Distributed Asynchronous Algorithms & Software Systems For Wide-Area Monitoring of Power Systems

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Project Goal

To translate current state-of-art centralized processing algorithms for wide-area monitoring of large power grids using large volumes of Synchrophasor data to a completely distributed cyber-physical architecture.

**Intellectual Merits:**
1. Distributed oscillation monitoring
2. Distributed voltage monitoring
3. Distributed middleware
4. Fault-tolerance
5. Experimental verification using Exo-GENI network
6. Real-time testing of QoS and cyber-security

Technical Approach

Proposed Distributed Cyber-Physical Architecture for PMU-PDC Communication:

- **Dynamic Rate Control Problem (DRCP):**
  - Find optimal PMU data exporting rates, and frequency of information exchange between local PDCs and inter-regional PDCs to minimize computation error between centralized and distributed estimation.

- **Dynamic Link Assignment Problem (DLAP):**
  - Find optimal communication topologies in real-time connecting local and inter-regional PDCs to maximize computational speed for the overall global estimation/monitoring/control problem.

Problem statement: Compute power flow oscillation frequencies (eigenvalues), mode shapes (eigenvectors), damping, and residue from PMU measurements using distributed algorithms implemented via DRCP and DLAP.

Power System Dynamic Model:

\[ M \Delta \omega = \left[ \begin{array}{cc} -K & -P \\ 0 & I \end{array} \right] \Delta \delta + \left[ \begin{array}{cc} 0 & \omega_0 \Delta \phi \\ 0 & 0 \end{array} \right] \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} \Delta P_r \\ \Delta \phi_r \end{bmatrix} \]

Due to load

\[ \Delta \theta (t) = \frac{h_1 + h_2 z^{-1} + h_3 z^{-2} + L + h_n z^{-n}}{1 + a_1 z^{-1} + a_2 z^{-2} + L + a_n z^{-n}} \]

Sparse distributed optimization:
1. ADMM, Stochastic Gradient
2. Round-Robin ADMM for fault tolerant optimization

New Algorithms and Results using ADMM

1. Update both primal and dual estimation variables at every local control center:
   \[ \begin{align*}
   \beta^{(k+1)}_i &= \left( H_i^T H_i + \rho I \right)^{-1} H_i^T \omega^{(k)}_i - w^{(k)}_i + \rho \beta^{(k)}_i \\
   w^{(k+1)}_i &= w^{(k)}_i + \rho \left( H_i^T \beta^{(k)}_i - \omega^{(k)}_i \right)
   \end{align*} \]

2. Gather the values of \( \beta^{(k)}_i \) at the central ISO
3. Compute the average of \( \beta^{(k)}_i \) at the central ISO
4. Broadcast the average to local control centers and iterate to Step 1

Fault-Tolerance & Cyber-Security

- Design application specific fault-tolerance mechanisms to meet real-time needs of the DRCP and DLAP monitoring algorithms
- Crash failures
- Byzantine failures – Graph designs to prevent arbitrary byzantine faults
- Leverage the redundancy of sensors and the correlation among sensor data to reduce the cost of fault-tolerance
- Protecting a small subset of PMU data may be necessary and sufficient to detect false data injection attacks
- Leverage application characteristics to design approximate or safe algorithms that can tolerate asynchrony and message loss

Experimental Testbed

- Participated in US Ignite Application Summits 2013-2017, and in Smart America Challenge 2014 Initiative of NIST and US White House
- Federated ExoGENI-WAMS: Multi-vendor PMU-based hardware-in-loop simulation tested at NCSU to showcase wide-area oscillation monitoring and control

Broader Impacts

- Smart America Challenge 2014, US Ignite 2013-2017 demos
- Undergraduate, K-12 and minority education via Science House and FREEDM ERC programs at NC State
- Undergraduate summer internship at Information Trust Institute at UIUC
- Industry collaborations with power utilities and vendors such as SCE