Diagnosis, Device Placement, and Auxiliary Control for Resilience

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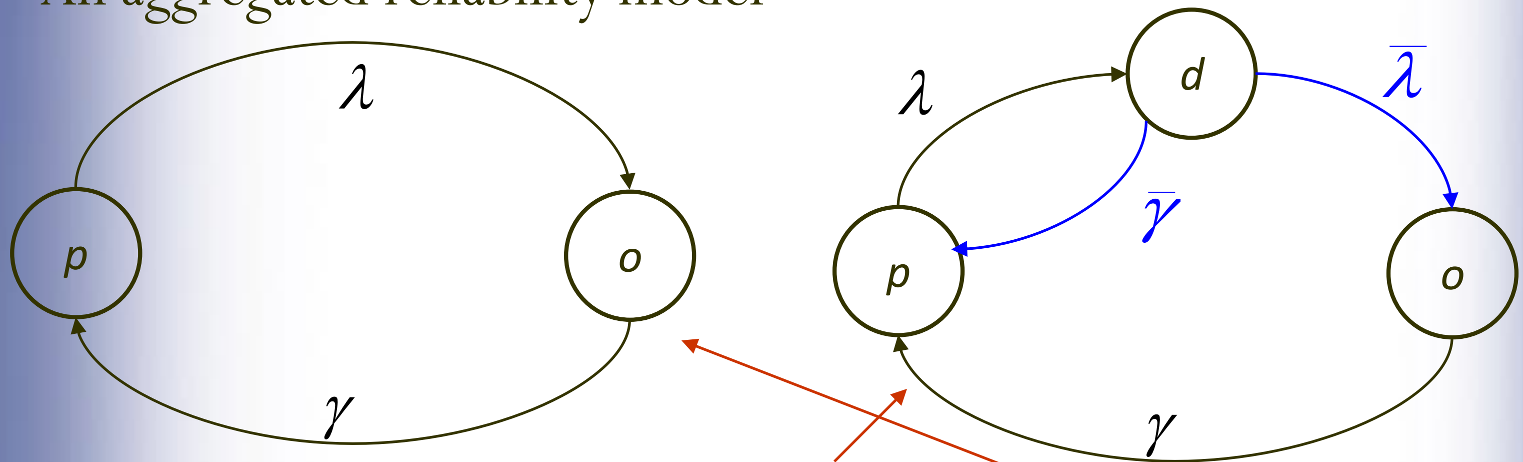
Reliability of power systems:
ability to provide uninterrupted service: adequacy (availability)
and ability to withstand disturbances: security (transient stability)

Motivation and objectives

- Protection misoperations
  - Failure to trip, false trip
  - 1965 NE, 2003 NE, 2011 SW blackouts
- Challenges
  - Rare/high impact events costly to prevent and costly not to prevent
  - Response speed required of protection functions
- Objective
  - Introduce a framework that enables us to formally address the challenges and examine the technology readiness

What makes the gird more reliable?

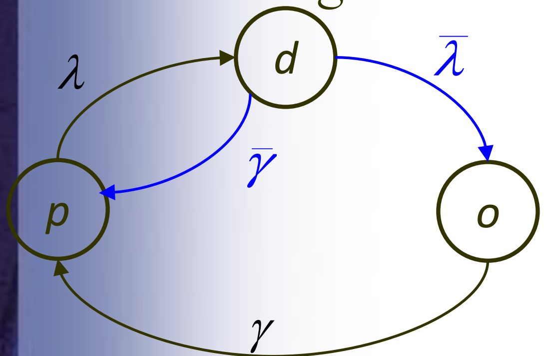
- An aggregated reliability model

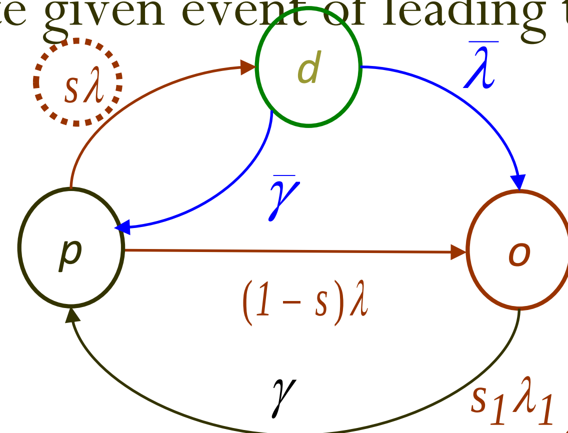


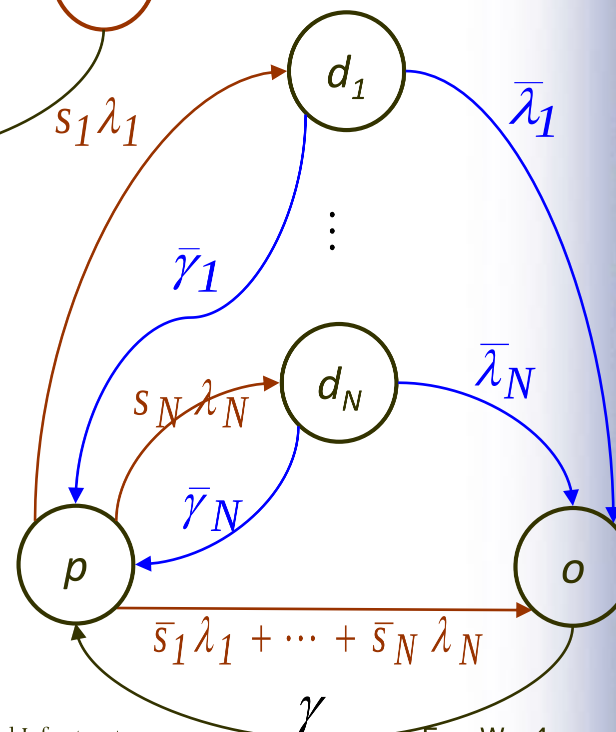
$$\pi_O = \frac{\lambda}{\lambda + \gamma + (\lambda + \bar{\gamma})\gamma / \bar{\lambda}} \cong \frac{\lambda}{\lambda + \gamma + \gamma\bar{\gamma} / \bar{\lambda}} < \frac{\lambda}{\lambda + \gamma}, \quad A = 1 - \pi_O$$

  - Reliability benefits greatly from diverting all critical faults to state *d*, at which a more expeditious recovery to normal from the degraded state (N-1 secure)
  - Assumption: protection is perfect
    - How to quantify the imperfection?

- Introducing security index
  - s: security (conditional probability of successful transition into the degraded state given event of leading to the transition)

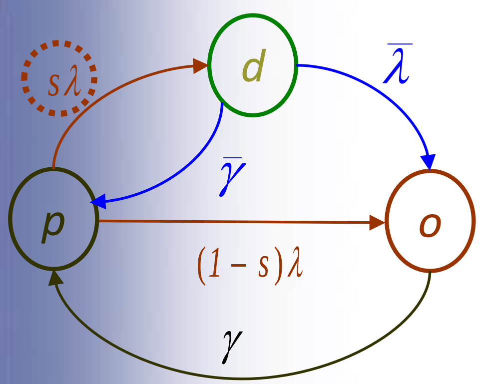


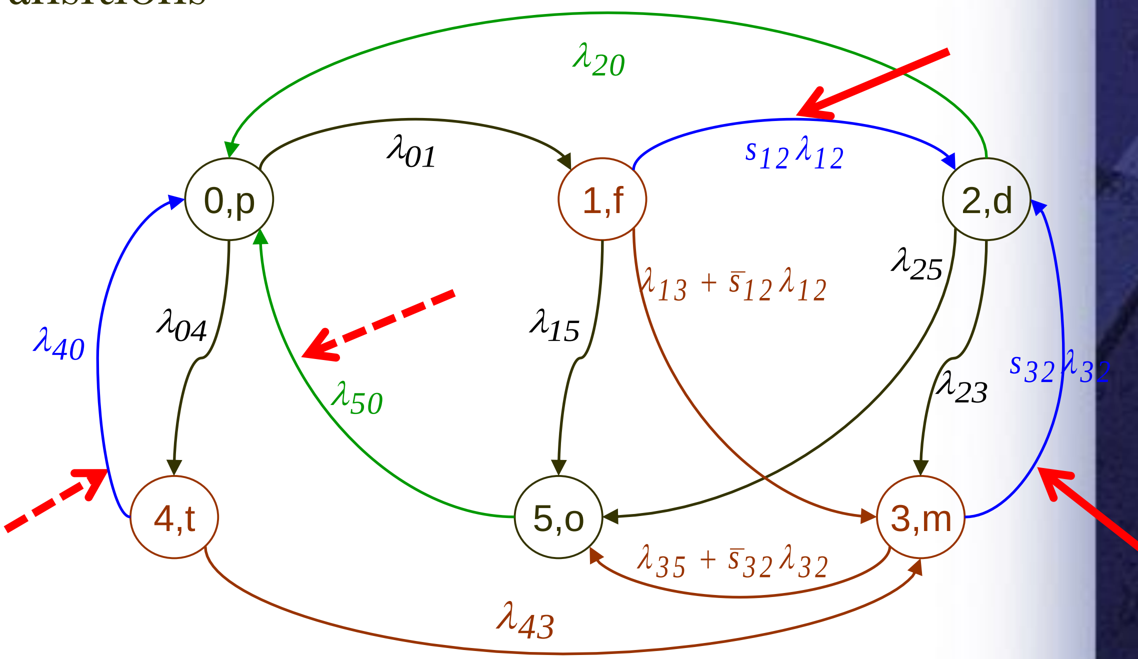




  - Expansibility
    - Modes $\{f_0, f_1, \cdots, f_N, f_{N+1},\}$
  - Scalability - linear w.r.t. system size
  - Evaluation of s_i?

- Inclusion of insecure states in order to develop auxiliary control
  - Pre-fault state is split to include an aggregated false trip state
  - Degraded state is split to include an aggregated fault-on state
  - Outage state is split to include an aggregated misoperated state with fault-on
  - Controllable transitions





Security and availability

Control performance

diagnosis performance

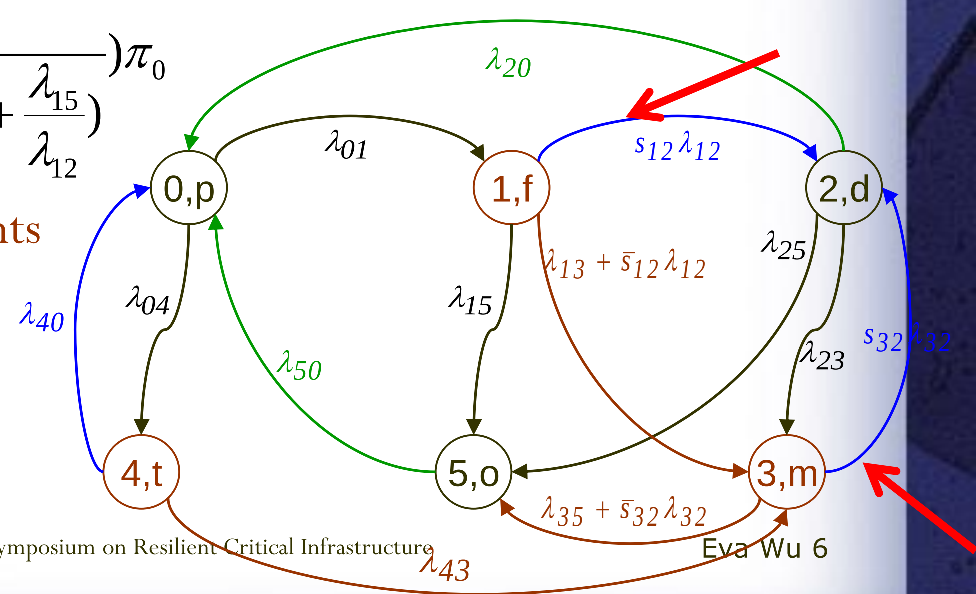
- Security of controllable transitions
  - $s_{ij} = c_{ij} p_{ij}$
    - conditional probability of correct mode identification
    - conditional probability of correct control action)
  - Control and diagnosis risks (Poisson decomposition)
  - Event probability, availability

$$P[2\,|\,1] \cong s_{12}$$

$$P[2\,|\,3] \cong s_{32}$$

$$A_s \cong 1 - \frac{\lambda_{01}}{\lambda_{05}}\left(1 - \frac{s_{32}\bar{s}_{12} + s_{12}}{\left(1 + \frac{\lambda_{25} + \bar{s}_{32}\lambda_{23}}{\lambda_{20}}\right)\left(1 + \frac{\lambda_{15}}{\lambda_{12}}\right)}\right)\pi_0$$

  - Technological requirements



Summary of computational requirements

- Auxiliary control criterion
  - Estimated post-fault stability region in a physical state space based on the system energy function established by protective control action *u* exerted at time *t*
  - Estimated fault-on physical state at the time *t* that has a probability called a fault-coverage of being in the post-fault stability region.

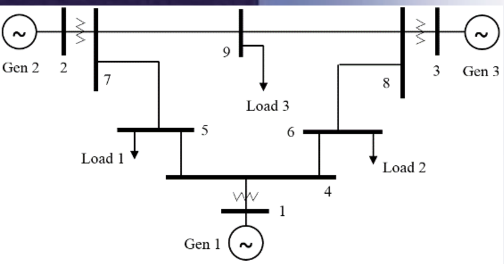
$$c_{i,u}(t) = \int_{x,t} \overbrace{J_{i,u}(x,t)}^{\text{Characteristic function in product space }(x,\, t)} \underbrace{f_{(\hat{x},\hat{t}_0)}(t,x,t_0)}_{\text{Joint distribution of state, fault onset time}} \, dx\, dt_0$$

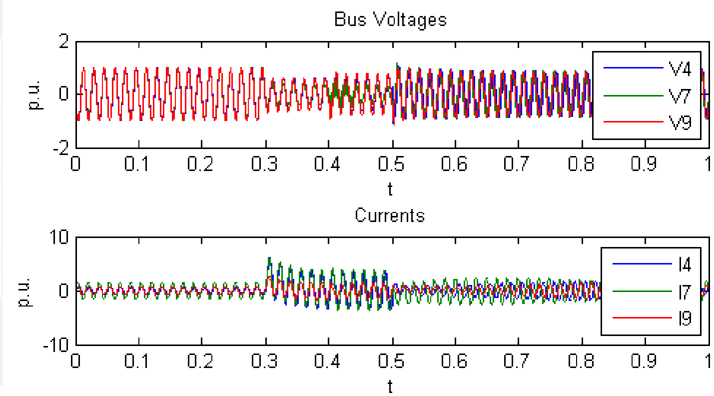
- Diagnosis criterion
  - A conditional probability simplex (conditioned on knowledge of the protective control action *u*) in an N+1 dimensional information space
  - Estimated information state, representing system mode probability distribution at time *t*

$$p_{f_i}(t_k) = \frac{p_{f_i}(t_{k-1})\rho_{\xi_{f_i}}(t_k)}{\underbrace{\sum_j p_{f_j}(t_{k-1})\rho_{\xi_{f_j}}(t_k)}_{\text{Probability of model matching}}}.$$

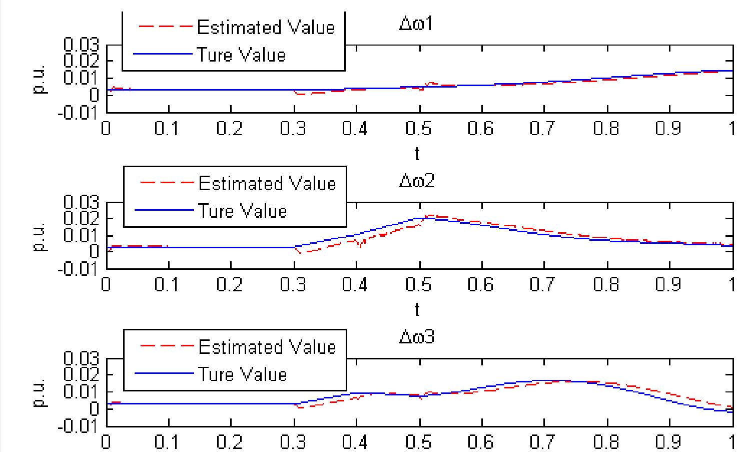
Example: security profiles of a 9-bus system

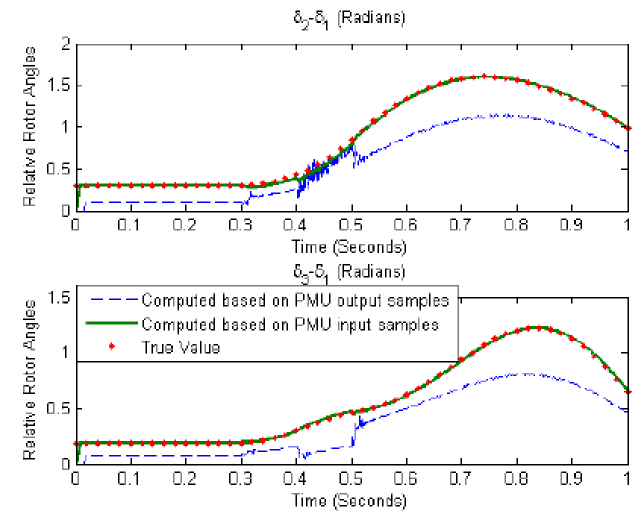
- PMU-based in electromechanical state tracking
  - Input samples at 24 samples/cycle
  - No swing dynamics involved



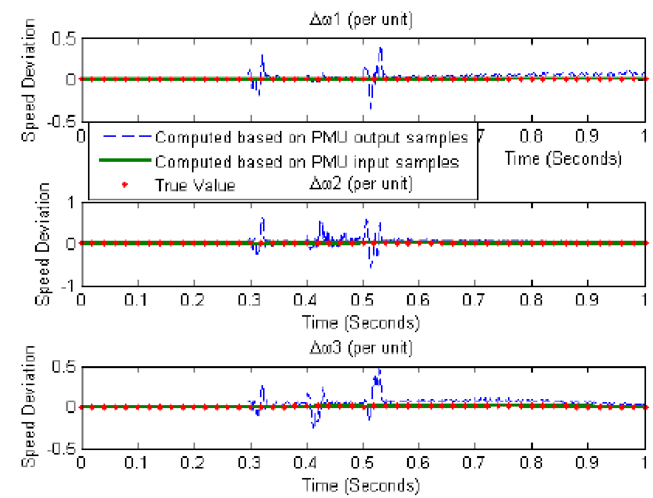


6 transmission line faults considered
3 PMU-like sensors at buses 4, 7, and 9





(b) Estimated relative rotor angles

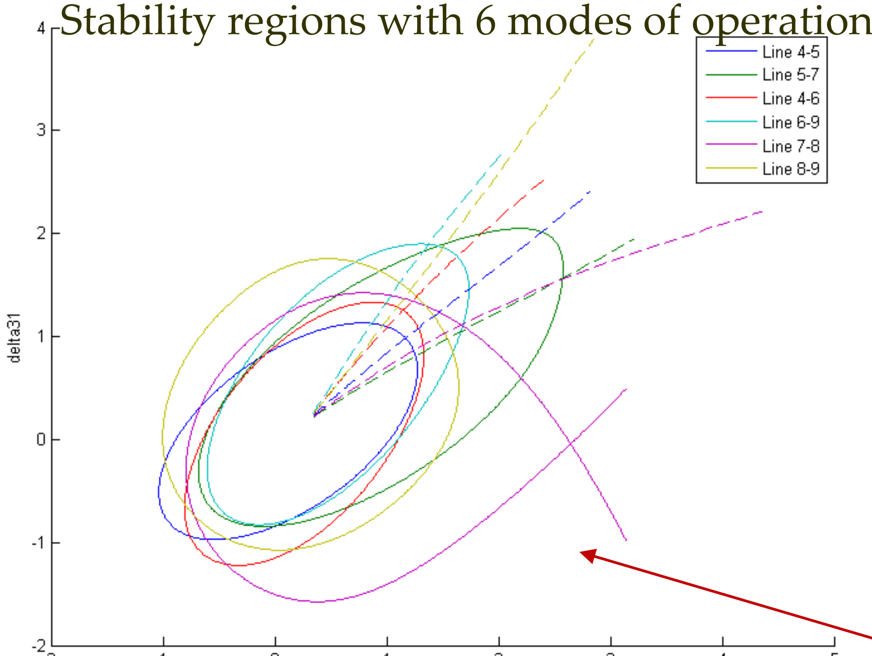


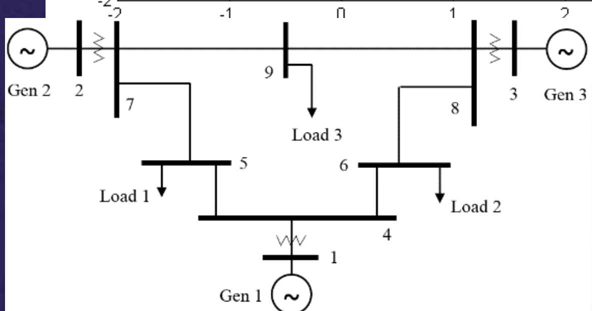
(c) Estimated rotor speed deviations

$$c_{i,u}(t) = \int_{x,t} J_{i,u}(x,t) \boxed{f_{(\hat{x},\hat{t}_0)}(t,x,t_0)} dx\, dt_0$$

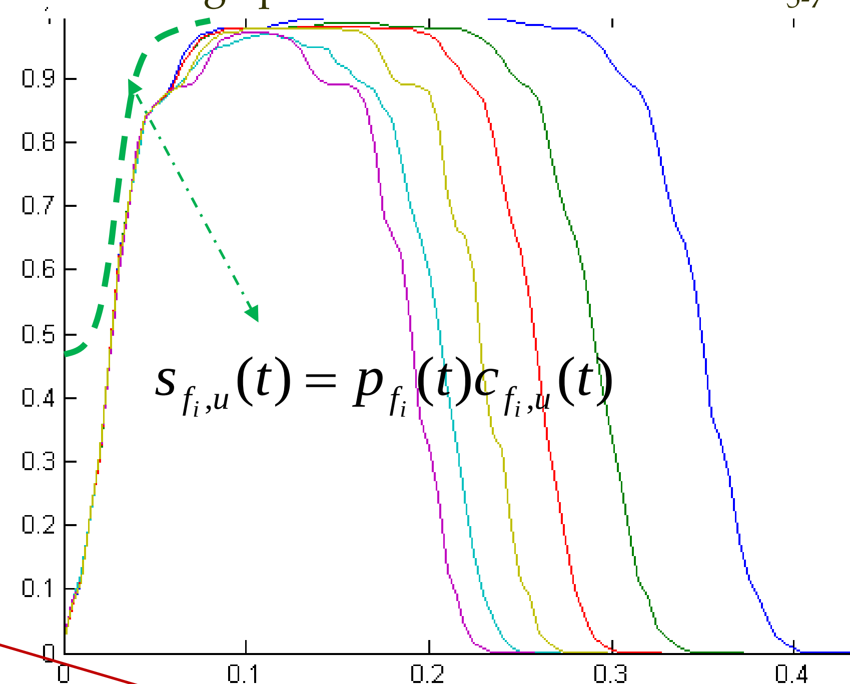
- PMU-aided auxiliary control
  - Bad news: diagnosis necessary
  - Good news: opportunity for recovery from protection misoperation

Stability regions with 6 modes of operation





Coverage profiles evaluated over $\text{RoA}_{5\text{-}7}$

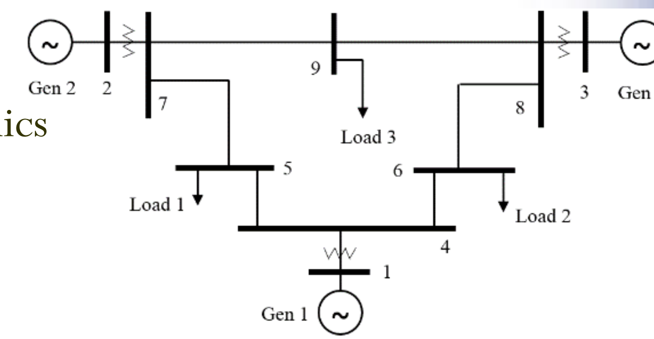


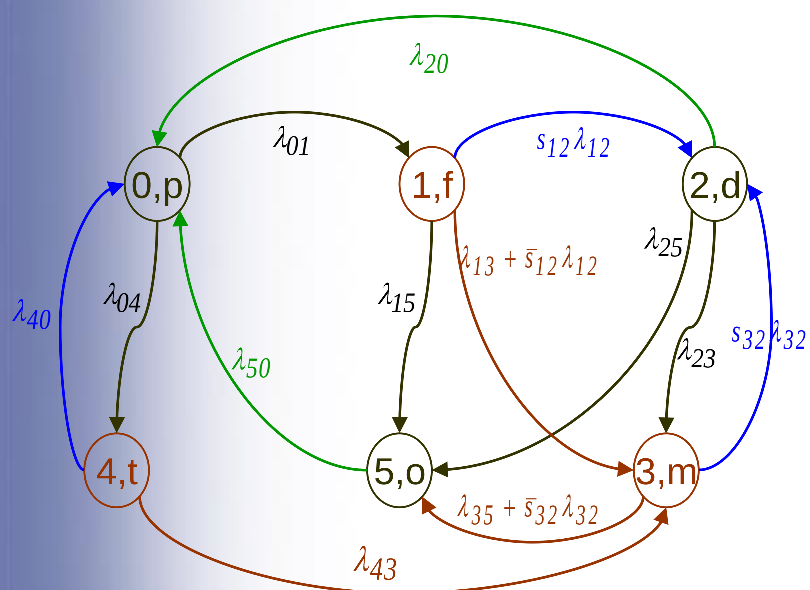
$$s_{f_i,u}(t) = p_{f_i}(t)c_{f_i,u}(t)$$

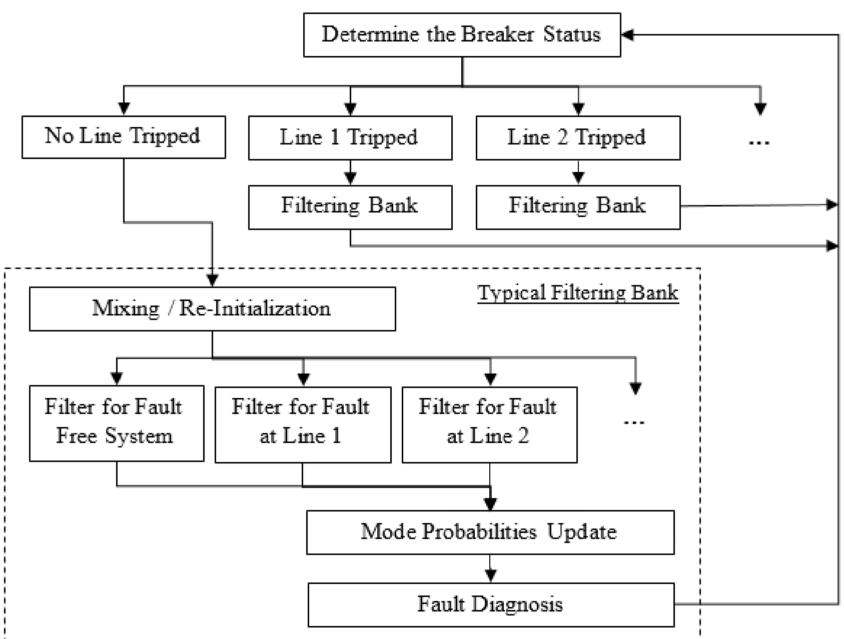
$$c_{i,u}(t) = \int_{x,t} \boxed{J_{i,u}(x,t)} f_{(\hat{x},\hat{t}_0)}(t,x,t_0)\,dx\,dt_0$$

Example: diagnosis using PMUs & multiple model filter banks

- Computing mode probability
  - Diagnosis to identify which equipment should be removed in the face of protection misoperations
    - A bank of filters are designed for each known state of protection system
  - Use of PMU-like sensors
    - Filters built on electric network dynamics
    - Inputs: estimated generator voltages
    - Outputs: other sensor input samples







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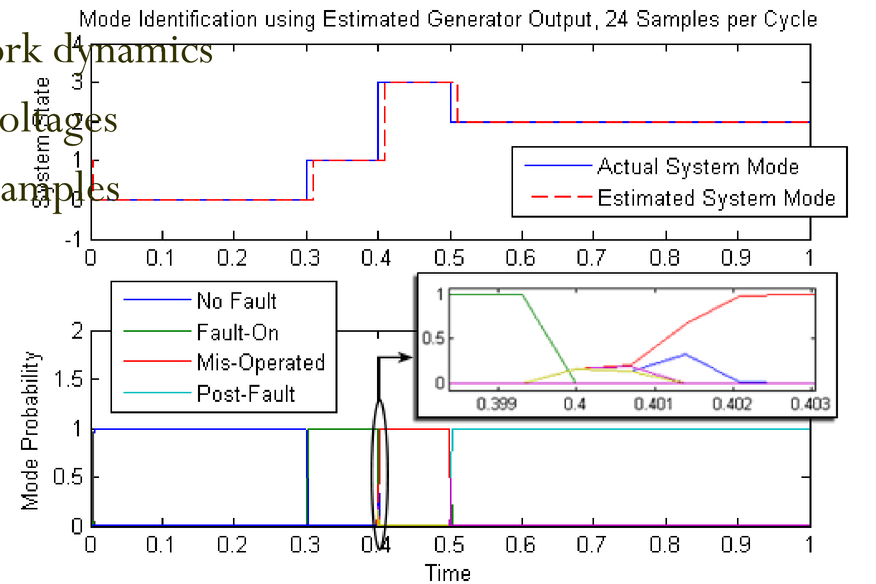

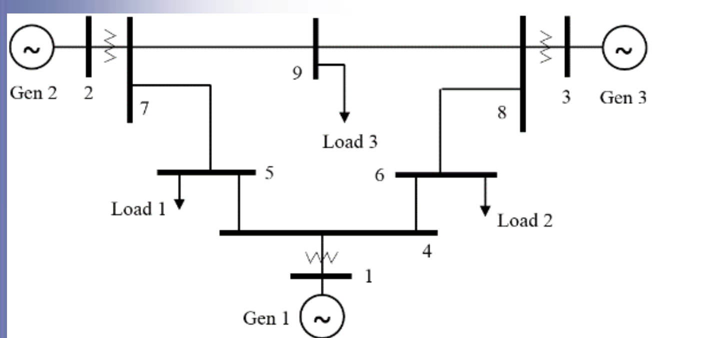

Desired secondary protection functions

True mode	Identified mode by primary protection	Control action by secondary protection
f_i	f_i	no action
f_i, $i > 0$	f_0	recover from failure to trip
f_i,	f_j, $j \neq i$	recover from false trip

Hybrid simulation for robustness study

- Assumptions
  - Short-to ground uniformly distributed along transmission
  - Single representative fault-on model/line

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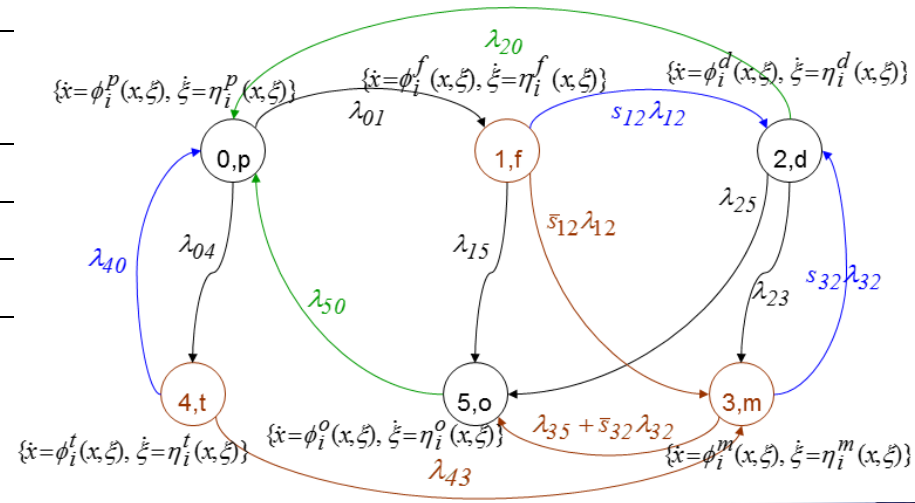

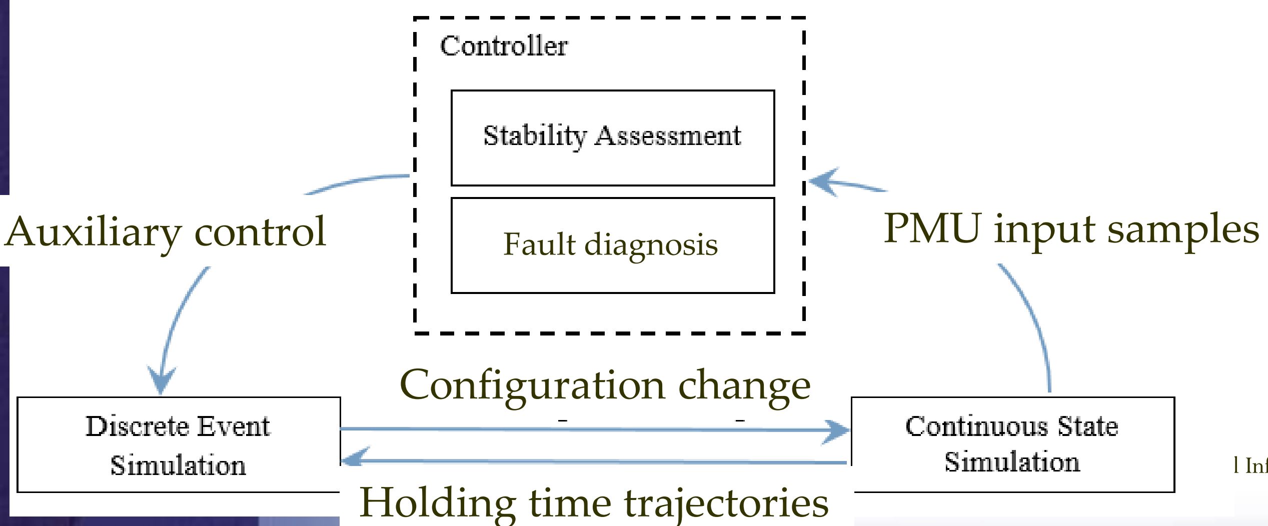

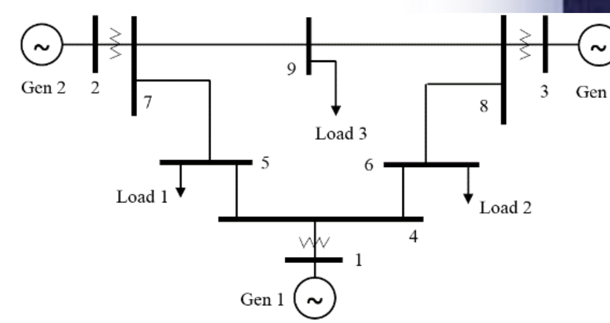

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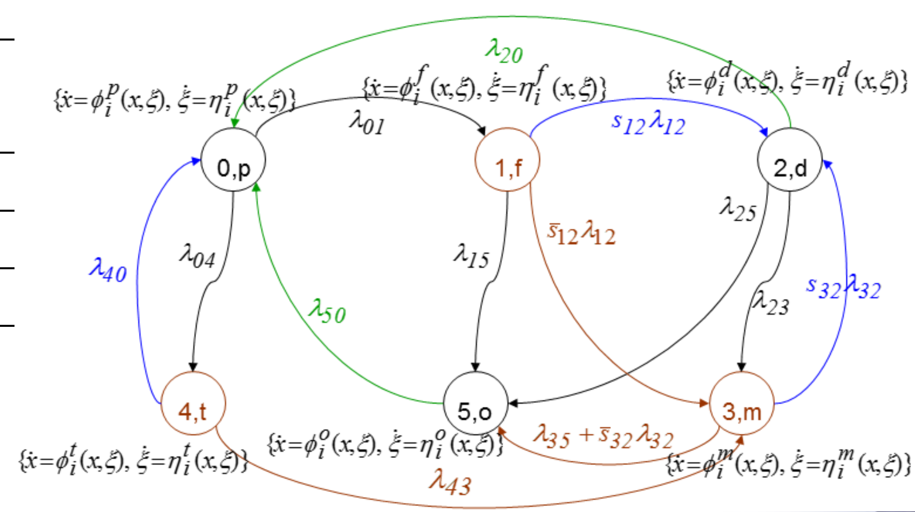
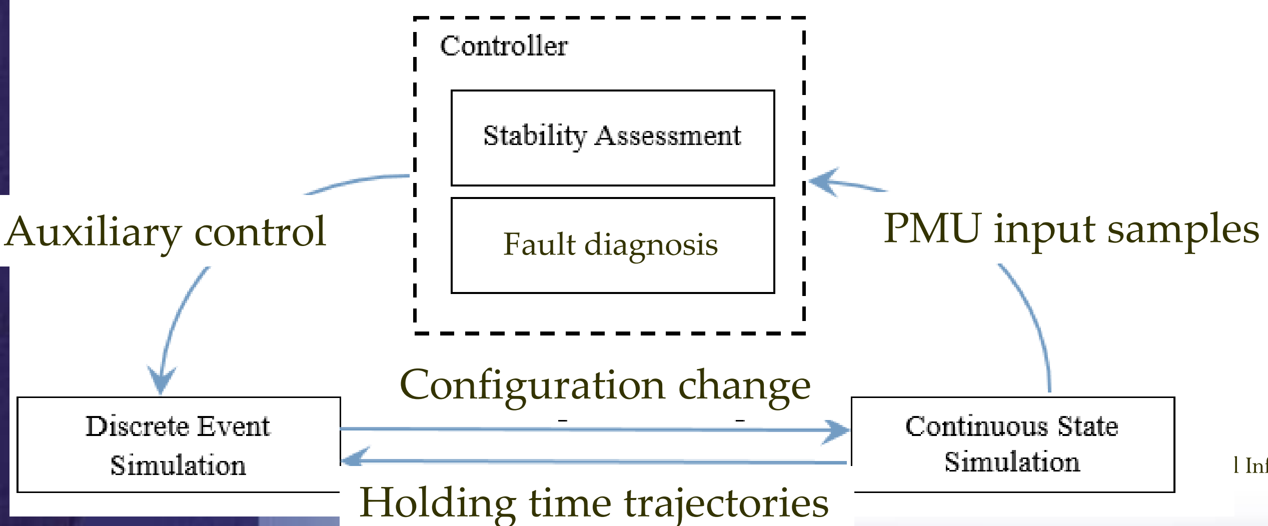
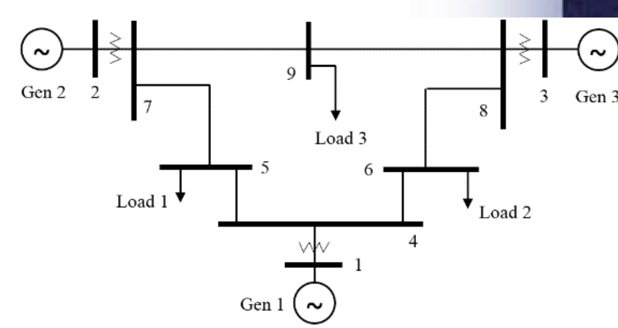
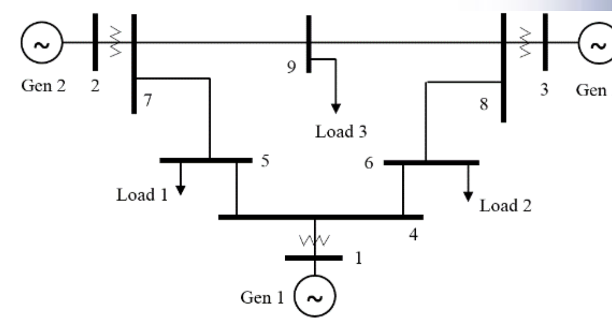


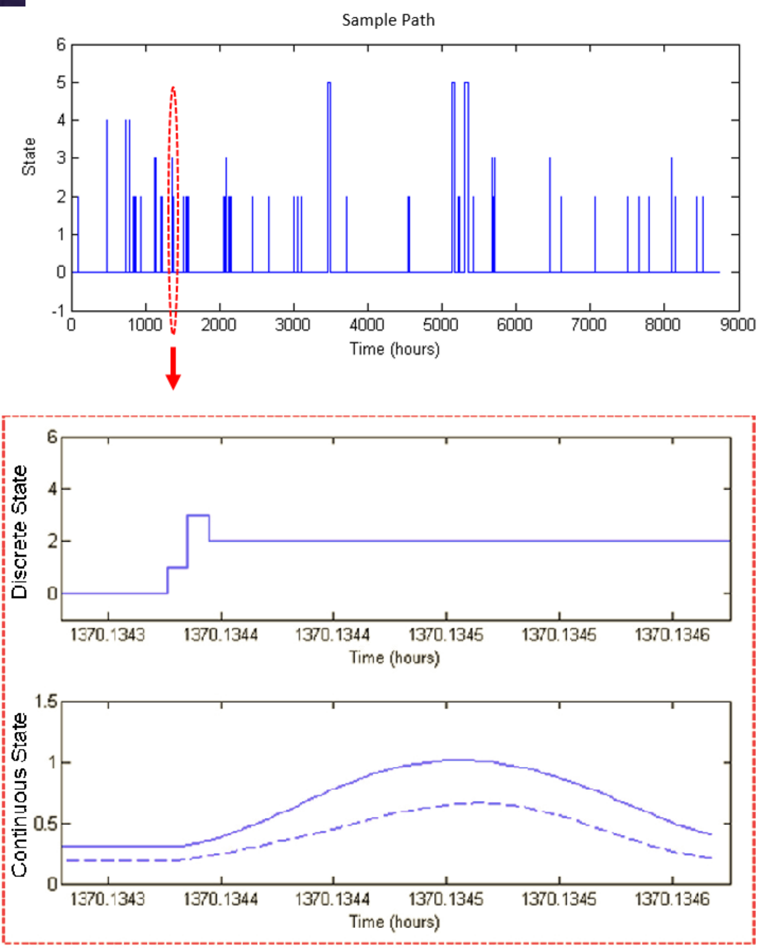


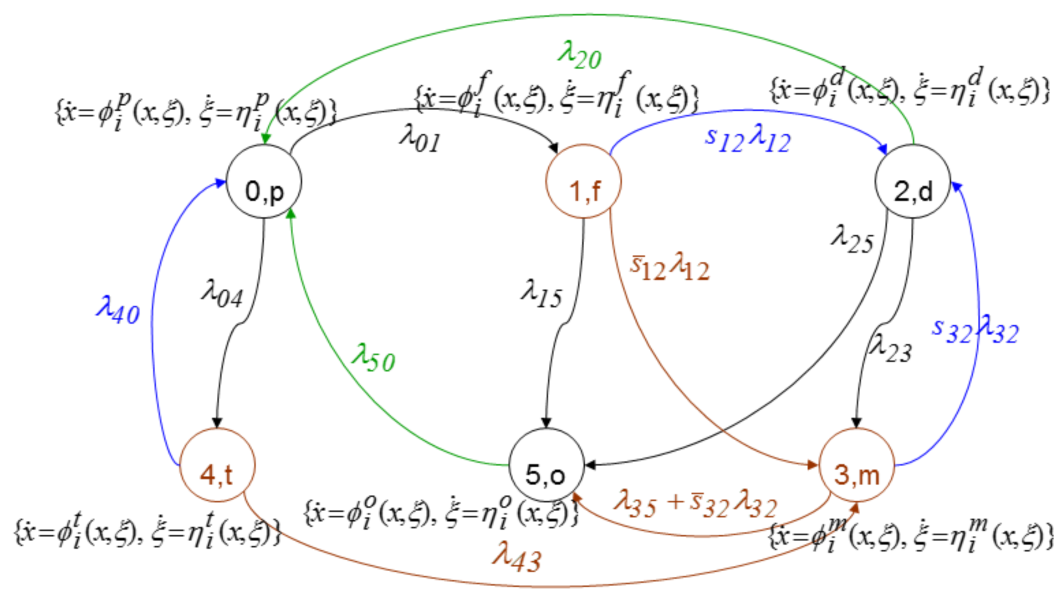


- Steady-state probability and event probability

	π_0	π_2	π_5	$Prob[d\|m]$
w/o secondary protect.	0.9425	0.0165	0.0406	0.0000
w/ secondary protect.	0.9643	0.0212	0.0137	0.4024







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