U.S. DEPARTMENT OF ENERGY
Electricity Delivery & Energy Reliability

Advanced Grid Modeling 2014 Peer Review

Reduced Order Models of Distribution Dynamics with Application to FIDVR

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LANL
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6/17/2014

Program Overview

Partners: LANL, Cal Tech, Columbia, and U. of Michigan

Collaborators: MIT, Landau Institute, ENS-Paris, NICTA-Australia, Moscow Inst. of Physics, U. of Washington,…

Research Areas

- *Power System Control Under Uncertainty*
    - *Chance-Constrained Optimal Power Flow (LANL, Columbia, Michigan)*
    - *Distributed Control of Load for Frequency Control (Cal Tech, LANL)*
- *Transmission Effects of Distribution Grid Dynamics*
    - *PDE Models of Distribution Dynamics (LANL, Michigan, Landau Institute, ENS-Paris)*
    - *Distribution Dynamics Model Reduction (LANL, Michigan)*
- *Coupled, Interdependent Infrastructures—Gas-Grid Coupling*
    - *Stochastic Temporal Dynamics of Coupled Power and Gas Systems (LANL)*
    - *Coupled Gas-Grid Reliability, Operations, and Design (LANL, NICTA-Australia, MIT)*

Outreach

- *Winter School 2015—January 15-17*
- *Winter Conference 2015—January 18-19,*

Outreach

Winter School (Jan 15-17,2015)

- 9 X 2-hour lectures from experts in Distributed Control, Optimization, and Stochastic Methods
- Focused on graduate students and postdocs
- Application of these methods to grid control, design and optimization

- Ian Hiskens (Michigan)
- Florian Dorfler (UCLA/ETH)
- Steven Boyd (Stanford—not confirmed)
- Daniel Bienstock (Columbia)
- Steven Low (Cal Tech)
- Pascal vanHentenryck (NICTA-Australia)
- Antonio Conejo (Ohio State)
- Duncan Callaway (UC Berkeley)
- Konstantin Turitsyn (MIT)

Winter Conference (Jan 17-18, 2015)

16 invited presenters

- Ian Dobson (Iowa State)
- Seth Blumsack (Penn State)
- Paul Hines (Vermont)
- David Hill (Sydney)
- Bernie Lesieutre (Wisconsin—TBD)
- Javad Lavaei (Columbia)
- Krishnamurthy Dvijotham (Washington/Cal Tech)
- Chris DeMarco (Wisconsin—TBD)
- Alejandro Dominguez-Garcia (Urbana)
- Goran Andersson (ETH)
- Jakob Stoustrup (PNNL)
- Shmuel Oren (UC Berkeley)
- P.R. Kumar (Texas A&M)
- Eugene Litvinov (ISO-NE)
- Janusz Bialek (SkTech)
- Michael Ferris (Wisconsin)

Context/Vision—Distribution Dynamics

- *Existing dynamical simulations of high voltage transmission grids typically use:*
  - *detailed models of generators and transmission*
  - *simplified aggregate models of loads that do not account for the complex spatiotemporal interactions of the loads*

- *The need for better dynamical load models*
  - *Encroaching on stability boundaries—Impact of load dynamics is growing*
  - *Collective, nonlinear (and undesired) dynamical load behaviors (FIDVR) driven by typical transmission grid behavior, e.g. normal fault clearing.*
  - *Deployment of active consumer loads will yield new "load" dynamics.*

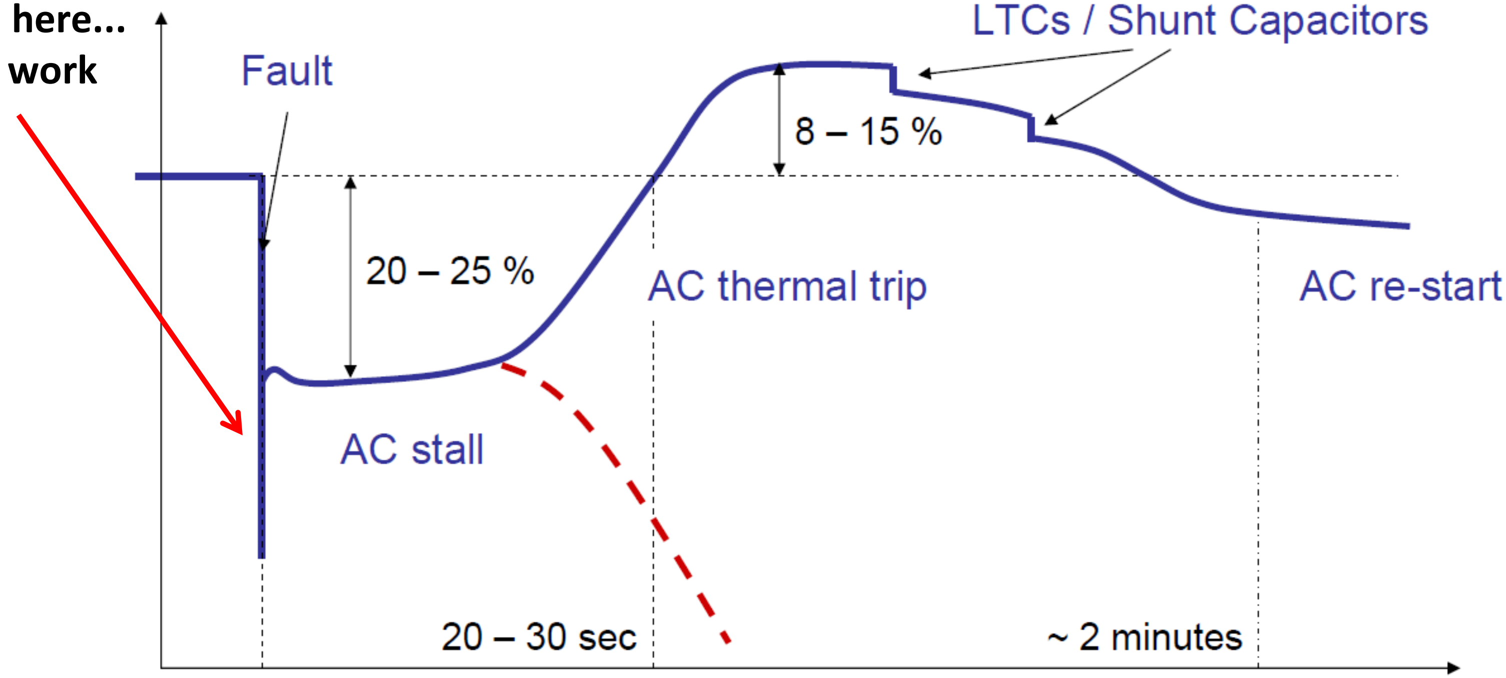
- *Our approach*
  - *Model/Understand the complex spatiotemporal interactions of loads*
  - *Develop low-dimensional representations suitable for simulations of transmission dynamics*

Presentation Outline

- *Project Purpose—Develop understanding of FIDVR dynamics (and other complex distribution dynamics) and fast/simple models for integration into transmission simulations*
- *Significance and Impact—Improved understanding of the effect of complex load dynamics on transmission dynamical stability without significant increase in computational burden*
  - *FIDVR Example—What are the dynamics under consideration?*
- *Technical Approach*
  - *Distribution Dynamics Model*
  - *Analysis of Dynamics—Comparison with related work*
  - *Model Uncertainty—Inclusion of Disorder*
- *Technical Accomplishments*
  - *FIDVR critical clearing time*
  - *Effects of disorder/load uncertainty*
  - *Low-Dimensional Models*
- *Conclusions*
- *Future Work*

Significance and Impact—FIDVR Example

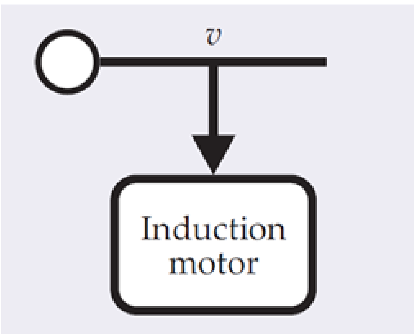
Induction motor stalling dynamics occurs here... Focus of current work



Related work in this general area

- PNNL—statistical model of stalling and thermal tripping
- Iowa State—statistical model of stalling with power flows
- LBNL/ASU/SEL—PSCAD and RTDS simulation of stalling dynamics

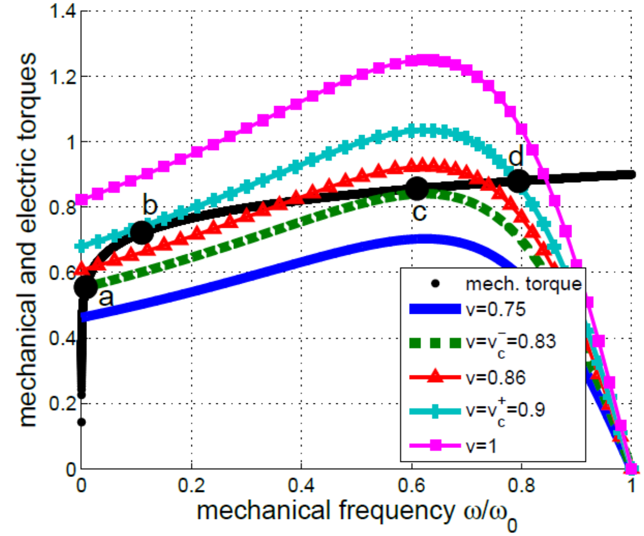
Technical Approach—Distribution Dynamics Model
Induction Motor Dynamical Model

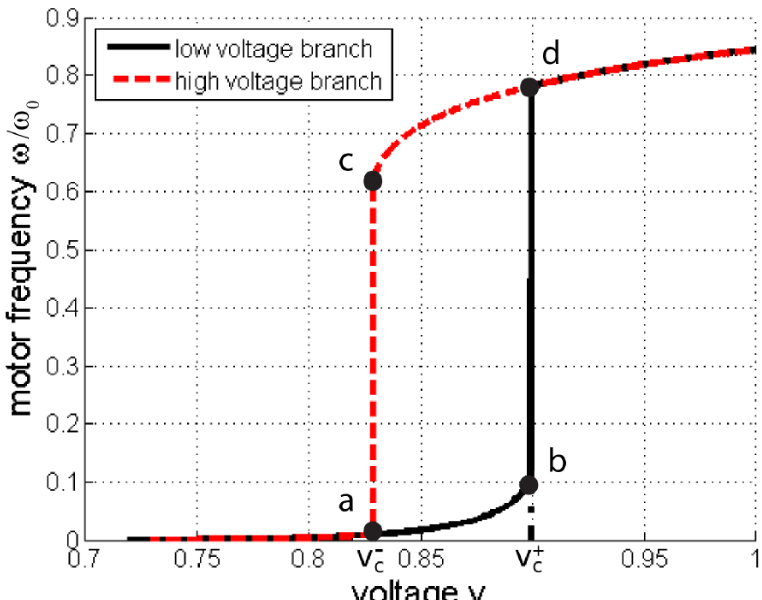


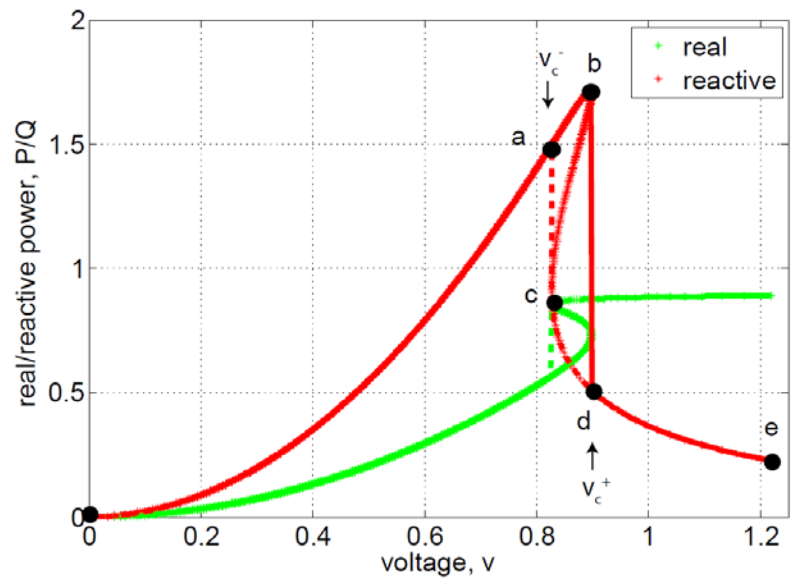
$$\mu \frac{d}{dt}\omega = \frac{p}{\omega_0} - t_0 \left(\frac{\omega}{\omega_0}\right)^{\alpha},$$

$$p = \frac{s r_m v^2}{r_m^2 + s^2 x_m^2},$$

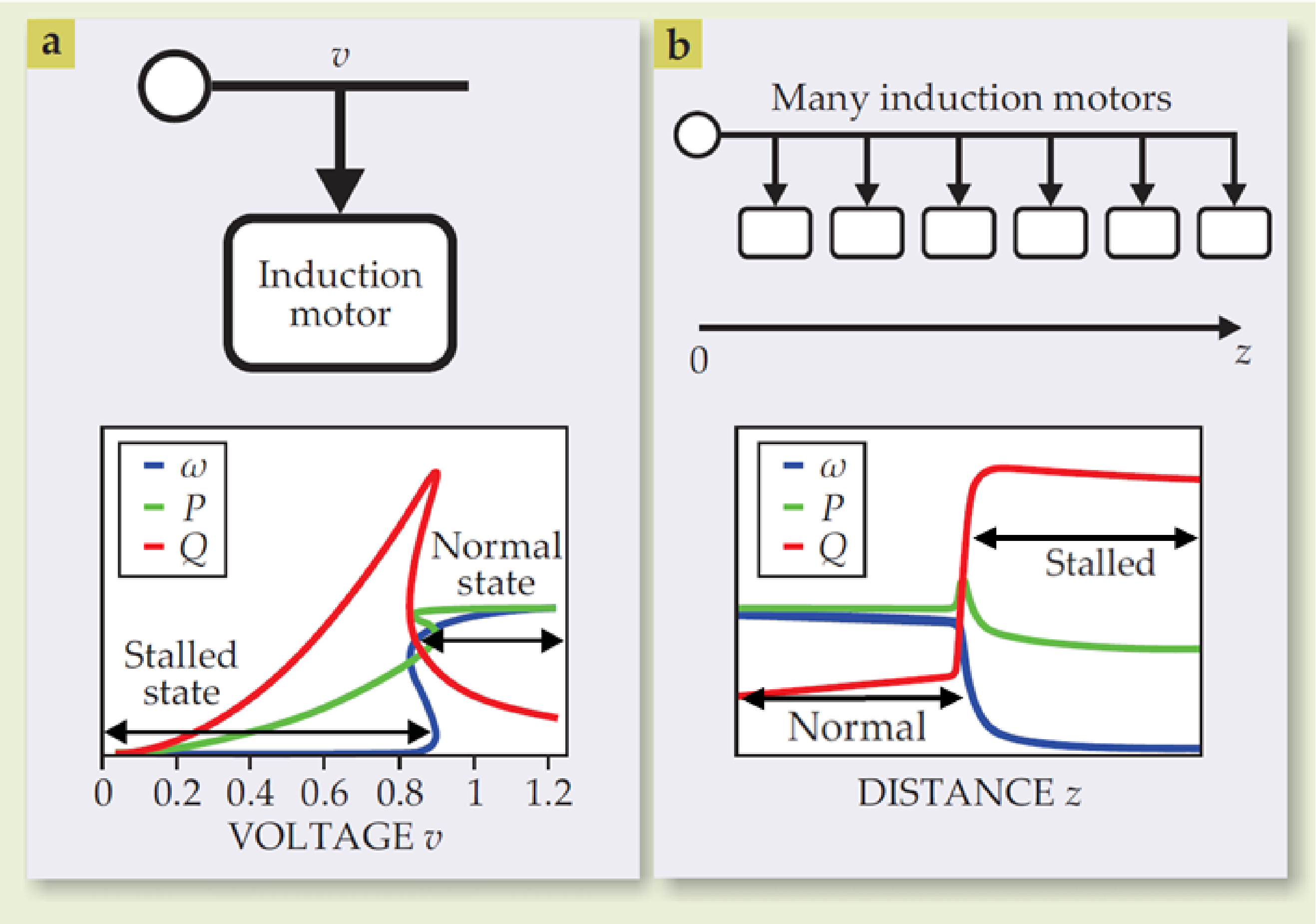
$$q = \frac{s^2 x_m}{r_m^2 + s^2 x_m^2} v^2.$$







Technical Approach—Distribution Dynamics Model
Spatially Continuous Power Flow



<u>Power flow equations</u>

$$\partial_z \rho = -p - r\frac{\rho^2 + \phi^2}{v^2},$$

$$\partial_z \phi = -q - x\frac{\rho^2 + \phi^2}{v^2},$$

$$\partial_z v = -\frac{r\rho + x\phi}{v}.$$

<u>Motor dynamics</u>

$$\mu \frac{d}{dt}\omega = \frac{p}{\omega_0} - t_0 \left(\frac{\omega}{\omega_0}\right)^{\alpha},$$

$$p = \frac{s r_m v^2}{r_m^2 + s^2 x_m^2},$$

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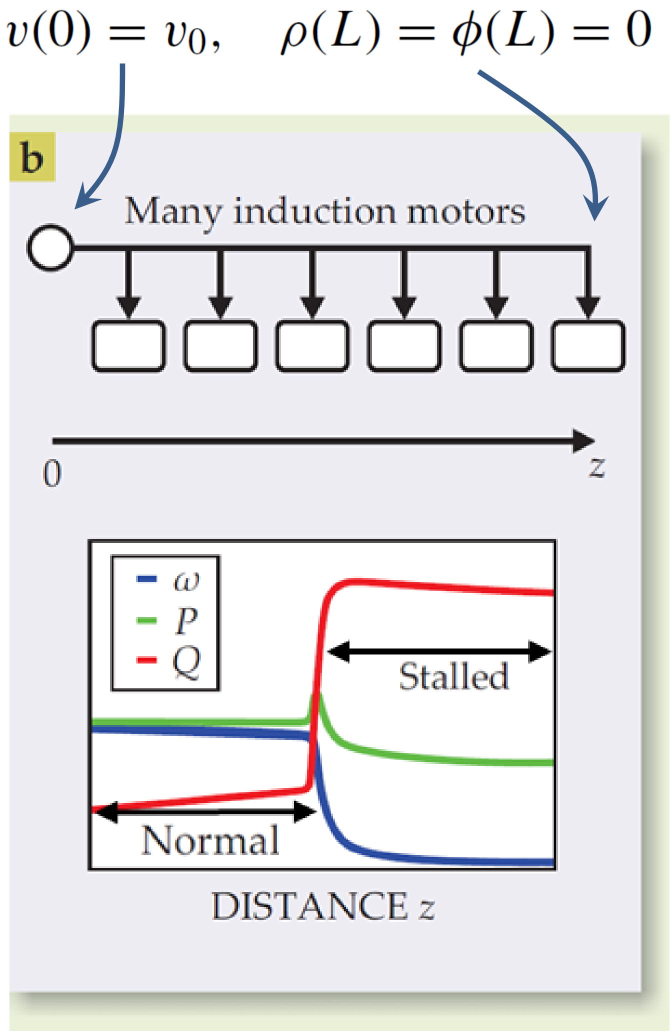
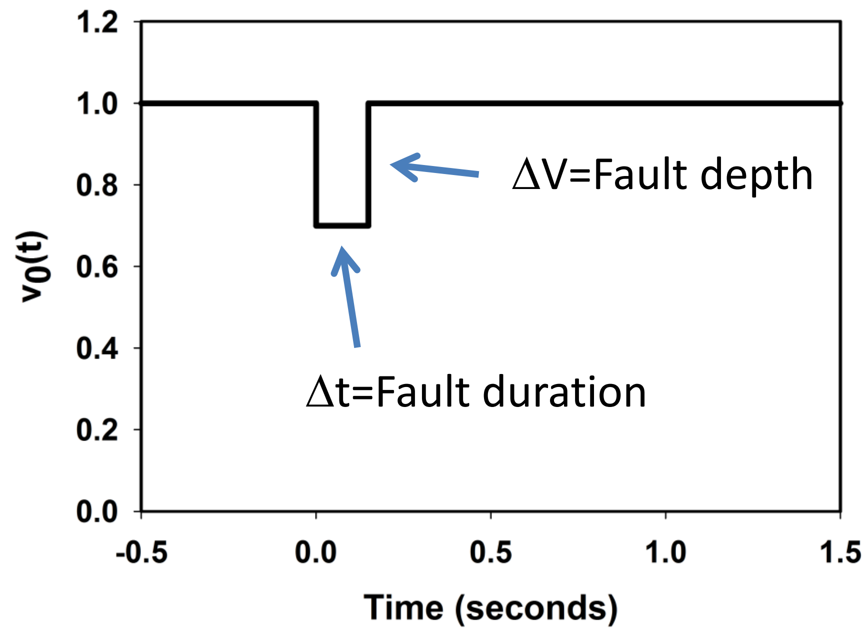
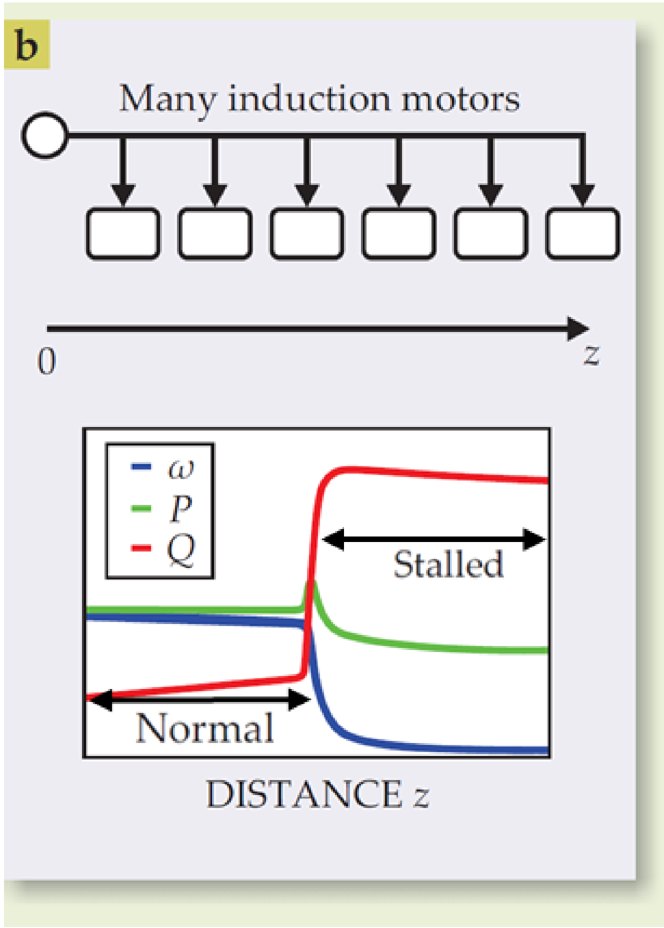
Technical Approach—Distribution Dynamics Model Boundary and Initial Conditions





- Using "simplified" boundary conditions that do not include transmission impedance
- Separates the distribution dynamics from quasi-static transmission impedance effects
- Impedance is included during integration into transmission simulations

Technical Approach—Model Uncertainty

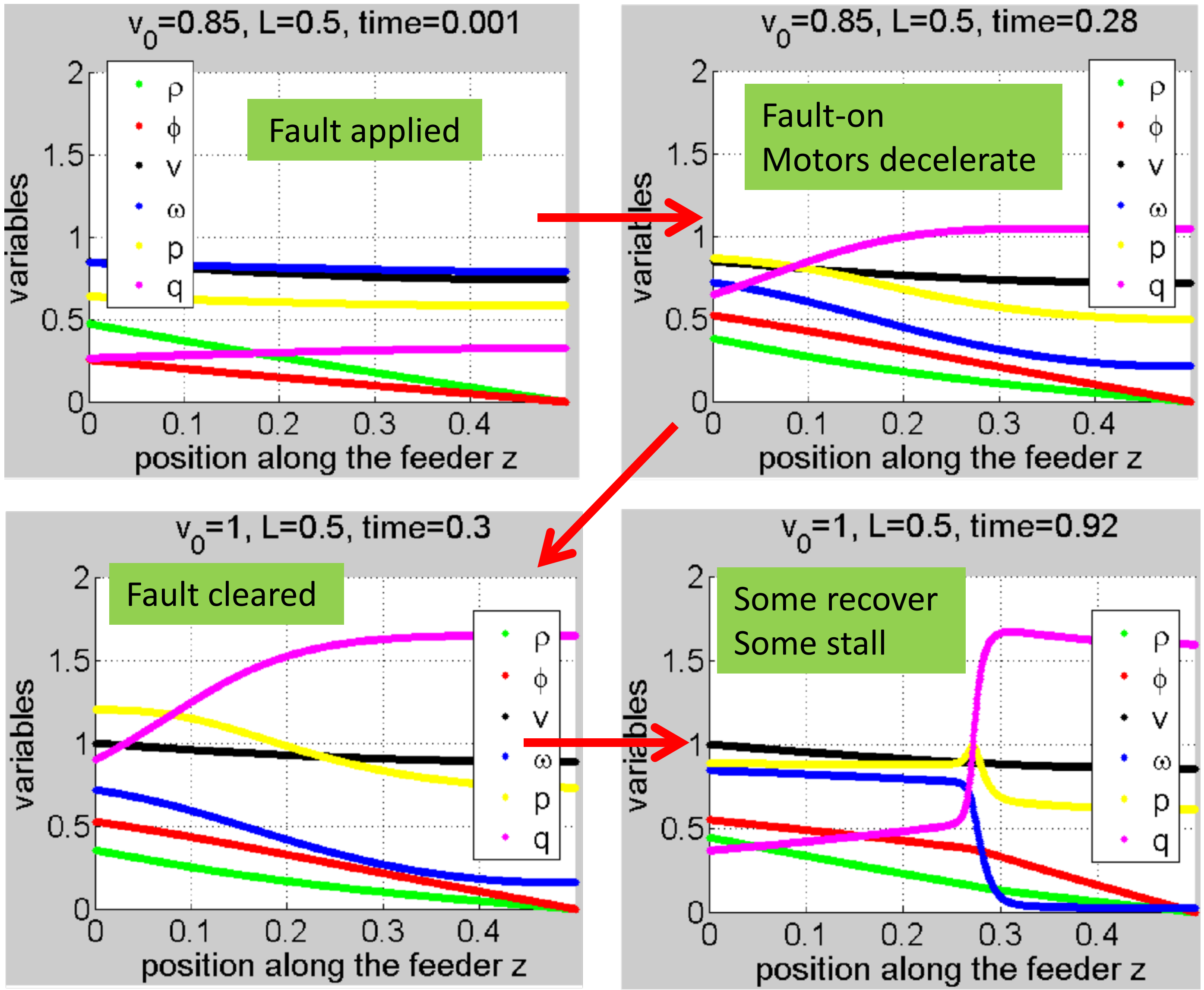


- Distribution circuit load composition is not very well known
- We account for this in general way by including randomness in load parameters
- Example: Uncertainty in motor loading

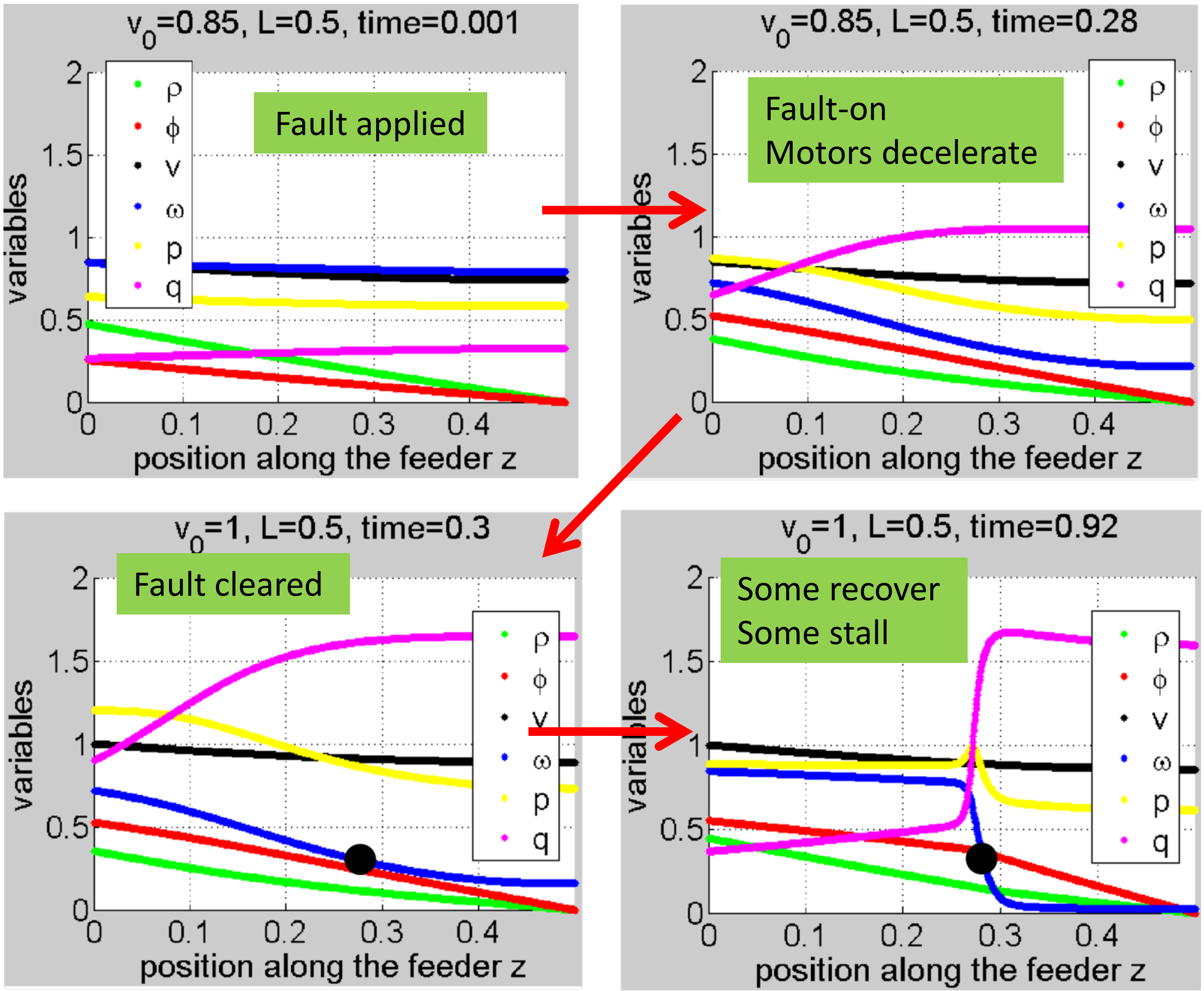
$$\delta(z) = \tau_0(z) - \bar{\tau}_0$$

$$\mathbb{E}\left[\delta(z_1)\delta(z_2)\right] = (\tau_0\Delta)^2 \exp(-|z_1 - z_2|/z_d)$$

Technical Approach—Analysis of Dynamics
Spatiotemporal Interaction of Load Dynamics



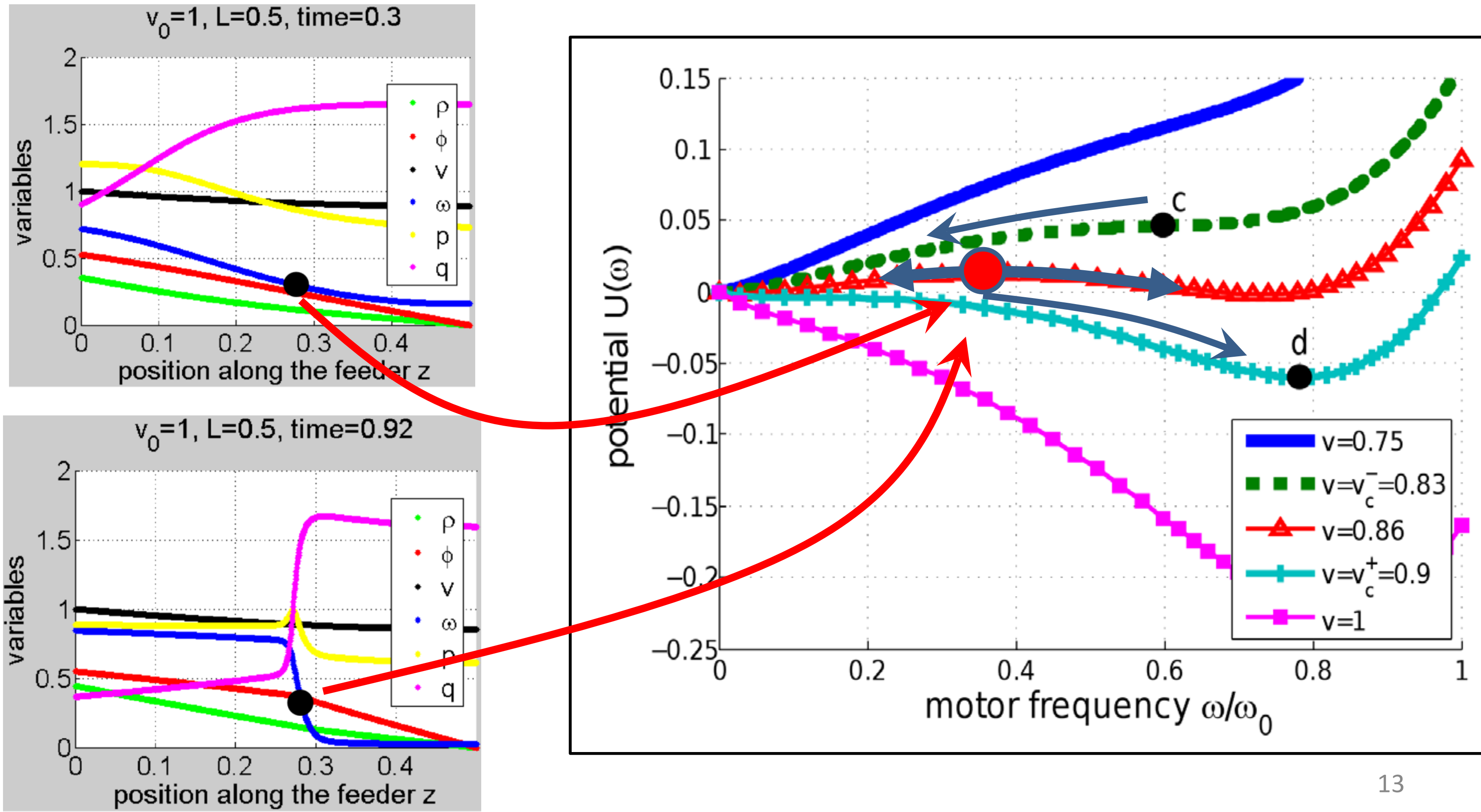
Technical Approach—Analysis of Dynamics
Final Location of Normal/Stalled Interface—T_{net}=0



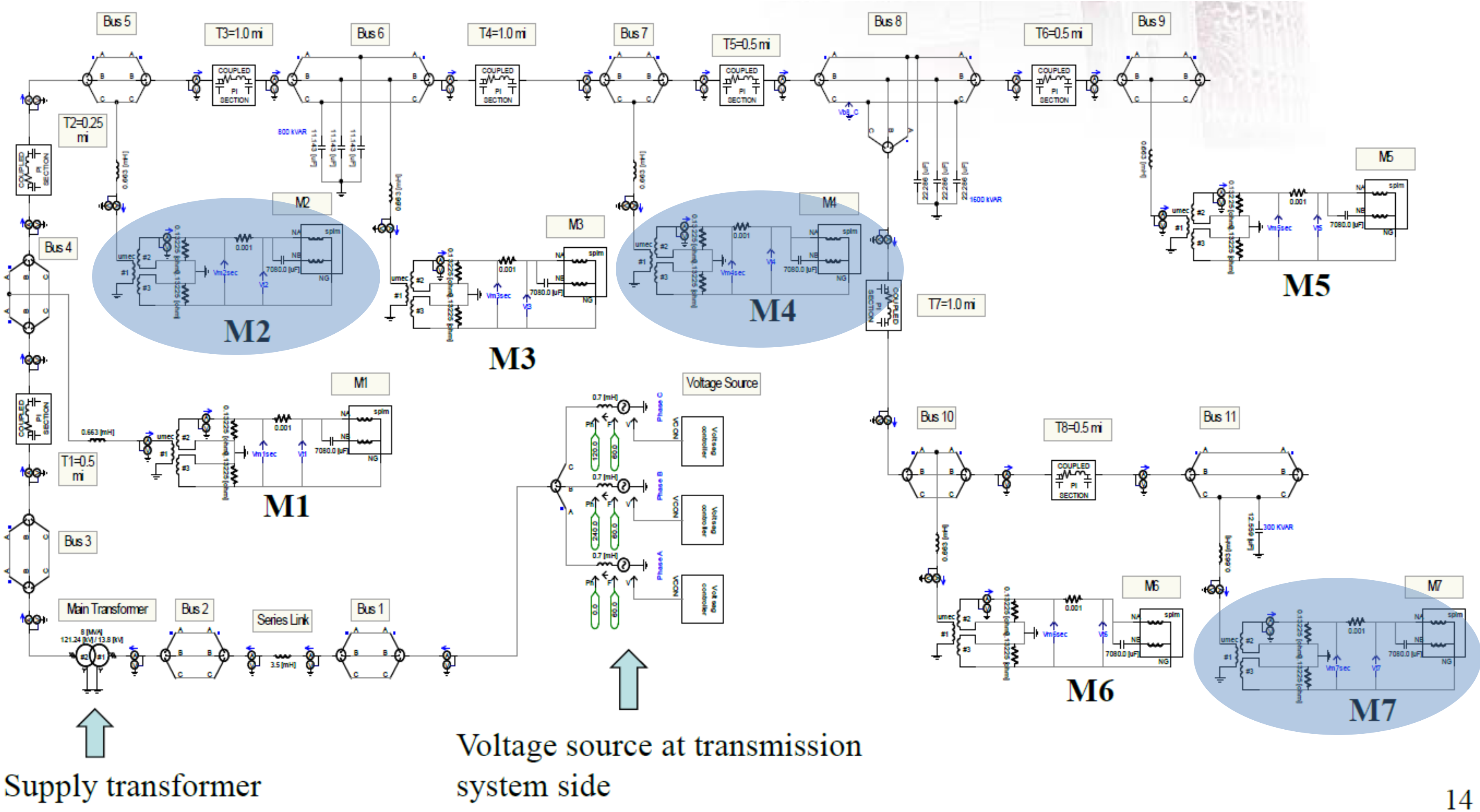
Technical Approach—Analysis of Dynamics Energy Function—Frozen Voltage

Post-fault voltage determines energy landscape

Post-fault motor angular speed determines final motor state



Technical Approach—Comparison to Related Work
PSCAD Model of Motors and Distribution Circuit (ASU)



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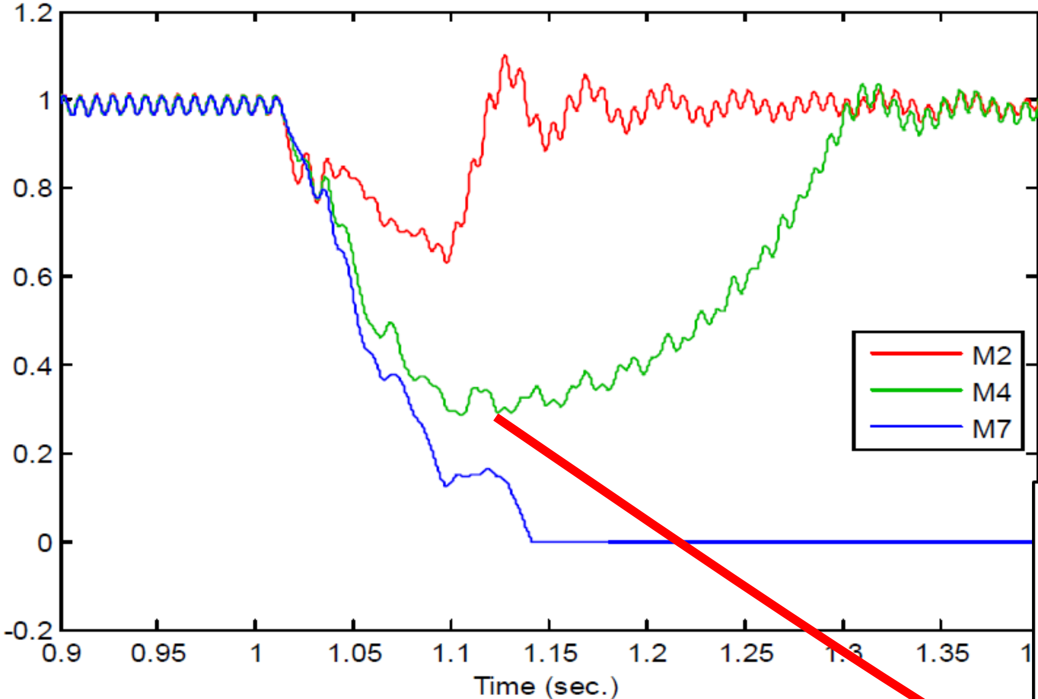
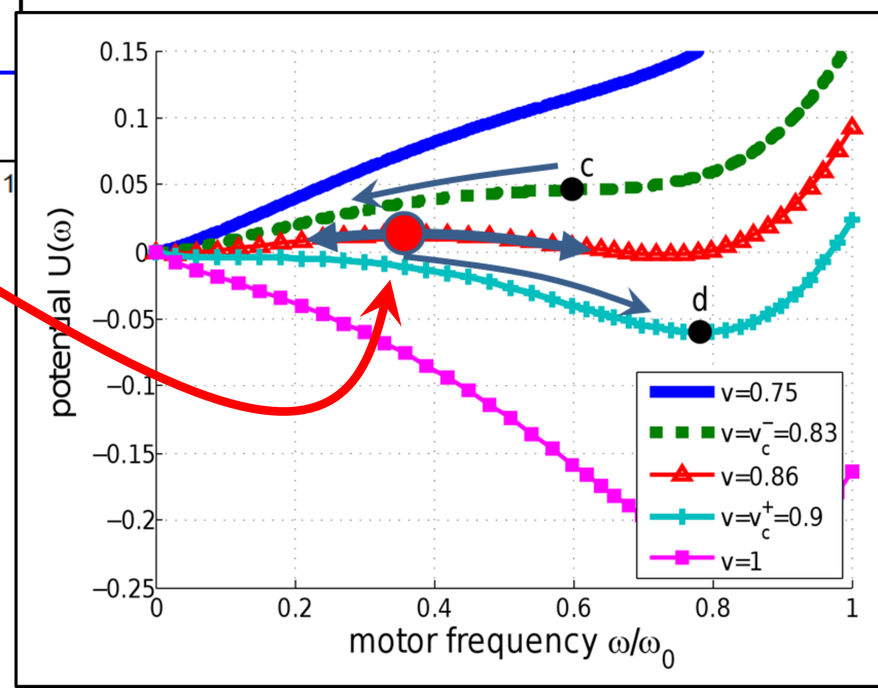


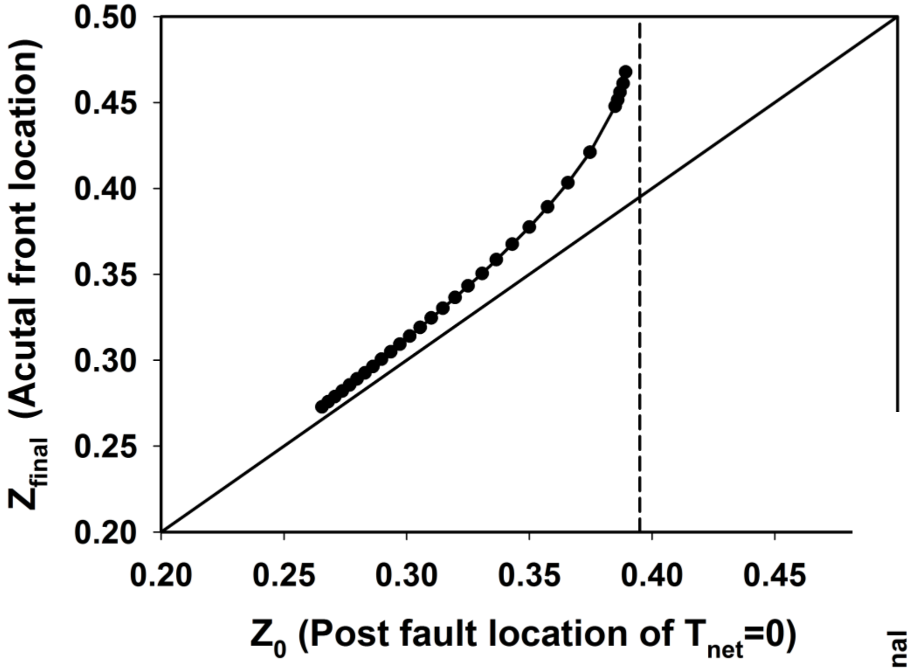
PSCAD model accounts for:

- Motor electrodynamics
- Angle dependent torque
- Resolves AC cycle
- Fault relative to AC phase

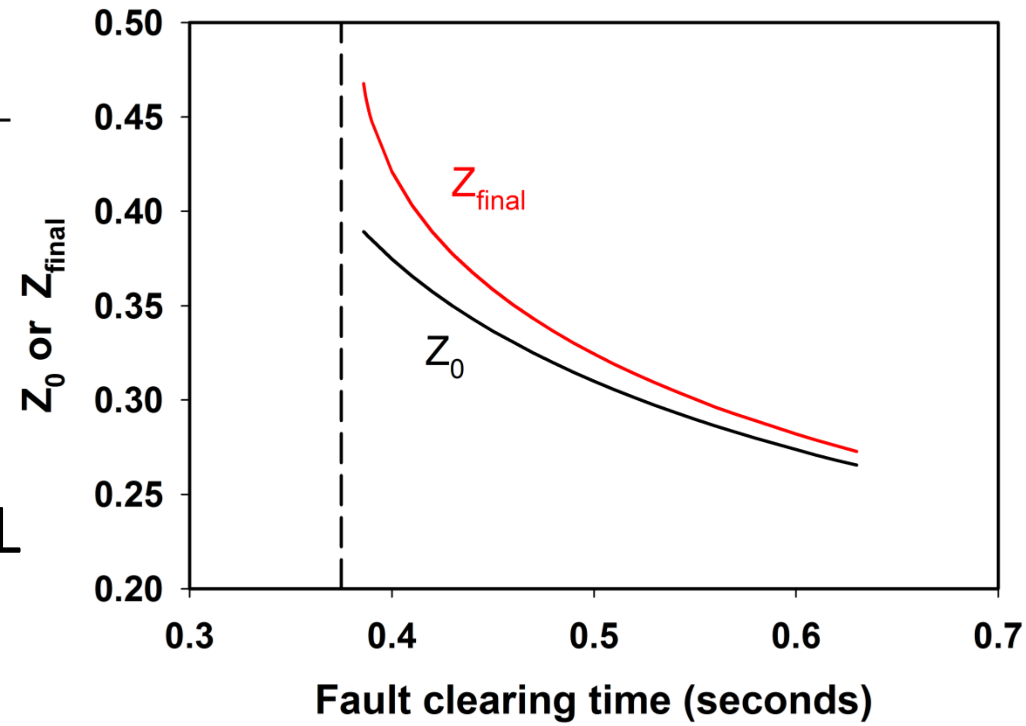


Dynamics of PSCAD model are consistent with our continuum power flow/phasor dynamics model

Technical Approach—Analysis of Dynamics Accuracy of the T_{net}=0 Condition

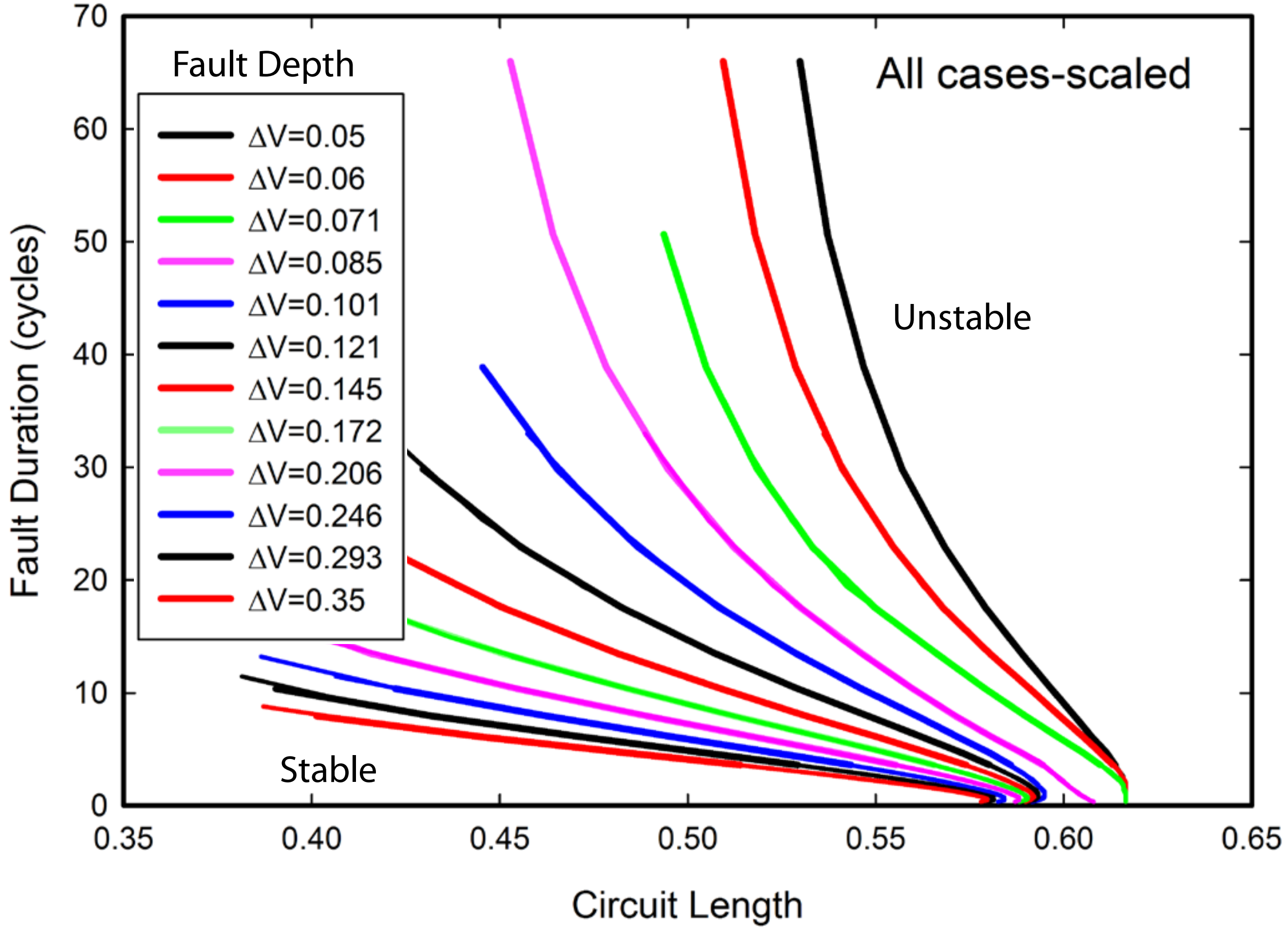


- T_{net}=0 condition provides a conservative estimate of
  - Final front location
  - Critical clearing time

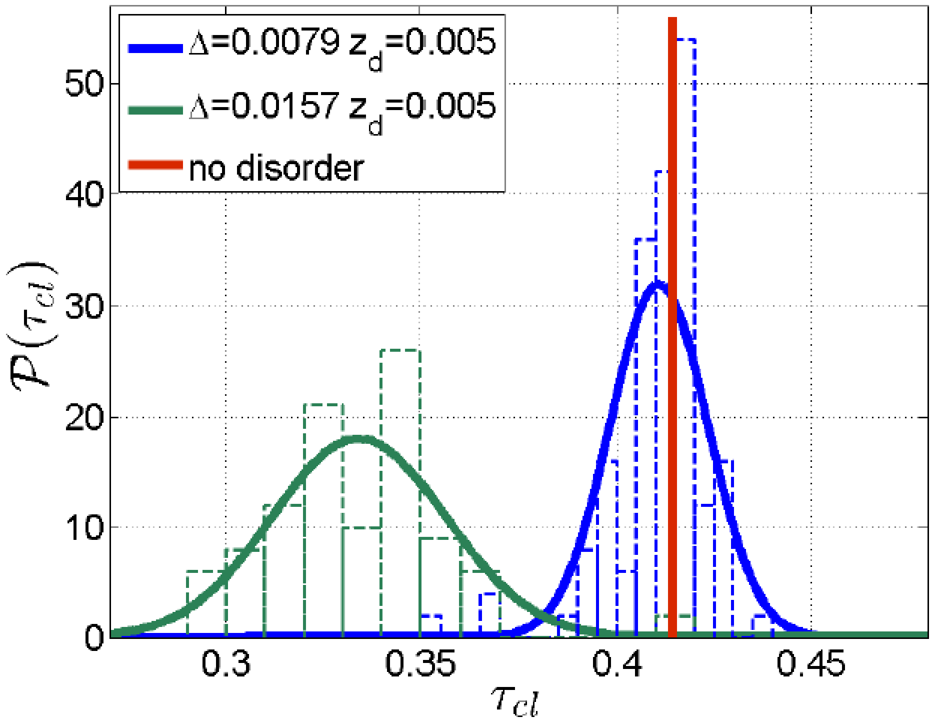


- Condition becomes less accurate as Z_0 approaches L
  - Finite size effects

Technical Accomplishments—Critical Clearing Time Computed Using the T_{net}=0 Condition



Technical Accomplishments—Effects of Model Uncertainty—Distribution of Critical Clearing Times



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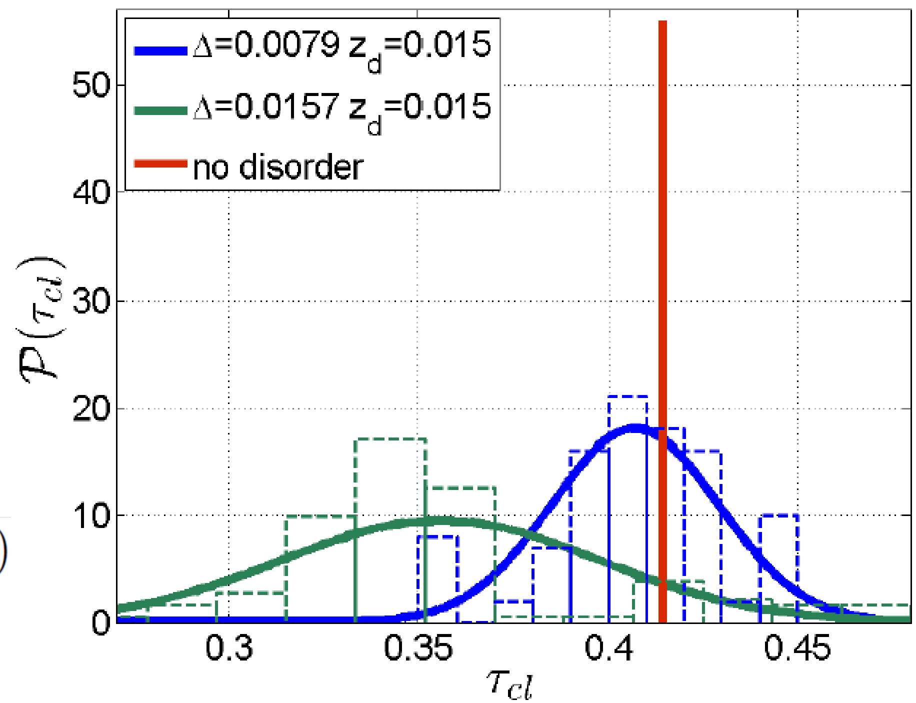
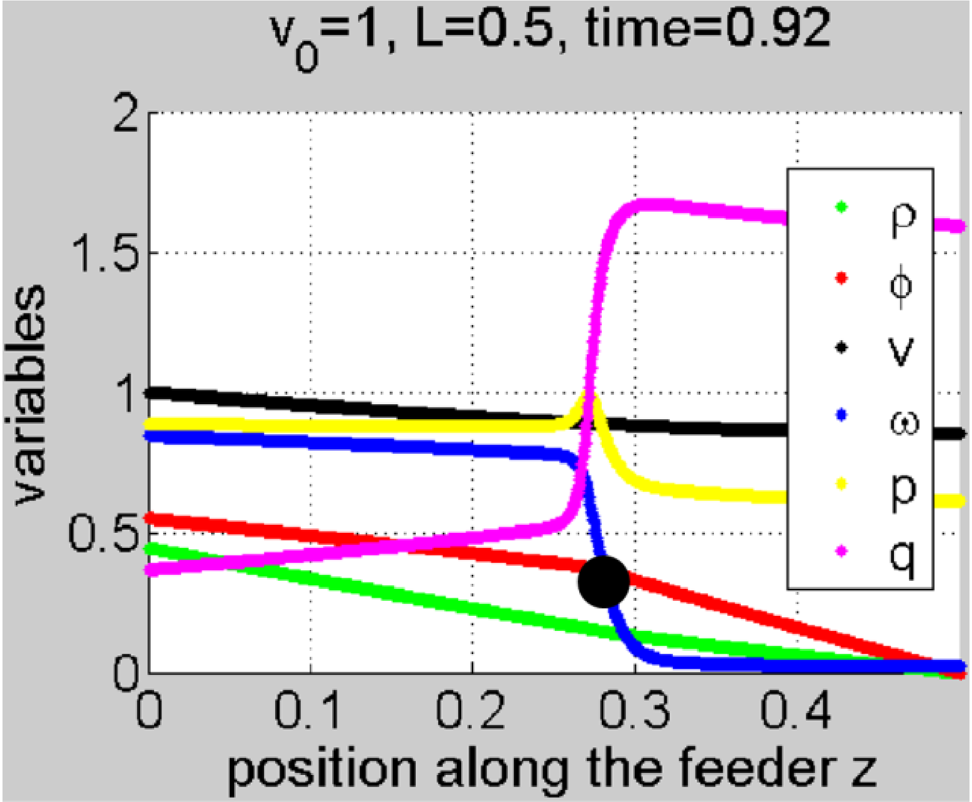


Technical Accomplishments—Low-Dimensional Models—Path Forward

- Normal/Stalled interface is the salient low-dimension feature the dynamics.
- Approximately constant motor speed ω on either side of the front
- Front location can be predicted based on T_{net}=0 point
- Algebraic relationships for pre/post-fault P and Q



Conclusion

- Developed a continuum power flow/phasor motor dynamics of distribution dynamics
  - Captures the salient features of FIDVR dynamics—comparable to PSCAD models
  - Used energy arguments to improve the understanding of the spatiotemporal aspects of induction motor stalling and FIDVR
  - Computed critical clearing times for one “class” of distribution circuit
  - Quantified the effect of load uncertainty on critical clearing times

Future Work—FY15

- Extension to a wider range of circuits, loading and fault conditions to understand its accuracy
  - GridLabD distribution circuit taxonomy
  - transmission line impedance
- Leverage the normal/stalled front for a low-dimensional model of the dynamics
- Investigate higher-order collective effects/interactions:
  - FIDVR cascading between circuits in a substation
  - FIDVR cascading to adjacent substations
  - Integrate reduced-order models into transmission simulations
- Validation on real-world event data
- Extend to smart/active load dynamics

Acknowledgements/Contacts

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