PSERC

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Distribution System Voltage Control under Imperfect Communications

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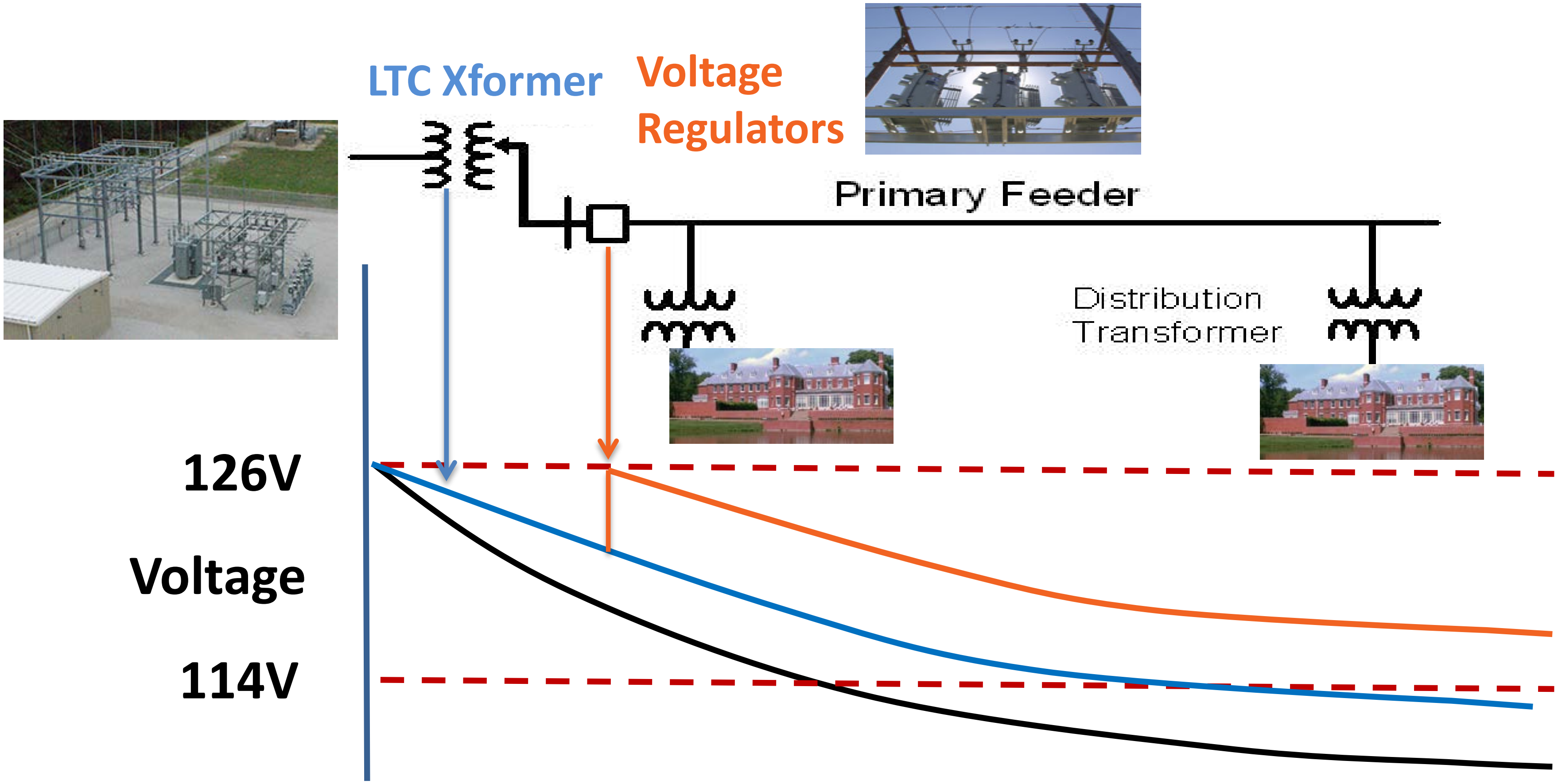
Voltage control

- Ideally, we all want to plug into a constant voltage source at 120V
- Voltage control/stability in bulk transmission grid more closely related to reactive power (VAR) load balance
  - Fast decoupled power flow (FDPF) model
- Real power could also affect voltage fluctuations in distribution systems because of the higher r/x ratio

Cartoon: W-R-O-N-G Voltagggeeee for a vintage machine like Myself [Source: jantoo.com]

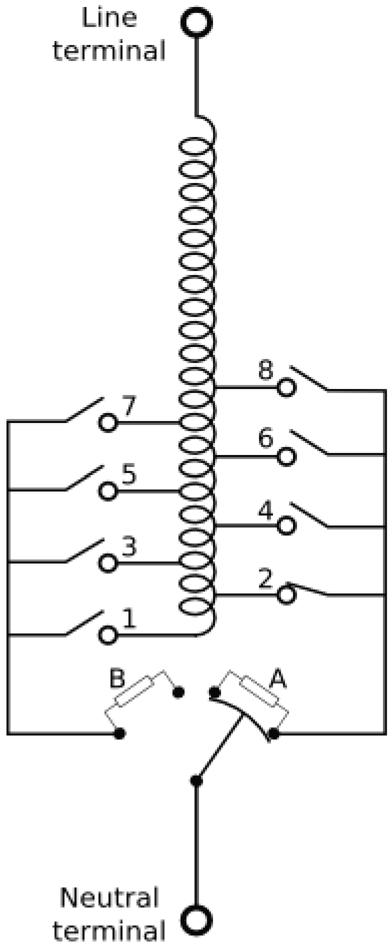
Voltage control in distribution systems

- Typical control devices: load tap changer (LTC) transformers, voltage regulators, and capacitor banks



Load tap changer (LTC)

- A selector switch device attached to power transformers
- To maintain a constant low-side or secondary voltage with a variable primary voltage supply
- Or to hold a constant voltage out along the feeders on the low-voltage side for varying load conditions
- Also termed as tap changing under load (TCUL) transformers

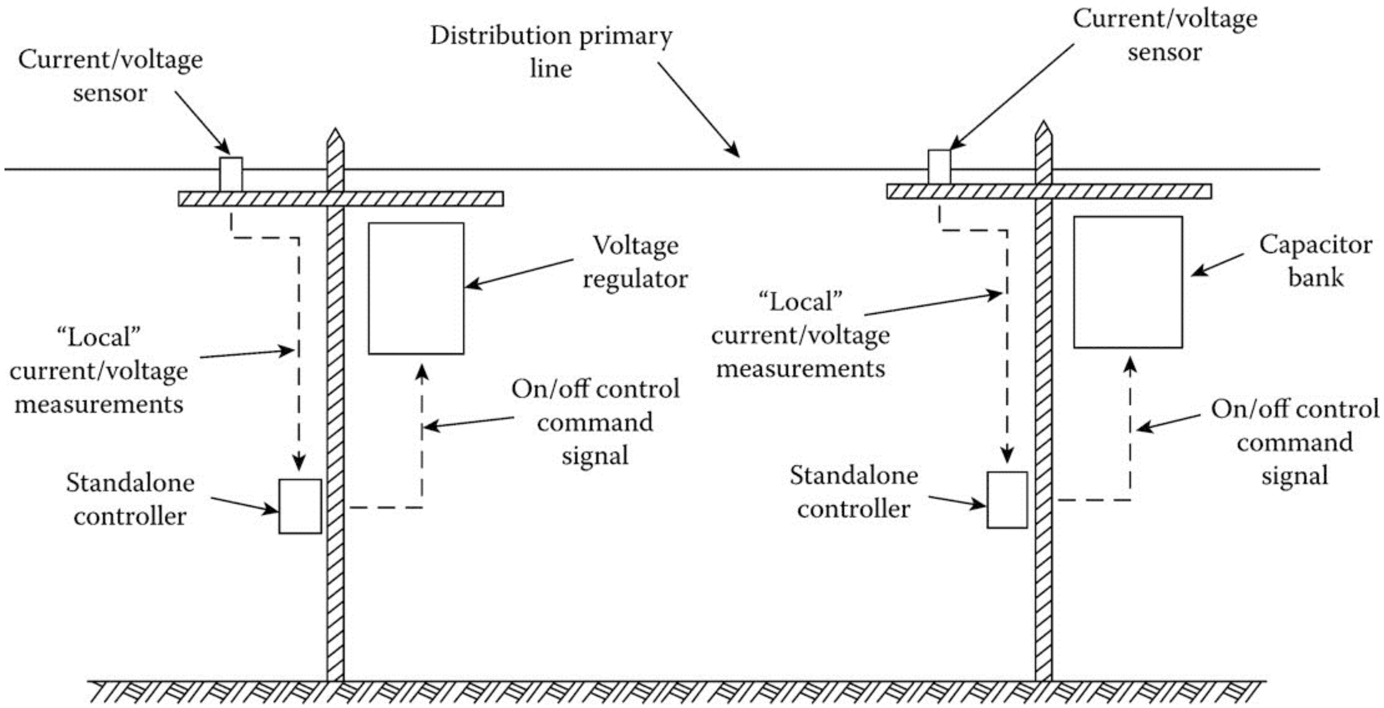


"Tap changing switch" by BillC at English Wikipedia

[Gonen's book, 2014]

Voltage regulators and capacitors

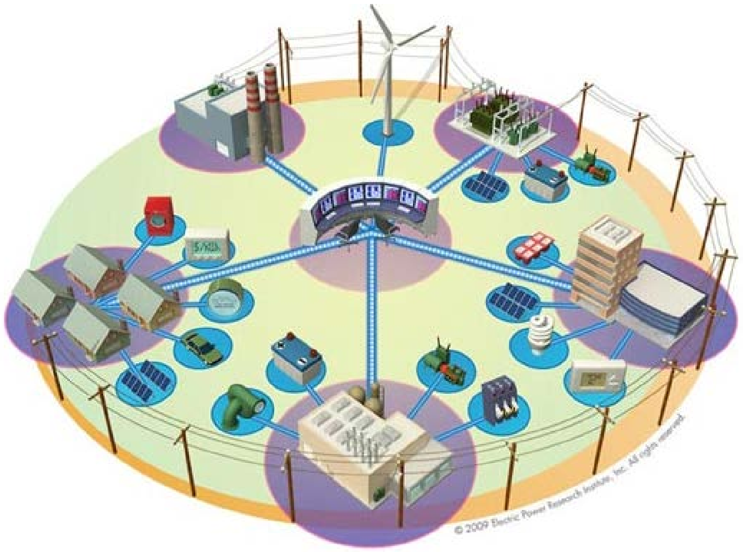
- **Voltage regulators: induction devices in shunt or series with regulated circuit for the control of its voltage**
- **Capacitors: perform power factor correction with additional switching and protective elements**



[Gonen's book, 2014]

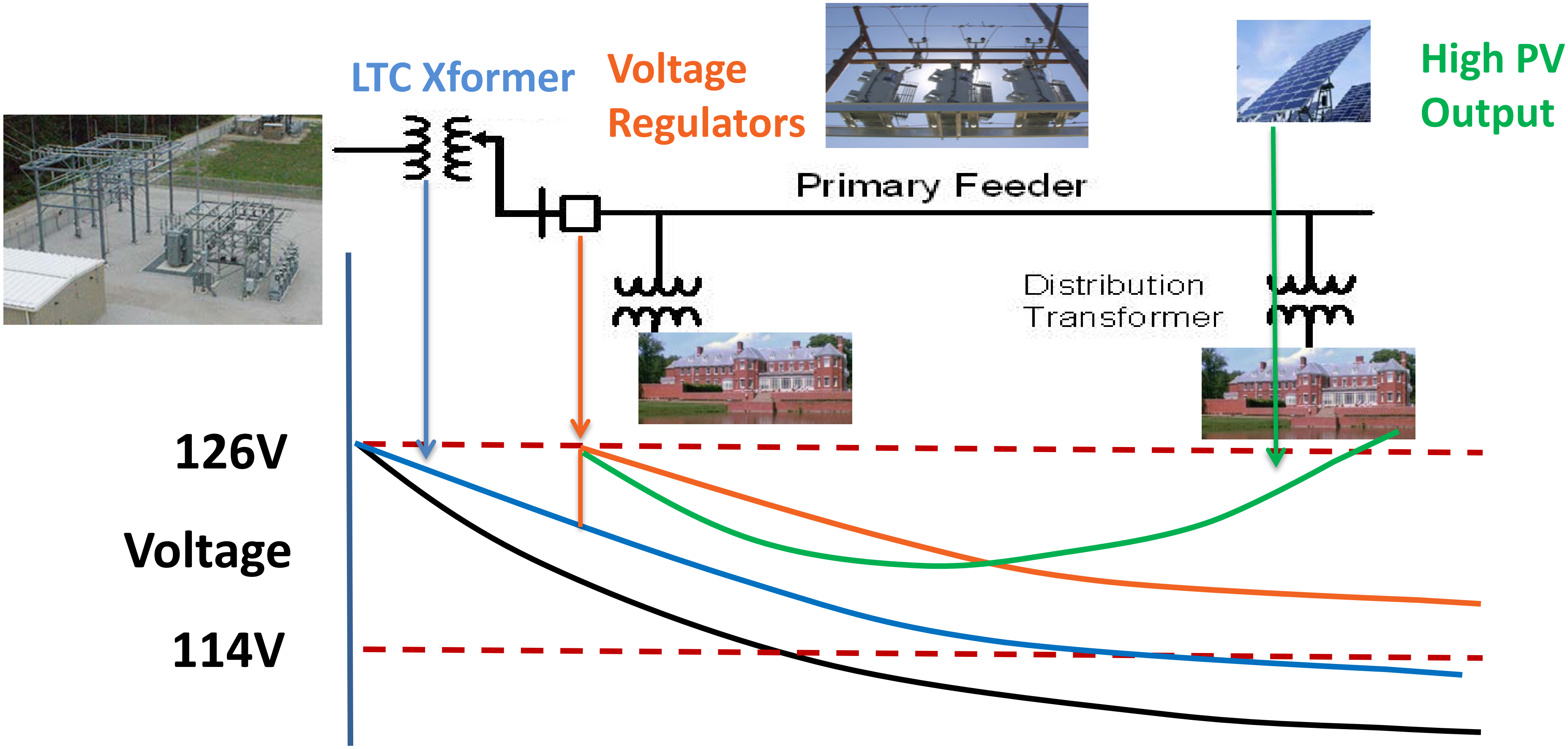
Volt/Var control (VVC)

- Traditional VVC relies on individual, independent, stand-alone control devices that react to local measurements
- Challenged by rapid changes in distribution loads due to penetration of distributed generations and electric vehicle charging



Source: EPRI Smart Grid Demo

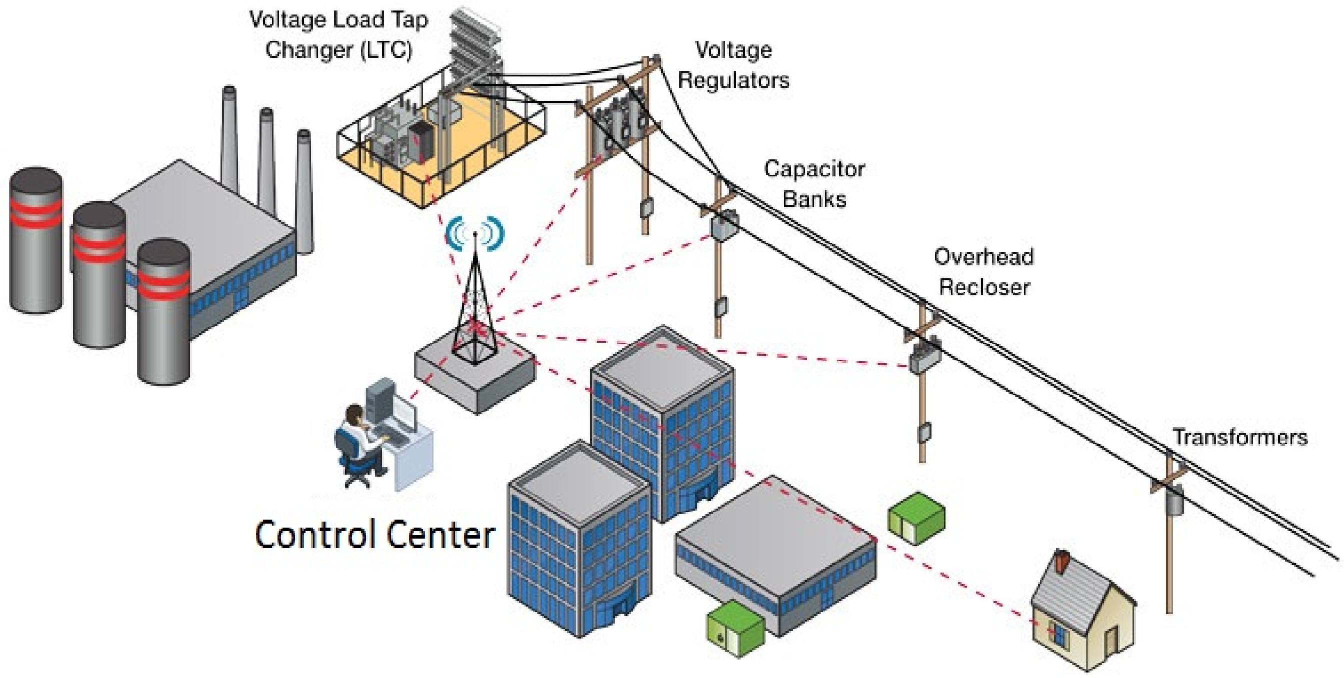
An example



- Real power injection increases local voltage
- Non-decreasing voltage profile due to DG outputs

Centralized VVC

- An integrated approach that computes and executes coordinated control for all devices [Cf. optimal power flow (OPF)]
- Enabled by two-way communications between a centralized controller and remote meters/devices



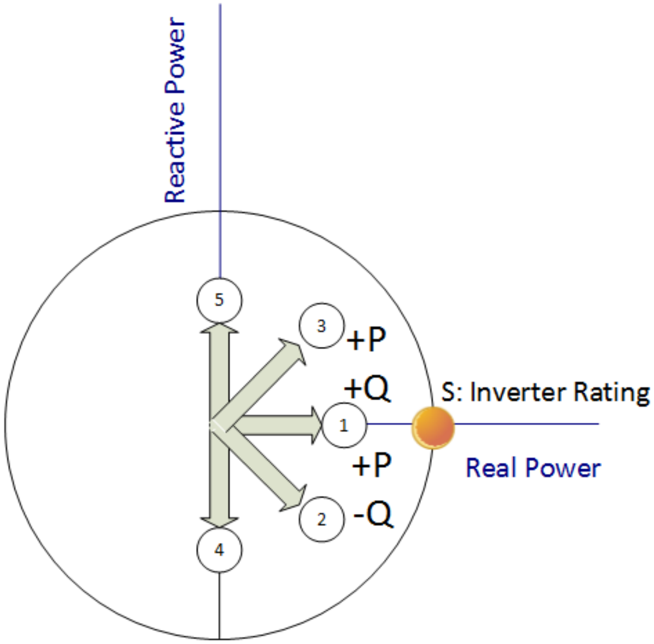
Source: Eaton Yukon IVVC solution

Additional VAR sources

- DGs/battery devices also offer new venues for VAR support
- Synchronous generation: exciter control
- Inverter-connected devices: VAR control

  [Lopes et al '07],[Turitsyn et al '11]

- Most of these VAR sources currently operated under fixed power factor



Optimal voltage control

- OPF problem formulation [Farivar et al '12] [Zhang et al '15]
- A two-stage approach of slow/fast time-scales [Robbins et al '13]
- (De-)centralized solvers for three-phase systems [Dall'anese-Zhu-Giannakis'13]

minimize *Power losses* + *Load demand* + *VAR costs*

subject to $\underline{V} \leq V \leq \overline{V}$ → Voltage regulation

$\underline{P_g} \leq P_g \leq \overline{P_g}$

$\underline{Q_g} \leq Q_g \leq \overline{Q_g}$ → DG limit constraints

Power flow equations → Convex relaxation

E. Dall'Anese, **H. Zhu**, and Georgios B. Giannakis, "Distributed Optimal Power Flow for Smart Microgrids," *IEEE Trans. Smart Grid*, Sep. 2013.

Optimal transformer tap control

- **An OPF approach to optimize three-phase transformer taps**
- **A virtual-bus based transformer model**
- **(De-)centralized solvers using convex relaxation**

minimize *Power losses* + *operational costs*

subject to $\underline{V} \le V \le \overline{V}$ → Voltage regulation

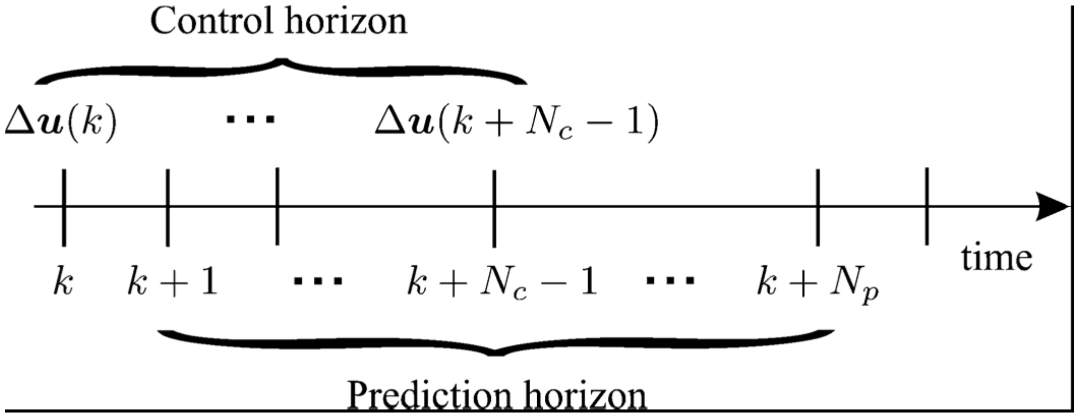
$\underline{a} V_p \le V_s \le V_p \overline{a}$ → Tap constraints

Power flow equations → Convex relaxation

B. A. Robbins, **H. Zhu**, and A. D. Domínguez-García, "Optimal Setting of the Taps of Voltage Regulation Transformers in Distribution Systems," *IEEE Trans. Power Systems* , 2015.

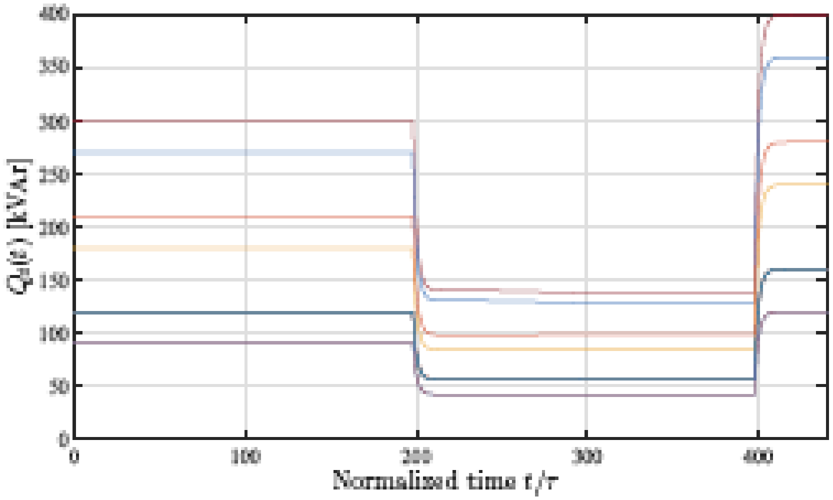
Alternative approaches

- Adaptive control: sequentially updates the DG VAR output at each bus [Yeh et al '12]
- A model predictive control (MPC) framework [Valverde et al '13], [Wang et al '14]
  - Coordinated management of DG real/reactive power generation and transformer tap positions



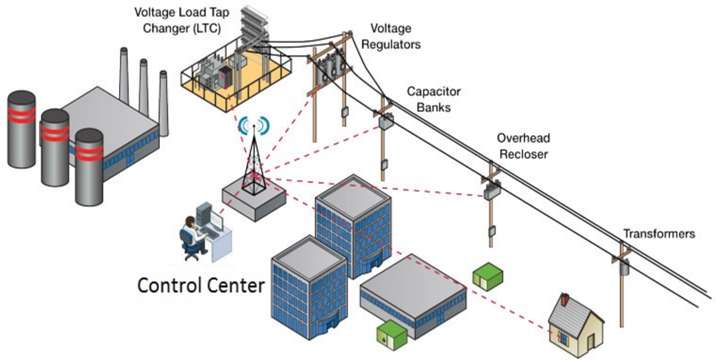
Stochastic control

- **Stochastic-approximation VVC method that deals with system uncertainty and measurement noise [Bazrafshan et al '14], [Kekatos et al '15]**
- **A dual-subgradient approach that accounts for the dynamics/ delay in updating inverter control setpoints [Dall'anese et al '15]**



E. Dall'Anese, S. V. Dhople, and G. B. Giannakis, "Photovoltaic Inverter Controller Seeking AC Optimal Power Flow Solutions," *IEEE Trans. on Power Systems,* to appear. [Online] Available at: http://arxiv.org/abs/1501.00188

Summary of centralized VVC



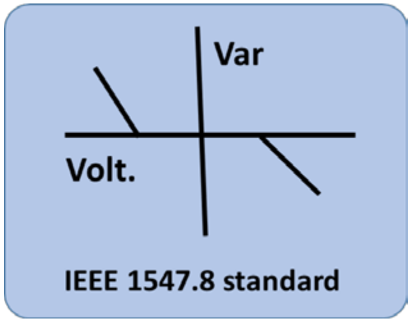
- With all information available, centralized decision-making can improve the overall system operations
- But it requires high-quality high-throughput two-way communications to remote devices
- Communication failures/delays can result in suboptimal and instable control, especially for distribution systems with rapid load variations and intermittent DGs

1. Local VVC at no communication requirements
2. Distributed VVC resilient to communication link failures

Fast local inverter VAR control

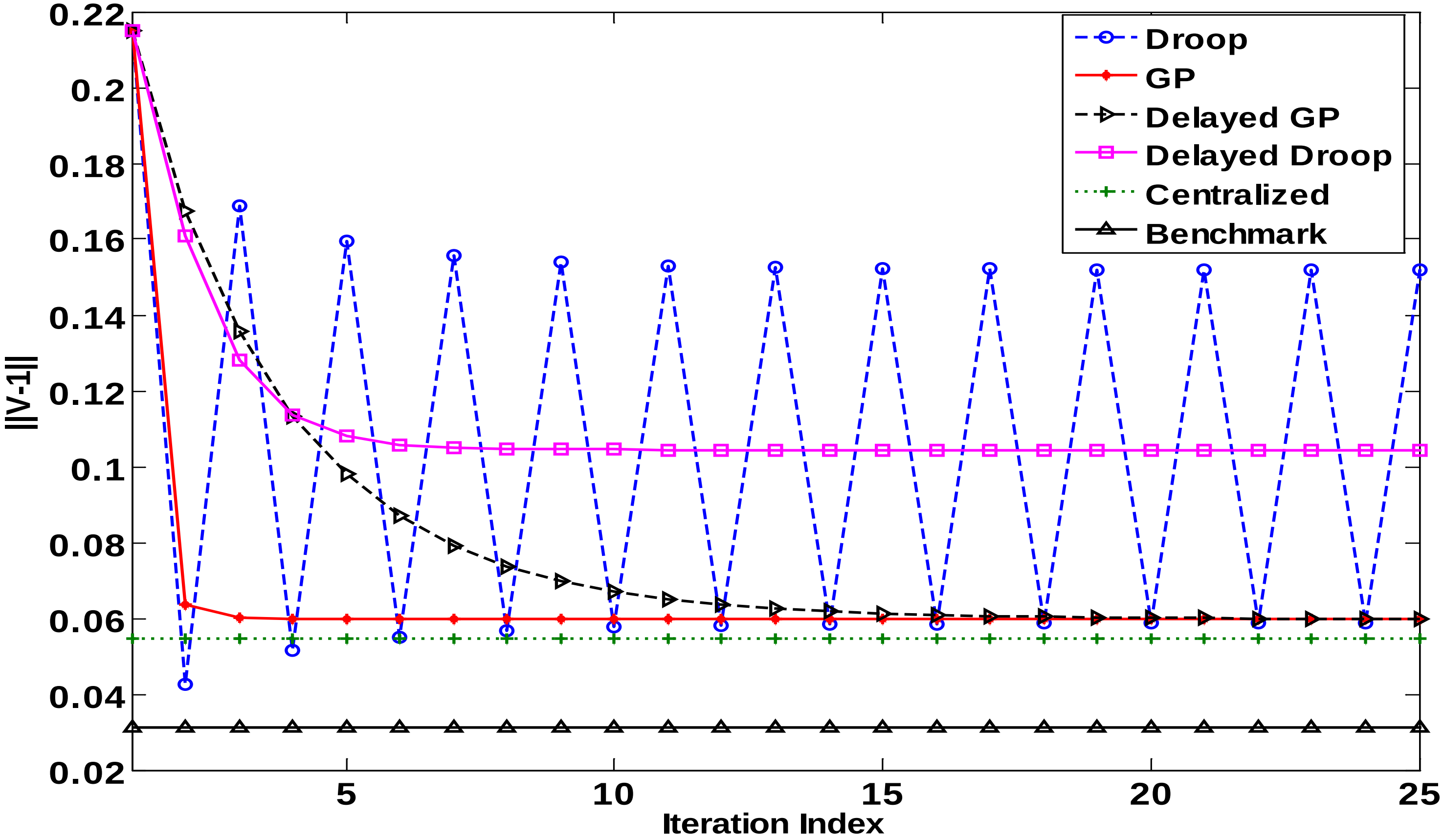
- At no communications, inverters can determine VAR outputs based on local bus voltage magnitudes
  - Can quickly and accurately respond to voltage violations

- Droop control (IEEE 1547.8) [Farivar et al '13]
  - Instability arises under high PV penetration [Jahangiri et al '13]
  - Integral control at unlimited inverter VAR [Zhang et al '12], [Li et al '14]

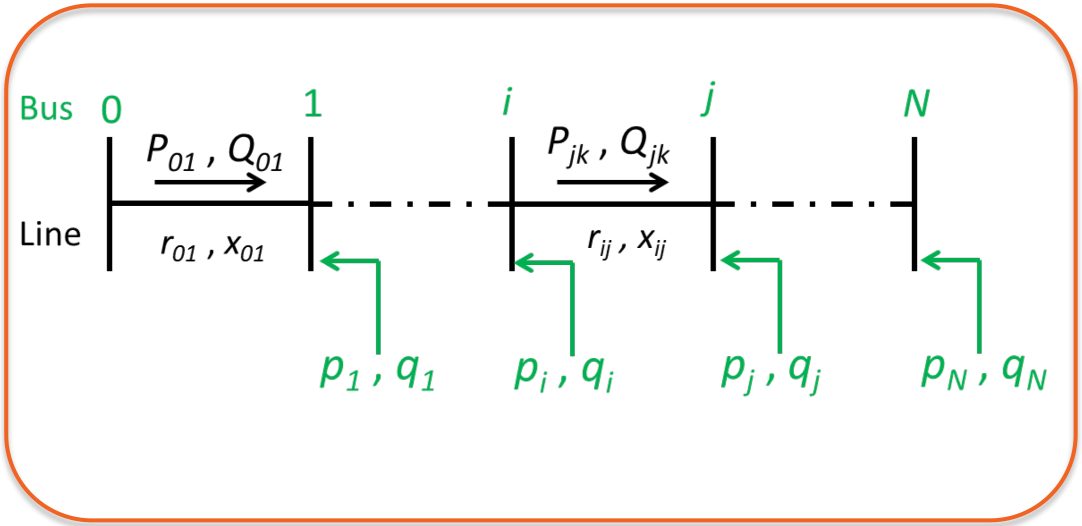


Instable droop control

- A radial 16-bus single-phase case with r/x ratio ≈ 0.635
- Bus loading ~ (70+j30)kVA; abundant VARs (±100kVar)



Matrix LinDistFlow model



$$\Longleftrightarrow \quad \mathbf{V} \approx \mathbf{X}\mathbf{q} + \mathbf{V}_0$$

- $\mathbf{X}^{-1} = \mathrm{B}$ is the power network B bus matrix (dc power flow)
- Equivalent to fast decoupled power flow (FDPF) model

$$\Delta \mathbf{V} \approx \mathbf{X}\Delta \mathbf{q} \quad \Longleftrightarrow \quad \Delta \mathbf{q} \approx \mathbf{B}\Delta \mathbf{V}$$

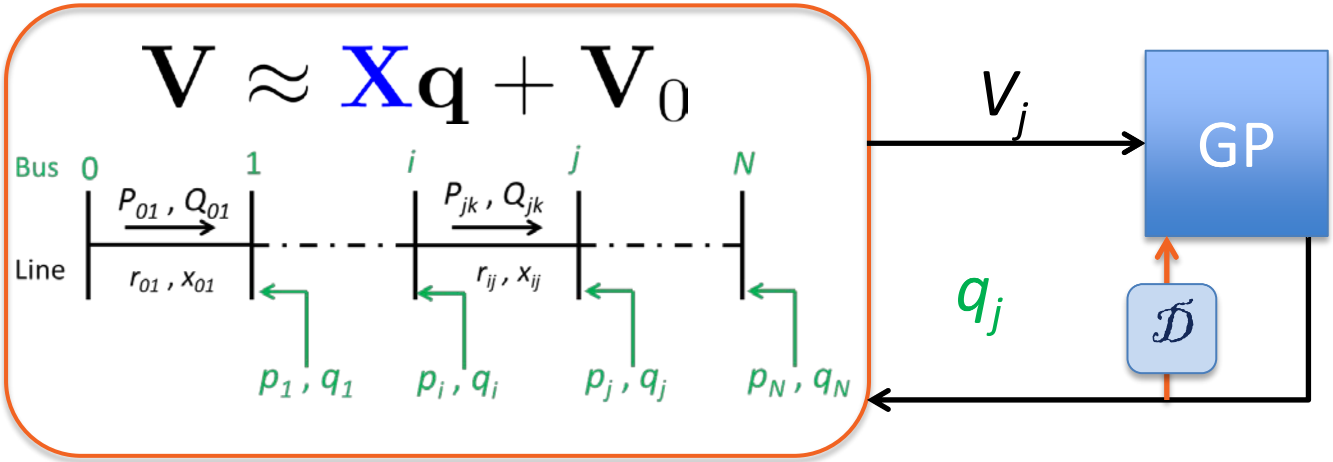
Gradient-Projection (GP) based VAR control

minimize *Weighted V mismatch* + *VAR costs*

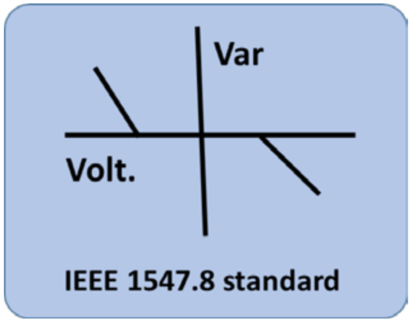
$(\mathbf{V}-\mathbf{1})^T\mathbf{B}(\mathbf{V}-\mathbf{1})+\mathbf{q}^T\mathbf{C}\mathbf{q}$ ⇨ Quadratic

subject to $\underline{q_j} \le q_j \le \overline{q_j}$ at every bus *j*

- **Optimal GP iteration** $q_j(t+1)=\mathbb{P}_j\left[(1-d_jc_j)q_j(t)-d_j(V_j(t)-1)\right]$



Features of GP-based local control



- Droop control: setting $d_j = 1/c_j$

$$q^g(t+1) = \mathbb{P}_j\big[-d_j(V_j(t)-1)\big]$$

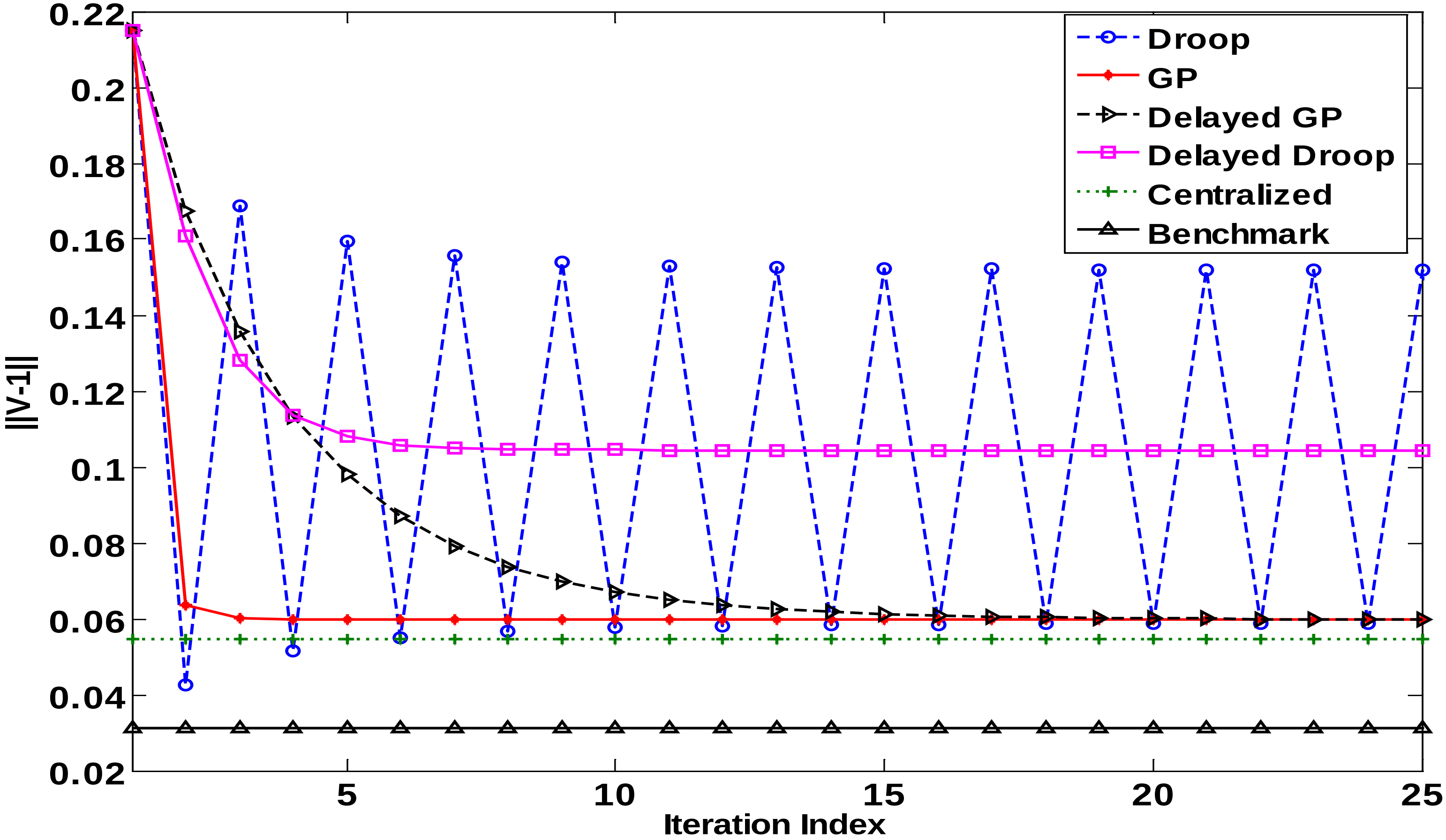
  - c_j has to be large enough to ensure stability [Farivar et al '13]
  - A delayed + droop scheme in [Jahangiri et al '13]
- Requiring minimal coordination with control center
  - GP-based control can be stabilized with any arbitrary c_j
- Generalizing unbalanced (three-phase) distribution networks

$$\mathbb{B}\Delta\mathbb{v} \approx \Delta\mathbb{q}$$

- Allowing for asynchronous control updates (plug-and-play)

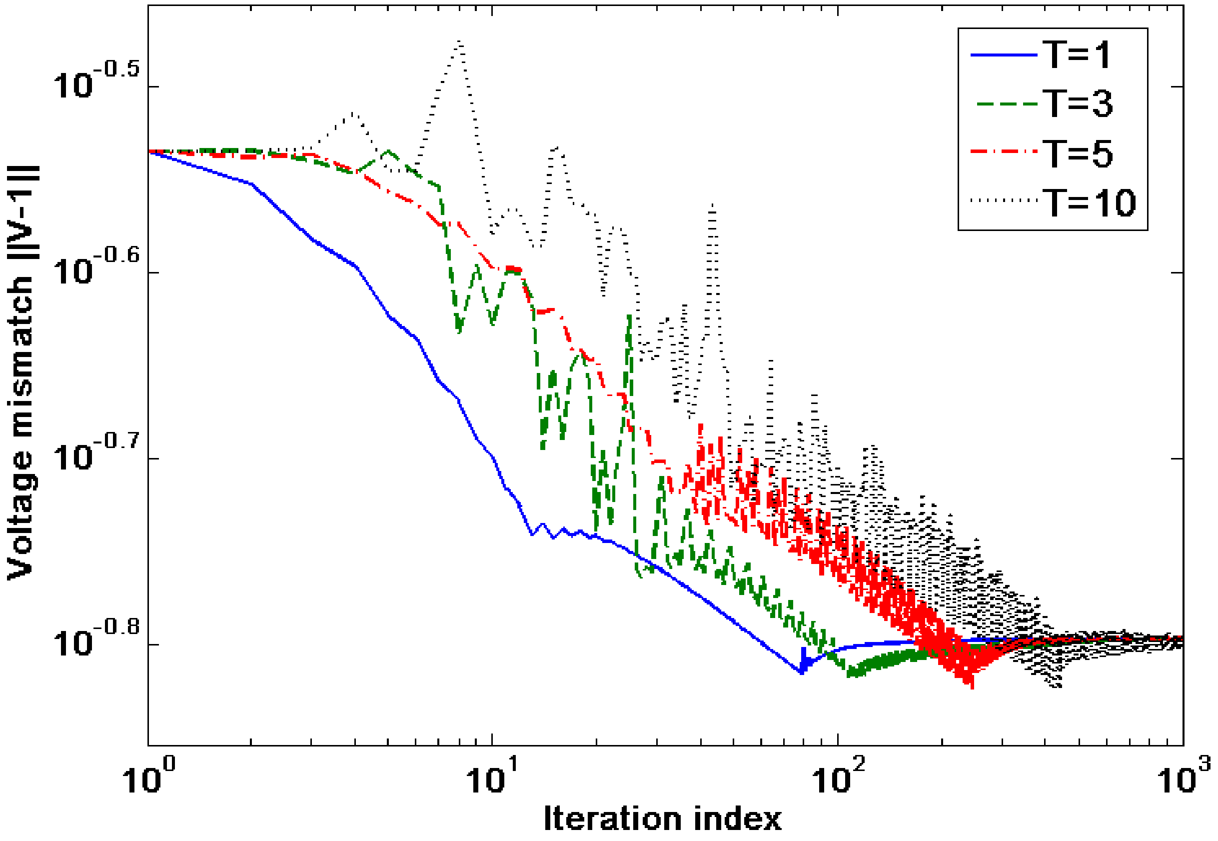
Static system tests

- A radial 16-bus single-phase case with r/x ratio ≈ 0.635
- Bus loading ~ (70+j30)kVA; abundant VARs (±100kVar)
- NOTE: voltage obtained by solving ac power flow (not the linearized model)!



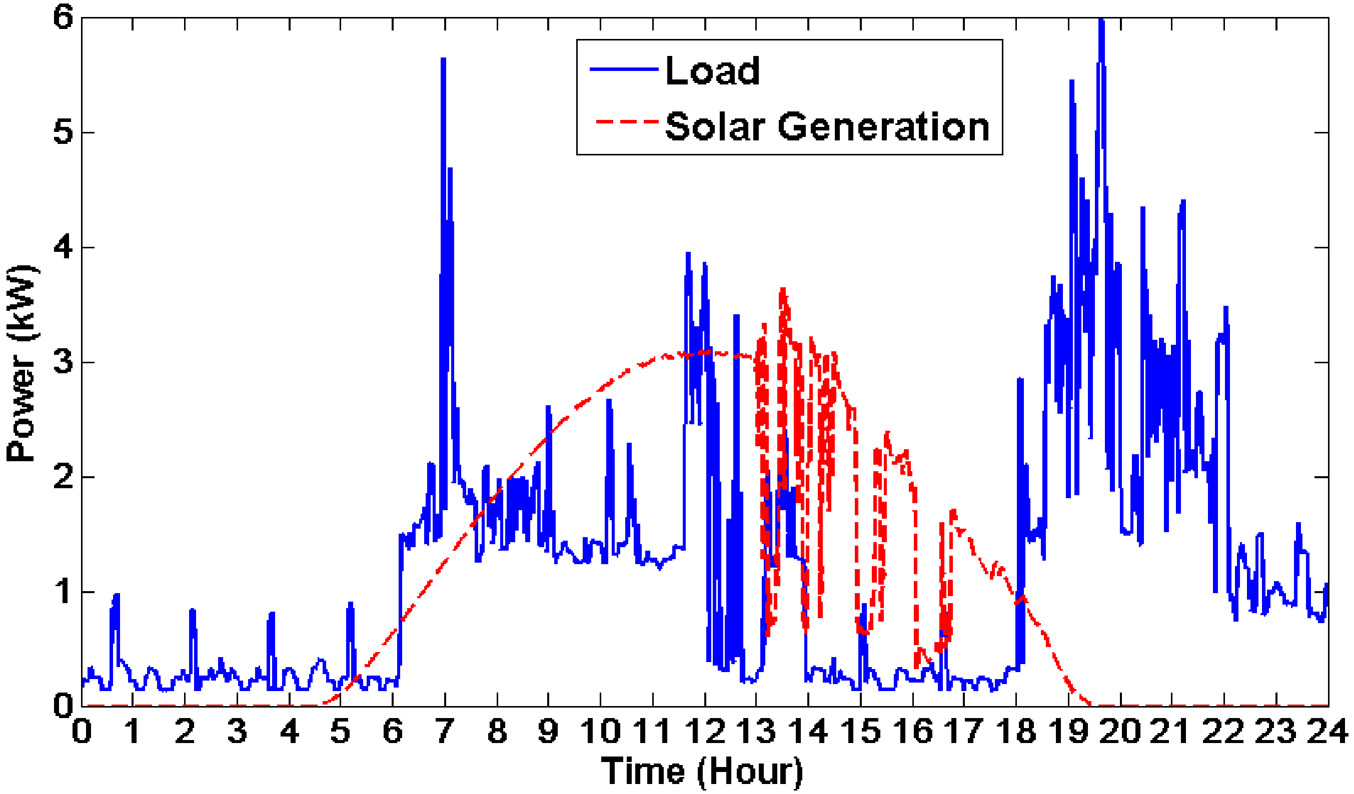
Asynchronous updates

- Each bus randomly updates every $t \in [1, T]$ iterations
- Guaranteed to converge; larger T slows down convergence speed



Dynamic system tests

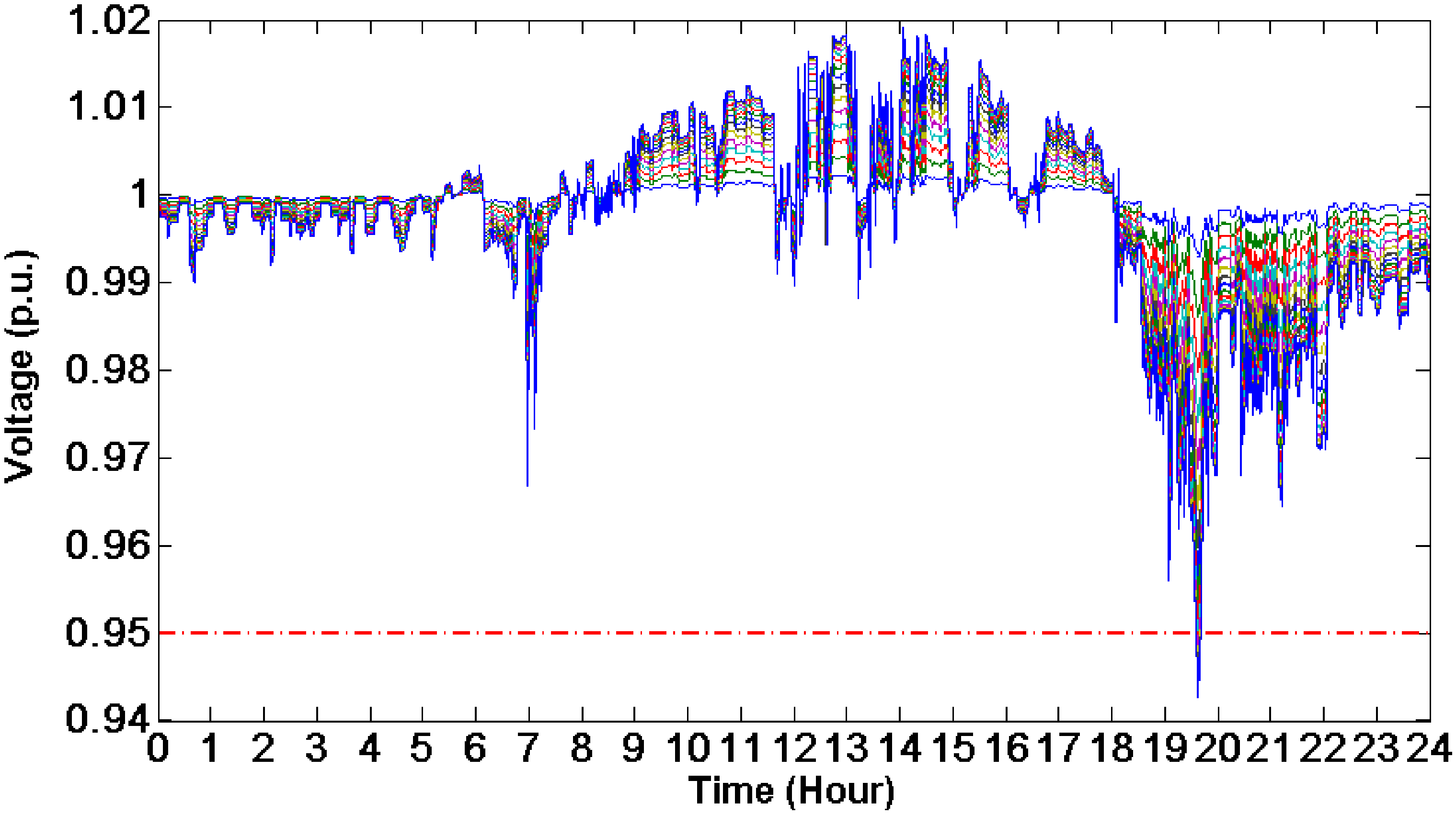
- Daily profile of residential load and solar PV output every minute
- Heavy loading during the evening (18:00-22:00)
- High solar variability in the afternoon (12:00-17:00)



Source: https://archive.ics.uci.edu/ml/datasets/Individual+household+electric+power+consumption

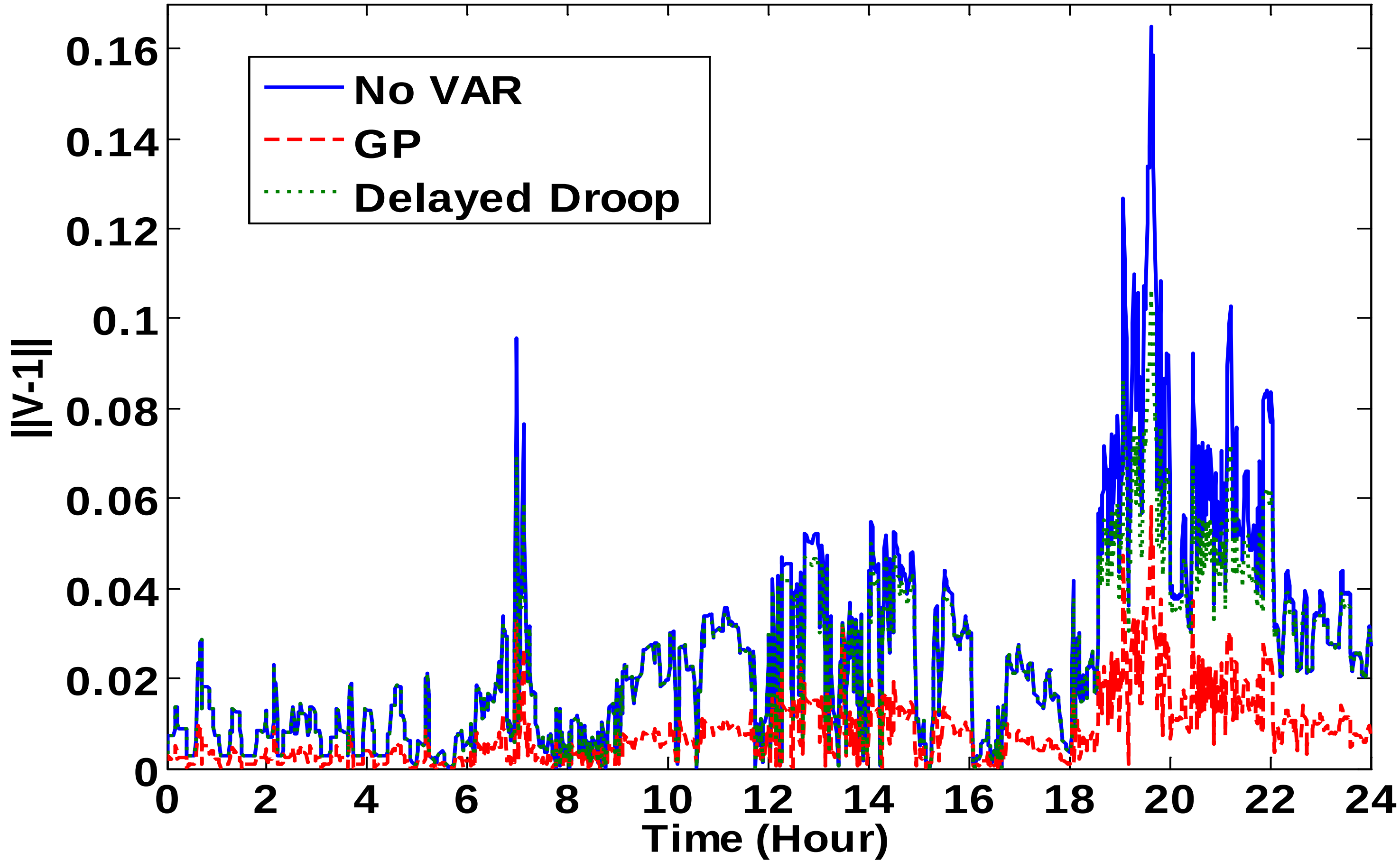
Daily voltage profile at no inverter VAR

- Over-voltage during noon hours, and low-voltage in the evening
- More severe at the end of feeder



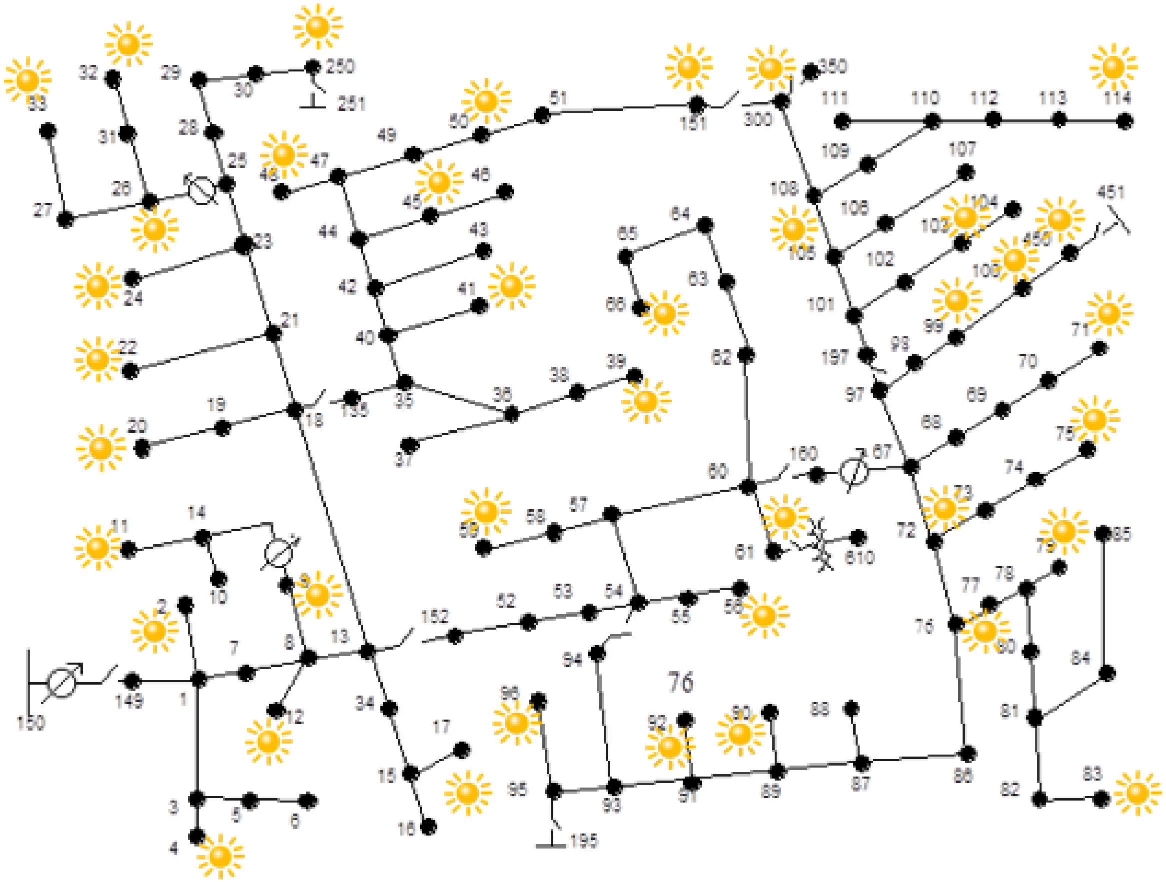
Dynamic VAR control

- Local VAR control updates every 5 seconds
- Proposed GP-based scheme effectively reduce voltage mismatch



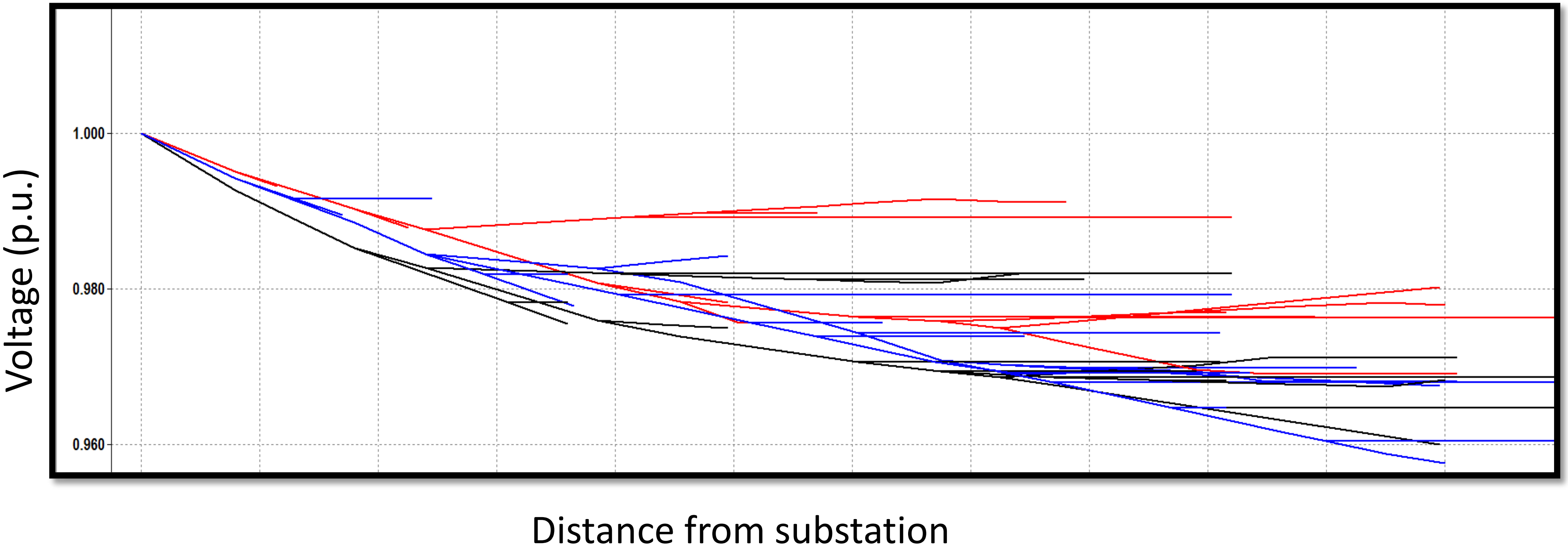
Three-phase system tests

- **Local control can be easily implemented on three-phase systems**
- **IEEE 123-bus test cases with 30% solar penetration**



Three-phase voltage profile

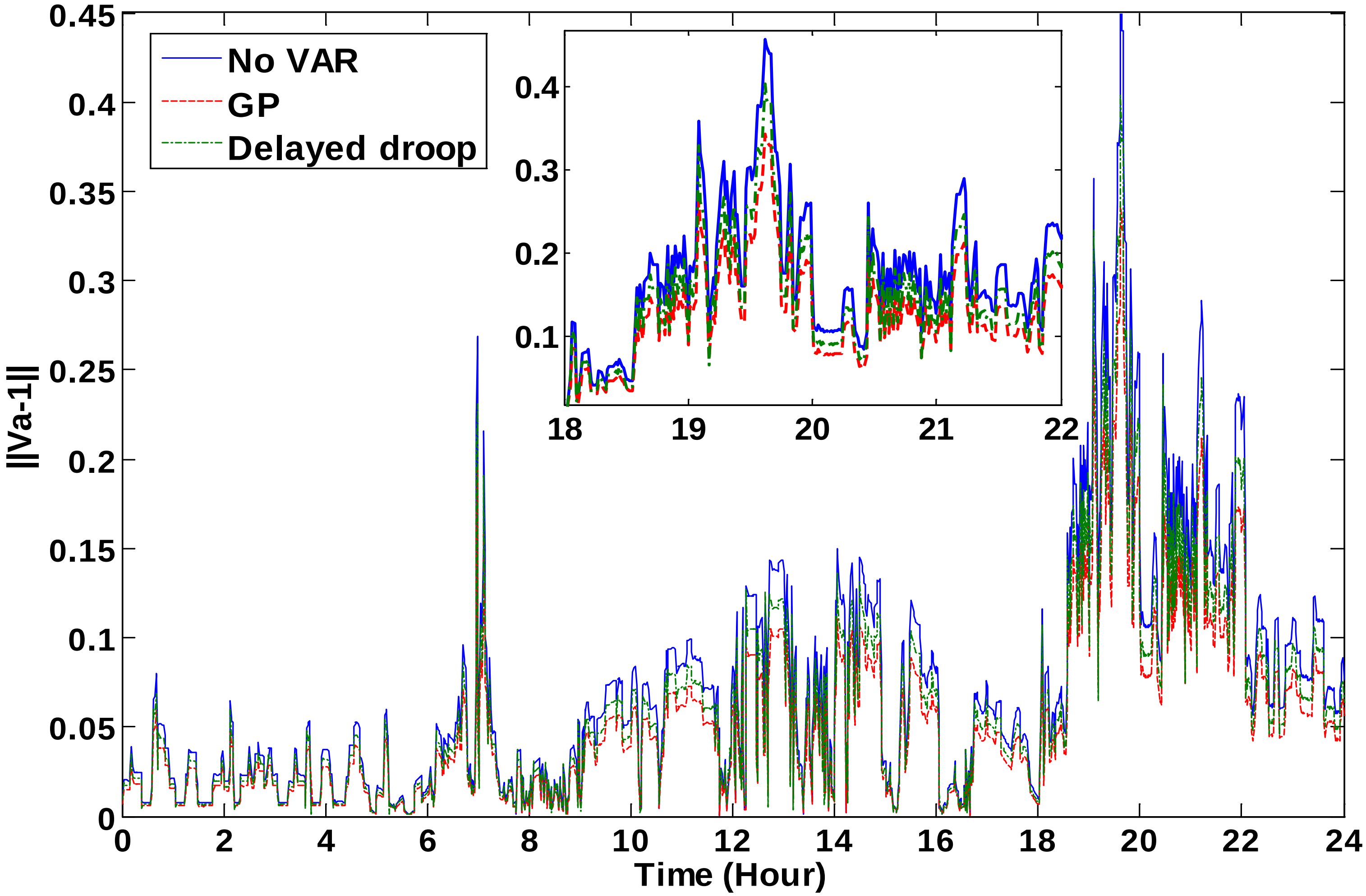
- **Actual voltage profile obtained using OpenDSS**
  - Phase a: black; Phase b: red; Phase c: blue



Dynamic voltage mismatch

Need communications to share information globally!

- **Local control less effective under low solar penetration level**



Drawbacks of local control

- It minimizes a weighted mismatch norm, instead of $\|\mathbf{V}-\mathbf{1}\|^2$

minimize *Weighted V mismatch* + *VAR costs*

$$(\mathbf{V}-\mathbf{1})^T\mathbf{B}(\mathbf{V}-\mathbf{1})+\mathbf{q}^T\mathbf{C}\mathbf{q}$$

subject to $\underline{q_j} \leq q_j \leq \overline{q_j}$ at every bus *j*

- Global objective: unweighted voltage mismatch norm

minimize *V mismatch* + *VAR costs*

$$\|\mathbf{V}-\mathbf{1}\|^2+\mathbf{q}^T\mathbf{C}\mathbf{q}$$

subject to $\underline{q_j} \leq q_j \leq \overline{q_j}$ at every bus *j*

Distributed VAR control

- Key of parallelization lies in the structure of $\mathbf{B}\Delta\mathbf{V} \approx \Delta\mathbf{q}$

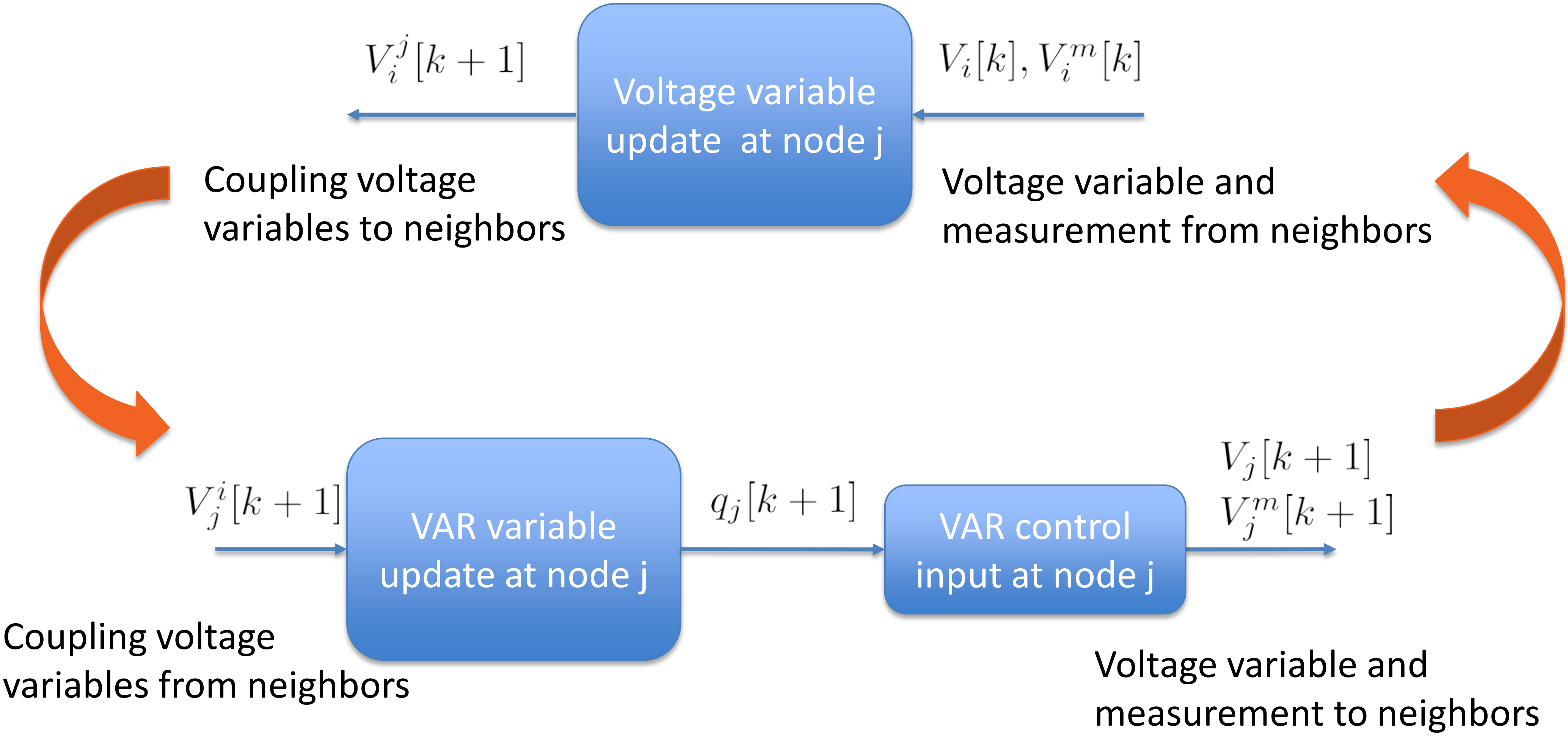
- Power flow constraint at bus *j* just involves its neighboring buses

$$\sum_{\forall i \in \mathcal{N}_j} B_{ji}V_i + B_{jj}V_j = q_j + c_j$$

- Distributed solver (ADMM): communications between one-hop neighboring buses

- Also holds for unbalanced three-phase systems $\mathbb{B}\Delta\mathbb{v} \approx \Delta\mathbb{q}$

Communication Links



$V_i^j[k+1]$

Voltage variable update at node j

$V_i[k], V_i^m[k]$

Coupling voltage variables to neighbors

Voltage variable and measurement from neighbors

$V_j^i[k+1]$

VAR variable update at node j

$q_j[k+1]$

VAR control input at node j

$V_j[k+1]$
$V_j^m[k+1]$

Coupling voltage variables from neighbors

Voltage variable and measurement to neighbors

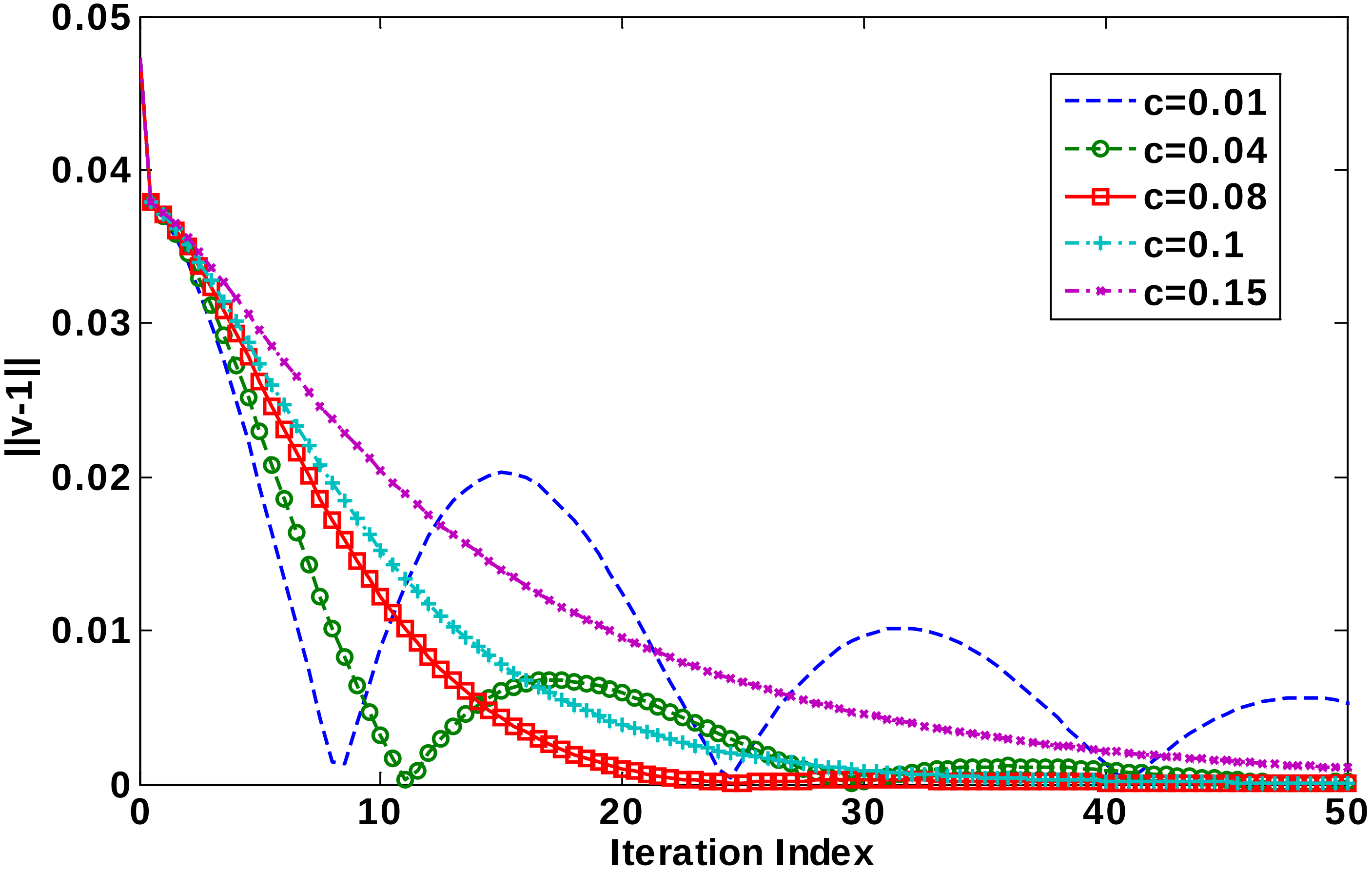
Features of distributed control

- Simple local computation tasks: linear /QP updates
- Implemented online by incorporating dynamic voltage measurement
  - Neighboring buses only exchange voltage variables
  - Existing methods collect/exchange real/reactive power measurements [Sulc et al '14], [Robbins et al '15]
- Extended to unbalanced three-phase systems
- Asynchronous updates guaranteed to converge [Lutzeler et al ' 13]

$$\mathbb{B}\Delta \mathbb{v} \approx \Delta \mathbb{q}$$

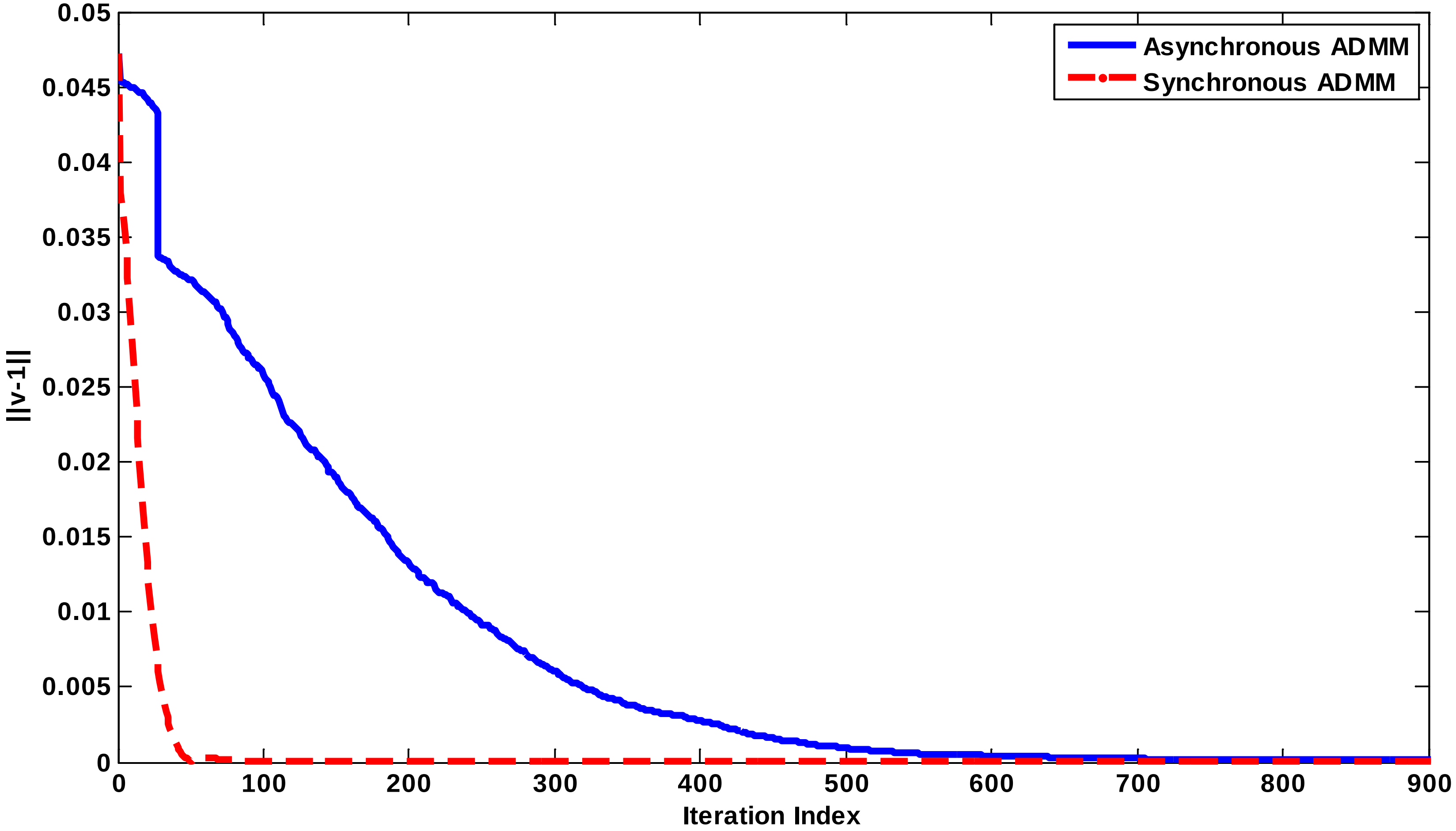
Static system tests

- The same 16-bus single-phase case with r/x ≈ 0.635
- Various VAR provision cost coefficients *c*



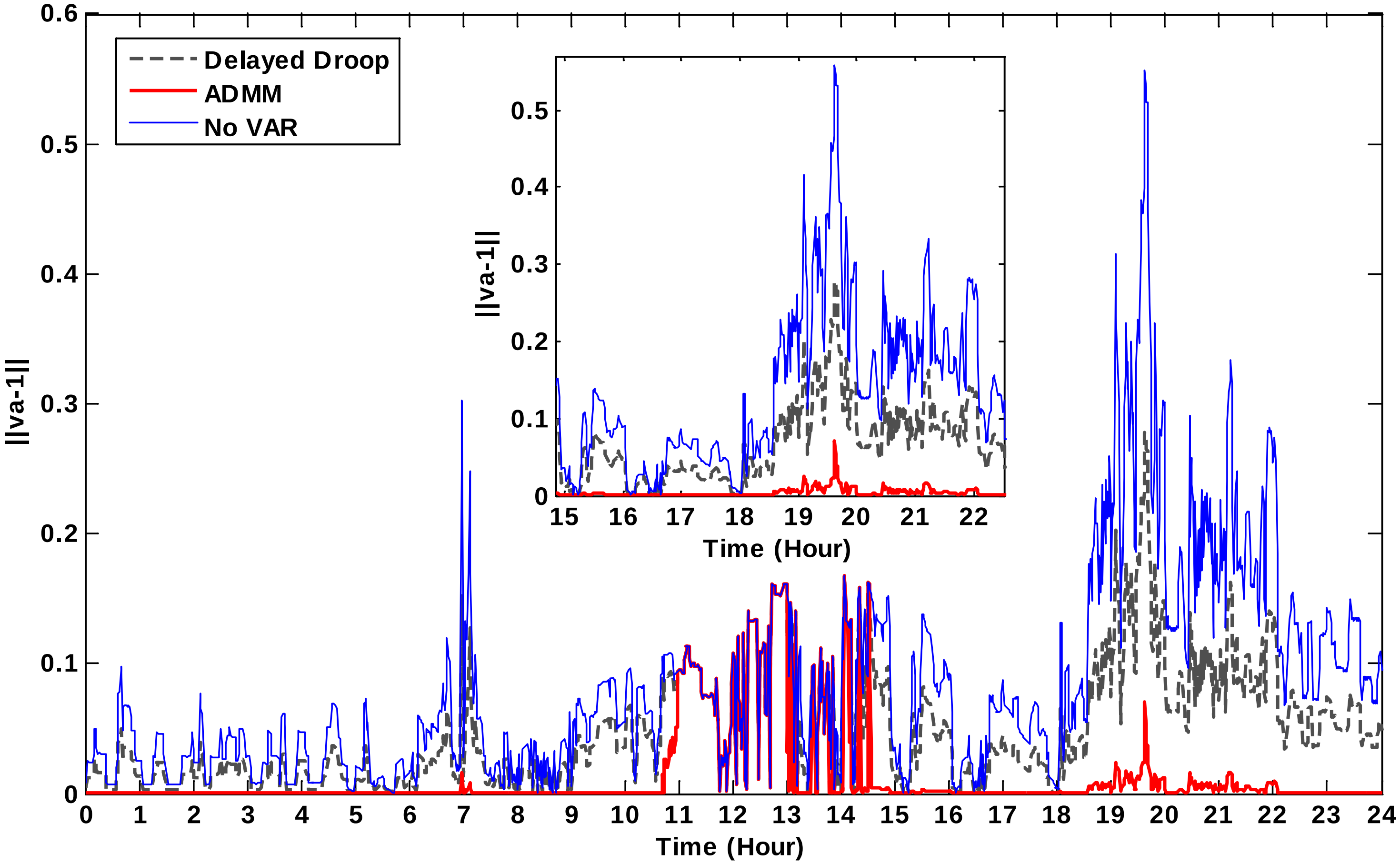
Asynchronous updates

- **Each link randomly fails with given probability $^1/_{|\mathcal{N}_j|}$**



Dynamic tests for the 123-bus system

- Both local and distributed methods update every 3 seconds
- Distributed control more effectively reduces voltage mismatch



Conclusions

- Distribution system voltage control challenged by increasing load variations and intermittent DG output
- GP-based local control tackles the instability of droop control
- Distributed control seeks the globally optimal solution
- Both applicable to unbalanced systems and imperfect update/communication scenarios
- Future research: how does it interact with LTC or other devices?

Acknowledgements

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Thank you!

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