High Performance Computing for Situational Awareness in Power System Grid

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<table>
<thead>
<tr>
<th>Element</th>
<th>Transmission-level Simulation</th>
<th>Components*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation</td>
<td>~10^2</td>
<td>~10^2</td>
</tr>
<tr>
<td>Transmission</td>
<td>~10^4</td>
<td>~10^3</td>
</tr>
<tr>
<td>Substations</td>
<td>~10^4</td>
<td>~10^4</td>
</tr>
<tr>
<td>Distribution Feeders</td>
<td>~5 x 10^4</td>
<td>~5 x 10^4</td>
</tr>
<tr>
<td>Customer Meters</td>
<td>~10^7</td>
<td>~10^7</td>
</tr>
<tr>
<td>Appliances/Equipment</td>
<td>~5 x 10^8</td>
<td>~10^7</td>
</tr>
</tbody>
</table>

*Western U.S.

- 500kV
- 60kV
- 10kV
- 120V
Situational Awareness in Power Grid Is An Interconnection-Scale Issue

But ... today’s grid operations data and software can’t support the real-time analysis required for dynamic situational awareness of such large and complex systems
Power System Dynamic Model

Differential Algebraic Equations
\[
\begin{align*}
\frac{dx}{dt} &= f(x, y) \\
0 &= g(x, y)
\end{align*}
\]

- **Dynamic models**
- **Power flow model**

**State Variables:**
- \(x\): State Variables
- \(y\): Algebraic Variables

**WECC Power System**
- 2,700 generators
- 3rd-order model
- 8,100 state variables
- Plus other dynamic models

**State Variables:** an order of \(10^4\)

Source: J. Hauer, 2004
Steady-State Model

Power Flow Equation

\[ 0 = g(V, \theta, P, Q) \]

Breaker-Oriented Model (EMS)
WECC Power System

- 10,000 buses
- 16,000 lines
- 2,700 generators
- 20,000 unknowns in power flow model
- 40,000 analog measurements
- 100,000 digital measurements

State Variables:
- An order of \(10^4\) (PF) & \(10^5\) (EMS)

Does not seem that bad but…
For effective decision support we need to run analysis in seconds!!
Telemetry Data

- High-Level Real-Time View of WECC System
  - 500 kV AC
  - 367 lines
  - 167 buses
  - ~70 PMUs

- Data Volume and Rates
  - SCADA system: ~4 seconds
    6 GB/day
  - Phasor system: 1/30 second
    5 GB/day ➔ 3 TB/day
Electricity Infrastructure Operations Center
Blackout of 2003

August 13, 2003
Normal

August 14, 2003
Blackout

Source: NOAA/DMSP

> Lack of situational awareness!

> How to improve situational awareness?

Source: Blackout Final Report
Once the cascade began, the 2003 blackout swept from Ohio to NY in nine seconds!

Operators had no way to see imminent instability!

Resolving state-estimates & computing contingency analysis takes 2-4 min

Data collection cycle
State Estimation
Core of Power System Monitoring and Operations

- Static
- Interval of minutes
- Time-skewed data

Source: L. Jones, AREVA
Weighted Least Square State Estimation

- Nonlinear Optimization Problem
  - Maximum Likelihood Weighted Least Squares (WLS) method
  - Weighted Least Absolute Value (WLAV)
    - LP problem (Simplex, Karmarkar)
- Our focus is on the WLS method
  - Iterative procedure requires a solution of a large sparse set of linear equations $A\Delta x = b$ obtained through linearization in each iterative step of Newton-Raphson
- The main computational effort is the solver of linear equations – highly irregular sparsity patterns
  - **Direct Methods** give fast solution on a serial processor but offer **limited coarse-grain parallelism**
  - **Iterative Methods** are slower on serial processor but offer **higher coarse-grain parallelism**

WLS Method

\[ z = h(x) + e \]

Truncated Taylor series expansion:

\[ z = h(x^*) + H(x^*)\Delta x + e \]

\[ H = \frac{\partial h(x)}{\partial x} \bigg|_{x=x^*} \]

Min \( (z-h(x))^\top R^{-1}(z-h(x)) \)

\[ x^{k+1} = x^k + A (z-h(x^k)) \]

\[ A = [H^\top R^{-1}H]^{-1}H^\top R^{-1} \]

R – noise covariance matrix
z – measurement vector
H – Jacobian matrix of h
x – state vector (voltage&angle)
h – nonlinear function
Architectural Considerations

- Characteristic of the problem
  - need for near real-time operation
  - Problem sizes not very big + fine grain computations
  - Irregular communication
- Focus on shared-memory multiprocessor systems rather than on clusters
- SGI Altix with 128 1.5 GHz Itanium-2 CPUs
  - Shared memory programming models
    - Pthreads, OpenMPI, System V shared memory
  - Standard MPI distributed memory programming model
- Cray MTA-2 multithreaded system
Parallel WLS State Estimation

- Critical to accelerate solution of the Weighted Least Square Algorithm
  - Solve very large problems >10,000-100,000 bus systems
  - Exploit emerging systems with multi-core processors
    - Rely on efficiency of shared memory communication
    - Such systems will be broadly available and affordable to industry

- Solution of Sparse Linear System of Equations is the core computational kernel in the WLS algorithm

- Deployed State-of-the-art Direct Solvers
  - SuperLU is frequently used for solving PDEs

- SGI Altix shared memory system
  - Multithreaded version of SuperLU
  - MPI version slower
    - SGI MPI (shared memory)

<table>
<thead>
<tr>
<th># Processors vs. Programming Model</th>
<th>1</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT-SuperLU</td>
<td>0.209s</td>
<td>0.147s</td>
<td>0.169s</td>
</tr>
<tr>
<td>MPI-SuperLU</td>
<td>1.106s</td>
<td>1.102s</td>
<td>1.102s</td>
</tr>
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</table>
Ordering Scheme and Speedup

Approximate Minimum Degree Produces Best Speedups!
Ordering Scheme and Time to Solution

Multiple Minimum Degree
Is FASTEST
BUT
Not Much Faster Than
Serial Algorithm
Conjugate Gradient in State Estimation

Shared memory version of Conjugate Gradient

- Load balancing in the sparse matrix-vector product
- Experimental evaluation on the SGI Altix shared memory system
- Better performance and scalability compared to SuperLU package (both multithreaded and MPI versions)

![Graph showing execution time vs. number of processors for SuperLU and our CG]

Full State Estimation on Cray MTA-2

- Cray MTA-2 parallel multithreaded architecture
- Parallelization of the full WLS State Estimation Code done based on Cray language directives
- WECC model simplified: ~14000 buses
Challenges in Dynamic State Estimation

- Non-linearity of the model
- Large set of ODEs and Algebraic Equations
- Sparsity
- Real-time operation requirements
- Need solvers effective for the power system area
- Data management for telemetry data
- We are developing Extended Kalman Filter
Added Complexity of Problem Scales

Data Volume/Rate and State Estimation Requirements
- SCADA: ≈ 4 seconds ➔ 100 time speedup
  6 GB/day
- Phasor data: 1/30 second ➔ $10^4$ time speedup
  5 GB/day ➔ 3 TB/day

Problem Size
- Currently contingency analysis: N-1 only = ~20000 cases, BPA runs only 500 select cases every 5 minutes.
- N-2 = ~$10^8$; N-3 = ~$10^{12}$; N-4 = ~$10^{17}$ ➔ a Peta-scale problem

Other Factors
- Weather – load, wind power
- Environment
- …

It can not be solved with hardware and software currently used. We must explore advanced computing
Outlook into the Future
with HPC Power System Computation

Better Models and Simulation
- Model identification/validation/enhancement
- Topology/parameter estimation and identification
- Faster dynamic simulation

Better Monitoring
- Dynamic stability monitoring
- Response adequacy measurement and monitoring
- Power quality monitoring/enhancement

Better Control
- SPS/RAS design and operation
- Reactive power coordination
- Resource adequacy, commitment & scheduling
- Fault/outage management
Questions?