Advanced Inverter Functions for Distributed Solar Integration

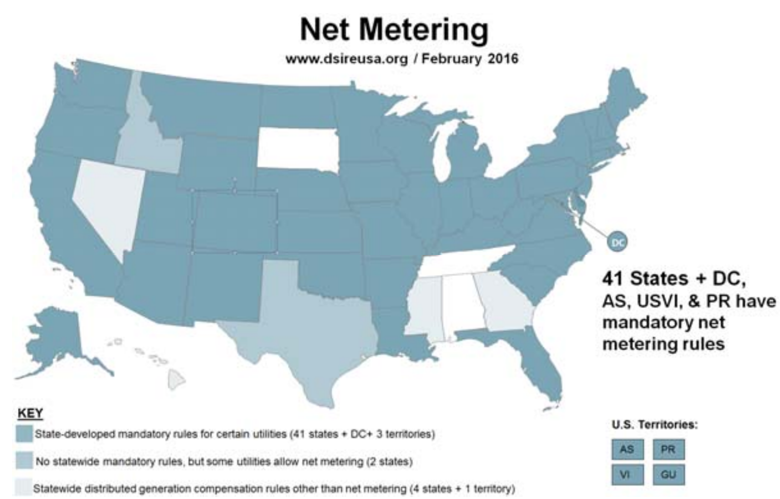
1. DOE Sunshot and state-wide incentives for distributed solar.
2. Managing voltage fluctuations with smart inverters
3. The need for PV to provide ride-through and grid support
4. Evolution of IEEE Standard 1547
5. On-going research into PV inverter functions and models

Tom McDermott, *tem42@pitt.edu*

Pittsburgh IEEE PELS Chapter
February 23, 2016

Sponsors: EPRI Electric Power Research Institute, FirstEnergy, Duquesne Light Our Energy…Your Power

State Net Metering Policies put the focus on distributed resources rather than transmission-connected plants.



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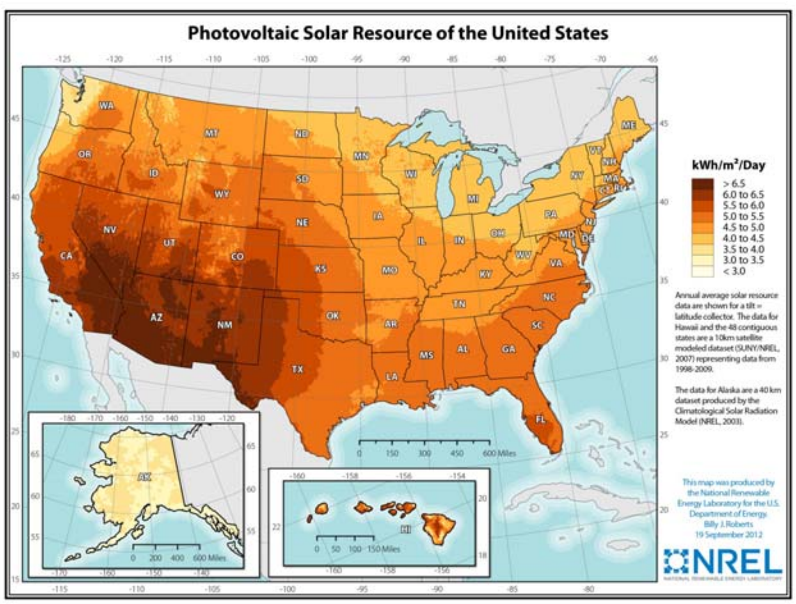
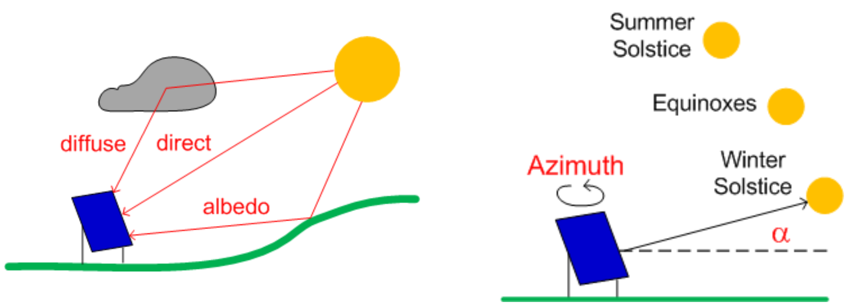
Net metering tiers can distort the interconnection; a 3 MW generator becomes three 1-MW generators.

Source: Neil LaBrake, Jr., National Grid

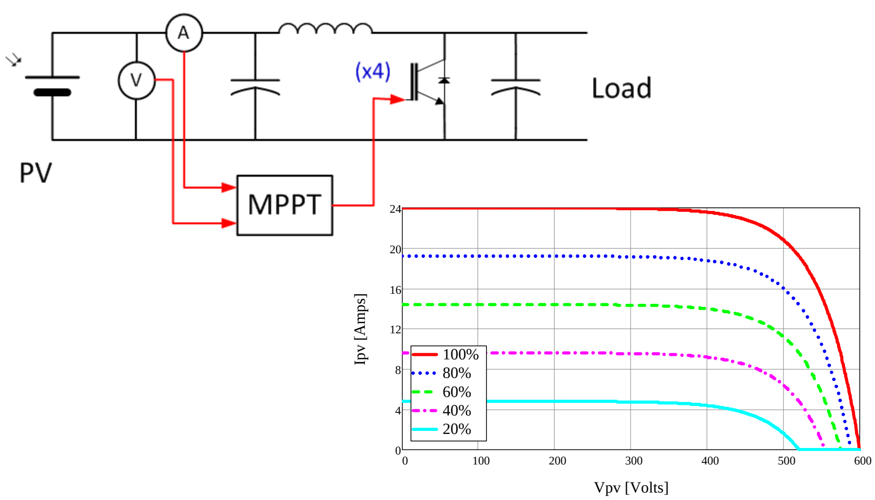


PV Angle Effects may enhance (or degrade) the economics of a PV interconnection.



- Best elevation depends on latitude and season
- Best azimuth depends on time of day

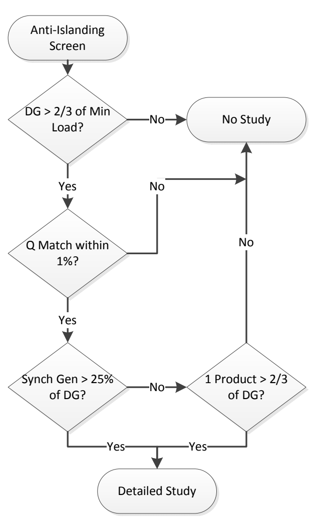
The inverter optimally matches the photovoltaic DC output voltage to the AC load via Maximum Power Point Tracking.

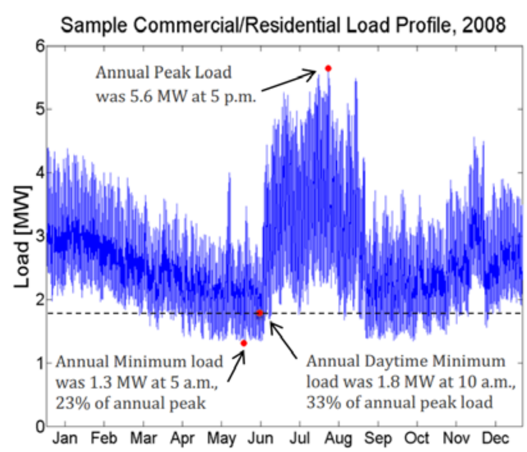


There are three main concerns with integrating VG on distribution systems.

1. Voltage Fluctuations
   a) Inverters can operate at fixed power factor
2. Fault Currents and Overvoltages
   a) Inverters contribute only 1.1 – 2.0 times rated
   b) Inverters shut down quickly upon open-circuit or short-circuit conditions
3. Unintended Islanding
   a) Utility-interactive inverters have built-in anti-islanding detection schemes to operate in 2 s

Sandia, NREL and EPRI have promoted updates to the 15% screening criteria for no-study PV interconnects.

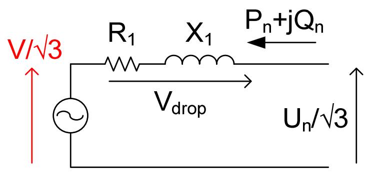


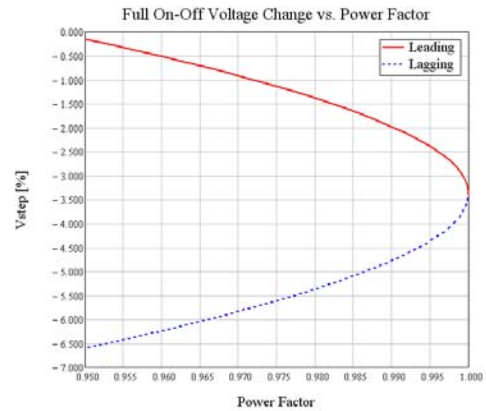


Coddington et. al.: Updating Interconnection Screens for PV System Integration

Optimal (fixed) power factor dispatch alleviates voltage fluctuations, until vendors implement IEEE 1547a

Estimated % Voltage Change:





$$V_{drop} = \frac{100}{U_n^2}(R_1 + jX_1)(P_n - jQ_n)$$

$$\frac{dV}{U_n} = \sqrt{(100 - \mathrm{Re}V_{drop})^2 + (\mathrm{Im}V_{drop})^2} - 100$$

(R, X in ohms, S_n in MVA, U_n in kV)

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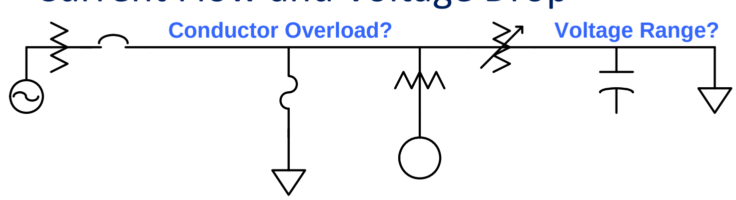
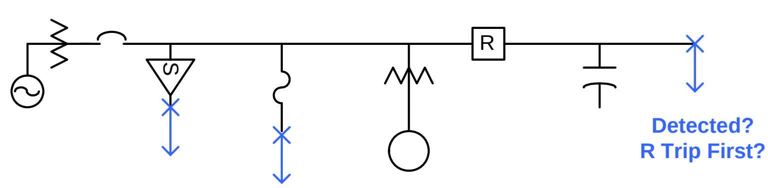
Basic Distribution Software Tasks have been limited to load flow and short circuit analyses.

- Current Flow and Voltage Drop



- Overcurrent Protective Device Coordination



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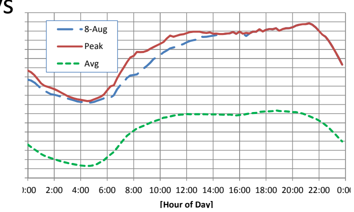
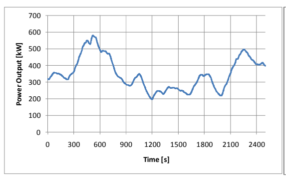
Quasi-static Time Series (QSTS) Simulation addresses load and generation variability.

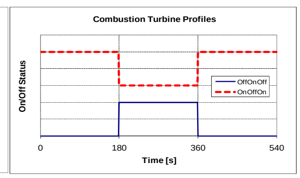
- Time-stepping through a variable power profile
- Tap changers are active, with time delays
- Capacitor controls with time delays
- Controls remember state at next time
- But it's not a dynamic simulation:
  - No inertia
  - No numerical integration
  - Simple RMS load flow solution at each time step



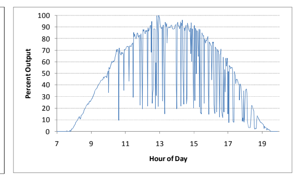
Daily Load Variations)



40-minute Wind



Conventional Generator



Daily PV (50 kW Unit)

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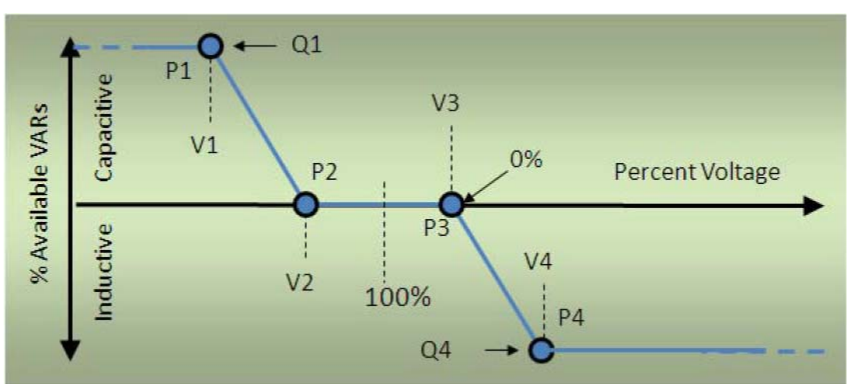
Intelligent Volt-Var function attempts to hold a constant voltage using percent available VARs.



Source: "Common Functions for Smart Inverters, v3", EPRI 3002002233, February 2014

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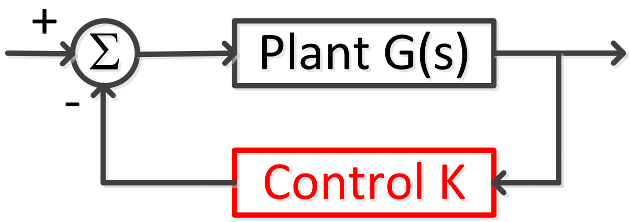
"Percent available" output means the physical slope [VARs/volt] varies.



Would you choose to make this gain block non-linear or time-varying?

What was the intent? "'Available VARs'" implies whatever the DER is capable of providing at the moment, without compromising Watt output. In other words, *Watt output takes precedence over VARs* in the context of this function".

Source: "Common Functions for Smart Inverters, v3", EPRI 3002002233, February 2014, p. 9-3.

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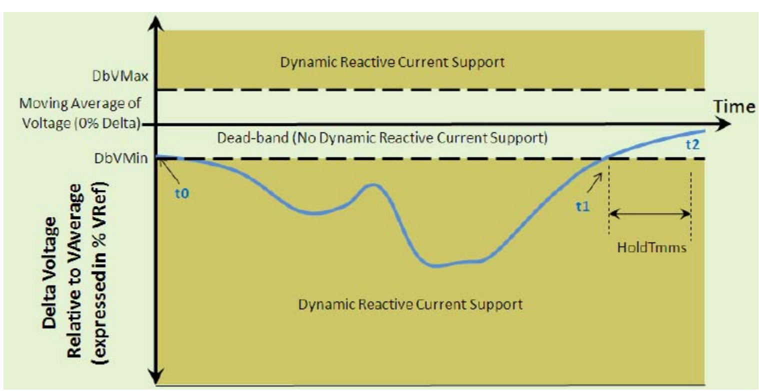
Dynamic Reactive Current function provides an event-based response to changes in voltage.



Source: "Common Functions for Smart Inverters, v3", EPRI 3002002233, February 2014

Tested with a three-phase high-impedance fault in EPRI 3002002271

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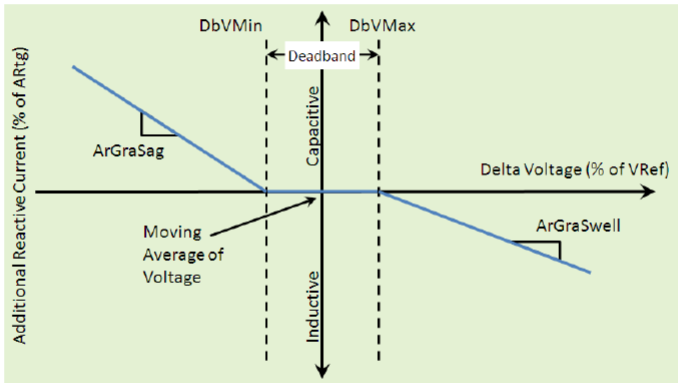
Dynamic Reactive Current function provides reactive power in percent of rating.



Source: "Common Functions for Smart Inverters, v3", EPRI 3002002233, February 2014

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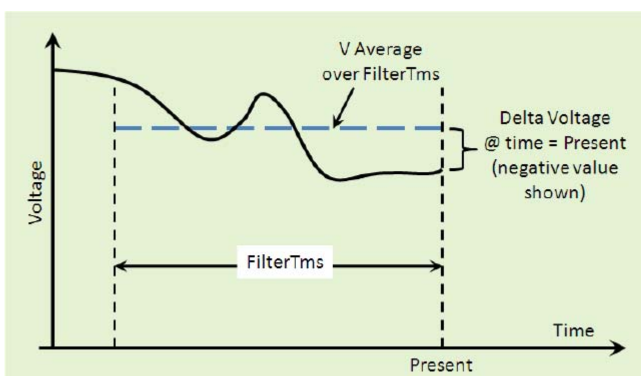
Dynamic Reactive Current function uses a moving average to define the voltage set-point.



Source: "Common Functions for Smart Inverters, v3", EPRI 3002002233, February 2014

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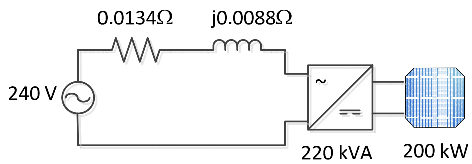
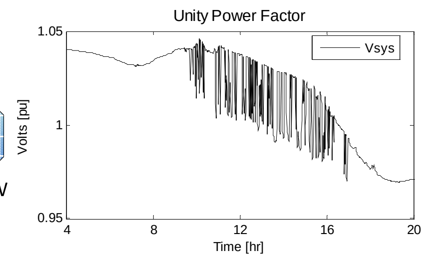
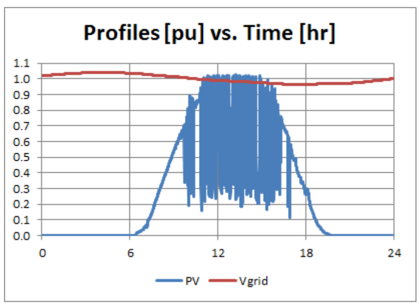
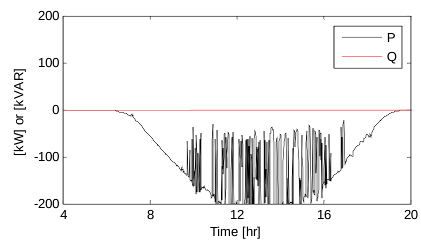
A voltage-control test circuit includes both grid voltage and solar output variability.









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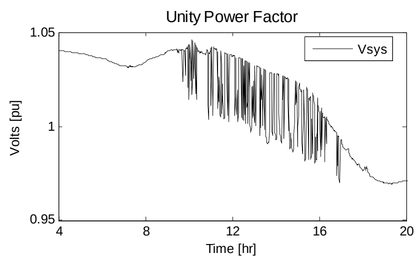
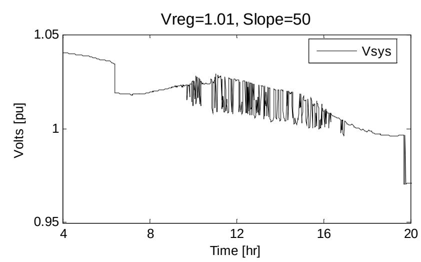
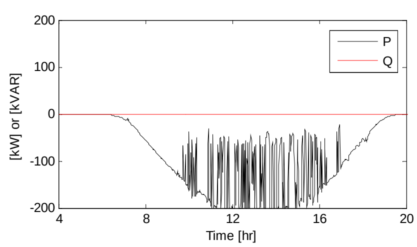
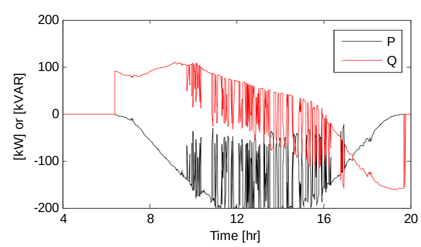
Intelligent Volt-VAR mitigates fluctuation, but constrains operation (e.g. voltage reduction requires communication).









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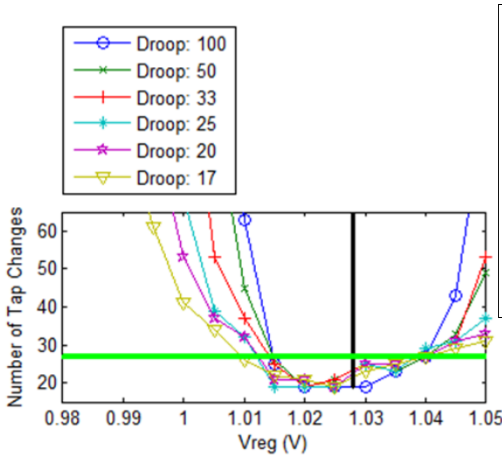
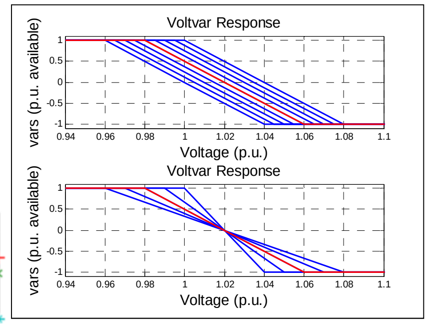
The burden of choosing settings; detailed studies needed; the wrong choice makes things worse.





Source: Abate, McDermott, Rylander and Smith, "Smart Inverter Settings for Improving Distribution Feeder Performance", IEEE PES General Meeting, Denver, CO, July 2015.

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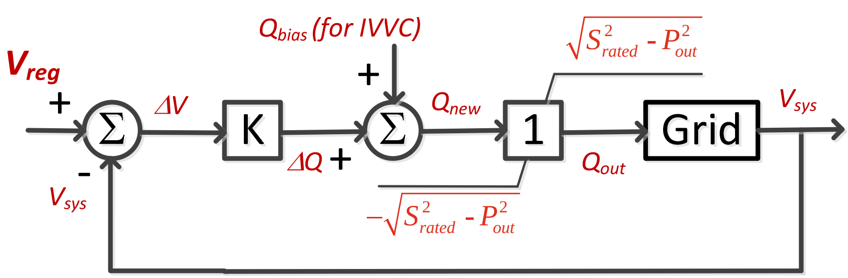
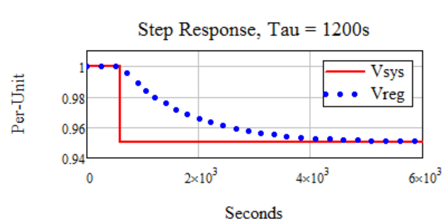
Adaptive Voltage Regulation provides the best of both intelligent volt-VAR and dynamic reactive current.



$$V_{reg} - = \Delta V\left[1 - e^{-\Delta t/\tau}\right]$$



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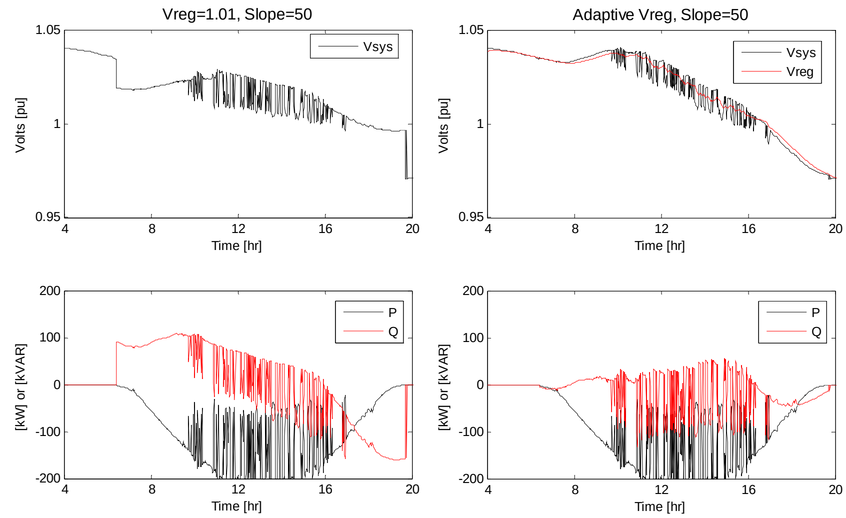
Adaptive Voltage Regulation mitigates fast voltage fluctuation while tracking slower grid voltage trends.



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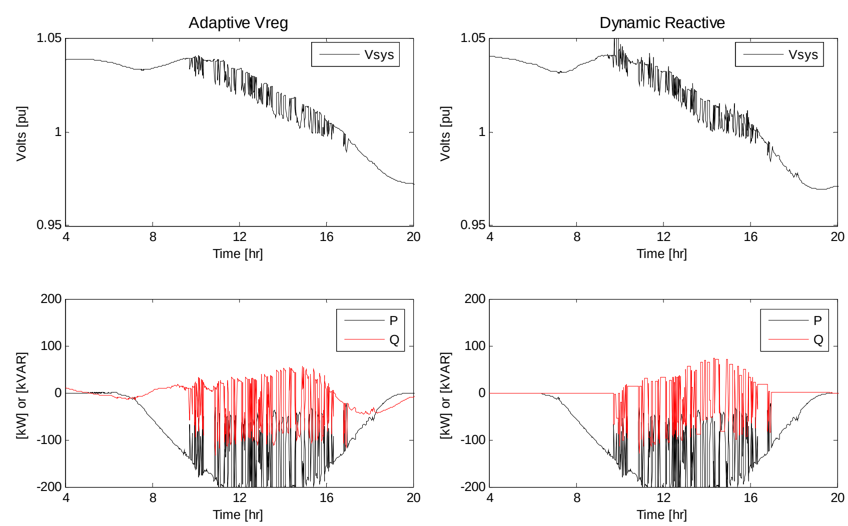
Dynamic Reactive Current performance may be close to Adaptive Voltage Regulation; Slope = 50.



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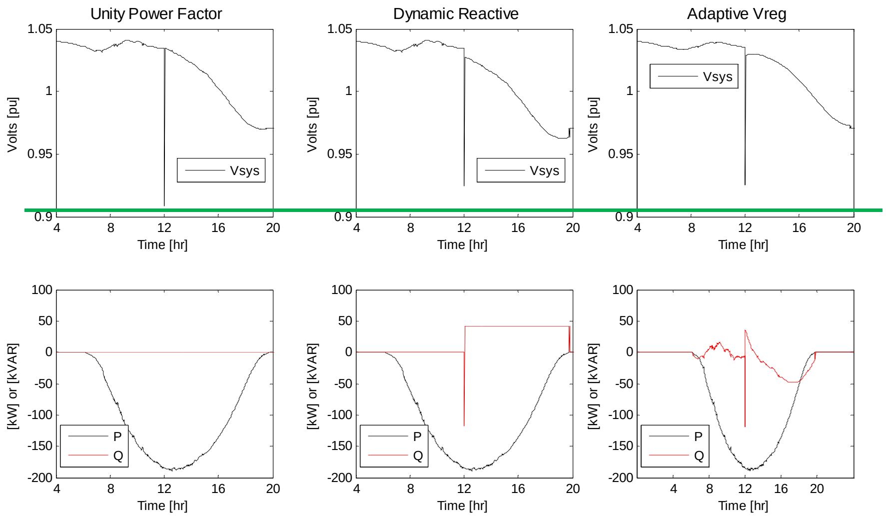
Dynamic Reactive Current and Adaptive Vreg tested with high-impedance fault on clear day.



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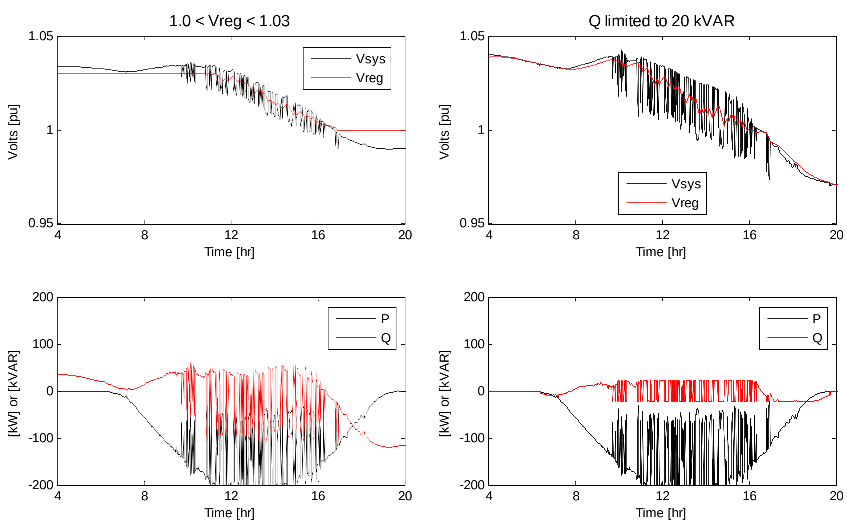
Voltage regulation set-point and reactive power can be limited, if desired.



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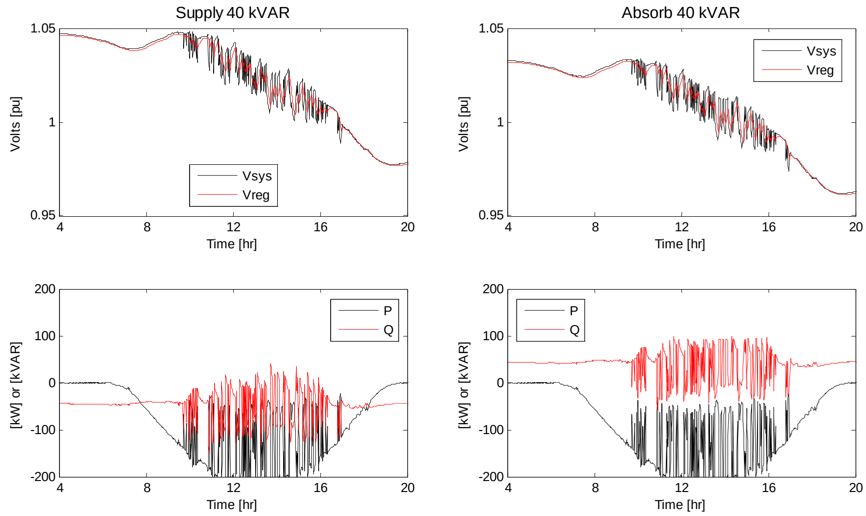
Instead of attempting to regulate the grid voltage, dispatch reactive power (i.e. the bias point is not zero).



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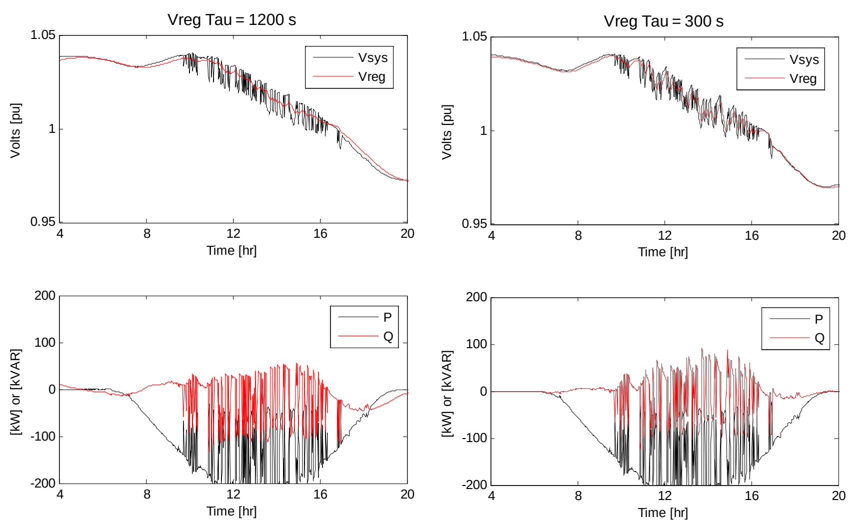
Shorter Vreg time constants don’t necessarily work better; the optimal value seems to be 1200 seconds.



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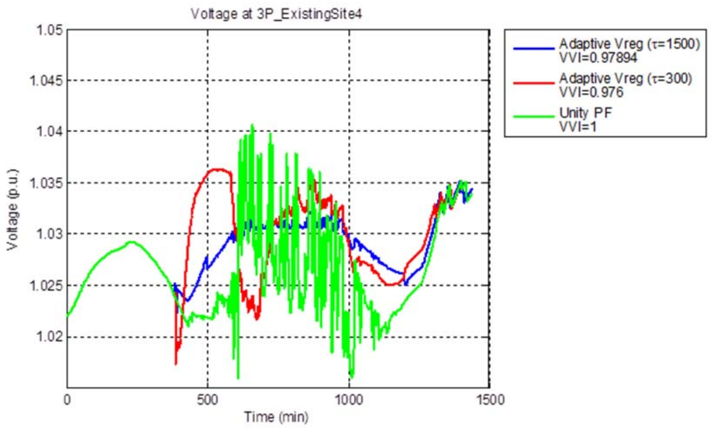
Results from an actual feeder with 1.7 MW of PV show that Adaptive Voltage Regulation performs well.



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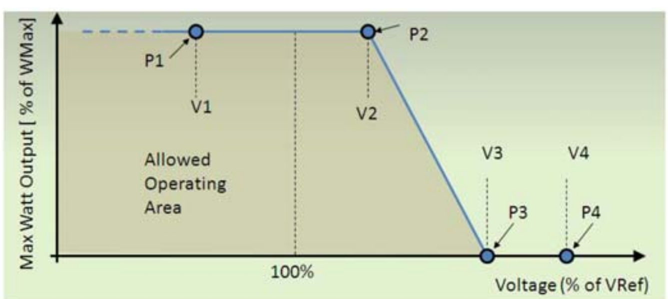
Volt-Watt function can limit steady-state voltage rise, especially with low X/R ratios (Hawaii uses this).



Simplified Formula: $\Delta V \propto R\Delta P + X\Delta Q$

But do we really want to control ΔV this way, even if ΔP has more leverage than ΔQ?

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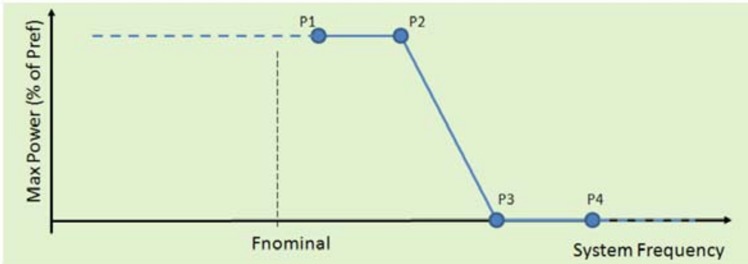
A Frequency-Watt function can help dampen system frequency swings.



- P is the real power output [pu]
- P_{pre} is the pre-disturbance real power output [pu]
- f is the disturbed system frequency [Hz]
- *db* is a single-sided deadband (default to 0.1 Hz)
- k is the per-unit frequency change corresponding to 1 per-unit power output change (defaults to 0.05)

$$P = P_{pre} - \frac{f - (60 + db)}{60k}$$

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Conclusion – Adaptive Voltage Regulation should be the default behavior of PV inverters.

- The default settings work well (so far…):
  - Slope = 30
  - Tau = 1200 s
  - 0.95 ≤ Vreg ≤ 1.05 [pu]
- Without smart-grid communications
  - No need for detailed coordination studies
  - No wake-up time for inverter’s voltage response
- With smart-grid communications
  - Fail-safe behavior
  - Dispatch reactive power, just like shunt capacitors
- Default high-frequency roll-off as well

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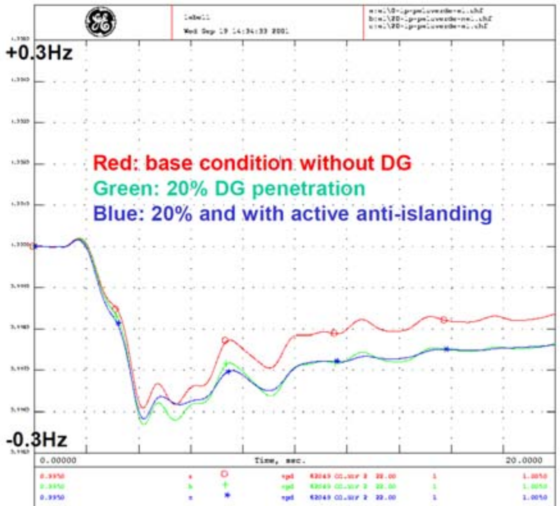
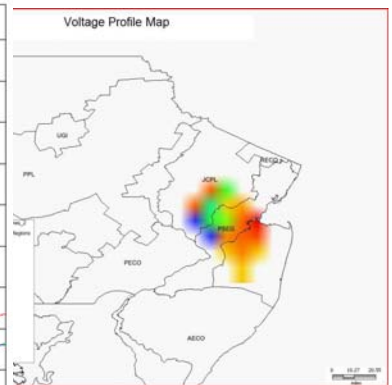
Bulk system planners have been concerned with losing large amounts of DG after a fault.



Source: Nick Miller, GE



Source: Mahendra Patel, PJM
(shaded region has V < 50%)

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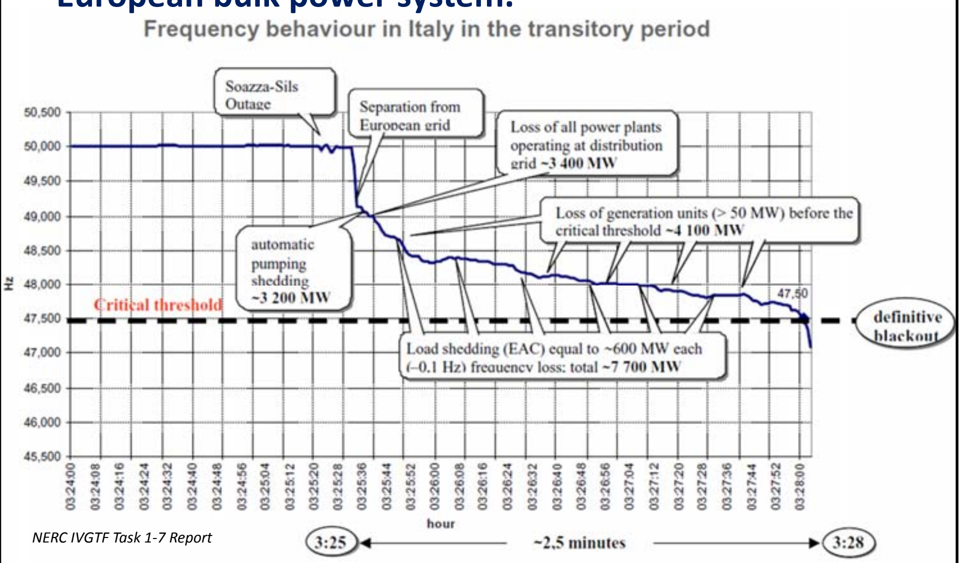
Loss-of-DG events have caused problems in the European bulk power system.



NERC IVGTF Task 1-7 Report

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IEEE 1547a-2014 allows voltage regulation and requires more adjustability in voltage and frequency trip settings.

Table 2—Interconnection system default response to abnormal frequencies

	Default settings		Ranges of adjustability	
Function	Frequency (Hz)	Clearing time (s)	Frequency (Hz)	Clearing time (s) adjustable up to and including
UF1	57	0.16	56 – 60	10
UF2	59.5	2	56 – 60	300
OF1	60.5	2	60 – 64	300
OF2	62	0.16	60 – 64	10

As mutually agreed upon by the Area EPS and DR operators, DR shall be permitted to provide modulated power output as a function of frequency in coordination with functions UF1, UF2, OF1, and OF2. Operating parameters shall be specified when this function is provided.

Table 1 ~~Default~~ Interconnection system default response to abnormal voltages

Default settings[a]		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
V < 45	0.16	0.16
45 < V < 60	1	11
60 < V < 88	2	21
110 < V < 120	1	13
V > 120	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted

[b] Base voltages are the nominal system voltages stated in ANSI C84.1-~~2006~~11, Table 1.

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After more than 10 years, IEEE 1547 is in a full revision process to more fully address the issues.

Before 2012: a 5-year Life Cycle (if "Reaffirmed")
Since 2012: a 10-year Life Cycle

75% Ballot Return and 75% Yes

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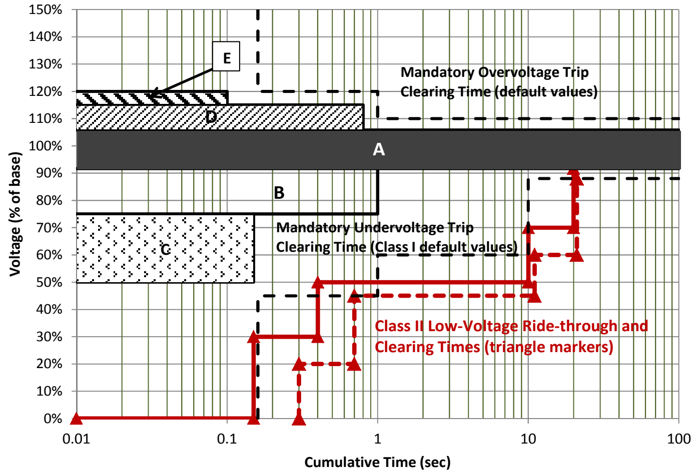
An early draft of P1547 clause 4.2 opens the door to technology-dependent ride-through requirements.



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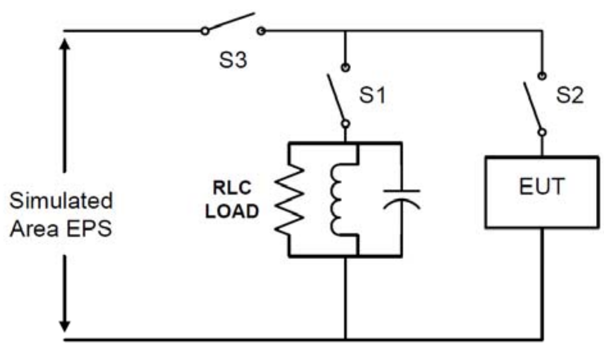
One of "shall do" standards (1547.1-2005) supports UL 1741, which defines how single inverters are tested.



NOTES

1—Switch S1 may be replaced with individual switches on each of the RLC load components.

2—Unless the EUT has a unity output p.f., the reactive power component of the EUT is considered to be a part of the islanding load circuit in the figure.

Figure 2—Unintentional islanding test configuration

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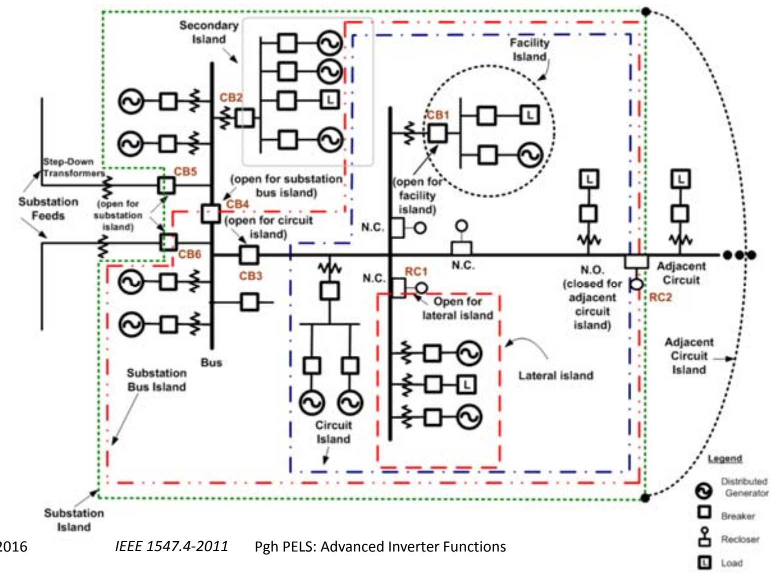
How to strengthen the provisions for intentional islanding (aka micro-gridding) with new functions?



2/23/2016 *IEEE 1547.4-2011* Pgh PELS: Advanced Inverter Functions 37

What islanding detection methods will be reliable in multi-inverter and high-penetration scenarios?

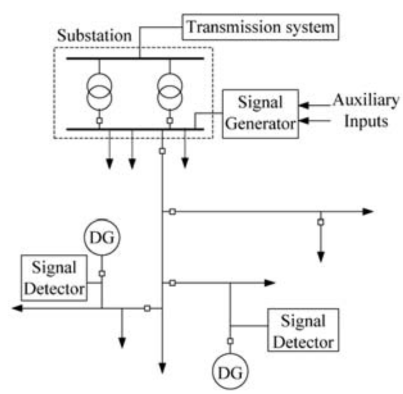


Fig. 1. Illustration for the proposed anti-islanding scheme.

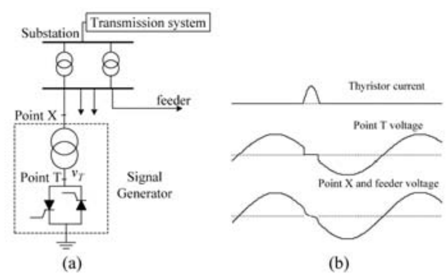


Fig. 2. Signaling method and resulting waveforms.

- Xu et. al.: A Power Line Signaling Based Technique for Anti-Islanding Protection of Distributed Generators—Part I: Scheme and Analysis
- Wang et. al.: A Power Line Signaling Based Scheme for Anti-Islanding Protection of Distributed Generators—Part II: Field Test Results

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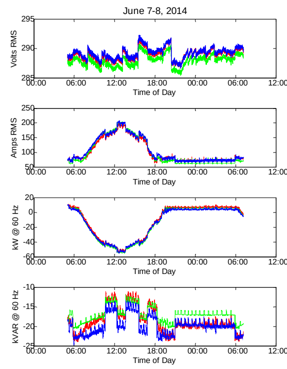
Pitt and Duquesne Light are monitoring PV output variability at multiple sites, on a 1-second time scale.



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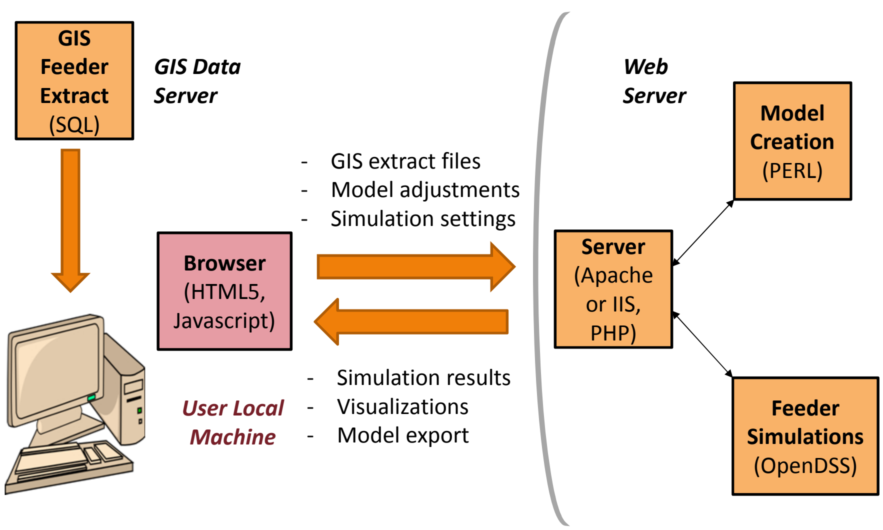
OpenDSS running on a Web Browser enables engineers at FirstEnergy to simulate voltage fluctuations.



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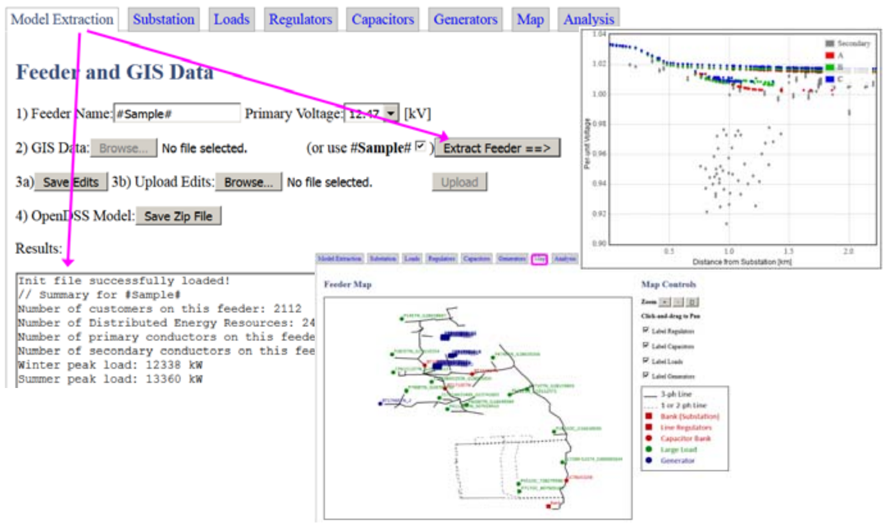
The user can extract and analyze OpenDSS feeder models from the Geographic Information System.



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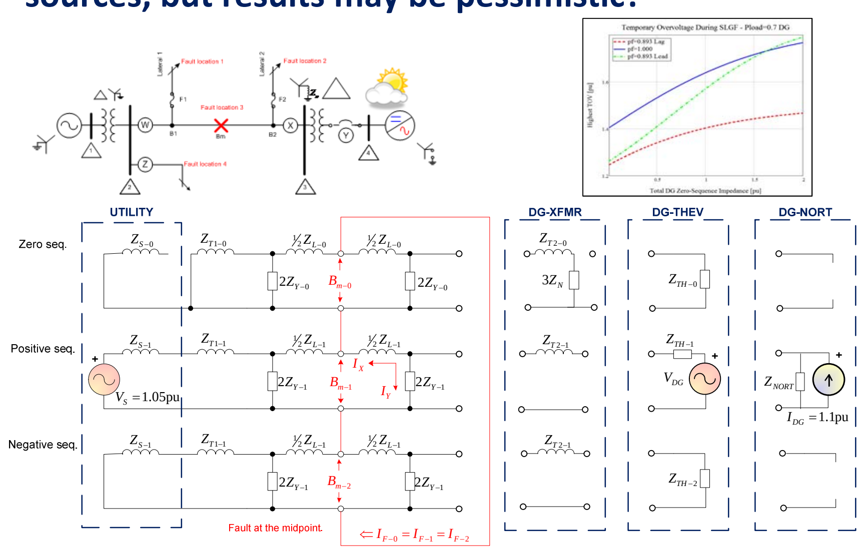
Symmetrical components can work with PV inverter sources, but results may be pessimistic?



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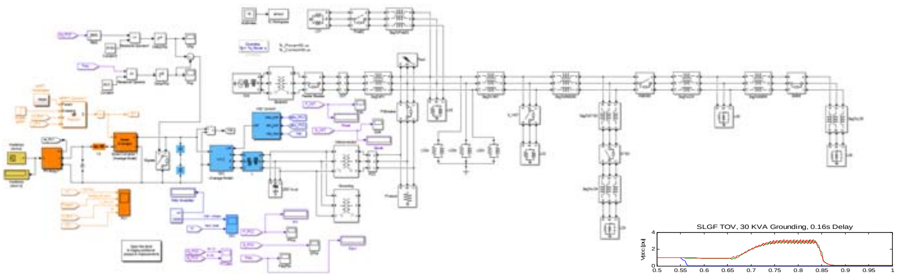
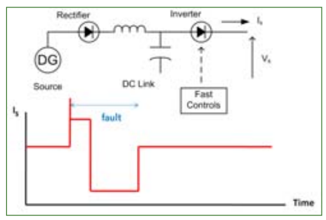
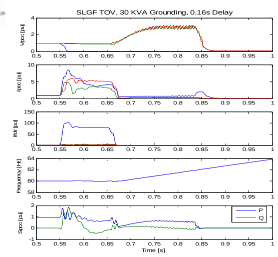
Detailed PV transient models present issues with software licenses, proprietary data & learning curves.



Simplified for OpenDSS





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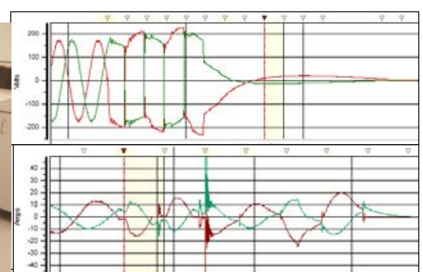
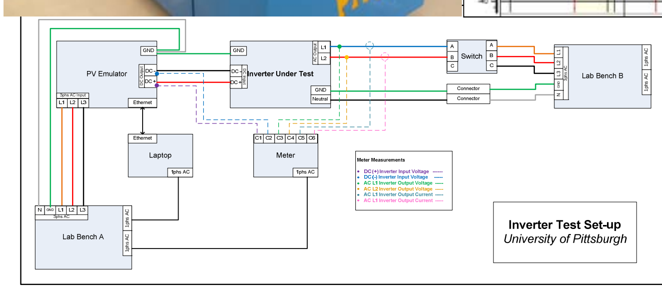
Inverter open-circuit and short-circuit behavior testing to identify models for application studies.





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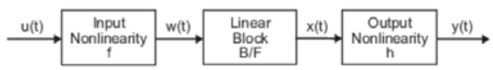
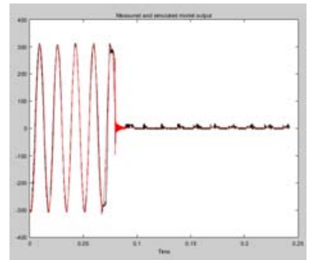
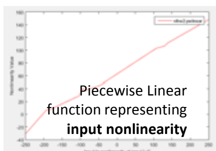
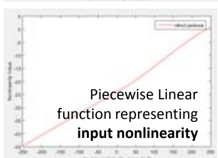
Creating a better PV inverter model for OpenDSS, using system identification.

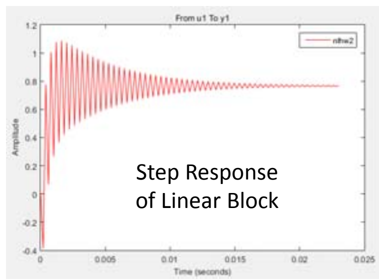
Hammerstein-Weiner Modeling Framework

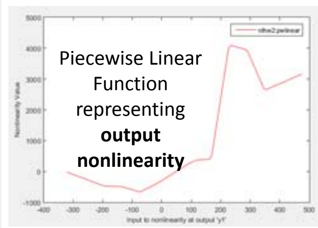












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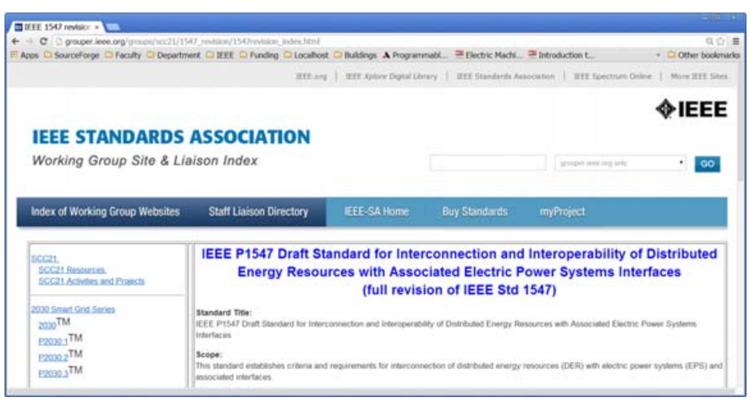
What can you do? The next P1547 meeting will be in Juno Beach, FL, March 8-9. We need consistent participation!



http://grouper.ieee.org/groups/scc21/

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