Coordination and Control of Distributed Energy Resources for Provision of Ancillary Services

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D-G Group Research Overview

- Renewable Resources Integration
  - Impact of wind integration on system dynamic performance
  - Stochastic models of PV systems for quantification of reliability/energy-yield
- Health Monitoring and Fault Diagnosis of Electrical Energy Systems
  - Fault detection and isolation algorithms for FACTS devices
  - Health monitoring of micro-grids and other small-footprint power systems
- Reliability Models for Next Generation Electric Power Grids
  - Impacts of coupling between the system cyber and physical layers
  - Impacts of coupling between system dynamics and component stress
- Coordination and Control of Distributed Energy Resources
  - Distributed reactive power support for voltage control
  - Distributed energy storage for frequency and peak-shaving control

Outline

Outline

The Potential of Distributed Energy Resources (DERs)



- On the power grid, there exist many DERs that can be potentially used to provide ancillary services
- Power electronics grid interfaces commonly used in DERs can be utilized to provide reactive power support
  - Voltage control in subtransmission and distribution
- Plug-in-hybrid vehicles (PHEV) can be utilized for providing active power for up and down regulation
  - Energy peak-shaving during peak hours and load-leveling at night

Control and Coordination of DERs

- Proper coordination and control of these DERs is key for enabling their utilization for ancillary services
- One solution can be achieved through a centralized control strategy where each DER is commanded from a central controller
  - It is necessary to overlay a communication network connecting the central controller with each distributed resource
  - It requires knowledge of the distributed resources that are available on the distribution side at any given time
- We propose an alternative approach that utilizes distributed strategies for control and coordination of DERs
- These strategies offer several advantages, including the following
  - More economical as they do not require communication infrastructure between a centralized controller and the various devices
  - They do not require complete knowledge of the distributed resources available
  - Potentially more resilient to faults and/or unpredictable behavioral patterns by the distributed resources

Basic Setup

- The DERs can be thought of as nodes in a network, where each node can exchange information with neighboring nodes
- Through an iterative process with neighboring nodes (presumable nodes in close proximity)
  - Each DER in the network will compute the amount of active or reactive power that it needs to provide
- Collectively, the local control decisions made by the resources should have the same effect as the centralized control strategy (or, if multiple solutions are possible, be one of the feasible solutions)
- Such a solution could rely on inexpensive and simple communication protocols, e.g., ZigBee technology
- We discuss several algorithms to solve this coordination/cooperation problem under various conditions

Outline

Graph-Theoretic Notions

- The exchange of information between nodes where resources are located can be described by a directed graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$:
  - $\mathcal{V} = \{1, 2, \ldots, n\}$ is the vertex set (each vertex corresponds to a node)
  - $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of directed edges, where $(j, i) \in \mathcal{E}$ if node j can receive information from node i
- The graph is undirected if and only if whenever $(j, i) \in \mathcal{E}$, then also $(i, j) \in \mathcal{E}$, i.e., if node j can receive information from node i, then node i can also receive information from node j
- All nodes that can transmit information to node j are said to be neighbors of node j and are represented by the set $\mathcal{N}_j = \{i \in \mathcal{V} : (j, i) \in \mathcal{E}\}$
- The number of neighbors of j is called the in-degree of j and denoted by $\mathcal{D}_j^- = |\mathcal{N}_j|$
- The number of nodes that have j as neighbor, i.e., j can transmit information to these nodes, is called the out-degree of j and is denoted by $\mathcal{D}_j^+$
- In undirected graphs, $\mathcal{D}_j^- = \mathcal{D}_j^+$ for all nodes j

Distributed Algorithms Formulation

- Let $\pi_j[k]$ be the amount of active or reactive power demanded from the distributed resource located in node j at the k round of information exchange between nodes
- The proposed distributed algorithms determine the amount of resource that will be contributed by node j by performing linear iterations of the form

$$\pi_j[k+1] = p_{jj}[k]\pi_j[k] + \sum_{i \in \mathcal{N}_j} p_{ji}[k]\pi_i[k], \tag{1}$$

  where the $p_{ji}[k]$'s are a set of (potentially time-varying) weights, and $\pi_j[k]$'s are non-negative quantities
- Each node updates its demanded amount to be a linear combination of its own demanded amount and the demanded amount of its neighbors
- The choice of $p_{ji}[k]$'s will depend on the problem constraints
- We provide algorithms when
  - There is no limit on the amount of active or reactive power that each resource can provide
  - The maximum (or minimum) amount of active or reactive power each resource can provide is limited

Outline

The Basic Setup

- There is a leading node that knows the total amount of active or reactive power ρ_d that needs to be provided by the remaining n nodes
- This leader can communicate with $l \geq 1$ nodes, and initially sends a command demanding ρ_d/l units of active or reactive power from each of them
- Unless ρ_d changes, the leader will not subsequently communicate with the nodes
- Let $\pi_j[k]$ be the active or reactive power demanded from node j at step k, and define the corresponding active or reactive power demand vector as $\pi[k] = [\pi_1[k],\ \pi_2[k], \ldots, \pi_j[k], \ldots, \pi_n[k]]'$
- Define the collective active or reactive power demand as $\rho[k] = \sum_{j=1}^{n} \pi_j[k]$
- The objective is to design a distributed iterative algorithm that, at step k, updates the active or reactive power demand from node j based on
  - Its own current active or reactive power demand $\pi_j[k]$
  - Current active or reactive power demanded from neighbors of j

  such that after m steps the collective active or reactive power demand equals the total active or reactive power demanded by the leader: $\rho[m] = \sum_{j=1}^{n} \pi_j[m] = \rho_d$

Uneven Splitting Algorithm

- The simplest solution, which results in constant weights p_{ji}, is for each node j to equally split its current value among itself and the nodes that have j as neighbor

$$\pi_j[k+1] = \frac{1}{1+\mathcal{D}_j^+}\pi_j[k] + \sum_{i \in \mathcal{N}_j} \frac{1}{1+\mathcal{D}_i^+}\pi_i[k] \tag{2}$$

  where $\mathcal{D}_i^+$ the number of nodes that i can transmit information to (the out-degree of node i)

- Algorithm (2) does not necessarily split the total active or reactive power demand ρ_d evenly among all the nodes, but it ensures that $\sum_{j=1}^{N} \pi_j[k] = \rho_d, \ \forall k \geq 0$
- Provided the directed graph describing the exchanges between nodes has a single recurrent class, which necessarily makes it aperiodic by construction due to the fact that $\frac{1}{1+\mathcal{D}_j^+} \neq 0$, the steady state solution provided by (2) is unique

Sketch of Convergence Proof

- The splitting algorithm (2) can be rewritten in matrix form as

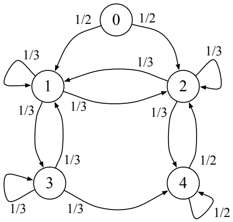
$$\begin{aligned} \pi[k+1] &= P_c \pi[k], \\ \pi[0] &= \pi_0, \end{aligned} \tag{3}$$

  where $\pi_0 = [\pi_1[0],\ \pi_2[0], \ldots, \pi_j[0], \ldots, \pi_n[0]]'$ with $\pi_i[0] = \rho_d / l$ if i is a neighbor of the leader node and $\pi_i[0] = 0$ otherwise
- By construction, matrix P_c is column stochastic and also primitive
- The Perron-Frobenius theorem for non-negative matrices states that P_c has a unique eigenvalue with largest modulus at $\lambda_1 = 1$
- Let x be a right eigenvector of P_c associated with λ_1 and let y be a left eigenvector of P_c associated with λ_1 such that $x'y = 1$
- Again, from the fact that P_c is column stochastic, the entries of vector y must be all equal
- Without loss of generality, let $y = [1, 1, \ldots, 1]'$, and since $x'y = 1$, the entries of x must add up to one
- Then the steady-state solution of (3) is given by

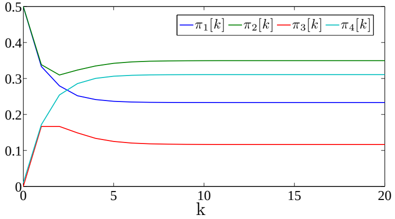
$$\pi^{ss} = xy'\pi_0 = (\sum_{j=1}^{N} \pi_j[0])x. \tag{4}$$

- Since $\sum_{j=1}^{N} \pi_j[0] = \rho_d$ and the entries of x are nonnegative and add up to one, it follows that entries of π^{ss} are nonnegative and add up to ρ_d

Uneven Splitting Example



(a) Network topology.



(b) Node demanded capacity evolution.

Figure: Four-node network implementing uneven splitting strategy.

- The leader initially splits $\rho_d = 1$ in half and passes it to nodes 1 and 2.
- Each node updates its value as follows

$$\begin{aligned}
\pi_1[k+1] &= \tfrac{1}{3}(\pi_1[k] + \pi_2[k] + \pi_3[k]), \\
\pi_2[k+1] &= \tfrac{1}{3}(\pi_1[k] + \pi_2[k]) + \tfrac{1}{2}\pi_4[k], \\
\pi_3[k+1] &= \tfrac{1}{3}(\pi_1[k] + \pi_3[k]), \\
\pi_4[k+1] &= \tfrac{1}{3}(\pi_2[k] + \pi_3[k]) + \tfrac{1}{2}\pi_4[k],
\end{aligned} \tag{5}$$

  with $\pi_1[0] = \pi_2[0] = 1/2$, and $\pi_3[0] = \pi_4[0] = 0$.
- The steady-state solution is given by $\pi^{ss} = [0.23,\ 0.35,\ 0.11,\ 0.31]'$

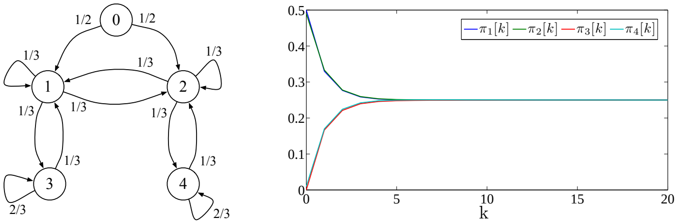
Even Splitting Algorithm

- A solution to reach even splitting can be easily obtained when $\sum_{i=1}^{n} p_{ji} = \sum_{i=1}^{n} p_{ij} = 1$ for all $j = 1, 2, \ldots, n$
- The simplest realization of such algorithm is obtained when the graph describing the exchanges of information is undirected, which results in $\mathcal{D}_j^- = \mathcal{D}_j^+ := \mathcal{D}_j, \ \forall j = 1, \ldots, n$
- Define the maximum degree of the network as $\mathcal{D} = \max_j \{\mathcal{D}_j\}$
- One way even splitting can be achieved is by having each node j update its value as follows

$$\pi_j[k+1] = (1 - \frac{|\mathcal{N}_j|}{1+\mathcal{D}})\pi_j[k] + \sum_{i \in \mathcal{N}_j} \frac{1}{1+\mathcal{D}} \pi_i[k], \tag{6}$$

  where $|\mathcal{N}_j| = \mathcal{D}_j^+$ denotes the number of elements in the set $\mathcal{N}_j$
- Even splitting can also be achieved if instead of $\mathcal{D}$, we use any upper bound $\mathcal{D}' \geq \mathcal{D}$ in (6)

Even Splitting Example



(a) Network topology. (b) Node demanded capacity evolution.

Figure: Four-node network implementing even splitting strategy.

- Each node updates its value as follows

$$\begin{aligned}
\pi_1[k+1] &= \tfrac{1}{3}(\pi_1[k] + \pi_2[k] + \pi_3[k]), \\
\pi_2[k+1] &= \tfrac{1}{3}(\pi_1[k] + \pi_2[k]) + \tfrac{1}{2}\pi_4[k], \\
\pi_3[k+1] &= \tfrac{1}{3}\pi_1[k] + \tfrac{1}{3}\pi_3[k], \\
\pi_4[k+1] &= \tfrac{1}{3}\pi_2[k] + \tfrac{2}{3}\pi_4[k],
\end{aligned} \tag{7}$$

  with $\pi_1[0] = \pi_2[0] = 1/2$, and $\pi_3[0] = \pi_4[0] = 0$.
- The steady-state solution is $\pi^{ss} = [0.25,\ 0.25,\ 0.25,\ 0.25]'$
- The key is that the corresponding transition matrix is doubly stochastic

Outline

The Setup

- We now address the case where nodes have limits on the amounts of active or reactive power they can provide
- Let π_j^{max}, for $j = 1, 2, \ldots, n$, be the maximum active or reactive power that node j can provide (its maximum capacity)
- Define the corresponding maximum active or reactive power capacity vector as $\pi^{max} = [\pi_1^{max},\ \pi_2^{max}, \ldots, \pi_n^{max}]'$.
- Let $\rho[k] = \sum_{j=1}^{n} \pi_j[k]$ be the collective active or reactive power capacity demanded from the nodes at instant k, and ρ_d be the collective active or reactive power demand.
  - We assume that $\rho_d \leq \sum_{j=1}^{n} \pi_j^{max} := \chi^{max}$
- The objective is to design a distributed iterative algorithm that, at step k, updates the active or reactive power demanded from node j based on
  - Current active or reactive power demand $\pi_j[k]$
  - Current active or reactive power demanded by neighbors of j

  such that after m steps:
  - $\pi_j[m]$ reaches a steady state value $\pi_j^s \leq \pi_j^{max}, \forall j$
  - $\sum_{j=1}^{n} \pi_j^{ss} = \rho_d \leq \chi^{max}$

Fair Splitting Algorithm

- A simple solution to the constrained problem can be obtained if each node could compute (or knows) the ratio ρ_d/χ^{max}
- Then, the total active or reactive power demand can be collectively provided by having each node j provide

$$\pi_j := \frac{\rho_d}{\chi^{max}}\pi_j^{max} \leq \pi_j^{max} \tag{8}$$

- This can be achieved if the nodes run twice (with appropriate initial conditions) the following algorithm

$$\pi_j[k+1] = \frac{1}{1+\mathcal{D}_j^+}\pi_j[k] + \sum_{i \in \mathcal{N}_j} \frac{1}{1+\mathcal{D}_i^+}\pi_i[k]. \tag{9}$$

- Let $\hat{\pi}[k]$ denote the solution to (9) achieved with initial conditions set to initially demanded capacity
- Let $\check{\pi}[k]$ denote the solution to (9) achieved with initial conditions set to maximum capacities
- At each iteration step, each node j computes

$$\pi_j[k] = \frac{\hat{\pi}_j[k]}{\check{\pi}_j[k]}\pi_j^{max} \tag{10}$$

- Then

$$\lim_{k\to\infty} \pi_j[k] = \lim_{k\to\infty} \frac{\hat{\pi}_j[k]}{\check{\pi}_j[k]}\pi_j^{max} = \frac{\rho_d}{\chi^{max}}\pi_j^{max} = \pi_j \tag{11}$$

Sketch of Convergence Proof

- As before, the linear iteration in (9) can be rewritten in matrix form as

$$\pi[k+1] = P_c \pi[k], \tag{12}$$

- By construction, matrix P_c is column stochastic and also primitive (assuming the graph is strongly connected)
- Since P_c is column stochastic, it follows that

$$\textstyle\sum_{j=1}^{N} \hat{\pi}_j[k] = \rho_d, \quad \sum_{j=1}^{N} \check{\pi}_j[k] = \chi_{max}, \ \forall k. \tag{13}$$

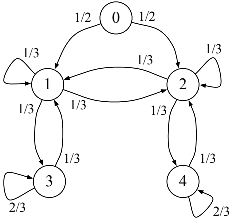
- Since P_c is primitive, Perron-Frobenius ensures that $\hat{\pi}_j^{ss} := \lim_{k\to\infty} \hat{\pi}_j[k] = \alpha \lim_{k\to\infty} \check{\pi}_j[k] =: \alpha \check{\pi}_j^{ss}$, $\forall j$, for some $\alpha > 0$
- Thus, $\rho_d = \sum_{j=1}^{N} \hat{\pi}_j^{ss} = \alpha \sum_{j=1}^{N} \check{\pi}_j^{ss} = \alpha \chi_{max}$, and therefore

$$\alpha = \frac{\rho_d}{\chi^{max}}. \tag{14}$$

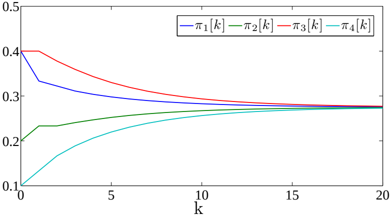
- Then, the contribution $\pi[k]$ of each will asymptotically converge to the desired value π_j

$$\pi[k] = \lim_{k\to\infty} \frac{\hat{\pi}_j[k]}{\check{\pi}_j[k]} \pi_j^{max} = \frac{\hat{\pi}_j^{ss}}{\check{\pi}_j^{ss}} \pi_j^{max} = \alpha \pi_j^{max} = \frac{\rho_d}{\chi^{max}} \pi_j^{max} = \pi_j. \tag{15}$$

Fair Splitting Example



(a) Network topology.



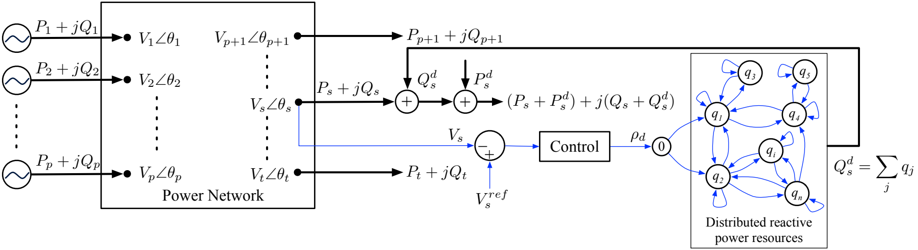
(b) Evolution of $\check{\pi}_j$ in the algorithm second run.

Figure: Four-node network implementing even splitting strategy.

- Take $\rho_d = 1$ and $\pi^{max} = [0.4,\ 0.2,\ 0.4,\ 0.1]$ so that $\chi^{max} = 1.1 > \rho_d$
- Each node runs twice (in parallel) the same algorithm used in the even splitting example
  - For the first run, initial conditions are $\hat{\pi}[0] = [0.5, 0.5, 0, 0]'$
  - For the second run, initial conditions are $\check{\pi}[0] = \pi^{max} = [0.4,\ 0.2,\ 0.4,\ 0.1]'$
- The solution of the first run is equivalent to the solution of the even splitting algorithm example, i.e., each node computes $\rho_d/4 = 0.25$
- On the second run, each node computes $\sum_{j=1}^{4} \pi_j^{max}/4 = 0.275$
- The contributions are $\pi = \alpha[0.4,\ 0.2,\ 0.4,\ 0.1]'$, where $\alpha = 0.25/0.275$

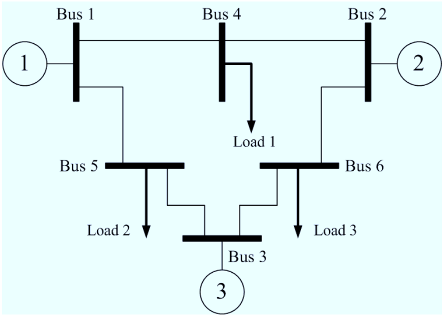
Outline

Reactive Power Support



- Operational conditions require the voltage at bus s of the electrical network to be maintained at a reference voltage V_s^{ref}
- In order to achieve this requirement, we control the total reactive power demand at bus s, which is given by $Q_s + Q_s^d$, where
  - Q_s is the reactive power injected in bus s provided by the network, and
  - Q_s^d is the reactive power injected in bus s provided by DERs
- By controlling Q_s^d, the total demand of reactive power at bus s can be effectively controlled

WECC 3-machine 6-bus system



From	To	R	X
1	4	0	0.0720
2	4	0	0.1008
1	5	0	0.1610
2	6	0	0.1700
3	5	0	0.0850
3	6	0	0.0920

- We implement two control architectures:
  - All load buses can provide reactive power through coordination of DERs
  - Only bus 6 can provide reactive power through coordination of DERs
- For each of the architectures, we implement distributed coordination algorithms with and without constraints on DER capacity
  - For simplicity, we assume the same DER network with four nodes showed in previous slides
- We compare the performance of control architectures and distributed algorithms for a contingency in generator 2

Base Case: No Reactive Power Support

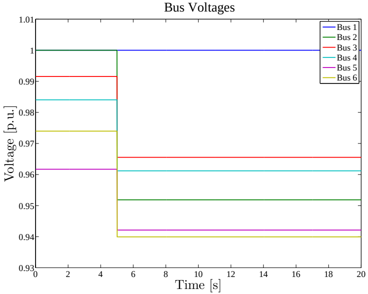


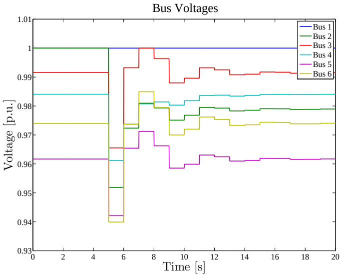
Figure: Voltages before and after contingency.

Bus #	P_g	Q_g	P_L	Q_L
1	1.5840	0.5388	0	0
2	0.8500	0.3458	0	0
3	0.7160	0.5500	0	0
4	0	0	1.00	0.35
5	0	0	1.25	0.50
6	0	0	0.90	0.30

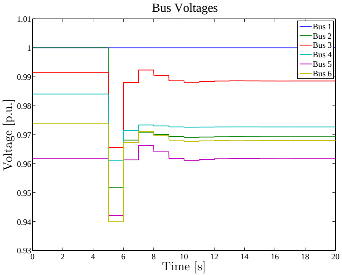
Table: Pre-contingency power flow solution

- Prior to contingency: Generator 5 is at maximum capacity
- After contingency:
  - Generator 5 becomes a PQ bus, and Generator 1 picks up all the reactive power demand
  - Voltages on buses 5 and 6 fall outside $\pm 5\%$ of the nominal value (1 p.u.)

Voltage Control on All Load Buses



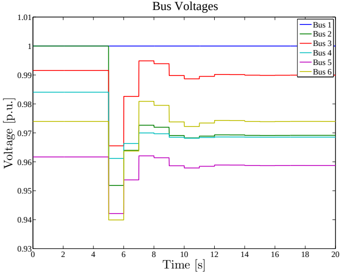
(a) Unconstrained capacity.



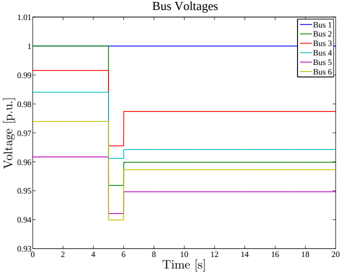
(b) Constrained capacity.

- With no constraints on DERs (unrealistic), system voltage profile is recovered in 10s
- With constrains on DERs reactive power, system voltage profile is recovered to acceptable limits
  - Voltags on all buses are within $\pm 5\%$ of the nominal value (1 p.u.)

Voltage Control on Load Bus 6



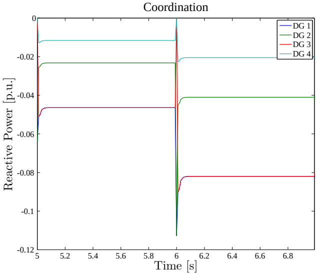
(c) Unconstrained capacity.



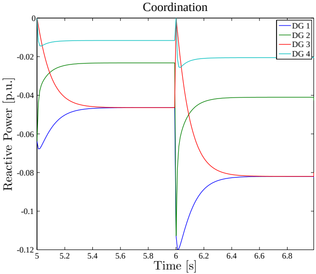
(d) Constrained capacity.

- Through sensitivity analysis, it can be shown that bus 6 voltage is the most sensitive to loss of generator 2
  - DER-based reactive power support is only available in this bus
- With no constraints on DERs
  - Voltages on buses 3, 5, and 6 are very close to pre-contingency values
  - Voltages on buses 2 and 4 are restored to values within $\pm 5\%$ of the nominal value (1 p.u.)
- With constraints on DERs
  - All bus Voltages are restored to values within $\pm 5\%$ of the nominal value (1 p.u.)

Distributed Algorithm Performance



(e) Non-Adapative Fair Splitting Algorithm.



(f) Adapative Fair Splitting Algorithm.

- The non-adaptive algorithm converges much faster than the adaptive algorithm (not discussed in the presentation)
- Both algorithms converge fast enough so the effect on the system is not noticeable
  - The adaptive algorithm has advantages if the DER network topology changes
- For larger DER networks, convergence speed of the distributed algorithms might play an important role
  - Careful analysis will be needed to justify the algorithm chosen

Outline

Summary and Path Ahead

- We have presented distributed control algorithms that can be used to determine (in a distributed fashion) the amount of active or reactive power that needs to be provided by distributed active and reactive power resources
- These strategies have the potential to enable assets already present in distribution systems as active and reactive power support resources
- We showed how these algorithms can be used to provide reactive power support for voltage control
- Ongoing work is investigating convergence speed issues in different algorithms for the constrained case
- Ongoing work is conducting case studies in larger networks, including distribution networks
- Further work will investigate the algorithms performance in the presence of faults, e.g., broken communication links, and nodes not updating their value