Dynamic Performance Analysis of an Inverter-Based PV Plant during Sunrises and Sunsets through Synchrophasors*

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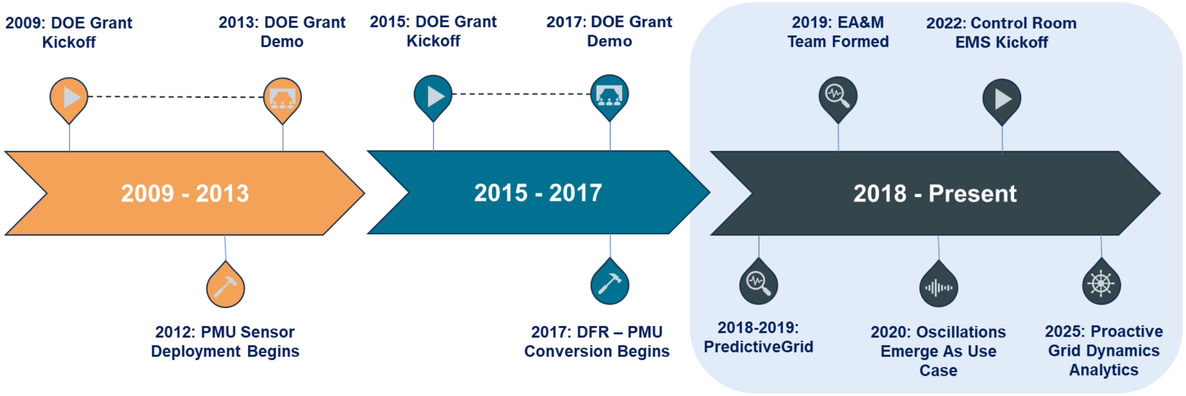
Synchrophasor program timeline



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Source [1]

Grid Dynamics Analytics at DE

Internal Device Dynamics

Driven by unobservable internal changes, these behaviors are hard to anticipate-making detection more practical than prediction

Local Plant-Grid Interactions

Emerge from evolving grid conditions where previous controller turning/configuration fall short.
Often explainable and sometimes preventable

Cycling Behavior

Historically rare but increasingly observed, cycling behavior is driven by repetitive load changes and can appear oscillatory despite not being inherent system dynamics

Mitigation Approach Shift

- Thinking beyond classical oscillation characterization approaches.
- Shift from plug-and-play metrics (frequency, damping, source) to custom, measurement-driven analytics.
- Focused on underlying mechanisms

Data-driven analytics

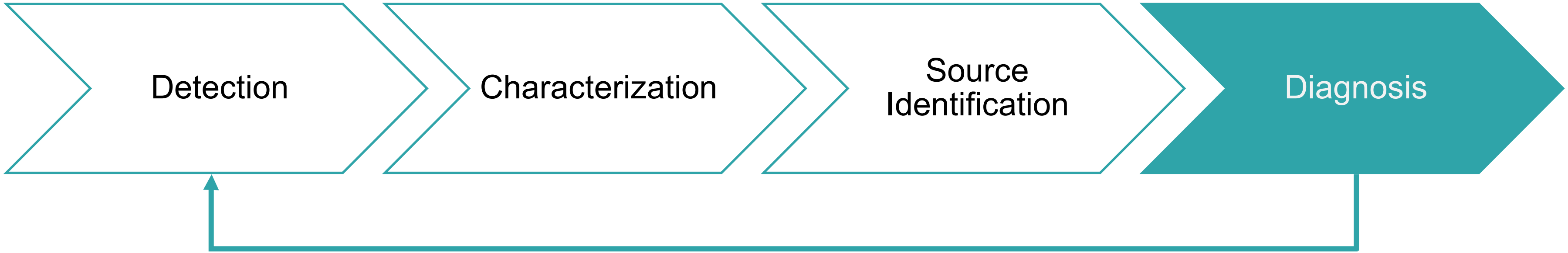
- Inverter-based resources dynamics [2, 3, 4, 5]
- Oscillation analysis [6, 8, 9, 10, 11, 12, 13]
- Data center dynamics [6, 7]
- Synchrophasor data quality and time synchronization [14, 15]
- Synchrophasor analytics [16, 17, 18, 19, 20]

Introduction

- **Changing Grid Paradigm:** Growing penetration of inverter-based resources (IBRs) is altering power system dynamics
- **Monitoring Practice**: Synchrophasor-based tools support real-time monitoring of system behavior
- **Interpretation Challenge:** Existing tools are grounded in traditional grid assumptions and may respond differently to nonlinear IBR dynamics
- **Operational Implication:** IBR-driven events can therefore be difficult to interpret using current frameworks
- **Opportunity:** Beyond real-time monitoring, measurement-based engineering analytics for long-term performance can help reveal unforeseen and evolving dynamics over time
- **This Work:** Real-world synchrophasor data is analyzed over multiple days, showing how IBR responses affect monitoring outcomes and motivate deeper interpretation [2]

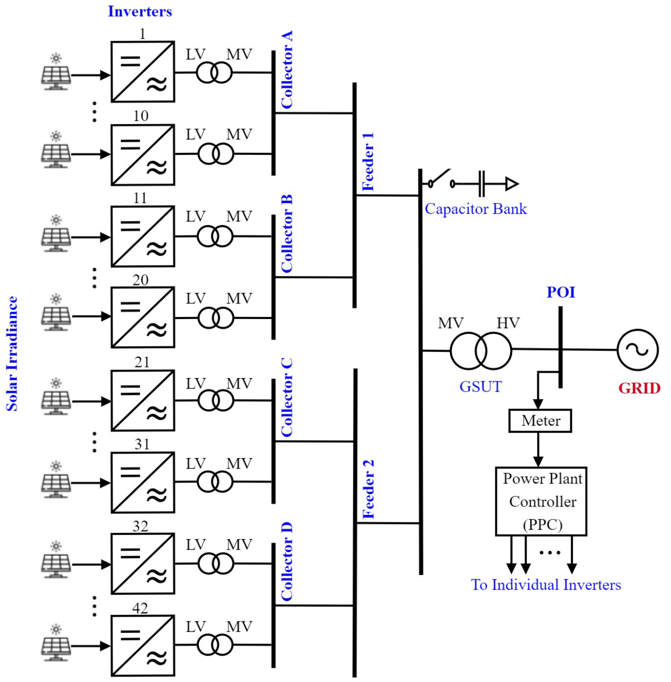
Diagnosis: Long-Term Measurement Data Analytics

Event analysis does not end at identifying the source - it begins there.



Understanding underlying behaviors requires to repeat the analysis process to better improve the diagnosis.

PV Plant Details



Power Plant Controller (PPC)

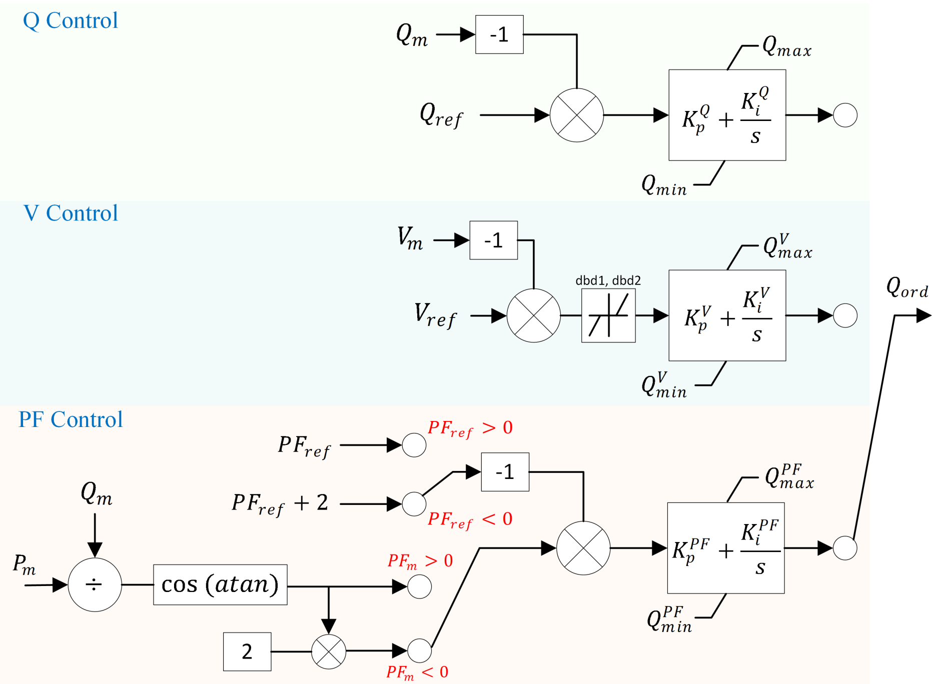
PPC Function: Regulates voltage and power factor (PF) at the Point of Interconnection (POI) by adjusting inverter reactive power and capacitor bank switching

Control Inputs: Continuous monitoring of POI voltage and PF

Power Factor Limit: PPC operation is restricted to within ±5% of unity, corresponding to 0.95 leading to 0.95 lagging PF at the POI

Voltage Limit: PPC maintains POI voltage within ±5% of the utility-rated voltage

Hierarchical PPC control and modes



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Event Description

First Occurrence

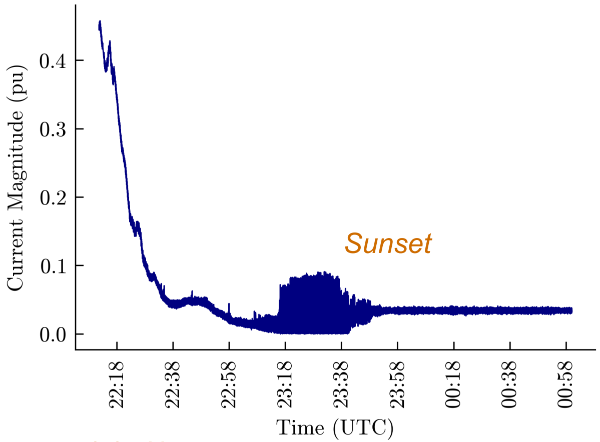
Reported Event: An oscillation alarm persisted for ~ 40 minutes

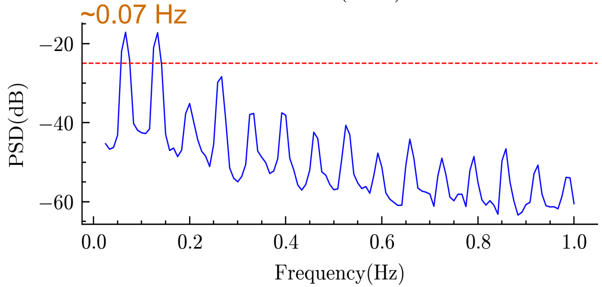
Monitoring Context: A synchrophasor-based tool monitors PSD of PMU signals and issues alarms when predefined thresholds are exceeded

Time-Domain Observation: POI current reflects the aggregated response of 42 inverters and coincides with sunset, when plant output approaches zero

Frequency-Domain Analysis: PSD (Welch's method) revealed multiple spectral peaks and harmonics, consistent with nonlinear behavior emerging from a non-sinusoidal time-domain response

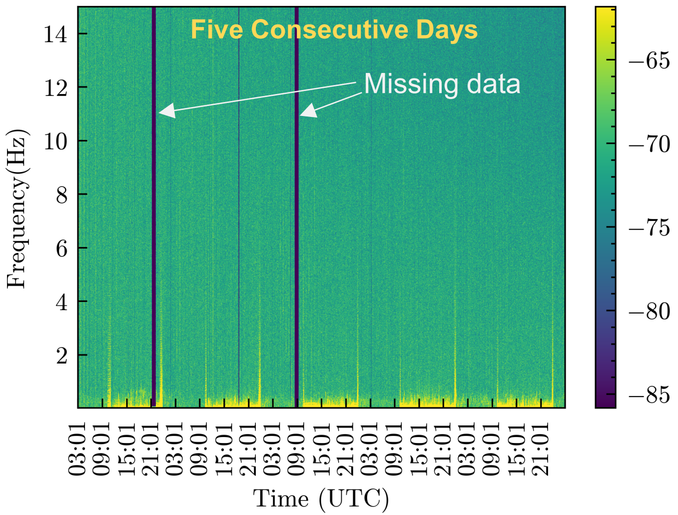
Key Insight: Nonlinear IBR responses captured by high-rate PMU measurements can appear oscillatory to conventional detection tools

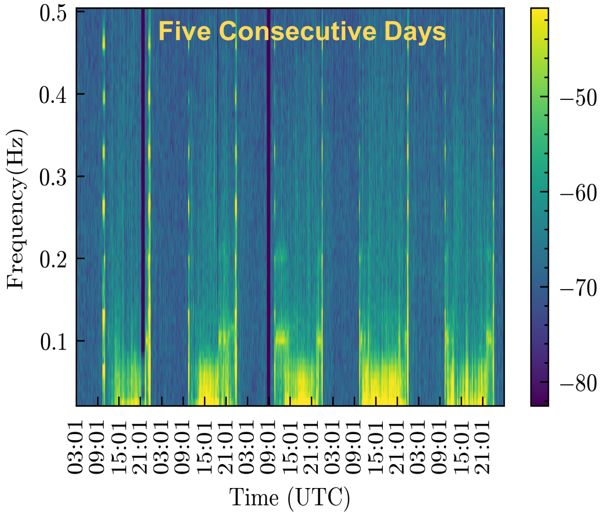




Long-Term Trend Analysis

STFT-Spectrograms of the plant output current





Persistence: This behavior persists beyond the five-day window, indicating a repeatable operating condition

Observed Pattern: Recurs daily during sunrise and sunset during periods of low active power output
(elevated spectral power - yellow spikes)

Frequency Characteristics: A zoomed low-frequency spectrogram reveals harmonic components consistent with nonlinear behavior observed in the single-event analysis

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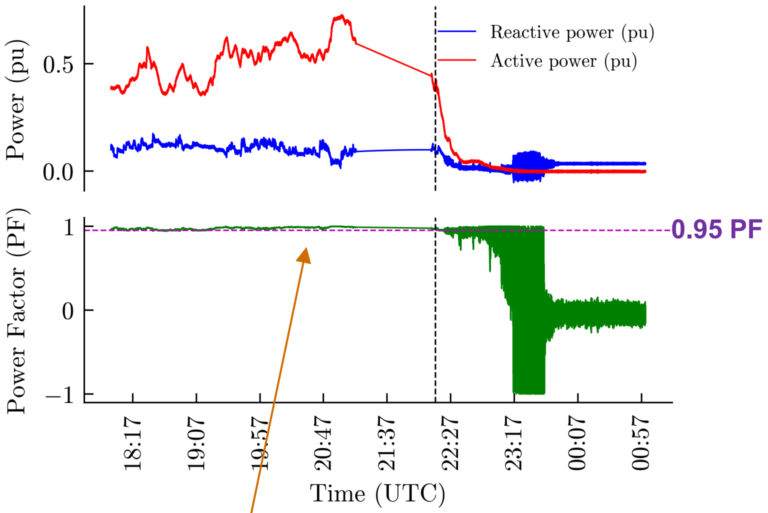
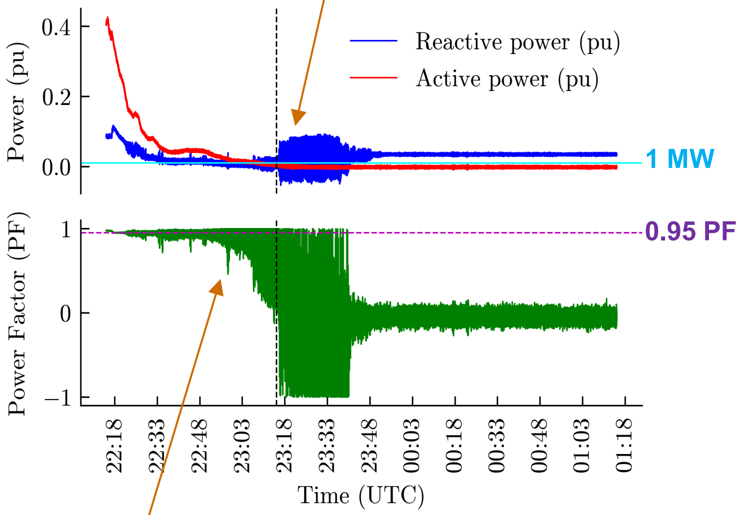
Root Cause Analysis

Only seen by reactive power



Large fluctuations in MVAR as MW approaches near zero

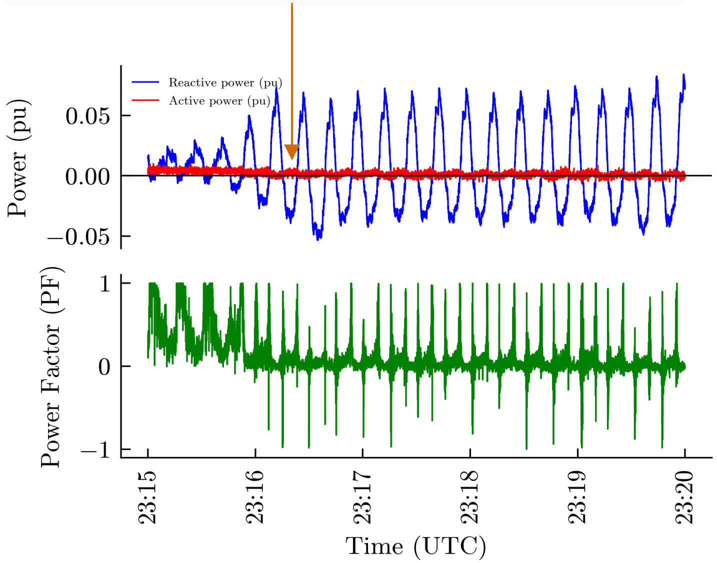


Power Factor (PF) within 1 and 0.95 limits

- PF gradually worsens during ramp down
- Slow PPC and communication delays

Root Cause Analysis

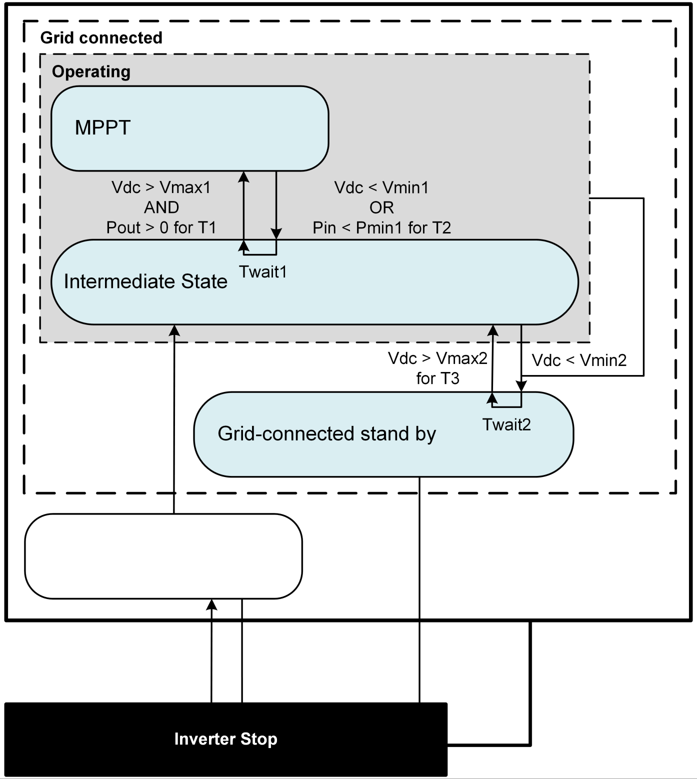
P fluctuates between small $+ve$ P and $-ve$ P



- *42 inverters × 22 kW = 924 KW (close to 1 MW)*
- MPPT: Maximum Power Point Tracking

- PPC : If P output < 1 MW:
  - AVR disabled and 0 (MVAR) setpoint to all (42) inverters
- Inverters: If V_{dc} < 860 V or P_{in} < 22 kW:
  - MPPT mode to grid-connected stand-by mode
- Less accurate Q and PF measurements at low dc power
- Small positive P: Insufficient irradiance
  - Attempts to maintain PF (0.95, 1)
- Negative P:
  - Reverse flow from the grid to energize equipment like transformers and cables (Reversal in measured PF)
  - Attempts to maintain PF (-0.95, -1)
- PPC voltage control disabled:
  - Inverters still produce MVAR to maintain PF within limits, but fails

Inverter's State Transition Diagram



Conclusions

- Recurrent low-frequency abnormal behavior observed **during sunrise and sunset** at a PV plant
- Activity falls within inter-area frequency ranges but does **not represent grid dynamics or known oscillation mechanisms (e.g., FO)**
- Behavior appears **near zero active power**, when **PPC logic changes**, **inverter operating modes may transition**, and **measurements become unreliable** at low DC power
- Non-sinusoidal responses generate **harmonics** but monitoring tools interpret only the fundamental (low-frequency) component as an oscillation → analysts **must confirm harmonic content** when alarms are triggered
- Plant **operating context is essential** to avoid misinterpretation of oscillation alarms
- Future monitoring must distinguish **plant-driven responses from true system dynamics**

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More details in the full paper:

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