Dynamic behavior of islanded distributed energy sources

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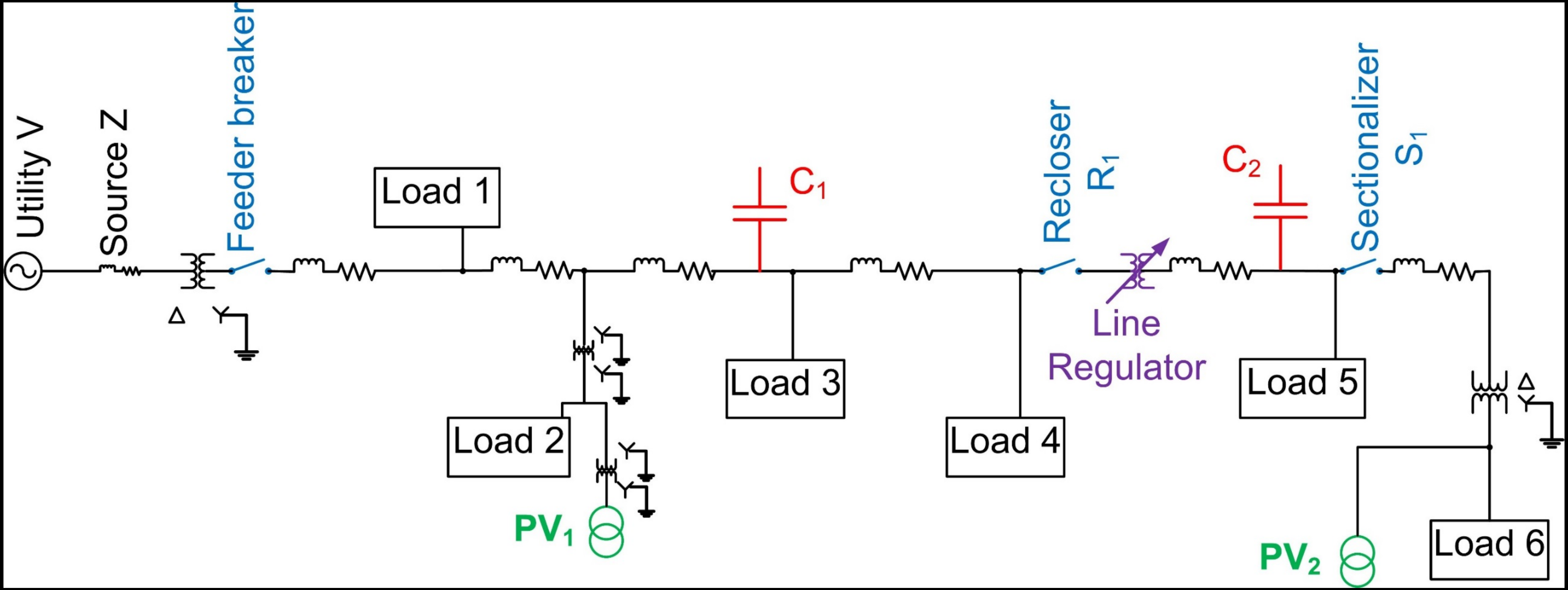
Outline

- Islanding basics
- Key differences between inverter and rotating generator behaviors
- Voltage and frequency behaviors in unintentional islands
  - Inverters
  - Synchronous machines
- Example case studies

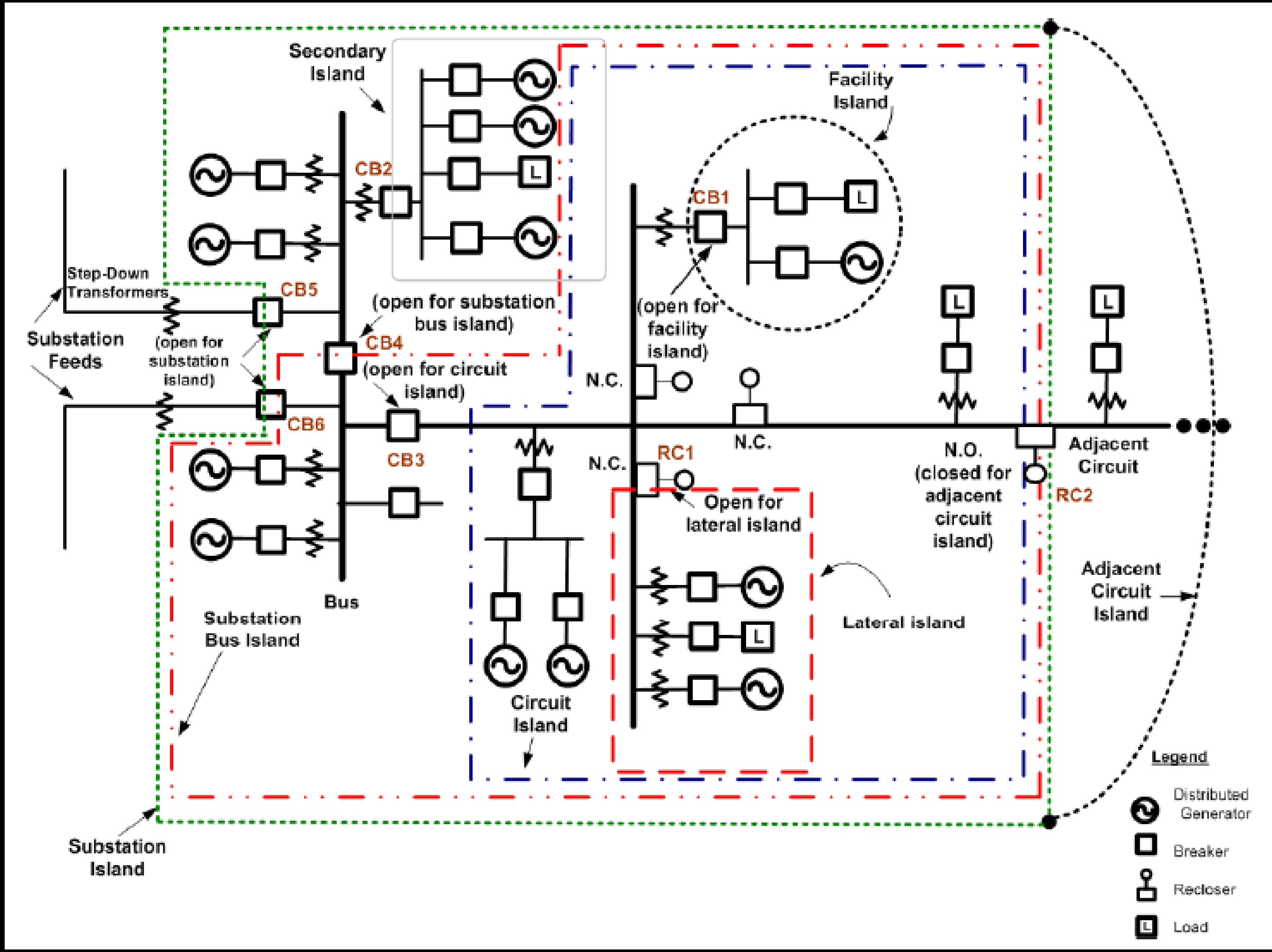
Unintentional (unplanned) islanding



Unintentional, or unplanned, islands can form at the feeder breaker, R_1, or S_1.
If this happens, the DER (PV) must cease to energize in ≤ 2 s.

Planned islands can be good!

Planned islands (e.g., microgrids) can improve reliability, maximize efficiency of use of local resources, and in some cases improve economics.



This figure is from 1547.4-2011

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Risks with unplanned or unintentional islands

- **Equipment:** damage or malfunction due to abnormal voltage and frequency
- **Asynchronous reclosure:** reclosure into an island whose voltage is significantly out of phase
- **System functions:** disruptions with certain system functions, such as UFLS
- **Safety:** risk to anyone who may come in contact with equipment that is disconnected from the grid but still energized

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A word about probabilities and risk…

The formation of a stable unintentional island is <u>extremely</u> unlikely.

1. A large number of conditions must converge:
   a. Breaker opens to form an island *without a fault*
   b. At least a reasonable match exists between sinks and sources
   c. Matching is maintained during the island event
2. Getting inverters to maintain a stable *intentional* island is nontrivial; stabilizing an island when we're not trying to is difficult.

Because the *likelihood* of an island is very low, the actual *risk* posed by an island must be taken in the proper context: low, but can be possible.

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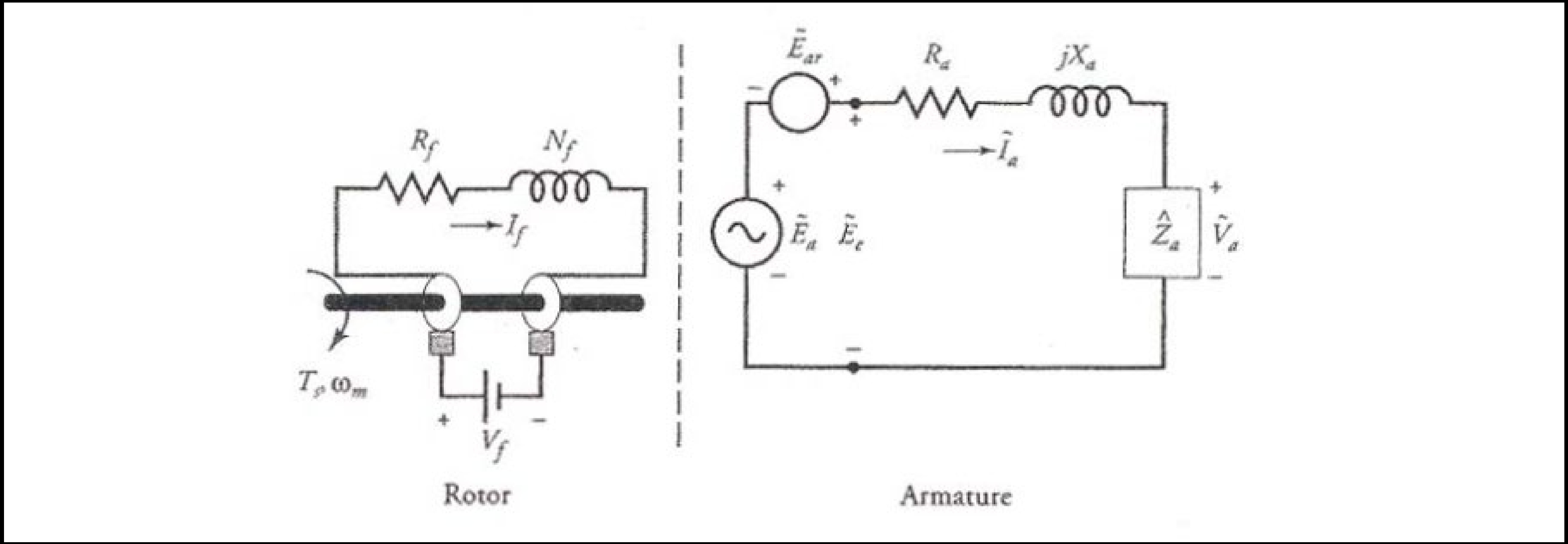
Synchronous generators



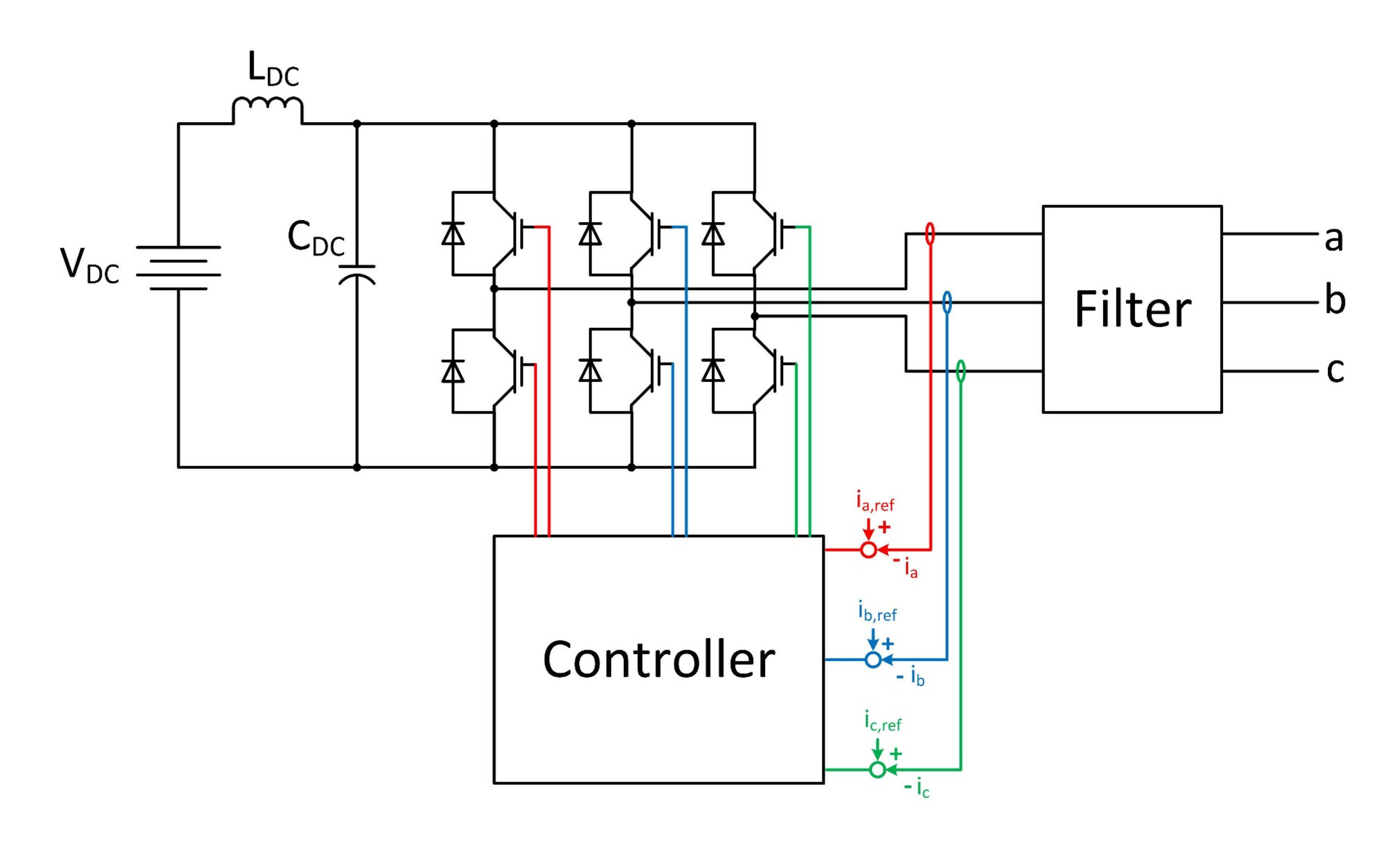
A synchronous generator is well-represented by a voltage source behind an impedance (mostly reactance).

Rotating machine characteristics

- Behavior is physics-dominated
  - Generically modeled with very good accuracy
  - Fault behaviors well known—transient, subsynchronous, synchronous periods
  - Impedances, inertia, and protection are needed
- Real power closely linked to frequency; reactive power closely linked to voltage
- Power factor:
  - Synchronous machines usually rated to 0.8 pf lagging (sourcing vars); do NOT like to sink vars
  - Induction machines are always leading (absorbing vars), nearly always capacitively compensated to ~ 0.9 pf
- **Dynamics: relatively slow (cycles to seconds)**

Inverters

Examples:
- PV
- Type IV WTs
- Microturbines
- Batteries and most other storage
- Note about diodes



Inverter characteristics

- **Behavior is much more software-determined than for rotating machines**
- This provides enormous flexibility, but also means that generic models will be highly approximate
- Inverters behave like constant-power current sources
  - *Usually* very low fault current (< 1.6 pu), but there are exceptions
  - Limited ability to drive overvoltages as compared to spinning generation
- Can operate at any power factor as long as current limits not violated
- **Dynamics: fast (subcycle to single-digit cycles)**

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Behavior of inverter-driven unplanned islands

- Voltage change driven *mostly* by real-power mismatch:

$$Z_{load} = \frac{V_{nom}^2}{P_{load}} \qquad \rightarrow V_{nom}^2 = P_{load} Z_{load}$$

$$V_{isl}^2 = P_{DER} Z_{load} \rightarrow \frac{V_{isl}}{V_{nom}} = \sqrt{\frac{P_{DER}}{P_{load}}}$$

- Frequency change driven *mostly* by reactive power mismatch:

$$f_{isl} \approx f_{EPS} \sqrt{\frac{(Q_L + Q_{LG})}{(Q_C + Q_{CG})}} \rightarrow \frac{f_{isl}}{f_{EPS}} = \sqrt{\frac{Q_{L,isl}}{Q_{C.isl}}}$$

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For inverter-based islands

- In general, if there is a P imbalance:
  - For GLR < 1, V falls.
  - For GLR > 1, V rises.
- In general, if there is a Q imbalance:
  - For a net-inductive island, f rises.
  - For a net-capacitive island, f falls.

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What these equations say about V/f: inverter-only islands

- The voltage in the island is mostly determined by the GLR.
- The voltage equation works up to a GLR of somewhere around 2:1.
  - SPOV and antiparallel rectifiers kick in
- For frequency, if the island is net-inductive, island frequency tends to rise. If the island is net-capacitive, frequency tends to fall.

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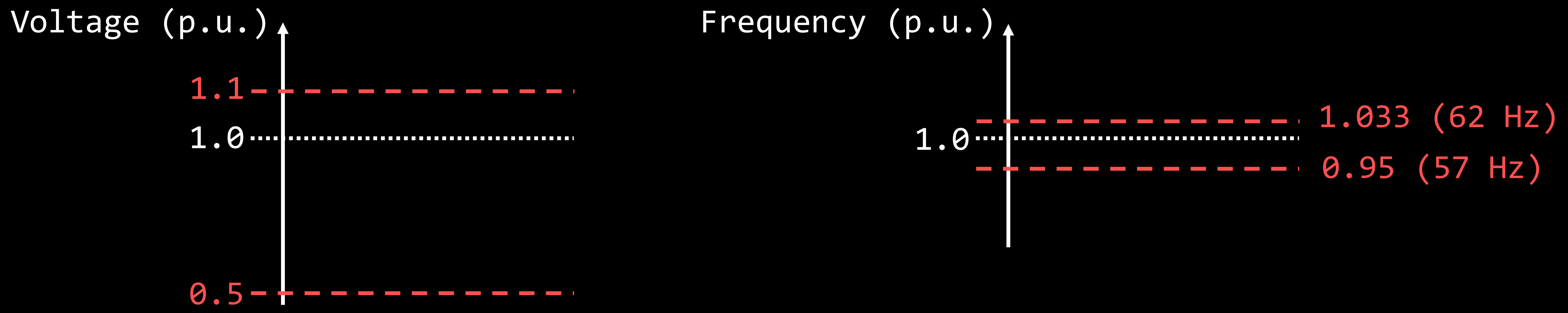
Voltage and frequency sensitivity

- The allowable operating regions for voltage are much wider than those for frequency for under 2 s



- Additionally, var mismatch tends to decrease PLL stability (step in phase).
- End result: for inverter-only islands, sensitivity to var mismatch is higher than to watt mismatch.

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Voltages and loading imbalance

When grid-tied, the island phase voltages are:

$$V_a = V_{a,S} + \left(I_{a,PV} - I_{a,load}\right) Z_{a,line}$$

Because V_S is ≈ balanced and Z_{line} is small, the phase voltages are ≈ balanced and separated by 120^o.

When islanded, the island phase voltages are ≈ determined by Ohm's Law:

$$V_a = I_{a,PV} Z_{a,load}$$

If load is not balanced, the island phase voltages won't be either.

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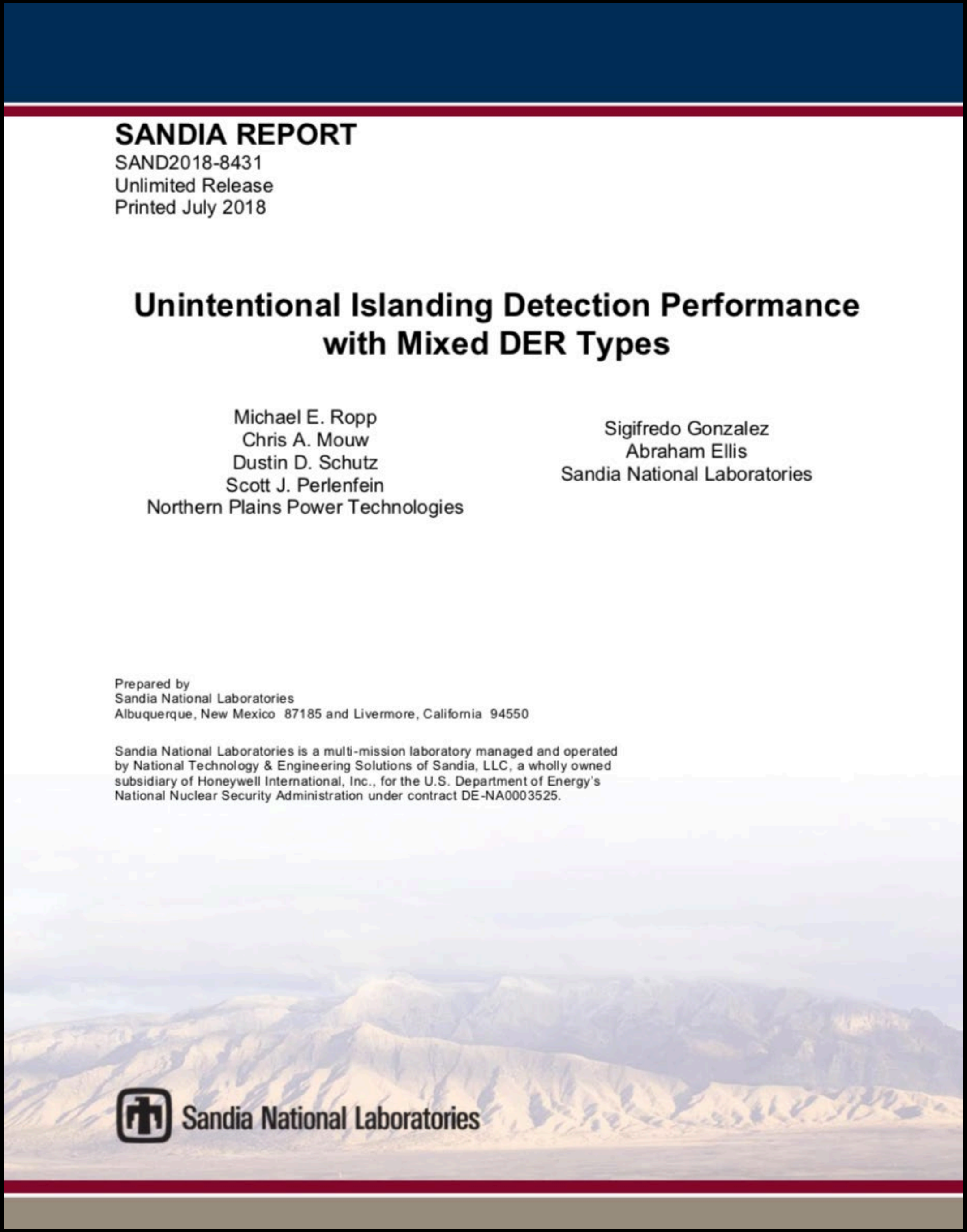
New report just out: SAND2018-8431

New Sandia report that covers:

- Mixtures of dissimilar inverters
- Mixtures of inverters and rotating machines
- Impact of ride-throughs
- Inverter AI groups



SANDIA REPORT
SAND2018-8431
Unlimited Release
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Unintentional Islanding Detection Performance with Mixed DER Types

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The AI Groups (W.I.P.)

- **AI Group 1:** fundamental-freq pos-seq perturbation that grows continuously in magnitude as frequency error increases, with no dead zone.
- **AI Group 2A:** Group 1 but not continuous to the trip limits, except *not* a dead zone.
- **AI Group 2B:** Group 1 or 2A, but with a dead zone.
- **AI Group 2C:** Properties of Group 1, 2A or 2B, but unidirectional feedback.
- **AI Group 3:** pos-seq perturbation without feedback (Z detection).
- **AI Group 4:** harmonic injection specifically for AI.
- **AI Group 5:** passive AI only (i.e. RoCoF, other relays)
- **AI Group 6:** negative sequence manipulation.

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Ground fault overvoltage (GFOV)

- GFOV can occur when a 1LG fault occurs on a four-wire circuit that has lost its zero-sequence path to ground (i.e., when the feeder breaker opens and disconnects the circuit from the substation transformer).
- Theoretical OV: 1.73 pu.
- GFOV is usually NOT a problem with inverter-based DER on distribution circuits.
  - *Inverters do not reinforce phase-phase voltages and thus do not drive GFOV in the way that synchronous generators do.
  - *As long as the GLR is not too high, the load effectively grounds the circuit (IEEE C62.92.6).
- GFOV can be a problem upstream from substation transformers if the high-side winding is delta.

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*GFOV references

- M. Ropp, A. Hoke, S. Chakraborty, D. Schutz, C. Mouw, A. Nelson, T. Wang, J. Chebahtah, M. McCarty, “Ground Fault Overvoltage with Inverter-Interfaced Distributed Energy Resources”, IEEE Transactions on Power Delivery, special issue “Contemporary Problems in Power Quality”, 32 (2), April 2017, p. 890-899.
- IEEE Standard C62.92.6-2017: Guide for Application of Neutral Grounding in Electrical Utility Systems, Part VI – Systems Supplied by Current-Regulated Sources”.

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Load rejection overvoltage (LROV)

- LROV can occur when a circuit that was exporting power is islanded. DER power cannot change instantaneously, and for a brief moment the power must flow into the local loads.
- LROV is not a major issue with sync gens.
  - V behind Z—output current drops quickly on LROV
- For inverters:
  - Act as power-controlled current sources
  - Current can't drop instantly→LROV
  - **BUT: "antiparallel rectifier" limits maximum LROV**
  - **Typical max values ~ 2 pu, but depends on V_{DC}**

$$\frac{V_{isl}}{V_{nom}} = \sqrt{\frac{P_{DER}}{P_{load}}}$$

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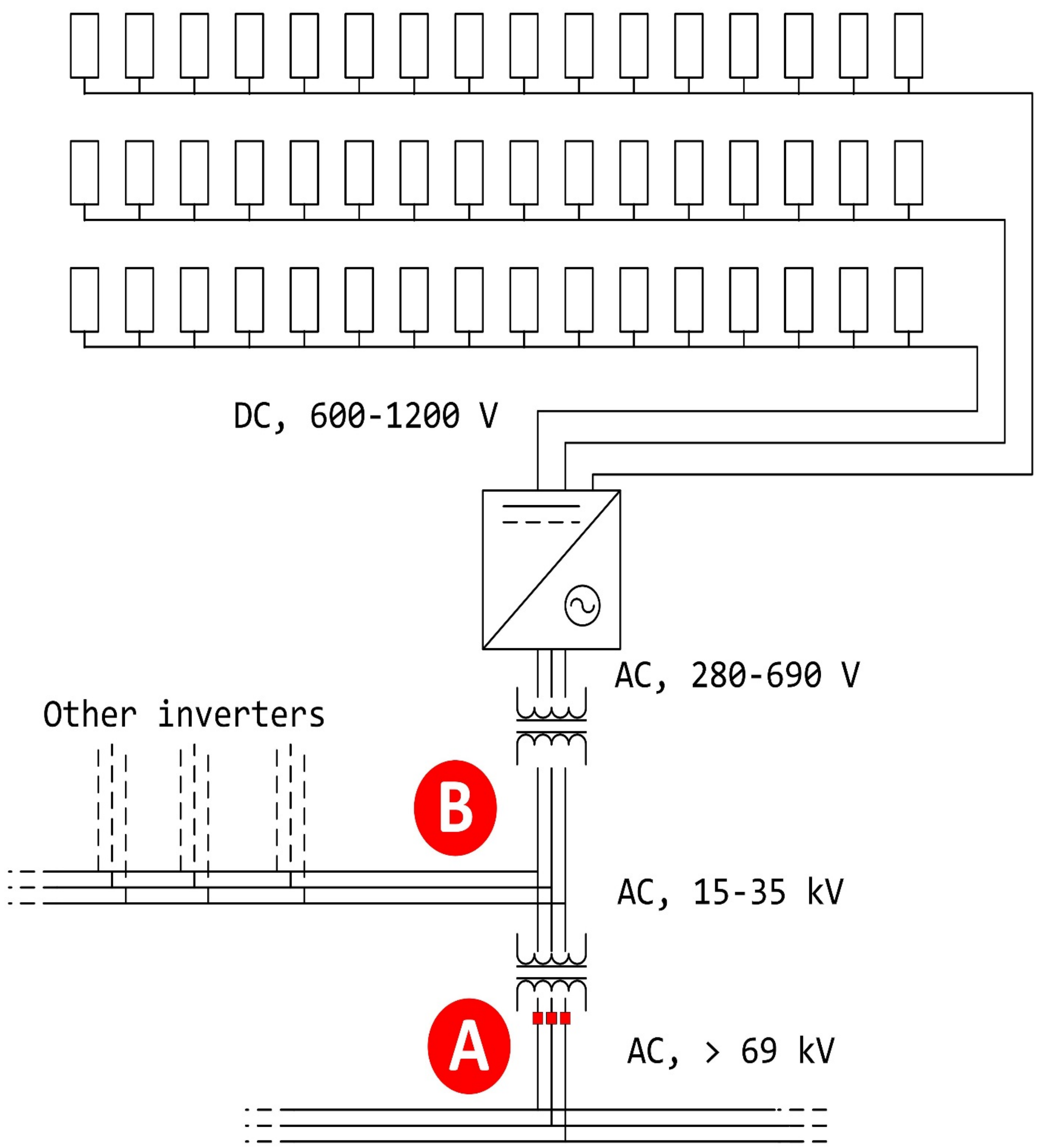
Ferroresonant overvoltage (FROV)

- FROV can occur with DERs, primarily within the PV plant itself: if the breaker at **A** opens while the plant is exporting, FROV can occur at **B**.
- FROV can reach as high as 5 pu
- **This is a specialized topic—won't discuss further here**



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Examples of results seen with different islanding scenarios

Risk-of-islanding and TrOV studies

- In a case in which there's doubt, one can commission a **risk-of-islanding study** to get an idea of whether and what mitigation may be required.
- How it works:
  - Need a highly detailed control model of the inverter—usually in MATLAB/Simulink, PSCAD, EMTP-RV or similar
  - Need a *reasonably* detailed model of the circuit; level of detail needed depends on the anti-islanding type used
  - Run a matrix of simulations at different loading conditions and determine the run-on time (ROT) at each condition
  - Check each ROT against IEEE 1547-2018 2-s limit
- **Contact us for more details.**

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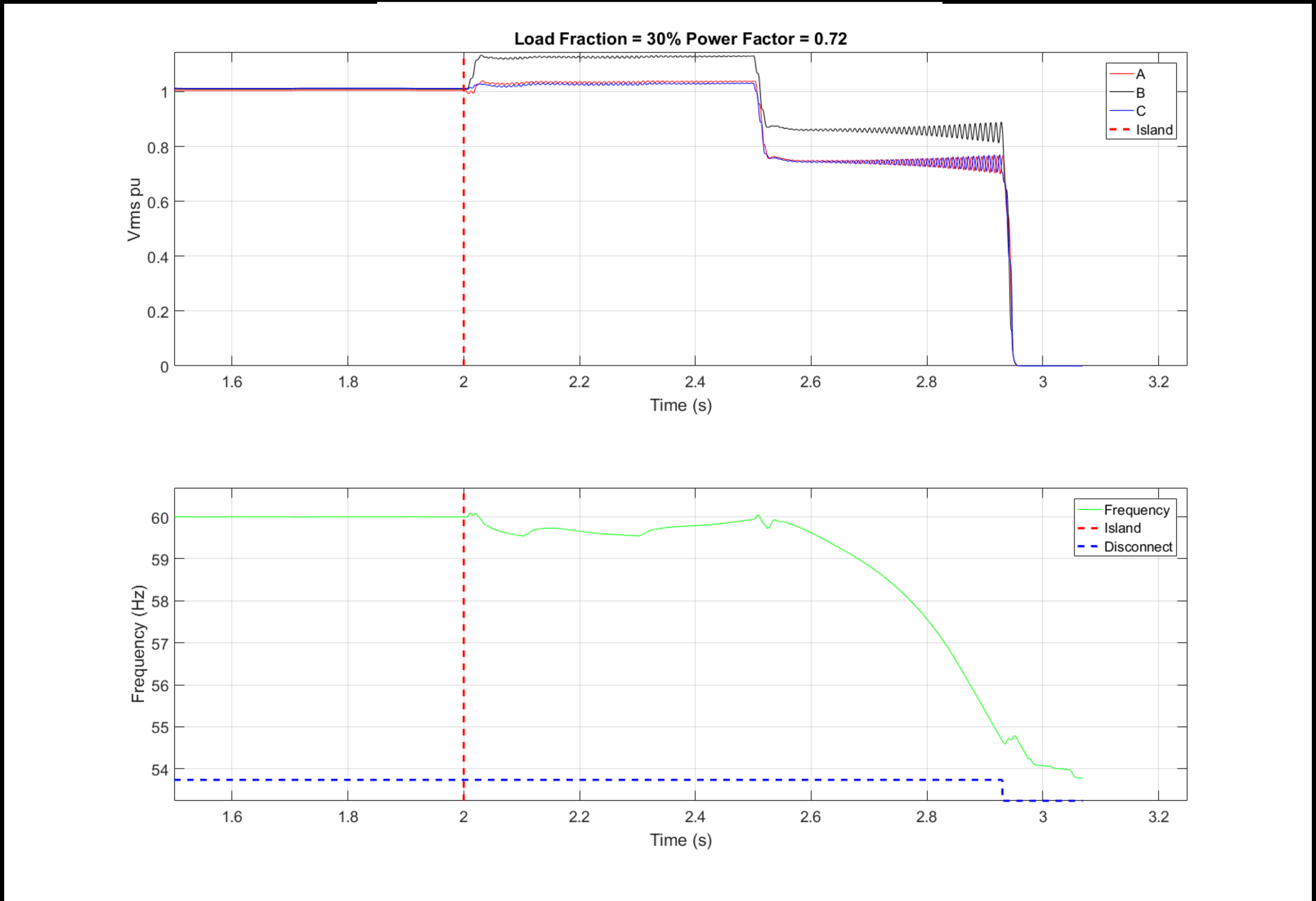
Example 1

Two PV plants with dissimilar inverters, AI groups 2A and 2B. Island is slightly net-capacitive. GLR close to but slightly above 1.0.

Note the phase-phase voltage imbalance. 1st plant trips on OV ~0.5 s into island.

Frequency declines due to net-capacitive island; eventually active AI "pushes it over".

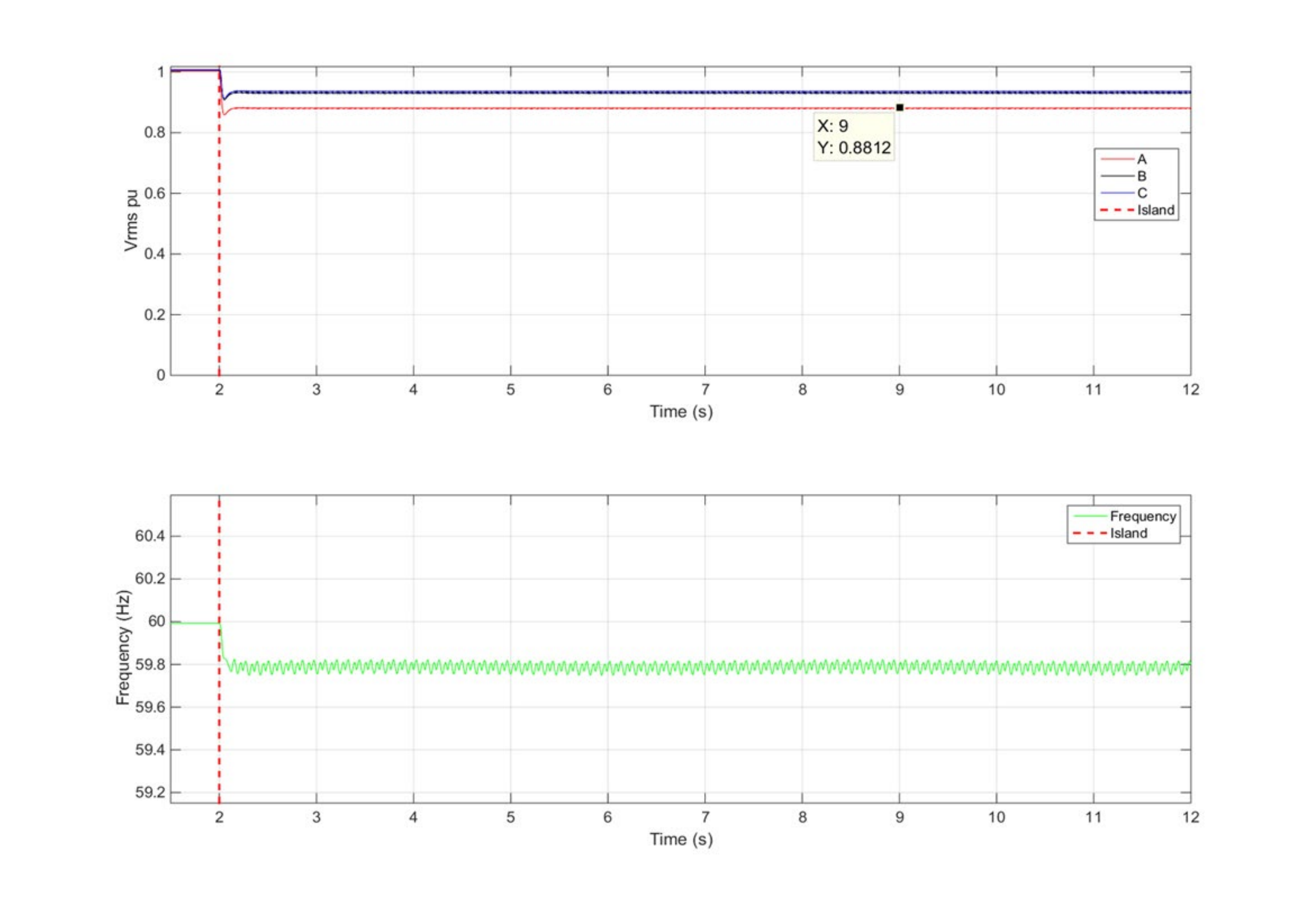


Example 2

Six PV plants, no rotating generation, high capacitance. Island has a GLR slightly below unity and is slightly net-capacitive.

Note phase-phase imbalance again, but it’s fairly small.

The frequency changes quickly at the outset but then stabilizes. Result: stable island. Mitigation required (recommendation: RoCoF).



Parameter sweeps

- RoI should be considered over a wide range of loading conditions
  - From min to max load with margin added, and from unity pf down as necessary.
- Load sweeps like this are typically presented as a 3-D surface plot or a "heat map" of the run-on time (ROT) versus loading faction (LF) and power factor (PF).
- We typically check islands formed at any device that can isolate part of the circuit with loads, sources and capacitors.
- If there's more than one capacitor configuration, we check those too.

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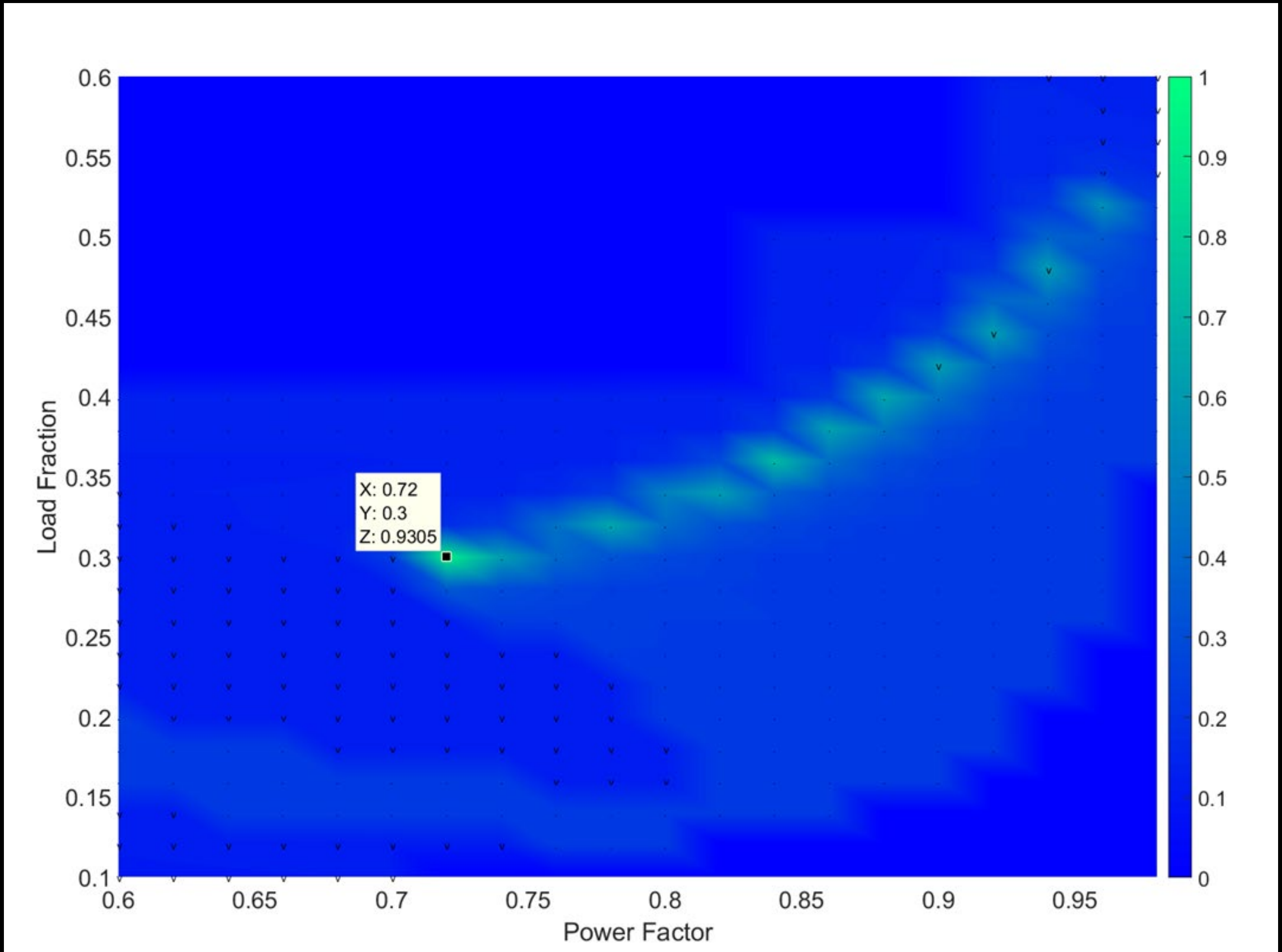
Example 3

This is a "typical" surface plot of ROTs vs LF and PF when there are only inverters in the island and most are from AI Groups 1-2. ROTs tend to be fairly short (max here is just under 1 s), and we see a "ridge" of elevated ROTs where P-mismatch and Q-mismatch effects partially counterbalance. *Most ROT surface plots look like this.*



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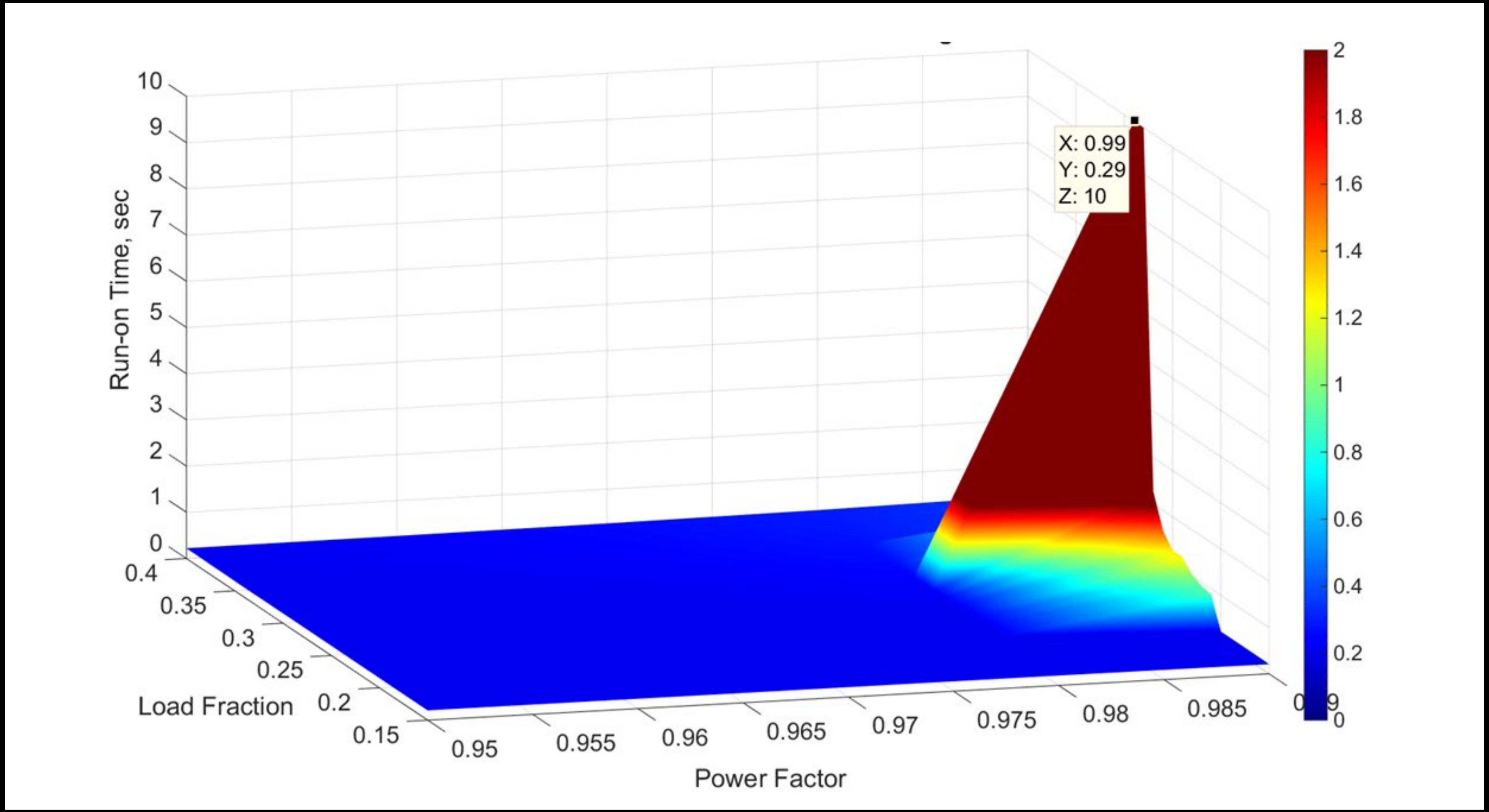
Example 4a

This surface plot is for a case that has:

- 7 MW of DER
- Six PV plants, about 50% of DER
- One sync-gen plant, about 50% of DER

There is a very small region in which ROTs are quite long. Mitigation recommended.



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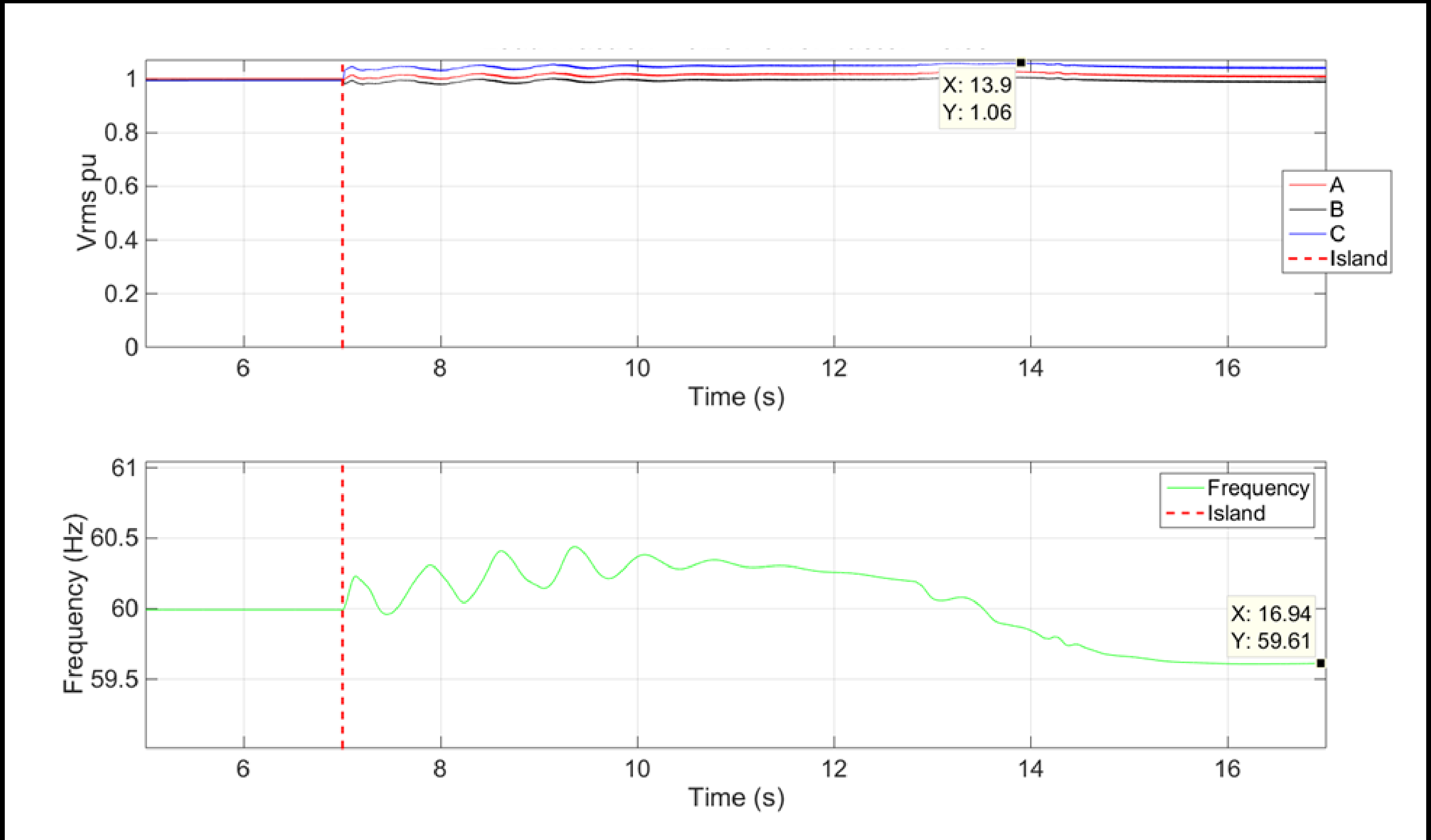
Example 4b

These plots show the voltage (top) and frequency (bottom) during the island event for one of the extended ROT conditions.

The island is stable; it would not de-energize without an external perturbation, such as a change in load.



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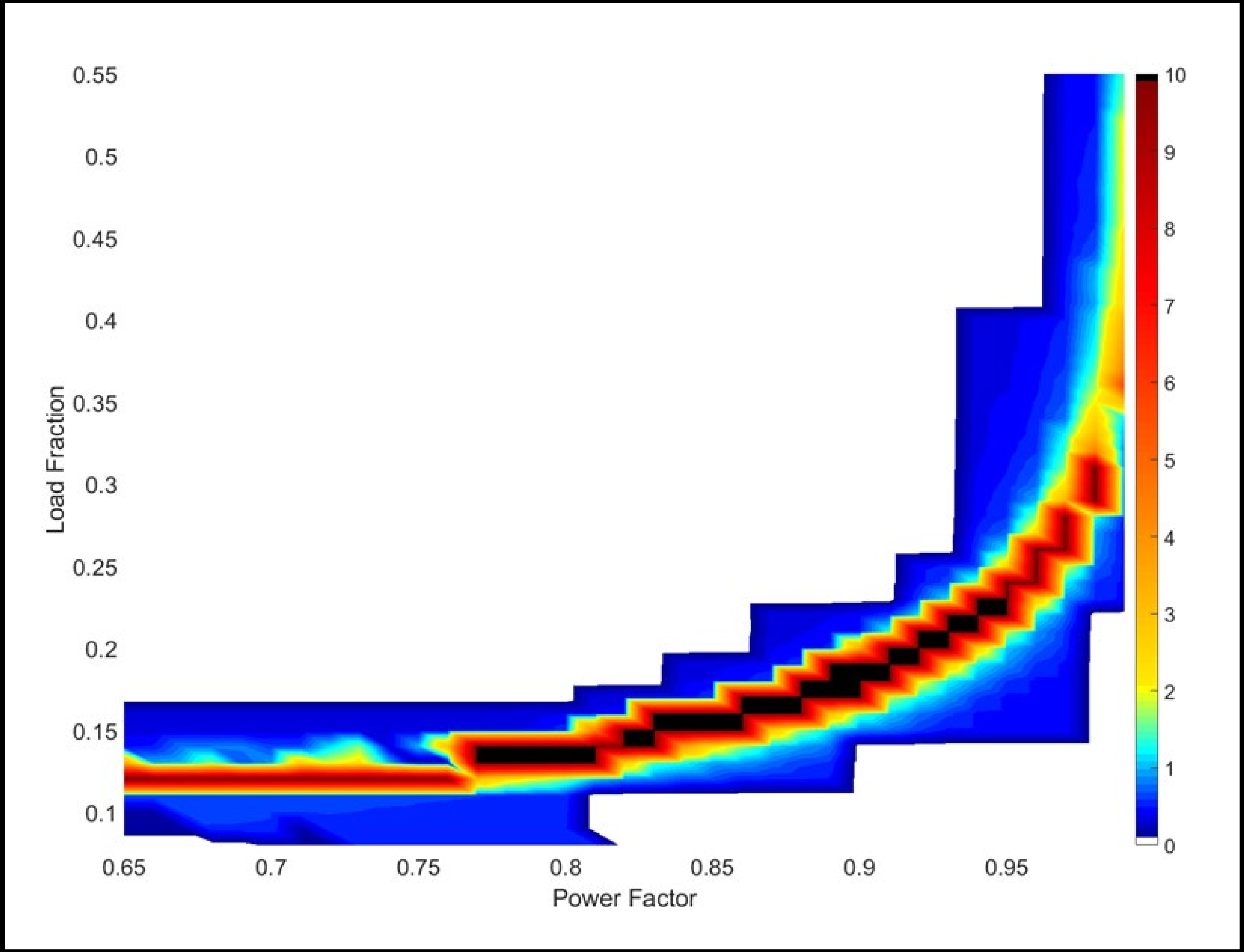
Example 5

This case is for an island with 75% PV (Group 2B) and 25% synchronous generation. The "ridge" extends well above 2 s in this case. Mitigation would be recommended.



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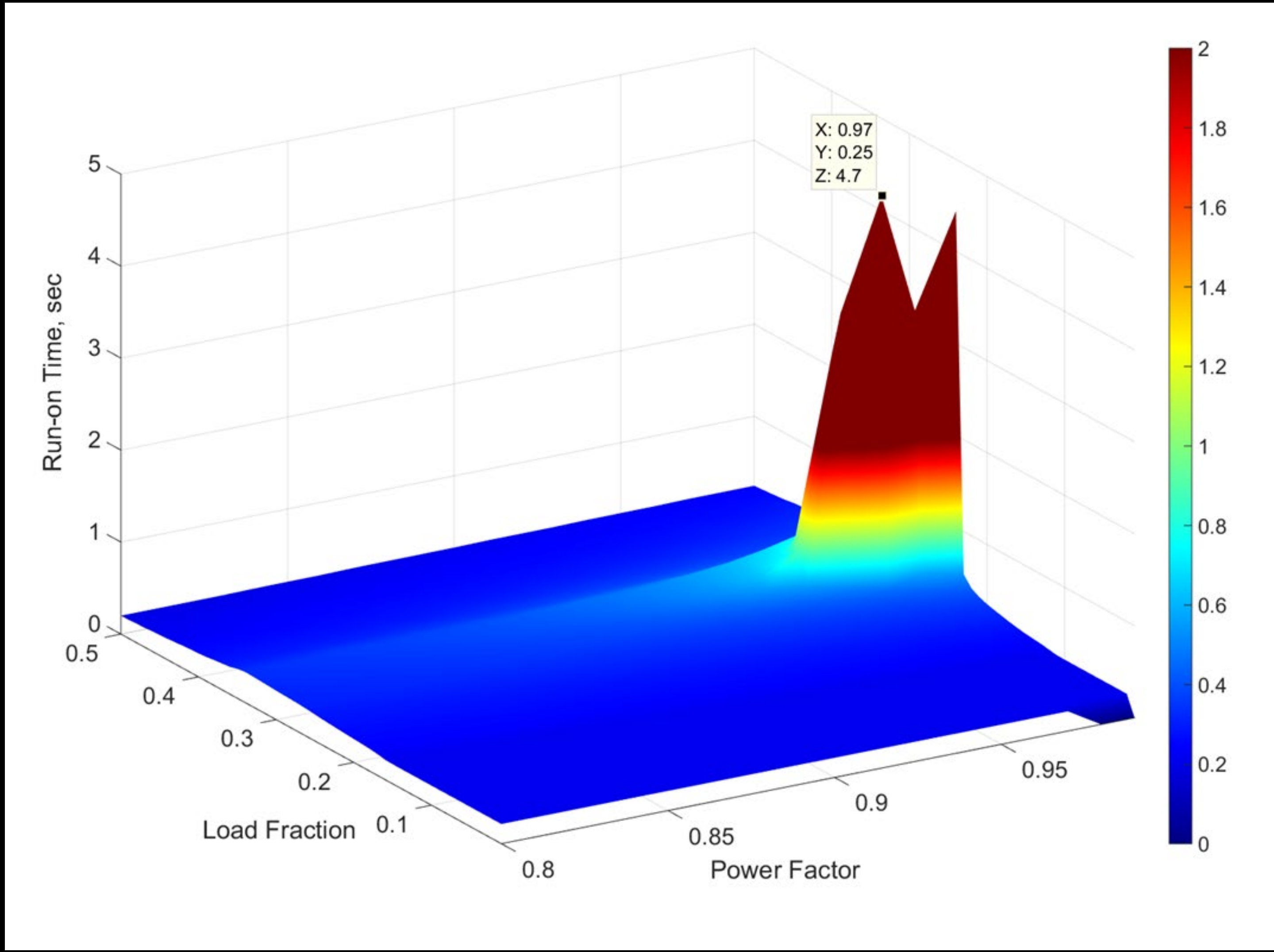
Example 6a

This is a case with inverters and induction generators. There is a wide range of LF and PF for which the ROT exceeds 2 s—but, the maximum ROTs are less than 5 s. Long, but not indefinite.



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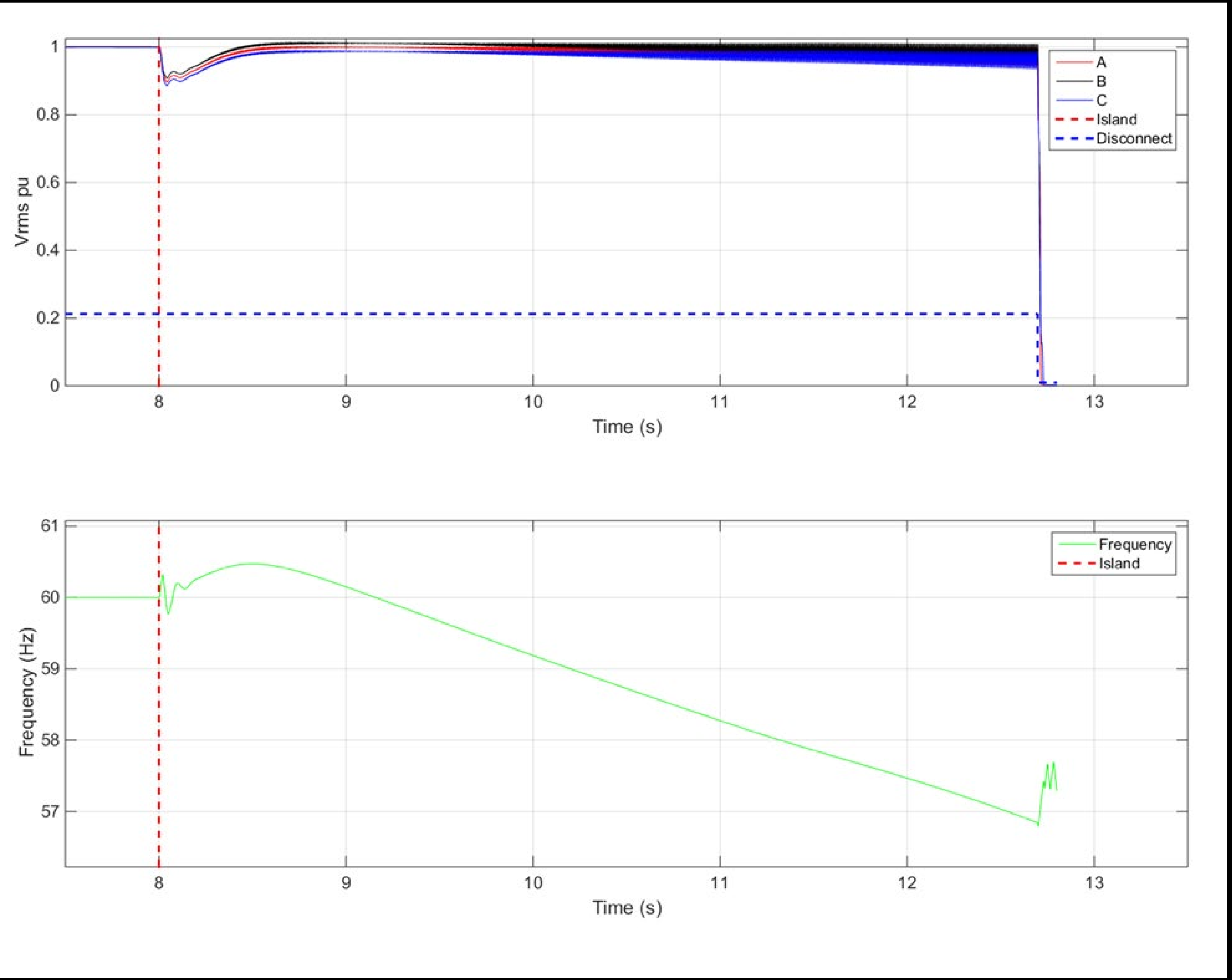
Example 6b

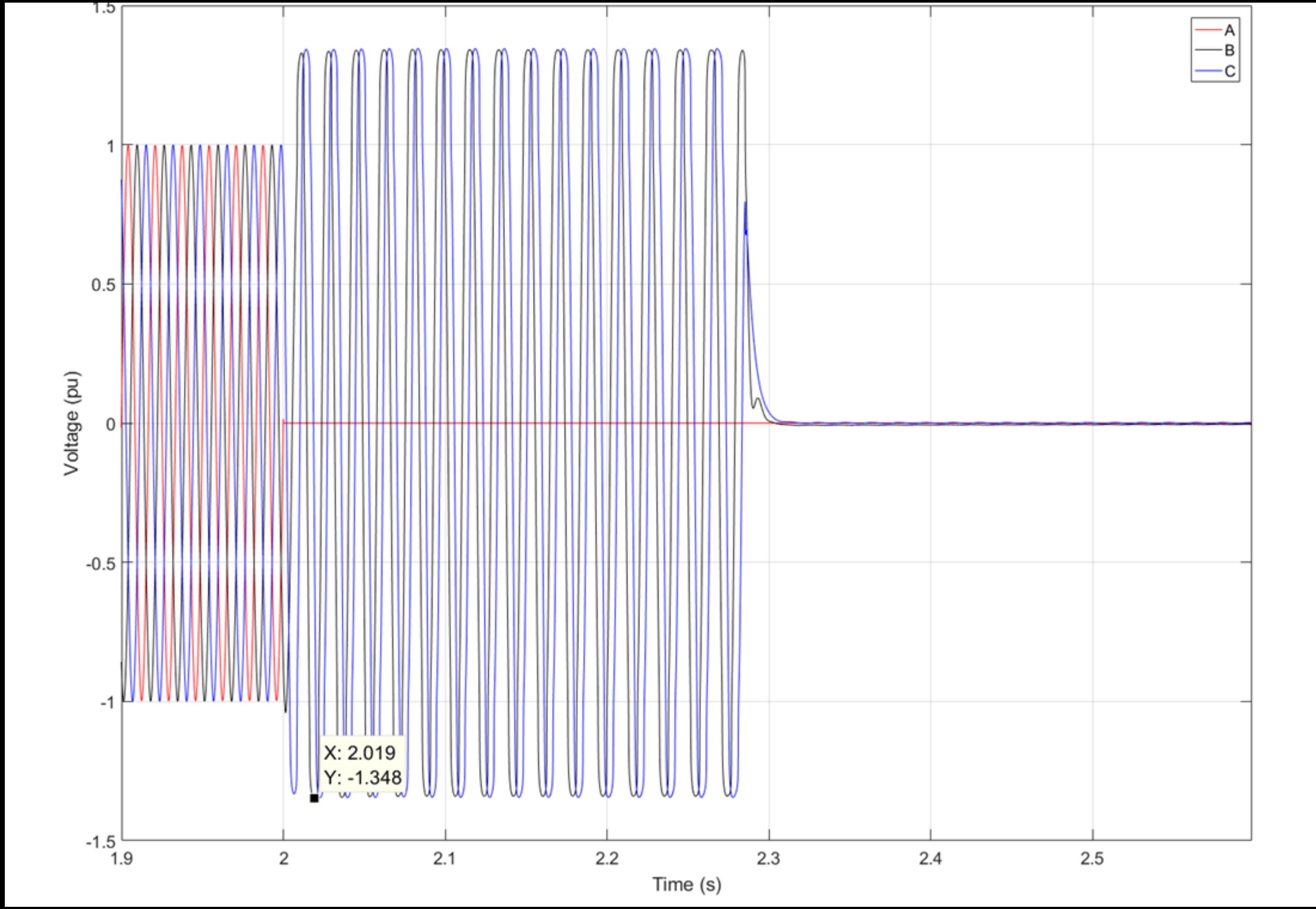
Here are the voltages and frequencies vs. time for the longest-ROT case on the previous slide. The frequency decline is slow, but eventually gets to the UF trip.



Example 7a

This is a simulation of GFOV upstream from a substation transformer winding. GLR = 1.44. The island forms at 2 s. Zero-sequence voltage appears.

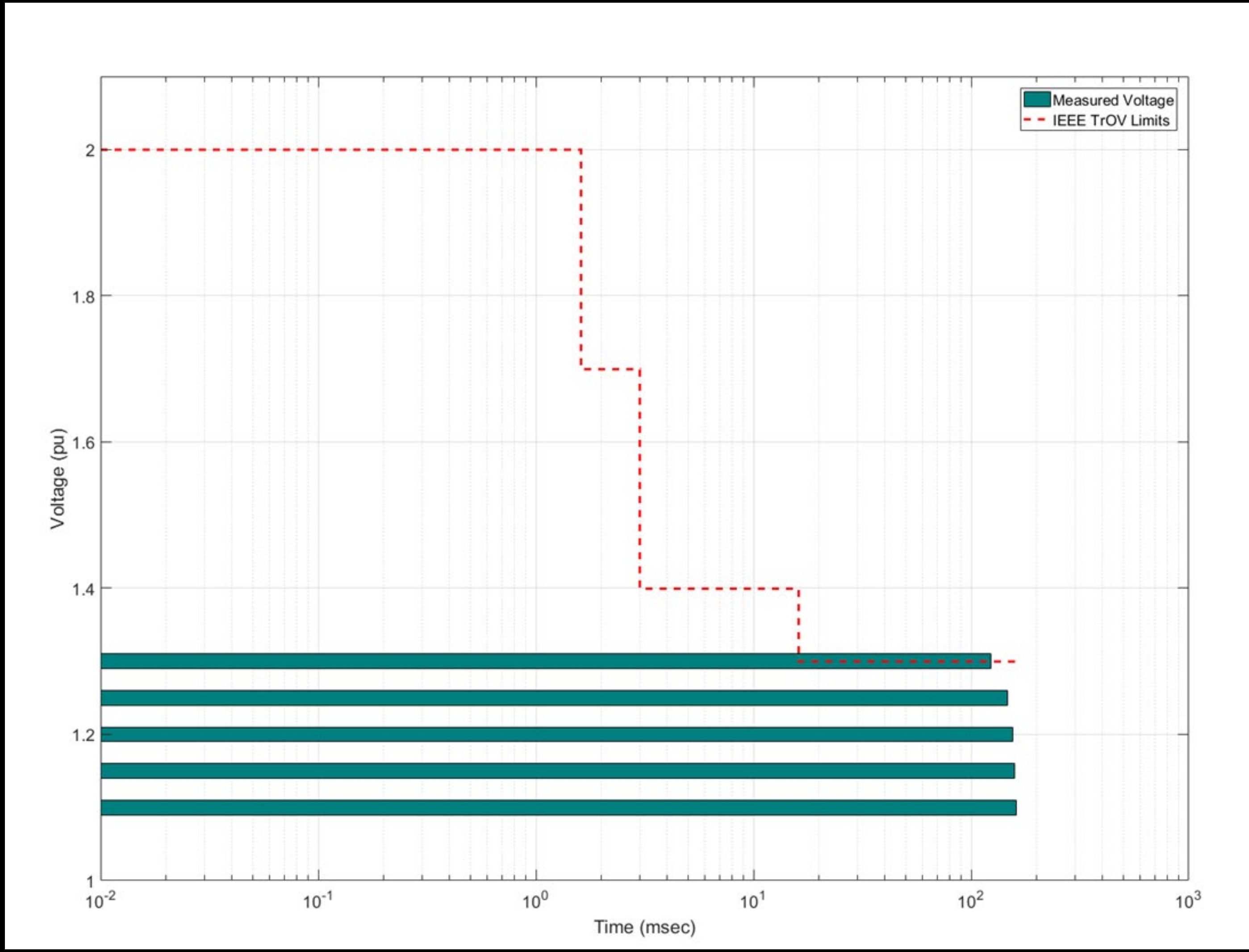
Peak voltage of 1.348 pu



Example 7b

Voltage-versus-duration plot for the case on the previous slide. This would be a borderline case; it passes, but just barely.

Arrester energy was also OK in this case.



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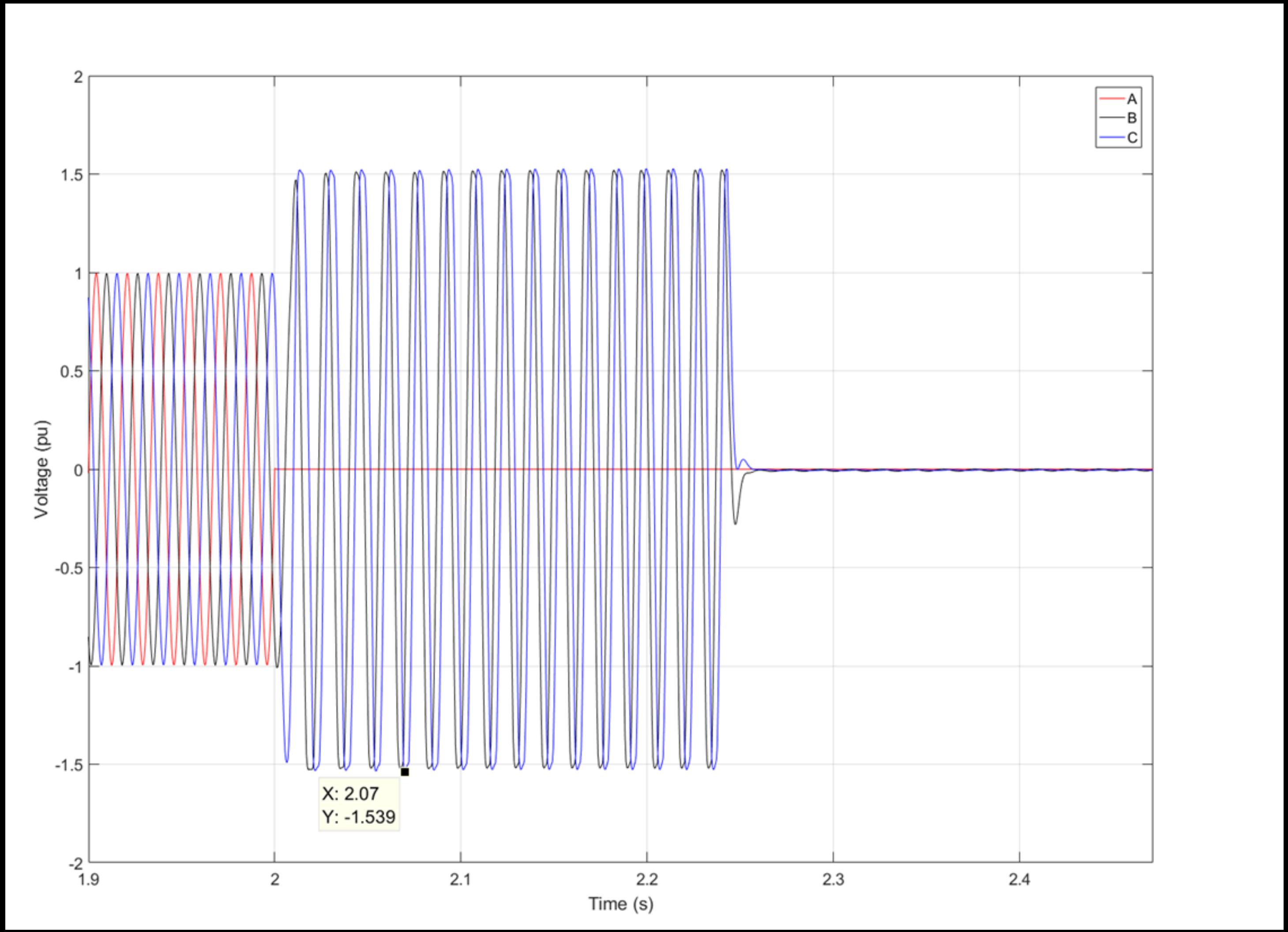
Example 8a

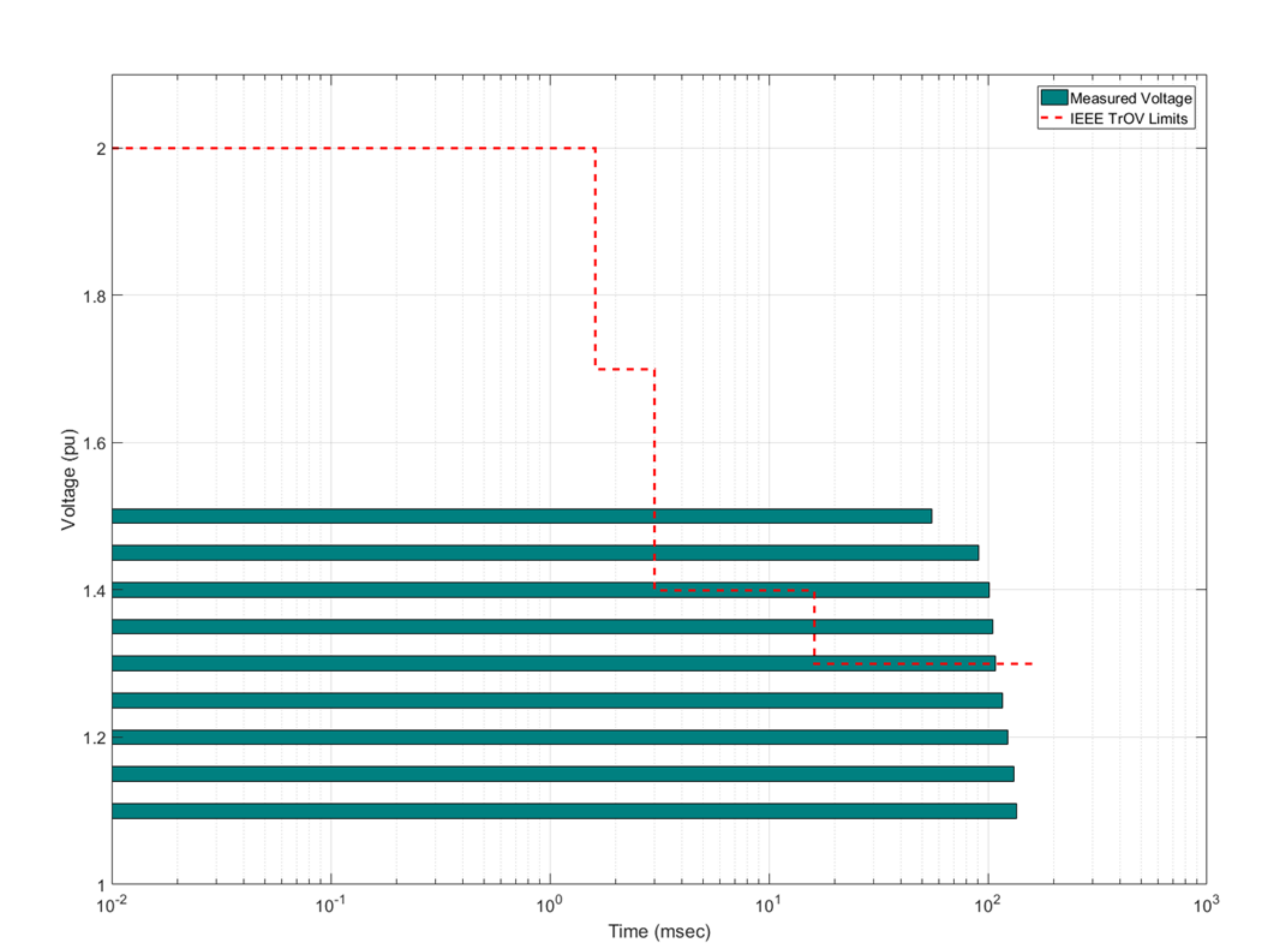
This is another case of GFOV above the substation transformer delta winding. GLR = 1.33. Notice that the voltage is higher 1.539 pu.



Example 8b

This is the voltage-versus-duration result for the case on the previous slide. In this case the TrOV curve is breached and mitigation is required.

Difference in arresters' relative MCOV between Examples 7 and 8 was the difference in GFOV risk.



Conclusions

- Island dynamics can be complex, especially when there is a mix of dissimilar DERs.
- Rules of thumb for island voltage and frequency behavior have been presented here.
- USUALLY, UL-certified inverter-based DER installations trip off in less than 2 s for all conditions tested.
- Whenever there is doubt, a risk-of-islanding study can answer questions and indicate candidate solutions.

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THANK YOU!

Questions?

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