Assessment of IEEE 1547 Low-Voltage Ride-Through Criteria Impact on Bulk Power System Dynamics Following Transmission Path Fault

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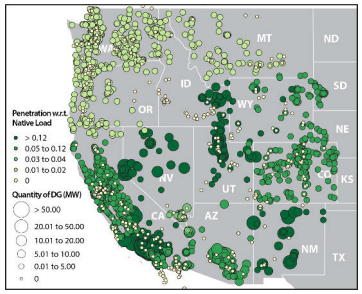
Initial PSLF Simulation: Western Interconnection, Path 61, Fault Induced Delayed Voltage Recovery

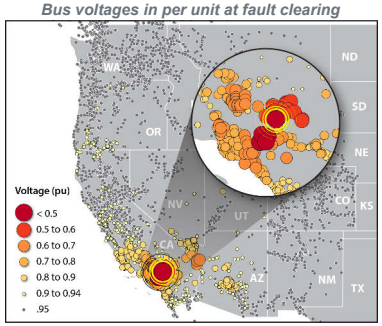
- *Heavy Summer 2023 planning case with high levels of utility scale (~17%) and distributed renewable energy (~5%).*
  - *More than 21,000 buses; 190 GW of load; 9 GW of photovoltaic distributed generation acting as negative load.*
  - *Distributed generation (DG) modeled within dynamic composite load model (CMPLDWG).*
- *Three-phase fault on 500-kV Lugo bus; Z = 0 + j0.034, cleared after six cycles with associated Lugo-Victorville line trip.*

DG on the Western Interconnection

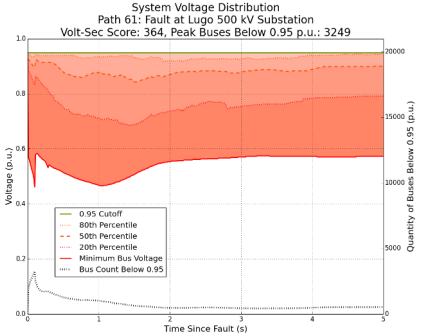


- *Based on work from the Western Wind and Solar Integration Study Phase 3.*
- *Output at power flow instance.*

Bus voltages in per unit at fault clearing



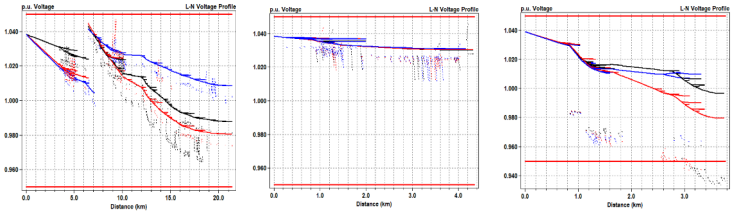
- *Wide impact on voltage profiles, particularly in Southern California.*
- *Spatial voltage profile at fault-clearing moment in simulation.*



- *FIDVR occurs.*
- *Prolonged low voltages at nearly 1,000 buses.*
- *Indicative that type of distributed generation ride-through criteria will heavily influence aggregate distributed generation output.*

OpenDSS Feeder Simulations with PSLF-Generated Voltage Profiles

California Feeders with Secondaries

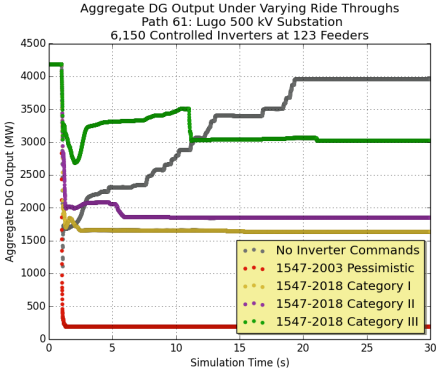


Commercial/residential: 12 kV | *Industrial: 16 kV* | *Residential: 4 kV*

- *123 unique voltage profiles from PSLF Path 61 fault simulation.*
- *50 inverters compliant to relevant IEEE 1547 ride-through criteria on each feeder, located on secondaries.*
- *Proportional representation of residential/commercial/industrial feeders based on impacted region.*
- *Four simulations of each unique voltage profile dependent on type of ride-through criteria.*
- *All ride-through control based on pessimistic interpretation of standard—i.e., if current injection is not explicitly required, then current injection is assumed to be zero.*

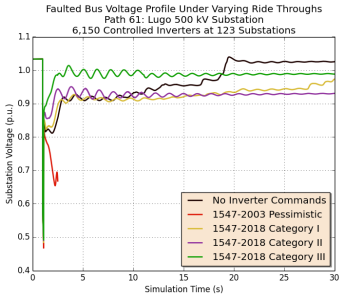
IEEE 1547 Implementation Envelopes

Voltage	IEEE 1547 2013 Pessimistic	IEEE 1547: 2018 Category I	IEEE 1547: 2018 Category II	IEEE 1547: 2018 Category III
$V < 0.3$	Immediate trip	Immediate trip	Immediate trip	Momentary cessation; trip after 1.0 s
$0.3 \leq V < 0.5$			Momentary cessation; trip after 0.32 s	
$0.5 \leq V < 0.65$		Momentary cessation; trip after 0.16 s		Continuous operation; trip after 10.0 s
$0.65 \leq V < 0.7$			Trip after: 3 s + (8.7 s/p.u.) × (V − 0.65 p.u.)	
$0.7 \leq V < 0.88$		Trip after 0.7 s + (4 s/p.u.) × (V − 0.7 p.u.)		Continuous operation; trip after 20.0 s
$0.88 < V$	Continuous operation	Continuous operation	Continuous operation	Continuous operation

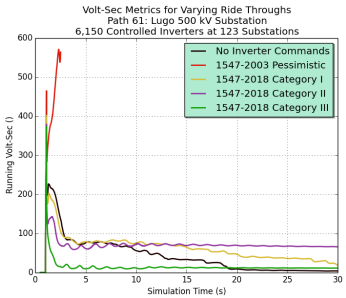


Western Interconnection Response with OpenDSS Distributed Generation Commands

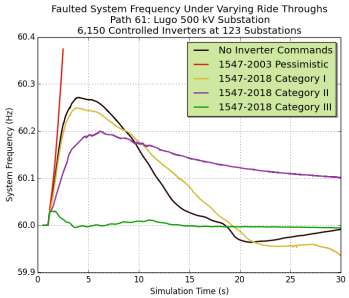
Path 61 fault scenario re-simulated but with explicit distributed generation commands at the 123 buses from OpenDSS simulations



- *Pessimistic case results in simulation divergence.*
- *Categories I and II exhibit similar voltage recoveries.*
- *Category III results in no FIDVR.*
- *None show the complete recovery seen in the original simulation because of lack of full distributed generation recovery.*



- *Running volt-sec metric:*
  - $\sum_{n=1}^{N} \Delta t(max(0, v_L - b_n^t))$
  - *N: bus count; Δt: simulation time step; v_L: voltage cutoff (0.95); b_n^t: bus n voltage at time t*
- *Captures system-wide voltage profile.*
- *Corroborates no FIDVR with Category III ride-through.*



- *Center-of-inertia frequency:*
  - $\omega(t) = \frac{\sum_{i=1}^{G}(MVA_i \cdot \omega(t)_i)}{\sum_{i=1}^{G} MVA_i}$
  - *G: generator count; MVA_i: generator i MVA rating; $\omega(t)_i$: generator i frequency*
- *High frequencies because of low voltage -> static load decrease.*
- *Category II is similar to original.*
- *Category III shows large improvement over initial frequency.*

Key Findings

- ***Under heavy loading conditions, the Western Interconnection is susceptible to widespread voltage influences from transmission faults.***
- ***Categories I and II yield similar real power results. Category III yields a respectively smaller total real power output.***
- ***FIDVR events can persist well beyond the trip times specified in the IEEE 2018 ride-through criteria.***

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