Numerical Methods for Simulating Electric Power Systems Revisited

Marriage of Physics-Based Rigor and Data-driven Learning?

Marija D. Ilić
Professor, ECE and EPP
Carnegie Mellon University
October 15, 2015
PaiFest, UIUC
Pai and my CMU students; Springer editor Alex Greene--2012
Pai and Nandini with my former MIT students--2015
The way it is... changes under way...

**The way it is...**
- small systems rigor
- challenge of real-world systems
- fundamental role in control room

**Changes under way**
- parallel processing inherent (distributed decisions driven); object oriented—Ian mentioned
- big challenge of numerical “seams”
- changing role of numerical methods
Small systems rigor

- Rigorous modeling, analysis and simulations—the basis for linking physics and analysis in a system with little or no on-line data
- Use for educating ourselves and students how electric power systems work; make up for the inability to have hardware tests
- Plugged with modeling assumptions which, in turn, lead to hard technical problems but, at the same time, have been hard to verify
The most general system model (includes protection, control saturation)

\[
\frac{dx(t)}{dt} = f(x(t), y(t), d(t), t)
\]

and

\[
g(x(t), y(t), d(t), t) = 0 \quad h(x(t), y(t), d(t), t) \leq 0
\]

with

\[
f(x(0), y(0), d(0), 0) = 0
\]
Secure regions---overall technical objective

- The security region $S$ is then a set of initial states $\theta(0) = [x(0), y(0), d(0)]$ which satisfy the general dynamic model for the set of disturbances $d(t), t \geq 0$

$$S = \theta(0)|\frac{dx(t)}{dt} = f(\theta(t), t) ; h(\theta(t), t) \leq 0$$

- In order to find such a limit normally requires a sequence of simulations which repeatedly vary generation torque.
Modeling issues

- Different sub-models used for analyzing whether different operating sub-objectives are met
- Different remedial actions will be needed depending on the sub-models used.
- Conclusions regarding ability to meet operating objectives very sensitive to models used—models are *not* the real-world systems!

Real world---Partial differential equations—ordinary differential equations-algebraic equations

The case of: ODE-based nonlinear model stable; algebraic equations (constant PV, PQ---power flow)—multiple solutions; no solutions; robust/non-robust
Can our model capture system operating objectives---generation supply load?
Effects of load modeling in analyses results
Simulation setup for assessing operating sub-problems

--- The puzzle of PQ load model...

\[ \dot{x}_i = f_i(x_i, p_i, u_i) \]
\[ \dot{x}_j = f_j(x_j, p_j, u_j) \]

\[ x_i = \begin{bmatrix} i_{Sd1} \\ i_{Sq1} \\ i_{R1} \\ \omega_1 \\ \theta_1 \end{bmatrix} \]
\[ p_i = \begin{bmatrix} v_{Sd1} \\ v_{Sq1} \end{bmatrix} \]
\[ u_i = \begin{bmatrix} v_{R1} \end{bmatrix} \]

\[ x_j = \begin{bmatrix} q_{TLLd2} \\ q_{TLLq2} \\ i_{TLMd2} \\ i_{TLMq2} \\ q_{TLRd2} \\ q_{TLRq2} \end{bmatrix} \]
\[ p_j = \begin{bmatrix} i_{inLd2} \\ i_{inLq2} \\ i_{inRd2} \\ i_{inRq2} \end{bmatrix} \]
Simulation setup for assessing operating sub-problems

--- The puzzle of PQ load model...

\[
x = \begin{bmatrix} x_i \\ x_j \end{bmatrix}
\]

\[
y^* = g(x^*) = \begin{bmatrix} P_L(T_M) \\ Q_L(T_M) \end{bmatrix}
\]

\[
\begin{bmatrix} P_L(T_M) \\ Q_L(T_M) \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{X_{TL}}V_1V_2 \sin \delta_{12} \\ \frac{1}{X_{TL}}(V_1V_2 \cos \delta_{12} - V_2^2) + b_{\text{shunt}}V_2^2 \end{bmatrix}
\]

\[
V_2 \angle \delta_2 = \begin{cases} V_2^s \angle \delta_2^s & \text{equilibrium set I} \\ V_2^u \angle \delta_2^u & \text{equilibrium set II} \end{cases}
\]

\[
\begin{cases} V_2^s \angle \delta_2^s \\ V_2^u \angle \delta_2^u \end{cases} \Rightarrow \begin{cases} x_j^s* \\ x_j^u* \end{cases}
\]

Two equilibria for the system
Simulation setup for assessing operating sub-problems

--- The puzzle of PQ load model...

**Equilibrium Set (Stable)**

\[
\begin{align*}
V_1 &= 1.0143 \\
\delta_1 &= -1.1227 \\
V_2 &= 1.0106 \\
\delta_2 &= -1.1424
\end{align*}
\]
Simulation setup for assessing operating sub-problems
--- The puzzle of PQ load model...

- Equilibrium Set (Unstable)

\[
\begin{align*}
V_1 &= 1.0143 \\
\delta_1 &= -1.1227 \\
V_2 &= 0.0778 \\
\delta_2 &= -1.3732
\end{align*}
\]
Back to physics?

- Which of these two is a *physical* solution—the one which has a stable dynamic response (if/how does one get from $x(0)$ to it)
- Is the equilibrium argument (based on physics) sufficient to tell us whether power produced can be delivered?
- Must understand fundamental transfer limits of the transmission line itself (lost science)
Transmission line limits? (Kevin Bachovchin)

\[
\begin{align*}
\dot{x}_j &= f_j(x_j, p_j, u_j) \\
\dot{x}_k &= f_k(x_k, p_k, u_k)
\end{align*}
\]

\[
\begin{bmatrix}
q_{TLLd} \\
q_{TLLq} \\
i_{TLMd2} \\
i_{TLMq2} \\
q_{TLRd2} \\
q_{TLRq2}
\end{bmatrix}
\quad \begin{bmatrix}
i_{inLd2} \\
i_{inLq2} \\
i_{inRd2} \\
i_{inRq2}
\end{bmatrix}
\quad \begin{bmatrix}
i_{Ld3} \\
i_{Lq3}
\end{bmatrix}
\quad \begin{bmatrix}
v_{Sd3} \\
v_{Sq3}
\end{bmatrix}
\]

\(\times\) denotes dependent capacitor charge (not a state variable)
Power Delivered to Load vs. Line Inductance

- Multiple simulations run, varying the transmission line inductance
- The reactive power delivered to the load is always zero (purely resistive load)
- The real power delivered to the load has a quadratic shape and is maximum with an inductance of 2.5 $\mu$H
Now instead of plotting the power vs. the line inductance, we plot vs. the resulting characteristic impedance of the line.

The real power delivered to the load is maximum when the characteristic impedance of the transmission line $Z_C$ matches the resistance of the load ($R_L = 5\,\text{m}\Omega$).
Power Out of Infinite Bus vs. Characteristic Impedance

- Real power out of the infinite bus matches the real power consumed by the load
- If $Z_C = R_L$,
  - reactive power out of infinite bus is zero
  - Reactive power consumed by inductor exactly cancels the reactive power produced by the capacitor
- If $Z_C < R_L$,
  - Infinite bus absorbs reactive power produced by line
- If $Z_C > R_L$,
  - Infinite bus produces reactive power consumed by line
Now we vary the resistance of the load $R_L$

- When $R_L = Z_C$,
  - Reactive power out of infinite bus is zero
  - However, the real power is not a maximum
  - We get more real power by reducing the load resistance

**Conclusion**: Condition for maximizing real power delivery is different when optimizing load resistance compared to optimizing line inductance
Unstable Simulation Due to Mechanical Torque

- The synchronous machine can cause the system to go unstable if the maximum $\tau_M$ is exceeded.
Unstable Simulation Due to Line Inductance

- The transmission line can also cause the system to go unstable if the maximum line inductance is exceeded.
Power into SM vs. Transmission Line Inductance Curve

- Real and reactive power affected much more by varying transmission line inductance than by varying mechanical torque.
Challenges and opportunities of physics-based rigor approach

- CMU approach--- Can not teach the role of “smarts” without understanding the root cause problem. We do it..
- The challenge— diverse background. Lost in rigor.
- Expectations--- the “magic” of smart grids..
- The challenge---*Must* put rigor in context with today’s students.
- Opportunity—use these methods to better understand the new systems (micro-grids)
Challenge of real-world systems

- Which of the phenomena we model and simulate can be used how?
- Very strong assumption---Perfect information
  - Accuracy of data
  - System parameters not known
- Scaling up problems
- Changing nature of industry
- Cyber security issues—virus will spread fast in a “flat” model
Fundamental role in control rooms--today

- The “culture” of computer applications in control centers based on the adopted modeling approach
- Integration of information across different programs (power market input insufficient to ensure physically reliable operation)
- Major role of numerical methods to facilitate this information exchange (wide open R&D area)
Changes under way..

- Potential to store data and understand temporal trends over different time scales and at different spatial granularity
- Utilities must account for the effects of user’s uncertainties
- Large body of work—in context of market simulations (transactive energy control, for example)
- Almost nothing on how dynamics needs
- Qualitatively different modeling, simulations approach
New Hardware, New Smarts?

- Penetration of new technology
  - Renewable generation
  - Storage
  - Distributed Generation (DGs)
  - PMUs and other sensors
  - Wire-based devices that can measure or actuate
The need for simulators of power system dynamics

**Manufacturers**
- Component model evaluation
- Parameter estimation
- Control tuning
- Protection verification

**Consumption**

**Generation**
- Integration studies
- Compliance with grid codes
- Power system stabilizer tuning
- Dynamic interactions against grid

**Transmission**
- Evaluate grid stability under contingencies
- Estimate stability margin
- Dynamic interactions between components

Source: www.sig-ge.ch
Numerical integration of PS dynamics in practice*

- **Traditional (industry-oriented)**
  - Three phase instantaneous time
    - EMTP
    - Matlab PST
    - GridLab-D
  - Single phase TVP domain
    - PSAT
    - Power Factory

- **Recent (cyber-enabled)**
  - Integration of existing solutions
    - Mosaik
    - SysML
  - Focus on cyber-physical
    - DETER
  - Heterogeneity driven
    - Modelica
    - SGRS

*Not a comprehensive list
Distributed implementation of SGRS

Design proposition:
1) Ensure high modularity
2) Each power system component behaves as a separate module

Benefits:
1) Simple to handle heterogeneity
2) Simple to add/remove components in runtime
3) Preserves privacy

Challenges:
1) scalability in terms of numerical integration speed (constrained by communications)

Source: www.sig-ge.ch

Computation: ~90%
Communication: ~10%
SGRS Framework Details

- Map power system to distributed simulation of power system modules
- Computational distribution abstracted away from user through implementation of interfaces in modules
- Simulation cluster managed by broker and scheduler algorithms
- Access to framework via web interface and remote connection
TE – Market for EVs

- Simulation of charging strategies for electric vehicles
- Different methods for smart charging:
  - Fast charging
  - MPC based charging – price taker; time of use; ALM
  - MDP based charging – ALM
- Cost comparison
The key challenge: Combining Dynamics and ALM

- Based on prices, market computes active power set points $P^*$ from each component
- Since currently the market does not specify reactive power set points $Q^*$, data for $Q^*$ is randomly created
- Place a voltage source inverter and a flywheel variable speed drive controller on the hydro and diesel generator buses
- Control the sum of the power out of the hydro and diesel generators to match the active and reactive power set points
Simulation Results – Wind Generator Bus

Stable Case:

Unstable Case:

Reactive Power Load Consumption

Wind Generator Bus Voltages

v\textsubscript{B2d}

v\textsubscript{B2q}
Back to basics---fundamental (new) challenges

- Market simulators “work” – strong assumptions (equilibria, no voltage problem)
- Can one extend these simulators to account for dynamics in a modular way?
- Standards and protocols for dynamics?
  - specifications based on physics-based rigorous modeling
  - numerical methods to support these simulators
From flat models to distributed models for dynamics?

- Data-driven predictions/learning at the distributed level
- Very detailed models at the distributed level
- At the system level — coarse information (range of power and rate of change of power)
- This is how AGC works today
- Need extensions to faster time scales — waveform relaxation-like exchange of information at the system level according to the well-defined protocols
Introducing Interaction Variables

\[
\dot{x}_i = f_i(x_i, x_j, u_i) \\
z_i = E_i(x_i) \\
x_i \to \begin{bmatrix} \bar{x}_i \\ z_i \end{bmatrix}
\]

Proposed interaction variables:
Accumulated energies $z_i, z_j$ as states of the model

\[
\dot{x}_j = f_j(x_j, x_i, u_j) \\
z_j = E_j(x_j) \\
x_j \to \begin{bmatrix} \bar{x}_j \\ z_j \end{bmatrix}
\]

Accumulated energy interaction variable

From physical state space to energy state space

Proposed approach - Communicate aggregated info

- Proposed approach:
  - Reduce communication rate by communicating the “right” information
  - We propose aggregate state variable (called interaction variable) as the “right” information to communicate

- Properties:
  - Straightforward combination with lower-level numerical integration methods
  - Automated approach (in contrast to n-order component models)
Module implementation – Method 1

Flow interactions coming from other modules at time \( K_i \)

- Compute interaction variable at \( K_i + 1 \) using internal states at \( \frac{\tau_i}{\tau_i} K_i \)
- Interaction at \( K_i + 1 \)
- Integrate internal states from \( \frac{\tau_i}{\tau_i} K_i \) to \( \frac{\tau_i}{\tau_i} (K_i + 1) \)
- Internal states at \( \frac{\tau_i}{\tau_i} (K_i + 1) \)
- Recompute interaction variable at \( K_i + 1 \) using internal states at \( \frac{\tau_i}{\tau_i} (K_i + 1) \)

Zoom-in level

Zoom-out level

Flow Interactions going toward other modules at time \( K_i + 1 \)
Module implementation – Method 2

Flow Interactions coming from other modules at time $K_i$

- Compute internal states at $K_i + 1$
  - Internal states at $K_i + 1$
    - Compute interactions at $K_i + 1$

Zoom-in level

Zoom-out level

Flow Interactions going toward other modules at time $K_i + 1$
Info to exchange? (generator)
Information to exchange from FACTS?
Full model vs. Method 2
Component $i$ – Generator

(a) Interaction variable $z_i$

(c) Flow interaction $p_i$

(e) Internal states $\bar{x}_i$
Full model vs. Method 2
Component $j$ – Transmission line
Relevance to utilities

- Distributed smarts (even at the power electronics switching rate) can be deployed and understood without danger of instabilities.
- Account for the effects of storage on system dynamics.
- Ensure QoS despite persistent fluctuations.
- Can be done so that the information is secure, and only minimal info about the interactions (defined by protocols and standards) exchanged.
Closing remarks..

❖ Need to marry different cultures
❖ Hard to “zoom in” (rigor) and “zoom out” (data-driven functionalities)

❖ Probably the two could be combined
  - instead of flat modeling/simulations assuming perfect information
  - combine with learning at the lower levels and design model-based standards and protocols for parallel processing at the system level