Thursday, 9/28/23

Applications: Grid-Connected PV Systems

1. Historical

Before 1990: stand-alone” PV systems were the vast majority of PV systems.

In the 1990’s: a shift started toward grid-connected PV systems:

PV power plants

Home/business PV systems tied to the AC grid

In 2000: grid-connected PV had overtaken stand-alone PV.

By 2009: more than 95% of PV cells were being used for grid-connected applications.

2. Small Grid-Connected PV Systems

These are typically roof mounted and 1 kW to 5 kW in size.

Consider a home mounted example:

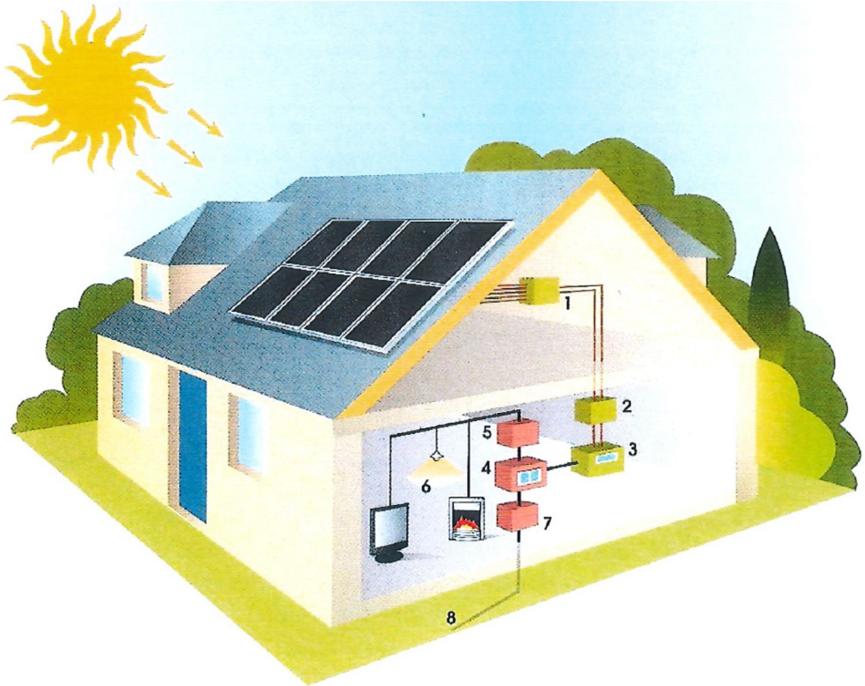


Figure 4.1 Connecting to the grid.

In the daytime, send any un-needed produced power to the AC grid for money.

In the nighttime, use power from the grid.

In effect, you are using the AC power grid for "energy storage."

> But: the "storage" is very "lossy" → the power company pays you a <u>lot</u> less for power than they charge you for it.

Referring to Figure 4.1, there are 8 major components:

(1) There are 8 PV modules on the sloped roof facing the sun. No concentration and no tracking are used.

(2) Box #1 is the "PV Combiner Unit" → an electrical junction box for connecting the PV modules in the desired configuration.

(3) Box #2 is the "Protection Switch" → a DC switch to isolate the PV modules from damaging power surges, such as from lighting striking the AC grid. It might also protect electronics further downstream from a lightning strike to the PV array.

(4) Box #3 is the "Inverter" → this device converts DC power from the PV array into AC power for internal use or for delivery to the AC power grid. To deliver AC power to the grid, the inverter must match the grid's voltage amplitude, frequency, and phase. It also must create an electrical load to the PV array at the MPP to extract the most power possible from the PV array.

(5) Box #4 is the "Energy-Flow Meter" → this meter is used to measure energy flow to and from the AC grid.

(6) Box #5 is the "Fuse or Breaker Box" → a standard circuit breaker box to protect the system from overloading or shorting faults.

(7) Box #6 is the "Electrical Loads."

(8) Boxes #7 and #8 are the "Junction Box and Cable" → for connecting to the AC power grid.

There are a number of possible issues with grid-connected home PV:

(1) Islanding → when the AC grid goes down but your PV system continues to supply power to the AC grid.

This is very dangerous for anyone working on the AC grid system!

Good grid-connected PV systems monitor the AC grid and disconnect from it when the grid goes down.

(2) Home use as grid backup

If your PV system only works when the grid is up, it won't provide you any power when the grid goes down. Many FL homeowners with expensive home PV systems found this out the hard way after a major hurricane took down the grid for days. In some areas, this is the law for grid connected home PV systems.

Even if the PV system will function without the grid being up, without storage batteries, it will only provide you with power during the day.

(3) Safety

Does your PV system affect fire risk or firefighting?

Safety of the firefighters during the day is a real concern because you cannot stop PV cells from producing electricity when exposed to the sun.

Does having the system on your home affect you homeowner's insurance?

(4) Business license

Does your country/state/city/county require you to have a business license to sell power back to the power company?

(5) EMP event

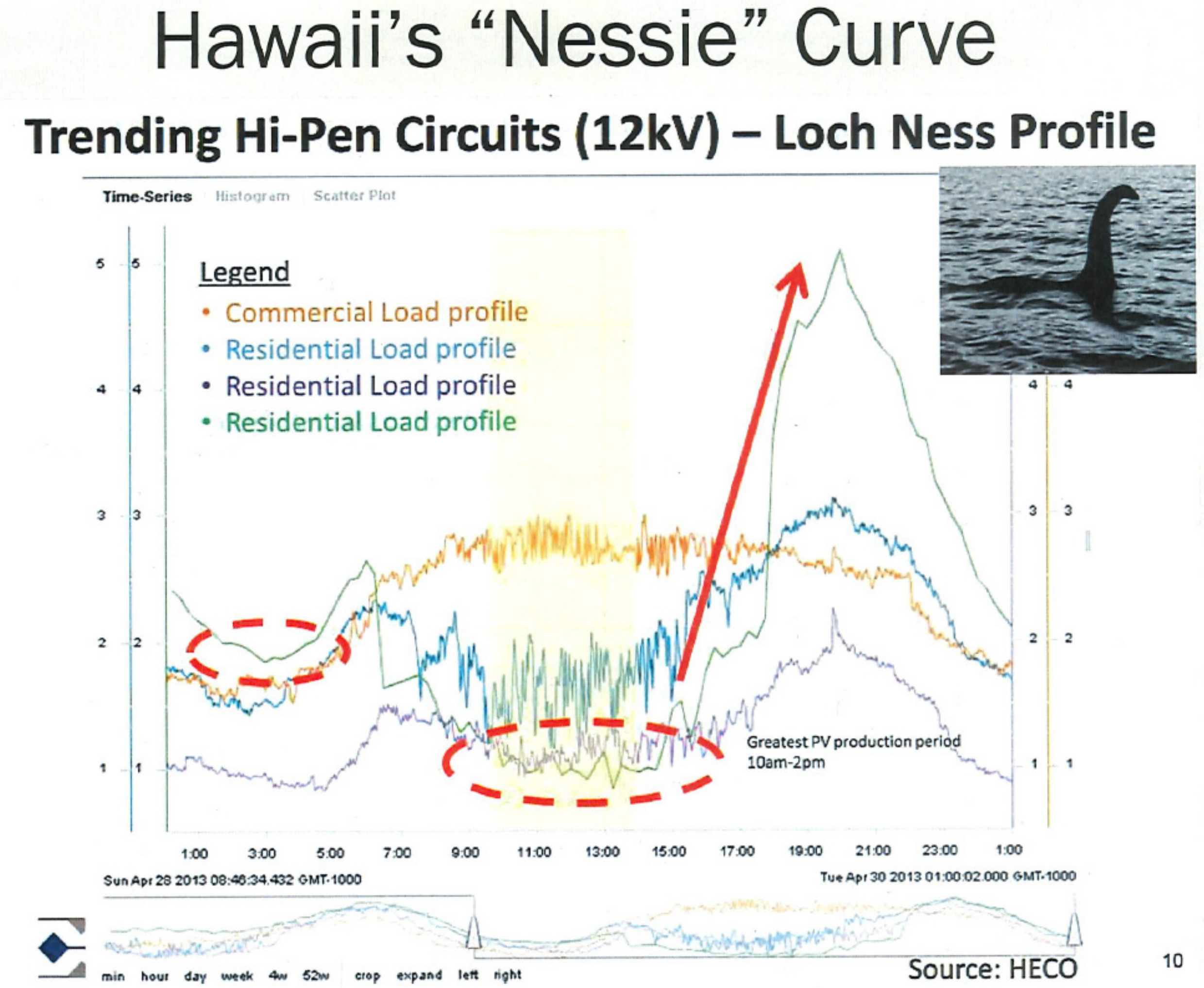
What if there is an EMP event? Is your PV system susceptible to the event? Officially, this is unknown.

The MPP tracker and inverter would likely be destroyed.

Many loads (those with modern electronics) would be destroyed.

The PV cells, storage batteries, motors, some lights, and heating elements should/might survive.

3. Consider some effects that happened in Hawaii with large numbers of grid-connected home PV systems:



Hawaii's "Nessie" Curve

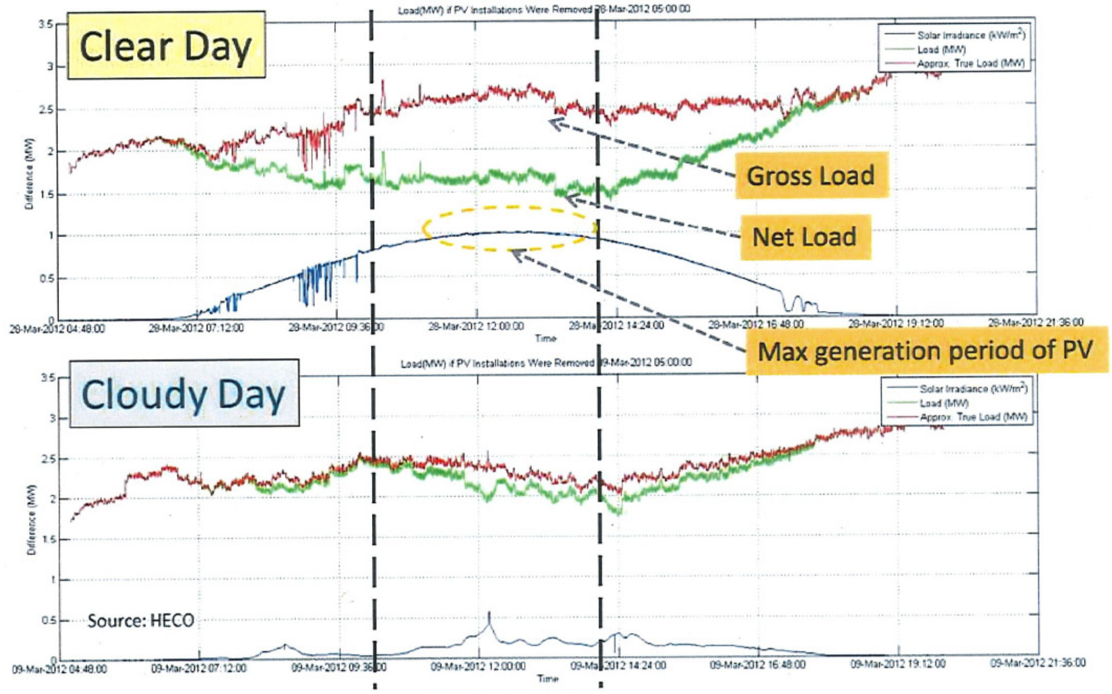
Trending Hi-Pen Circuits (12kV) – Loch Ness Profile

Legend
- Commercial Load profile
- Residential Load profile
- Residential Load profile
- Residential Load profile

Greatest PV production period 10am-2pm

Source: HECO

Gross vs Net? Understanding Solar Impact on Load



Clear Day

Gross Load

Net Load

Max generation period of PV

Cloudy Day

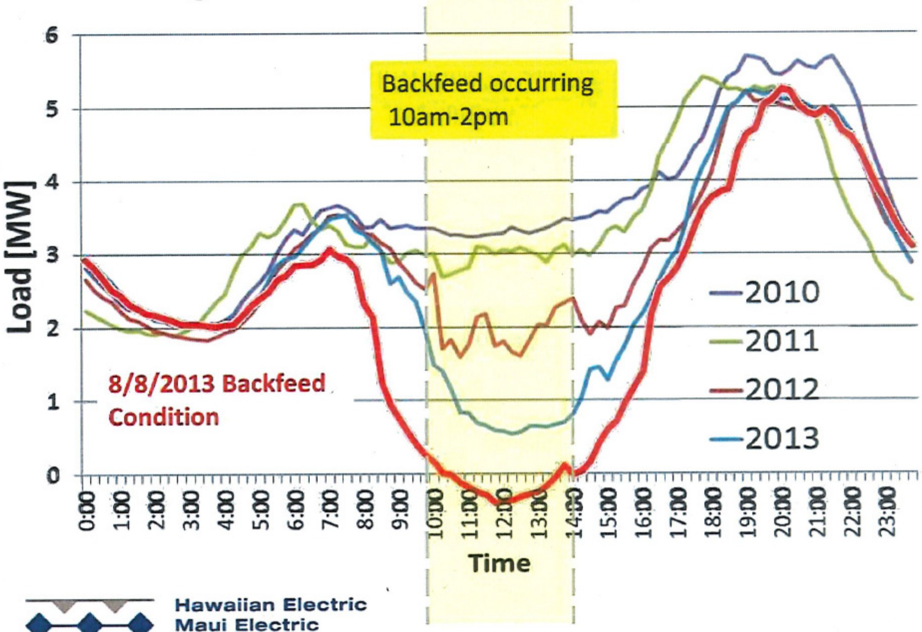
Source: HECO

Greatest Feeder PV to Load Variation Between 10 AM and 2 PM

Assume Linear Relation. Between Irrad. & Power

Tracking Change – 46kV Level

Average Transformer Load (MW) - December



Backfeed occurring 10am-2pm

8/8/2013 Backfeed Condition

Hawaiian Electric
Maui Electric
Hawai'i Electric Light

The Inverter

1. Introduction

The inverter converts DC to AC for delivery to a load or to the power grid.

The inverter must be highly efficient! Up to 98% efficiency is possible, at least at its maximum power rating.

2. The PV Side Operating Environment

The PV output varies widely: night/day, sunny/cloudy, summer/winter, etc.

We want the inverter load to the PV array to match the PV maximum power point (MPP). This process of tracking the MPP is called maximum power point tracking and the device that does this is called the Maximum Power Point Tracker (MPPT).

Large PV systems use multiple inverters, possibly one per PV module. This is useful when PV modules have different characteristics, or partial shading or a damaged cell occurs.

The PV array must be matched to the inverter, so that minimum/maximum current, voltage, and power stay within the operating limits of the inverter.

> Example: the maximum PV voltage might occur on a sunny cold winter day.

3. The Grid Side Operating Environment

The inverter delivers AC power to the grid. It must match the grid in terms of voltage, frequency, and phase.

There are two types of grid-connected inverter architectures:

(1) Self-Commutated: the inverter internally produces the AC signal, and then locks its output to the grid.

(2) Line-Commutated: the inverter senses the AC grid and uses it to achieve generation of the synchronized AC output.

The inverter must detect the presence of the grid's AC signal, or else disconnect from the grid. Failure to do this is called islanding (islanding is called "run-on" in Australia).

One question comes up about islanding: if multiple houses feed AC power onto the grid and the grid goes down, will each inverter be able to detect that the grid has gone down and then stop outputting power?

4. How an inverter works

An inverter typically consists of two stages:

(1) Boost Converter: this stage converts the ~ low voltage PV DC output to a higher DC voltage (a little higher than the AC grid's amplitude).

(2) AC H-Bridge Converter: this stage converts the DC voltage to AC voltage for power delivery to the power grid.

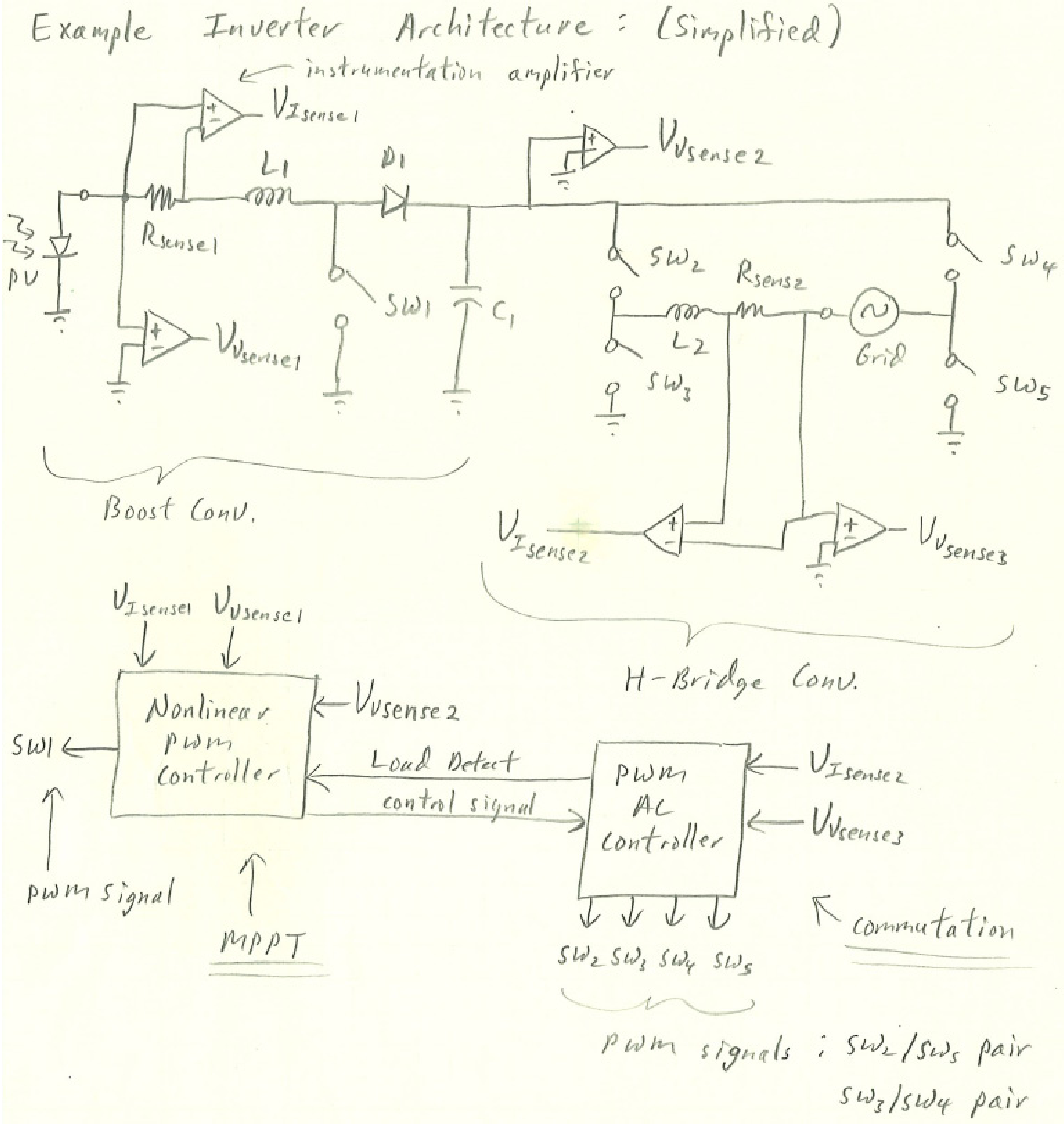
Other components of an inverter might include:

(1) Grid detection and synchronization

(2) MPPT

(3) Power factor (PF) correction

Consider a simplified architecture for an inverter:



The SW’s are power semiconductor devices: FETs, BJTs, IGBTs, etc.

The inverter is a very complicated electronic system.

Disciplines needed to develop an inverter: electronics, electromagnetics, controls, digital, programming, packaging, thermal, and power.

5. DC Isolated Inverter

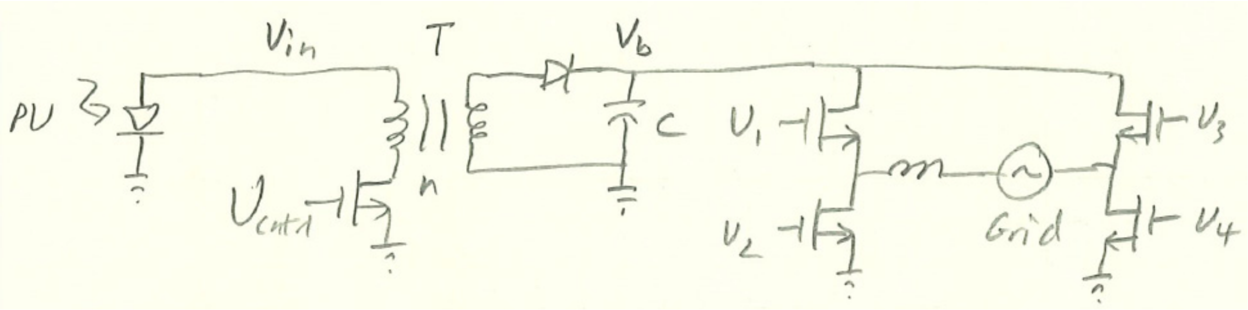
This inverter design uses a transformer to provide DC isolation between the PV array and the AC grid.

This DC isolation between the AC grid and the PV array is useful because:

(1) Power transistors are the most likely component to fail.

(2) When a transistor fails, it often fails into a permanent on state.

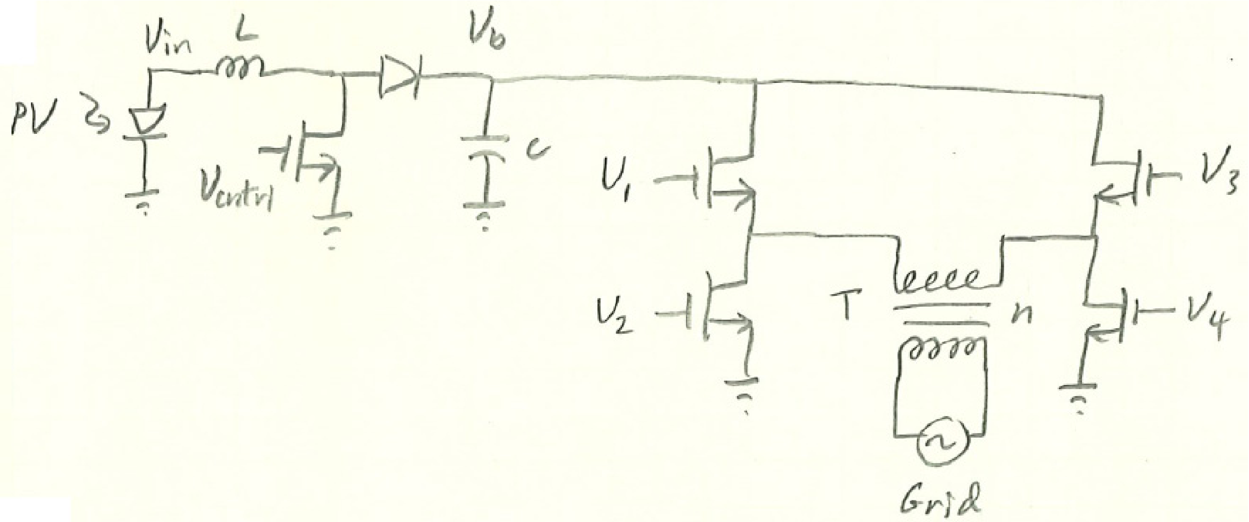
a. Boost Converter DC Isolation



Note: with the transformer, $V_b \geq V_{in}$, or $V_b \leq V_{in}$, or $V_b = -nV_{in}$.

Also, with a transformer, it can have multiple secondary outputs.

b. AC H-bridge Converter DC Isolation



The “working voltage” can be low and then stepped up at the transformer.

Note: in the previous two drawings of inverter architectures, controllers and sensing elements were left out of the drawings for simplicity.

6. Challenges to Inverter Scale-Up to PV Commercial Power Plants
    (1) Inverter size: Consider Fig. 4.5 → a 1.6 MW inverter (over 20 tons).
    (2) Inverter cooling: air or liquid cooling?

        Support infrastructure required: heat exchangers, chillers, fans, pumps, duct work and/or plumbing, water supply, etc.
    (3) Lightning protection
    (4) Surge protection
    (5) Facility security
    (6) Serviceability: the PV arrays output electricity whenever light shines on them.
    (7) Electrically connecting large numbers (possibly 100k's) of PV modules into strings and arrays.
    (8) Inverter output waveform purity and power factor
    (9) Islanding protection

Figure 4.5 Scaling up: this 1.6 MW_p inverter weighs over 20 tons (Padcon GmbH).

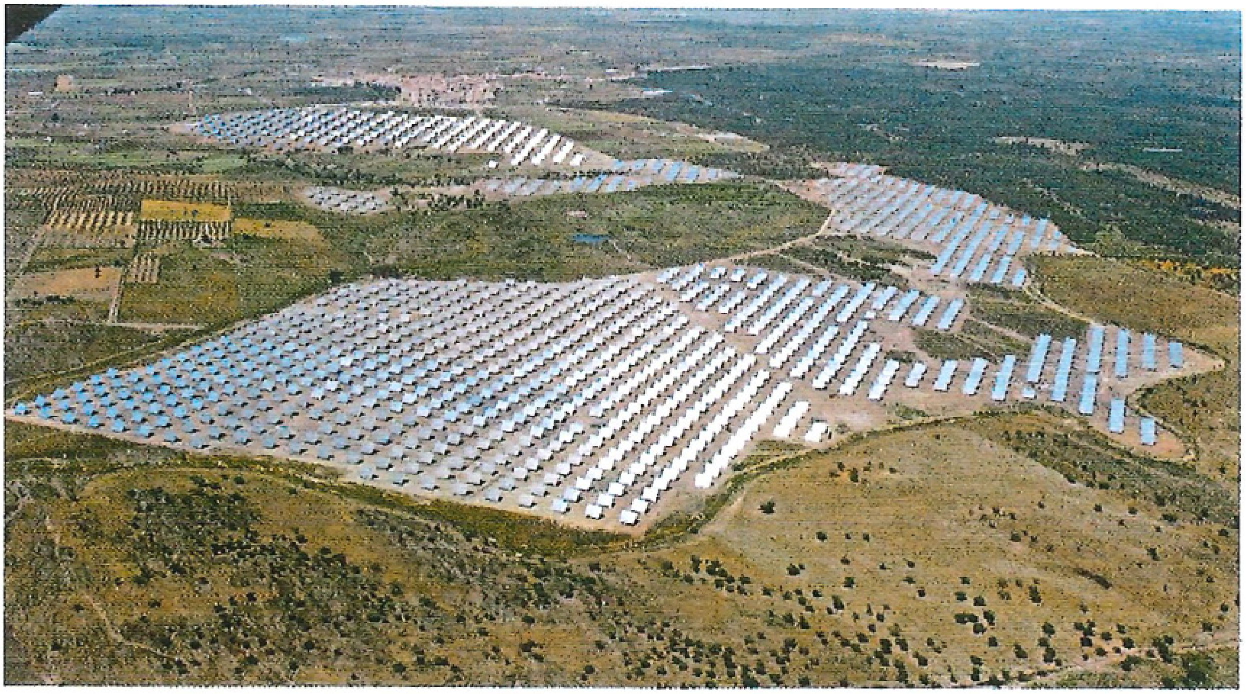


Figure 4.6 The Moura power plant in Portugal, rated at 45.6 MW_p, represents a big challenge for inverters as well as PV cells and modules (IEA-PVPS).

7. Example Commercially Available Inverter for PV

Fimer Solar Inverter: UNO-DM-6.0-TL-PLUS-US-Q

https://www.fimer.com/single-phase/uno-dm-60-tl-plus-q-us