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A Fast Quasi-Static Time Series Simulation Method for PV Smart Inverters with VAR Control using Linear Sensitivity Model

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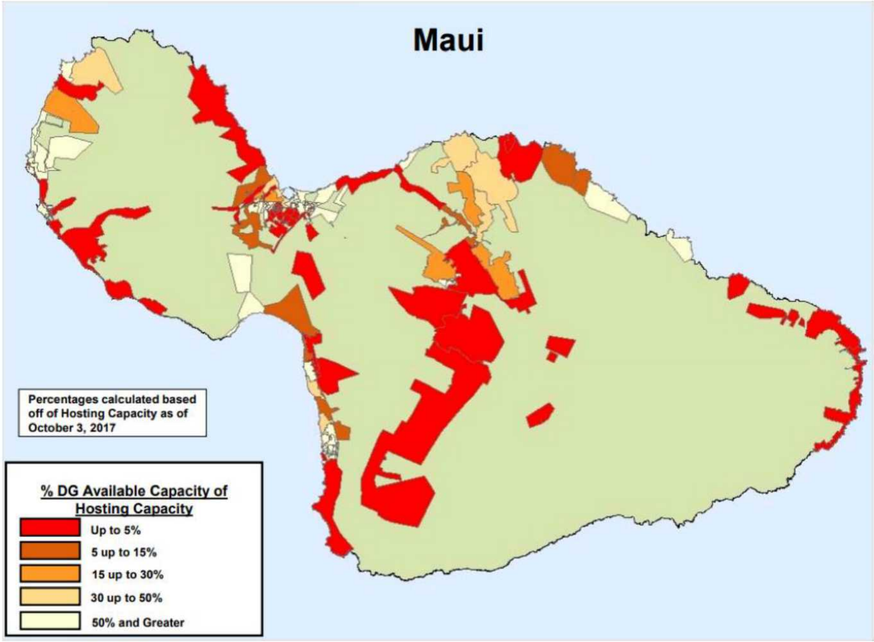
Outline

- Overview of:
  - IEEE 1547-2018
  - Smart Inverter VAR control
  - Quasi-Static Time Series (QSTS)
- Propose the Fast QSTS Simulation Method
  - Linear Sensitivity Model
  - Estimating Controller States
  - Smart Inverter abstraction
  - Parameter Estimation
  - Test Results & Summary

Solar Leading the Way

- U.S. market installed 10.6 GW_{dc} of solar PV capacity in 2017 [1]
- Distributed solar PV accounted for 41% of this capacity [1]
- Hawaii produces more distributed solar generation per capita than any other state [2]
- Inherent reliability issues due to intermittent nature of solar
  - Over/Under Voltages
  - Thermal Overloading
  - Increased LTC actions
- Various circuits reaching their hosting capacity limits



Hosting Capacity Map of Maui [3]

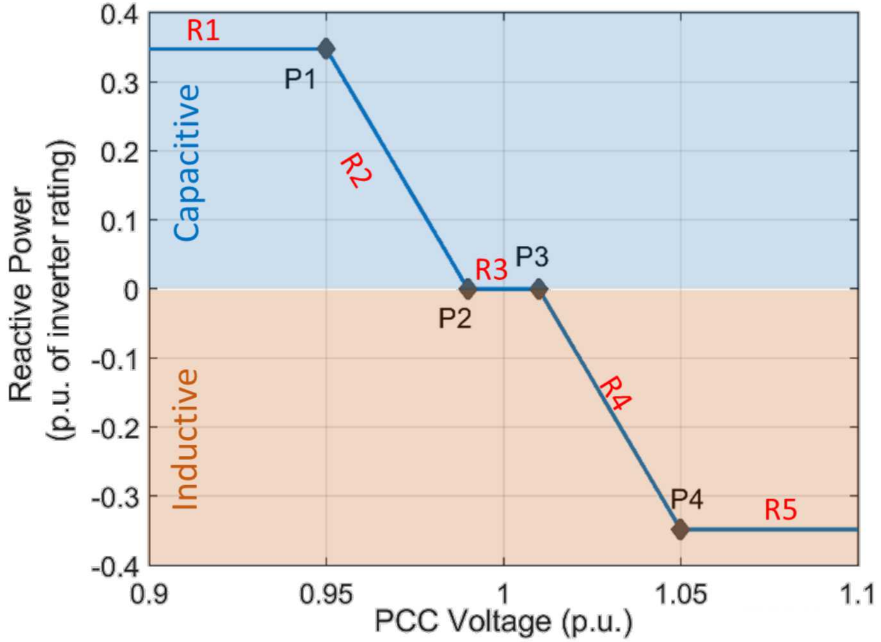
IEEE 1547-2018

- IEEE 1547 standard lists requirements for connecting the Distributed Energy Resource (DER) to the grid
- The first version (2003) did not allow DER to regulate voltage at the Point of Common Coupling (PCC)
- However, increased DER penetration resulted in power quality and reliability issues
- The latest version (2018) mandates active voltage regulation capabilities of grid-tied DERs
- Requires ‘Smart Inverters’ that are at least UL1741-SA complaint
- Hawaii PUC authorized their use in 2017

Smart Inverter VAR control

- Varying reactive power (VAR) injection or absorption to regulate PCC voltage
- Example: Fixed Power Factor (FPF) or Volt-VAR (VV)

- A typical VV curve has 3 regions :
  - A dead-band (R3)
  - Variable VAR injection/absorption (R2,R4)
  - Maximum VAR injection/absorption (R1,R5)



Evaluating VAR control

- How can we evaluate the performance of VAR control functions?
- Which mode should be used: FPF or VV ?
- VV curves have to be feeder specific not generic
- What value of dead-band and slope will result in the highest reliability?
  - Least duration of over/under voltages
  - Normal operations of Transformer LTCs
  - Limited number of Capacitor Bank operation
  - Lower Losses
- Quasi-Static Time Series analysis can answer these questions!

Quasi-Static Time Series Analysis

- What is Quasi-Static Time Series (QSTS) simulation?
  - A simulation that solves power flows chronologically through time
  - Each power flow solution uses the previous power flow results
  - Considers the control logic and time delays of all system controllers
- Why do we need 1-second resolution QSTS simulation?
  - Only second-level resolution simulations can capture possible interactions among system controllers (oscillatory behavior)
- What are the inputs to QSTS simulation?
  - Normalized time series data for loads and PV power injections (SCADA measurements and Irradiance data)

Quasi-Static Time Series Analysis

- Why is QSTS not widely applied?
  - The computational time for running yearlong high-resolution QSTS simulations takes 10 to 120 hours for realistic-sized distribution feeders
- Why is QSTS slow?
  - Yearlong 1-second resolution results in solving 31 million power flows
  - Although each power flow takes a fraction of a second to solve, multiply that with 31 million solves of a year scaling up the time
- Why is fast QSTS difficult?
  - Temporal interdependence between time steps
  - Interactions of system controllers
  - Presence of multiple valid power flow solutions
  - VAR control convergence issues

Key to fast QSTS is predicting controller events!

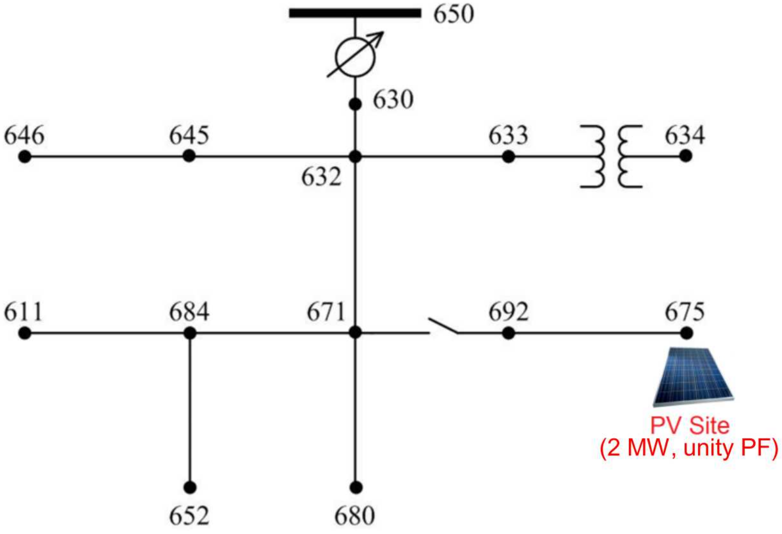
Linear Sensitivity Model (LSM)

- A sensitivity based model [4]:
  - Exploits correlation between phase voltage magnitude $v_\phi^{(j)}(t)$ and power injections $x_i(t)$
  - Sensitivity coefficients project into a linear space (α_0, β_i)
  - Multiple regression for fast computation of sensitivities
  - Type of ‘perturb-and-observe’ technique (no need for a Jacobian!)

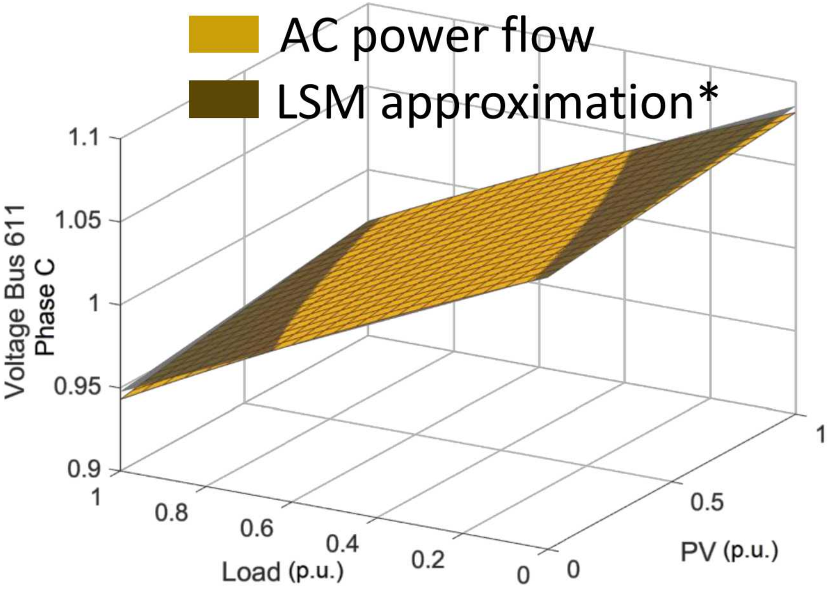
$$v_\phi^{(j)}(t) \simeq \alpha_0 + \sum_{\underbrace{i=1}_{k\text{-power injections}}}^{k} \beta_i x_i(t), \qquad \underbrace{\forall \phi \in \{A, B, C\}}_{\text{each phase}}$$

Geometric Interpretation

- For a circuit with no controllable elements:



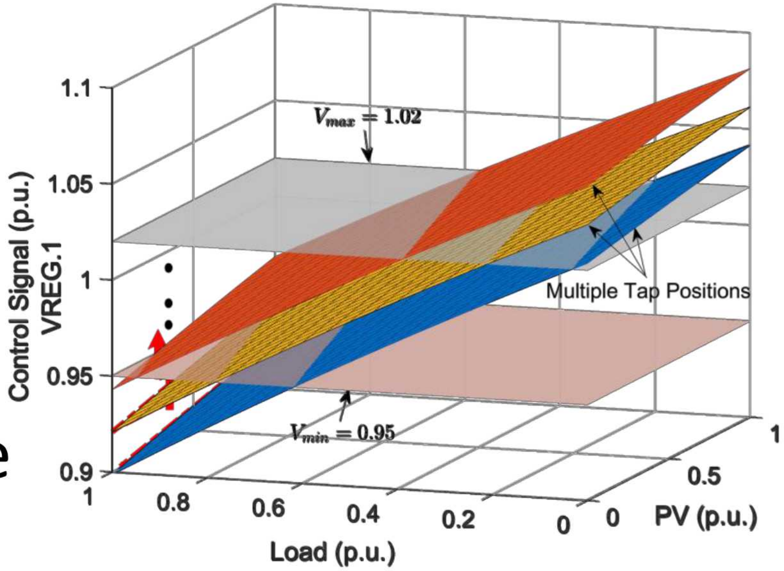
Modified IEEE-13 Bus
(all controls disabled)



Voltage-power manifold
(*36 point regression)

Impact of Controllers

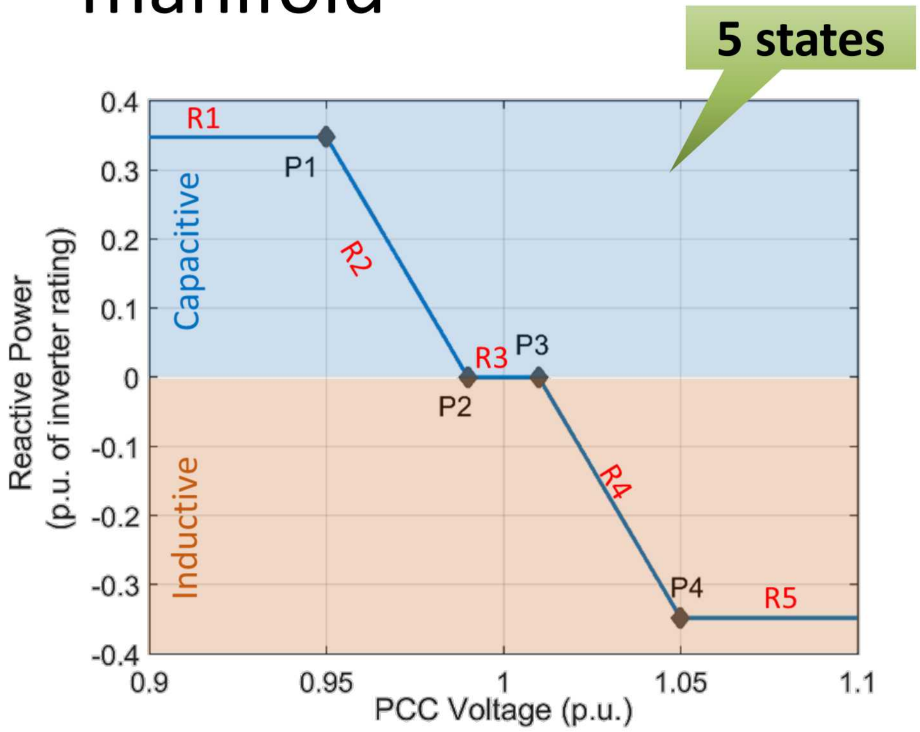
- Maintains bus voltage within specified band
- The control logic comprises of :
  - A ‘control’ voltage/signal
  - Unique well defined ‘states’
  - Predefined Transition ‘boundaries’



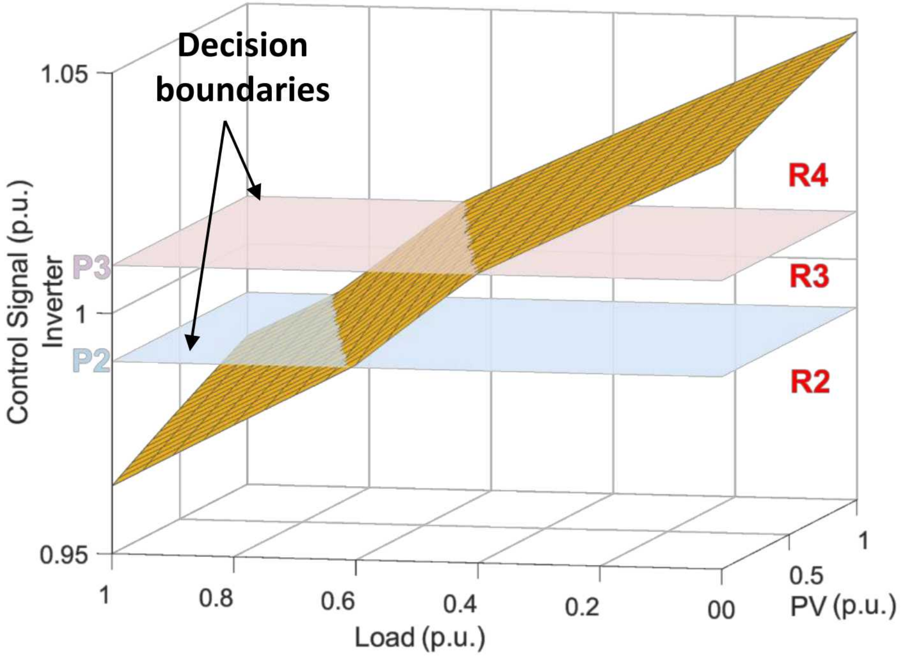
- Each state change causes discrete ‘jumps’ in the manifold
- Same in case of capacitor banks (only two states)
- Sensitivity coefficients need to be updated

Impact of Volt-VAR

- Causes ‘discontinuities’ in the voltage-power manifold



Volt-VAR curve

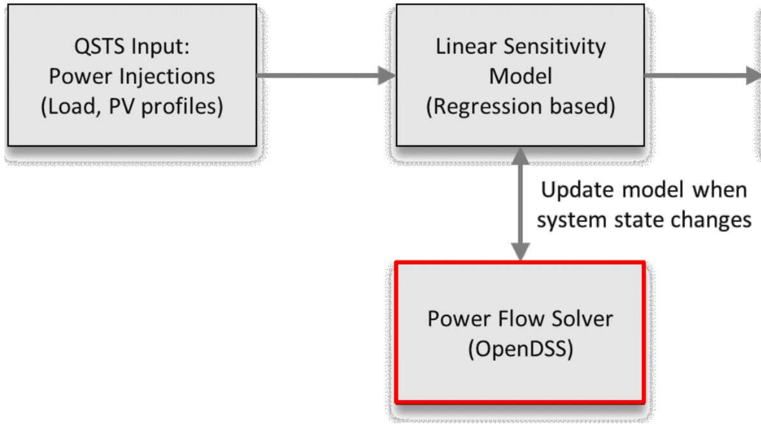


Voltage-power manifold

Estimating States

- Fidelity of LSM depends upon estimating the state of each controller
- For p-controllers, let $u_p(t)$ denote their state at time t
- The system state is then given by: $s_t = T(u_1(t), .., u_p(t))$ where $T : \mathbb{Z}_+^p \rightarrow \mathbb{Z}_+$ is a hashing function
- We propose an online estimation method:
  - Only compute coefficients for observed states s_t
  - For k-profiles, use only $k + 2$ points for regression
  - Select points in the neighborhood of $x_i(t)$

Fast QSTS Implementation



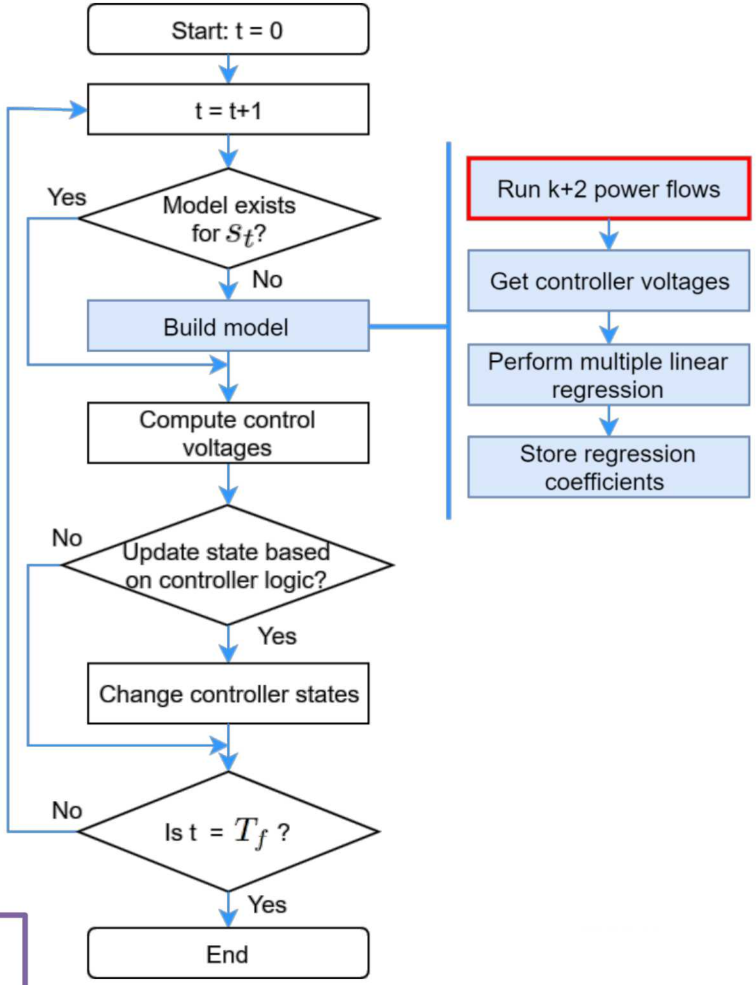
QSTS Input: Power Injections (Load, PV profiles)

Linear Sensitivity Model (Regression based)

QSTS Output: Bus Voltages, Transformer Taps, Capacitor states

Update model when system state changes

Power Flow Solver (OpenDSS)



Start: t = 0

t = t+1

Model exists for S_t?

Yes

No

Build model

Run k+2 power flows

Get controller voltages

Perform multiple linear regression

Store regression coefficients

Compute control voltages

Update state based on controller logic?

No

Yes

Change controller states

Is t = T_f ?

No

Yes

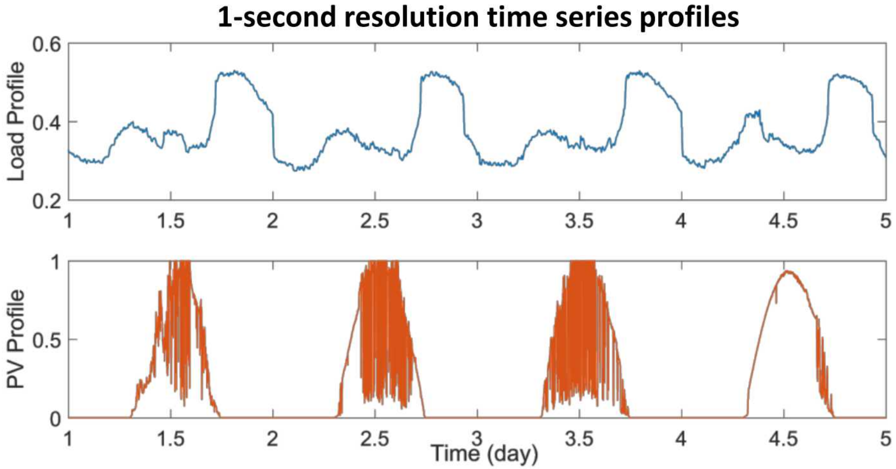
End

- Significantly reduces computation time
  - Power flow equations solved for only unique system states
  - Control logic evaluates (1) at each t

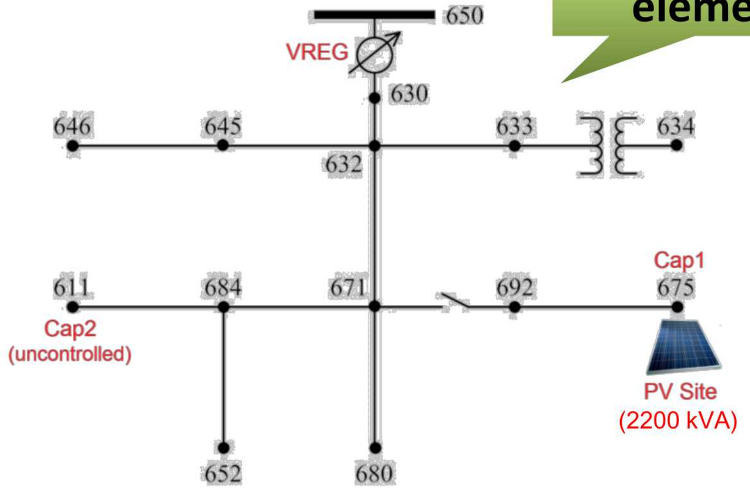
$$v_c(t) = \alpha_0 + \sum_{i=1}^{k} \beta_i x_i(t), \quad (1)$$

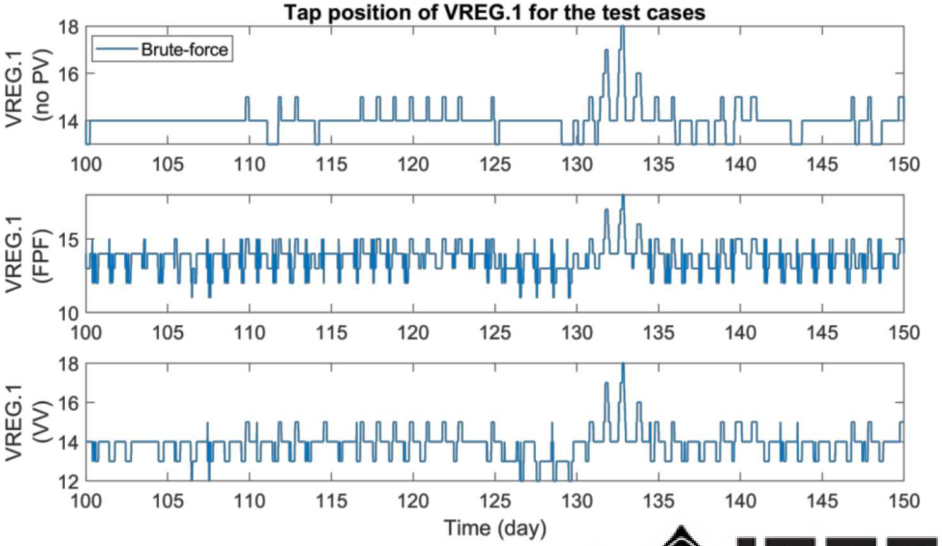
Matrix multiplication vs Matrix inversion

Test Circuit


1-second resolution time series profiles

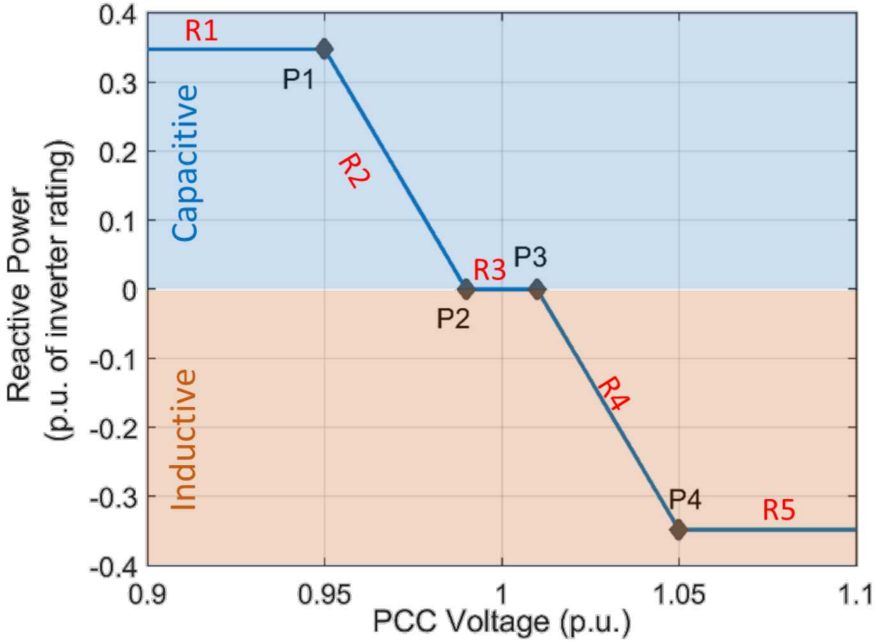
4 controllable elements

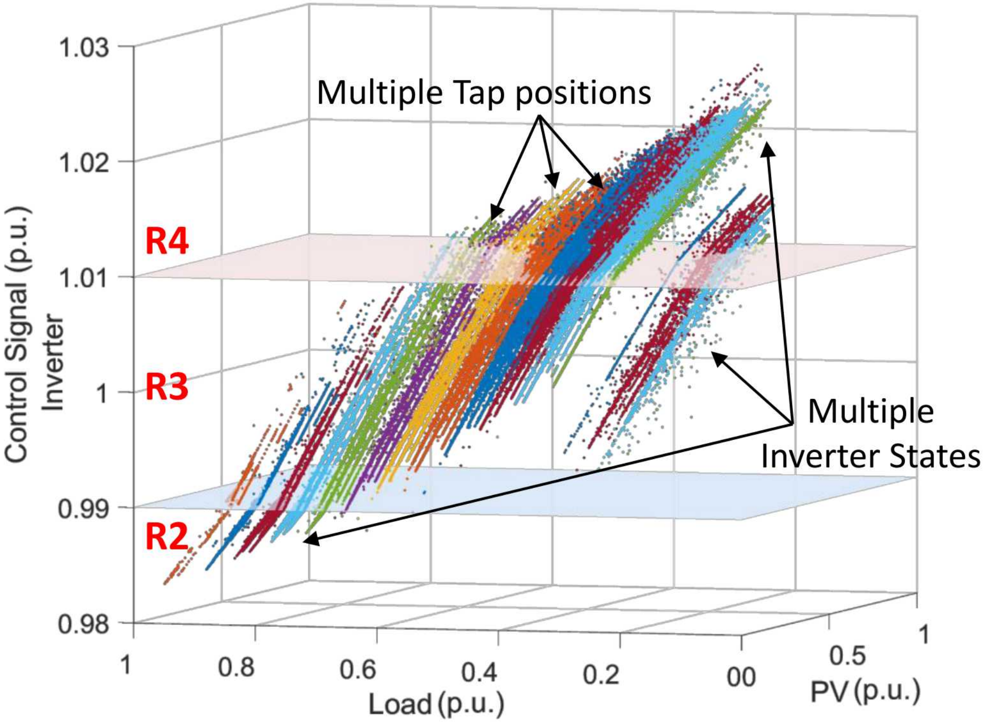



Tap position of VREG.1 for the test cases

- 3 test cases: No PV, Unity PF, Volt-VAR
- Increased LTC operations due to PV
- Volt-VAR damps the oscillatory behavior
- By running a set of candidate curves, optimal settings can be quickly determined

Volt-VAR Impact





- Inverter PCC voltage obtained by brute-force QSTS (~31.5 million points)
- Each individual point is a power flow solution in time
- Color-coded to represent different tap positions of VREG.1

Fast QSTS Results

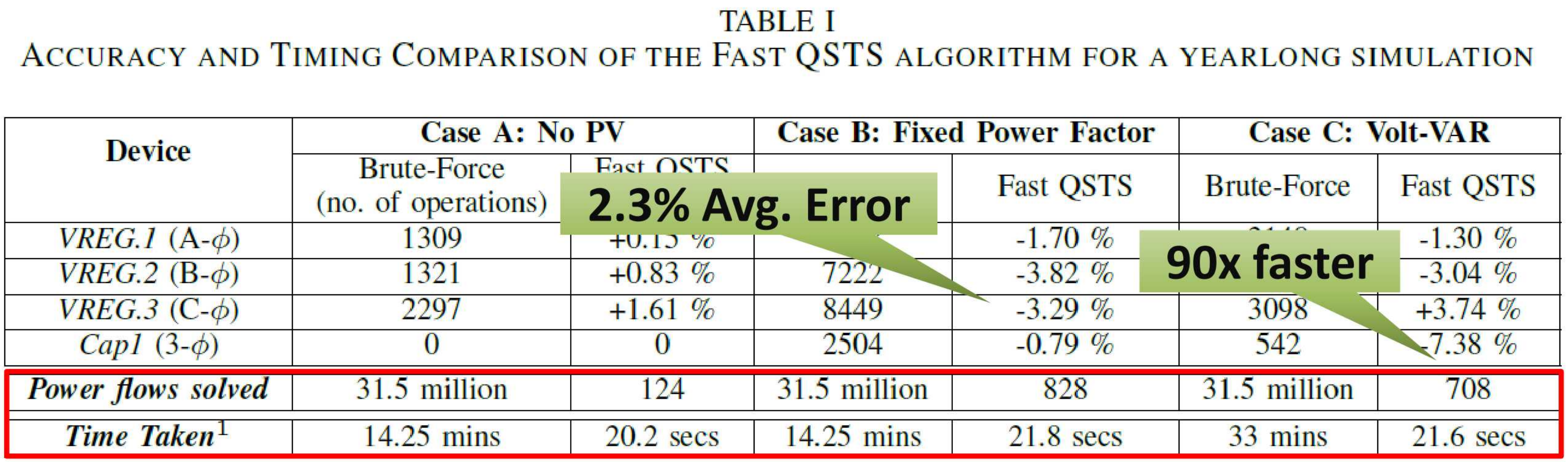
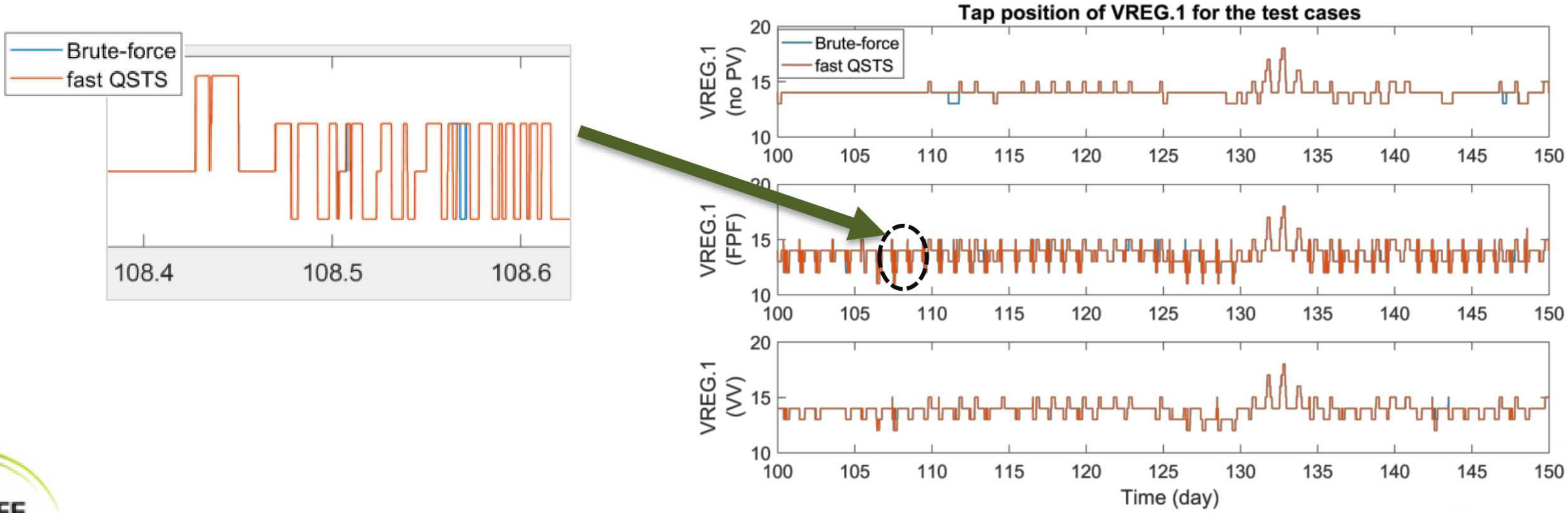


TABLE I
ACCURACY AND TIMING COMPARISON OF THE FAST QSTS ALGORITHM FOR A YEARLONG SIMULATION

Device	**Case A: No PV**		**Case B: Fixed Power Factor**		**Case C: Volt-VAR**	
	Brute-Force (no. of operations)	Fast QSTS	[illegible]	Fast QSTS	Brute-Force	Fast QSTS
VREG.1 (A-ϕ)	1309	[illegible]	[illegible]	-1.70 %	[illegible]	-1.30 %
VREG.2 (B-ϕ)	1321	+0.83 %	7222	-3.82 %	[illegible]	-3.04 %
VREG.3 (C-ϕ)	2297	+1.61 %	8449	-3.29 %	3098	+3.74 %
Cap1 (3-ϕ)	0	0	2504	-0.79 %	542	-7.38 %
Power flows solved	31.5 million	124	31.5 million	828	31.5 million	708
Time Taken[1]	14.25 mins	20.2 secs	14.25 mins	21.8 secs	33 mins	21.6 secs

2.3% Avg. Error

90x faster



Summary

- Linear Sensitivity Model:
  - A ‘perturb-and-observe’ technique that exploits correlation between phase voltage magnitude and power injections
  - Uses multiple linear regression to compute sensitivity coefficients
  - Projects nonlinear power flow equations into a linear space
- Significance of the proposed method:
  - Yearlong 1-second QSTS simulation in a matter of minutes
  - Quantifies the impact of dynamic VAR control
- Characteristics of the proposed method:
  - 90 times faster than brute-force QSTS
  - Can be used to track LTC and Cap states, Over/Under voltage duration, Max/Min Node voltage and Thermal loading
  - Scalable to any number of time series profiles, smart inverters and controllable elements

References

[1] https://www.seia.org/research-resources/solar-market-insight-report- 2017-year-review

[2] Union of Concerned Scientists, Clean Energy Momentum, Executive Summary (April 2017), p. 2.

[3] Hawaii Electric Co., Locational Value Maps

[4] M. Qureshi et al. “A Fast Scalable Quasi-Static Time Series Analysis Method for PV Impact Studies using Linear Sensitivity Model,” *IEEE Transactions on Sustainable Energy, 2018.*

Acknowledgment

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Questions?

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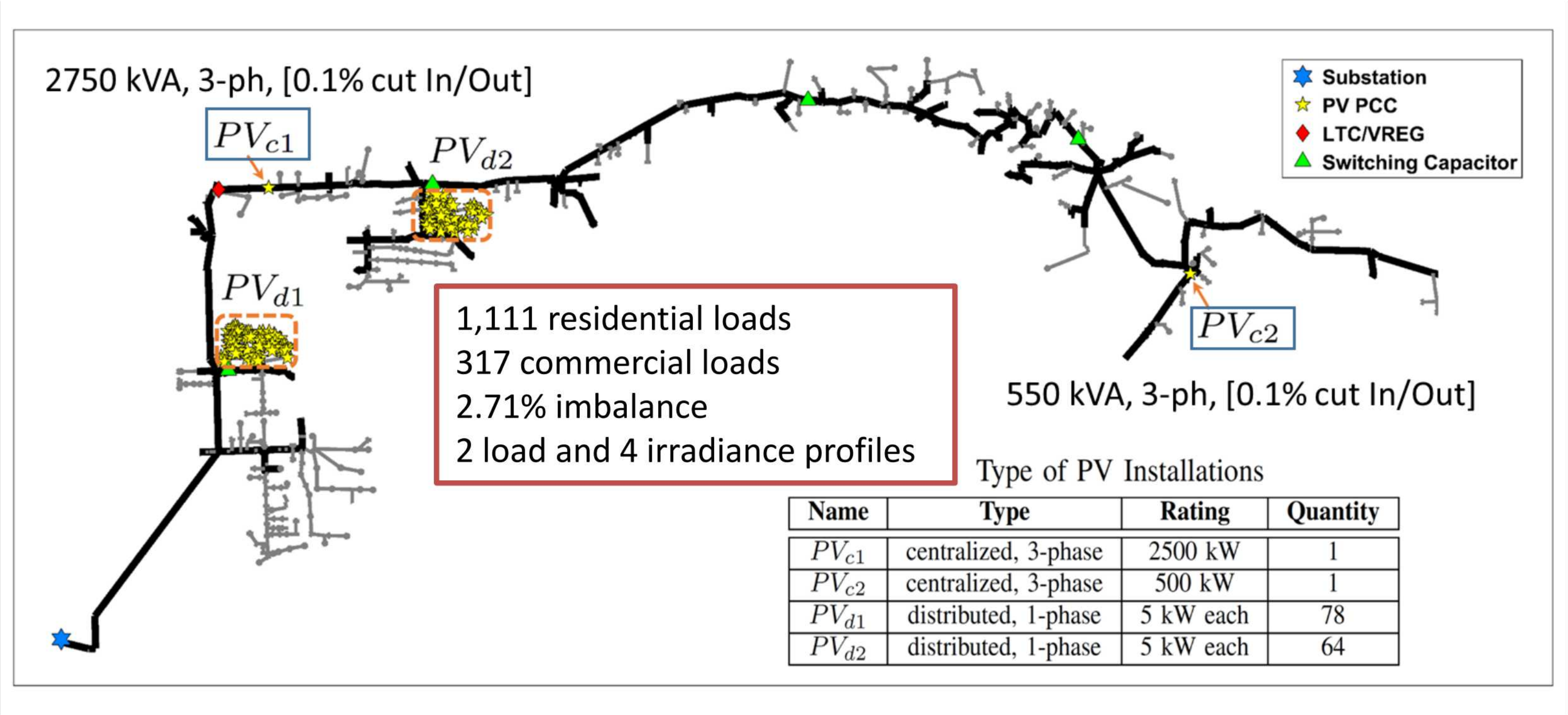
Realistic Test Circuit [4]



1,111 residential loads
317 commercial loads
2.71% imbalance
2 load and 4 irradiance profiles

Type of PV Installations

Name	Type	Rating	Quantity
PV_{c1}	centralized, 3-phase	2500 kW	1
PV_{c2}	centralized, 3-phase	500 kW	1
PV_{d1}	distributed, 1-phase	5 kW each	78
PV_{d2}	distributed, 1-phase	5 kW each	64

- Utility provided feeder with 5469 nodes, 9 controllable elements (21.7 km)
- 4 types of PV Installations with a total of ~50% penetration
- Each type following its own unique power injection profile
- 2 types of loads: residential and commercial
- 2 centralized PV systems with 2 different VV curves

Simulation Results

Control Element Name	BF Results # Actions	Fast QSTS %Error
Sub_LTC	2668	1.35 %
Xfmr_regulator1	4861	0.28 %
Xfmr_regulator2	4487	1.65 %
Xfmr_regulator3	4634	0.73 %
CAP : gt44787e	352	3.97 %
CAP : 111623e	30	6.66 %
CAP : 2293408e	18	11.1 % (20)
CAP : 1376029e_a	524	4.58 %
CAP : 1376029e_b	742	0 %

Metric	BF Results	Fast QSTS %Error
Feeder Highest Voltage	1.0612 p.u.	0.00034 p.u.
Feeder Low Voltage	0.9052 p.u.	0.00018 p.u.
ANSI over duration	232.86 Hrs	15.31 Hrs
ANSI under duration	1004.4 Hrs	14.7 Hrs
Nodal Highest Voltage	Max Error (0.0038 p.u.)	
Nodal Lowest Voltage	Max Error (0.0010 p.u.)	

3.36 % Avg. Error

132 times faster

	Brute Force	Fast QSTS
Total Power flows solved	~31.5 million	57,915
Total Computation Time	67.43 Hrs (2.81 Days)	30.6 minutes