Equation–Free System-Level Dynamic Modeling and Analysis in Energy Processing

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Goals

Main goal - a comprehensive framework for system-level analysis that relaxes some conventional modeling assumptions.

Applications in energy processing - power systems, industrial electric drives, and power electronic systems.

Key characteristics - multi-physics, multi-scale systems; models sometimes contain proprietary and legacy code, logical variables and measurement-based data.

Bottom line - analytical scaffolding built around a component-level simulator, possibly including an equation-based approximate system-level description.

A motivating example

Transient stability in power systems often includes following modeling assumptions:

1. stator and network transients that are neglected,
2. either balanced operation or decoupled positive, negative and zero sequences
3. decoupled real and reactive loads,
4. simple mechanical models, including constant power input and rigid body motions for rotors,
5. simple models for magnetic saturation and for the effects of frequency variations.

Reasonable, but has to be established in advance.

Component-level (micro) descriptions

Physics-based, nonlinear models:

1. the nonlinear nature of energy transformations,
2. the need to make predictions based on extrapolations,
3. a long history of modeling components for design purposes, and
4. the need to organize prior information.

Some challenges:

1. insufficient data for reliable model ID,
2. objections to model fitting (“universal ODE”).

System-level (macro) descriptions

Model simplifications, “averaging” - reasonable in most cases, but may fail:

1. new components (DER),
2. non-standard component models (proprietary and legacy software, computer code with logical variables - protection)
3. uncertainties in parameter values, and
4. propagating faults (e.g., active adversary).

What if we use micro-level models throughout:

1. unwieldy because of size and complexity,
2. the answers would likely contain too much data.

History of System-level Modeling

Three paradigms, according to A. Mees:

1. *Newton*- modeling a system with a differential equation, and then providing a formula for the solution,
2. *Poincare* - explicit Differential / Algebraic equations, but no formula for solution - qualitative information obtained *directly* (e.g., stability),
3. *Algorithmic* - no explicit equations, but computer code; qualitative information obtained directly - computer-aided analysis (e.g., bursts of simulation).

Two-level Analysis

We do not have an explicit macro model, but we do have a micro level simulation model that can be initialized at wish - assume we are looking for steady-state at the system level:

1. Given the current state of the system $\mathbf{x}$, the time-stepper computes the future state $\mathbf{\Phi}(\mathbf{x};\tau)$ where τ is the “reporting time”,
2. Note that $\mathbf{x}(\tau) \equiv \mathbf{\Phi}(\mathbf{x};\tau)$
3. Consider $\mathbf{\Psi}(\mathbf{x}) \equiv \mathbf{x} - \mathbf{\Phi}(\mathbf{x};\tau)$ whose zeros correspond to steady states,
4. We would like to avoid the need to explicitly calculate the Jacobian $\mathcal{D}\mathbf{\Psi} \equiv \partial\mathbf{\Psi}(\mathbf{x})/\partial\mathbf{x}$ in a Newton-Raphson procedure; this is possible if we use matrix-free solvers for linear equations.

Two-level Analysis (2)

A closer look at the Newton-Raphson - given the current solution guess $\mathbf{x_c}$,

$$\mathbf{A} \cdot \mathbf{\Delta x} = \mathbf{b} \tag{1}$$

where $\mathbf{A} = \mathcal{D}\mathbf{\Psi} \mid_{x=x_c}$ and $\mathbf{b} = -\mathbf{\Psi}(\mathbf{x_c})$.

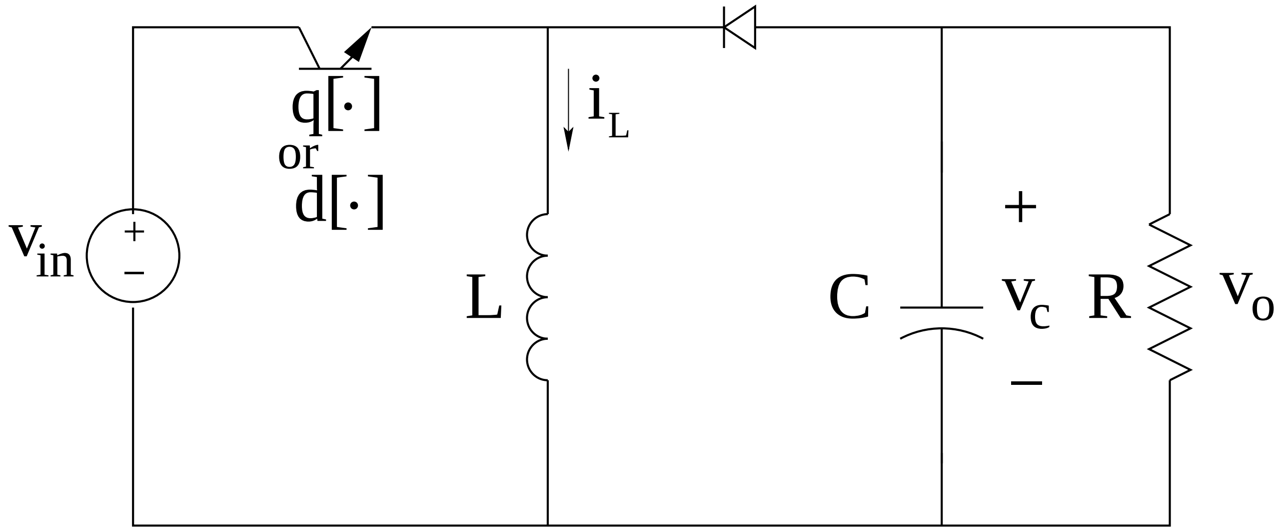
1. At each step of a matrix-free method, such as GMRES, that is solving (1), we do not need to explicitly calculate the Jacobian matrix $\mathbf{A}$. It always occurs in the form of a matrix-vector product $\mathbf{A} \cdot \mathbf{v}$.
2. We can use the finite difference approximation $\mathcal{D}\mathbf{\Psi} \cdot \mathbf{v} \approx [\mathbf{\Psi}(\mathbf{x} + \varepsilon \mathbf{v}) - \mathbf{\Psi}(\mathbf{x})]/\varepsilon$ for a suitably small ε.
3. We are motivated to precondition (1) using a regular matrix $\mathbf{P}$

$$\mathbf{P} \; \mathbf{A} \; \mathbf{\Delta x} = \mathbf{P} \; \mathbf{b} \tag{2}$$

We use *approximate* macro-level models to generate $\mathbf{P}$ that is close to $\mathbf{A}^{-1}$ - equation-assisted modeling.

Example

DC/DC power converter



Example (2)

Up/Down DC/DC power converter, micro (switched) model - let $x = [i_L \quad v_C]^T$ so

$$x[k+1] = \underbrace{\begin{bmatrix} 1 & \frac{(1-q[k])T}{L} \\ \frac{-(1-q[k])T}{C} & 1 - \frac{T}{RC} \end{bmatrix}}_{F} x[k] + \underbrace{\begin{bmatrix} \frac{Tq[k]}{L} \\ 0 \end{bmatrix}}_{G} v_{in}[k] \qquad (3)$$

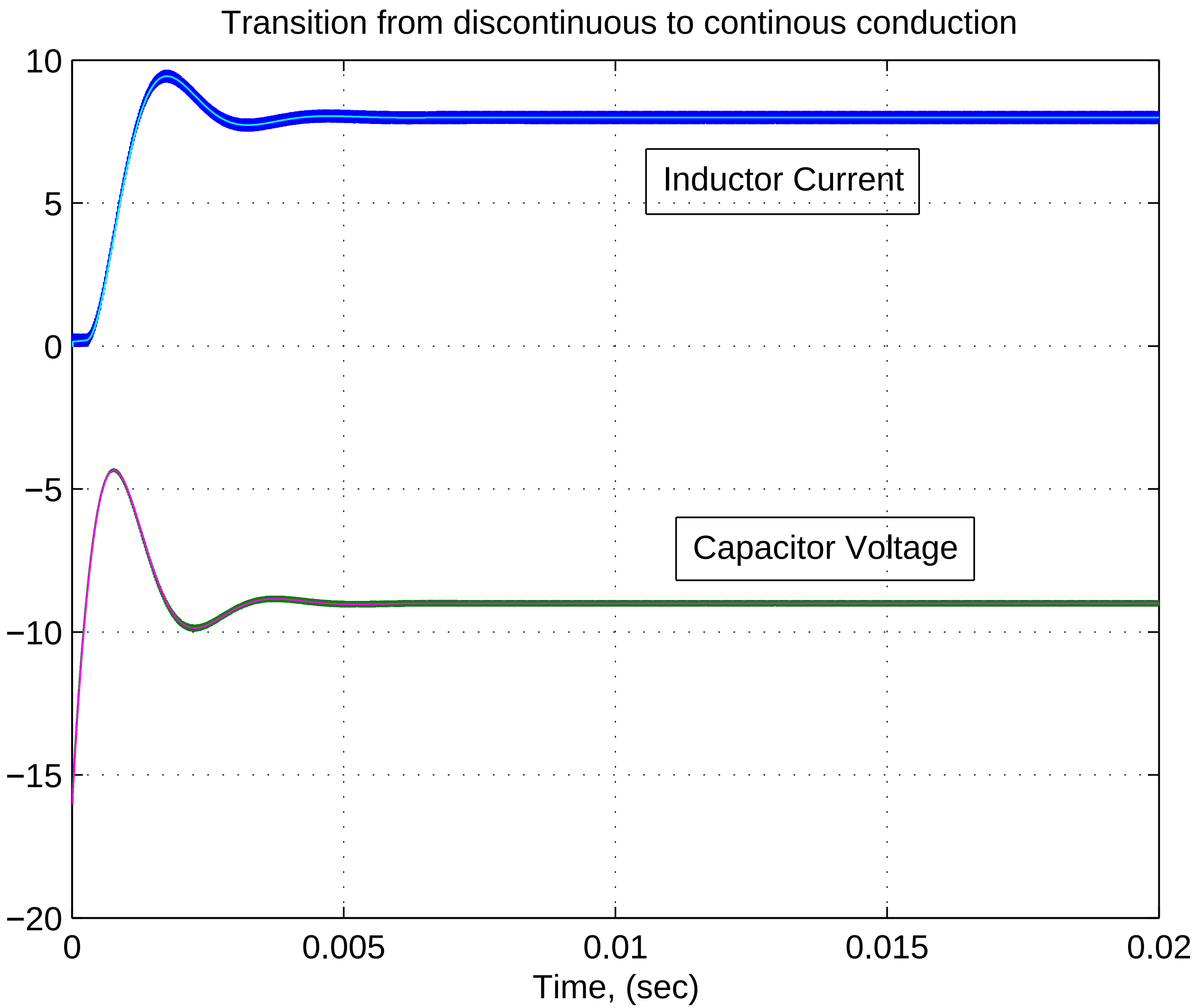
and $q[k]$ is the $(0-1)$ switching function in the k-th step.

The macro model, in continuous conduction is

$$x[k+1] = \left(1 - \frac{T_s}{RC}\right) x[k] + \frac{v_{in}^2[k] T_s^2 d^2[k]}{2LCx[k]} \qquad (4)$$

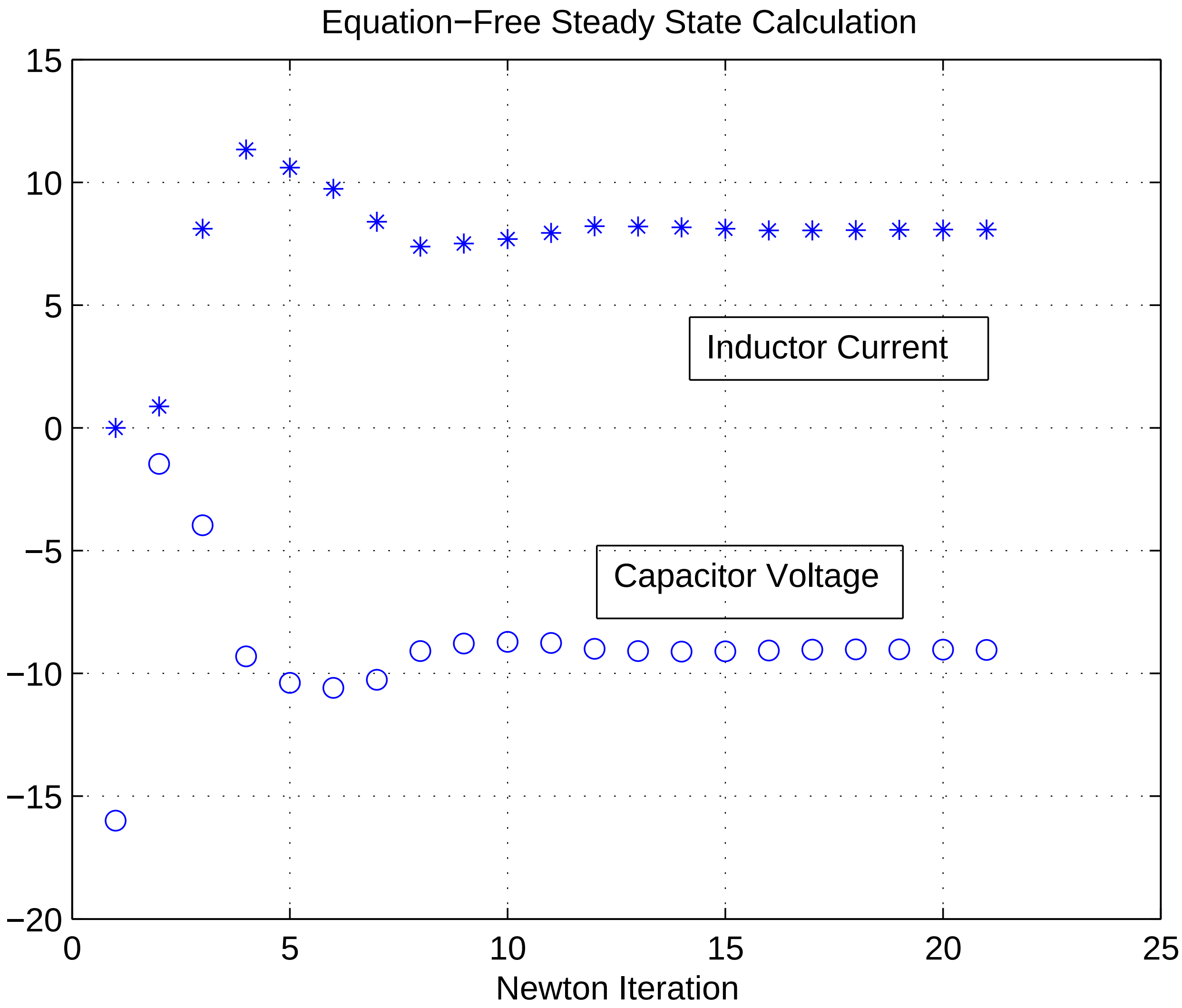
Example (3)

Large transient of interest - discontinuous to continuous conduction:



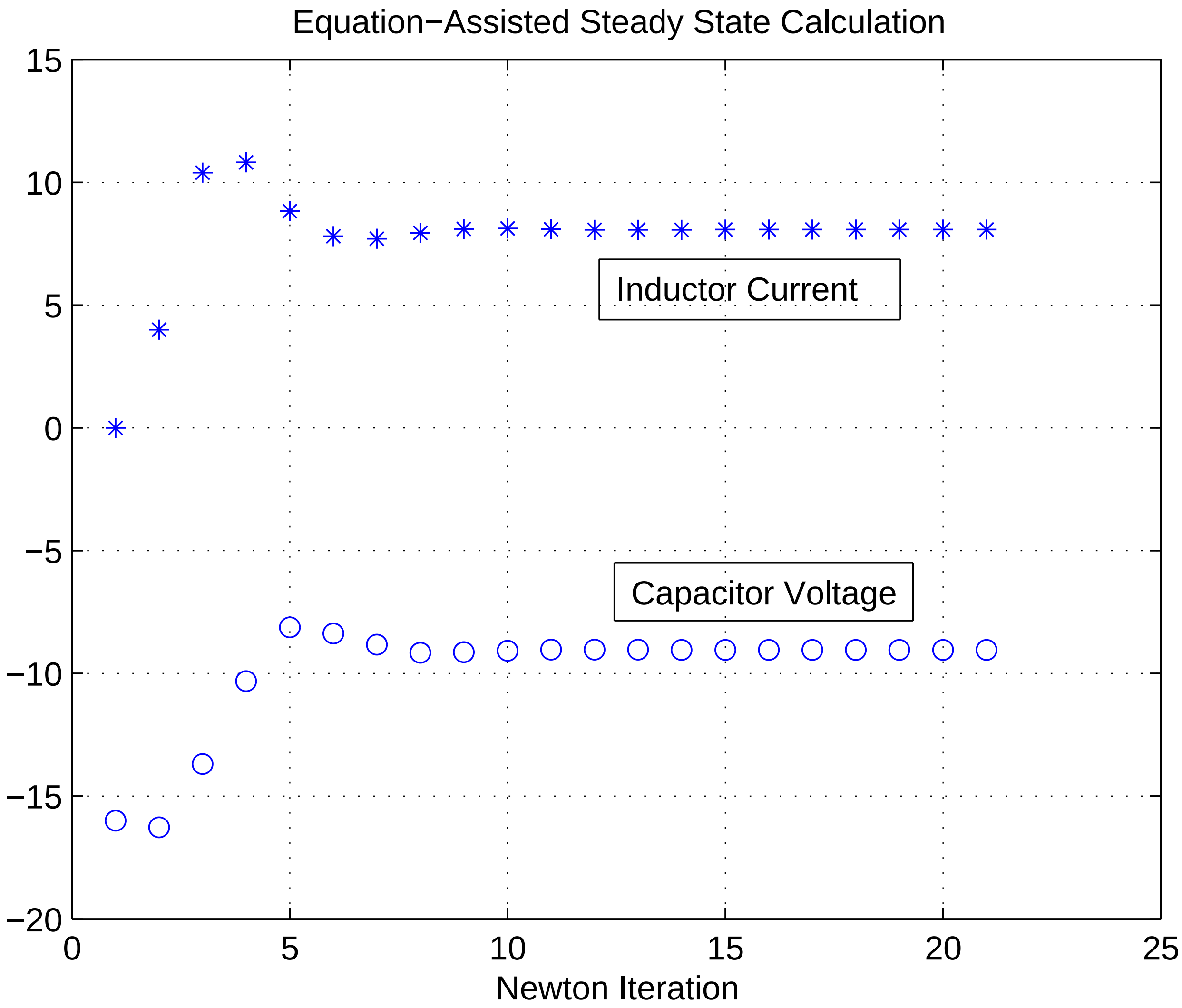
Example (4)

Equation-free calculation of steady states:



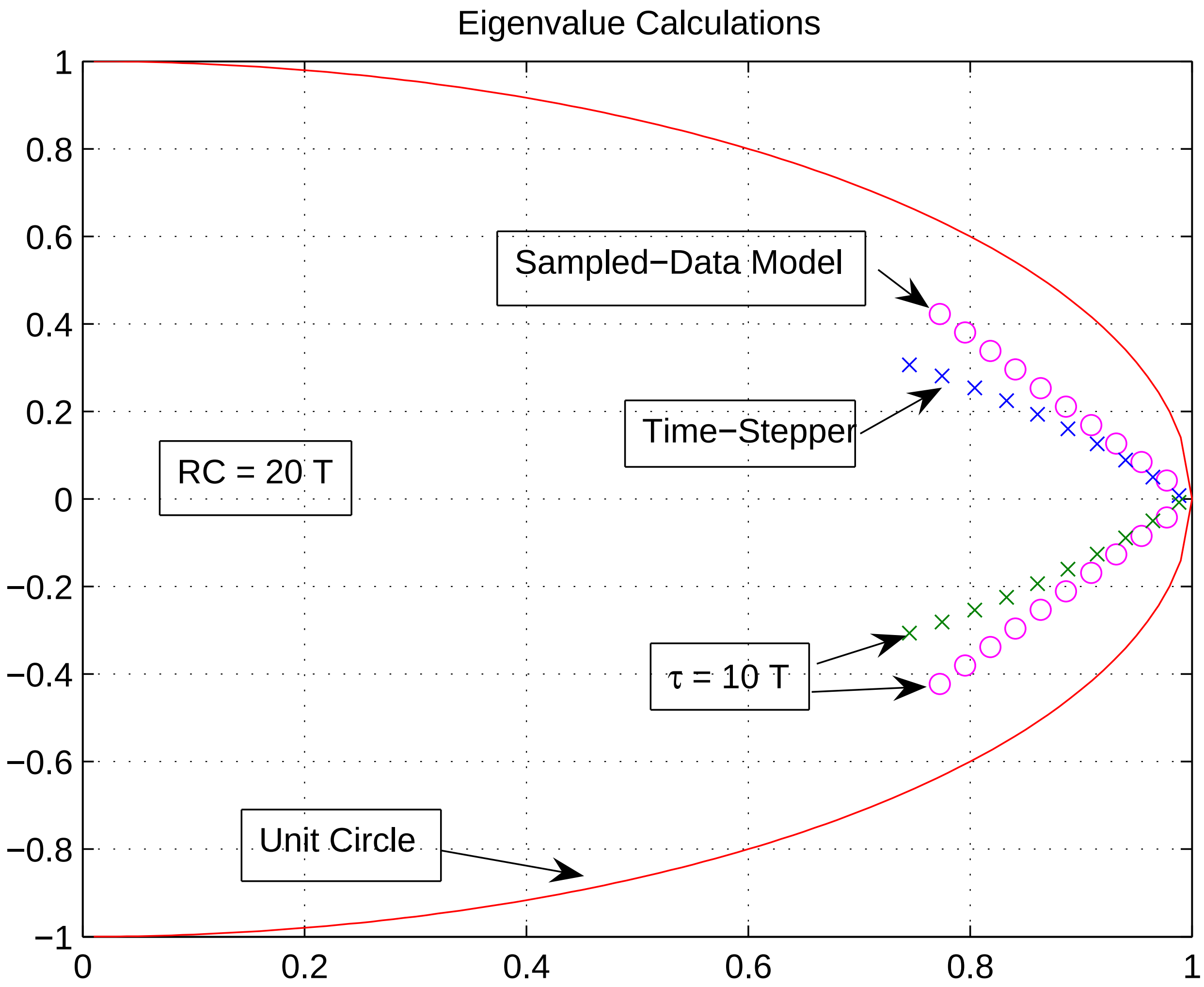
Example (5)

Equation-assisted calculation of steady states:



Example (6)

Small-signal stability analysis:



Conclusions

An electric energy systems take on Molecular Dynamics (MD):

- contributing to realism of models,
- expanding the realm of tractable models,
- complementary with existing procedures,
- likely computation-intense,
- possible applications - DG, large buildings, and ships.