Dynamic behavior of islanded distributed energy sources

Chris Mouw
Northern Plains Power Technologies
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, R₁, or S₁. 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
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
A word about probabilities and risk...

The formation of a stable unintentional island is extremely 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.
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)**
Behavior of inverter-driven unplanned islands

• Voltage change driven mostly by real-power mismatch:

\[
Z_{load} = \frac{V_{nom}^2}{P_{load}} \quad \rightarrow \quad V_{nom}^2 = P_{load}Z_{load}
\]

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

• Frequency change driven mostly by reactive power mismatch:

\[
f_{isl} \approx f_{EPS} \frac{\sqrt{(Q_L + Q_{LG})}}{\sqrt{(Q_C + Q_{CG})}} \quad \rightarrow \quad \frac{f_{isl}}{f_{EPS}} = \sqrt{\frac{Q_{L,isl}}{Q_{C,isl}}}
\]
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.
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.
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.
Voltages and loading imbalance

When grid-tied, the island phase voltages are:

\[ V_a = V_{a,S} + (I_{a,PV} - I_{a,\text{load}})Z_{a,\text{line}} \]

Because \( V_S \) is \( \approx \) balanced and \( Z_{\text{line}} \) is small, the phase voltages are \( \approx \) balanced and separated by 120°.

When islanded, the island phase voltages are \( \approx \) determined by Ohm’s Law:

\[ V_a = I_{a,PV}Z_{a,\text{load}} \]

*If load is not balanced, the island phase voltages won’t be either.*
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
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.
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.
*GFOV references*


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 $V_{DC}$

\[
\frac{V_{isl}}{V_{nom}} = \sqrt{\frac{P_{DER}}{P_{load}}}
\]
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
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.**
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.
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.
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.
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.
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.
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.
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.
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.
THANK YOU!

Questions?
chris.mouw@northernplainspower.com