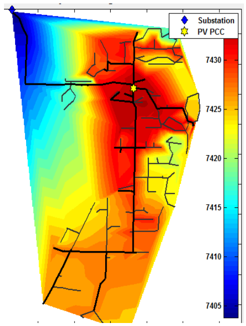
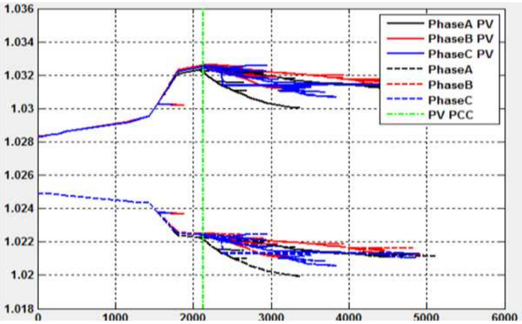
SAND2014-4865C





Evaluation of Reactive Power Control Capabilities of Residential PV in an Unbalanced Distribution Feeder

John Seuss[1], Matthew J. Reno[1,2], Robert J. Broderick[2], and Ronald Harley[1]

[1] Georgia Institute of Technology [2] Sandia National Laboratories

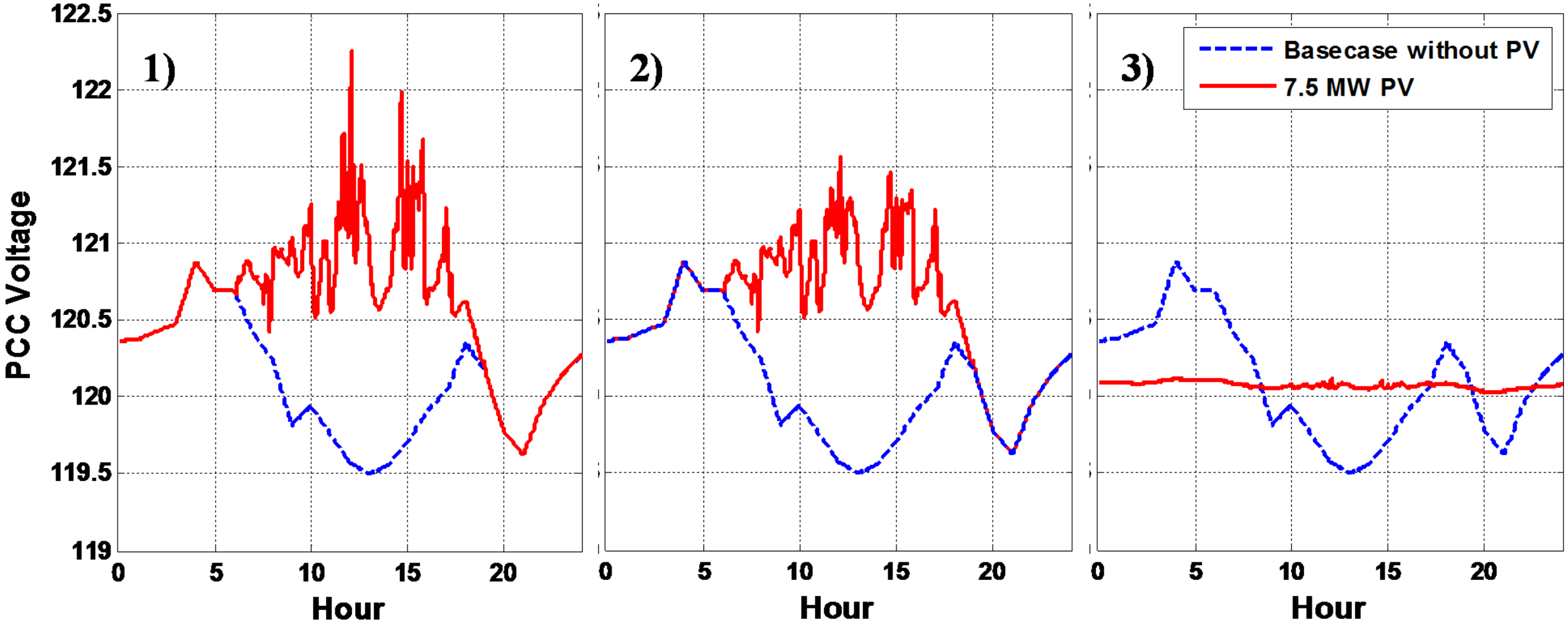
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2013-XXXXP

Outline

- Introduction
- Optimal dispatch of reactive power
- Results
- Analysis
- Conclusions / Future Work

Motivation for Work

- Voltage violations on distribution feeders due to large scale PV deployment is becoming a problem
  - PV inverter reactive power can help mitigate this



- What is the capability of PVs to perform voltage regulation?

Optimization Problem

- The general formulation of the problem is:

$$\min_{\boldsymbol{u}} J(\boldsymbol{x},\boldsymbol{u}) = w_1 \sum_{i=1}^{n} (V_i - V^*)^2$$

$$s.t. \quad \boldsymbol{G}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{d}) = 0$$

$$|u_i| \leq q_i^{g,max}(t)$$

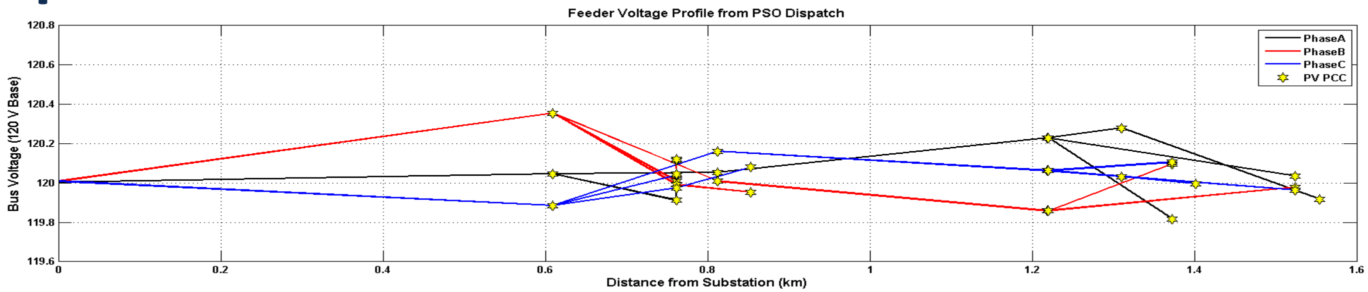
Losses term is needed for uniqueness of solution

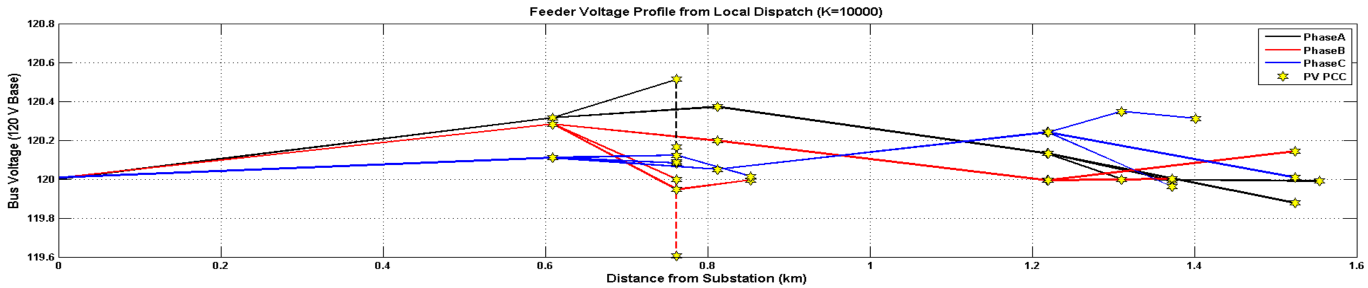
$$L_j = r_j |I_j|^2$$

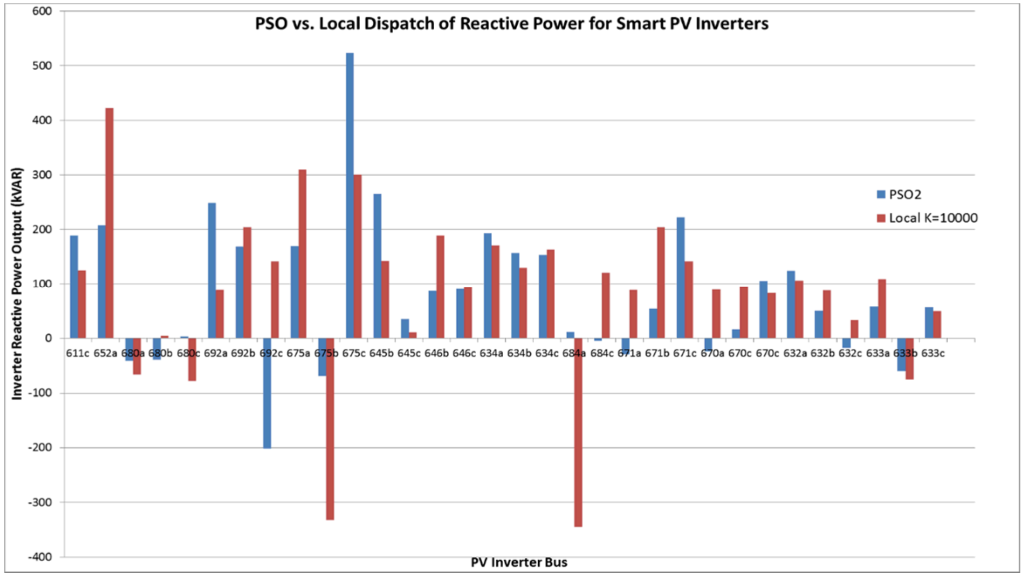
- Some key assumptions:
  - Unbalanced, three-phase feeder
  - No inverter power factor limitations
  - Watt priority control:

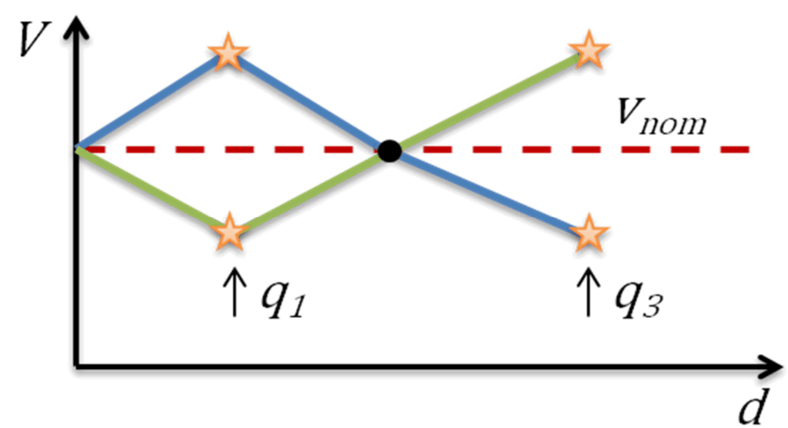
$$p_i^g(t) = S_i^{rated} I(t) \qquad q_i^{g,max}(t) = \sqrt{\left(S_i^{rated}\right)^2 - \left(p_i^g(t)\right)^2}$$

Uniqueness of Solution









Nonlinear Solution

- Solution via PSO algorithm:

$$\boldsymbol{u}_i(k) = \boldsymbol{u}_i(k-1) + \boldsymbol{v}_i(k)$$

$$\boldsymbol{v}_i(k) = \gamma \boldsymbol{v}_i(k-1) + \varphi_1 rand_1[\boldsymbol{p_i}(k) - \boldsymbol{u}_i(k-1)] + \varphi_2 rand_2[\boldsymbol{g}(\boldsymbol{k}) - \boldsymbol{u}_i(k-1)]$$

$$\boldsymbol{p_i}(k) = \operatorname{argmin}\left(\tilde{J}\Big|_{\boldsymbol{u_i}}\right), \forall k \quad \boldsymbol{g}(k) = \operatorname{argmin}(\boldsymbol{p}_i), \forall k$$

- To handle inequality constraints:

$$\min_{\boldsymbol{u}} \tilde{J}(\boldsymbol{x}, \boldsymbol{u}) = J(\boldsymbol{x}, \boldsymbol{u}) + \rho \sum_{k}^{p} \varphi_k(u_k)$$

$$\varphi_j(u_j) = \begin{cases} 0, & |u_j| \le q_j^{g,max}(t) \\ \mu + \dfrac{|u_j|}{q_j^{g,max}(t)}, & otherwise \end{cases}$$

Linearized Solution

- $G(\boldsymbol{x}, \boldsymbol{u})$ can be linearly approximated:

$$P_{j+1} = P_j + \Delta p_{j+1}$$
$$Q_{j+1} = Q_j + q_{j+1}^c - q_{j+1}^g$$
$$V_{j+1} = V_j - r_j P_j - x_j Q_j$$

- Updated objective function:

$$\hat{\boldsymbol{J}} = \boldsymbol{J}(\boldsymbol{x}, \boldsymbol{u}) + \boldsymbol{\lambda}^T \boldsymbol{G}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{d})$$

$$L_j(\boldsymbol{x}) \approx \frac{r_j}{V_0^2}(P_j^2 + Q_j^2)$$

- Solution must satisfy:

$$\left[\frac{\partial \hat{\boldsymbol{J}}}{\partial \boldsymbol{u}}, \frac{\partial \hat{\boldsymbol{J}}}{\partial \boldsymbol{\lambda}}\right]^{\boldsymbol{T}} = [0,0]^{\boldsymbol{T}}$$

Linearized Solution (cont.)

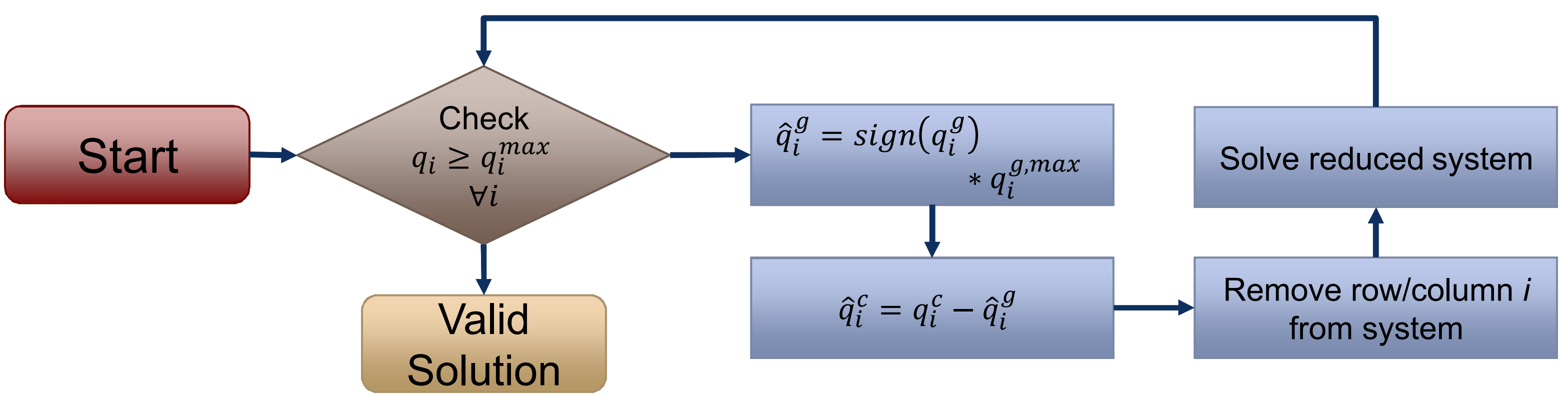
- Linearized solution:

$$\begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{P} \\ \boldsymbol{Q} \\ \boldsymbol{V} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \boldsymbol{R} & \boldsymbol{S} \\ 0 & \boldsymbol{I}-\boldsymbol{N} & 0 & 0 \\ \boldsymbol{U} & 0 & \boldsymbol{I}-\boldsymbol{N} & 0 \\ 0 & diag(r_i) & diag(x_i) & \boldsymbol{I}-\boldsymbol{N}^T \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{T} \\ \boldsymbol{\Delta p} \\ \boldsymbol{q^c} \\ \boldsymbol{V_n} \end{bmatrix}$$

$$\boldsymbol{R} = \{[(\boldsymbol{I}-\boldsymbol{N})^{-1}\boldsymbol{U}] \circ [\boldsymbol{r}1^T]\}^T$$

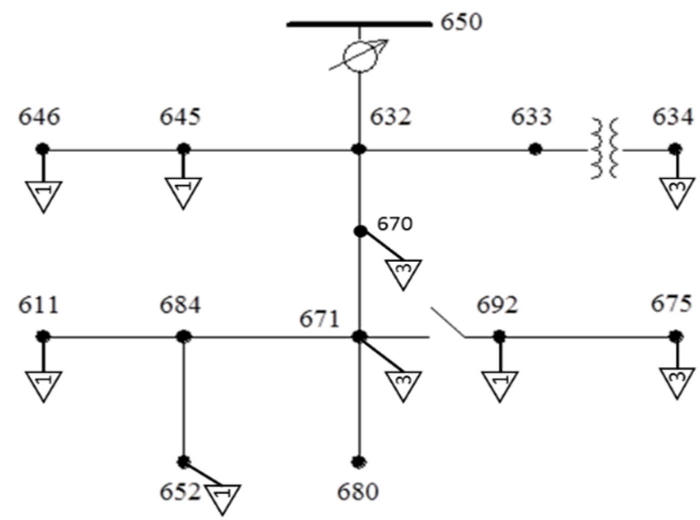
$$\boldsymbol{S} = (path_i \cap path_j) \cdot 2\boldsymbol{x}$$

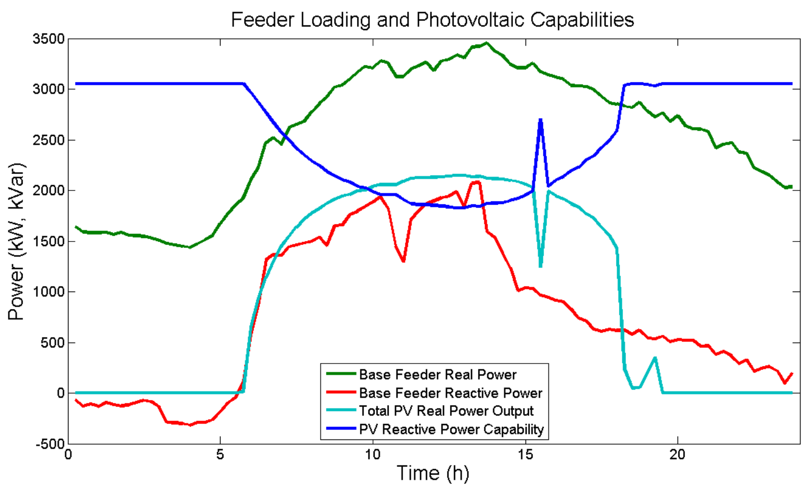
$$\boldsymbol{T} = \sum_i (path_i \cap path_j) \cdot 2\boldsymbol{x}$$



Study Feeder

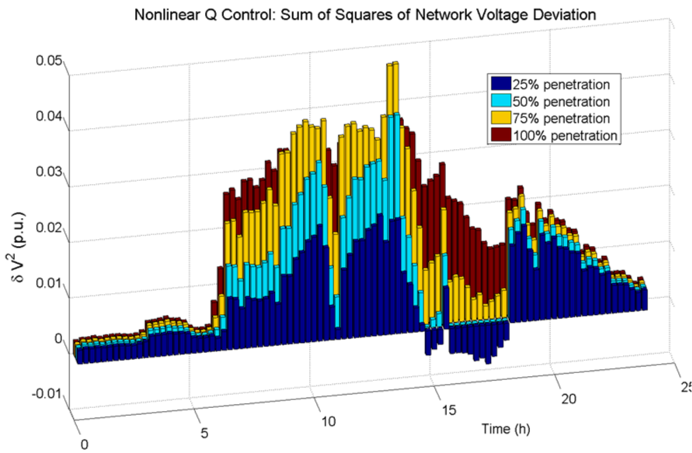
- IEEE 13-bus feeder
  - 3-phase, 4kV distribution feeder
  - 4.05 MVA peak load
  - 2 cap banks at Bus 675 and 611
  - Single voltage regulator sets Bus 632 to $1.0V_{pu}$ for all simulations
- PVs placed at each load, sized as a percent of local peak load based on penetration
  - $S_{PV,i}^{rated} = penetration * S_{load,i}^{peak}$
- Real and reactive load and solar insolation each scaled by separate daily curves of 15 min. intervals

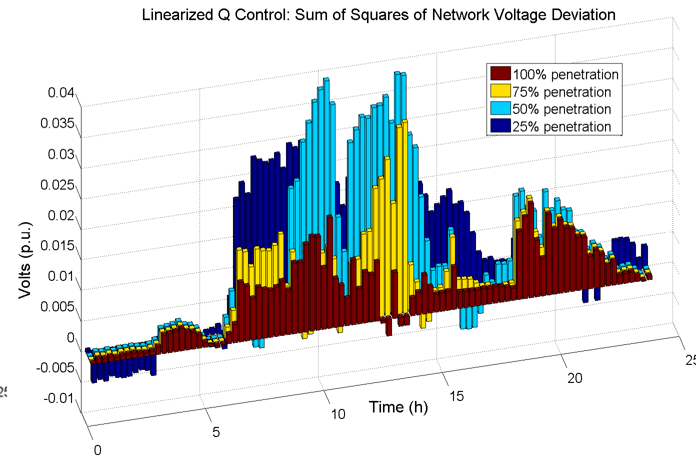


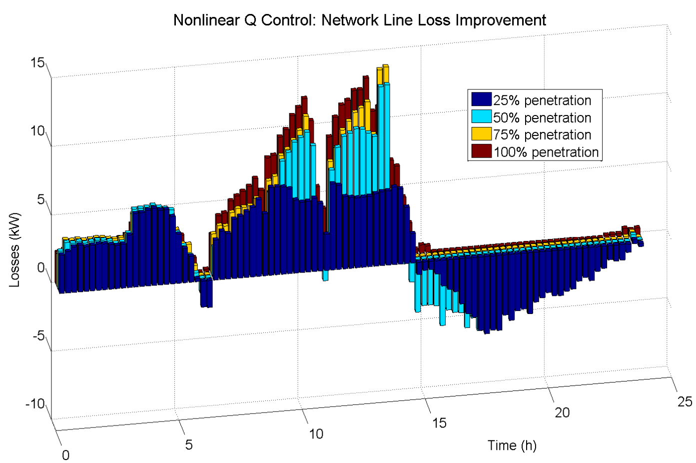


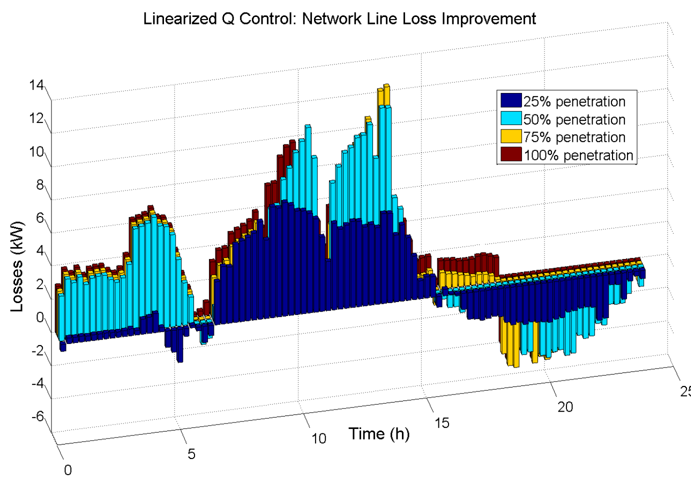
Results

Sandia National Laboratories
Georgia Institute of Technology









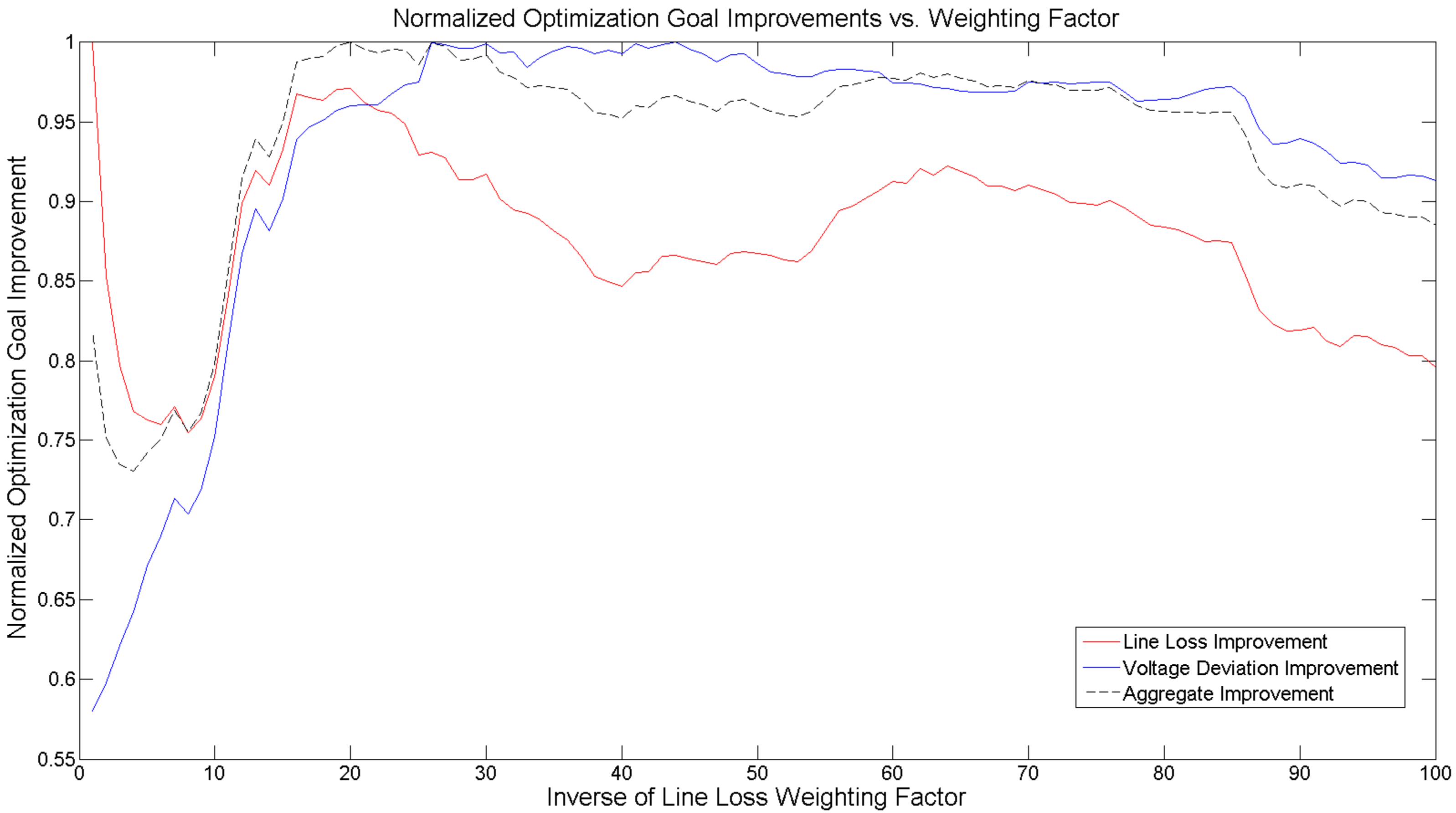
Optimization Improvement over Base Case (no Q control)

Analysis of Results

	Nonlinear PSO Optimization	Linearized Optimization	Local VAR Matching
Sum of Line Loss Improvements	890.3kW	719.9kW	368.7kW
Avg. Node Voltage Improvement (120V base)	3.11V	2.47V	2.57V
Computation Time (seconds)	54,639.51	7.69	7.02

- Nonlinear optimization is clearly the most accurate
  - Not adequate for running thousands of PV placement studies on large, realistic feeders
- Linearized approximation is orders of magnitude faster than nonlinear solution, with only about a 20% reduction in result accuracy

Analysis of Results



Linearized Objective Sensitivity to Weighting Factor Ratio w_1/w_2

Conclusions / Future Work

- Demonstrated
  - Linearized approximate dispatch can by used to quickly gauge a feeder's PV reactive power benefits
- Future:
  - More complex feeders investigated under varying conditions
  - Test a large number of PV placement scenarios
  - Compare benefit of dispatched reactive power to local control of reactive power

Thank you