On Measurements' Role in Supporting Capacitor Control

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Outline

- Background
- Emerging System Conditions
- Proposed Role of Measurements
  - Generator and Reactive Power Domains
- Focus Application: Capacitor Control for VSR
  - Centralized vs. Distributed Control
- Simulation Results
- Discussion & Summary

Background (1/4)

- Background Experience
  - Work with NSF, DOD – ONR, DOE
  - Work with PPL Electric Utilities
- Background (of this Talk!): EAPA Sept 25, 2012
  - “Practically Driven, Analytically Based Capacitor Control Methods” : generating feasible sequences between load levels
  - Secondary topic: centralized vs. distributed control

    → today’s focus applications

Background (2/4)

- Measurements will directly support distribution system analysis
  - Increased data (loads, in-line/feeder measurements)
  - Enables power system state estimation/analysis
  - Updated system level information allows for improved system optimization
- Computational Control Tools
  - Adapt to new operating conditions *
  - Repeatable, fast, offer playback

Background (3/4)

- Open Questions
  - What types of information do we need? (units: V, A, VA, etc.)
  - How much data/information is necessary for a control decision? (units: MB, bandwidth)
  - How often should we make control decisions? Leading to how often should we acquire data (units: min/hrs)
  - What other conditions trigger us to make control decisions? Leading to when should we be aware of the info. (units: switch statuses, V, A, VA, etc.)

Background (4/4)

- Common Capacitor Control Objectives:
  - Support voltage regulation
  - Achieve network loss reduction
  - Perform power factor correction
- Energy efficiency measures and legislation
  - Reduce network level energy consumption
- Renewed interest in conservation voltage reduction (CVR) via Voltage Spread Reduction (VSR)

Emerging System Conditions (1/2)

- System components are being embedded with intelligent controllers and remote actuation capabilities
- These components include:
  - feeder capacitor banks
  - sectionalizing switches
  - controllable loads
  - distribution generation
- An embedded information layer allows devices to communicate over new and existing telecommunication infrastructure
- This enables a shift from:

local and/or pre-set operation schemes

online optimization and control

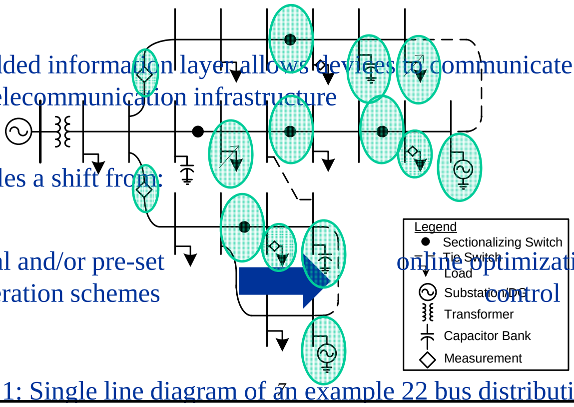

Figure 1: Single line diagram of an example 22 bus distribution system

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Emerging System Operation (2/2)

- Power injections increasingly varied
  - Distributed generation
  - Direct load control and demand side management participation levels still evolving
- Online optimization/quasi-steady state applications
  - Capacitor operating goals and “real-time” do not nec. align
  - Although objectives/time-frame distinct from switching/service restoration goals, capacitor actions may need to be tied to them

Proposed Role of Measurements (1/3)

- Enable adaptive control
- Develop updated distribution power injection/load patterns and forecasting
- Define areas of influence (domains) for:
  - Capacitors (voltage regulation) Feb 2014 IEEE Trans on Power Systems
  - Distributed generators (economic impacts)

May 2005 IEEE Trans on Power Systems

Proposed Role of Measurements (2/3)

- How many measurements?
  - Bad data filtering – historically performed via “expected” vs. sensed values
  - Organize distribution system into control areas
- Automatically triggered alerts
  - Power/electrical thresholds to vet data vs. only time intervals
  - *Area (goal-oriented) alerts vs. local measurement alerts*

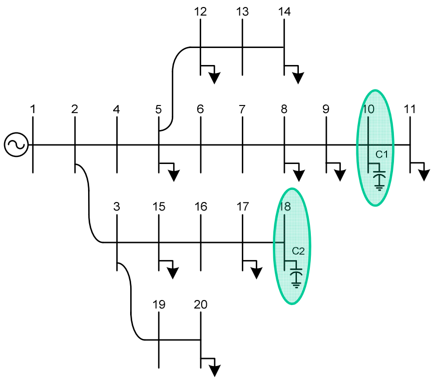

Figure 2: Single line diagram example 20 bus system

Proposed Role of Measurements (3/3)

- Defined and adjust areas to reflect changing operating conditions

- Areas can then be used to ID which subset of measurements are critical to re-evaluating control options

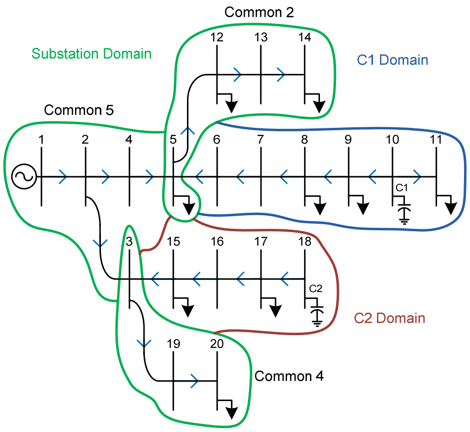

Figure 3: Reactive power domains and commons

Partitioning Methodology (1/10)

- Generators: real power domains can be identified
- Capacitors: reactive power domains depend on:
  - capacitor location
  - capacitor size
  - network component parameters
  - load distribution
  - distributed generator inputs

Positive Power Flow Direction (2/10)

- Used to “trace” reactive power flows back to a generator, capacitor, or substation

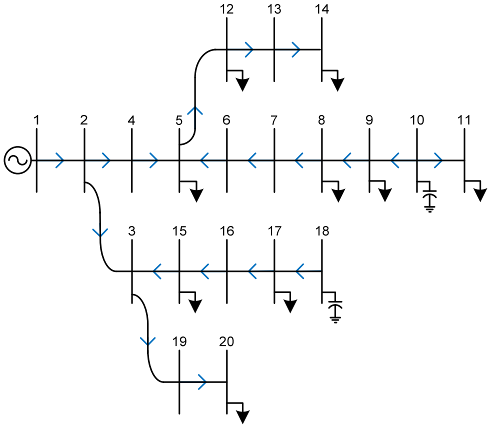

Figure 4: Arrows indicate positive reactive power flow direction on phase a

Reactive Power Domains (3/10)

- Common: contiguous set of branches and nodes supplied by same source

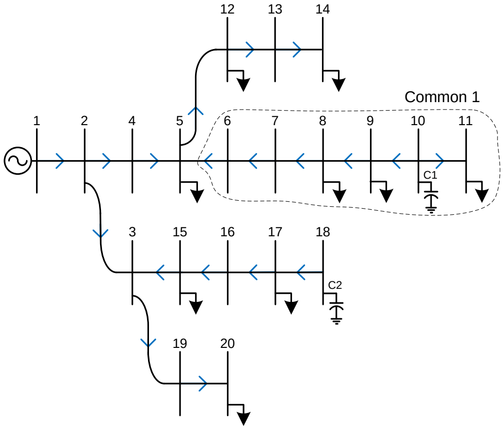

Figure 5: Common 1 sub-system supplied by capacitor C1

Reactive Power Domains (4/10)

- Loss on a branch or load at a node may be supplied by multiple sources

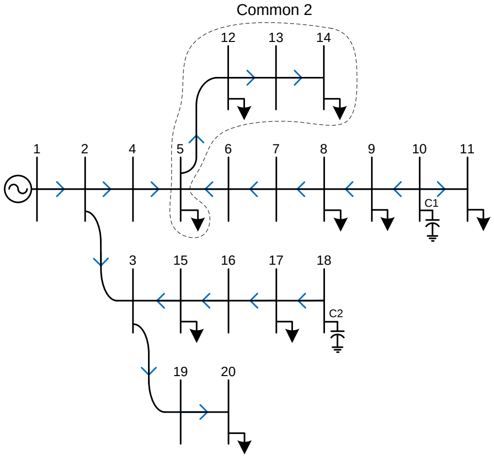

Figure 6: Common 2 sub-system supplied by C1 and the substation

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Reactive Power Domains (5/10)

- Domain: set of all commons attributed to a specific source

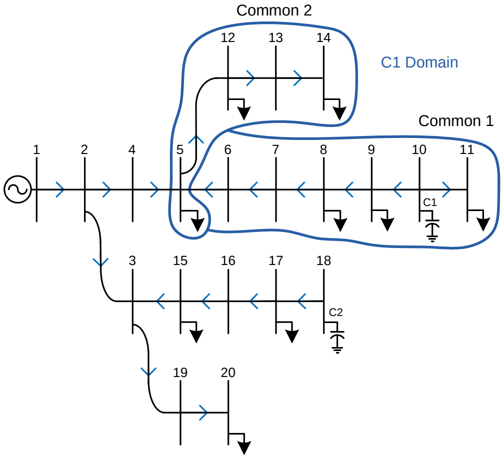


Figure 7: Domain of capacitor C1: Common 1 and Common 2

Reactive Power Domains (6/10)

- Similar treatment for other sources:

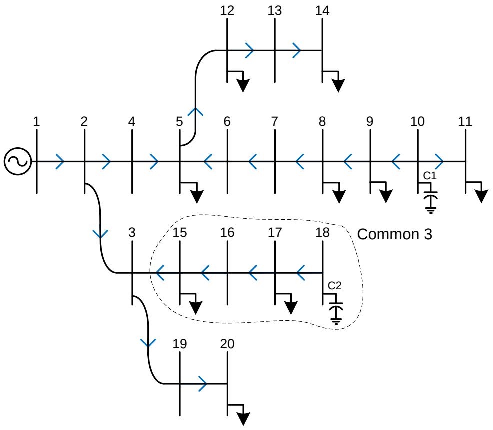


Figure 8: Common 3 sub-system supplied by capacitor C2

Reactive Power Domains (7/10)

Common 4 supplied by capacitor C2 and the substation

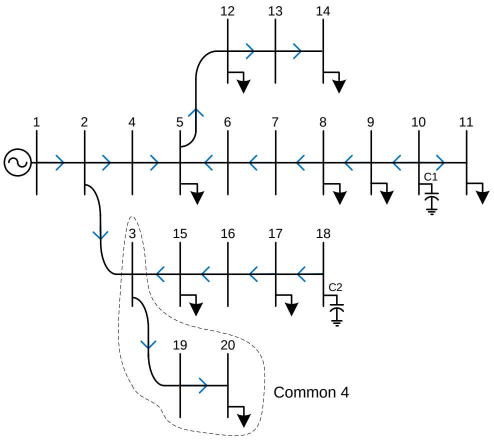


Figure 9: Common 4 sub-system supplied by C2 and the substation

Reactive Power Domains (8/10)

Domain of Capacitor C2: Common 3 and Common 4

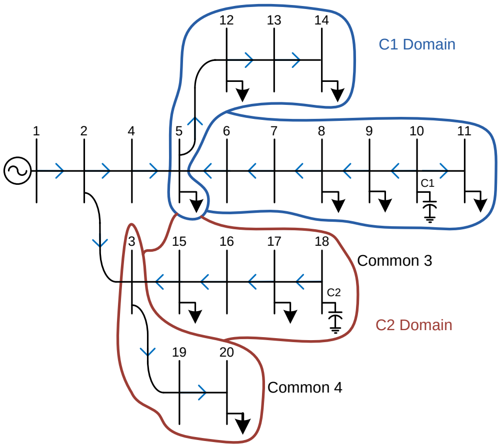


Figure 10: Domain of capacitor C2: Common 3 and Common 4

Reactive Power Domains (9/10)

Domain of Substation: Common 2, Common 4, and Common 5

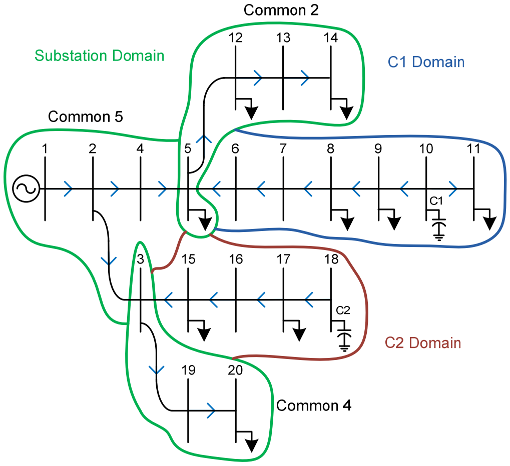
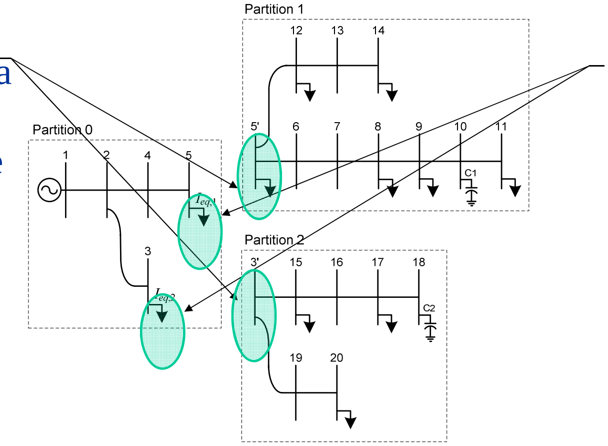


Figure 11: Substation Domain: Common 2, 4 & 5

Partitioned Test System (10/10)

- Distributed analysis employed to estimate state within each control area
- 2007 - M. Kleinberg, K. Miu, C. Nwankpa, “Distributed multi-phase distribution power flow” *Trans. of the Society for Modeling and Simulation International*



Equivalent source buses

Equivalent load buses

Figure 12: Test system partitioned based on capacitor reactive power domains

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Focus Application: Capacitor Control for VSR

Problem Formulation

- Capacitor control employed to support voltage regulation
- Centralized control formulated as mixed integer, non-linear constrained optimization problem
- Assumption: maximum voltage deviations occur with respect to substation voltage
- Simplified objective function considered for performing initial studies

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Centralized Control Formulation

- Centralized control problem formulation stated as:

$$\min_{u\in U}\ \max_{\substack{j\in M\\ p\in a,b,c}} \left\| \left|\overline{V}^{p}_{0,ref}\right| - \left|V^{p}_{j,meas}\right| \right\|$$

(1) minimize voltage spread

subject to:

$$f(V,\lambda,u)=0$$

(2) three-phase power flow

$$\left|I^{p}_{k}\right| \le I^{\max}_{k} \quad \forall\ k\in N,\ p\in a,b,c$$

(3) feeder current limits

$$P^{2}_{l}+Q^{2}_{l} \le (S^{\max}_{l})^{2} \quad \forall\ l\in F$$

(4) feeder loading limits

$$V^{\min}_{k} \le \left|V^{p}_{k}\right| \le V^{\max}_{k} \quad \forall\ k\in N,\ p\in a,b,c$$

(5) voltage magnitudes limits

where:

$\left|\overline{V}^{p}_{0,ref}\right|$: specified substation voltage magnitude, phase *p*

$\left|V^{p}_{j,ref}\right|$: voltage magnitude measurement, bus *j*, phase *p*

$F,\ N,\ M$: set of feeders, buses, and voltage measurements

u : capacitor control scheme

Centralized vs. Distributed Control

- Centralized Control
  - Optimization solver accesses all available network information
  - Attempts to coordinate control actions of all network capacitors
- Distributed Control
  - Network is divided into control areas
  - Each controller measures & analyzes respective network area
  - Control decisions based on conditions within a control area
  - Requires coordination and data sharing between control areas

Preliminary Distributed Controller Design

Preliminary Distributed Controller Design

- Distributed controller required to determine switching operations
- Similar formulation to centralized problem
  - voltage reference obtained from within control area
- Reference voltage is a computed value local to each control area
  - obtained through distributed analysis of the network
  - e.g. the equivalent source bus voltage
- Control is knowingly conservative: only measured voltage spread within each control area considered

Preliminary Distributed Controller

- For each control area:

$$\min_{u_i \in U_i} \max_{\substack{j \in M_i \\ p \in a,b,c}} \left| \left| \tilde{V}^{p}_{i,ref} \right| - \left| V^{p}_{j,meas} \right| \right|$$

(1) minimize voltage spread within control area

subject to:

$$f(V_i, \lambda, u_i) = 0$$

(2) three-phase power flow

$$\left| I^{p}_{k} \right| \le I^{\max}_{k} \;\; \forall\, k \in N_i,\; p \in a,b,c$$

(3) feeder current limits

$$P_l^2 + Q_l^2 \le (S_l^{\max})^2 \;\; \forall\, l \in F_i$$

(4) feeder loading limits

$$V^{\min}_{k} \le \left| V^{p}_{k} \right| \le V^{\max}_{k} \;\; \forall\, k \in N_i,\; p \in a,b,c$$

(5) voltage magnitudes limits

where:

$\left| \tilde{V}^{p}_{i,ref} \right|$: computed reference bus voltage magnitude, control area *i*

$F_i,\ N_i,\ M_i$: set of feeders, buses, voltage measurements, control area *i*

u_i : capacitor control scheme, control area *i*

Simulation Results

Case Study 1 – Test System

- Local, distributed and two centralized control cases are compared
- Capacitor C1 and capacitor C2 each have four available bank settings:
  - Bank Setting 0: 0 kVAR
  - Bank Setting 1: 300 kVAR
  - Bank Setting 2: 600 kVAR
  - Bank Setting 3: 900 kVAR
- Four load levels are investigated:
  - LL1: 45% of peak load
  - LL2: 55% of peak load
  - LL3: 70% of peak load
  - LL4: 100% of peak load

Capacitor Placement and Control

- Classification of capacitor allocation techniques
  H.N. Ng, M.M.A. Salama, A.Y. Chikhani, *IEEE Trans. on Power Delivery*, 2000

Computation of Capacitor Settings

- Local control switching setpoint at 0.985 p.u.
- Centralized and distributed control: exhaustive search over all settings
- 20 Bus Test Settings

– peak load: 2,881 kW and 1,863 kVAR

– two three-phase capacitor banks, three 300 kVAR banks each

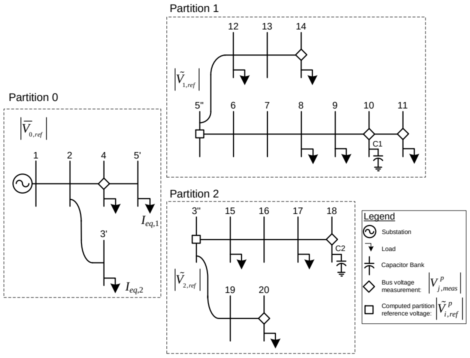

Figure 13: Centralized control voltage reference at substation

Simulation Results – Test System

Table 1: Capacitor bank setting (C1-C2) at each load level for each control scheme

Load Level	Control Scheme		
	Local (C1–C2)	Distributed (C1–C2)	Centralized (C1–C2)
LL1 (45%)	0-0	2-0	3-1
LL2 (55%)	1-0	2-1	3-2
LL3 (70%)	1-0	3-1	3-3
LL4 (100%)	2-1	3-1	3-3

Table 2: Maximum voltage spread in p.u. at each load level for each control scheme

Load Level	Control Scheme		
	Local	Distributed	Centralized
LL1 (45%)	0.007904	0.003320	0.001340
LL2 (55%)	0.007129	0.004935	0.002963
LL3 (70%)	0.009763	0.005404	0.005395
LL4 (100%)	0.012512	0.010264	0.010255

Observations

- Distributed control:
  - significant improvements over local settings as expected
  - suboptimal settings compared to centralized control
  - approach centralized solutions at higher load levels

- At low loading levels, distributed control produced significantly larger voltage spread than centralized control
  - regulation concerns not as critical during these periods

Case Study 2 – Utility Feeder

- Results presented next on utility feeder:
  - 8361 kW, 2746 kVar
  - 12.9 kV
  - 948 bus, 1224 node
  - 4 capacitor banks
- Capacitor banks have three available bank settings:
  - Bank Setting 0: 0 kVAR
  - Bank Setting 1: 300 kVAR
  - Bank Setting 2: 600 kVAR
- Three load levels investigated, based on utility AMI data:
  - LL1: Light loading
  - LL2: Average loading
  - LL3: Peak load

Utility Feeder Diagram

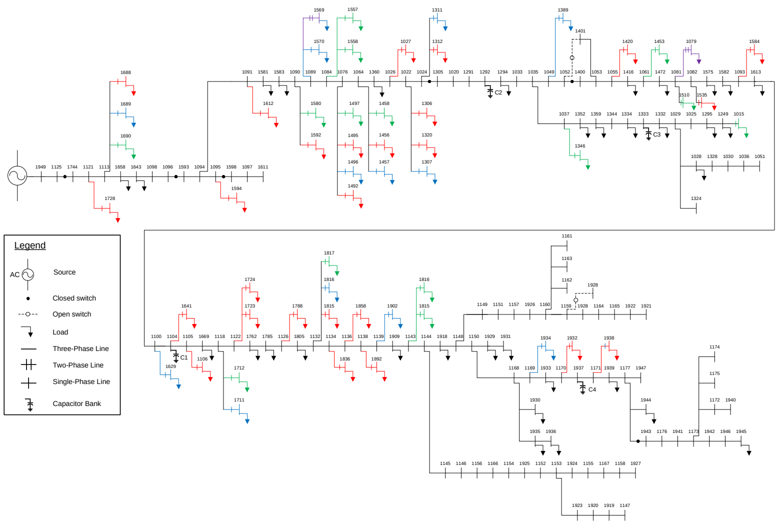

Figure 14: 948 bus, 1224 node multi-phase unbalanced distribution system

Partitioned Utility Feeder

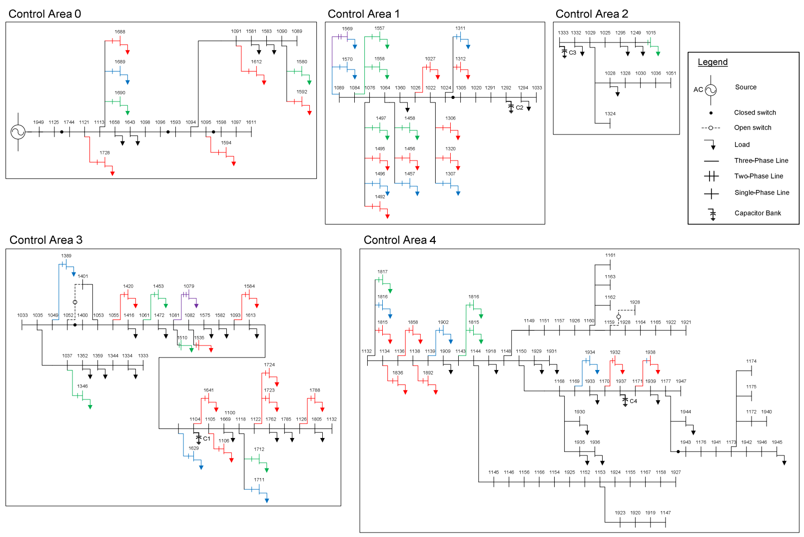

Figure 15: Test system partitioned based on reactive power domains

Simulation Results – Utility Feeder

Table 1: Computed capacitor settings and resulting voltage spread at each load level

Load Level	Centralized Controller		Distributed Controller	
	Capacitor bank settings	Voltage spread (p.u.)	Capacitor bank settings	Voltage spread (p.u.)
LL1 (Light)	2-1-2-0	0.001820	0-1-2-1	0.0022433
LL2 (Average)	2-2-2-2	0.017955	2-2-2-2	0.017955
LL3 (Peak)	2-2-2-2	0.023220	2-2-2-2	0.023220

Table 2: Computed capacitor settings and resulting system losses each load level

Load Level	Centralized Controller		Distributed Controller	
	Capacitor bank settings	P_{loss} (kW)	Capacitor bank settings	P_{loss} (kW)
LL1 (Light)	0-1-1-0	8.38079	1-1-0-0	8.40419
LL2 (Average)	2-2-2-2	55.17571	2-1-2-1	57.02187
LL3 (High)	2-2-2-2	126.96227	2-2-2-1	127.52827

Observations

- Peak load:
  - typical that all capacitors switched to maximum tap setting
  - observed for both centralized and distributed control
- Average load: distributed controller matches centralized solution for all references
- Peak and average load:
  - distributed controller finds globally optimal solution across varying levels of coordination
- Light load: distributed control resulted in feasible, sub-optimal solutions
  - typically represents non-critical operating periods,

Discussion & Summary

Summary

- As push towards advanced distribution automation continues, distributed online control viable
- A study of distributed capacitor control has been presented:
  - reactive power domains employed to partition into control areas
  - distributed analysis used to analyze system
- Controller designed to regulate voltage within control areas
- Suboptimal settings as compared to a centralized solver
  - advantage: reduced communication requirements and stand-alone capability
- Significant improvements over strictly local control possible:
  - support adoption of advanced distribution automation

Discussion

- Additional measurement capabilities really enhance capacitor control possibilities
- To improve design of distribution system measurement systems:
  Power engineering analysis and values should still be utilized

Related Publications & Presentations

[1] M. Kleinberg, N. Segal, K. Miu, H. Lehmann, T. Figura, “A Partitioning Method for Distributed Capacitor Control of Electric Power Distribution Systems,” *IEEE Transactions on Power System*s, Feb. 2014.

[2] M. Kleinberg and K. Miu, “A Study of Distributed Capacitor Control for Electric Power Distribution Systems,” Proc. of the North American Power Symposium, Boston, MA, Aug. 2011. *(Third Place - Best Student Paper Competition)*

[3] N. Segal, M. Kleinberg, A. Madonna, K. Miu, H. Lehmann, T. Figura, "Analytically Driven Capacitor Control for Voltage Spread Reduction," Proc. of the 2012 IEEE Power and Energy Society Transmission and Distribution Conference and Exposition, Orlando, FL, May 8, 2012.

[3] N. Segal and K. Miu, "An Investigation of Capacitor Control Actions for Voltage Spread Reduction in Distribution Systems," 2012 IEEE Power and Energy Society Transmission and Distribution Conference and Exposition, Student Poster Contest, May 9, 2012 *(2nd Place, Graduate Student Poster Competition)*

[4] K. Miu, N. Segal, M. Kleinberg, A. Madonna, H. Lehmann, T. Figura, "Analytically Driven Power Distribution Applications," 2011 IEEE Power and Energy Society General Meeting, Supersession - Smart Grid Analytics, Detroit, MI, July 2011

[5] S. Tong and K. N. Miu, “Slack Bus Modeling and Cost Analysis of Distributed Generator Installations,” ASCE Journal of Energy Engineering, Vol. 133, Iss. 3, Sept. 2007, pp. 111-120.

[6] S. Tong and K. N. Miu, “A Network-Based Distributed Slack Bus Model for DGs in Unbalanced Power Flow Studies”, IEEE Transactions on Power Systems, Vol. 20, No. 2, May 2005, pp. 835-842.

[7] V. Cecchi; X. Yang; K. Miu; C. Nwankpa; “Instrumentation and Measurement of a Power Distribution System Laboratory for Meter Placement and Network Reconfiguration Studies”, IEEE Transactions on Instrumentation and Measurement, Vol. 56, Iss. 4, Aug. 2007, pp. 1224 – 1230