Lecture 14: Grid-Tied PV Systems

ECEN 4517/5517

Part of the power lab PV array on the roof of the EE wing

72 cell, 180 W PV panels

24 total panels, 4 kW system

ECEE Expo and Solar Power Competition

ECEN 4517/5517

Expo:

- Thursday, May 3, 9:00 am – noon

Solar Power Competition

- Tuesday section: 9:15 – 10:00 am
- Wednesday section: 10:15 – 11:00 am
- Thursday section: 11:15 am – noon
- Herbst plaza
- Posters not needed

Exp. 5 Report

- Due Friday May 4 by 3:00 pm, in power lab

Types of power systems using PV

1. Stand-alone
   - This is what we built in this lab
   - In the long term, the energy consumed by the load must exactly balance the energy generated
   - When you battery is full in the afternoon, stop charging and quit peak power tracking
   - When your battery is discharged at night, the loads will be unpowered
   - "Reliability" means no blackouts: always have the capability to generate more energy than will actually be used. This capability costs money.

Types of power systems using PV

2. Grid-tied
    - This is currently the most common PV installation
    - All energy that can be generated by the array is delivered to the public utility grid
    - The utility must take your power, whether they want it or not
    - Balancing load and generated power is the responsibility of the grid operators

      The total load power on the grid must balance the power generated, on an instantaneous basis
    - "Reliability" means no blackouts: always have the capability to generate more energy than will actually be used. This capability costs money. This responsibility is borne by the utility company

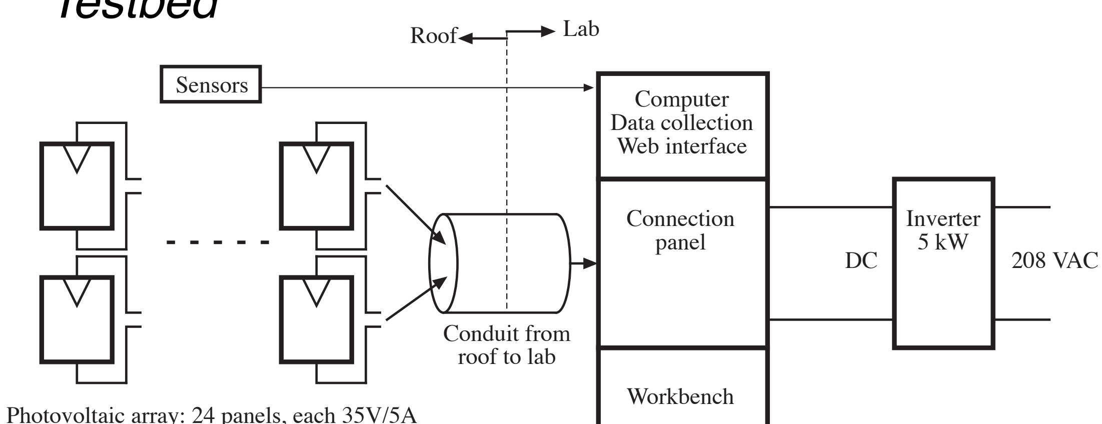
Types of power systems using PV

3. Microgrid
   - A collection of several AC sources and loads, which might include a PV array and its inverter
     - Example: a system with a solar array, battery bank, inverter, backup gas generator, maybe a wind turbine, and some ac loads
   - Larger than the standalone system from this semester: there are multiple ac sources
   - Not connected to the grid
   - Reliability is your responsibility, not the utility company's

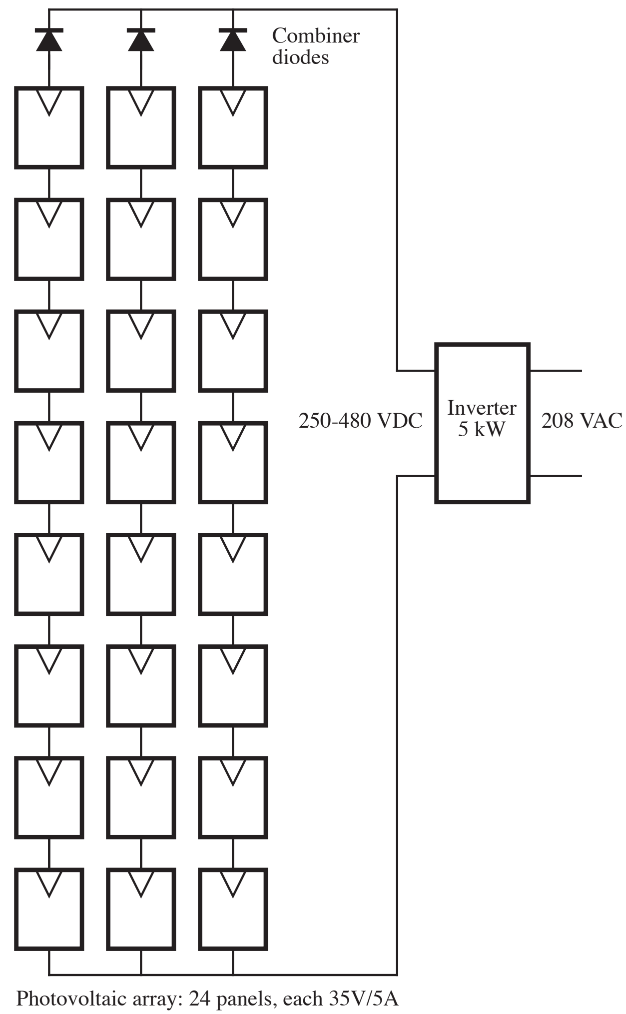
Our Grid-Tied PV System

- 8 x 3 array of PV panels on roof of EE wing
- 5 kW SMA inverter in power lab
- Each panel individually wired to switchboard in lab. System can be reconfigured in lab
- Monitoring system measures currents and voltages of each panel and bypass diode; results imported into Matlab

Testbed



Nominal schematic



Our rooftop 4 kW array

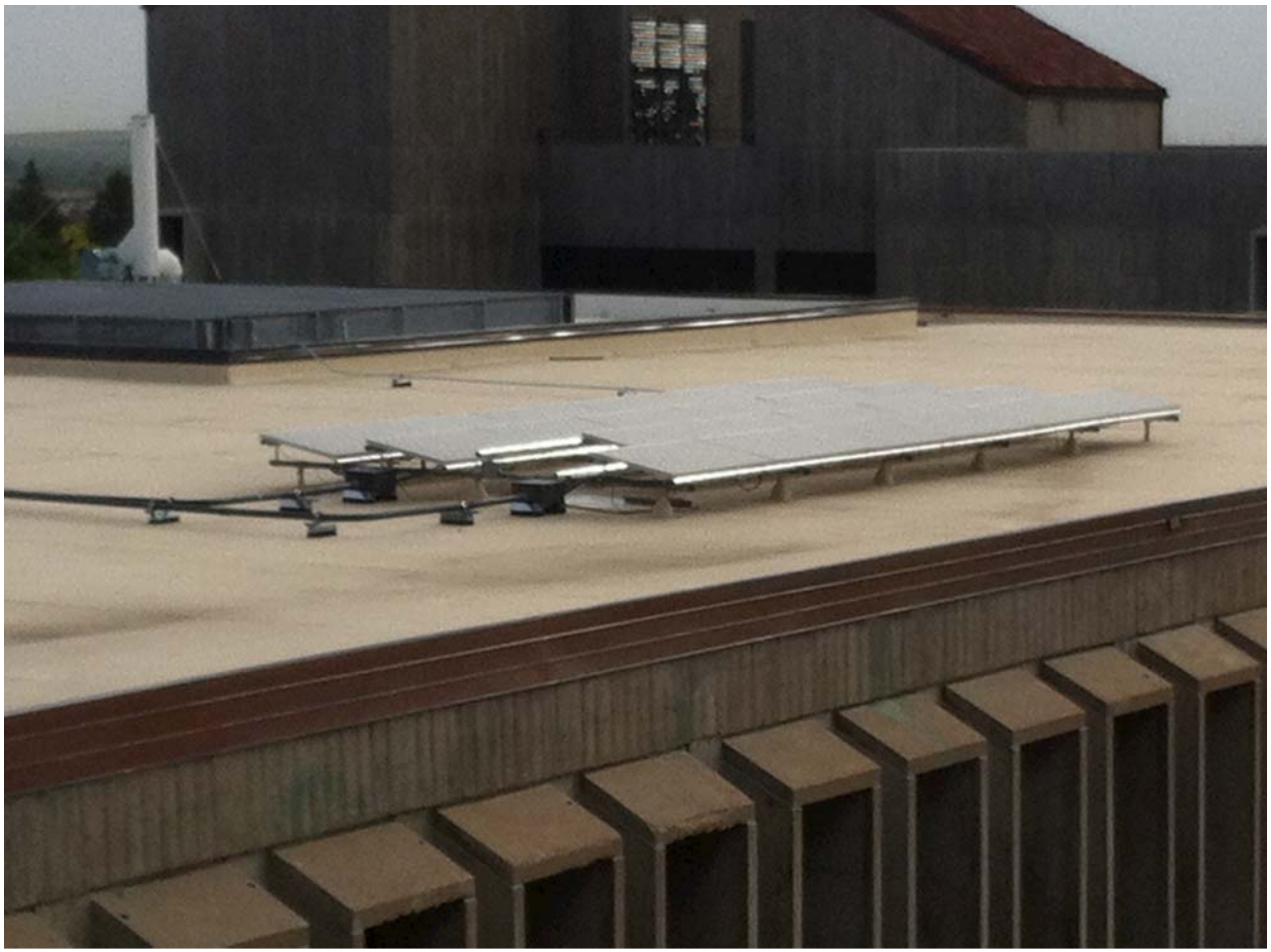


Photo taken this morning

Work on monitoring system and panel #18 is still underway

Racking system is anchored to building structure and is able to withstand Boulder wind storms. Array is south-facing with panels tilted at 10˚.

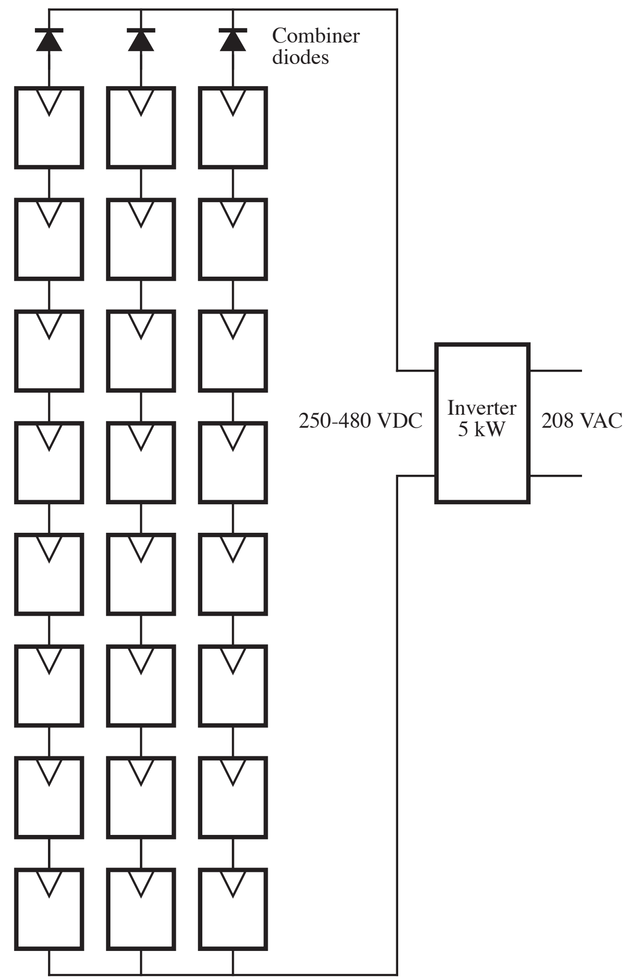
Constraints in a PV Array

With the nominal configuration shown, we have three strings of eight panels each. This series connection of panels builds up the voltage to that required by the inverter.

Each panel in a string must conduct the same current. Since each panel contains three bypass diodes, each string has a total of 24 bypass diodes. The *I-V* curve under partially shaded conditions can become quite complex.

Since the three strings are connected in parallel, they must operate with the same voltage. When bypass diodes conduct, the V_{MP}'s of the strings may differ significantly.

Combiner diodes prevent backfeeding of current through strings when a string V_{oc} is less than the system dc voltage. These are often omitted. Combiner boxes often contain fuses to meet NEC.



Photovoltaic array: 24 panels, each 35V/5A

Our rooftop panels
EcoSolargy SDM 180

ELECTRICAL DATA								
Pmax(±3%)	155W	160W	165W	170W	175W	180W	185W	190W
Vmp	34.6V	34.9V	35.6V	35.8V	36.2V	36.8V	37.5V	37.7V
Imp	4.48A	4.60A	4.65A	4.76A	4.85A	4.90A	4.95A	5.04A
Voc	44.0V	44.3V	44.4V	44.5V	44.7V	44.8V	44.9V	45.1V
Isc	5.0A	5.05A	5.10A	5.15A	5.20A	5.25A	5.30A	5.35A
Max system voltage	DC1000V(TUV) DC600V(UL)							
STC	Standard test conditions: irradiance: 1000W/ m^2 AM: 1.5 temperature: 25°c							

Temperature coefficients	
Nominal Operating Cell Temperature (NOCT)	45°c ±2°c
Temperature Coefficient of ISC (α)	0.038%/°c
Temperature Coefficient of VOC (β)	-0.34%/°c
Temperature Coefficient of Pmax	-0.48%/°c

For any PV panel:
The difference between STC (standard test conditions, in the laboratory) and NOCT (normal operating cell temperature, in the sun) is substantial. Buyer beware!

72 cells, 3 bypass diodes. STC: 180 W, 36.8 V, 25˚C
NOCT:

- The actual temperature in the sun when the air is 25˚C
- Datasheet says this is 45˚C
- Actual panel V_{MP} is 36.8V [1 + (20˚C)(-0.34%/˚C)] = 34 V
- Actual panel power is (180 W) [1 + (20˚C)(-0.48%/˚C)] = 163 W
- Actual panel V_{oc} is 44.8V [1 + (20˚C)(-0.34%/˚C)] = 41.8 V

Our inverter
SMA SunnyBoy 5000US

- Inverter starts after array V_{oc} reaches at lease 300 V
- Worst-case V_{oc} must not exceed 600 V
- During operation, array V_{mp} must lie in the range 250 – 480 V

In the US, standard building voltages for a 5 kW unit are:

- 120/240 V single-phase ac in residential buildings
- 120 V single phase / 208 V three-phase in commercial buildings

The Engineering Center has 208 V three phase. Our inverter is connected line-line to 208 Vac.

	SB 5000US	SB 600
Inverter Technology	True sine wave, low frequency tranformer	
AC Operating Voltage Range	183 - 229 (208 V nominal) 211 - 264 (240 V nominal) 244 - 305 (277 V nominal)	
AC Operating Frequency Range	59.3 - 60.5 (60 Hz nominal)	
Peak Power Tracking Voltage	250 - 480 V DC	
Range of Input Operating Voltage	250 - 600 V DC	
Maximum DC Power	5300 W	6400
Maximum Array Input Power (DC @ STC)	6250 W	7500
Maximum AC Continuous Output Power	5000 W	6000
Current THD	Less than 4 %	
Output Power Factor	0.95 - 1.0 (0.99 @ nominal conditions)	
Peak Inverter Efficiency	96.8 %	97.0
CEC weighted efficiency	95.5 %	95.5 % @ 20 95.5 % @ 2 96.0 % @ 27
Cooling	OptiCool, forced active cooling	
PV Start Voltage	300 V DC	
Maximum AC Continuous Output Current	208 V = 24 A 240 V = 20.8 A 277 V = 18A	208 V = 240 V = 277 V = 2
Maximum DC Input Current	21 A 25 A	
Maximum input short circuit current	36 A	
Maximum utility backfeed current to PV array	50 A AC	

Conditions at NOCT

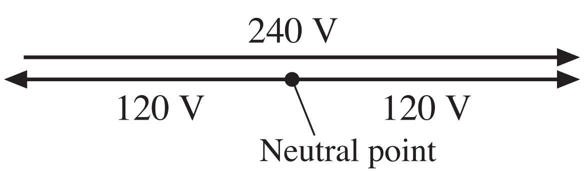
With three strings of 8 panels each, the relevant voltages are:

- Array V_{oc} = (8)(41.8 V) = 334 V
  This exceeds the inverter rated start voltage of 300 V
- Array V_{MP} = (8)(34 V) = 272 V
  This is within the inverter rated V_{MP} range of 250-480 V
- The array worst-case cold V_{oc} at (-25˚F = -32˚C) is
  (8)(44.8V)[1 + (-57˚C)(-0.34%/˚C)] = 428 V
  This is less than the inverter rated max input voltage of 600 V. It also meets the US NEC limit of 600 V.

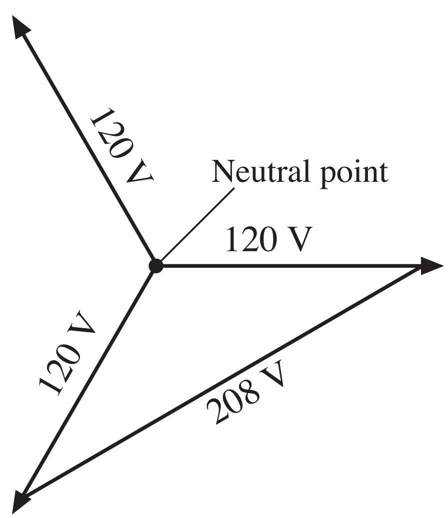
So a 3x8 array will work. A few more panels per string would give more margin. We are in danger of dipping below the rated V_{MP} range on hot days or in low light.

AC Voltage Phasors

Single-phase residential voltages in US



Three-phase commercial voltages in US



What is in your house

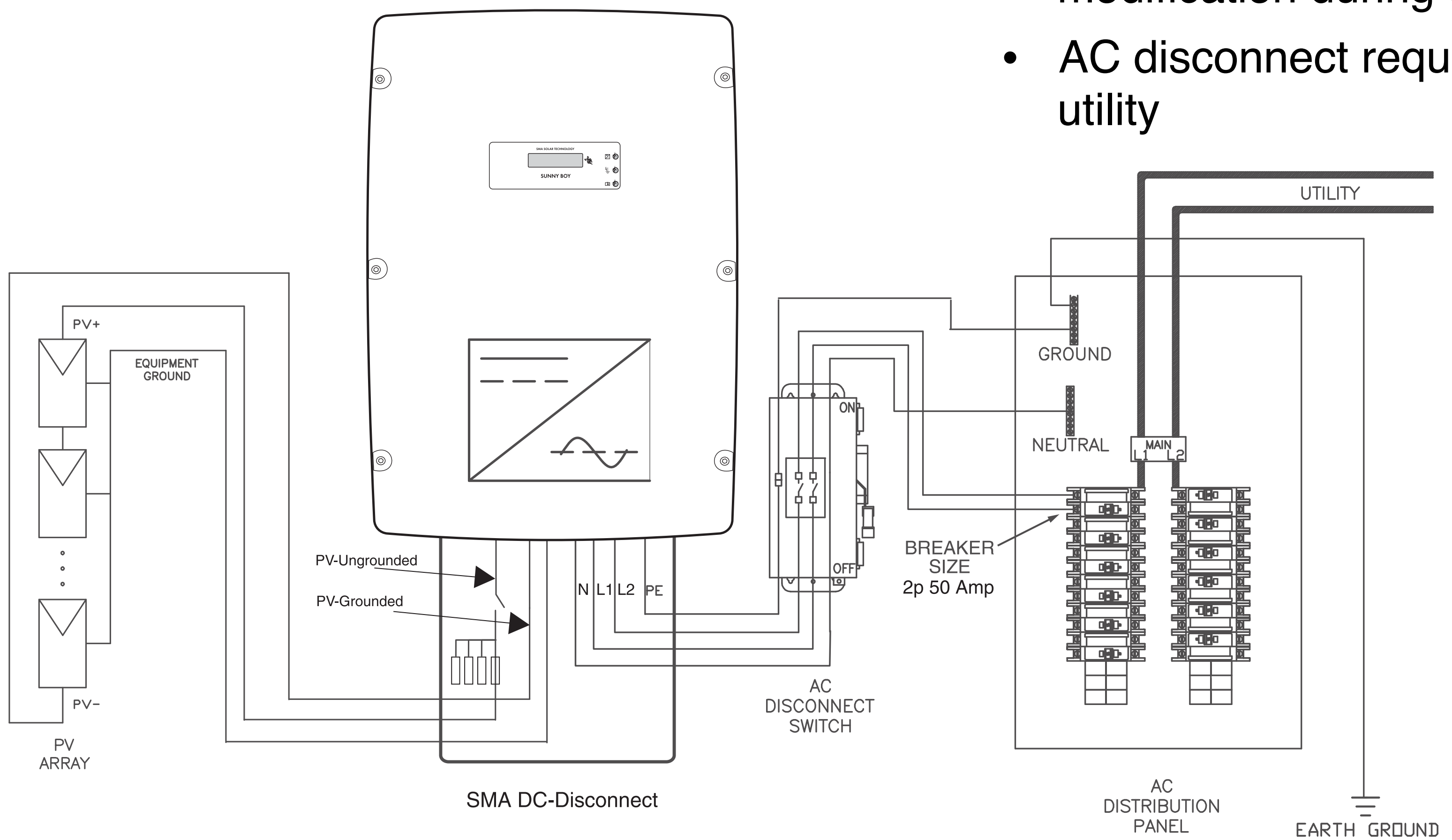
120/240 V single phase

What is in the engineering center

- 208 V three phase
- Note that three-phase is described by its line-line voltage
- To get single phase for wall outlets: use line-neutral voltage

How inverters are wired to the grid in the US

Sunny Boy Connections for 208 and 240 V AC grids

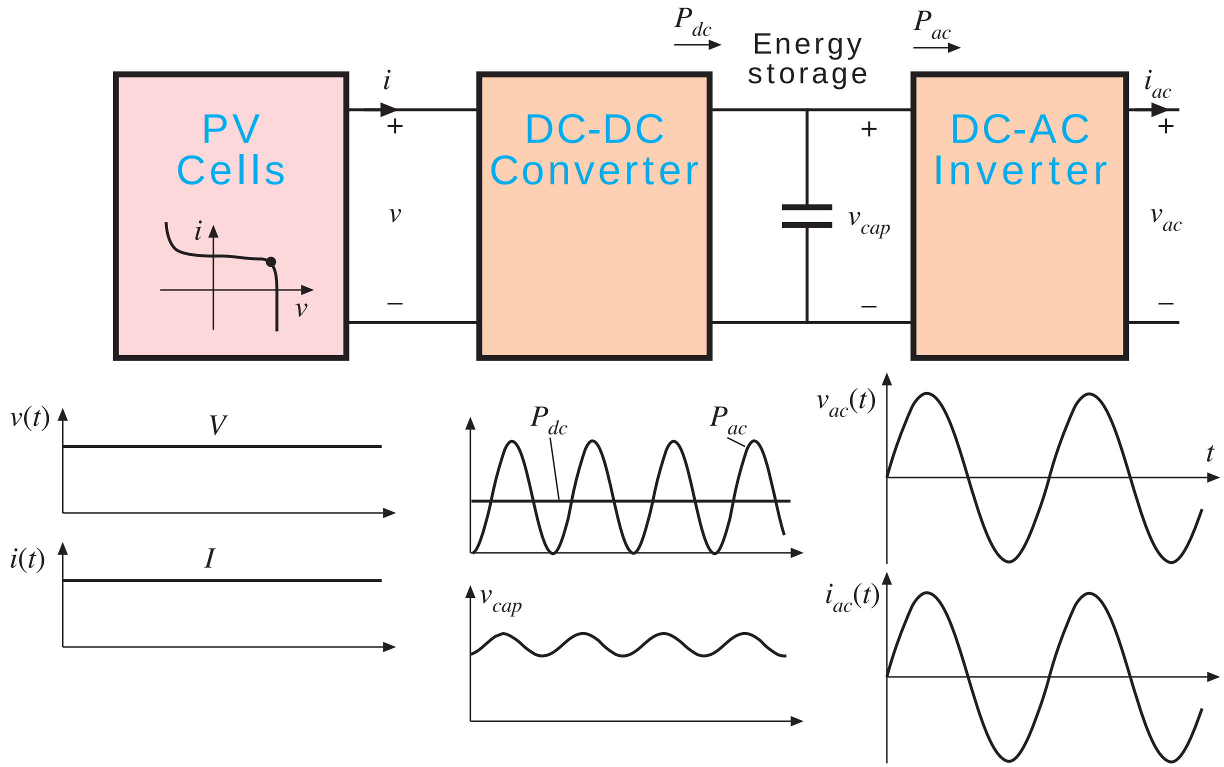


- DC disconnect switch allows modification during daylight
- AC disconnect required by utility

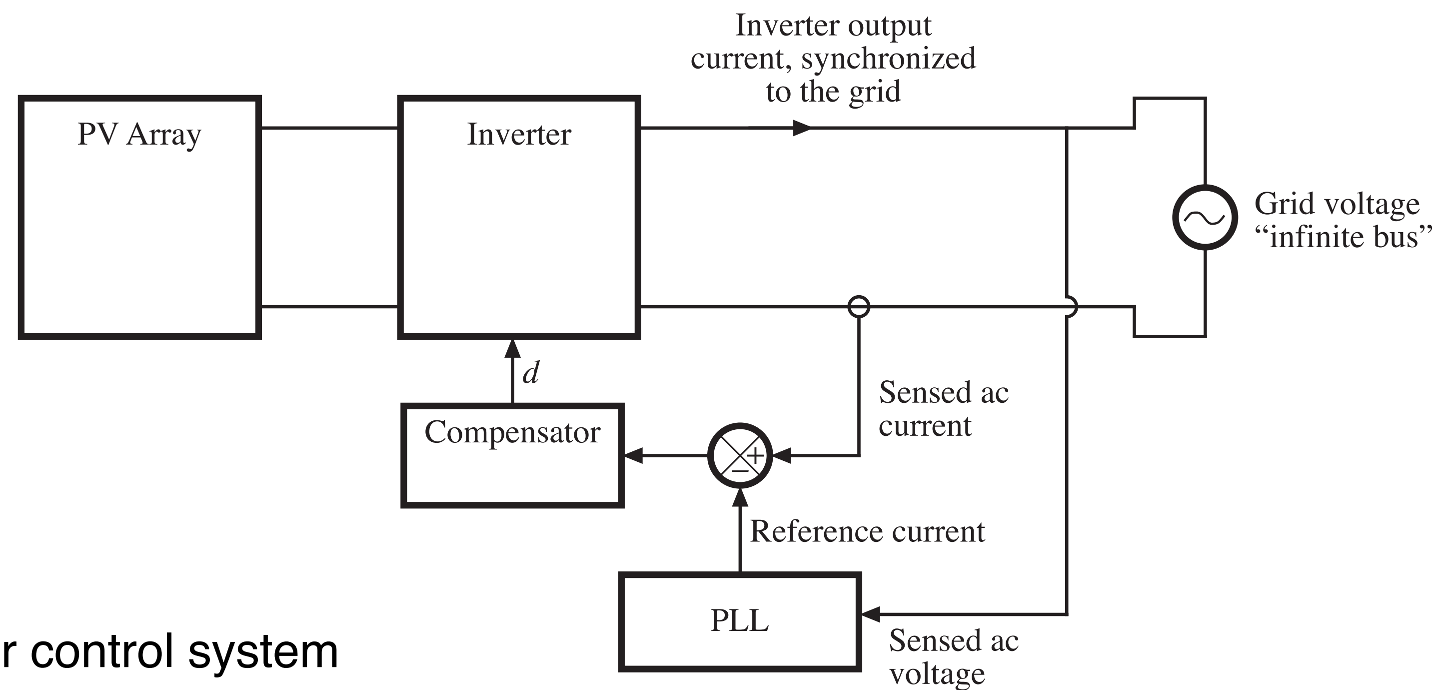
Single Phase Inverter:
Energy Storage is Required

In a single-phase system, the inverter must include a 120 Hz energy storage capacitor

The power supplied by the PV array is constant, but the power supplied to the AC grid pulsates at twice the ac grid frequency. A capacitor must store the difference.



Inverter controller



The inverter control system regulates its output current to be sinusoidal and in phase with the grid voltage

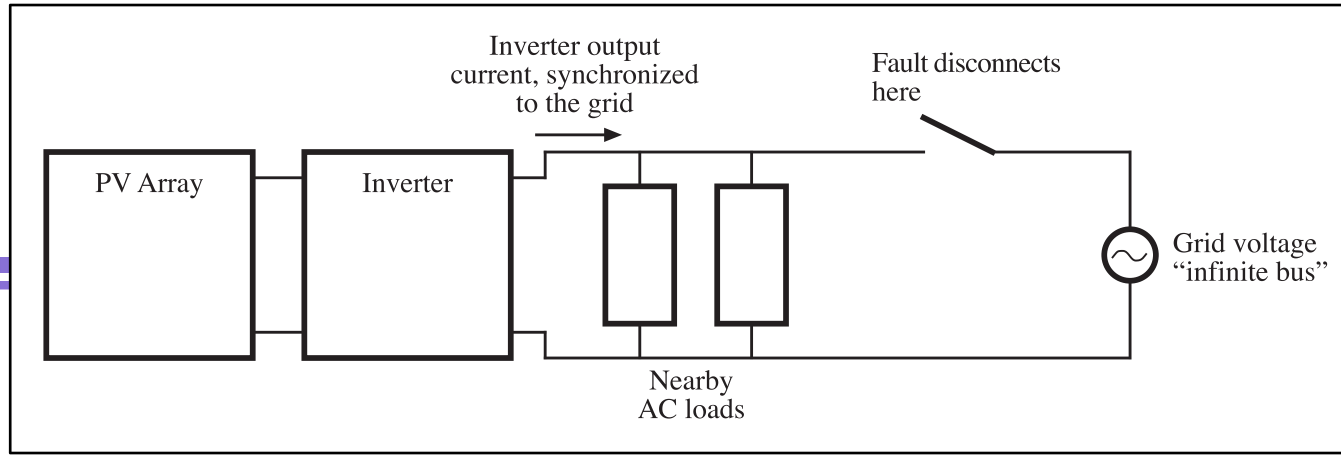
IEEE 1547

IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems

Requirements on grid-tied PV inverters. Some highlights:

- Inverter disconnects when grid voltage or frequency are outside normal range. Reconnection happens after the normal range is restored, plus a delay (nominal 5 minutes)
- Regulation of local grid voltage is not allowed
- AC current injected into grid must have THD < 5%
- Anti-islanding: inverter must shut down in less than 2 seconds under islanding conditions
- Withstand surges from grid
- No injection of dc into grid

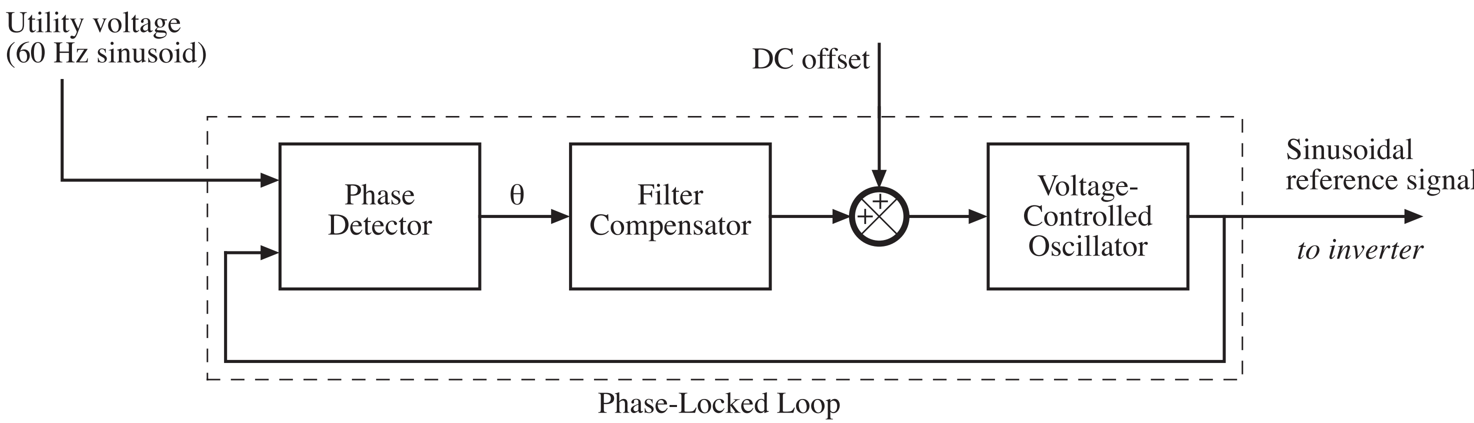
Islanding



In the event of a grid failure, it is possible that the PV inverter could continue to supply power and energize nearby loads. This is called "islanding"

- The utility company considers this to be very dangerous for their linemen
- During islanding, the PV inverter can backfeed power into the grid, through the local pole-mounted transformer, to the local distribution feeder (13.6 kV in Boulder)
- The utility line worker expects the distribution feeder to be de-energized. Backfeeding by household PV arrays can cause unexpected energizing
- The power company wants to know where all the PV arrays are, so that line workers can turn them off (with their padlocks on the ac disconnect switches)

Realization of Anti-Islanding



A phase-locked loop circuit (PLL, above) provides the reference signal to the inverter; the ac current injected into the grid follows this reference.

The PLL reference signal is therefore synchronized to the grid frequency.

The compensator typically includes an integrator (PI compensator). A DC offset is added to the output of this compensator; under normal conditions, this does not affect the output reference frequency.

Under islanding conditions, the DC offset causes the reference frequency to drift. When the inverter frequency drifts out of the allowed range, the inverter shuts down.