Photovoltaic (PV) Systems: Impact on Distribution Feeder Operation

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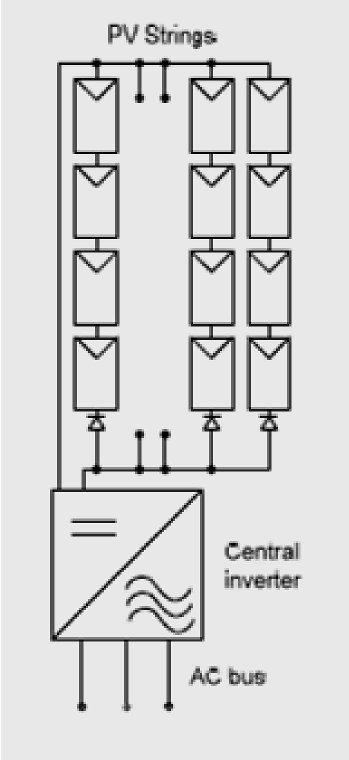
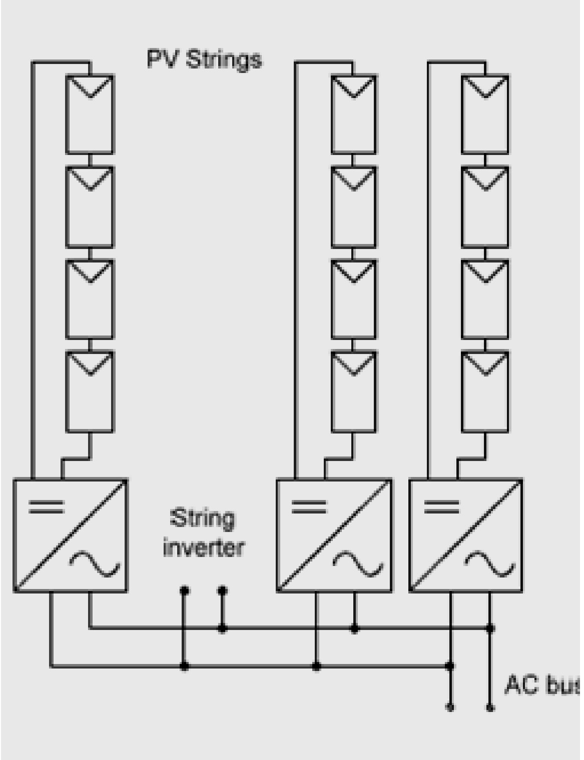
Overview

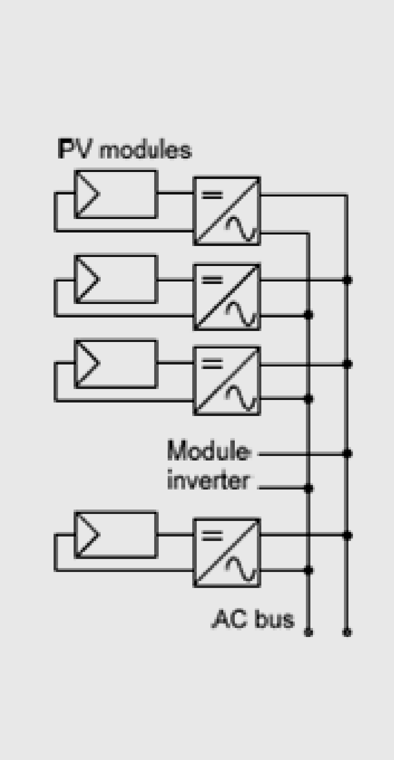
- Types of Inverter Configurations
- Types of Inverter Topologies
- Maximum Power Point Tracking
- Grid interconnection requirements (IEEE Std.1547)
  - Power Quality (Current Distortion)
  - Response to Utility Voltage and Frequency Deviations
- Experimental Tests (Response to Utility Voltage Deviations)
- Impact of High PV Penetration on Grid Operation
- Need for Design Modifications (Reactive Power Support).

Inverter Configurations

- Grid-tied inverters rely on the grid AC voltage and frequency – they do not regulate)
- On the other hand, stand-alone inverters regulate their own AC voltage and frequency.
- There are numerous configurations of grid-tied PV systems:







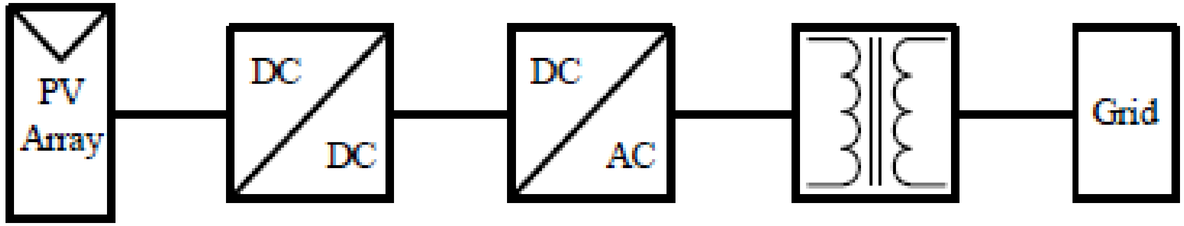
String Inverters (1kW-25 kW)

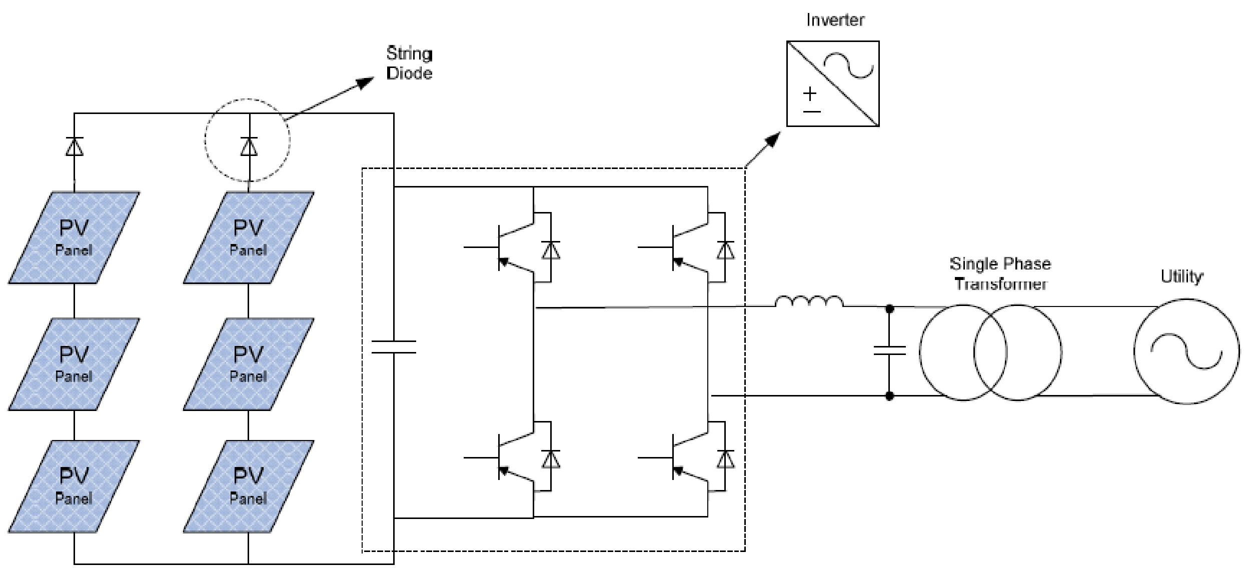
- These are used in small commercial and residential applications.
- Each string has its own (independent) inverter – no need for blocking diode,
- This method provides enhanced power harvesting from solar panels, particularly under partial shading.

Module-Incorporated Inverters (50 W – 350 W)

- Each solar panel module has its own inverter, thus maximizing solar power harvesting,
- Modular (plug-and-play) – simple system expansion,
- Lowest installation labor costs,
- Lower efficiency and high material cost (per W).

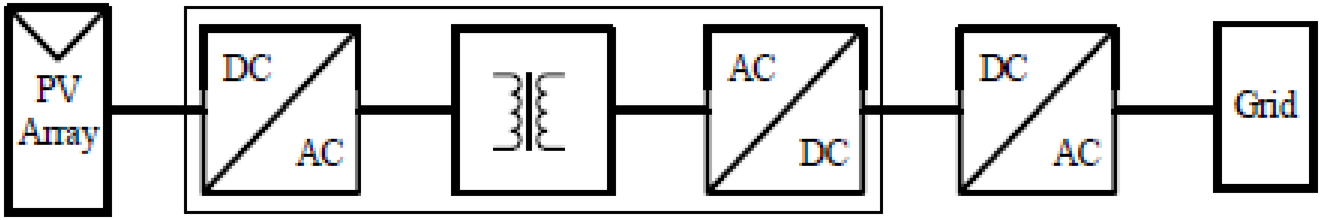
Single-Stage Inverter Topology

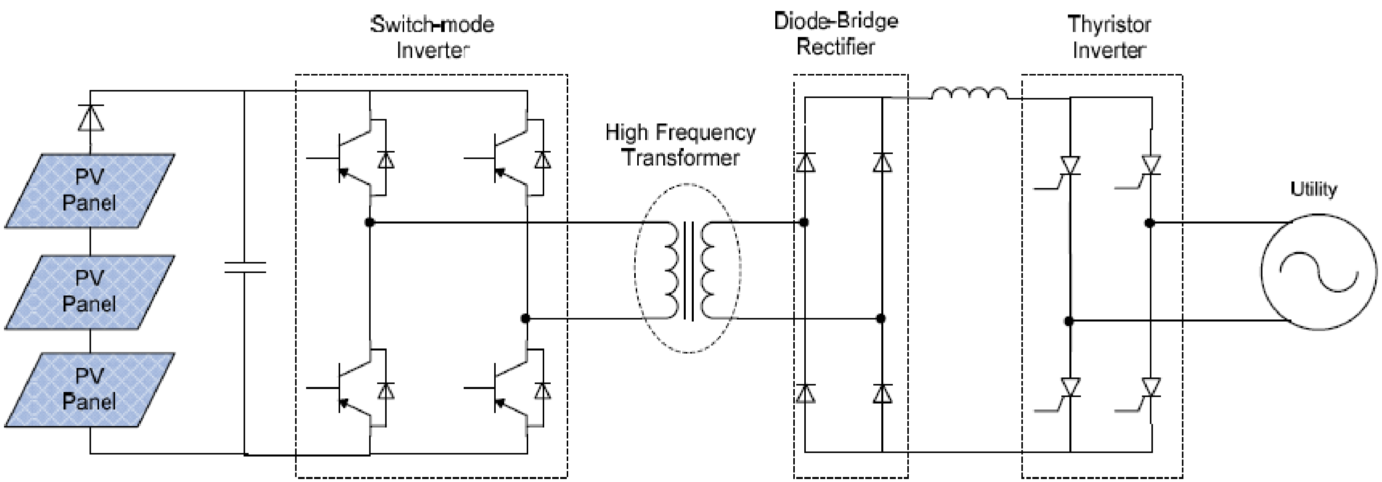




- This configuration requires a heavy line frequency (60 Hz) transformer (for voltage step-up and isolation).

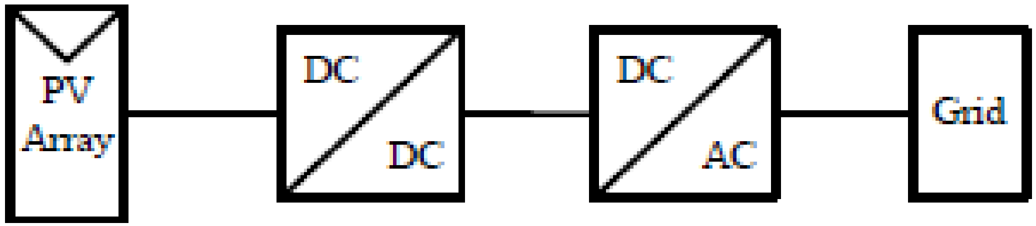
Two-Stage Inverter Topology

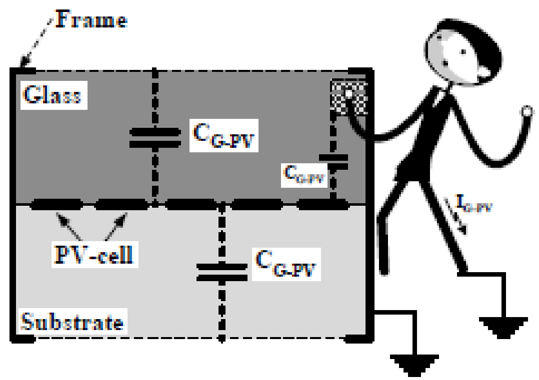




- This topology uses a high-frequency transformer for isolation → lighter weight and higher efficiency.

Transformless Inverters



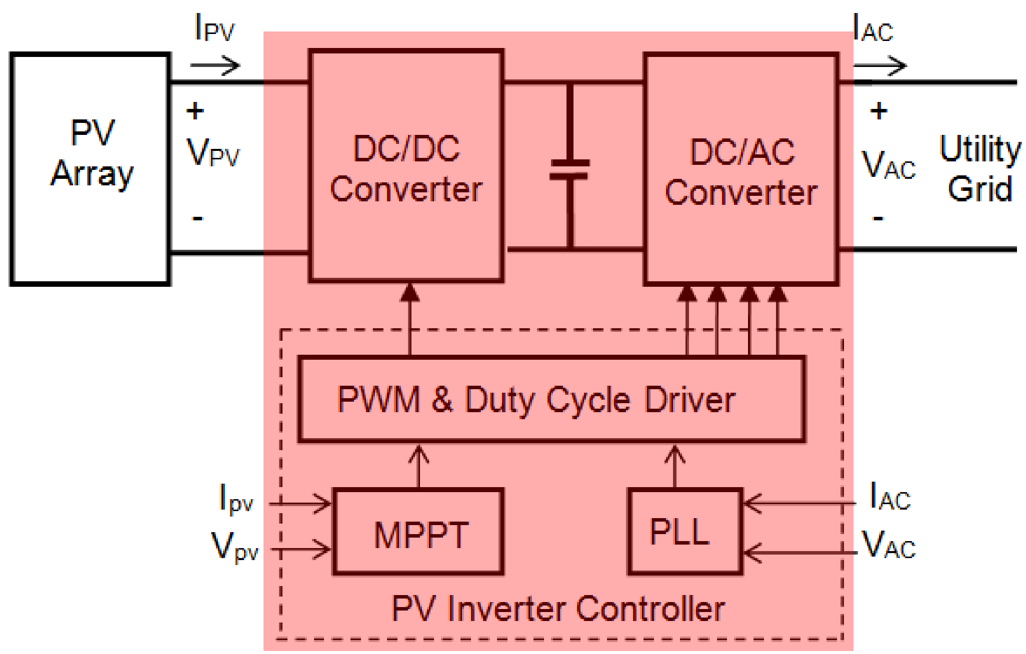


- Configurations without transformers are used in European countries and in Japan where DC side grounding is not mandatory.
- In the United States, until recently, the National Electrical Code (NEC) - Article 690 - required that the PV modules be grounded (for VDC > 50 V). Now abolished.
- Parasitic capacitance leads to ground leakage currents – electric shock possible under certain conditions.

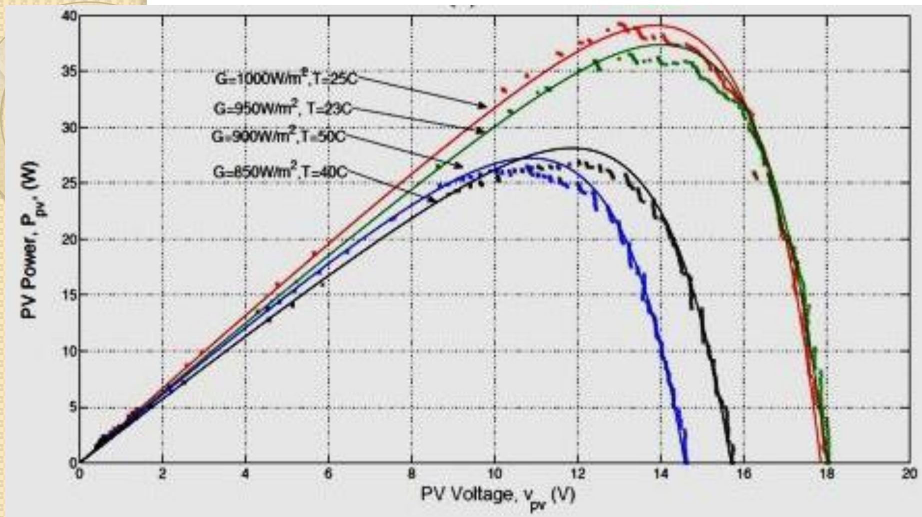
Grid-Tied PV Inverters

Major tasks of a grid-tied inverter:

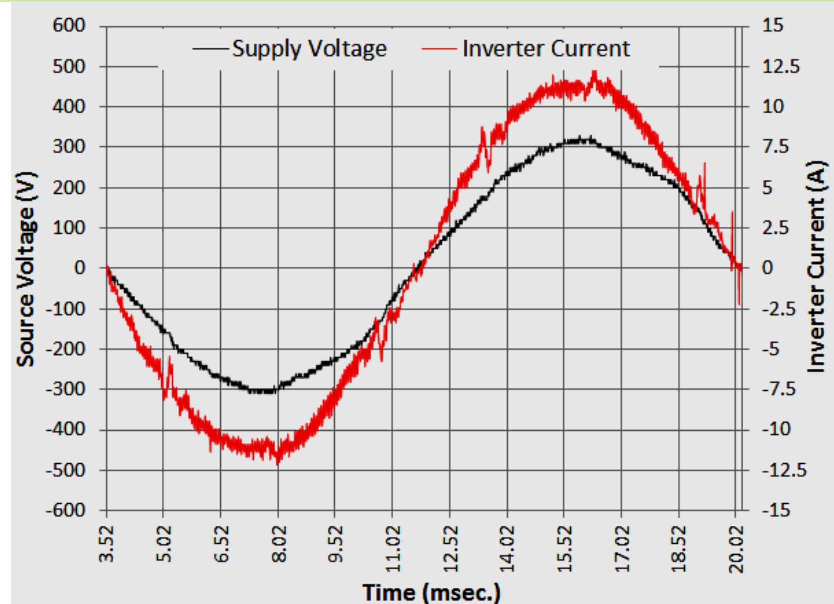
- Monitor the PV array, track the maximum power point (MPP) and operate at that point.
- Sense the presence of the grid, synchronize to it, and inject a sinusoidal current in phase with the voltage.
- Monitor the grid and disconnect in case of trouble (i.e., sufficiently large deviations in voltage or frequency).



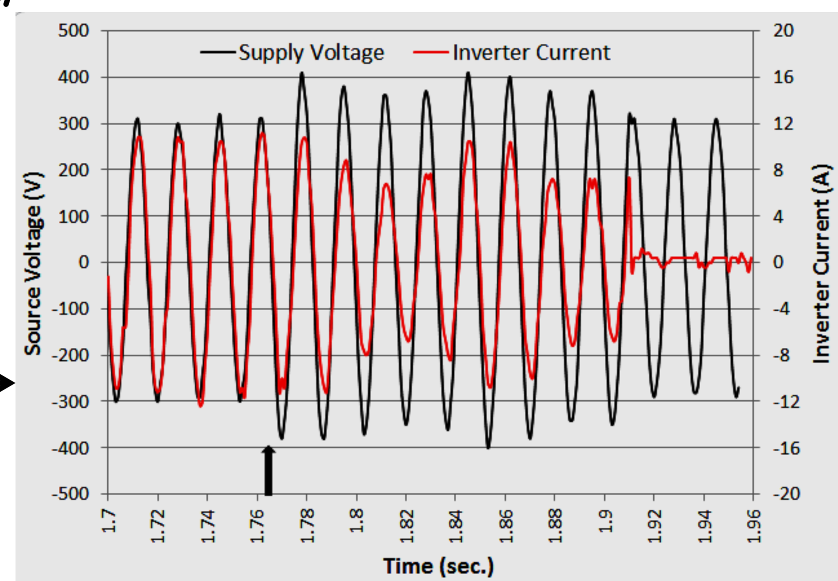
Functions of Conventional Grid-Tied PV Inverters



Maximum Power Tracking



Grid synchronization



Grid Monitoring - Disconnect

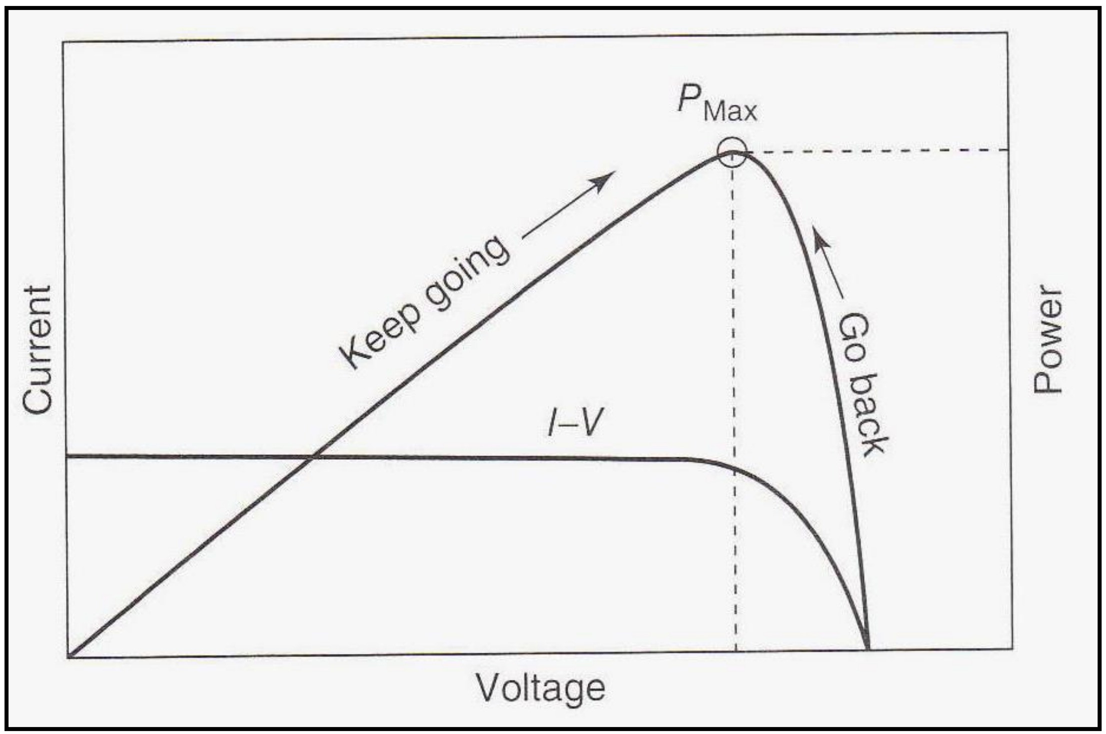
Harmonic Current Distortion Parameter Limits (IEEE Std. 1547)

Individual harmonic order h (odd harmonics)[b]	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	Total demand distortion (TDD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

Maximum Power Point Tracking (MPPT)

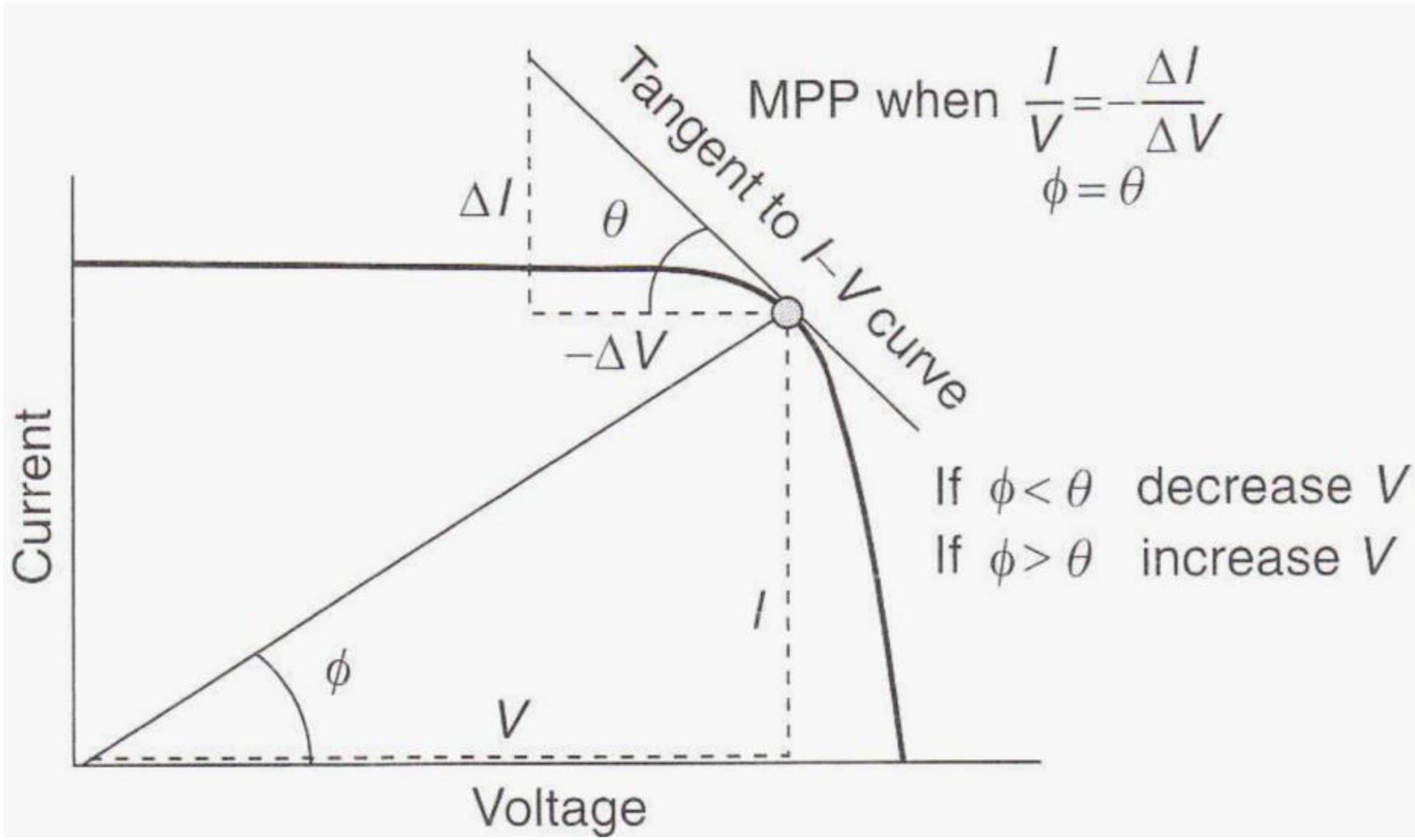
Tracking the maximum power point of a PV array is an essential task of the inverter.

Most common MPPT methods: perturb-and-observe (or hill climbing) method, and incremental conductance method.



Perturb-and-Observe Method

Maximum Power Point Tracking (MPPT)



Incremental Conductance Method

Newer gird codes have been recently developed which require "advanced" inverters to provide additional grid-friendly functions.

IEEE 1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

https://standards.ieee.org/standard/1547-2018.html

Required system response time to abnormal voltages

Default settings[a]		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
$V < 45$	0.16	0.16
$45 \leq V < 60$	1	11
$60 \leq V < 88$	2	21
$110 < V < 120$	1	13
$V \geq 120$	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted

[b] Base voltages are the nominal system voltages stated in ANSI C84.1-2011, Table 1.

Required system response time to abnormal frequencies

	Default settings		Ranges of adjustability	
Function	Frequency (Hz)	Clearing time (s)	Frequency (Hz)	Clearing time (s) adjustable up to and including
UF1	< 57	0.16	56 – 60	10
UF2	< 59.5	2	56 – 60	300
OF1	> 60.5	2	60 – 64	300
OF2	> 62	0.16	60 – 64	10

Advanced Inverter Functionalities

- Advanced inverters are controlled by software applications; and many of their electrical characteristics can be modified through software settings and commands.
- **<u>Common functions:</u>**
  - Inverters have the capability of "riding through" minor disturbances to frequency or voltage. These functions are called **under/over frequency ride-through and under/over voltage ride-through.**

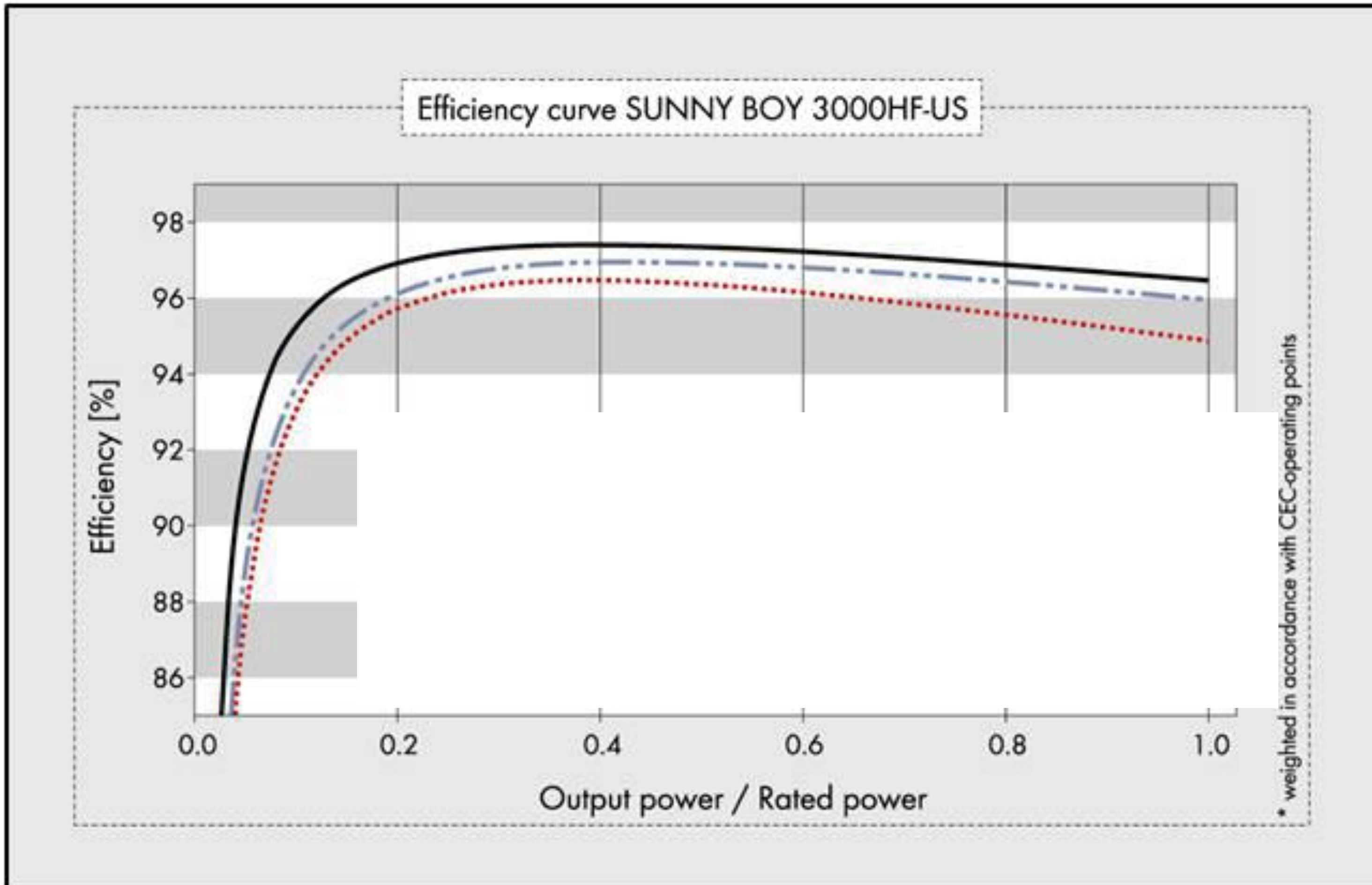
Advanced Inverter Functionalities

- **Injecting or absorbing reactive power into or from the grid (i.e., dynamic reactive power control).** These functions make system stability maintenance easier by keeping voltage and frequency within specified limits.
  - ✓ Oversizing an inverter allows reactive power generation/absorption even during peak irradiance.
- **Soft start** involves staggering the timing of reconnection of inverters on a single distribution circuit, to avoid spikes in the active power being fed onto the grid as it returns to normal functioning, limiting the risk of triggering another grid disturbance.

Typical Inverter Electrical specifications

Technical data	Sunny Boy 2000HF-US	
	208 V AC	240 V AC
Input (DC)		
Max. recommended PV power (@ module STC)	2500 W	
Max. DC power (@ cos φ = 1)	2200 W	
Max. DC voltage	600 V	
DC nominal voltage	480 V	
MPP voltage range	175 – 480 V	
Min. DC voltage / start voltage	175 V / 220 V	
Max. input current / per string	15 A / 15 A	
Output (AC)		
AC nominal power	2000 W	
Max. AC apparent power	2000 VA	
Nominal AC voltage / adjustable	208 V / ●	240 V / ●
AC voltage range	183 – 229 V	211 – 264 V
AC grid frequency; range	60 Hz; 59.3 – 60.5 Hz	
Max. output current	9.6 A	8.3 A
Power factor (cos φ)	1	
Phase conductors / connection phases	1 / 2	
Harmonics	< 4%	
Efficiency		
Max. efficiency	97.3%	

Inverter Efficiency Curve

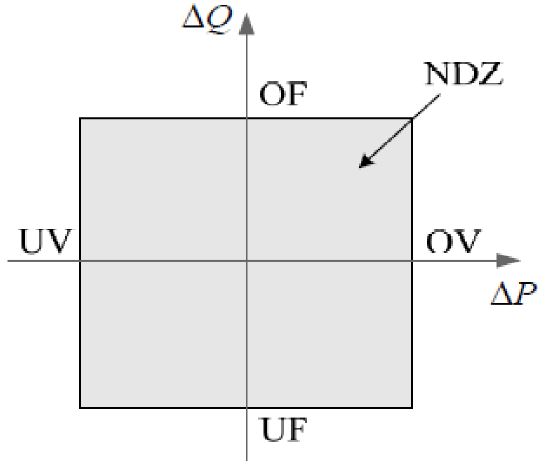


Islanding

- Islanding is the continued operation of the inverter when the grid has been removed intentionally, by accident, or by damage.
- Grid-tied inverters must be able to detect an islanding situation, and take appropriate action in order to prevent bodily harm and damage to equipment connected to the grid.
- In other words, if the grid has been removed from the inverter; the inverter should then stop attempts to supply power.

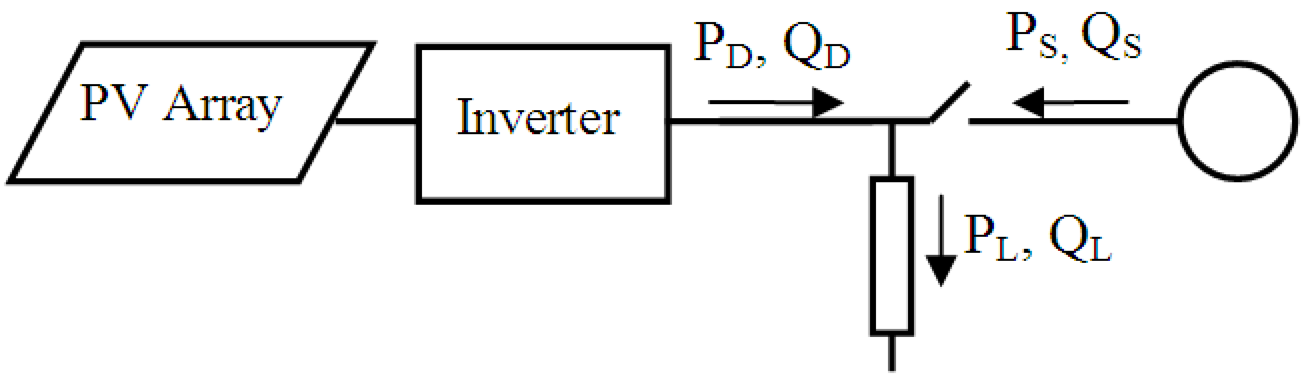
Inverter Islanding Detection –Passive Methods

- Standard protection of grid-connected PV systems consists of four relays that will prevent islanding under most circumstances.
  - over-voltage relay,
  - under-voltage relay,
  - over-frequency relay,
  - under-frequency relay.



- However, if the local load closely matches the power produced by the inverter, the voltage and/or frequency deviations after a power outage may be too small to detect, i.e., fall within the non-detection zone (NDZ).
- In this case, additional active schemes are required to minimize the probability of an island to occur.

Voltage and Frequency Deviations (Simple RL Load)



Let $P_S/P_D = \alpha$, and $Q_S/Q_D = \beta$.
Before utility disconnect,

$$P_D(1+\alpha) = \frac{V^2}{R} \qquad Q_D(1+\beta) = \frac{V^2}{\omega L}$$

After utility disconnect,

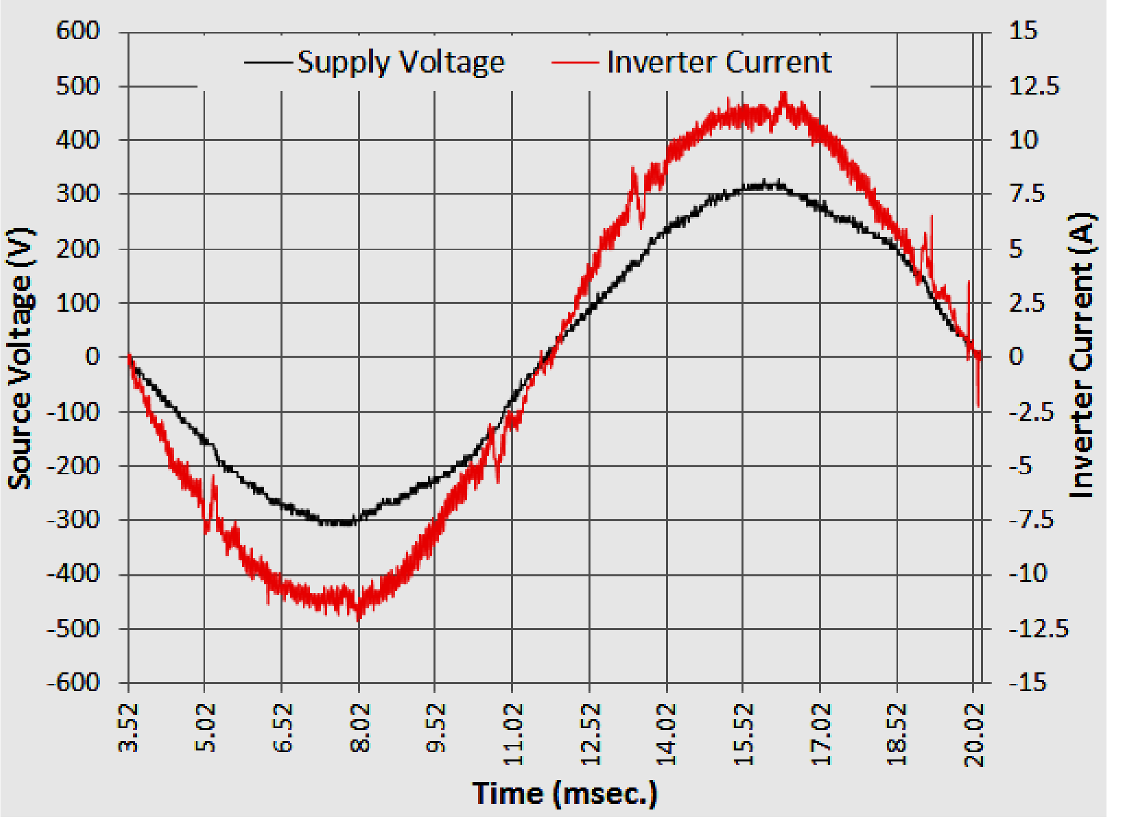
$$V' = \frac{1}{\sqrt{1+\alpha}} V \qquad \omega' = \frac{1+\beta}{1+\alpha} \omega$$

Response of 2 kW PV System to Voltage Disturbances

PV Array Size: 2 kW (peak)

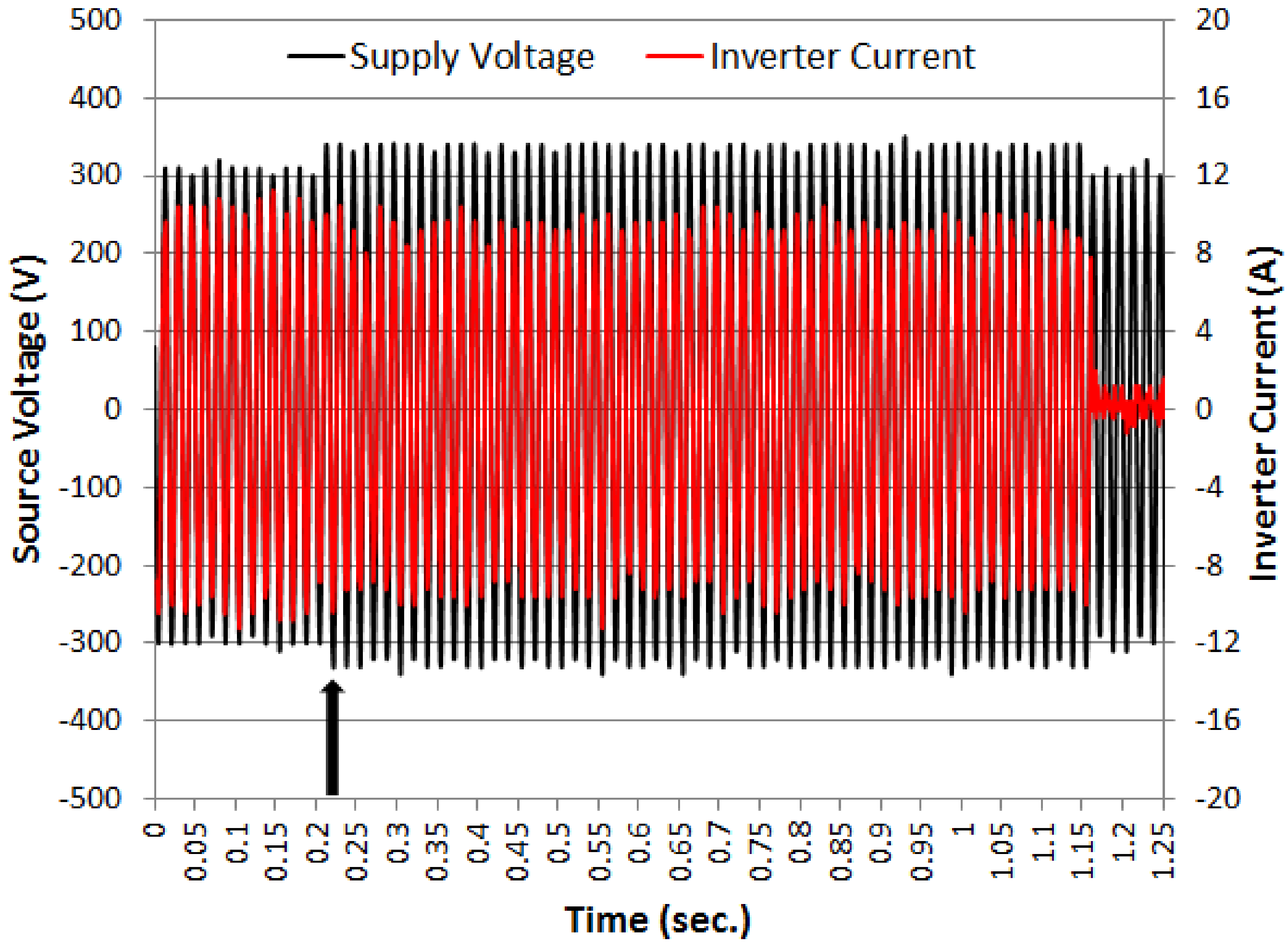
- Over-voltage test (1.1 pu <V < 1.2 pu) – will the inverter disconnect within 60 cycles?
- Over-voltage test (V > 1.2 pu) - will the inverter disconnect within 10 cycles?

Output Current



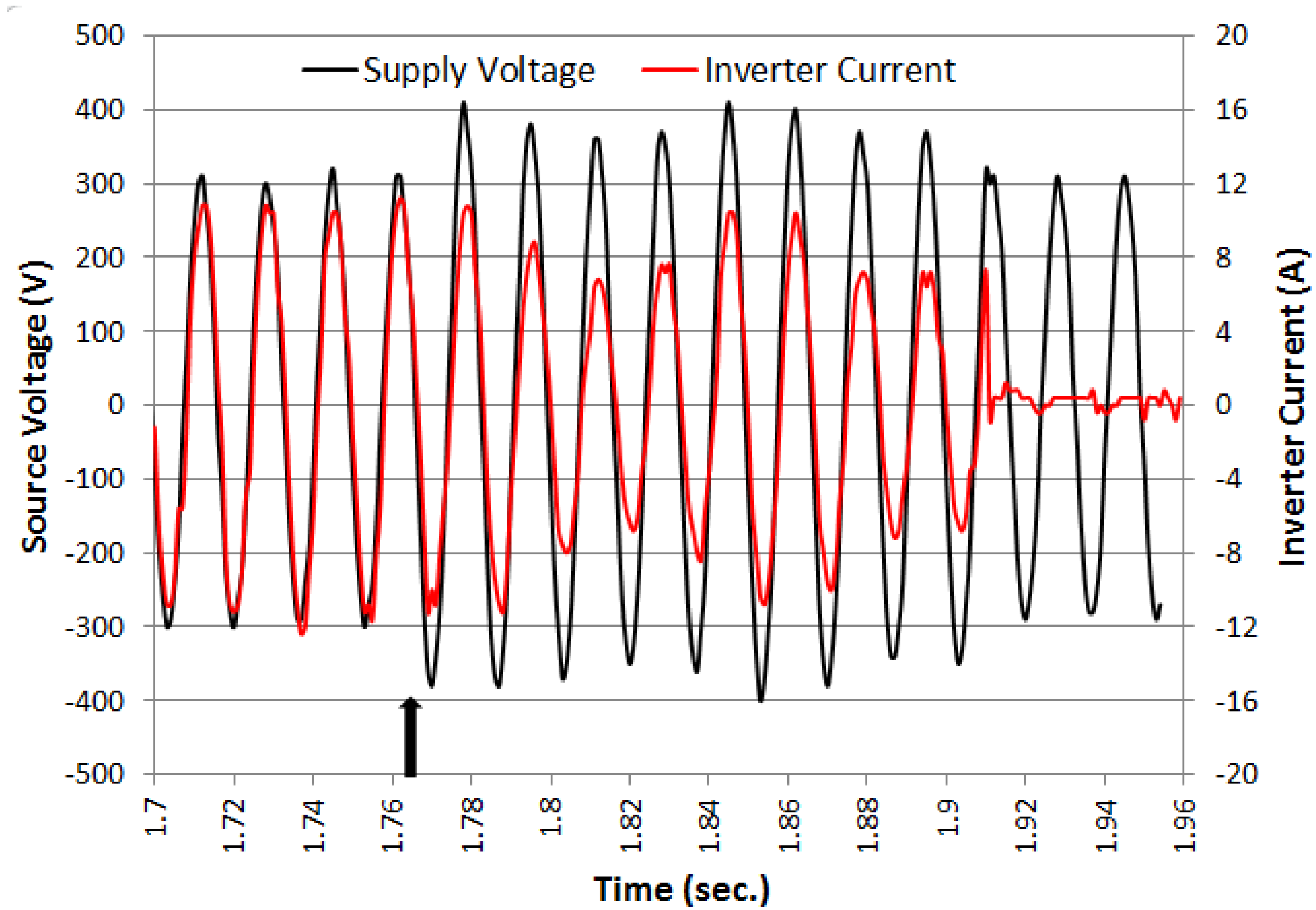
- The current THD is just below 4%.

Response to 14% overvoltage



- The inverter shut down after 56 cycles → The inverter is in compliance with IEEE Std. 1457.

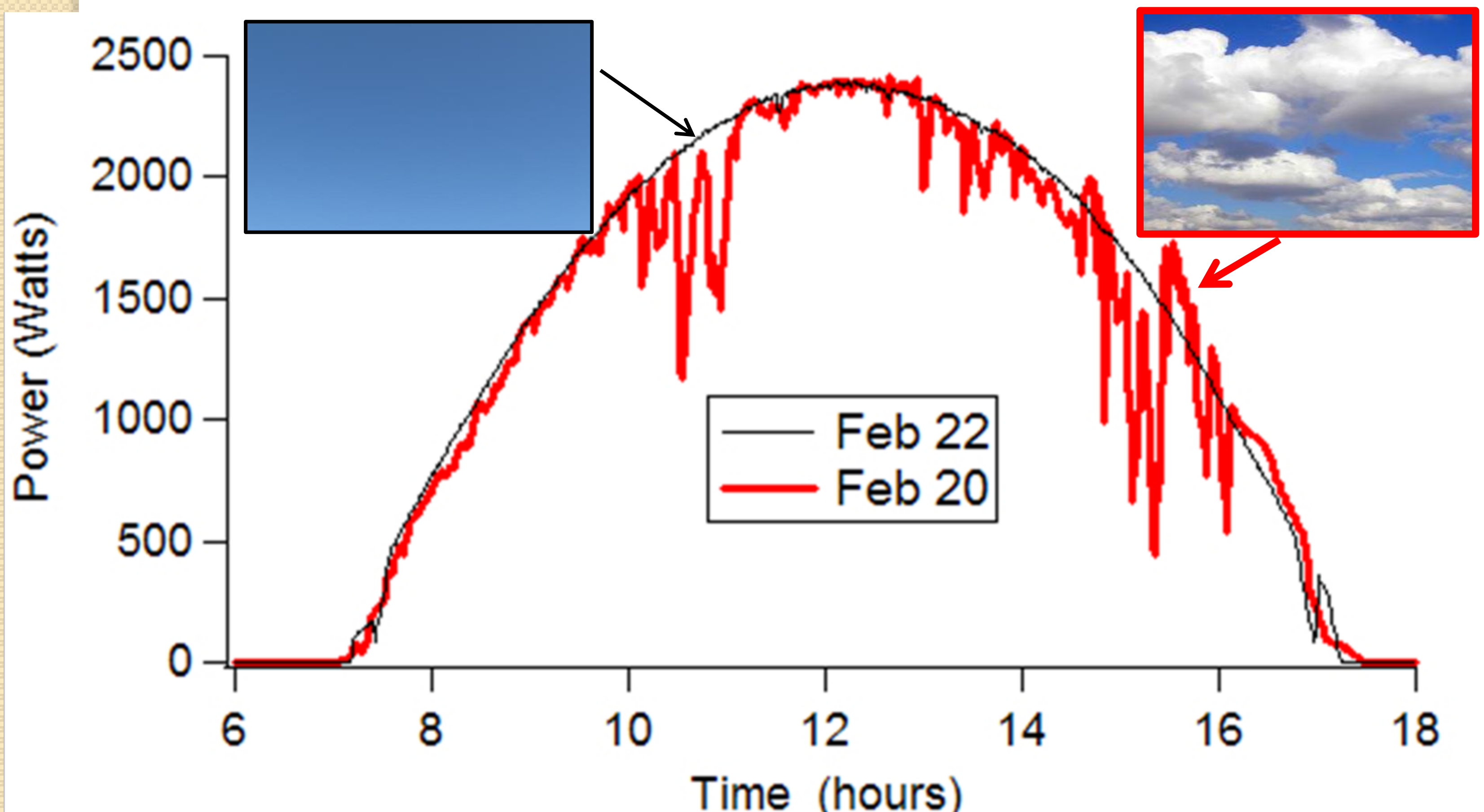
Response to 32% Overvoltage



The inverter shut down within 8 cycles → it is in compliance with IEEE Std. 1457.

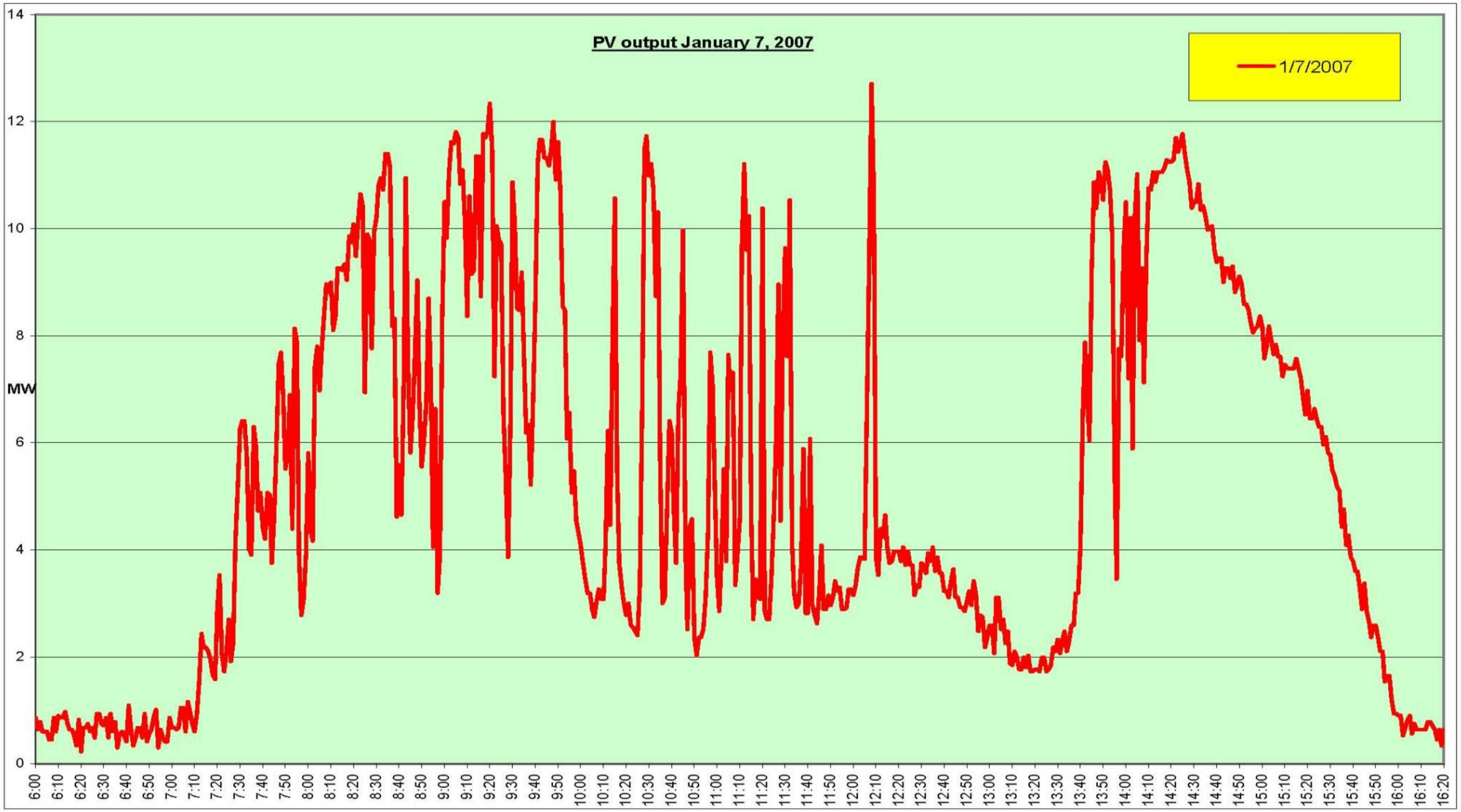
Impact on Grid Operation: PV Power Variability

Power generated by a 2.5 kW PV array on a clear day and on a cloudy day.



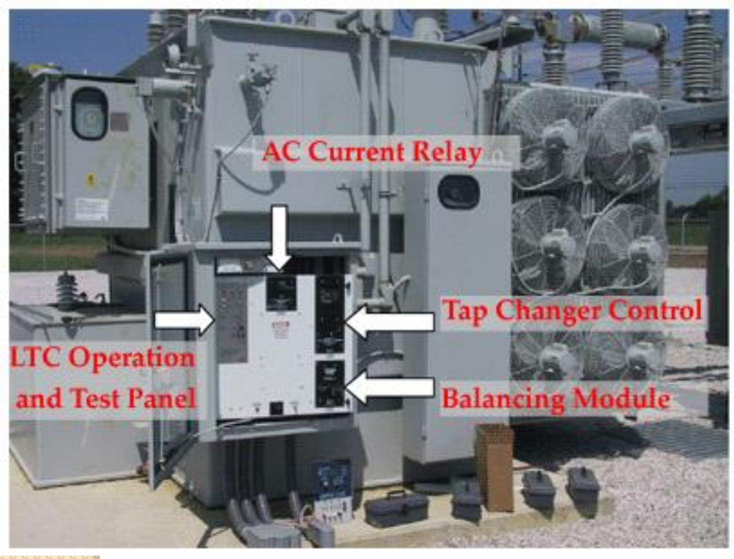
PV Power Variability of a Local 14 MW Plant

- PV power can change by up 50% in 0.5-1.5 minute time frame, and by up to 70% in 2-10 minute time frame, many times per day!

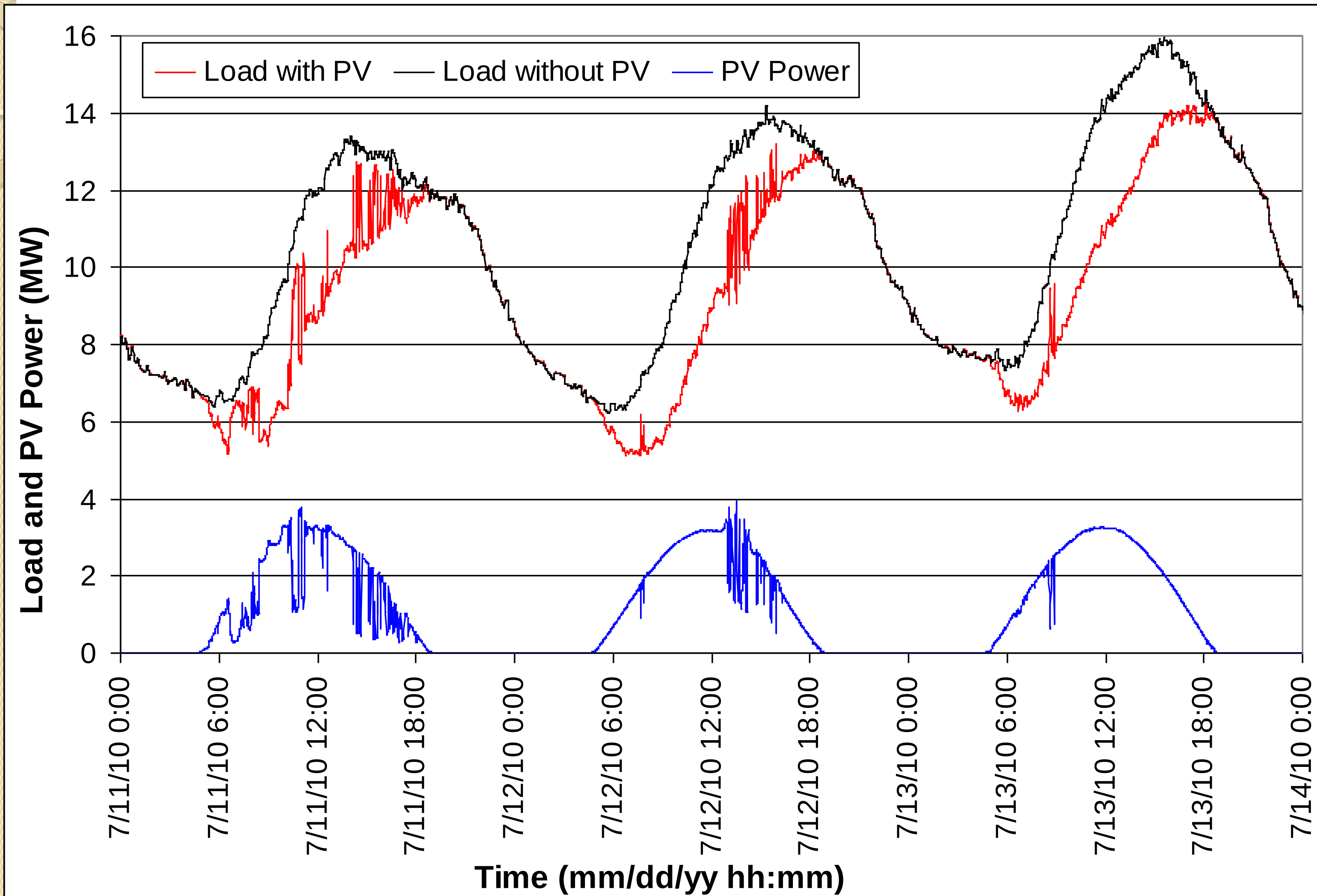


Impact of PV Power Fluctuations on Voltage Regulation (distribution level)

Large PV penetration on a distribution feeder leads to excessive operations of voltage regulation equipment (i.e., transformer LTC and Capacitor switching).



Example: Substation Transformer Net Load (with 20% PV)



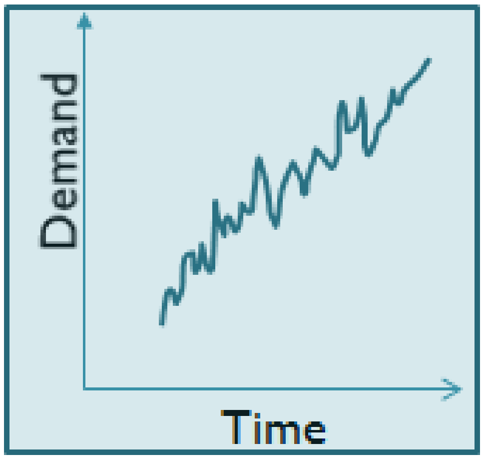
Simulated Number of Transformer Tap Changes with and without 20% PV Penetration

Date m/dd/yy	w/o PV	with 20% PV
7/11/10	20	92
7/12/10	10	42
7/13/10	10	26
Total	40	165

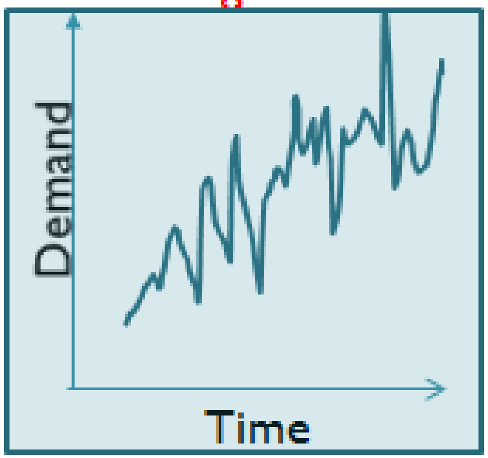
Impact of PV Power Variability (system level)

- The output of a PV plant changes according to the availability of sunlight, resulting in fluctuations in the plant output on all time scales.
- Large scale integration of variable generation can result in higher fluctuations on the system demand.

without PV



with large scale PV



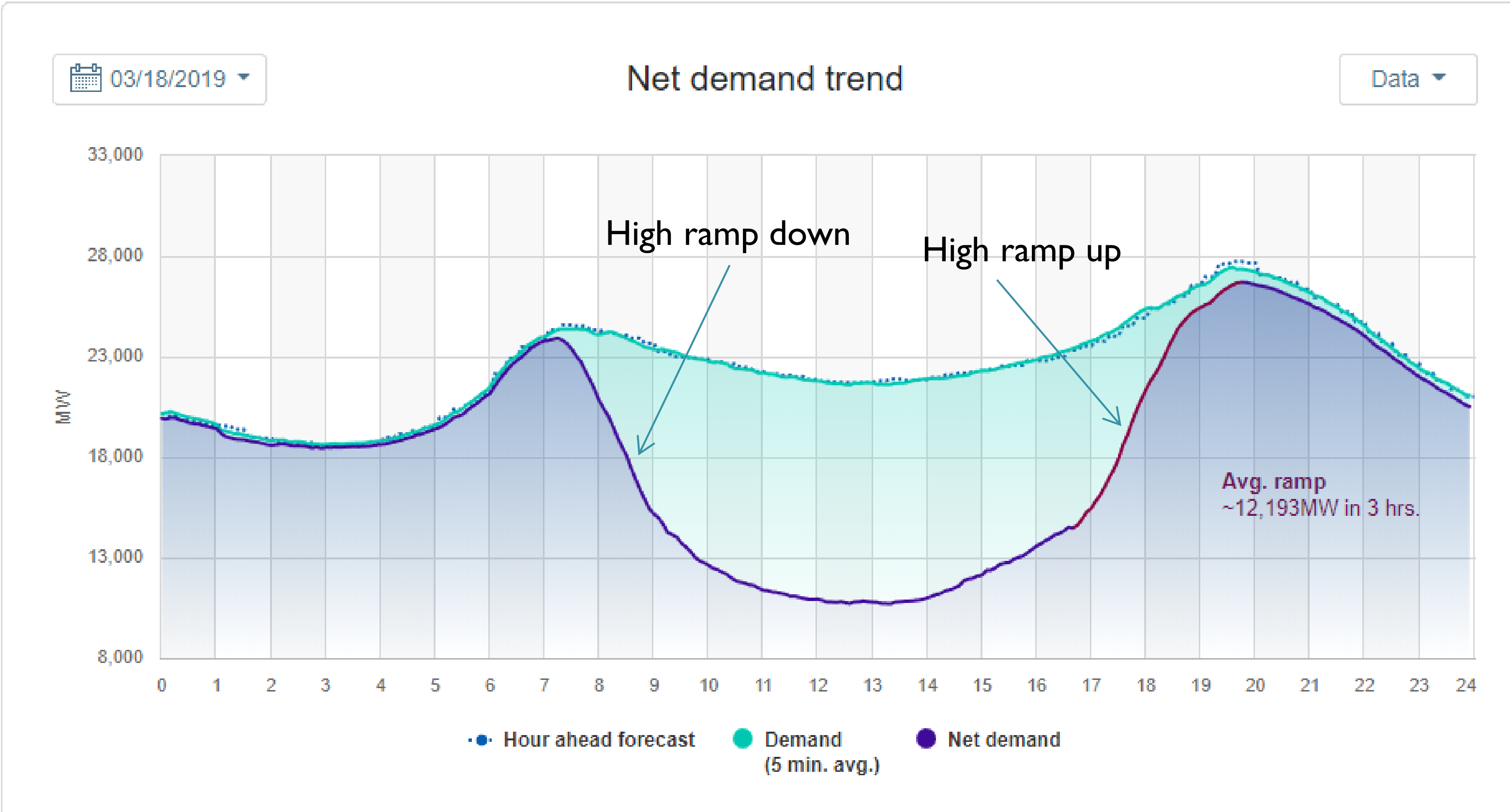
- → This increases regulation requirements that must be supplied by the conventional generating resources (e.g., combustion turbine units). Hence, a larger number of fast-acting generators are needed to maintain the balance between supply and demand. Additional ramping is needed during the early morning late afternoon hours.

CAISO (nearly 50% renewables around noon hour)

http://www.caiso.com/TodaysOutlook/Pages/default.aspx

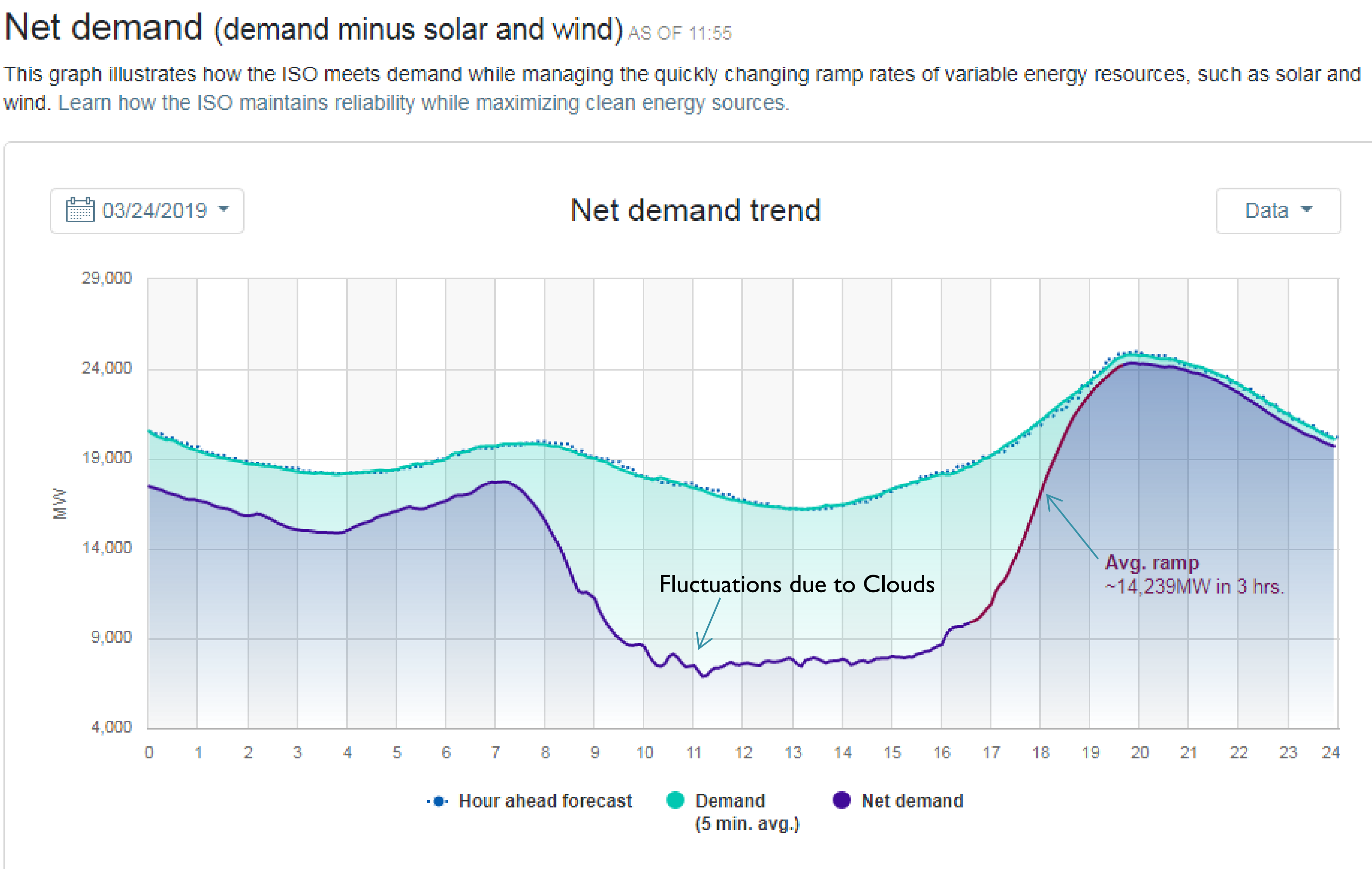
Today's Outlook | Demand | Supply | Prices | Emissions | AS OF **19:55 03/21/2019**

This graph illustrates how the ISO meets demand while managing the quickly changing ramp rates of variable energy resources, such as solar and wind. Learn how the ISO maintains reliability while maximizing clean energy sources.



California ISO Demand Curve

http://www.caiso.com/TodaysOutlook/Pages/default.aspx



California ISO Supply Curve

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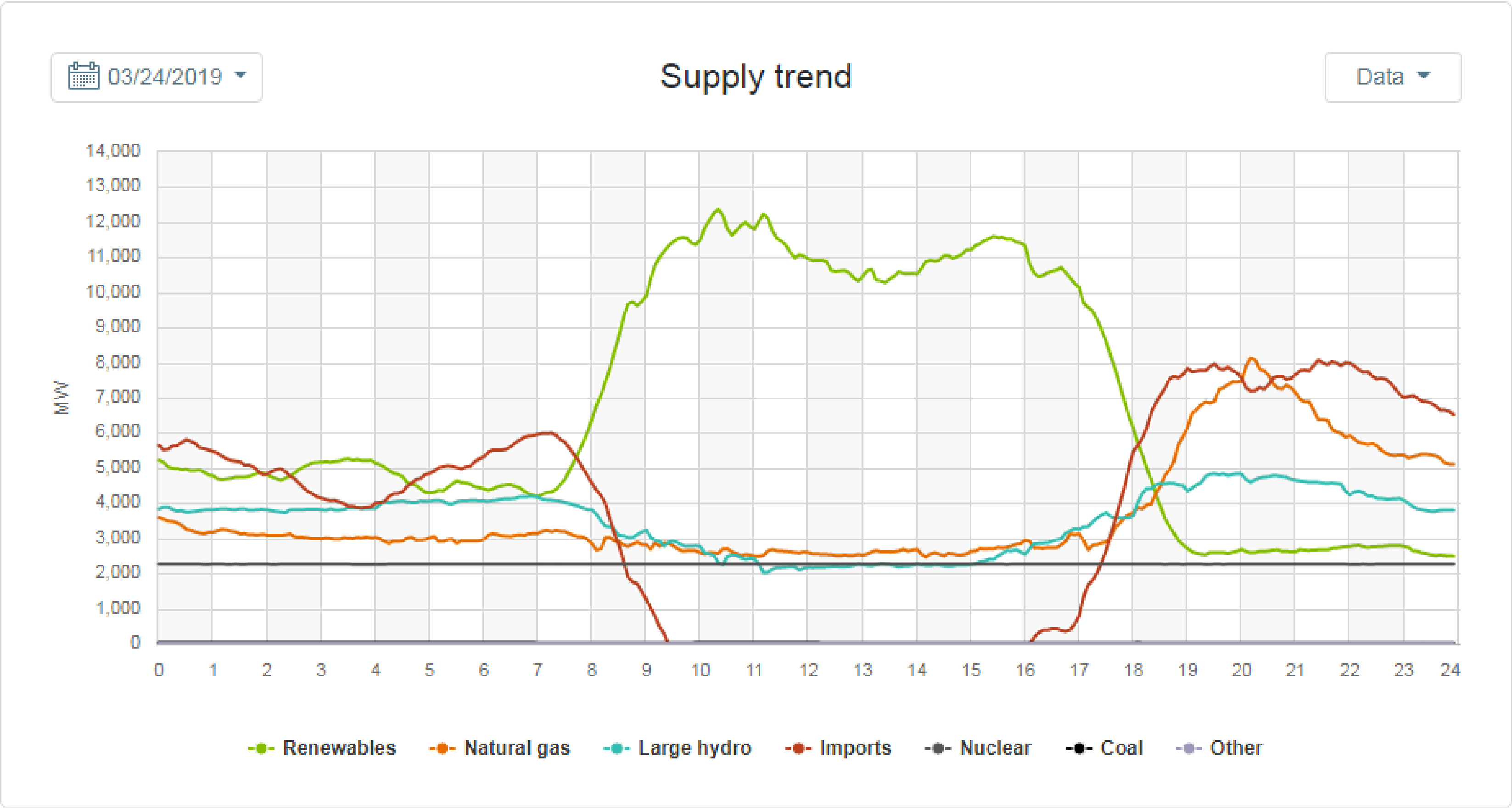

California ISO Renewables Curve

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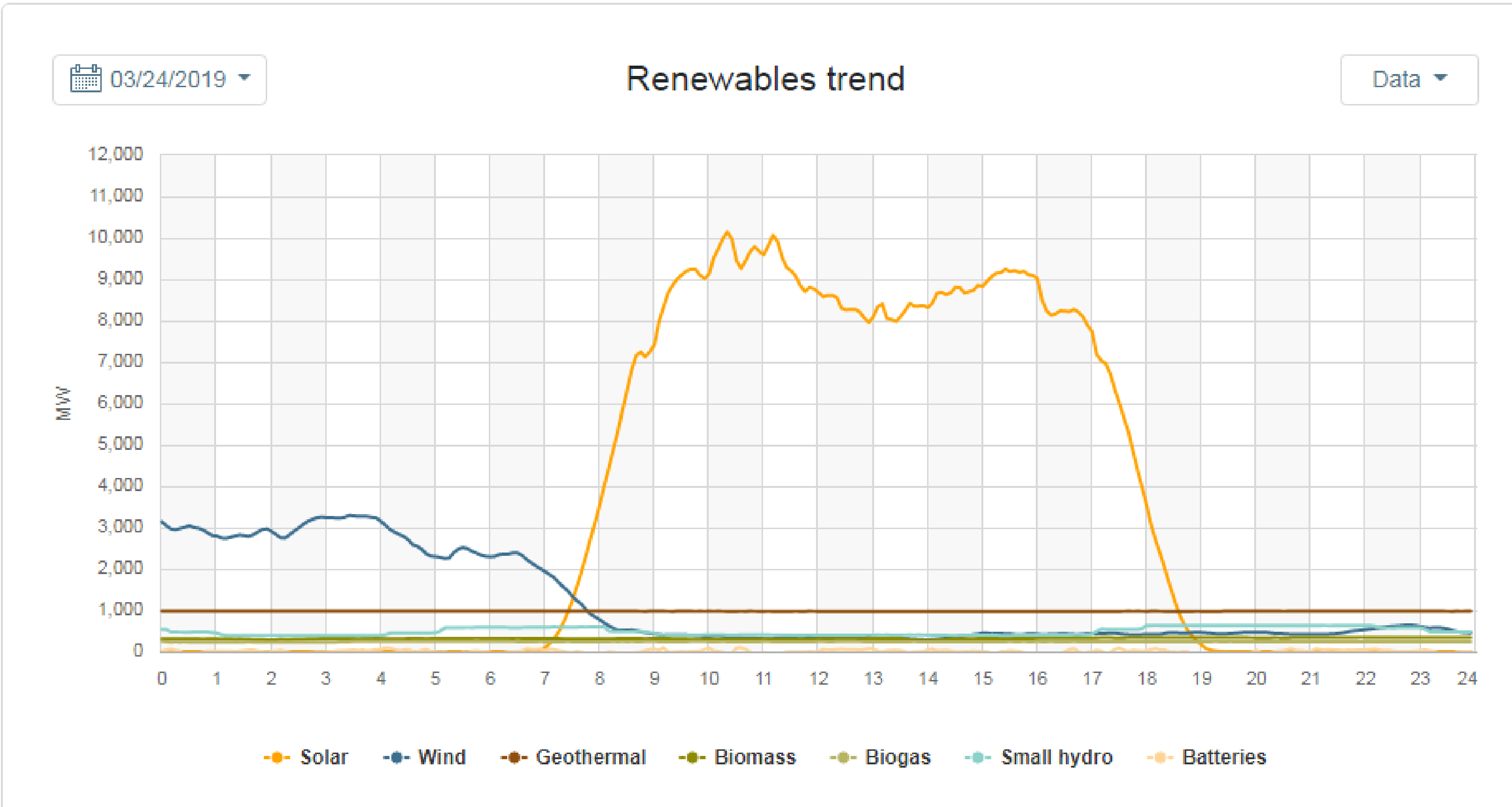

California ISO Battery Storage Curve

http://www.caiso.com/TodaysOutlook/Pages/default.aspx

More storage is being connected to the ISO grid, including non-generator resources, such as batteries, that can store electricity until dispatched.