Project Presentations

Thu (2 days) Sheng, Emily, Tingfeng, Mack, Jinghan.

Tue (4 days) Megan, Charles, Justin, Patrick, Joshua.

* Tue was oversubscribed. Selection via lottery. Sorry to all who did not get preferred days. Slot allocation OK.

* Title + Abstract update: By 8am day of presentation.
  → If you have link to your slides, please send → will be announced.
  → Anno email will be sent some day as talk.

* Format 8+5: 8 mins presentation, 5 mins Q+A.
  → If you need special accommodations, contact me asap.
  → Not going to be recorded.

* All attendees are judges:
  → Please ask questions to gauge quality. (±1% per good Q, ±1% per good A, 10% combined cap. This is your chance to fill up your participation points!!)
  → Select best presentation. End of all presentations: motion to nominate, debate, vote. Prof reserves nominal veto.
  → Judgement criteria: * Originality + creativity → Is the talk interesting?
  * Clarity of presentation; organization of materials → Did you learn something?
  * Knowledge of material → Is the speaker convincing?

* Scores will be posted on Compass.
12/1 Course Summary

1. Overview of Power System Analysis. ← Why?
2. Power Sys Models. ← What?
3. Linear Eqn
5. Lin & nonlin LSA.

Interconnection dramatically improves Reliability

Longer distance improve economies of scale. → cheaper resources further away. → efficiency. 
→ large scale interconnection → reliability.
→ Save $$$$$$ → ENORMOUS SOCIETAL BENEFIT.
\[ P = VI \cos(\theta_v - \theta_i) \]

\[ \bar{V} = V e^{j\theta_v} \]
\[ \bar{I} = I e^{j\theta_i} \]
\[ \Rightarrow P = \text{Re}\left\{ \bar{V} \bar{I} * \right\} \]

Define complex/voltage power to cope with AC.

Complex power

Power sharing:
- Droop control
- Frequency control

“droop control”

\[ I_1 \quad \text{or} \quad \frac{1}{R_1} \quad \text{or} \quad \frac{1}{R_2} \quad \leq \quad \text{DC (current balance)} \]

AC \rightarrow (frequency balance)

3600 rpm

AC

Load

Voltage \approx\text{torsional strain}

\[ X_1 \quad \text{or} \quad X_2 \]

\[ \text{transient stability} \quad \text{ensures dynamical safety} \]

\[ \text{power flow} \]

Solves AC coordination problem.

Makes large-scale AC possible!!

Unlocks long distances & economies of scale \Rightarrow efficiency + reliability \Rightarrow $$$

Generators don’t play nice

Hard to maintain voltage/current limits.

\[ P = VI \cos(\theta_v - \theta_i) \]
\[ \begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \\ \dot{v}_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \]

\[ S_{ik} = v_k \cdot i_k^* = P_k + jQ_k, \quad v_k = u_k e^{j\theta_k} \]

\[ p_1 + jq_1 = u_1 e^{j\theta_1} \left( Y_{11} u_1 e^{j\theta_1} + Y_{12} u_2 e^{j\theta_2} + Y_{13} u_3 e^{j\theta_3} \right) \]

etc for \( p_2 + jq_2, p_3 + jq_3 \).

\[ \theta_1 = \bar{\theta}_1 \quad u_1 = \bar{u}_1; \quad u_2 = \bar{u}_2 \]

\[ p_1(\theta_1, \theta_2, \theta_3; u_1, u_2, u_3) = \bar{p}_1 \]

\[ p_2(\theta_1, \theta_2, \theta_3; u_1, u_2, u_3) = \bar{p}_2 \]

\[ p_3(\theta_1, \theta_2, \theta_3; u_1, u_2, u_3) = \bar{p}_3 \]

\[ q_1(\theta_1, \theta_2, \theta_3; u_1, u_2, u_3) = \bar{q}_1 \]

\[ q_2(\theta_1, \theta_2, \theta_3; u_1, u_2, u_3) = \bar{q}_2 \]

\[ q_3(\theta_1, \theta_2, \theta_3; u_1, u_2, u_3) = \bar{q}_3 \]
AC PF: \( x = [\theta, u] \), \( F(x) = \left[ \frac{\partial q(\theta, u)}{\partial \theta} - \hat{\theta}, \frac{\partial q(\theta, u)}{\partial u} - \hat{u} \right] = 0 \)

Linearization: \( F(x) \approx F(\hat{x}) + \left[ \nabla F(\hat{x}) \right] (x - \hat{x}) \)

\( \text{Jacobian. linear} \)

\[ p(\theta) + \nabla p(\theta)(\Theta - \Theta) = \left[ \nabla p(\Theta) \right] \Theta \]

DC PF Solution \( \rightarrow \) ACPF Solution

AC PF: \( u_1 e^{\theta_1}, u_2 e^{\theta_2} \) linearize \( \rightarrow \) PQ \( \rightarrow \) Slack \( \hat{u}_1, \hat{\theta}_1, \hat{u}_2, \hat{\theta}_2 \)

Find \( \Theta, u \)
\[ \text{s.t. } p(\Theta, u) = \hat{P}, \quad \text{nonlinear.} \]

DC PF: \( \Theta, \hat{u}_1, \hat{\theta}_1, \hat{u}_2, \hat{\theta}_2 \)

Find \( \Theta \)
\[ \text{s.t. } \left[ \frac{\partial p(\Theta)}{\partial \Theta} \right] \Theta = \hat{P}, \quad \text{(no losses, no capacitors)} \]

(\( \Theta \))
Algorithm (Gaussian Elimination)
Input: $n \times n$ matrix $A$, $n \times 1$ vector $b$
Output: $n \times 1$ vector $x$ satisfying $Ax = b$.
1. Compute $A = P^T L U \leftarrow$ factor $O(n^3)$
2. Solve $L y = Pb$ via backsub.
3. Solve $U x = y$ via backsub.

Gain changer: Exploit sparsity, factor and backsub $O(n)$ time.

If $A^t$ exists, then $A = PLU$

Upper Triangular. $\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 5 \\ 6 \end{bmatrix}$

Lower Triangular. $\begin{bmatrix} 1 & 0 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 5 \\ 6 \end{bmatrix}$

$y = 6/4, x = 5 - 2(6/4)$.

$x = 5, y = [6-3(5)]/4.$
Case Study: 13,659-bus European model

Hardware: 2013 Macbook Air - 1.7 GHz Intel Core i7
- 8 GB 1600 MHz DDR3

13,659 x 13,659 DENSE matrix
1.49 GB for 186,568,281 elements

1. \[ x = A \backslash b \];
2. \[ [L, U, P] = lu(A); \]
   \[ y = L \backslash (P*b); x = u\backslash y; \]

47.938 seconds
47.514 seconds
2.234 seconds

13,659 x 13,659 SPARSE matrix
923 kB for 50,909 nonzeros

1. \[ x = A \backslash b \];
2. \[ [L, U, P, Q] = lu(A) \]
   \[ y = L \backslash (P*b); x = Q*(u\backslash y); \]

0.044698 seconds
0.044862 seconds
0.001752 seconds
Project Presentations

\[ F(x) = 0 \quad \Rightarrow \quad x \leftarrow x - [NF(x)]^{-1} F(x) \]

Quadratic convergence: \(< 10 \) iters to machine precision
But needs good initial guess.

Stiffness: Separation of timescales.

\[ \text{future} = F(\text{now}) \quad \Rightarrow \quad \text{Our problem} \]
\[ F(\text{future, now}) = 0 \quad \text{Solve for future} \]

Differential Algebraic Equation (DCAE) models.

\[ \begin{align*}
\dot{x} &= Ax + Bu, & o &= Cx + Dv \\
\text{State variable.} & \quad \text{algebraic var} \quad \text{(dynamic) (always steady state)}
\end{align*} \]

\[ (\text{reduction}) \quad \dot{x} = (CA - BD^{-1}C)x \leftarrow \text{nonstiff ODE} \]
**Static model**

Slack \( v_1, v_2 \), PQ

\[ i = Yv \]

**Network equations**

**Boundary Conditions**

Slack \( \rightarrow v_1 = V_1 \)

PQ \( \rightarrow v_2 i^* = S_2 \)

**Dynamic model**

\( v_1(t), v_2(t) \)

\[ i_1(t), i_2(t) \]

**Network equations**

**Steady-State**

(infinity fast)

**Dynamical behavior**

(slow)

**Device models**

\[ \dot{x}_1 = f_1(x_1, v_1) \]

\[ i_1 = g_1(x_1, v_1) \]

\[ o = f(x_2, v_2) \]

\[ i_2 = g(x_2, v_2) \]

**State variables:** Mechanical quantities (electromech)

**Algebraic variables:** Electrical quantities (electromagnetic)

Assume Electrical quantities are infinitely fast w.r.t mech.

\[ \times \] Most important: capture mech instabilities.

\[ \times \] EMT simulation avoid this assumption, much slower
General approach for Index-1 DAEs.

State equation
\[ \dot{x} = f(x, v), \quad \sigma = g(x, v) - Yv \]

algebraic equation

State variables

Assume \( \delta g/\delta v - Y \) is invertible

\[ \dot{x} = f(x, \phi(x)) \quad \text{where} \quad v = \phi(x), \quad Yv = g(x, v) \]

Implicit function

\[ \text{Newton-Raphson??} \]

RK 1 (Explicit Euler)
given \( x(t) = [\delta_1, w_1, \delta_2, w_2, \delta_3, w_3] \)

1. \( v(t) = \phi(x(t)) \rightarrow \text{compute s.s. voltages} \rightarrow [v_1, v_2, v_3] \)
2. \( \dot{x}(t) = f(x(t), v(t)) \rightarrow \text{compute torques} \rightarrow [\dot{\delta}_1, \dot{w}_1, \dot{\delta}_2, \dot{w}_2, \dot{\delta}_3, \dot{w}_3] \)
3. \( x(t + h) = x(t) + h \dot{x}(t) + O(h^2) \)

\[ x_{\text{final}} = x_{\text{initial}} + h \dot{x}_{\text{final}} \]

\[ x_{\text{final}} = x_{\text{initial}} + h \dot{x}_{\text{final}} \]

Diagram:

- \( E_1 \leq \delta_1 \)
- \( E_2 \leq \delta_2 \)
- \( E_3 \leq \delta_3 \)

\[ \text{P}_{\text{mech}}_1, \text{Re} \text{f}_{v.i^*} \]

\[ \text{P}_{\text{mech}}_2 \]

\[ \text{P}_{\text{mech}}_3 \]
\[ x(t) = [\delta(t), \dot{\delta}(t)] \]

**Network Equations**

\[ i(t) = -v(t) \]
\[ Y v(t) \]
\[ \leftarrow i(t) \]

**Generator Model**

\[ x(t) = f(x(t), v(t), E(t), P_{\text{mech}}(t)) \]
\[ i(t) = g(x(t), v(t), E(t)) \]

**Controller Models**

- **Exciter**
  - Auto Voltage Regulator
  - Response time: ms

- **Governor**
  - Response time: s

*Exciter: Regulate excitation to maintain output voltage, dynamically respond to improve stability.\)

*Governor: Help provide frequency response when power mismatch.*

Good luck on your projects!