Scheme based on Regression Analysis for the Determination of Power Flow Control Device Settings

Gabriela Hug (ghug@ece.cmu.edu)
Rui Yang (ruiy@andrew.cmu.edu)

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Outline

- Introduction
- Power Flow Control and Modeling
- Centralized vs. Distributed vs. Decentralized OPF
- Method based on Regression Analysis
- Simulation Results
- Conclusions

Optimal Locations for Wind Generation in the US

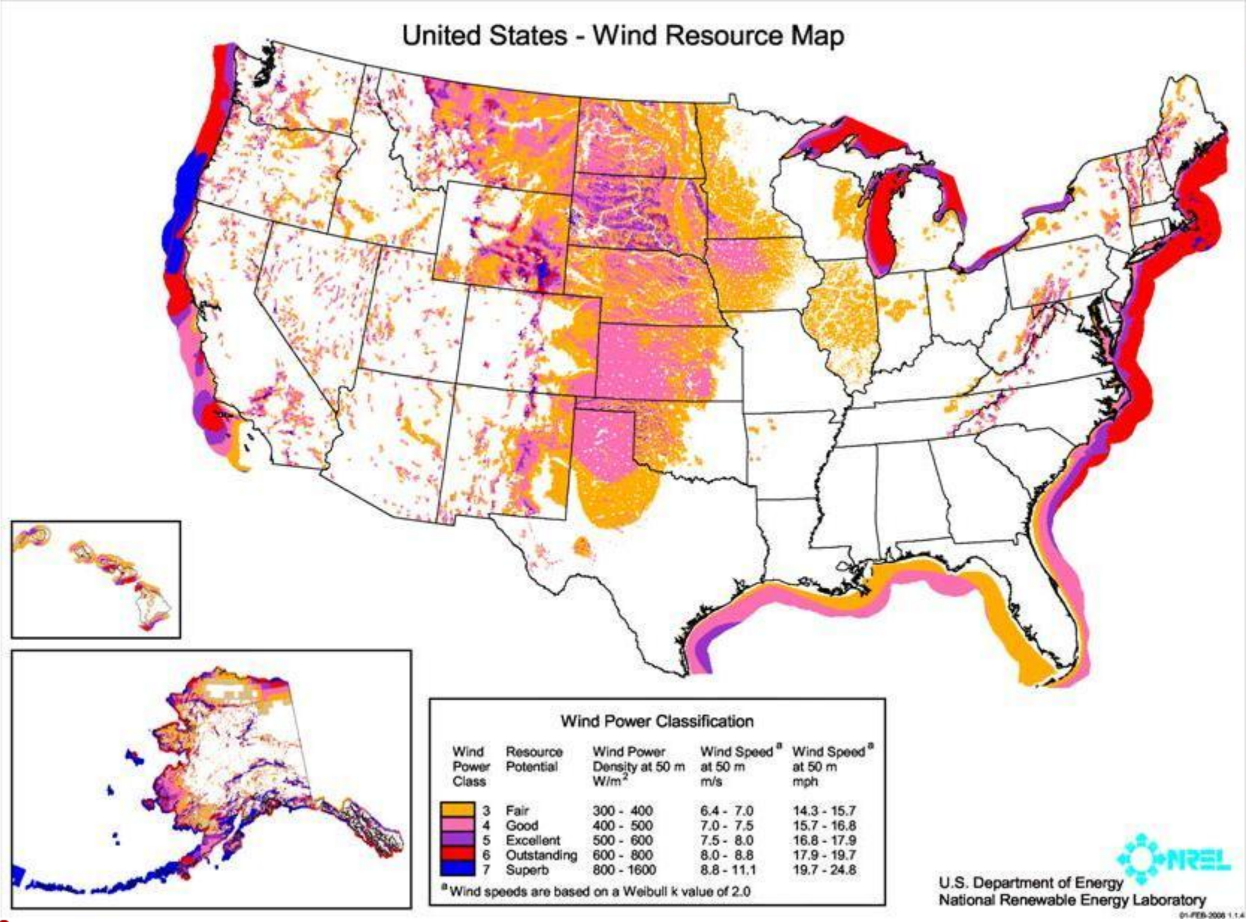
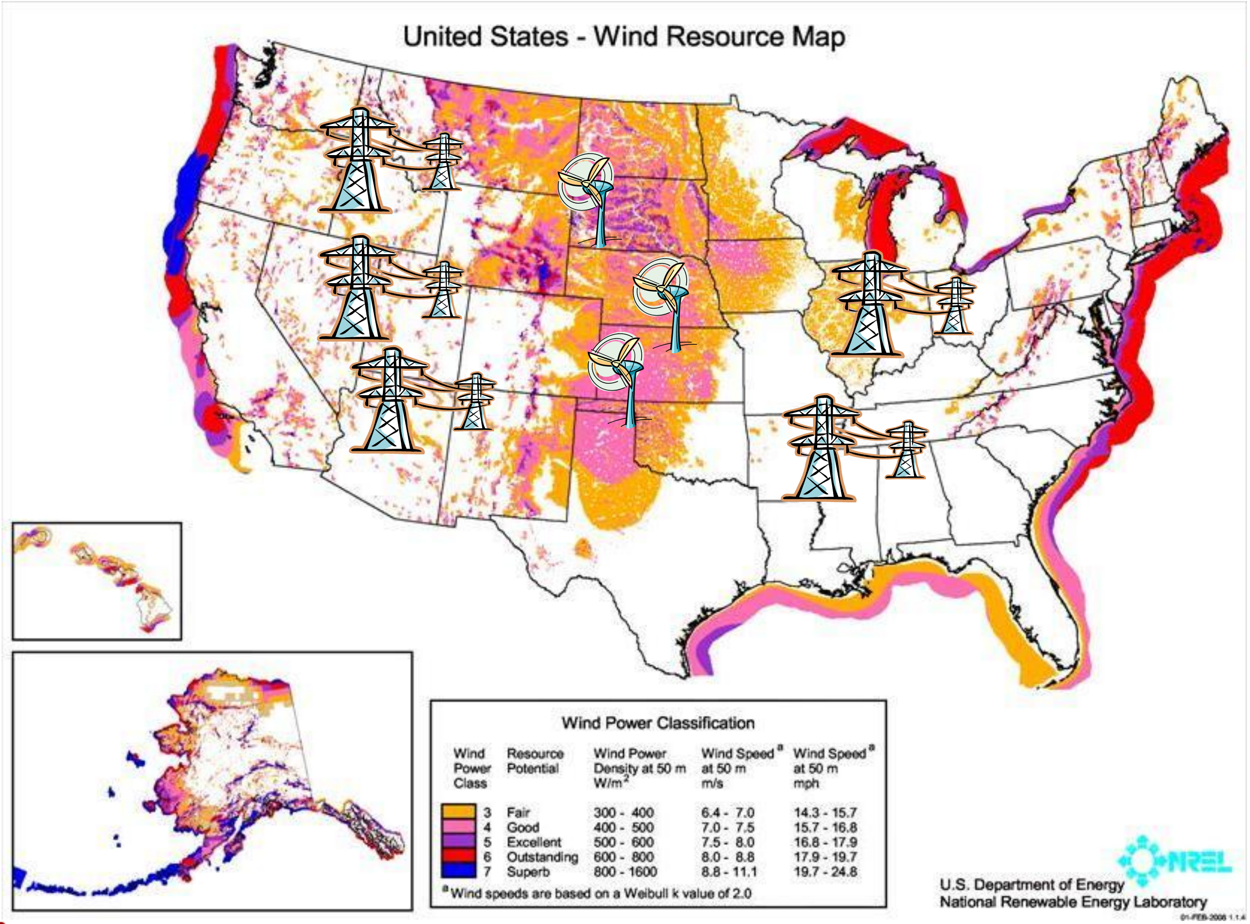


Image sources: http://www.nrel.gov/gis/wind.html; AEP; NYT;socialistaction.org

Solutions?

- Transmission lines



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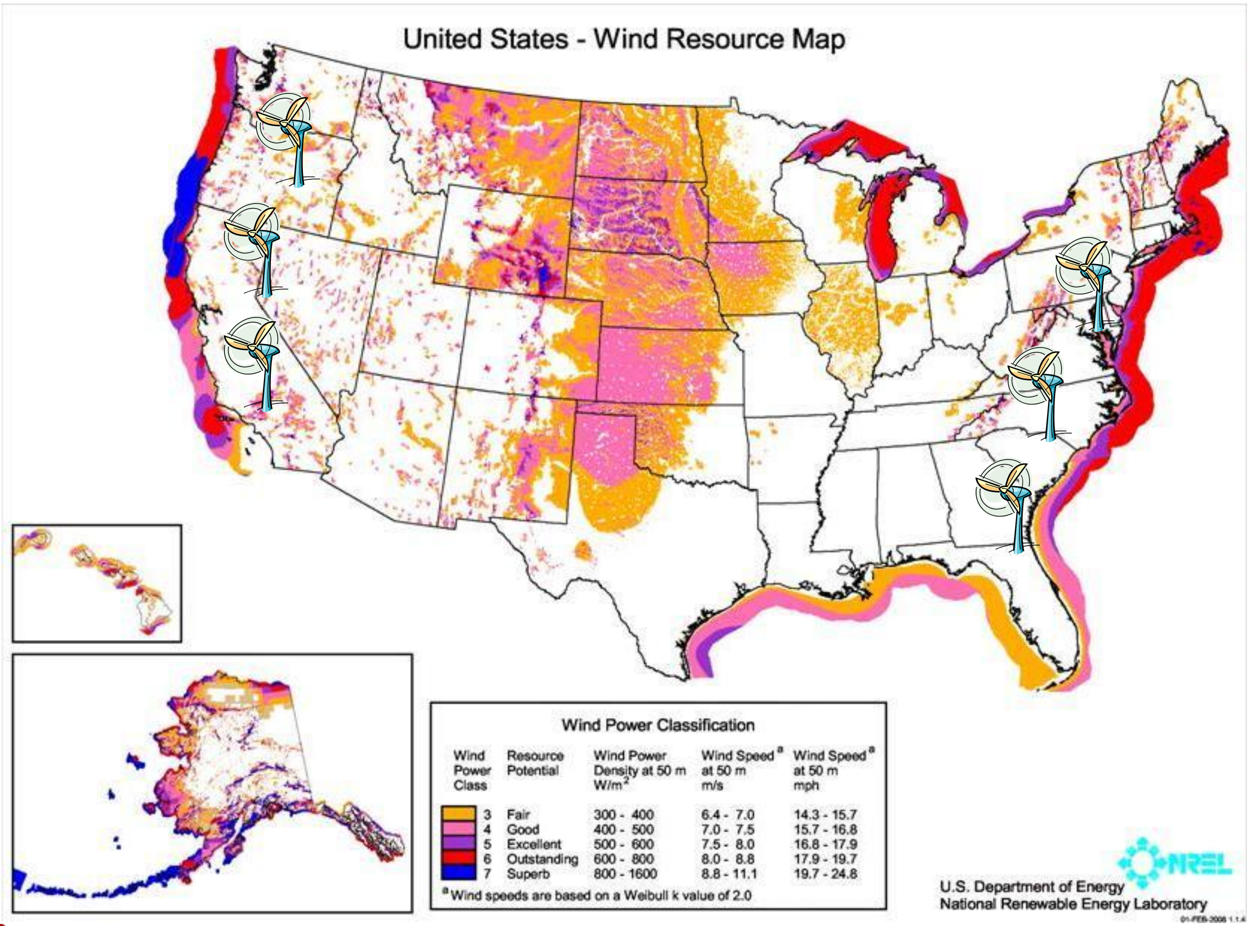
Solutions?

- Suboptimal location



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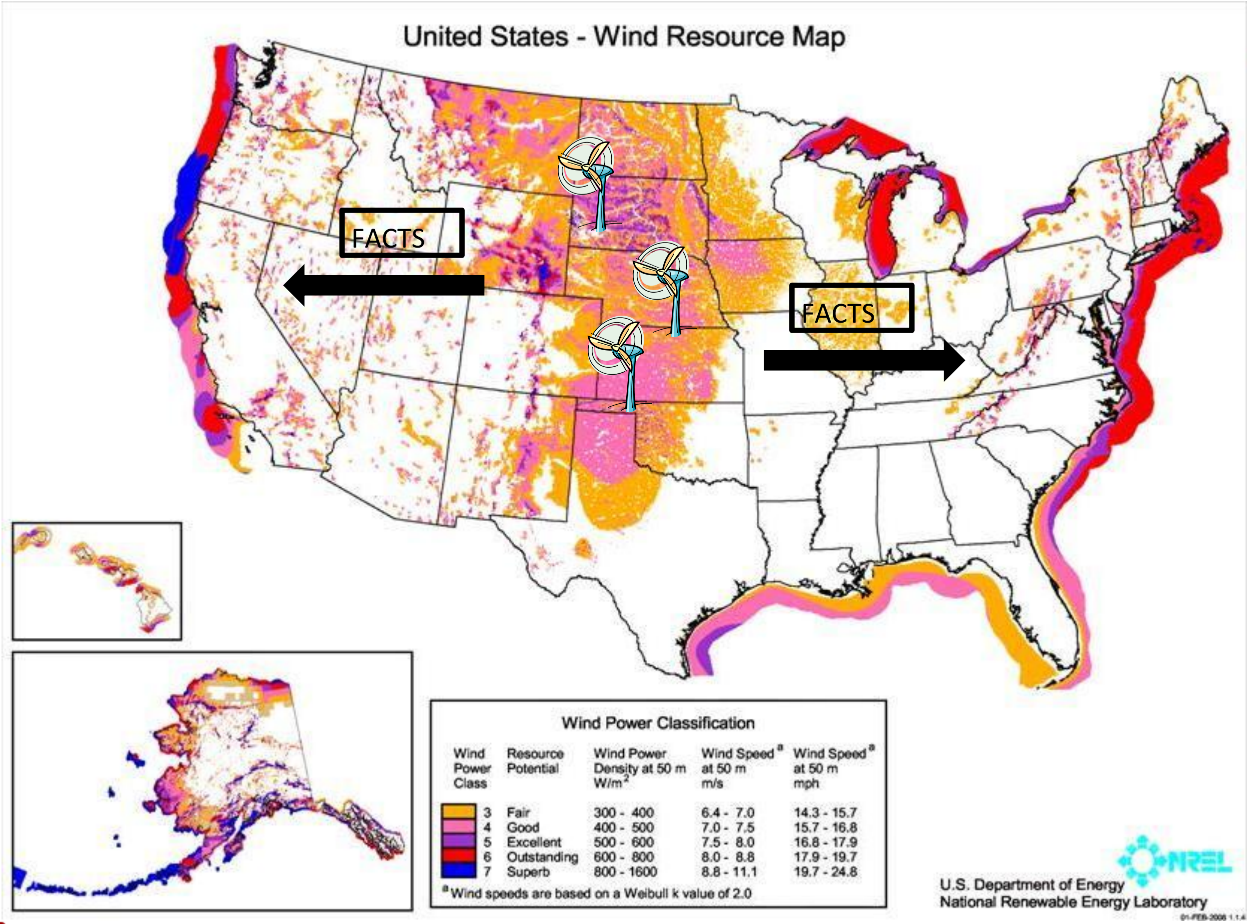
Solutions?

- Power Flow Control



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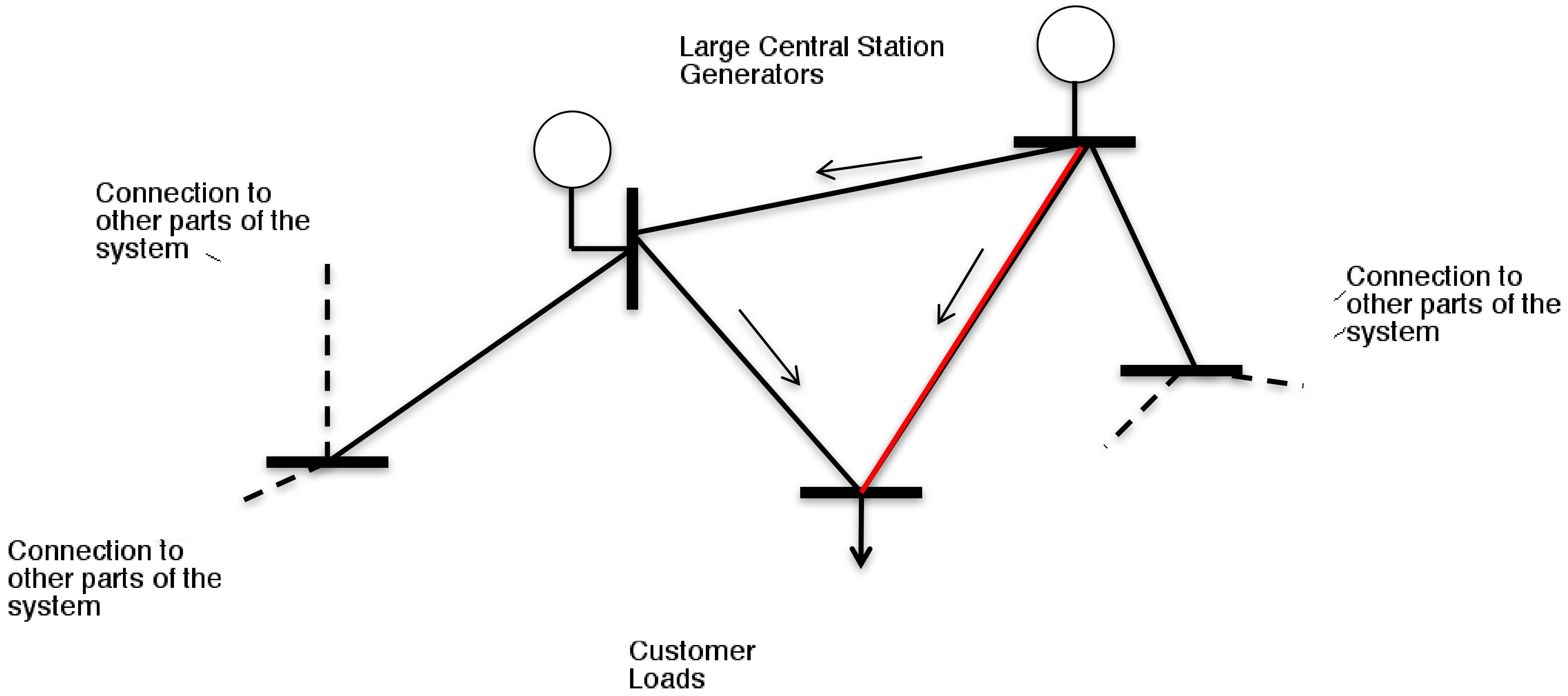
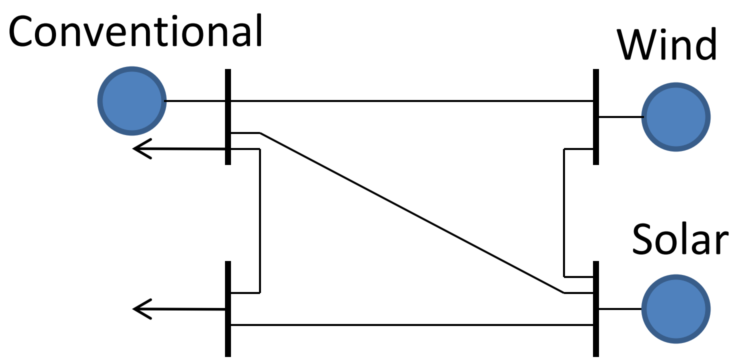
Limited Capacity of Transmission System

- Transfer capacity of a line is limited



Power Flow Control

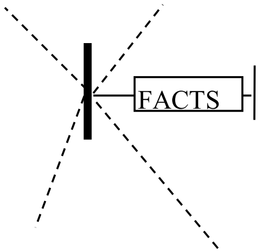
- Opportunities
  - Optimal usage of existing transmission system
  - Adjustable to required needs
  - Fast response



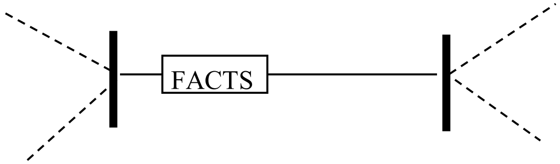
- Requirements
  - Control method taking into account variability
  - Communication/Sensing

What are FACTS Devices?

- FACTS = **F**lexible **A**lternate **C**urrent **T**ransmission **S**ystem
- ability to influence power flows and voltages
- based on thyristor technology
- Types:
  - Shunt connected
    - mainly influence voltages
    - SVC, STATCOM, etc.

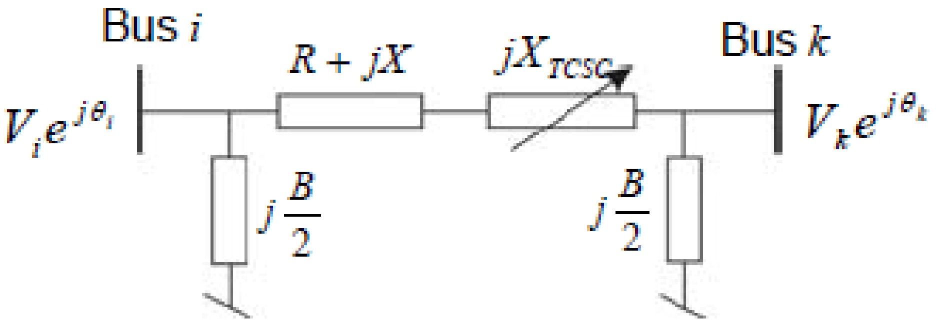


  - Series connected
    - mainly influence active power flow
    - TCSC, TCPST, etc.



Thyristor Controlled Series Compensator

- Modeling
  - variable reactance in series with line



$$X_{total} = X_{Line} + X_{TCSC}$$

$$\max(X_{TCSC,\min}, -0.9X_{Line}) \leq X_{TCSC} \leq \min(X_{TCSC,\max}, 0.4X_{Line})$$

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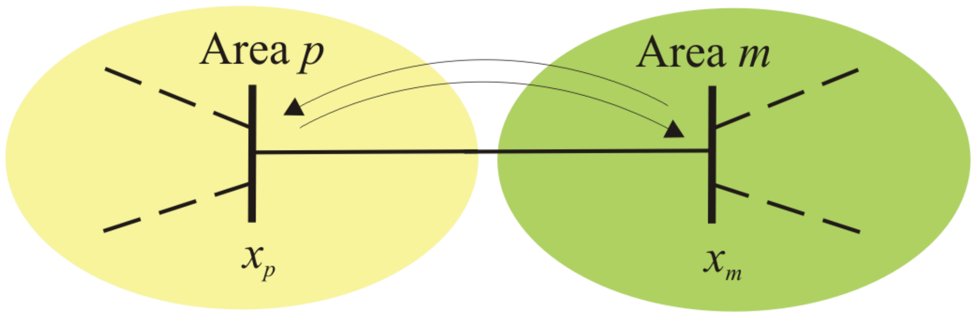
Approaches

- Centralized
  - Single controller
  - Information of the entire system needed
- Distributed
  - Controller for each area or device
  - Communication between devices needed
  - Based on local information and information received from other devices
- Decentralized Approach
  - Local controller for each device
  - Based on a limit amount of local information

Distributed Approach

- Decomposed Optimization



Lagrangian Relaxation
Optimality Condition Decomposition
…

Overall Problem

⇨ iterative process

Subproblem 1

Subproblem 2

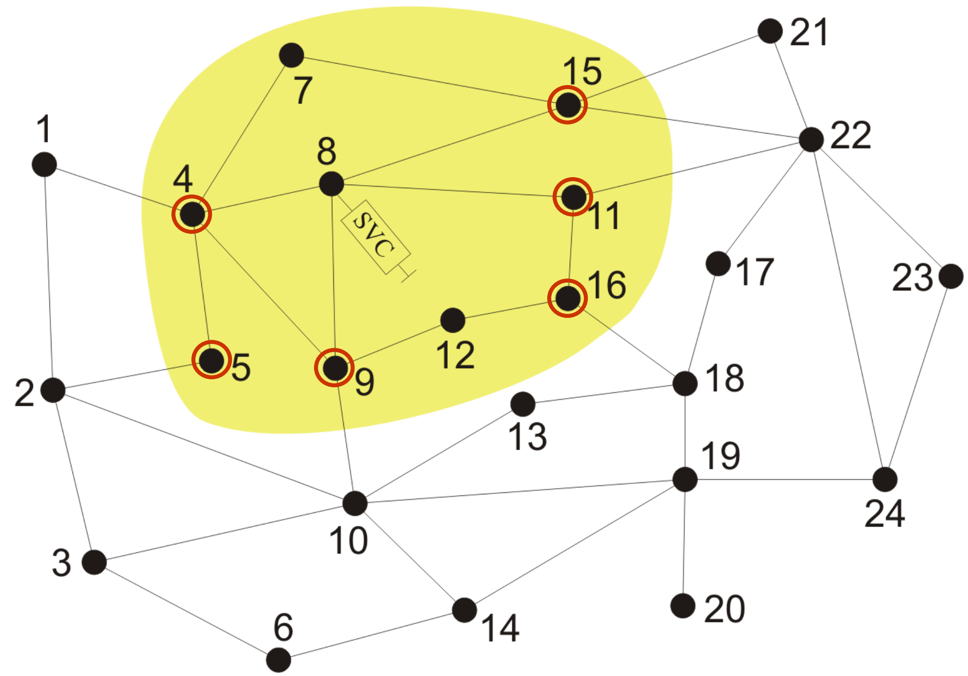
Decentralized Approach

- Limited OPF
  - Approximation of influence at border buses

$$V_i = V_{0_i} + K_{V_i - u} \cdot u$$

$$\theta_i = \theta_{0_i} + K_{\theta_i - u} \cdot u$$

  - Reduced Optimal Power Flow



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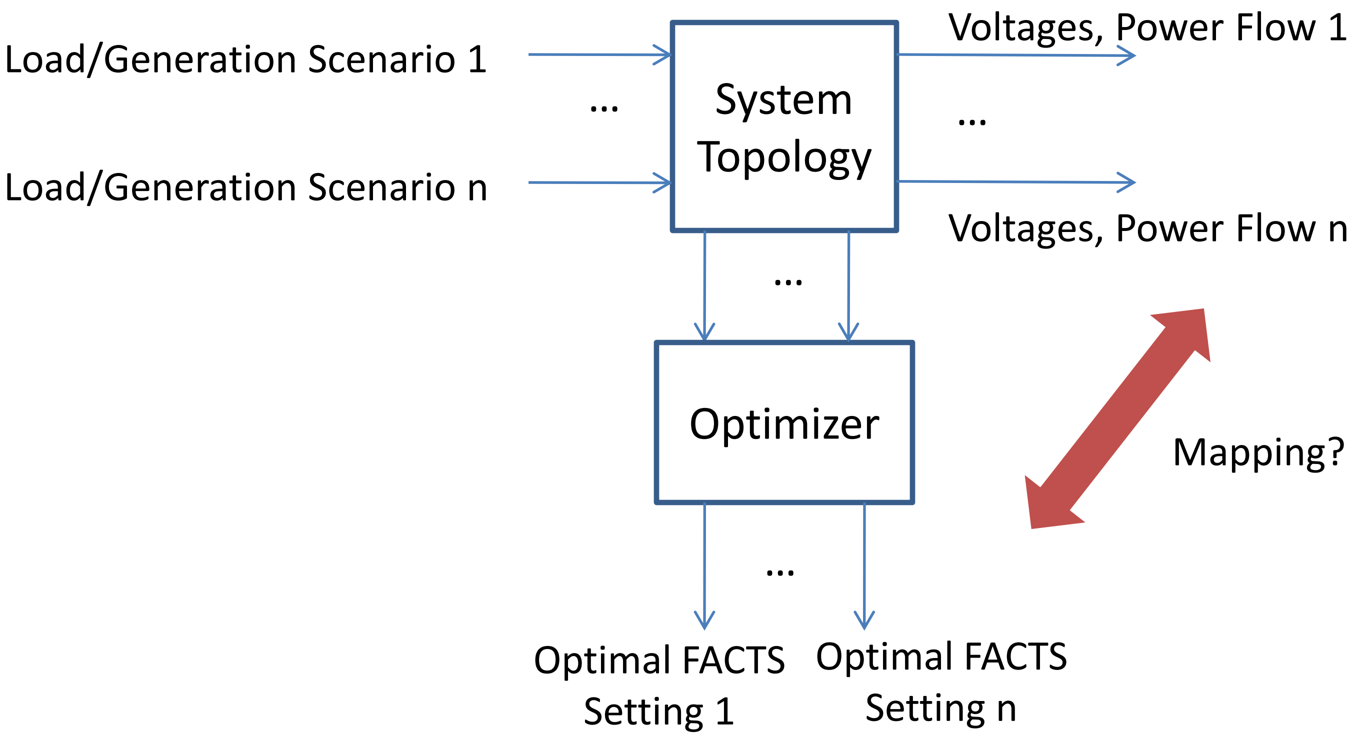
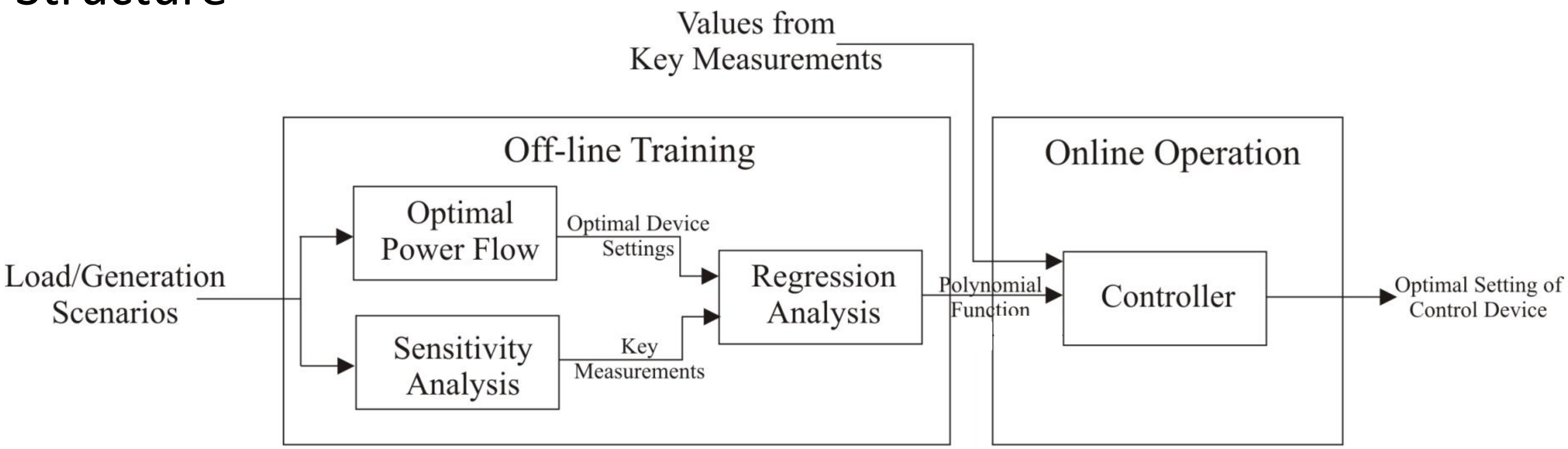
Mapping of System State to Optimal FACTS Setting



- Optimization Offline
- Use Mapping for Online Operation

Regression Analysis

- Structure



- Offline Simulation
  - Solve OPF for various generation and load scenarios
  - Determine function: optimal setting = f(local measurements)
- Online Decision Making
  - Function determined in offline simulation
  - Local measurements

Offline Simulation

- Optimization Problem
  - Control variable: setting of the FACTS device X_{TCSC} or $\eta_{TCSC} = \frac{X_{TCSC}}{X_{Line}}$
  - Objective function
    - Multiple choices
    - Maximize the minimum value of the capacity margin

$$\max\ (\min\ (P_{margin,ij}))$$

where the capacity margin of the transmission line is defined as

$$P_{margin,ij} = \frac{F_{ij}^{\max} - |P_{ij}|}{F_{ij}^{\max}}$$

Offline Simulation

- Optimization Problem
  - Constraints
    - Power flow equations $P_{G,i} - P_{L,i} - \sum_j P_{ij} = 0, Q_{G,i} - Q_{L,i} - \sum_j Q_{ij} = 0$
    - Model of the loads

$$\Delta P_{L,k} \sim random, \tilde{P}_{L,k} = P^0_{L,k} + \Delta P_{L,k}, \tilde{P}_{L,T} = \sum_{k=1}^{numLoad} \tilde{P}_{L,k}$$

$$P_{L,T} \sim random, P_{L,k} = \frac{P_{L,T}}{\tilde{P}_{L,T}} \tilde{P}_{L,k}$$

$$PF_{L,k} = \text{constant}$$

    - Device limits of TCSC

$$\max(X_{TCSC,\min}, -0.9X_{Line}) \le X_{TCSC} \le \min(X_{TCSC,\max}, 0.4X_{Line})$$

Offline Simulation

- Determining Key Measurements
  - Considered measurements
    - Active power flows and current magnitudes on lines
    - Voltage magnitudes and angles at buses
  - Sensitivity analysis
    - Assumption: if FACTS device setting has large influence on system value => system value gives important information for optimal device setting
    - calculate influence of FACTS device on considered measurements z

$$K = \frac{\Delta z}{\Delta X_{TCSC}}$$

Offline Simulation

- Regression Analysis
  - Key measurements $x = \begin{bmatrix} P_{ij(I)} & I_{mn(I)} & \theta_{p(I)} & \eta_{TCSC} \end{bmatrix}^T = \begin{bmatrix} x_1 & x_2 & \cdots & x_K \end{bmatrix}^T$
  - Optimal setting y
  - Polynomial fitting – quadratic function $f(x) = \frac{1}{2} x^T B x + a^T x + c$
  - Features and coefficients in the function $f(\tilde{x}) = \alpha^T \tilde{x}$

$$\tilde{x} = \begin{bmatrix} 1 & x_1 & \cdots & x_K & x_1^2 & x_1 x_2 & \cdots & x_1 x_K & x_2^2 & x_2 x_3 & \cdots & x_2 x_K & \cdots & x_K^2 \end{bmatrix}^T$$

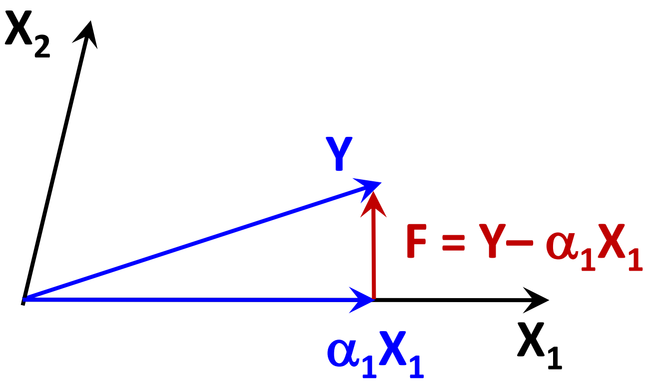
$$\alpha = \begin{bmatrix} c & a_1 & \cdots & a_K & 1/2 \cdot b_{11} & b_{12} & \cdots & b_{1K} & 1/2 \cdot b_{22} & b_{23} & \cdots & b_{2K} & \cdots & 1/2 \cdot b_{KK} \end{bmatrix}^T$$

  - Fitting – L_0-norm regularization problem

$$\min_{\alpha} \quad \left\| X\alpha - Y \right\|_2^2$$
$$s.t. \quad \left\| \alpha \right\|_0 \le \lambda$$

Offline Simulation

- Regression Analysis – Algorithm Used
  - Orthogonal Matching Pursuit (OMP)
    - Step 1: Calculate the inner products <X_i, Y>
    - Step 2: Select X_i that corresponds to the largest inner product magnitude
    - Step 3: Solve the coefficient α_1 by $\min_{\alpha_1} \left\| \alpha_1 \cdot X_1 - Y \right\|_2^2$
    - Step 4: Calculate the residue $F = Y - \alpha_1 \cdot X_1$
    - Step 5: recalculate inner products and coefficients, etc. until λ is reached



Offline Simulation

- Regression Analysis – Algorithm Used
  - Optimal value for number of the non-zero coefficients λ
    - Case-dependent
    - determined by cross-validation: calculate coefficients from training set and estimate errors from testing set

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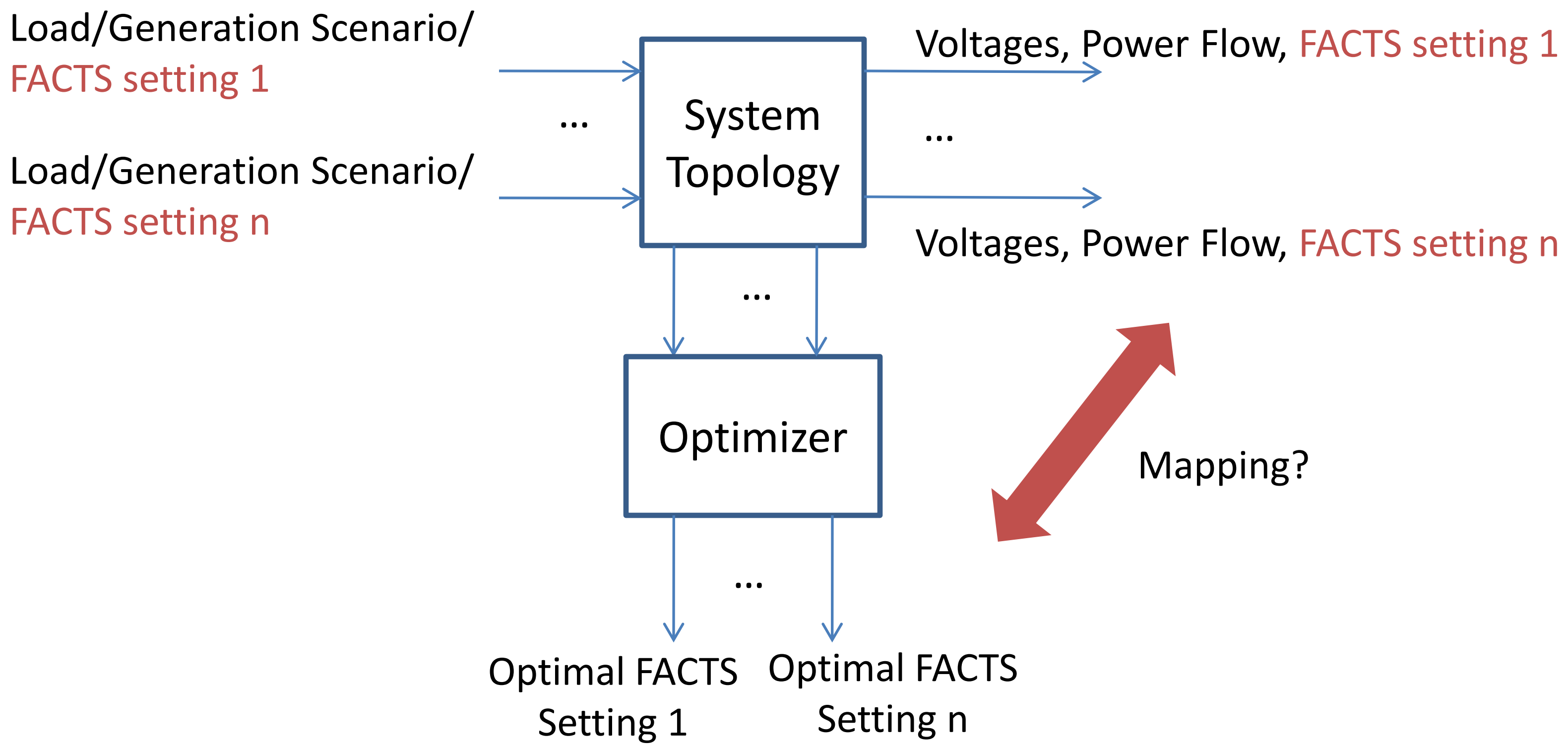

- Optimization Offline
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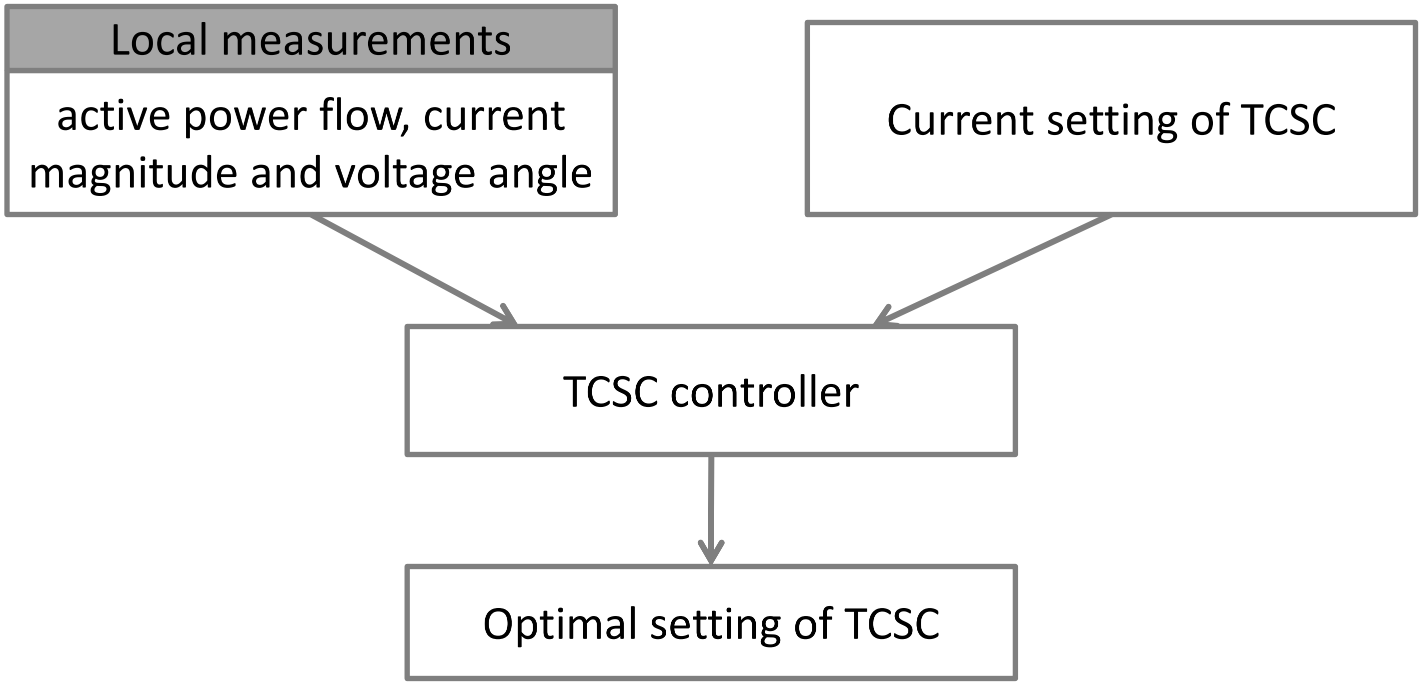
Online Decision Making

- Process



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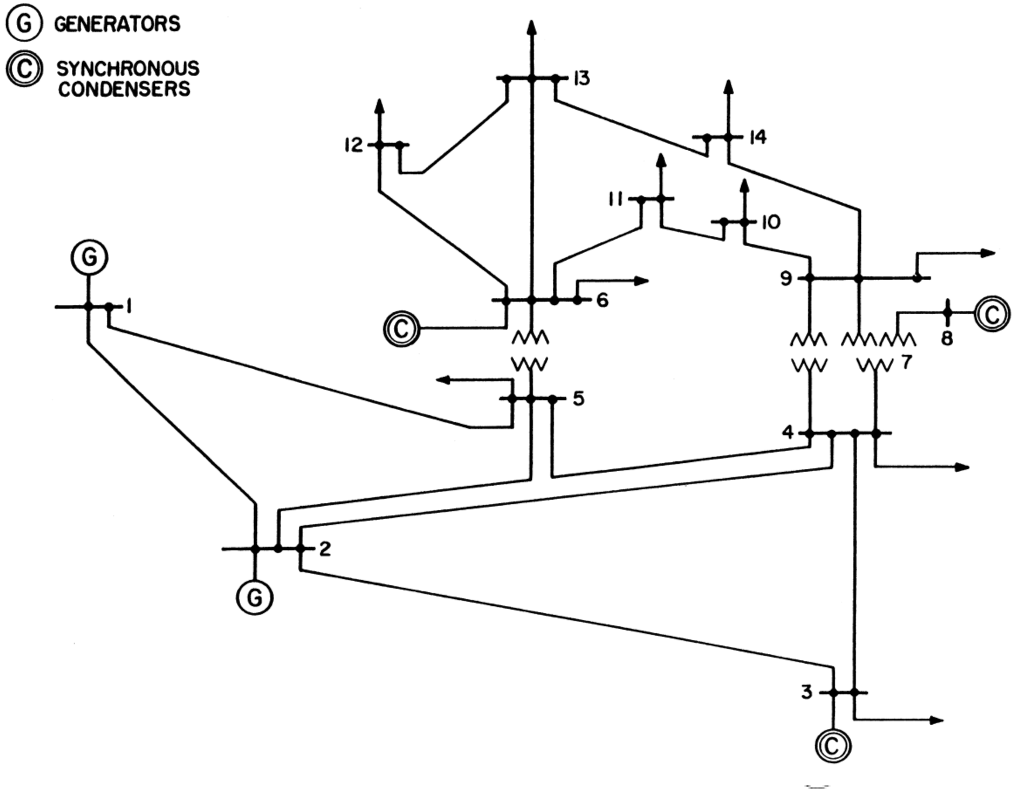
Simulation Results

- Simulation Setup
  - IEEE 14-bus system
  - Wind generator at Bus 2
  - Load center on north side
  - A single TCSC in Line 1-2
  - 1000 different generation/load scenarios



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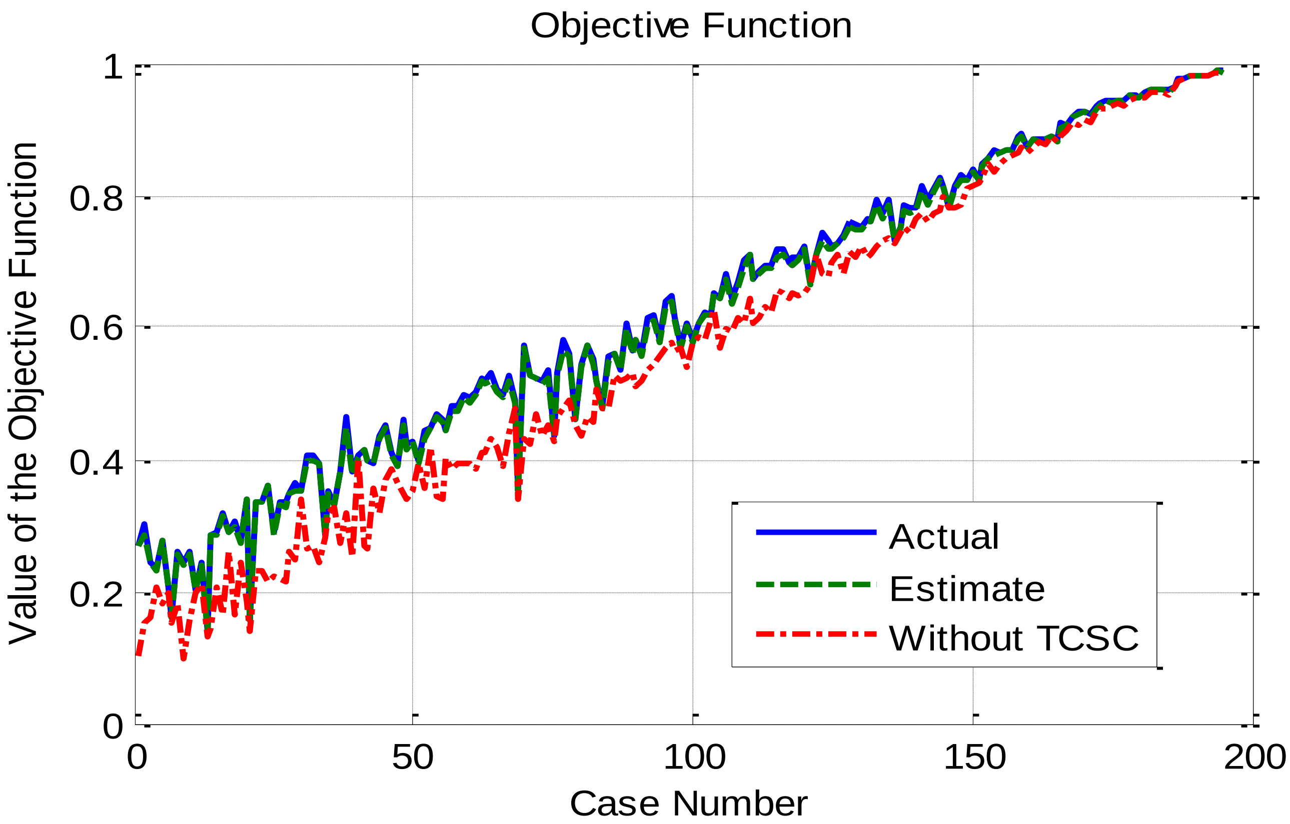
Simulation Results

- Initial Point X_{TCSC} = 0, no overloading



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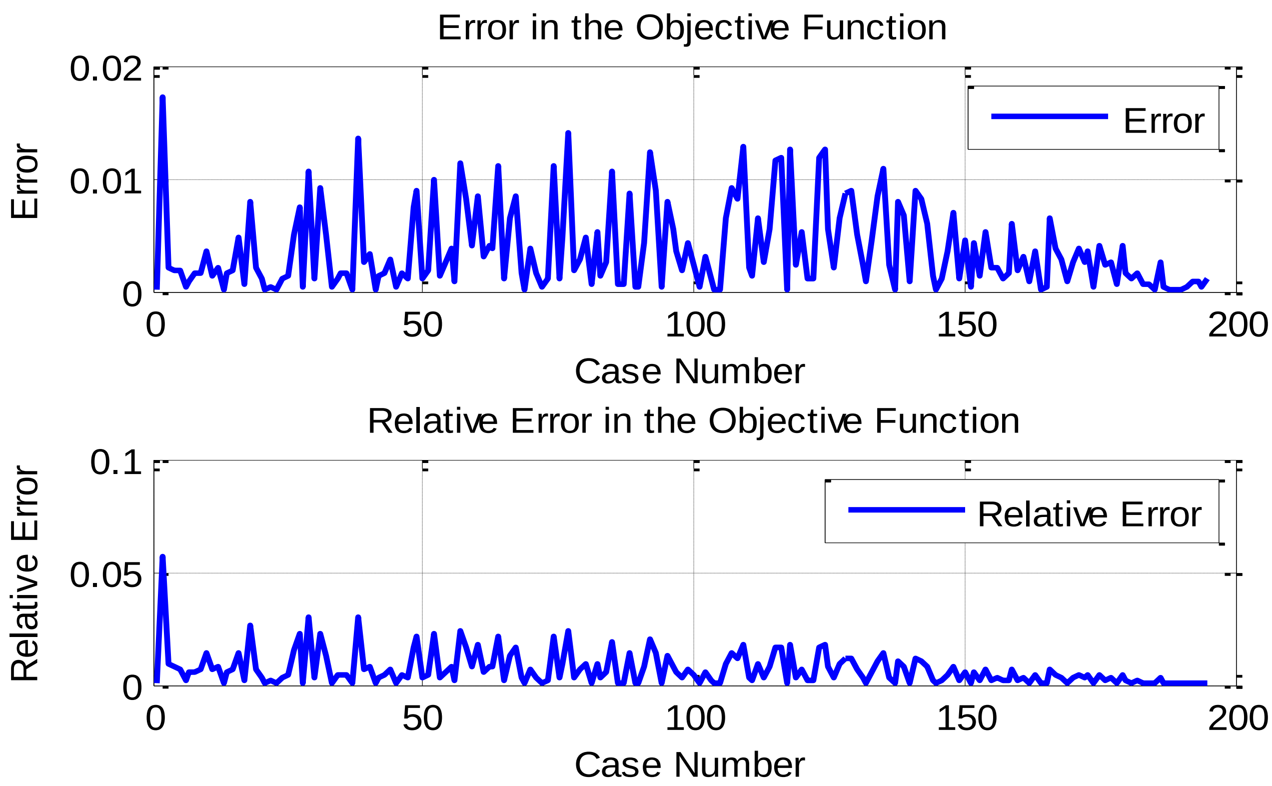

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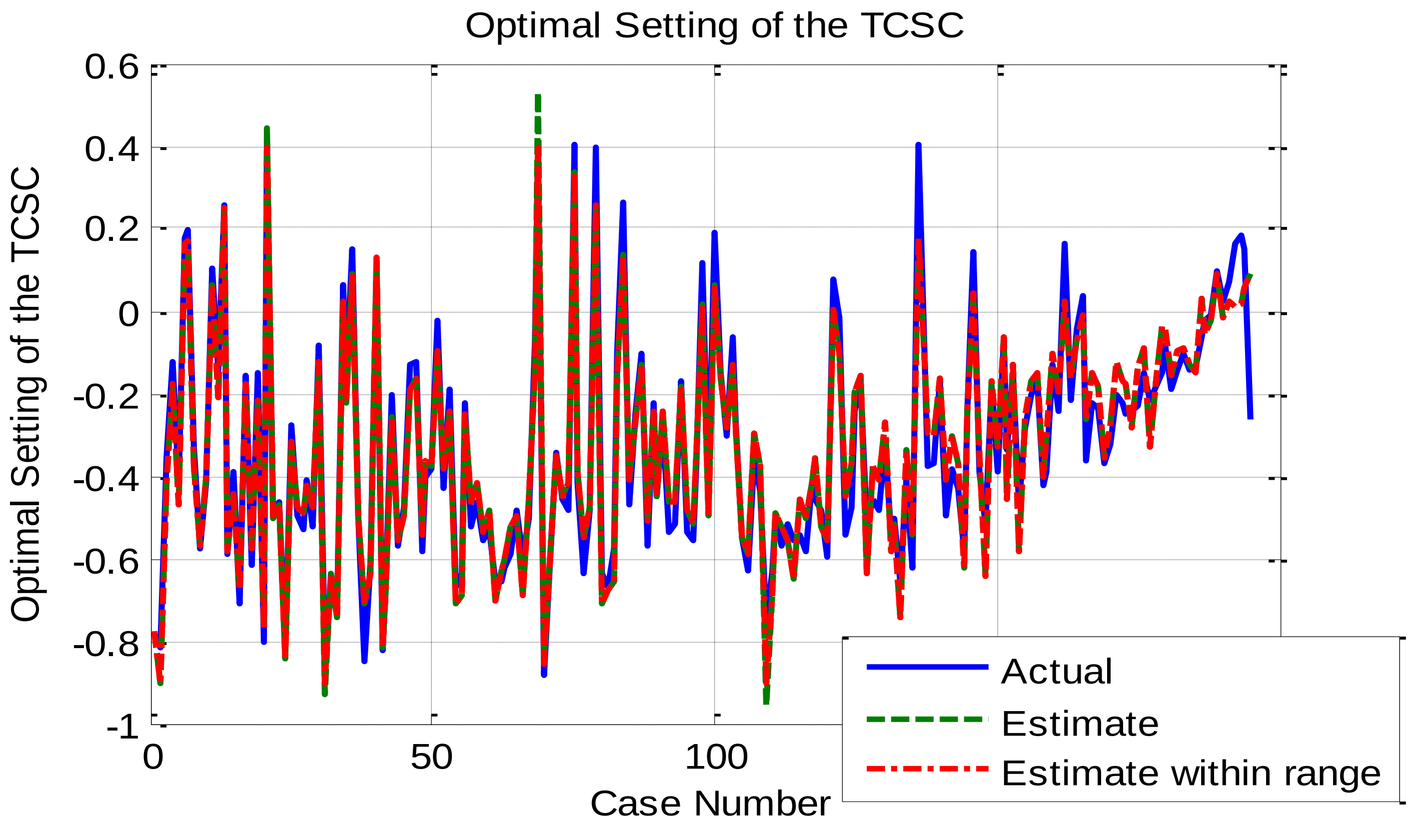

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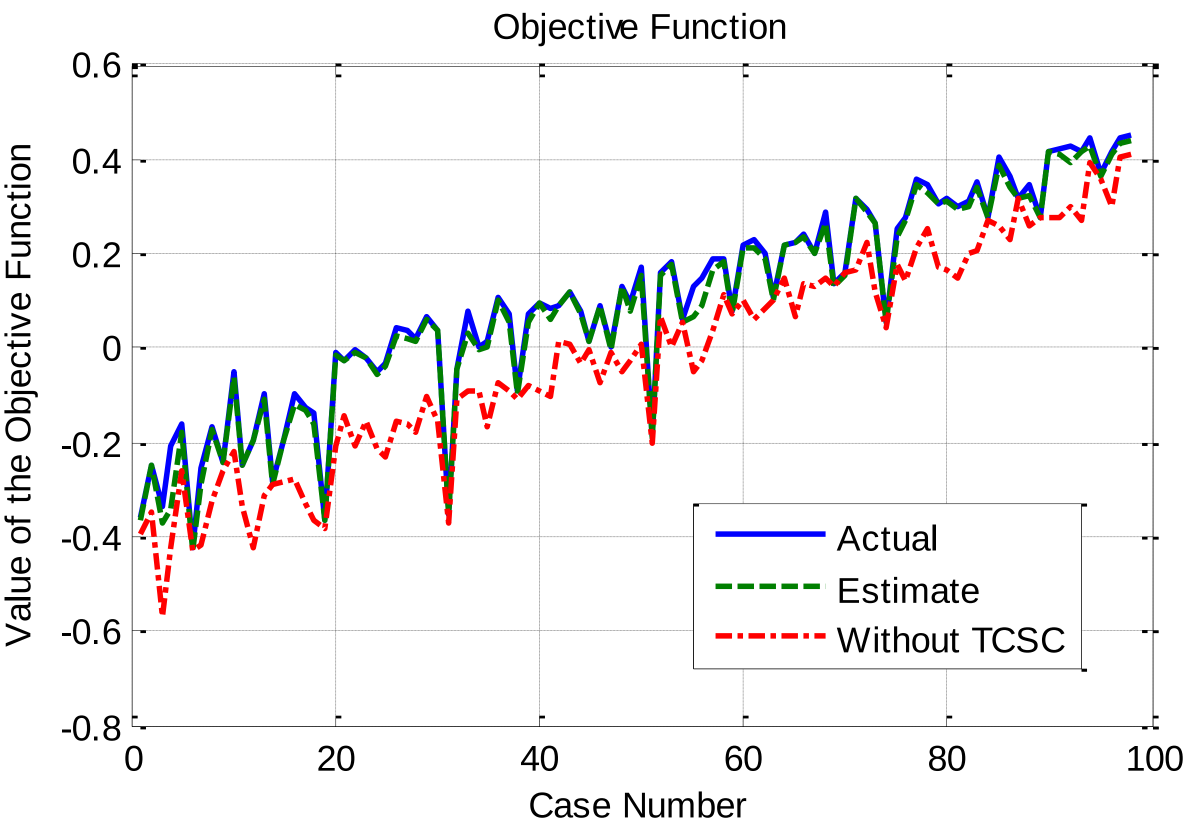

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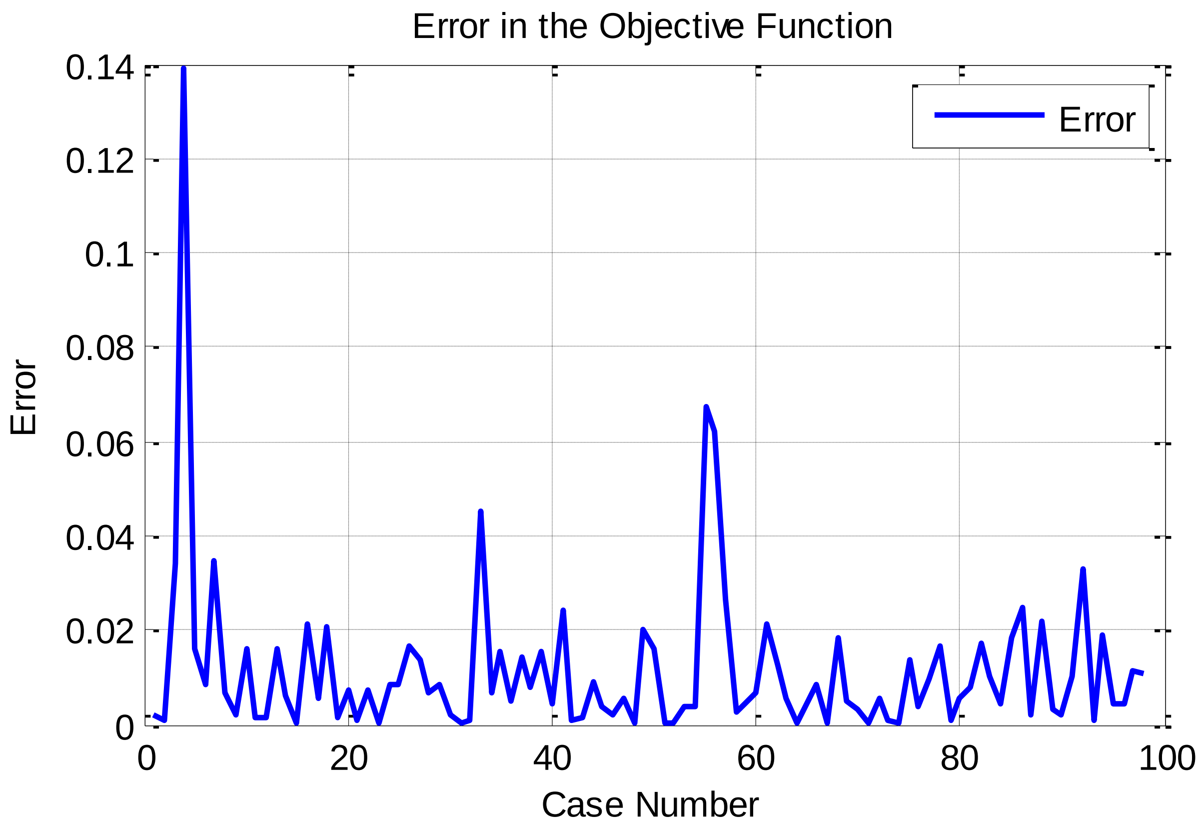

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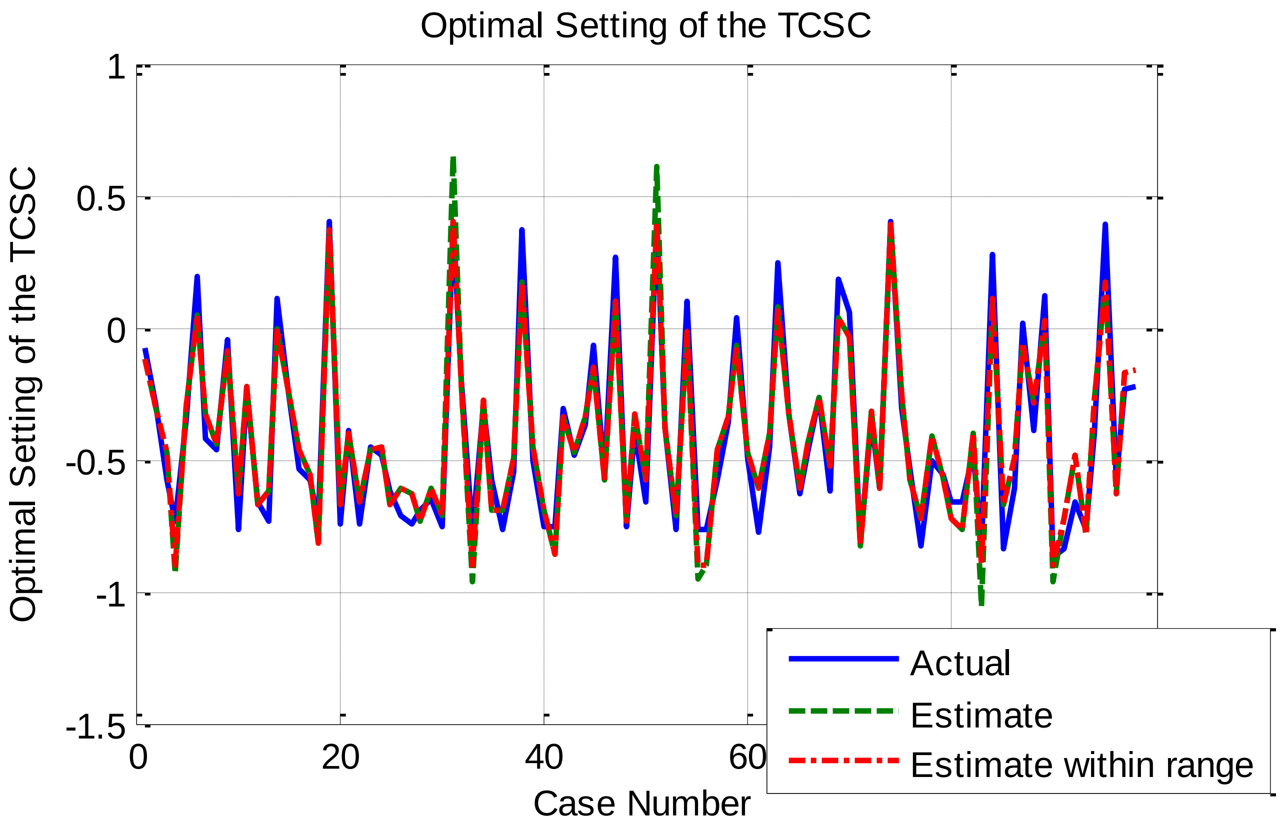
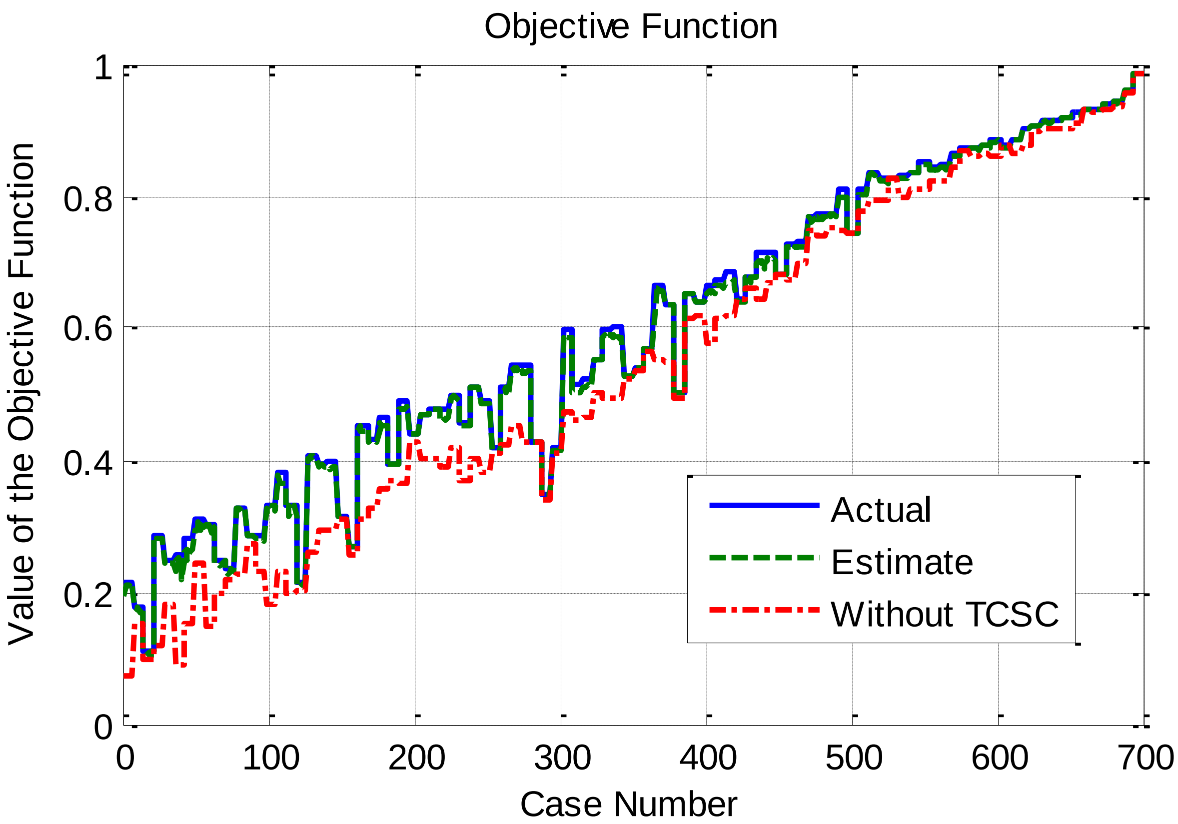


Simulation Results

- Initial Point $X_{TCSC} \neq 0$, no overloading



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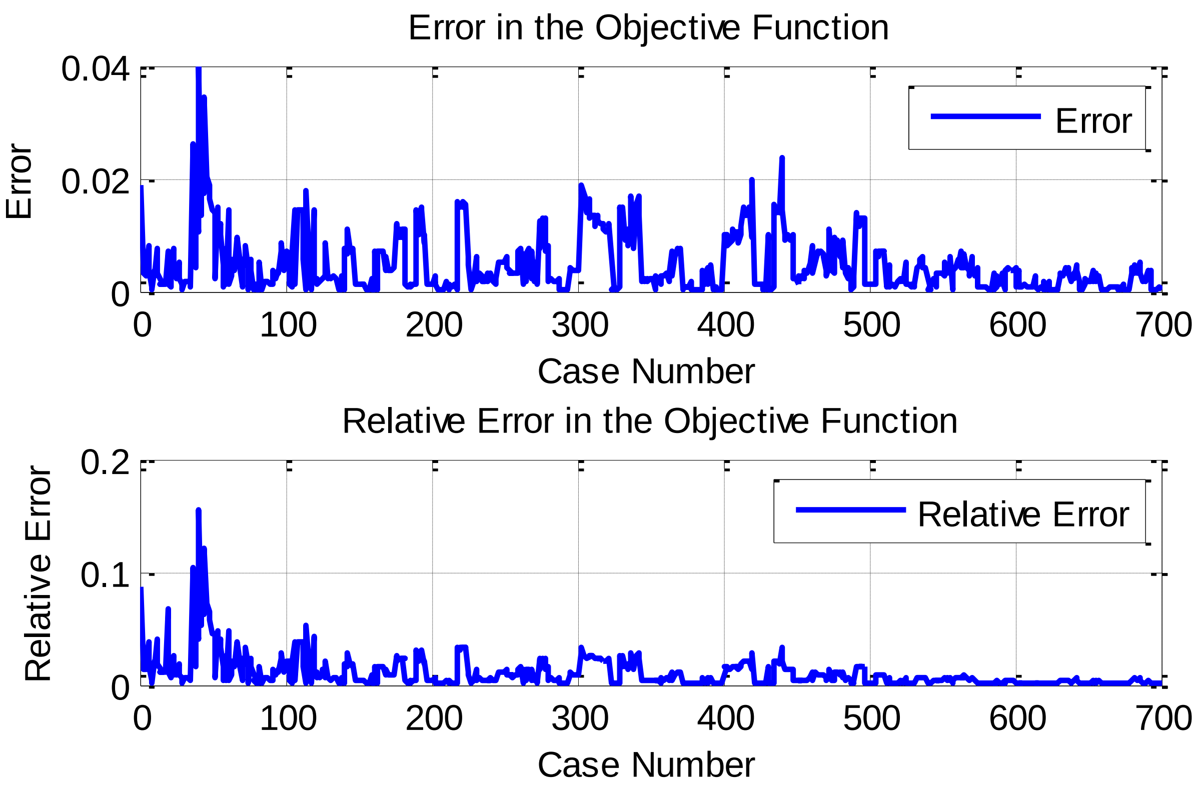

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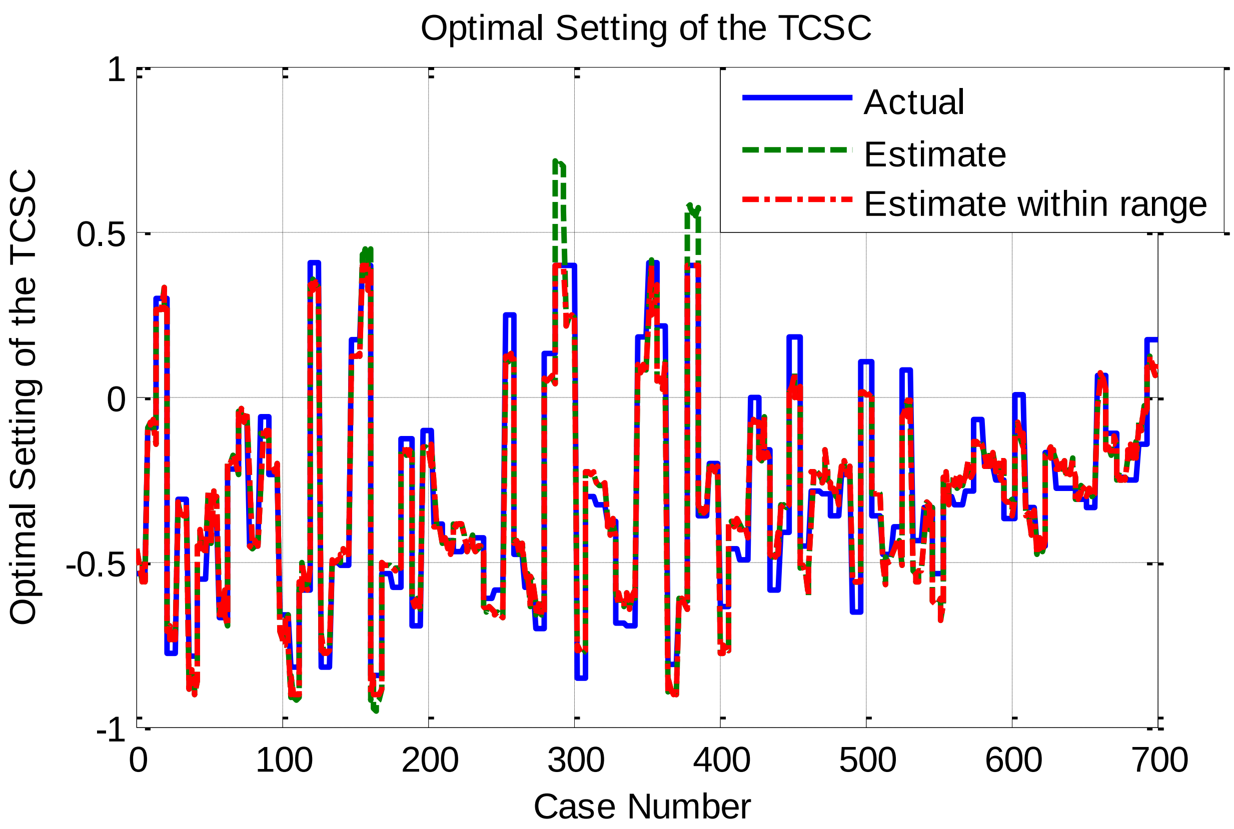

Conclusions

- Power flow control devices provide the opportunity
  - to improve the usage of the existing transmission system
  - to make the transmission system more flexible and adjust to the needs of flexible generation
- Usage of regression analysis might provide solution to determine optimal settings without solving OPF online

Future Work

- Multiple FACTS devices
- Larger System
- Incorporation of Dynamic Line Rating
- Implications on planning
- N-1 security