SAND2011-7226 C

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A Cascading Failure Simulator to Estimate Blackout Risk for Electric Power Infrastructure

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Project Goal

To develop a high performance cascading failure simulator which will provide grid operators with a real time estimate of blackout risk

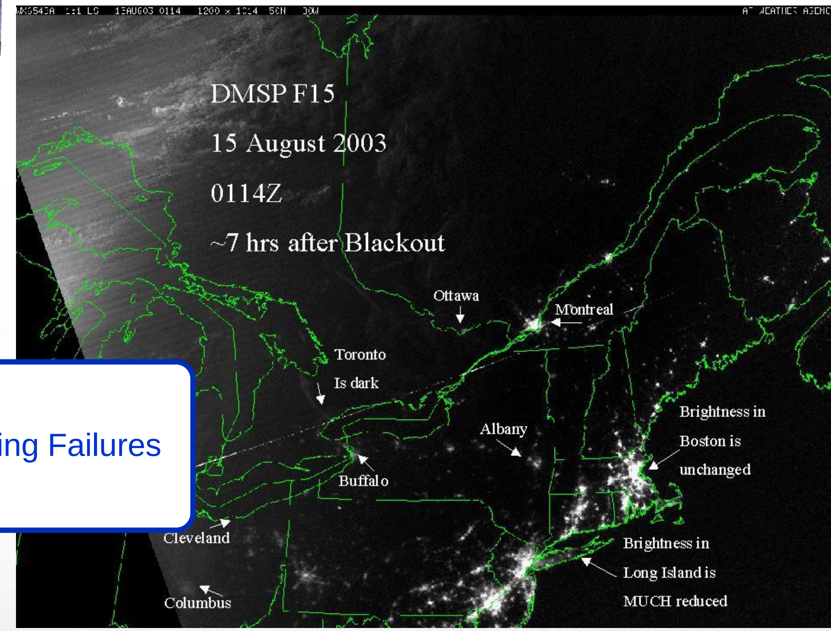
Outline

I. Cascading Failures in the Electric Power Grid
II. Modeling a Power System with DAEs
III. Risk Estimation
IV. Solving a System of DAEs
V. Future Work

I. Cascading Failures in the Electric Power Grid

Disturbance → Distribution Grid → Small Outages

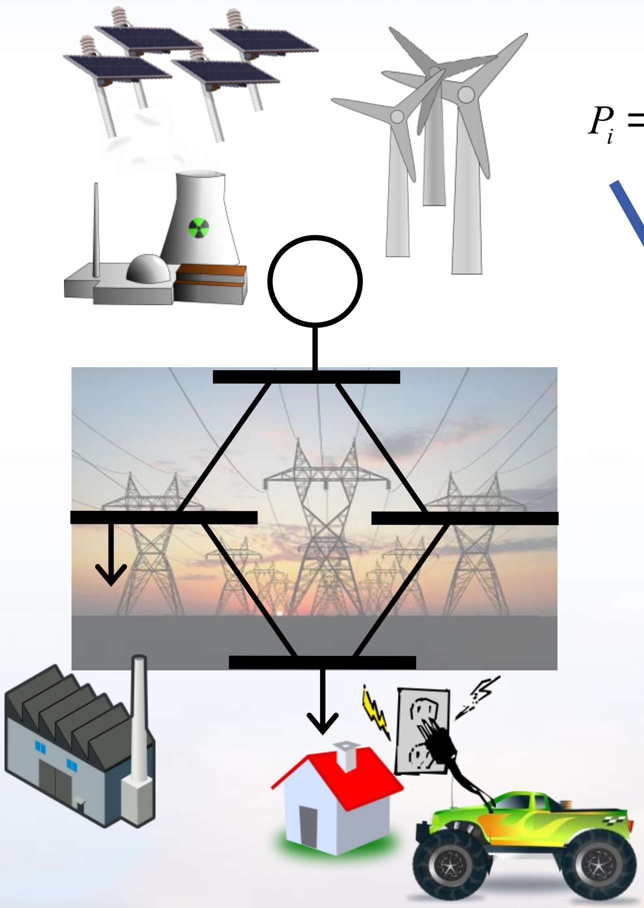
Disturbance → Transmission Grid → Cascading Failures



"Risk is the measure of the probability and severity of adverse effects" *(Lowrance, 1976)*

- $Risk_i = Pr(i) \times c(i)$

II. Modeling a Power System with Differential-Algebraic Equations



$$P_i = \frac{|E'_a||V_a|}{X'_d}\sin\delta + \frac{|V_a|^2}{2}\left(\frac{1}{X_q} - \frac{1}{X'_d}\right)\sin 2\delta$$

$$M\ddot{\delta} + D\dot{\delta} + P_i(\delta) = P_m$$

$$\dot{x}(t) = f(x(t), y(t), t)$$
$$0 = g(x(t), y(t), t)$$

$$P_i = \sum_{k=1}^{n} |V_i||V_k|\left(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}\right)$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|\left(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}\right)$$

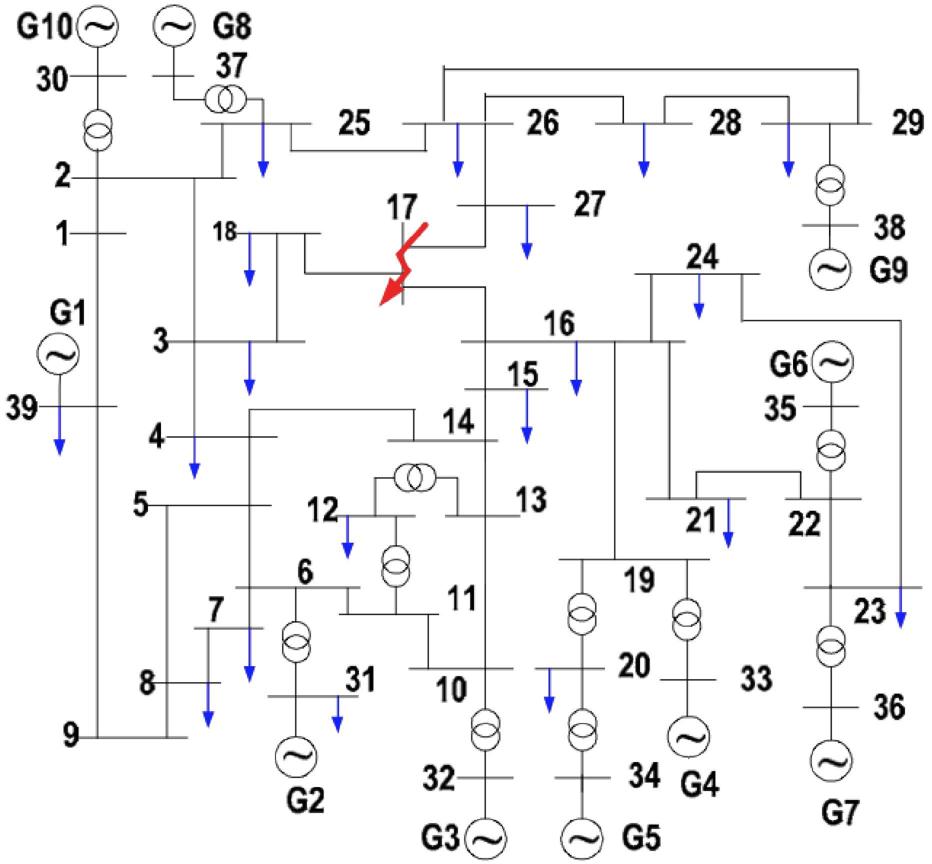
$$P_i = \sum_{k=1}^{n} P_{base}|V_i|^{\gamma}$$

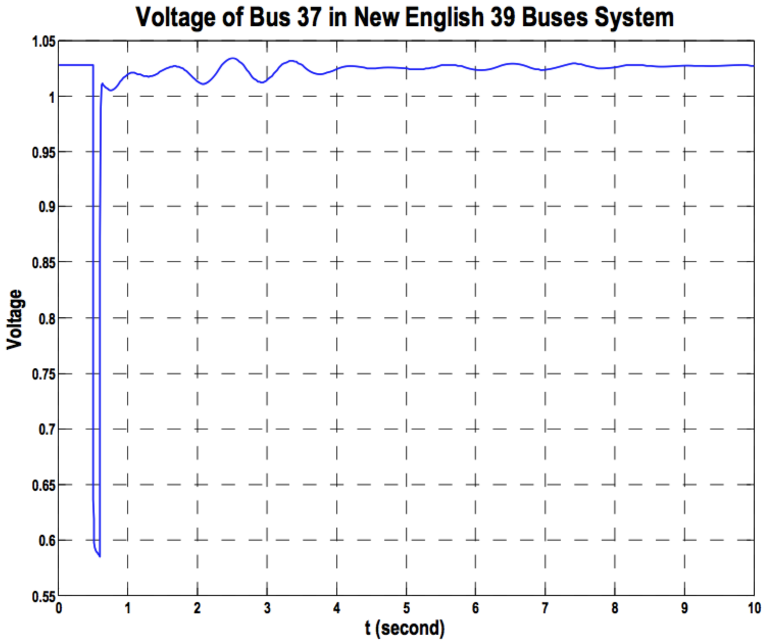
$$Q_i = \sum_{k=1}^{n} Q_{base}|V_i|^{\gamma}$$

II. Modeling a Power System with Differential-Algebraic Equations

Test case: New England 39 buses, 10 generators

Event: Fault on bus 17 lasting for 0.1 seconds





McCalley et al. 2010, Siemens PSS/E

II. Modeling a Power System with Differential-Algebraic Equations

Test case: New England 39 buses, 10 generators

Event: Fault on bus 17 lasting for 0.1 seconds

T1: 0 – 0.5 sec

2 LU decompositions

12 solutions of linear systems

T2: 0.5 – 0.6 sec

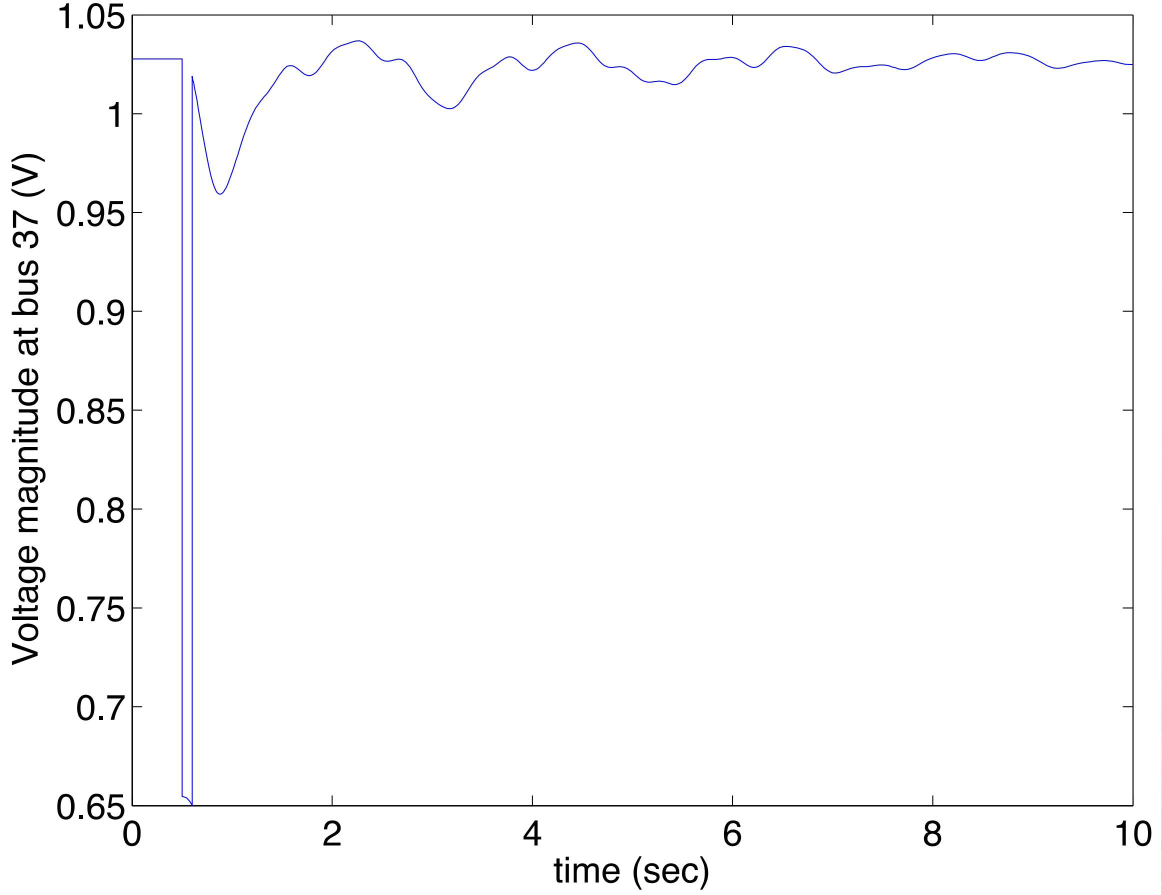
6 LU decompositions

20 solutions of linear systems

T3: 0.6 – 10 sec

91 LU decompositions

737 solutions of linear systems



III. Risk Estimation

- Importance Sampling (IS) is a method that improves the estimation of rare events by using modified sampling densities, which are constructed to improve the estimation of a statistical response of interest.

$$\mathrm{E}(r(X)) = \int r(x) f_X(x)\, dx \qquad \hat{\mathrm{E}}_{\mathrm{n}}(r(X)) = \frac{1}{n}\sum_{i=1}^{n} r(x_i)$$

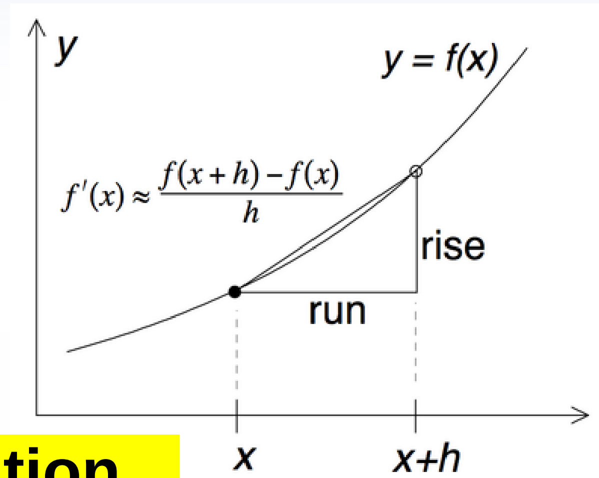
$$\mathrm{E}(r(X)) = \int r(x)\frac{f(x)}{h(x)}h(x)\,dx = \hat{\mathrm{E}}_h\left[r(X)\frac{f(X)}{h(X)}\right] = \frac{1}{n}\sum_{i=1}^{n}\frac{r(x_i)f(x_i)}{h(x_i)},\ x_i \sim h(X)$$

IV. Solving a System of DAEs

DAE

$$f(t, x, \dot{x}) = 0$$

$$\dot{x} = \frac{\sum_{i=0}^{q} \alpha_{n,i} \boldsymbol{y}_{\boldsymbol{n-i}}}{\Delta \boldsymbol{t}}$$

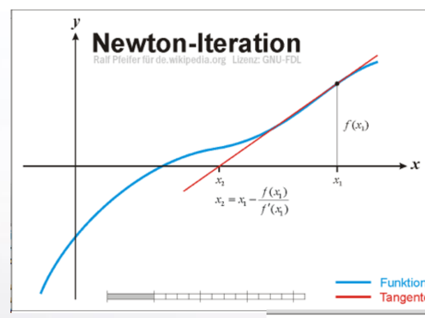


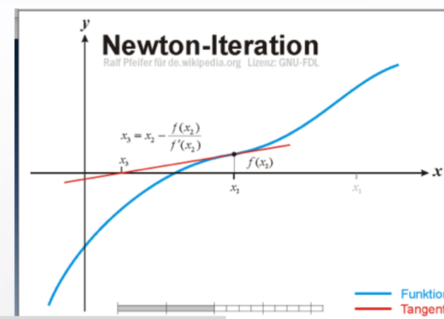
tep advance could ving hundreds tions!

Nonlinear Algebraic Equation

$$\boldsymbol{f}\left(\boldsymbol{t}, \boldsymbol{x}, \frac{\sum_{i=0}^{q} \alpha_{n,i} \boldsymbol{y}_{\boldsymbol{n-i}}}{\Delta \boldsymbol{t}}\right) = 0$$

Newton-Iteration

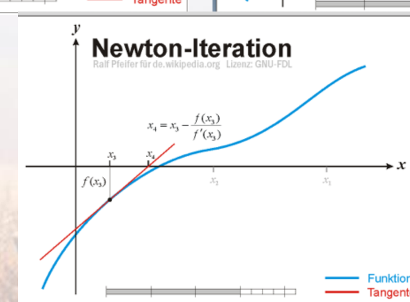




System of Linear Equations

$$(x_{n+1} - x_n) = -\boldsymbol{J}(\boldsymbol{x}_{\boldsymbol{n}})^{-1} F(x_n)$$

$$x = \boldsymbol{A}^{-1} b$$



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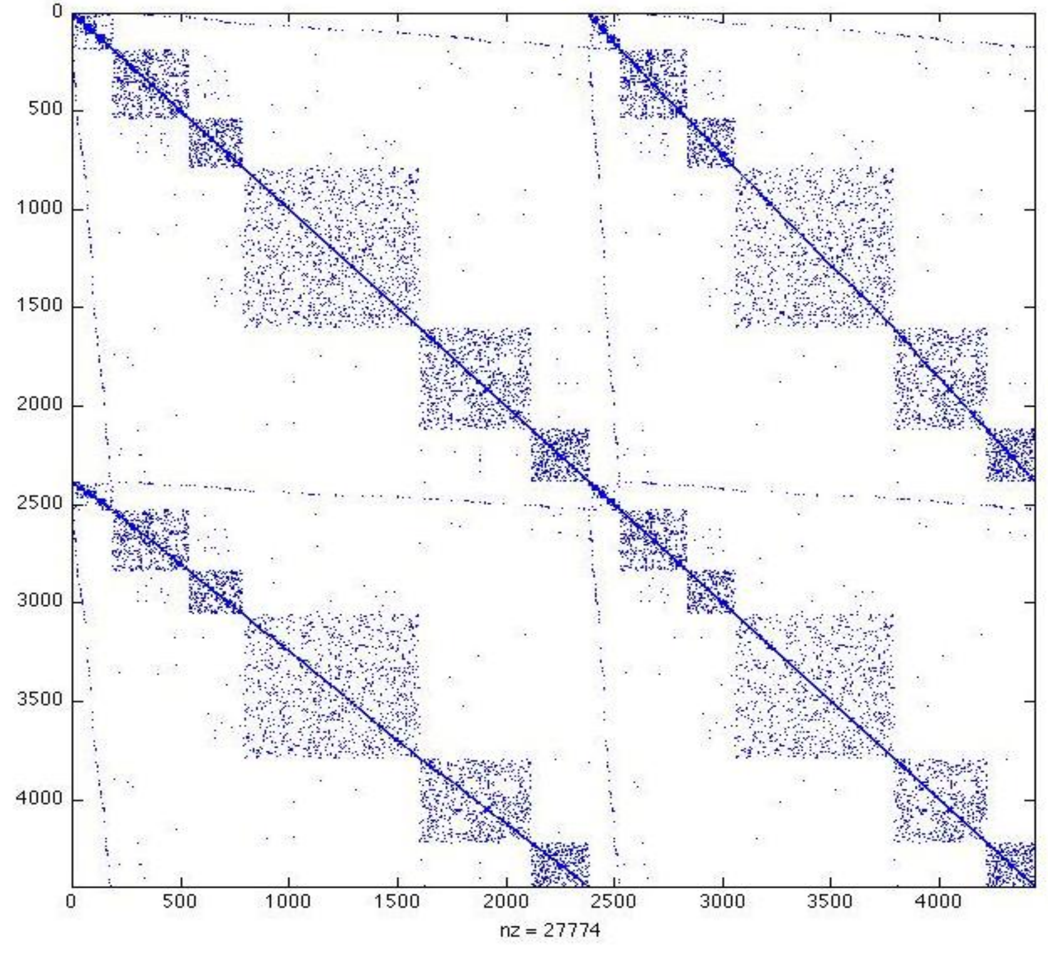
IV. Solving a System of DAEs
Power Flow Jacobian, Polish Power Grid



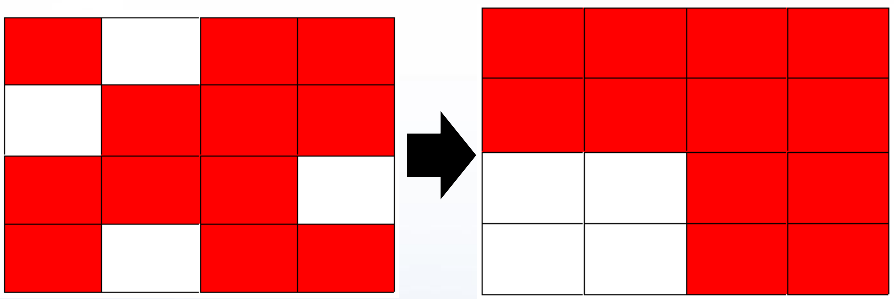
- **Sparse, only 0.001% of entries are non-zero**
- **4439 x 4439 (relatively small)**

IV. Solving a System of DAEs
Solving Ax = B

Symbolic Factorization

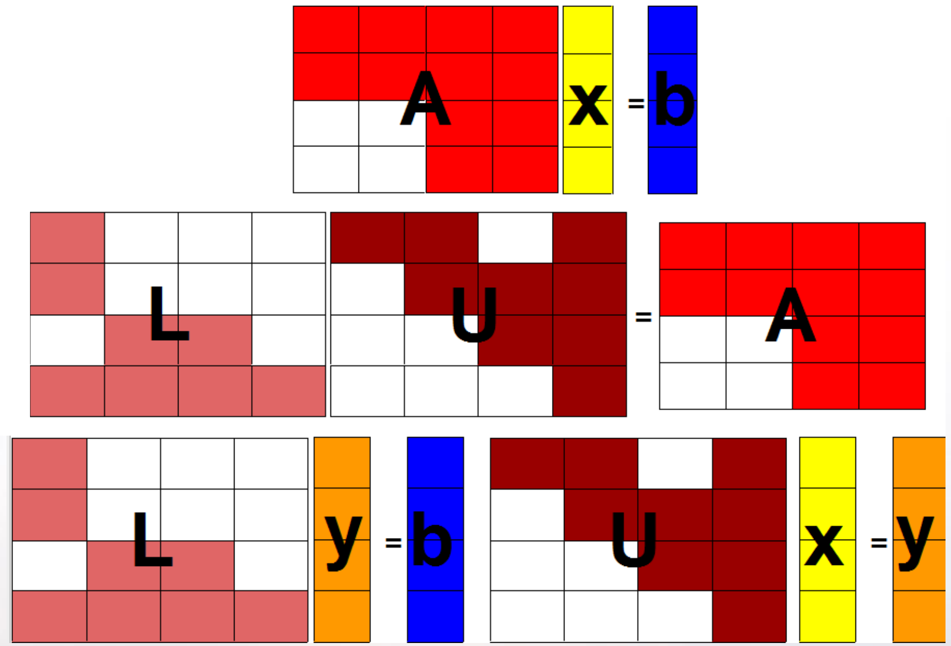
Rearrange A to make LU Decomposition easier

Original A **Ordered A**



Numeric Factorization

Decompose A into LU Matrices and solve



IV. Solving a System of DAEs
Linear Solver Comparison

	UMFPACK	LAPACK	Default KLU	SUPERLU
Symbolic Factorial Time	0.0049	0	0.0029	0
Numeric Factorial Time	0.0197	6.40	**0.0036**	0.0155
Total Time	0.033	6.44	0.010	0.016
Speed up	1	0.003	**5.47**	1.27

KLU - Developed by Tim Davis, Sandia Contractor for Xyce Circuit Simulator

Xyce™ PARALLEL ELECTRONIC SIMULATOR

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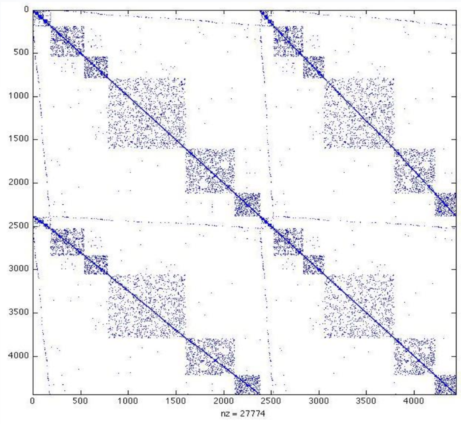
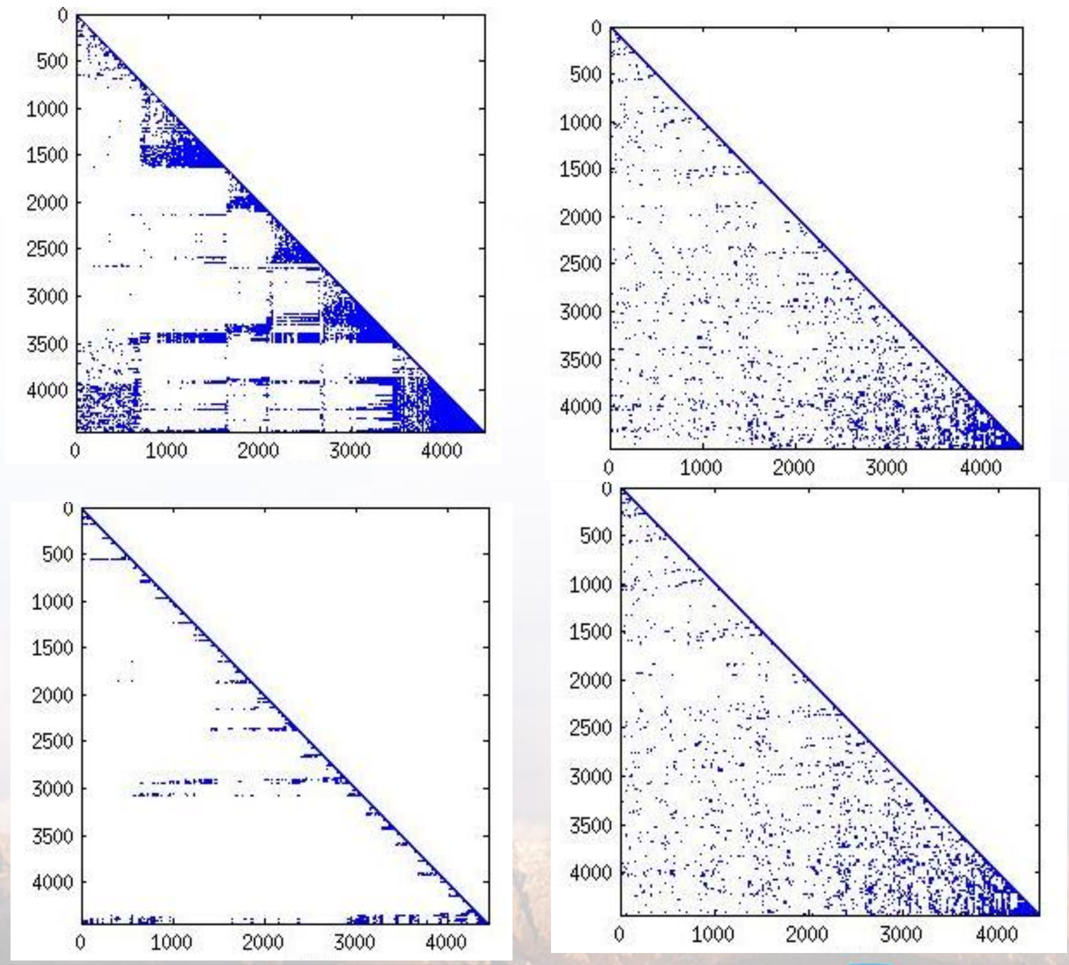
IV. Solving a System of DAEs
Evaluating KLU Algorithms



Non-zero structure of 4 Jacobian Decompositions



6x less memory allocation (more zeros)

64x less floating point operations

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IV. Solving a System of DAEs

DAE

$$f(t, x, \dot{x}) = 0$$

Nonlinear Algebraic Equation

$$\boldsymbol{f}\left(\boldsymbol{t}, \boldsymbol{x}, \frac{\sum_{i=0}^{q} \alpha_{n,i} \boldsymbol{y}_{\boldsymbol{n-i}}}{\Delta \boldsymbol{t}}\right) = 0$$

System of Linear Equations

$$(x_{n+1} - x_n) = -\boldsymbol{J}(\boldsymbol{x}_{\boldsymbol{n}})^{-1} F(x_n)$$

$$x = \boldsymbol{A}^{-1} b$$

System of Linear Equations

Completed – Using KLU solver with Block Triangular Form and Approximate Minimum Degree Ordering

IV. Solving a System of DAEs
Future Numerical Work

DAE

$$f(t, x, \dot{x}) = 0$$

Next: Optimize DAE solver from *Sandia's Trilinos Packages*

Nonlinear Algebraic Equation

$$\boldsymbol{f}\left(\boldsymbol{t}, \boldsymbol{x}, \frac{\sum_{i=0}^{q} \alpha_{n,i} \boldsymbol{y}_{\boldsymbol{n}-\boldsymbol{i}}}{\Delta \boldsymbol{t}}\right) = 0$$

Newton-Raphson non-linear solver
Completed – Using Trilinos NOx

System of Linear Equations

$$(x_{n+1} - x_n) = -\boldsymbol{J}(\boldsymbol{x}_{\boldsymbol{n}})^{-1} F(x_n)$$

$$x = \boldsymbol{A}^{-1} b$$

System of Linear Equations
Completed – Using KLU solver with Block Triangular Form and Approximate Minimum Degree Ordering

V. Future Work

- Incorporate advanced devices to the electric grid model (relays, exciters, governors…)
- Scale up the test simulations up to Eastern Interconnect grid size
- Integrate the Importance Sampling strategies through Sandia's Dakota software
- Continue optimizing the numerical techniques with Sandia's Trilinos software

Thanks for your attention

Questions? Comments?