Battery storage - Grid connectivity
What about stability ?

Grid Thumper : A new way of testing grid stability
In-The-Field Testing

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PSI
Power Sensors Ltd
A Division of Power Standards Lab

DARPA
Defense Advanced Research Projects Agency

Berkeley
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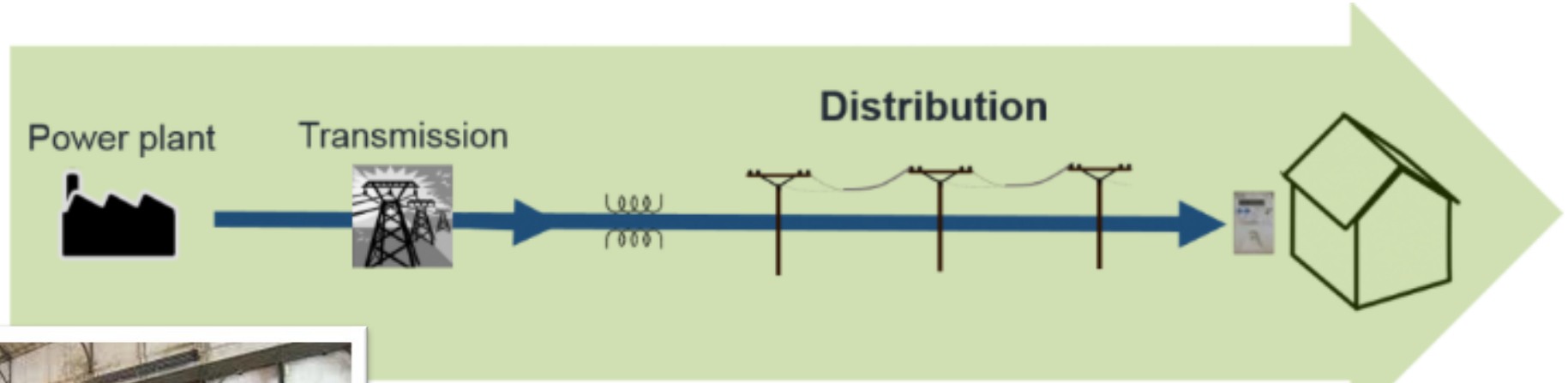
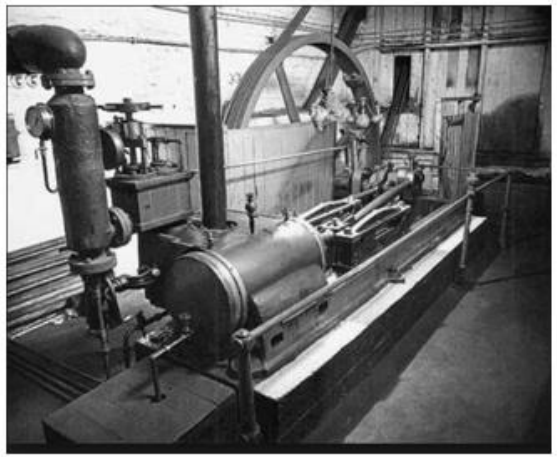
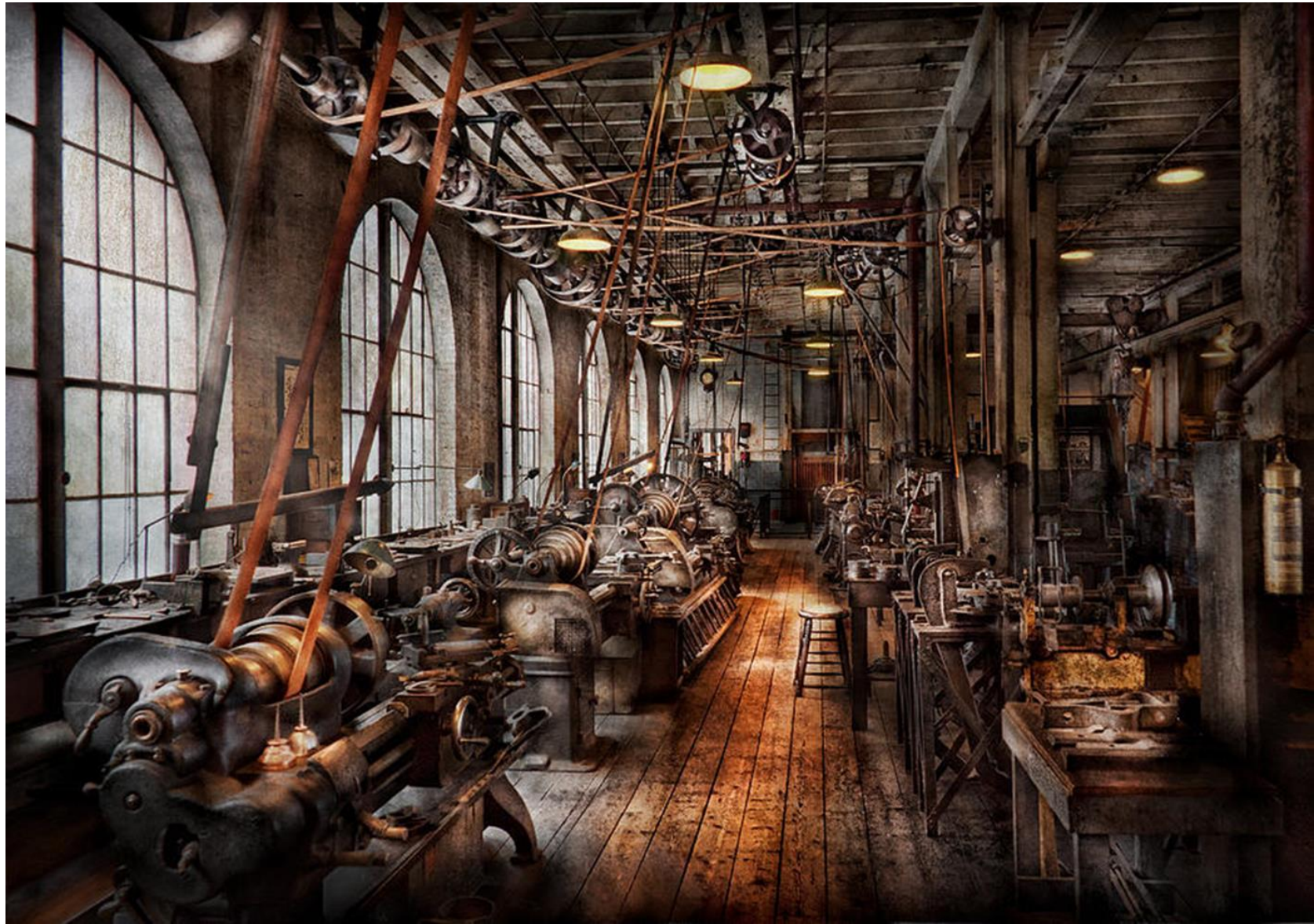
Traditional Transmission/Distribution Grid



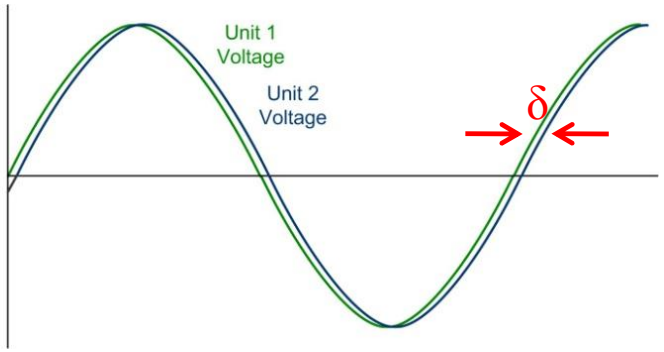
Traditional Transmission/Distribution Grid

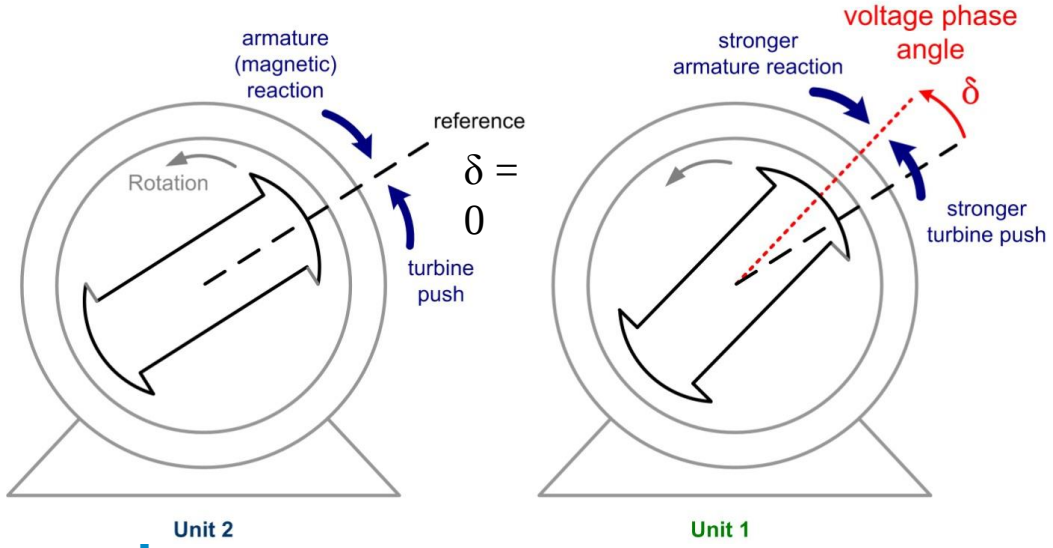


Steam engine that powered a factory for a century from 1860s to 1960s

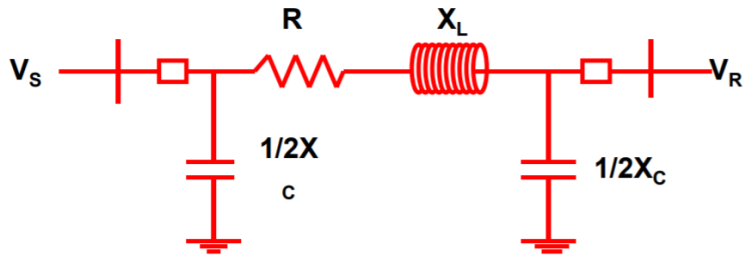


Traditional Transmission/Distribution Grid





power flows from Unit 1 toward Unit 2

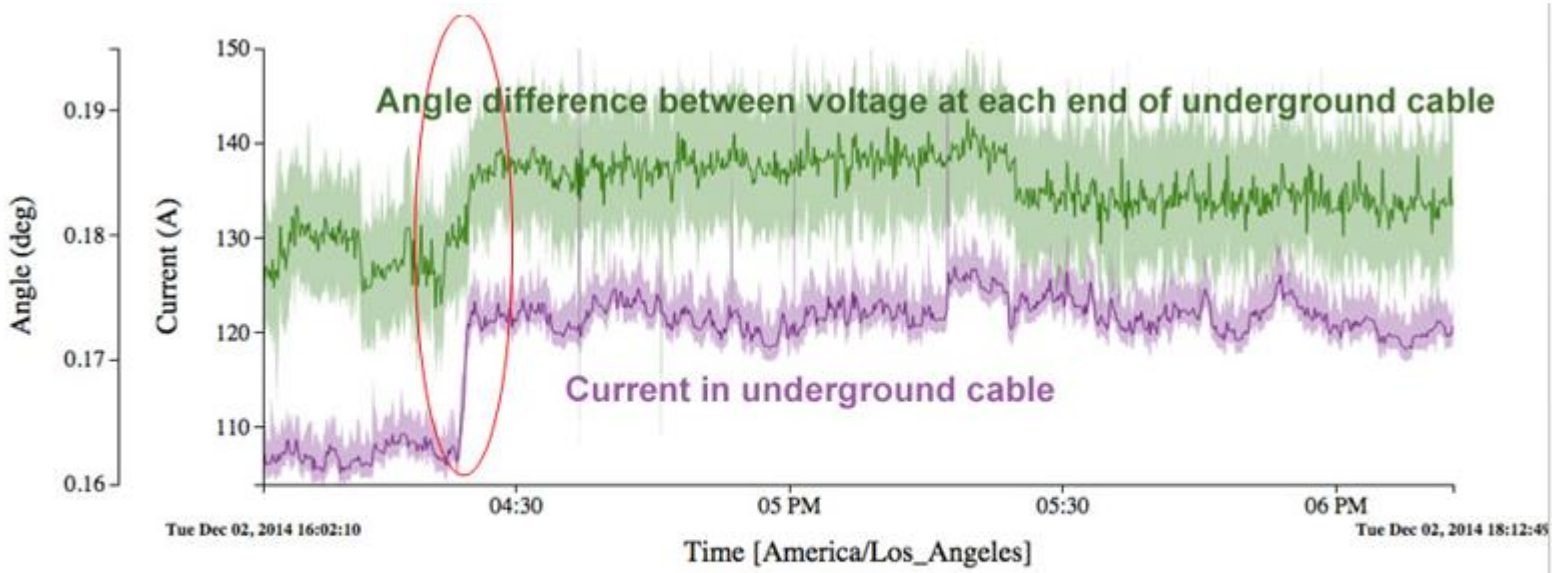


- Different lines have different values for R, X_L, and X_C, depending on:
  - Length
  - Conductor spacing
  - Conductor cross-sectional area
- X_C is equally distributed along the line

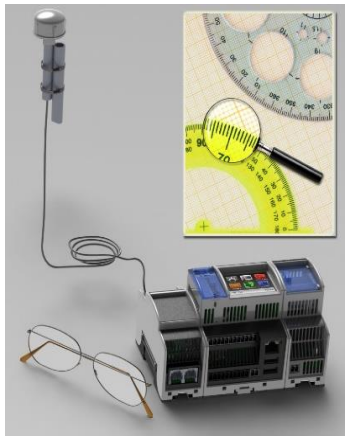
$$P \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$

In order to transfer real power across a transmission line, there must be an angle (delta) between the voltages at each end of the line

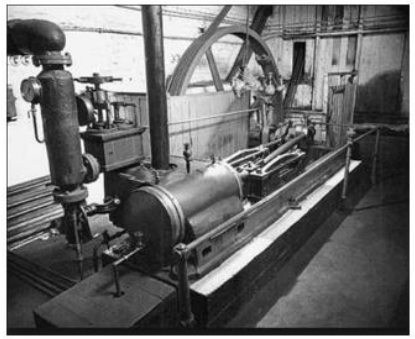
Traditional Transmission/Distribution Grid



An increase in current causes a voltage phase angle change of 0.008° - typical resolution of the micro-PMU.



Today's Transmission/Distribution Grid



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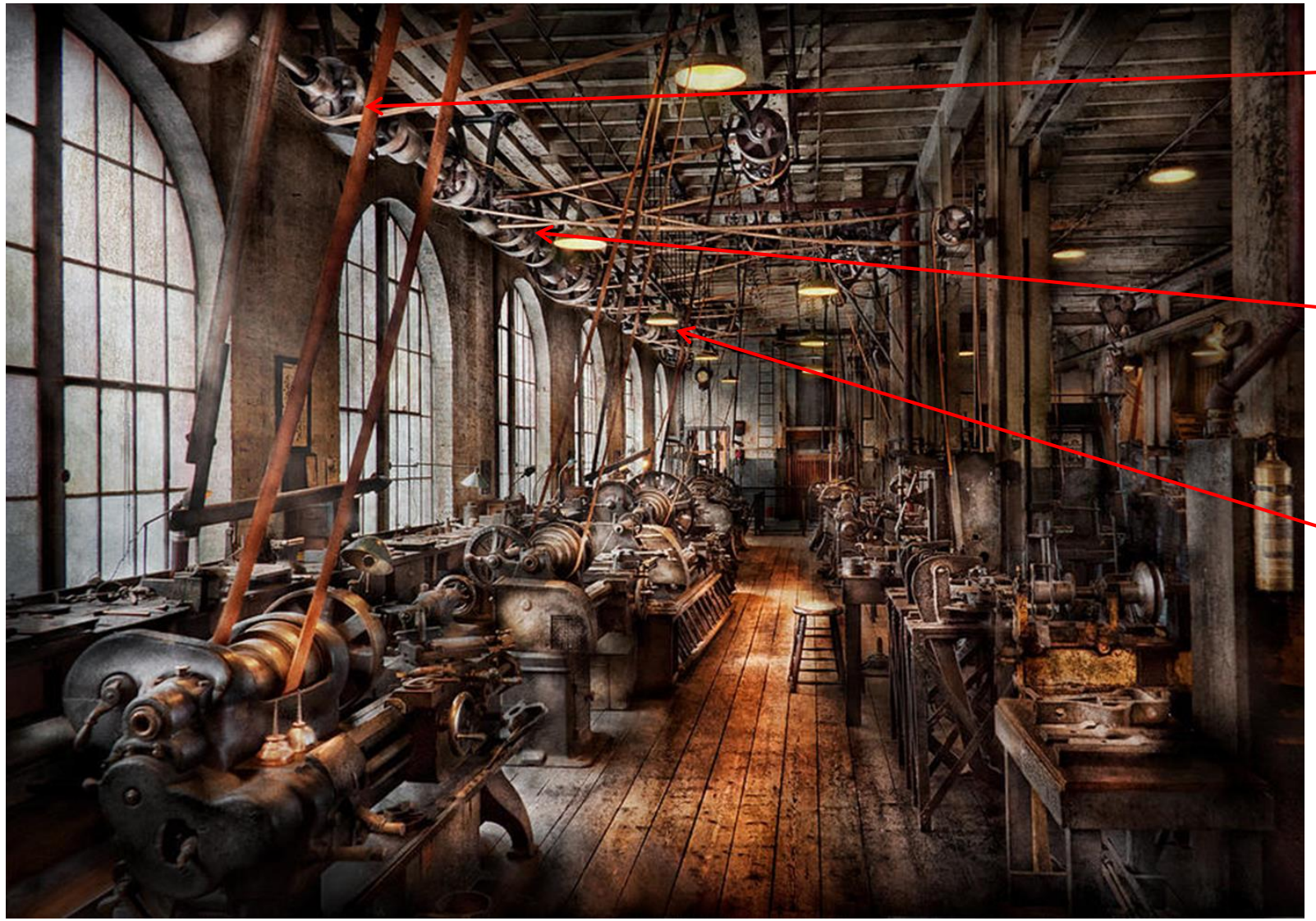
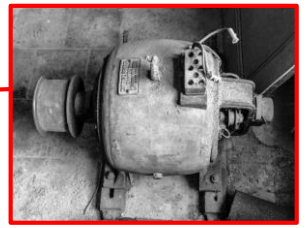
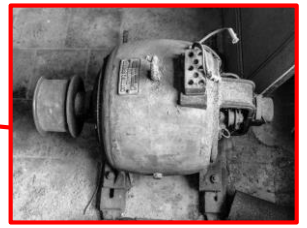
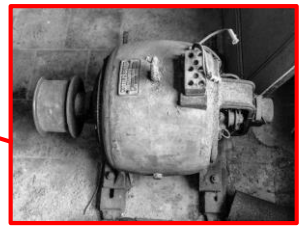


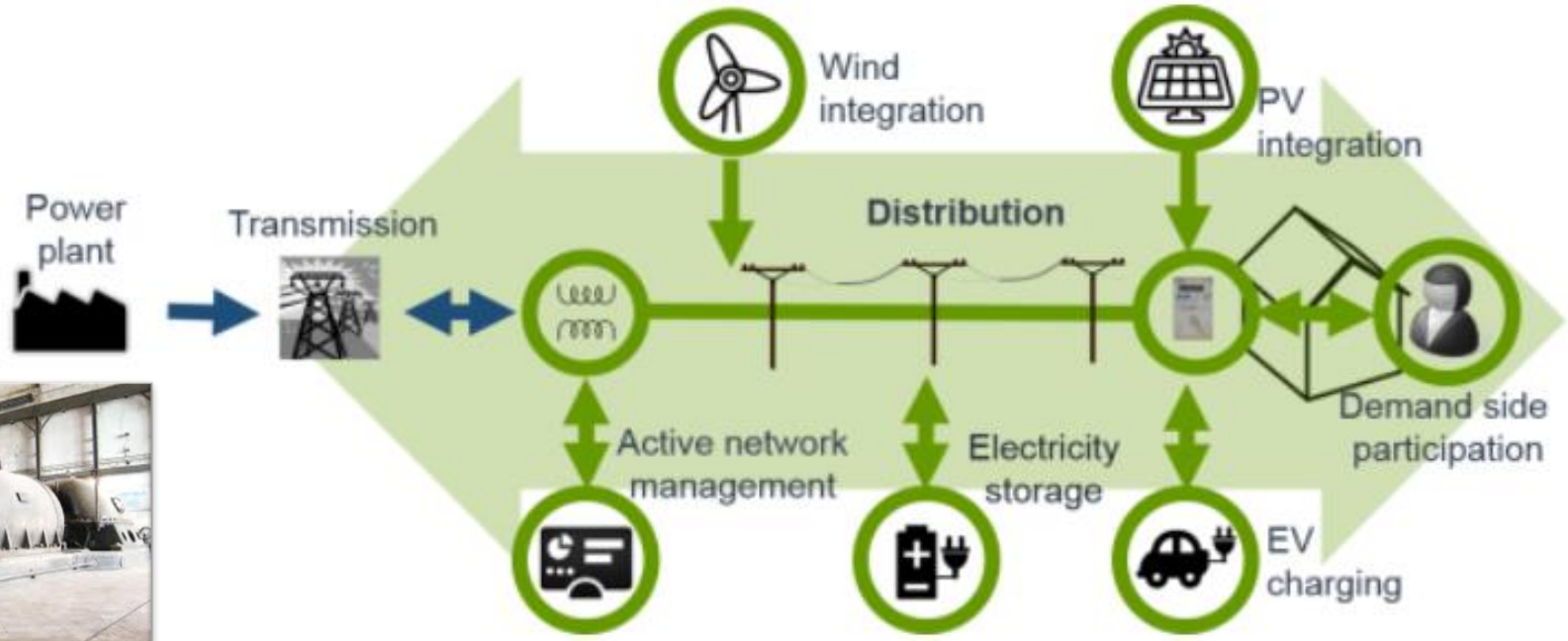






Adding RES (Renewable energy sources)

Today’s Transmission/Distribution Grid



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Future Transmission/Distribution Grid

- In the next 30 years, we're moving
  from
  current generation/transmission/distribution model
  To
  independently powered distribution grids.
  - **Distribution grids that use local renewables, local storage.**
  - Transmission for distribution interconnect;
  - Transmission for urban centers;
  - Transmission or relocation for energy-intensive industry (like aluminum.

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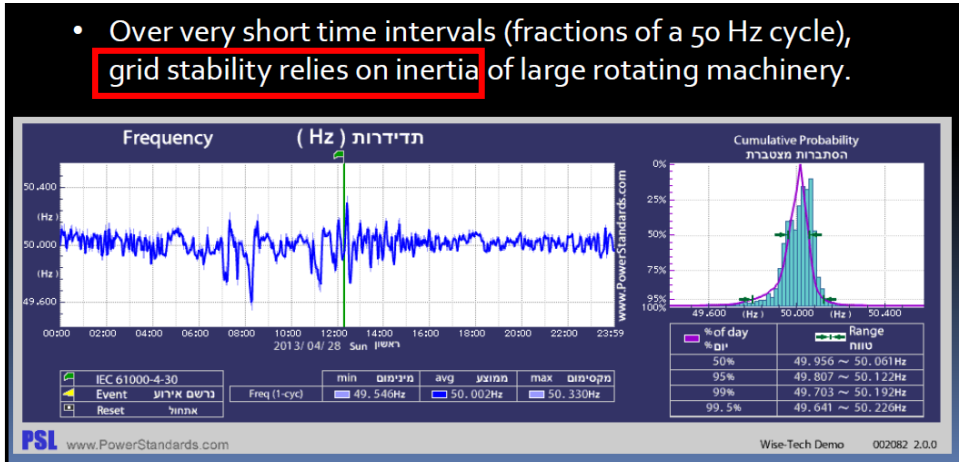
Challenge: Battery Energy Storage and Grid Stability

- Very Important:
  - It all has to be in balance (generation, network, loads)
  - If not, impact on frequency (and voltage)

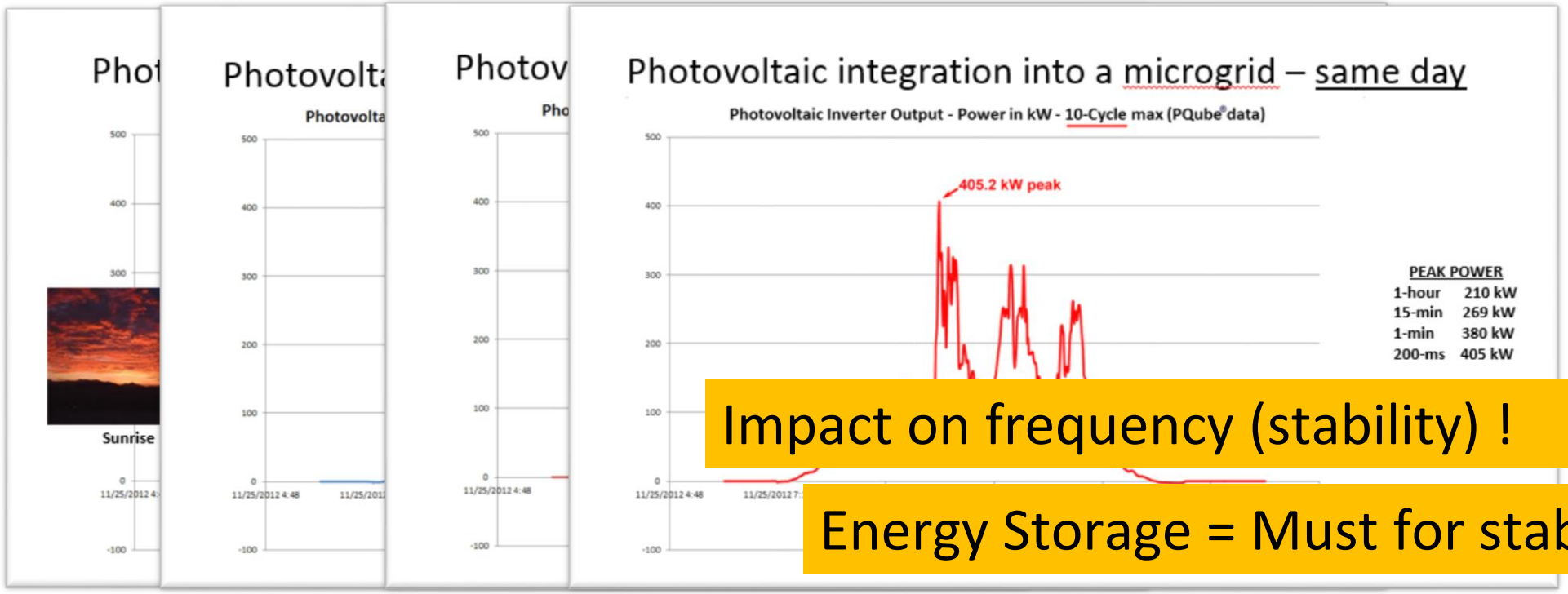


most "green" energy sources lack short-term inertia.

Challenge: Battery Energy Storage and Grid Stability

most "green" energy sources lack short-term inertia.

- Example: Why RES Energy storage & release at the sub-cycle level, and at the multiple minute level ?
- Lets look at the time scales of below example



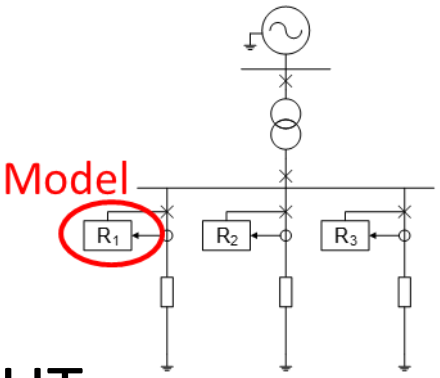
Impact on frequency (stability) !

Energy Storage = Must for stability

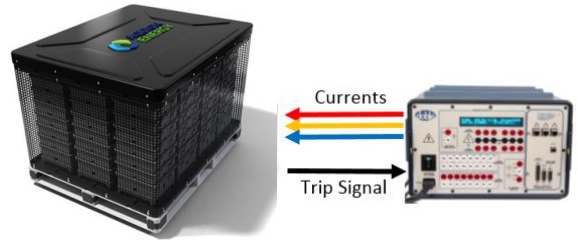
high resolution measurement instruments are required!

Battery Energy Storage: Measurement challenges

- How can we test performance on current and future grids ?



  - Perform network model simulation studies to get DUT specs & settings
    Limitation: A model of the DUT is tested – not the actual DUT

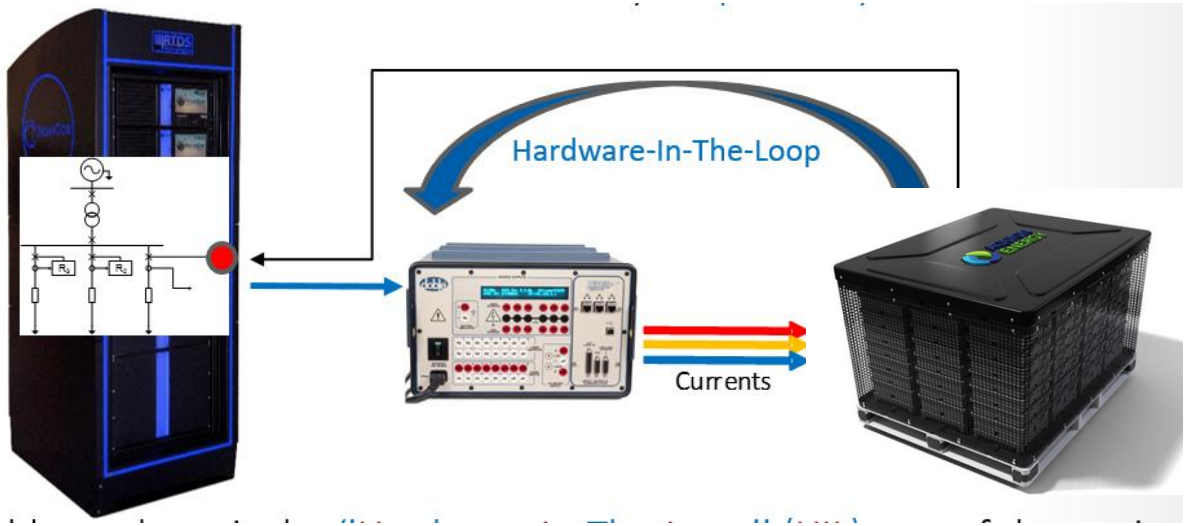


  - Test that the DUT operates according to these specs & settings with test equipment
    Limitation: The DUT is tested, but in isolation of the network.

Battery Energy Storage: Measurement challenges

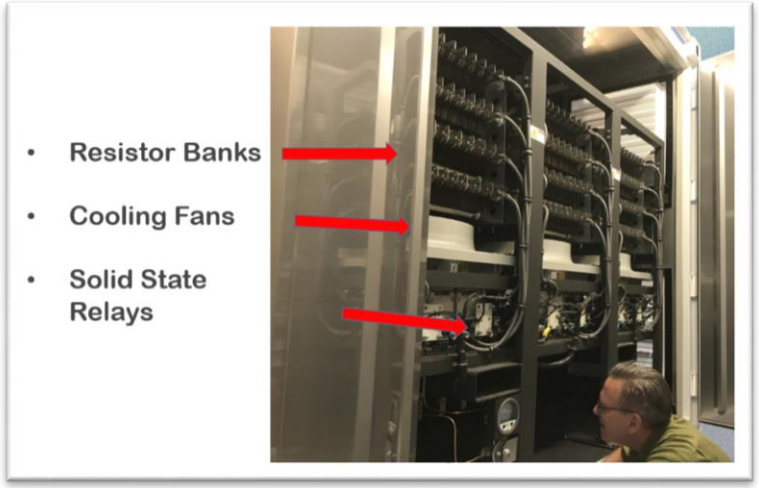
- How can we test performance on current and future grids ?

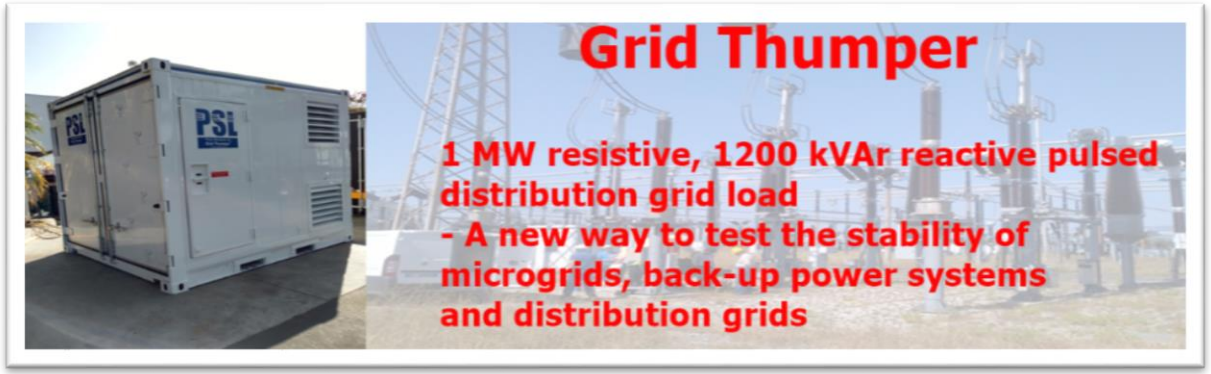
  - By using a RTDS system that allows us to test the actual DUT with a representation of the network in lab environment.
  - Limitation: Accurate model of network is needed. Every network is different !



Battery Energy Storage: Measurement challenges

- How can we test performance on current and future grids ?
- Only accurate test is Field test !
- What we need:
  - Actuator (Thumper)
    - Precise computer-controlled resistive loads
    - GPS synchronized
    - to create thumper signals on the grid





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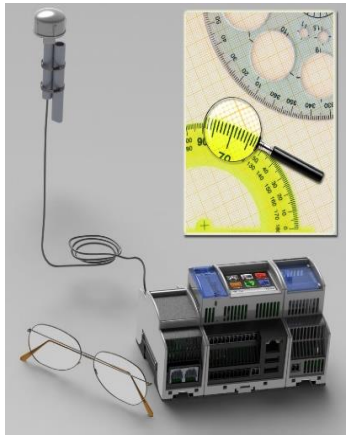
Battery Energy Storage: Measurement challenges

- What we need:
  - Accurate sensors to measure response
    - Remember meas. challenges: voltage, frequency, phasor angles
    - Very accurate PMU = “phasor measurement unit”
    - Measures Thumper effects
    - GPS synchronized



Traditional PMU
±1% precision (TVE)
±1˚ angle accuracy
±0.1% magnitude resolution
±0.1˚ angle resolution
15 readings per second

For transmission systems…

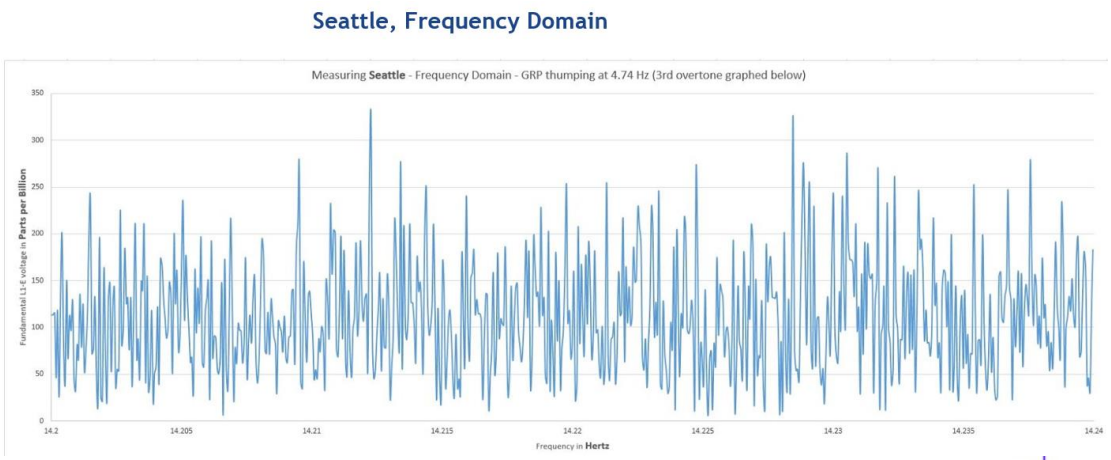
Micro-PMU
±0.05% precision (TVE)
±0.01˚ angle accuracy
±0.0002% magnitude resolution
±0.002˚ angle resolution
100 readings per second

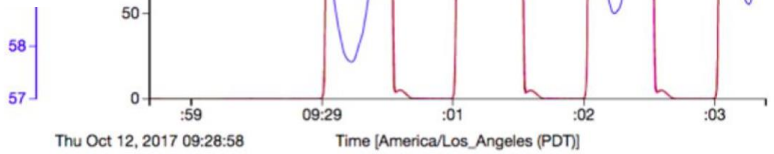
For distribution and microgrid

- Angles are tiny – two orders of magnitude smaller than transmission…
  (traditional transmission synchrophasor instruments don’t work very well)
- Solar variations are faster – clouds, inverter control loops
- Distribution grids are far more complex than transmission
- Underlying assumption (wrong) that power only flows from substations to loads

Battery Energy Storage: Measurement challenges

- What we need:
  - Database for analytics & visualization
    - Thumper signals and microPMU measurements are gathered in advanced database and visualization tool
    - Effects are statistically analyzed, visualized and reported





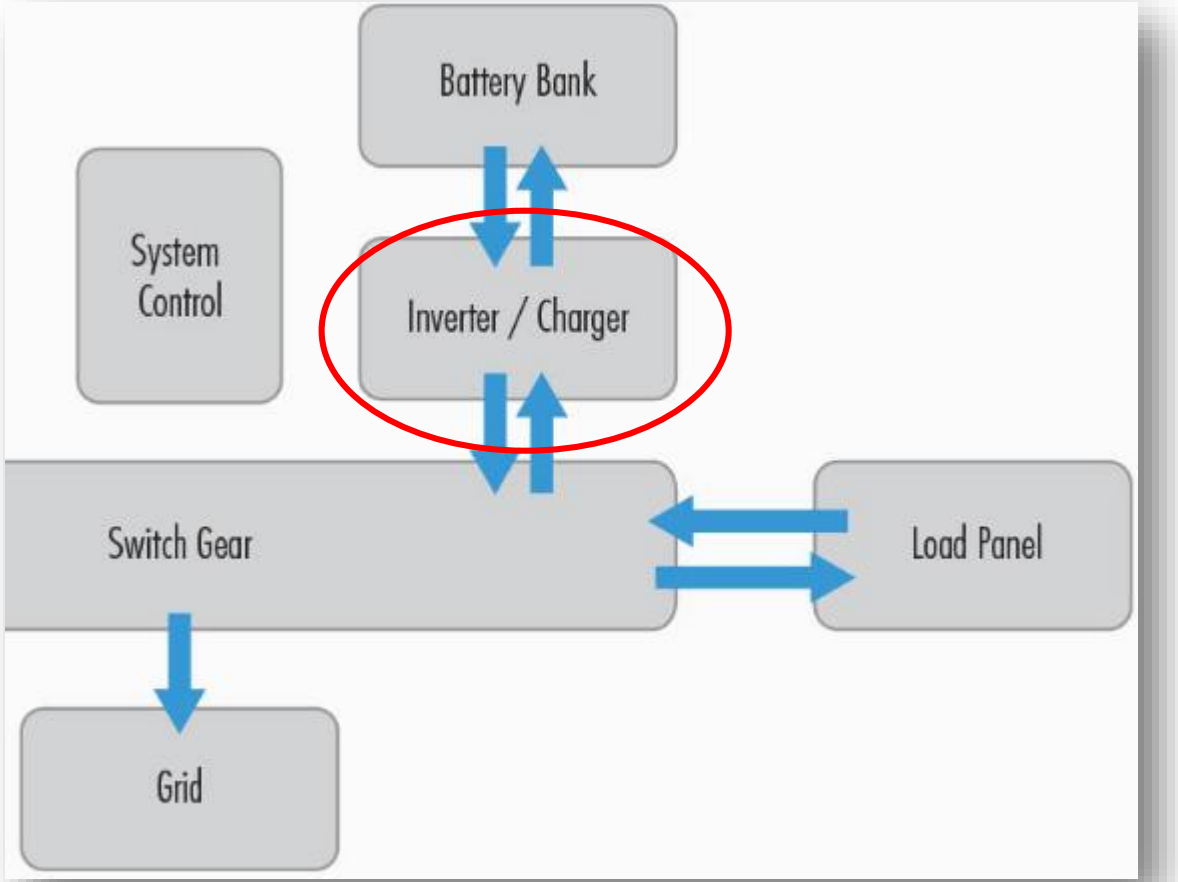
Battery Energy Storage: Measurement challenges

- So in summary:
  - Connect thumper to the network
  - Large resistive loads switched on/off with precisely timed pulses at adjustable levels.
  - Local and remote microPMU sensors measure changes in voltage (due to upstream inductance)
  - GPS time synched values are stored in a database.
  - Effects are statistically analyzed

Figure 8: *Alameda-East End, alternate route. Substations, distribution lines, and transmission lines between GRP at Alameda - PSL and the Alameda-East End microPMU.*
Approximate total distance: 45 km

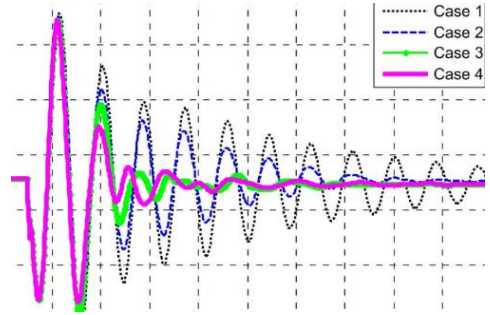
Battery Energy Storage test case

- Energy Storage building blocks



Battery Energy Storage test case: Inverter oscillation

- Energy storage Inverter
  - Inverters tend to oscillate in case of step changes
  - Your storage starts to store from and push energy to the network.
    So creating instability on the network.
  - Each inverter has his own control loop profile
    They all share the same grid
    Result: oscillations add up (big problem) or damp out



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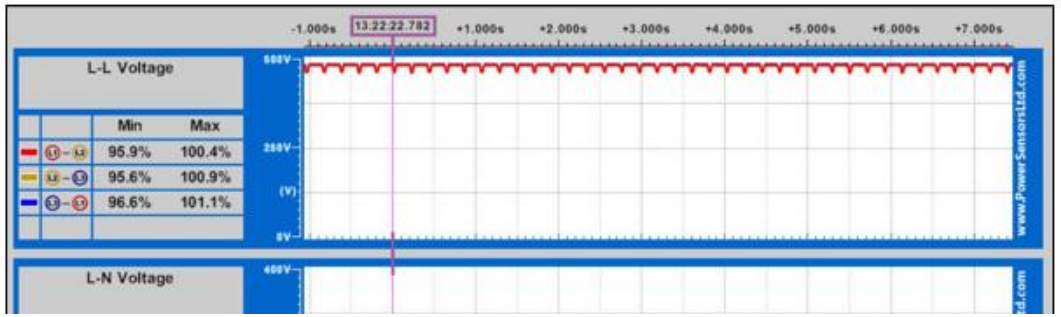
Battery Energy Storage test case: Inverter oscillation

- Energy storage Inverter
  - How we test this:
    - Exploratory test to observe the system
    - Measure stability with µPMU
    - Adjust test sequence at this oscillation frequency and observe system response

Test Event ID 248
Test set-up:
The source of the GRP is in Alameda, CA.
Time of test event (start): June 11, 2018, Start Time 13:22:00.000.000 PST
Duration: 5 hours
480V 3-phase, Measured Line to Neutral (277 VAC)
GRP Load: 340 kW
Period: 0.210970 sec. (4.74 Hz)
Duty cycle: 12% (“on” at start of each period)
Location of Thumper, source of forced oscillations:, PSL headquarters, Alameda CA

Battery Energy Storage test case: Inverter oscillation

Thumper (source)



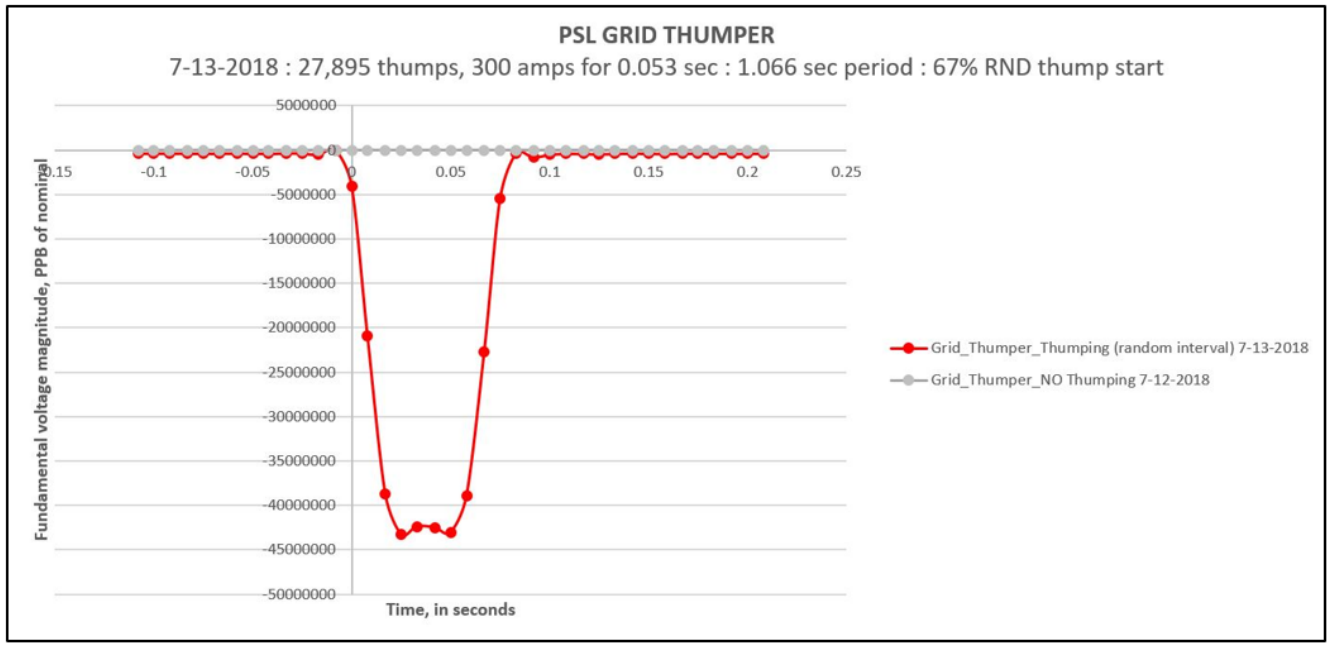


Figure 38: *Voltage change during Thump (red) compared to nominal, i.e., not thumping (gray). Average of 27,895 thumps, over 10 hours, measured at the PSL GRP.*

Figure 36*: Thumping RMS PQube3*

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Battery Energy Storage test case: Inverter oscillation

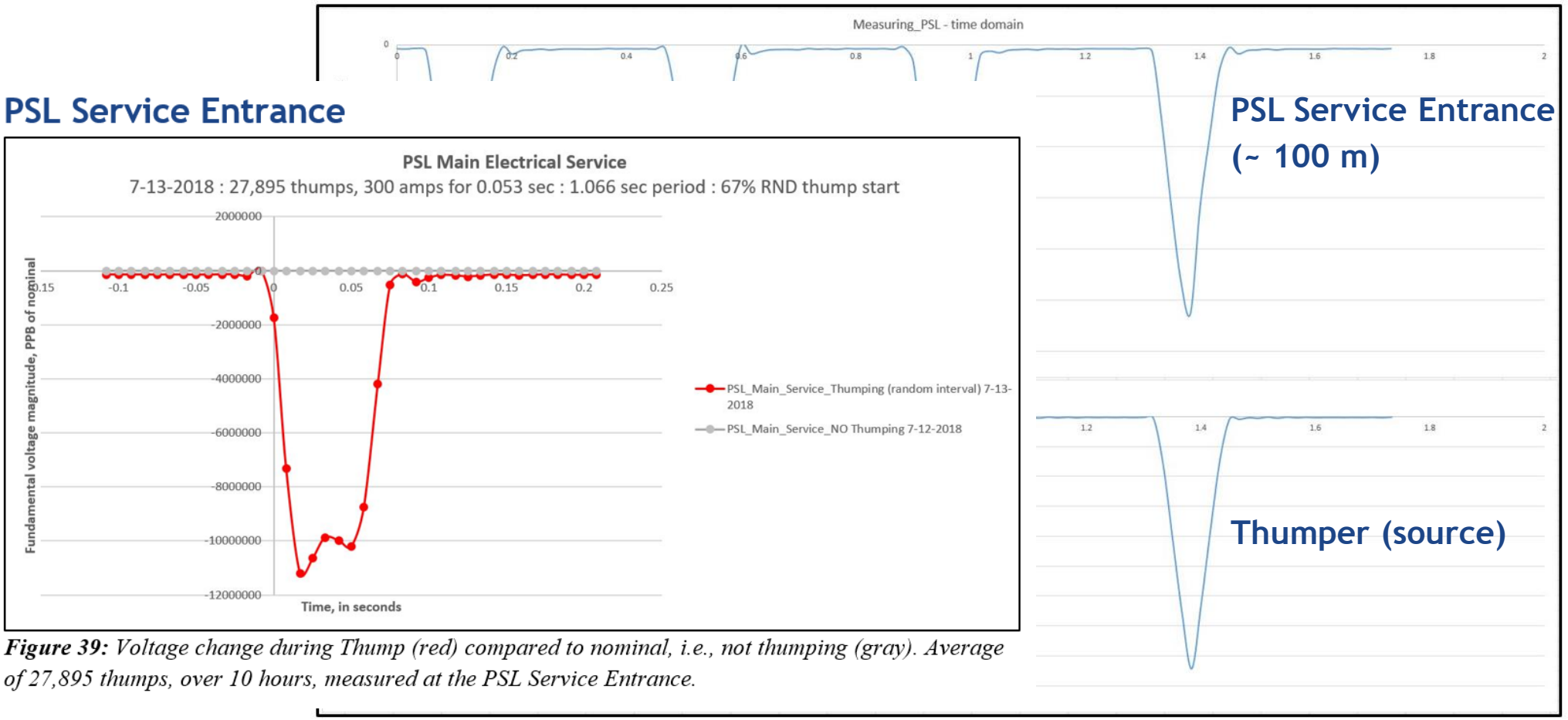

Figure 39: *Voltage change during Thump (red) compared to nominal, i.e., not thumping (gray). Average of 27,895 thumps, over 10 hours, measured at the PSL Service Entrance.*

Figure 21: *Time domain. Voltage measured during Test Event ID 248, measured at PSL service entrance (top) and GRP source (bottom).*

PSL Service entrance - About 100m distance

Battery Energy Storage test case: Inverter oscillation

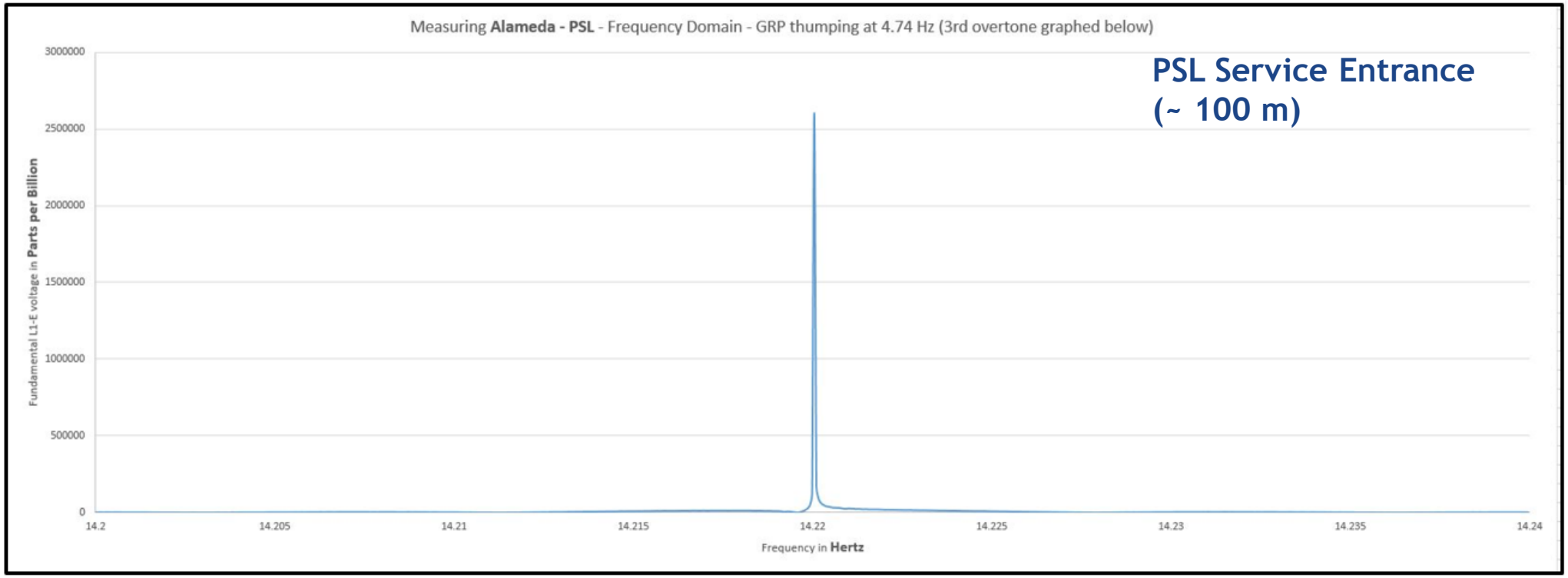

Figure 22: *Frequency domain. Voltage measured during Test Event ID 248, measured at PSL service entrance, third harmonic of thumping period (i.e., Thumping frequency (4.74 Hz) X 3 = 14.22 Hz (shown).*

PSL Service entrance - About 100m distance

Battery Energy Storage test case: Inverter oscillation

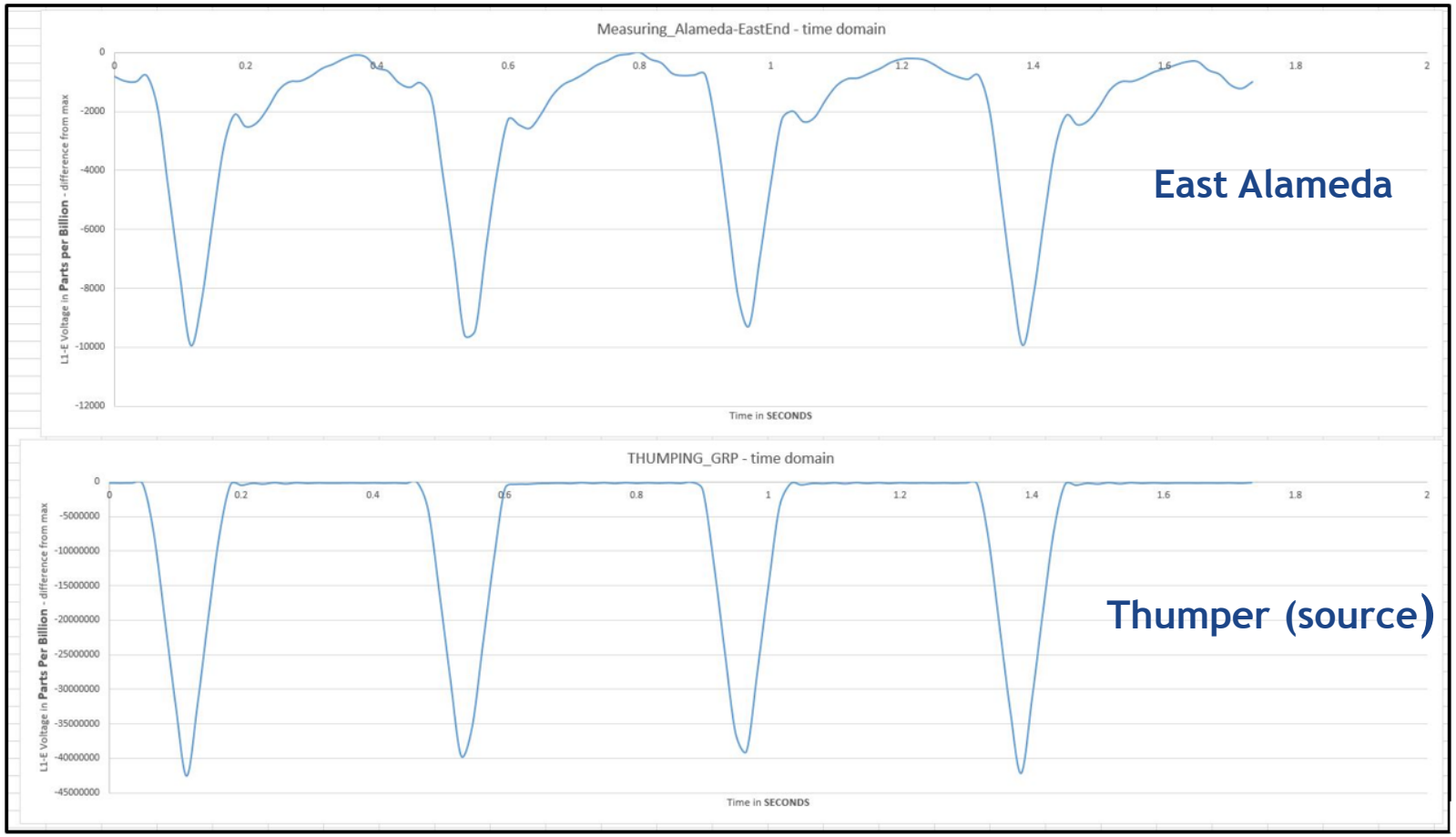

Figure 23: *Time domain. Voltage measured during Test Event ID 248, measured at Alameda East-End microPMU (top) and GRP source (bottom).*

Alameda East End - About 45km distance

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Battery Energy Storage test case: Inverter oscillation

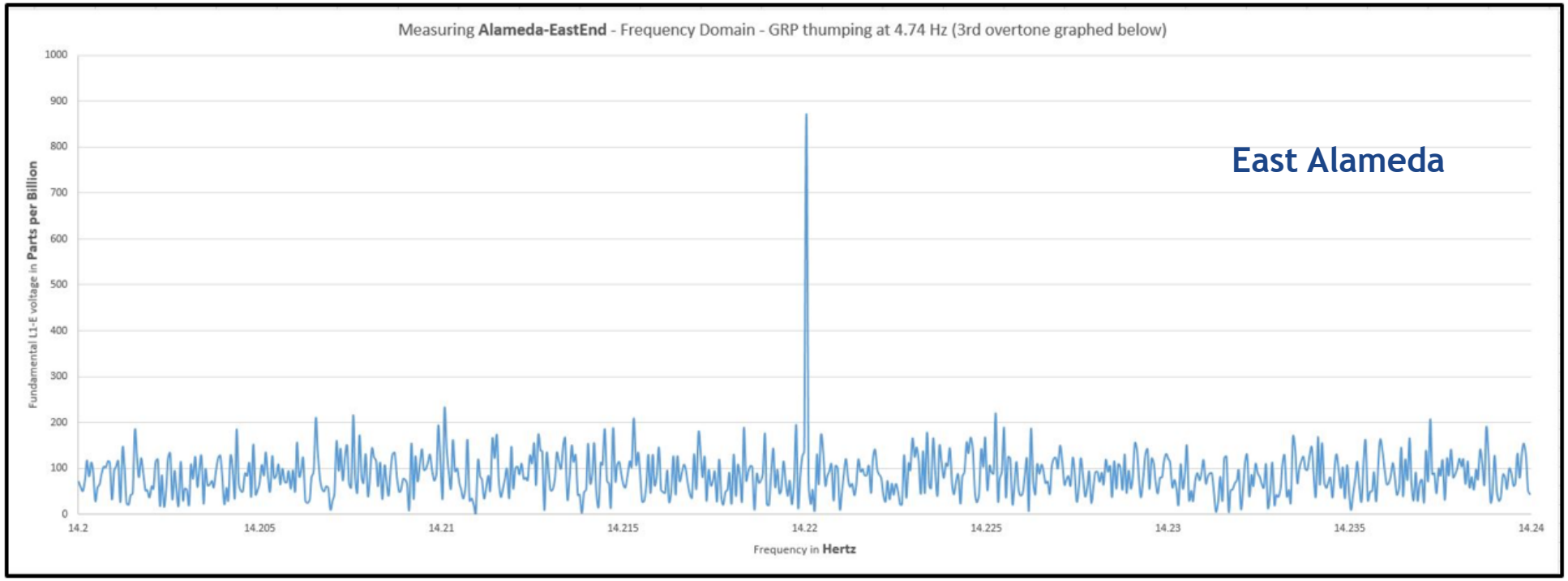
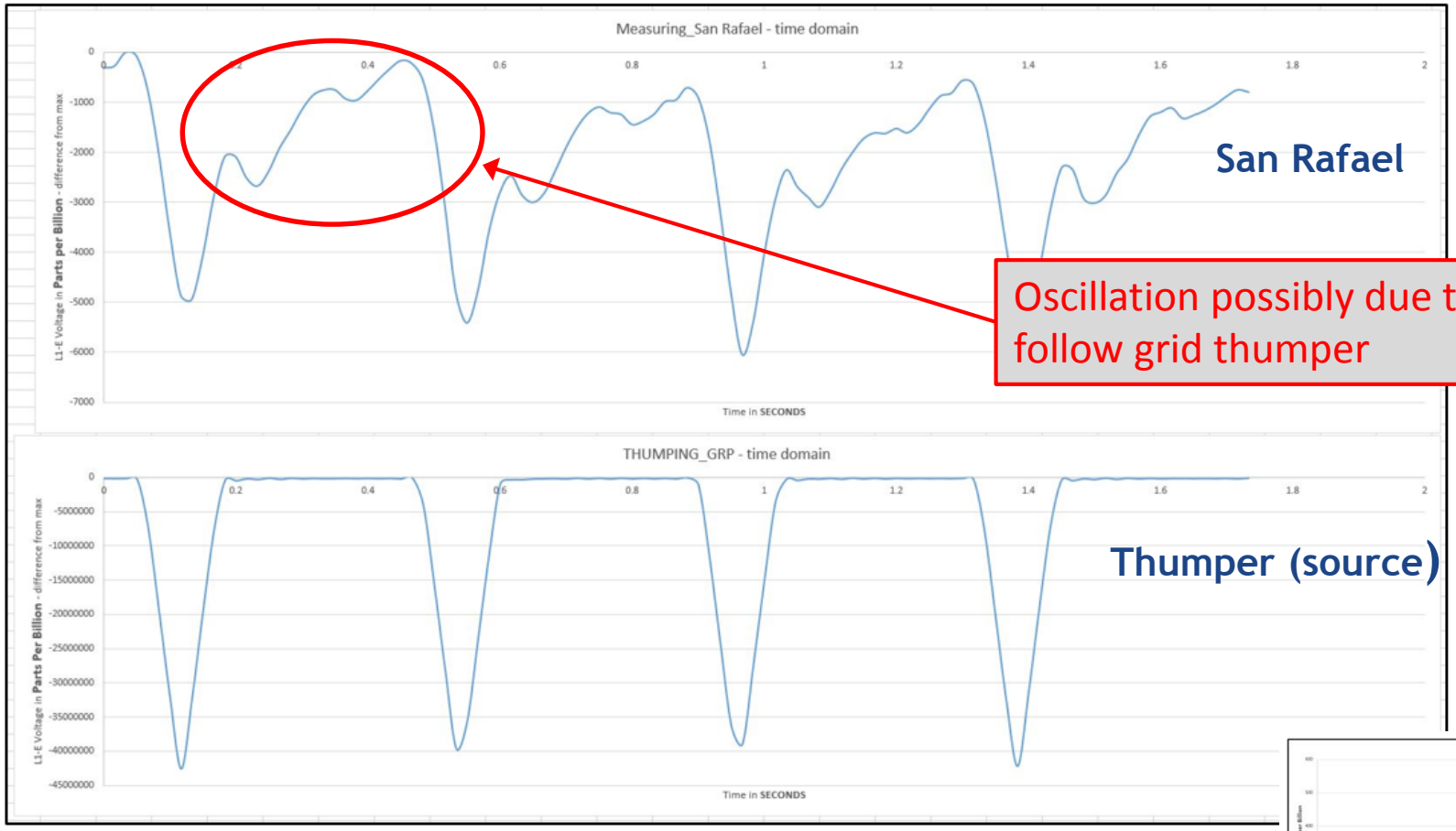


Figure 25: *Frequency domain. Voltage measured during Test Event ID 248, measured at Alameda East-End microPMU, third harmonic of thumping period (i.e., Thumping frequency (4.74 Hz) X 3 = 14.22 Hz (shown).*

Alameda East End - About 45km distance

Battery Energy Storage test case: Inverter oscillation



Oscillation possibly due to inverters trying to follow grid thumper

Figure 29: *Time domain. Voltage measured during Test Event ID 248, measured in San Rafa GRP source (bottom)*

San Rafael - About 110 km distance

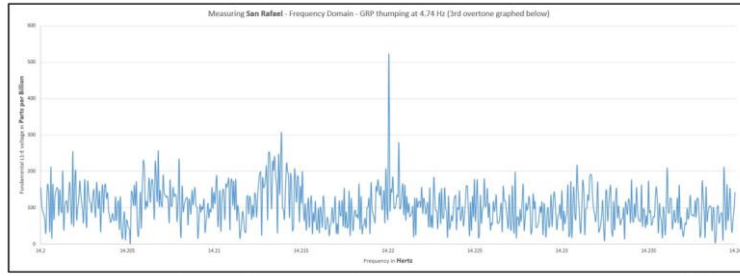
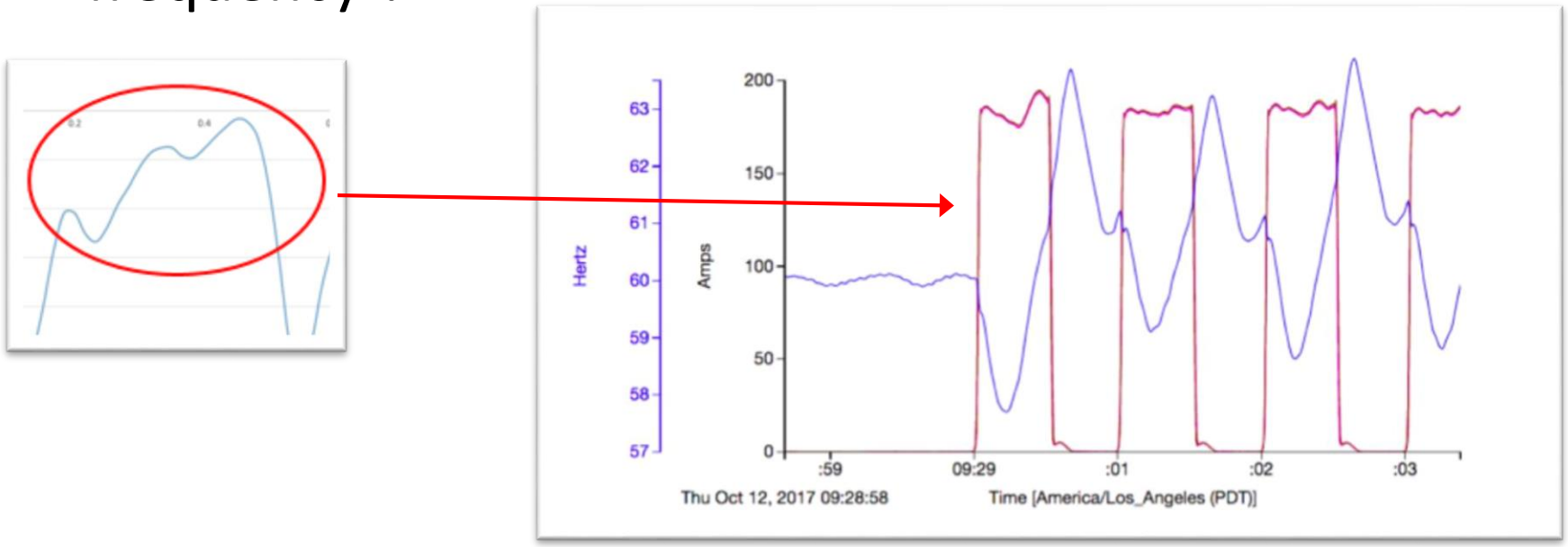


Figure 31: *Frequency domain. Voltage measured during Test Event ID 248, measured in San Rafael, third harmonic of thumping period (i.e., Thumping frequency (4.74 Hz) X 3 = 14.22 Hz (shown).*

Battery Energy Storage test case: Inverter oscillation

- What if we would adjust grid thumper switching frequency to oscillation frequency ?



Consequences ?

Battery Energy Storage test case: Inverter oscillation

- Conclusion:
  - Forced oscillations reveal characteristics not seen in steady-state

Grid Thumper Applications

- Distribution grid, Backup power testing
    - Characterize stability, especially with renewables
- Microgrid, Back-up power, Genset, UPS testing
    - Provide rigorous and well documented on-site test protocol
- Data centers, military bases, hospitals
    - Mission critical
- Electric Vehicle site analysis
- Department of Energy, Utilities

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Battery storage & Grid stability testing with Grid Thumper

- More information:
  - About Grid thumper research project
    - https://www.powerstandards.com/product/grid-thumper/highlights/
    - https://www.youtube.com/watch?v=G61IJMaSHh0
    - https://www.youtube.com/watch?v=W_TDRLO3yRs&t=163s

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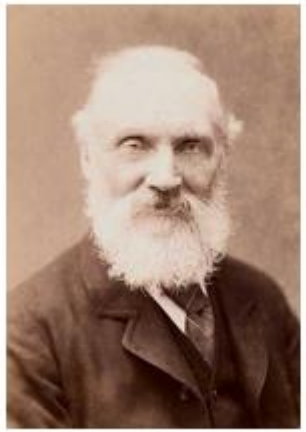
Battery storage & Grid stability testing with Grid Thumper

"If you can not *measure* it,
you can not *improve* it."



Lord Kelvin

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