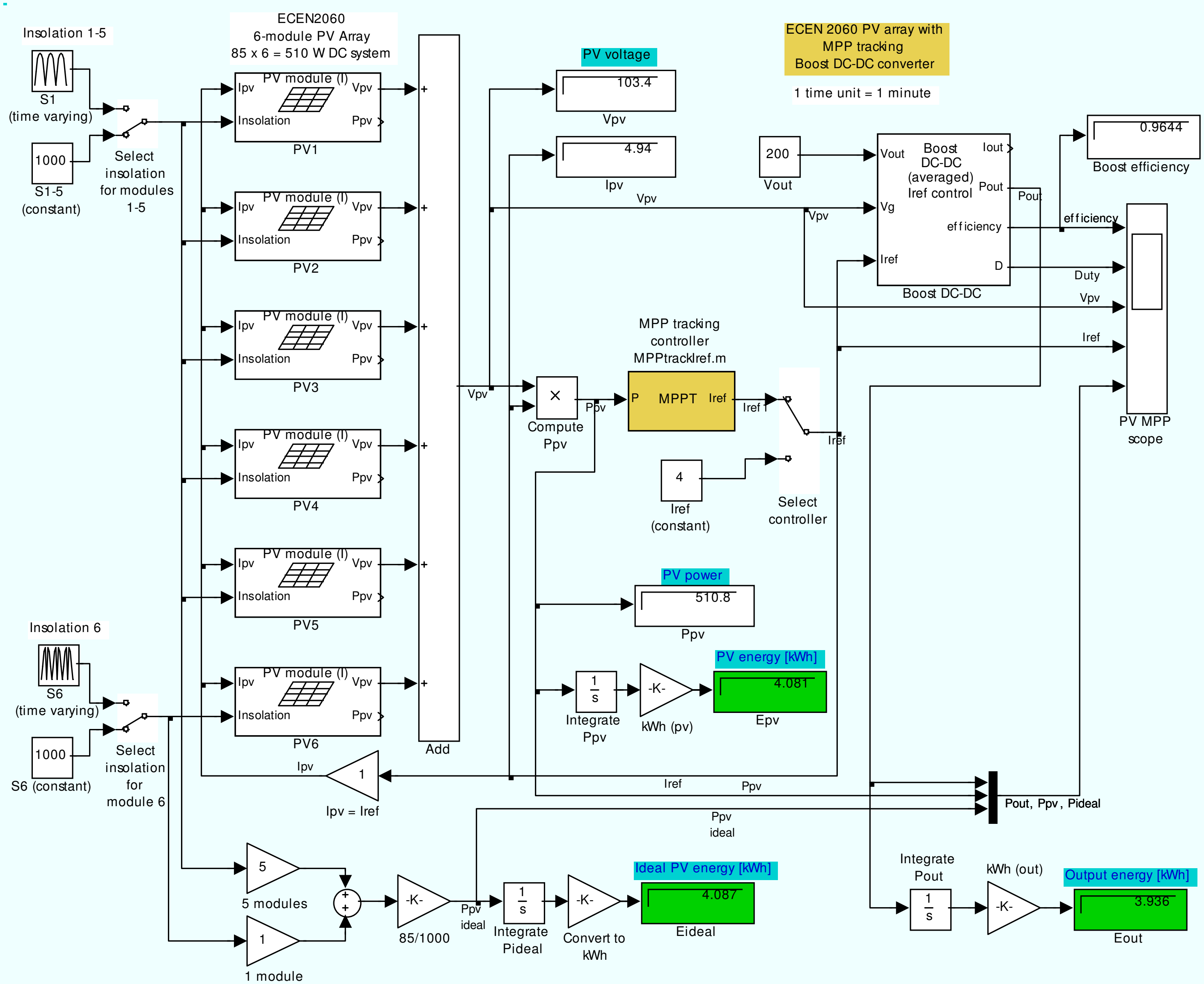

```
%
% ECEN2060 MATLAB script: InitializeMPPtrackIref.m
% Initialize MPPtrackIref
%
global Iref;
global Increment;
global Pold;
Pold = 0; % initial value for the sensed power
Iref = 4; % initial value for the current reference
Increment = -1; % initial direction: decrease reference current
```

MATLAB code: MPP tracking algorithm

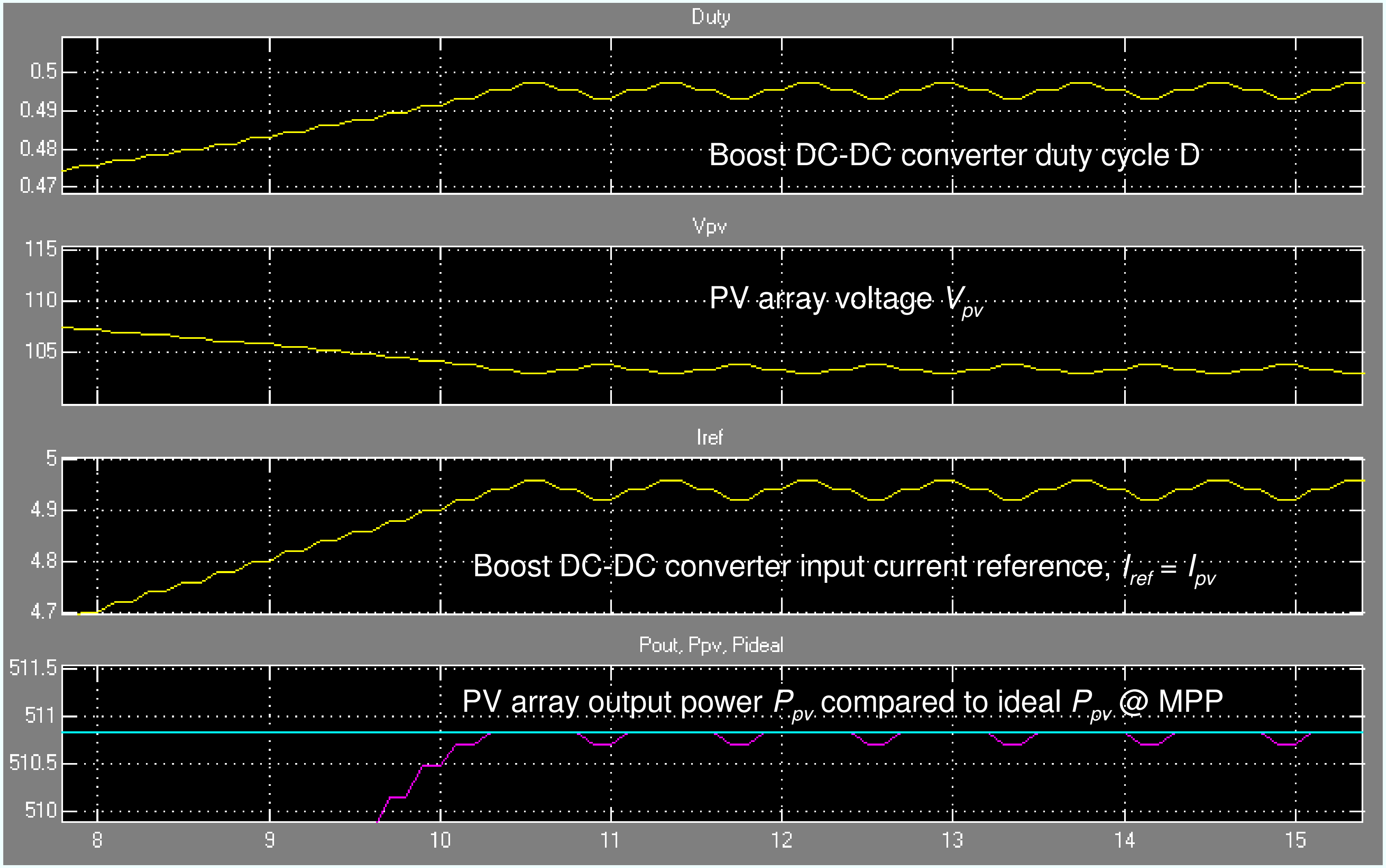



```
% ECEN2060 MATLAB code: MPPtrackIref.m
% Simple MPP "perturb and observe" tracking algorithm
% using Boost DC-DC input current Iref as the control variable
% Pold, Iref and Increment are initialized in InitializeMPPtrackIref.m
%
% Input: power P to be maximized
% Output: reference current
function y = MPPtrackIref(P)
global Pold;
global Iref;
global Increment;
IrefH = 5; % upper limit for the reference current
IrefL = 0; % lower limit for the reference current
DeltaI = 0.02; % reference current increment

if (P < Pold)
    Increment = -Increment; % change direction if P decreased
end
% increment current reference
Iref = Iref + Increment*DeltaI;

% check for upper limit
if (Iref > IrefH)
    Iref = IrefH;
end

% check for lower limit
if (Iref < IrefL)
    Iref = IrefL;
end

% save power value
Pold = P;
% output current reference
y = Iref;
```

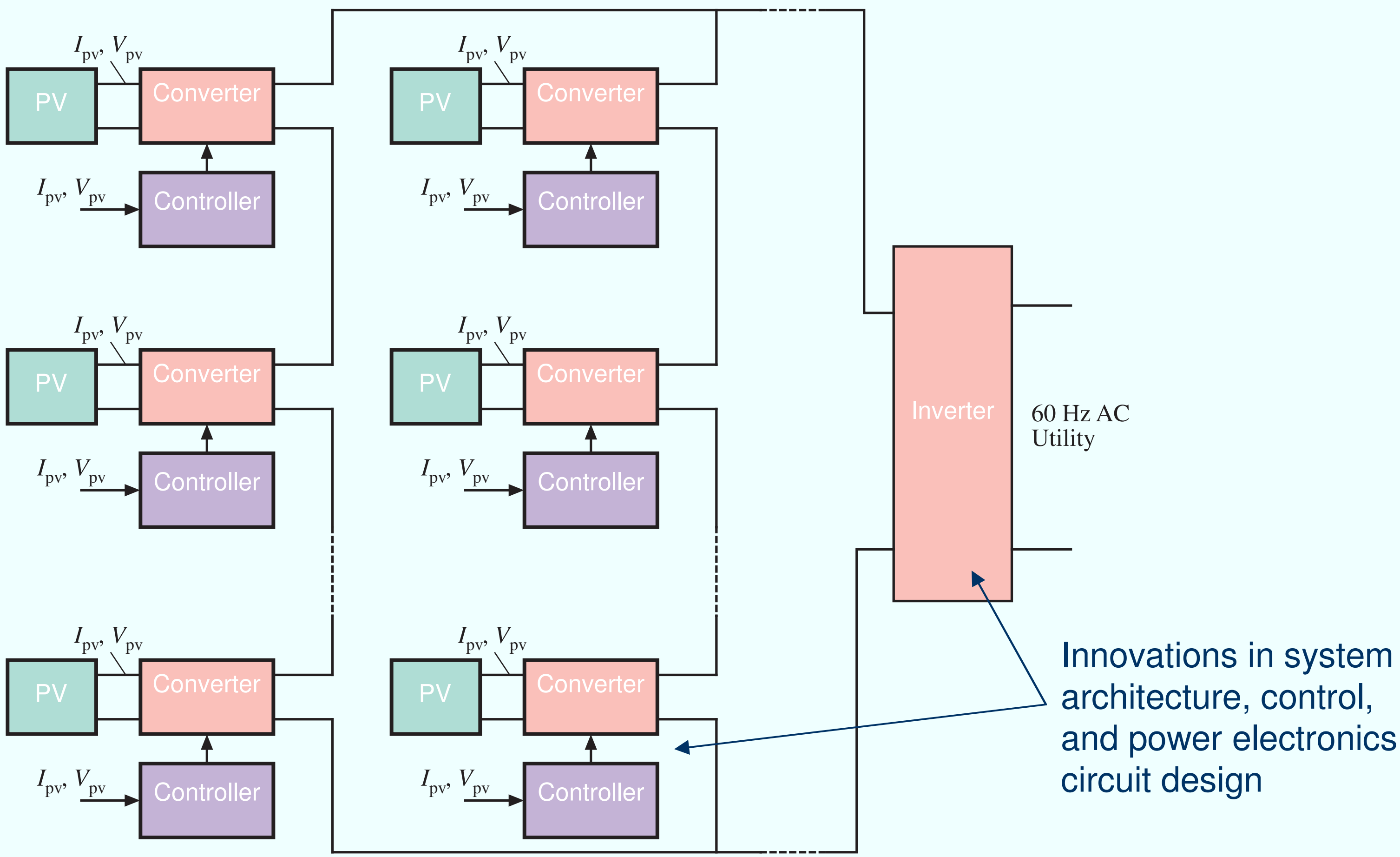
Simulation model: pv_boost_mpp_Iref.mdl



MPP tracking operation



The Future of
Grid-Connected PV Systems



- Modular power electronics: distributed DC-DC conversion
- Much improved performance in the presence of module mismatches or partial shading
- Scalable architecture
- Ongoing projects led by Profs. Erickson and Prof. Zane in the CoPEC lab at CU