SunShot
U.S. Department of Energy

Challenges for Solar Distribution Planning and Operations Workshop

AGENT-BASED COORDINATION SCHEME FOR PV INTEGRATION (ABC4PV)

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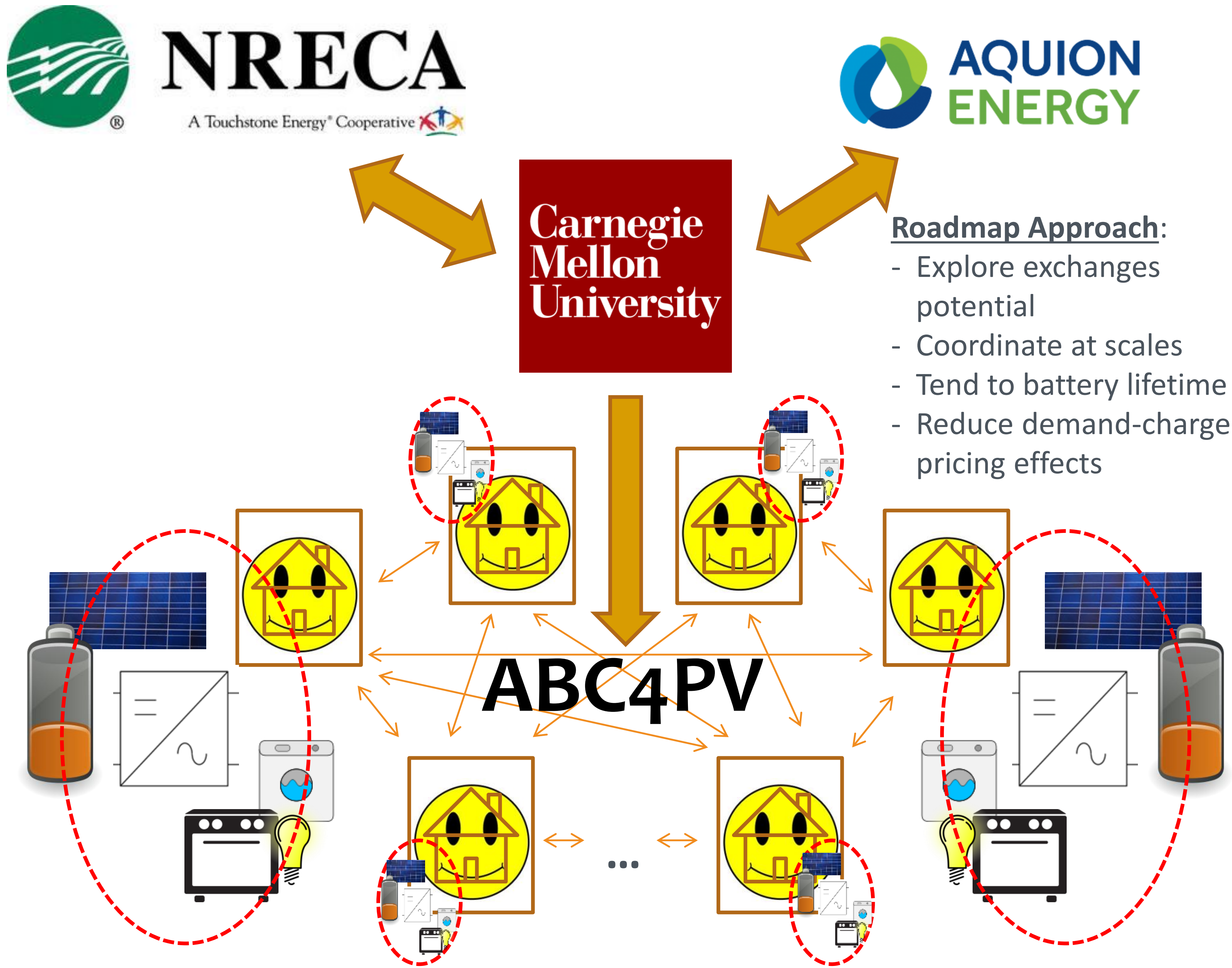
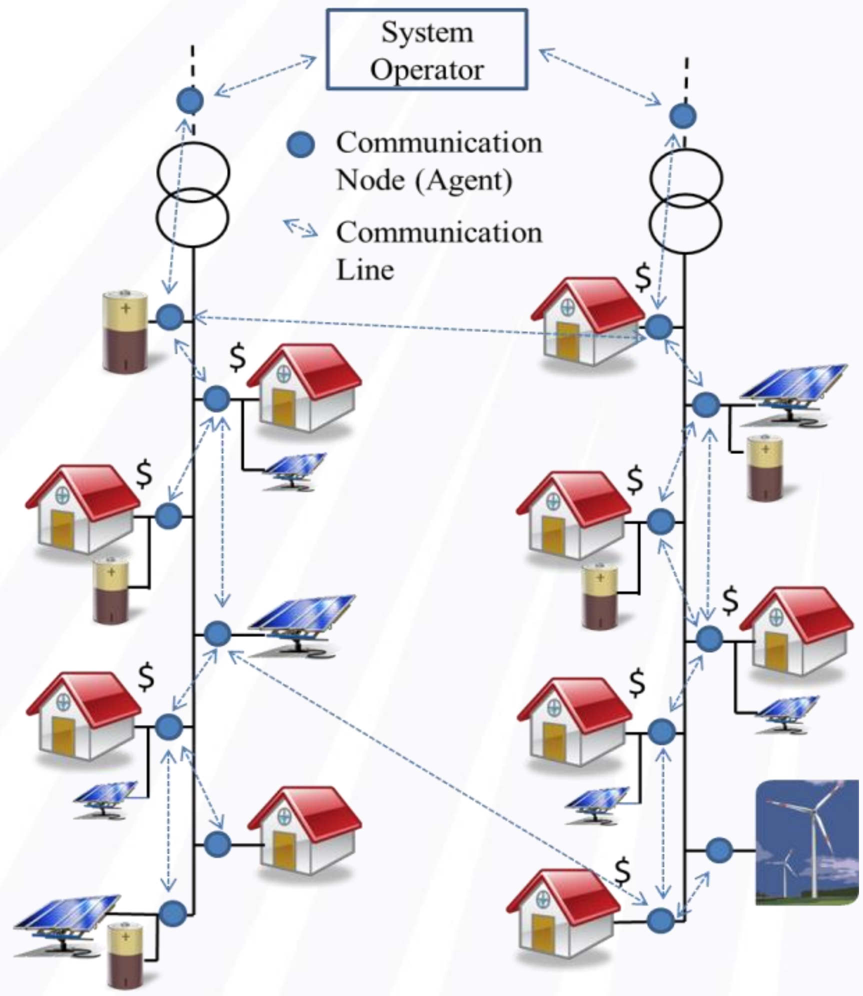
Overview

- ABC4PV main idea and objectives
- Focusing on Consensus+Innovation (C+I) framework
- What was the case for C+I before ABC4PV
- What was achieved for C+I through the ABC4PV


NRECA
A Touchstone Energy® Cooperative
AQUION ENERGY
Carnegie Mellon University
Roadmap Approach:
- Explore exchanges potential
- Coordinate at scales
- Tend to battery lifetime
- Reduce demand-charge pricing effects
ABC4PV
...

Approach: Inter-unit collaboration

- Agent-based distributed algorithm:
  - Units communicate and share information
  - Communication with system operator possible, not required
  - Computations carried out locally



Approach: Distributed optimization framework

- Form of updates (based on the Lagrangian multipliers and slack vars)
  - Mathematical formulation based on consensus + innovation approach:

$$\lambda_j^{(i+1)} = \lambda_j^{(i)} - \underbrace{\beta_i \sum_{l \in \omega_j} \left(\lambda_j^{(i)} - \lambda_l^{(i)} \right)}_{consensus} - \underbrace{\alpha_i \hat{d}_j^{(i)}}_{innovation}$$

where λ is the consensus variable and innovation term ensures

$$\sum_{j=1}^{J} \hat{d}_j(\lambda_j) = 0,$$

Considered Application:
- Consensus ensures cost optimality
- Innovation fulfills power balance & equipment constraints

⇒ Low computational effort required

What is Consensus?

- Think of Gossip, but reliable…
- Gossip = exchange of info at small scale of interaction
- Reliable = minimum info exchange
- Required to agree on a common value across stakeholders, e.g. marginal price of generation

<u>Example</u>:

20 players are dealt each one card from a 21-cards deck. Which card wasn't dealt to any of the players?

Why do we need Innovation?

- Innovation terms are the derivatives of the Lagrangian with respect to the updated variable
- Unless they become constant, there is no convergence
- All updates include innovation terms, but not all include consensus term

ABC4PV problem formulation

minimize $\sum_{i \in g} C(P_{g,i})$

s.t. $P_{g,i} - P_{l,i} = \sum_{j \in NBi} (g_{ij} - b_{ij}) \cdot (\theta_i - \theta_j)$

$$Q_{g,i} - Q_{l,i} = \sum_{j \in NBi} \left[(\theta_i - \theta_j) \cdot \left(\frac{g_{ij}^2}{b_{ij}} - g_{ij} \right) + \frac{|v_i|}{b_{ij}} \left(-g_{ij}^2 - b_{ij}^2 \right) + \frac{|v_j|}{b_{ij}} \cdot \left(g_{ij}^2 + b_{ij}^2 \right) \right]$$

$$P_{g,i,m} \le P_{g,i} \le P_{g,i,M} \quad \& \quad Q_{g,i,m} \le Q_{g,i} \le Q_{g,i,M}$$

$$|v_{i,m}| \le |v_i| \le |v_{i,M}|$$

$$(g_{ij} - b_{ij})^2 \cdot (\theta_i - \theta_j)^2 + \left[(\theta_i - \theta_j) \cdot \left(\frac{g_{ij}^2}{b_{ij}} - g_{ij} \right) + \frac{|v_i|}{b_{ij}} \left(-g_{ij}^2 - b_{ij}^2 \right) + \frac{|v_j|}{b_{ij}} \cdot \left(g_{ij}^2 + b_{ij}^2 \right) \right]^2 \le S_{ij,M}^2 \quad *$$

*can be easily expressed linearly

COPF approximation formulation in the C+I f/w (1/2)

$$L = \sum_{i\in g} C\left(P_{g,i}\right) + \sum_{i\in B} \lambda_i \cdot \left[-P_{g,i} + P_{l,i} + \sum_{j\in NBi} \left(g_{ij} - b_{ij}\right)\cdot(\theta_i - \theta_j) \right] +$$

$$+ \sum_{i\in B} \mu_i \cdot \left\{ -Q_{g,i} + Q_{l,i} + \sum_{j\in NBi} \left[(\theta_i - \theta_j)\cdot\left(\frac{g_{ij}^2}{b_{ij}} - g_{ij}\right) + \frac{|v_i|}{b_{ij}}\left(-g_{ij}^2 - b_{ij}^2\right) + \frac{|v_j|}{b_{ij}}\cdot\left(g_{ij}^2 + b_{ij}^2\right) \right] \right\} +$$

$$+ \sum_{i\in g} u_{P,i} \cdot \left(P_{g,i} - P_{g,i,M} + T_{P,i}^2\right) + \sum_{i\in g} l_{P,i} \cdot \left(-P_{g,i} + P_{g,i,m} + K_{P,i}^2\right) +$$

$$+ \sum_{i\in g} u_{Q,i} \cdot \left(Q_{g,i} - Q_{g,i,M} + T_{Q,i}^2\right) + \sum_{i\in g} l_{Q,i} \cdot \left(-Q_{g,i} + Q_{g,i,m} + K_{Q,i}^2\right) +$$

$$+ \sum_{i\in B} u_{V,i} \cdot \left(V_i - V_{i,M} + T_{V,i}^2\right) + \sum_{i\in B} l_{V,i} \cdot \left(-V_i + V_{V,i,m} + K_{V,i}^2\right) +$$

$$+ \sum_{i\in B} \sum_{j\in NBi} u_{\ln,ij} \left\{ \left(g_{ij} - b_{ij}\right)^2 \cdot (\theta_i - \theta_j)^2 + \right.$$

$$\left. + \left[(\theta_i - \theta_j)\cdot\left(\frac{g_{ij}^2}{b_{ij}} - g_{ij}\right) + \frac{|v_i|}{b_{ij}}\left(-g_{ij}^2 - b_{ij}^2\right) + \frac{|v_j|}{b_{ij}}\cdot\left(g_{ij}^2 + b_{ij}^2\right) \right]^2 - S_{ij,M}^2 + T_{l,ij}^2 \right\}$$

COPF approximation formulation in the C+I f/w (2/2)

$$\lambda_i(k+1) = \lambda_i(k) - \beta_\lambda \frac{\partial L}{\partial \theta_i} - \alpha_\lambda \frac{\partial L}{\partial \lambda_i}$$

$$\mu_i(k+1) = \mu_i(k) - \beta_\mu \frac{\partial L}{\partial |v_i|} - \alpha_\mu \frac{\partial L}{\partial \mu_i}$$

$$\theta_i(k+1) = \theta_i(k) + \beta_\theta \frac{\partial L}{\partial \lambda_i}$$

$$|v_i(k+1)| = \text{₱}\left(|v_i(k)| + \beta_V \frac{\partial L}{\partial \mu_i} \right)$$

$$P_{g,i}(k+1) = \text{₱}\left(P_{g,i}(k) - \alpha_P \cdot \left(\frac{\partial C(P_{g,i})}{\partial P_{g,i}} - \lambda_i(k+1) \right) \right) = \text{₱}\left(P_{g,i}(k) - \alpha_P \cdot \left(2 \cdot a_g \cdot P_{g,i} + b_g - \lambda_i(k+1) \right) \right)$$

$$Q_{g,i}(k+1) = \text{₱}\left(Q_{g,i}(k) + \alpha_Q \cdot \mu_i(k+1) \right)$$

$$u_{|v|,i}(k+1) = \text{₱}\left(u_{|v|,i}(k) + \beta_{|v|}\left(|v_i| - |v_{i,M}| \right) \right)$$

$$l_{|v|,i}(k+1) = \text{₱}\left(l_{|v|,i}(k) + \beta_{|v|}\left(-|v_i| + |v_{i,m}| \right) \right)$$

$$u_{\ln,ij}(k+1) = \text{₱}\left(u_{\ln,ij}(k) + \beta_{\ln} \frac{\partial L}{\partial u_{\ln,ij}} \right)$$

Proof of convergence of the C+I – Why?

- Ensures that a control set-point exists under ALL operating conditions
- If the control set-point is fixed, there is insight about the nature of the fixed point => Optimal in our case
- Convergence affects the cyber-security assessment of the tool
- Before the ABC4PV, convergence was proved only for the unconstrained DC OPF formulation… The one at hand is an "alternative" of the decoupled OPF

Proof of convergence of the ABC4PV C+I (1/2)

- Iteration Matrix (excl. ineq. constr.)

$$G_{itr} = \begin{bmatrix} \lambda_1 & \lambda_2 & 0 & \lambda_3 & \lambda_4 & 0 \\ 0 & \mu_1 & \mu_2 & \mu_3 & 0 & \mu_4 \\ 0 & 0 & v_1 & v_2 & 0 & v_3 \\ 0 & 0 & 0 & \theta_1 & \theta_2 & 0 \\ p_1 & 0 & 0 & 0 & p_2 & 0 \\ 0 & q_1 & 0 & 0 & 0 & q_2 \end{bmatrix}$$

- *P* and *Q* are monotonic sequences =>

$$\begin{bmatrix} \lambda_1 & \lambda_2 & 0 & 0 \\ 0 & \mu_1 & \mu_2 & \mu_3 \\ 0 & 0 & v_1 & v_2 \\ 0 & 0 & 0 & \theta_1 \end{bmatrix}$$

- Convergence conditions (***ρ***<1) properly met
- Updates of the power quality & line limit constraints

$$u_{|v|,i}(k+1) = \mathbb{P}\left(u_{|v|,i}(k) + \beta_{|v|}\left(|v_i| - |v_{i,M}|\right)\right)$$

i.e. persistent unitary eigenvalues (non-convergent in this context)

Proof of convergence of the ABC4PV C+I (2/2)

- Rewriting the updates in the lagrangian form

$$u_{|v|,i}(k+1) = \mathbb{P}\left(u_{|v|,i}(k) + \beta_{|v|} \frac{\partial L}{\partial u_{|v|,i}} \right)$$

- Of the gradient descent form
- Convergent to a fixed point if properly bounded

QED.

Improving Rate of ABC4PV COPF Convergence - Heuristic

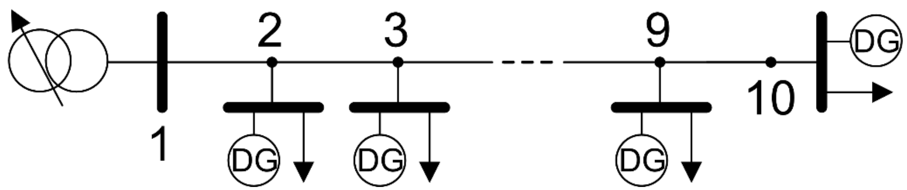
- Algorithm:

  (for the part of the iteration matrix with non-unitary eigenvalues)

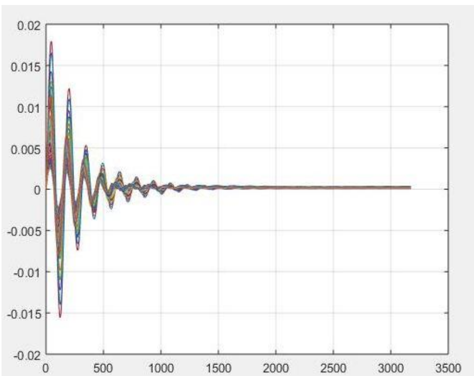
$$G_{itop} = \begin{bmatrix} \lambda_1 & \lambda_2 & 0 & \lambda_3 & \lambda_4 \\ 0 & \mu_1 & \mu_2 & \mu_3 & 0 \\ 0 & 0 & v_1 & v_2 & 0 \\ 0 & 0 & 0 & \theta_1 & \theta_2 \\ p_1 & 0 & 0 & 0 & p_2 \end{bmatrix}$$

  - Step 1: for all α_x & β_x determine min/max value for convergence
  - Step 2: for all α_x β_x exhaustively explore between min/max values of convergence
  - Step 3: for all α_x β_x not in G_{itop} , set minimum α_x β_x from Step 2

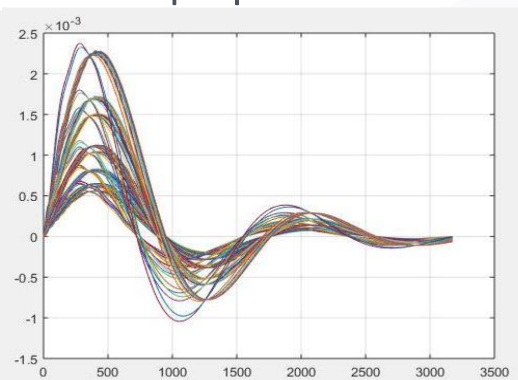
Rate of Convergence Assessment (10-bus system)



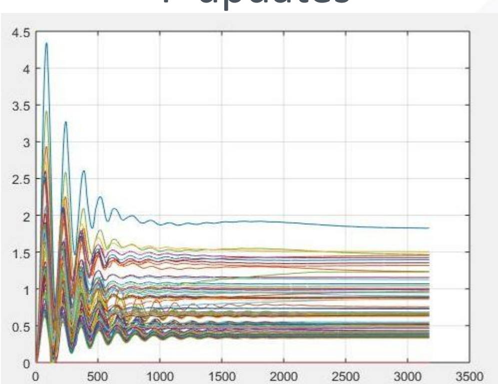
λ updates



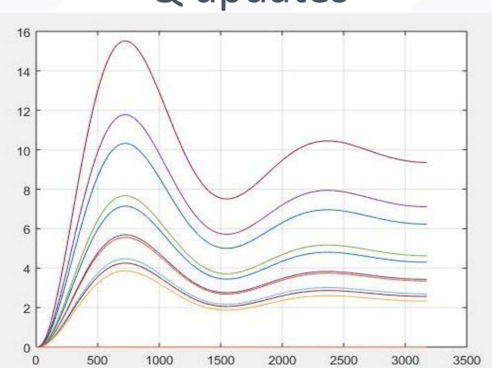
μ updates



P updates



Q updates



Bus	$P_{load,n}$ (kW)	$P_{DG,n}$ (kW)	BusK	BusL	Type	Length (m)
2	500	130	1	2	ACSR-95	1000
3	200	50	2	3	ACSR-95	5000
4	500	130	3	4	ACSR-95	1000
5	300	75	4	5	ACSR-95	500
6	100	25	5	6	ACSR-95	1000
7	200	50	6	7	ACSR-95	500
8	300	75	7	8	ACSR-95	1000
9	500	130	8	9	ACSR-95	500
10	200	50	9	10	ACSR-95	1000

DG f/c Error Intl	Convergence time (s)
±10%	0.9688±0.9588
±20%	0.8954±0.4638
±30%	1.2313±0.5601
±40%	1.3811±0.4382
±50%	1.5283±0.5044

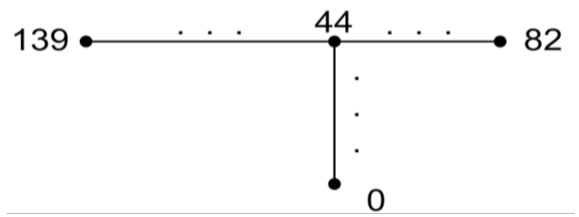
Load f/c Error Intl	Convergence time (s)
±10%	0.9792±0.4318
±20%	1.5562±0.6775

No DG units w/ random	Convergence time (s)
3	0.0245±0.0134
6	0.0456±0.0228
12	0.0300±0.0156
24	0.0048±0.0077
48	0.3344±0.3068
96	1.1879±0.4956
192	2.0577±1.0573

No of loads w/ random	Convergence time (s)
3	0.4234±0.0760
6	0.6920±0.0641
12	1.0727±0.0510
24	1.5146±0.0855
48	2.3048±0.5754

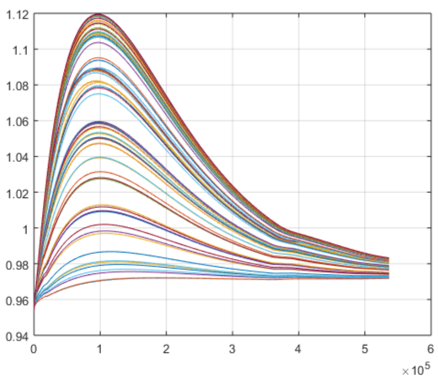
Left: cold start, Left: hot start

Rate of Convergence Assessment (Ikaria R-21 feeder)

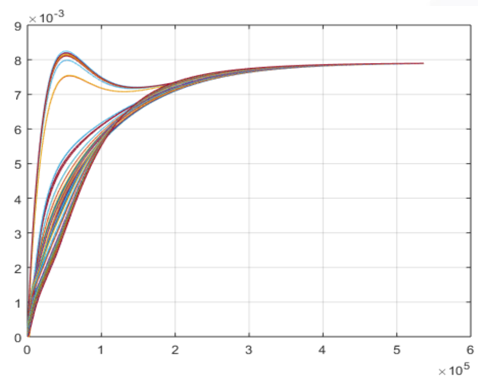


55 load/DG buses

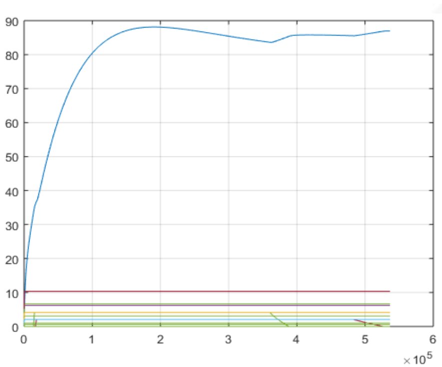
λ updates



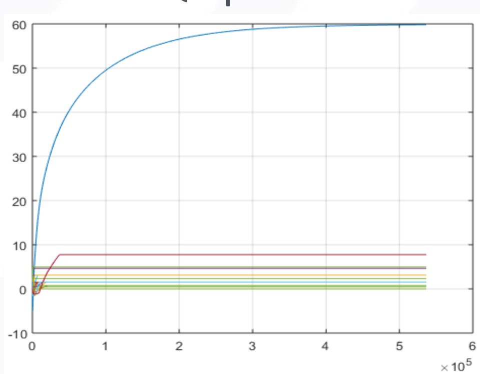
μ updates



P updates



Q updates



DG f/c Error Intl	Convergence time (s)
±10%	0.1203±0.0015
±20%	2.1362±6.0266

Load f/c Error Intl	Convergence time (s)
±10%	3.3830±7.5155

No DG units w/ random	Convergence time (s)
3	0.0808±0.0007
6	0.0945±0.0005
12	0.1040±0.0002
24	0.1084±0.0002
48	0.1115±0.0007
96	0.1620±0.0640
192	0.7121±1.3419

No of loads w/ random	Convergence time (s)
3	0.0791±0.1035
6	0.0755±0.0802
12	0.0904±0.0881
24	0.2444±0.5699
48	0.7432±1.9187

Left: cold start, Right: hot start

Concerns for Path forward

- C+I for convexified formulations?
- Explicit method optimizing acceleration parameters?
- Any concern/thought you would like to add?

Questions?