Adding Shaft Angle Measurement to Generator Protection and Monitoring

Greg Zweigle and Dale Finney
Schweitzer Engineering Laboratories, Inc.

Roy Moxley
formerly of Schweitzer Engineering Laboratories, Inc.

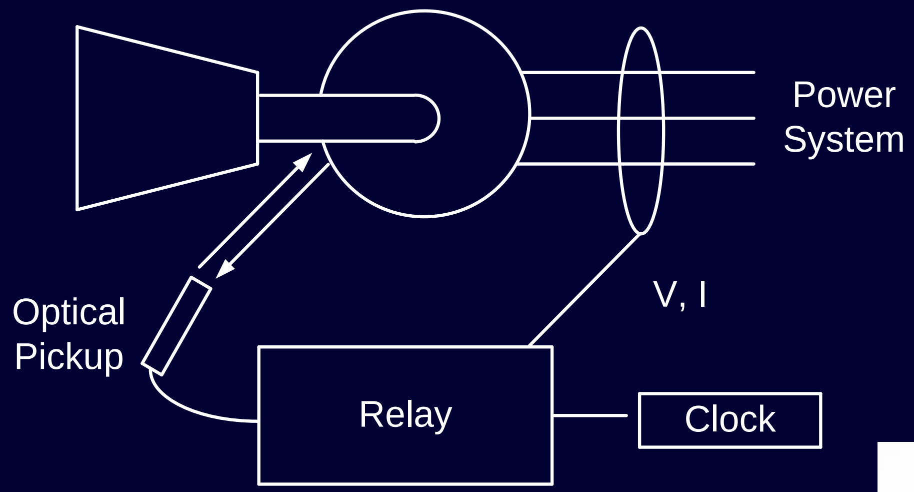
Topics

- Shaft angle measurement
- Generator relay solution benefits
- Applications
  - Subsynchronous resonance detection
  - Out-of-step protection
  - Machine parameter estimation
  - Transient stability control

Shaft Angle Measurement

- Optical – toothed wheel
- Magnetic – gear teeth
- Key phasor – shaft slot

Generator Relay Implementation



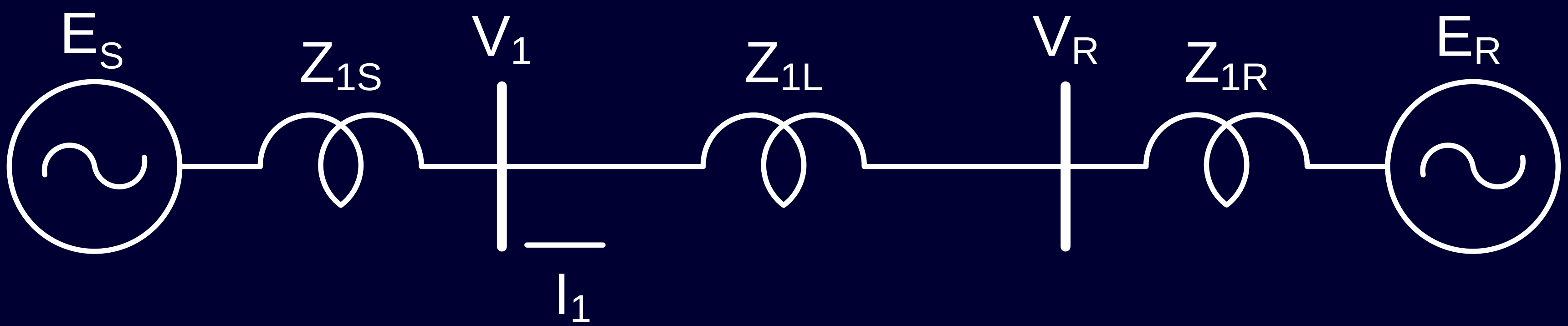
Subsynchronous Resonance

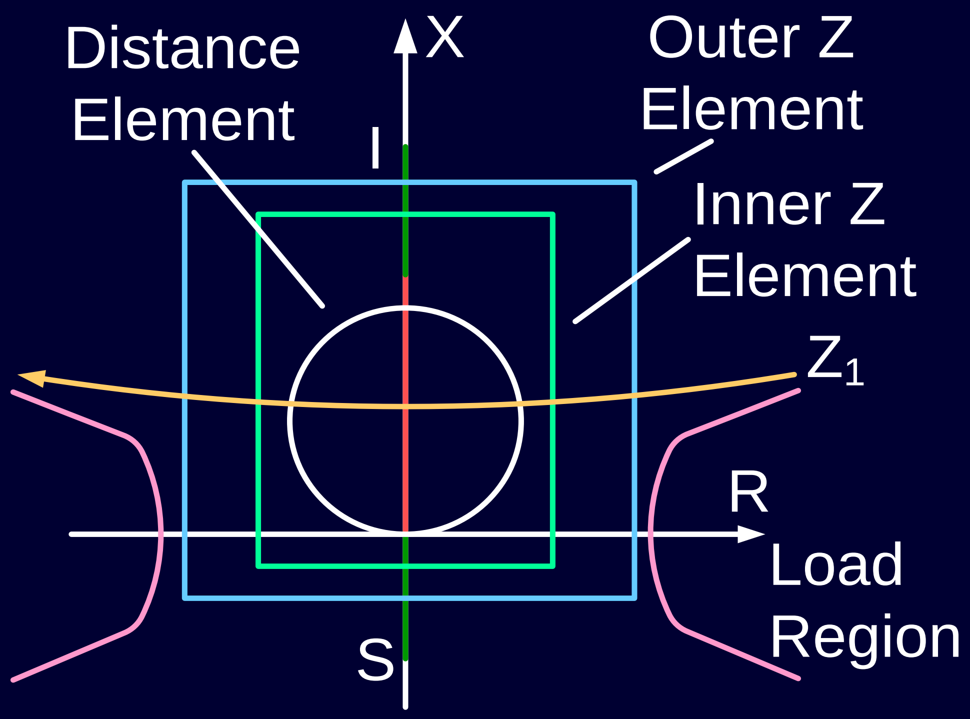
- Is an undamped energy exchange between the generator shaft system and the power system
  - Series compensated lines
  - Power electronics devices

Subsynchronous Resonance

- Has resonant frequencies that can be as low as 10 Hz
- Detected as a sustained oscillation in shaft angle

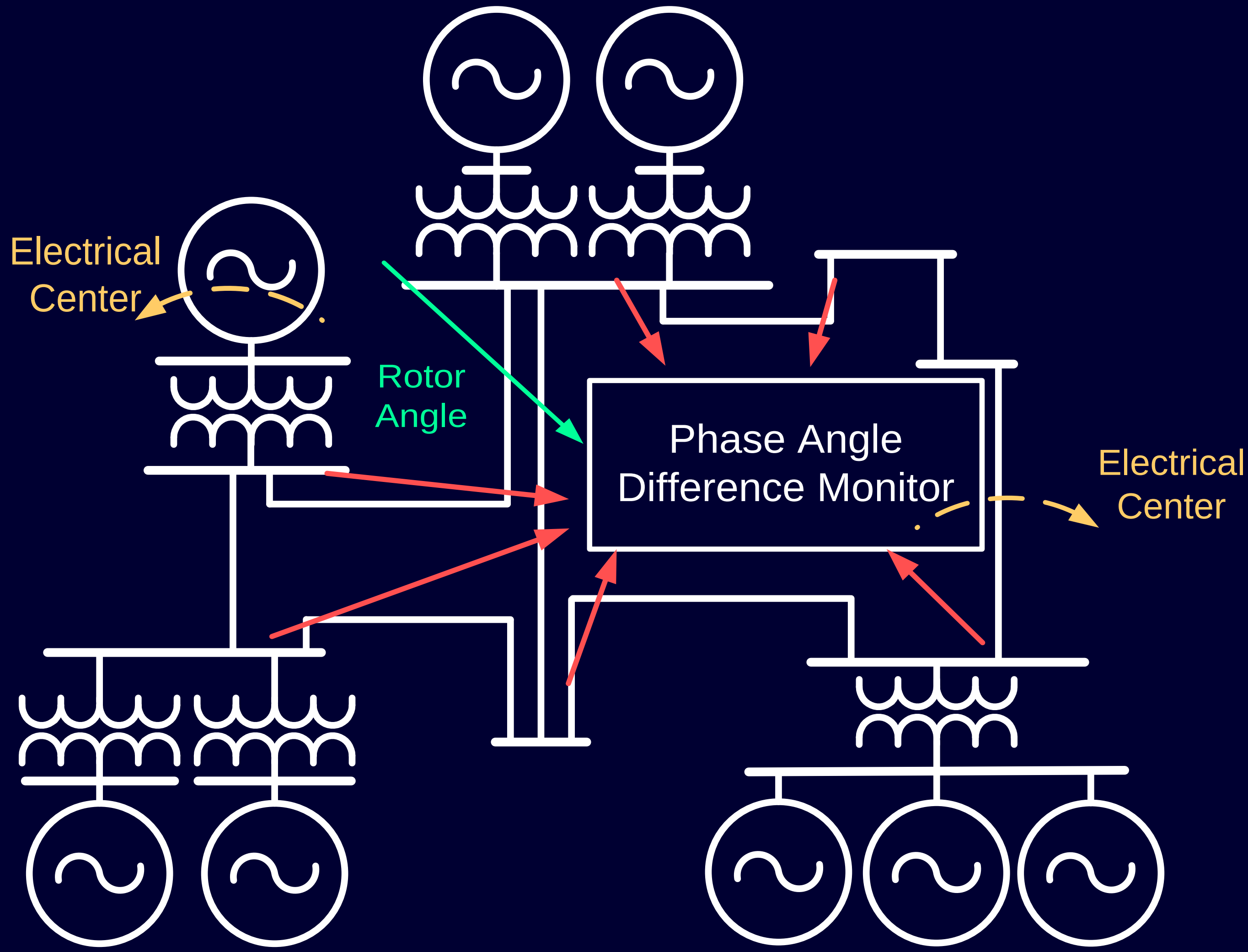
Out-of-Step Protection Measures
Speed of Z_1





Centralized Out-of-Step Scheme

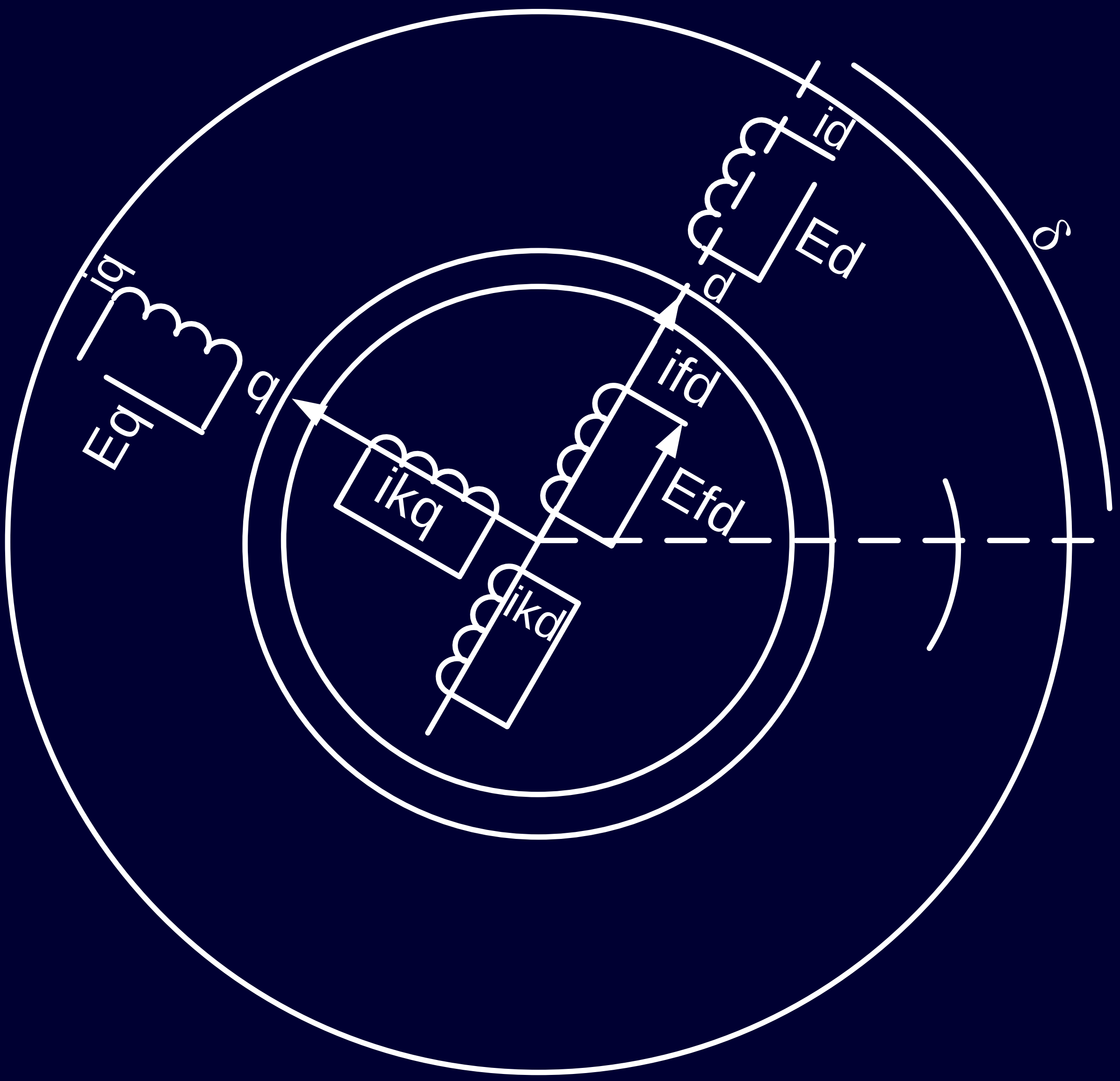
Adding Shaft Angle Provides Better Visibility



Generator Parameter Estimation

- Accurate system modeling
- Configuration of generator controls
  - AVR
  - PSS
- Detection of developing failures

Two-Axis Generator Model



- Ra, Ll
- Lad, Laq
- Rfd, Lfd
- Rkd, Lkd
- Rkq, Lkq

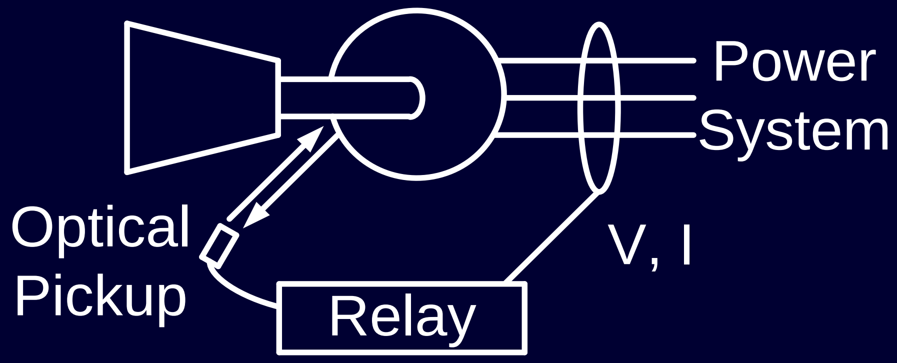
Estimation Methods

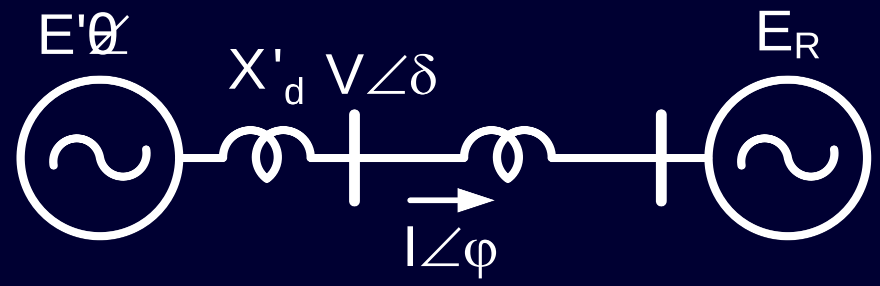
- Offline
  - Requires removal of the generator from service
  - Requires significant cost and effort to carry out testing
- Online
  - Uses generator terminal measurements captured during a disturbance - can be automated
  - Parameters are obtained with the machine under normal operation
  - Parameters are obtained more often

Estimation from Inputs/Outputs

- Terminal voltages and currents
- Additional measurements
  - Field voltage
  - Field current
- Shaft angle resolves terminal measurements to dq components

Online X'_d Measurement After a Disturbance





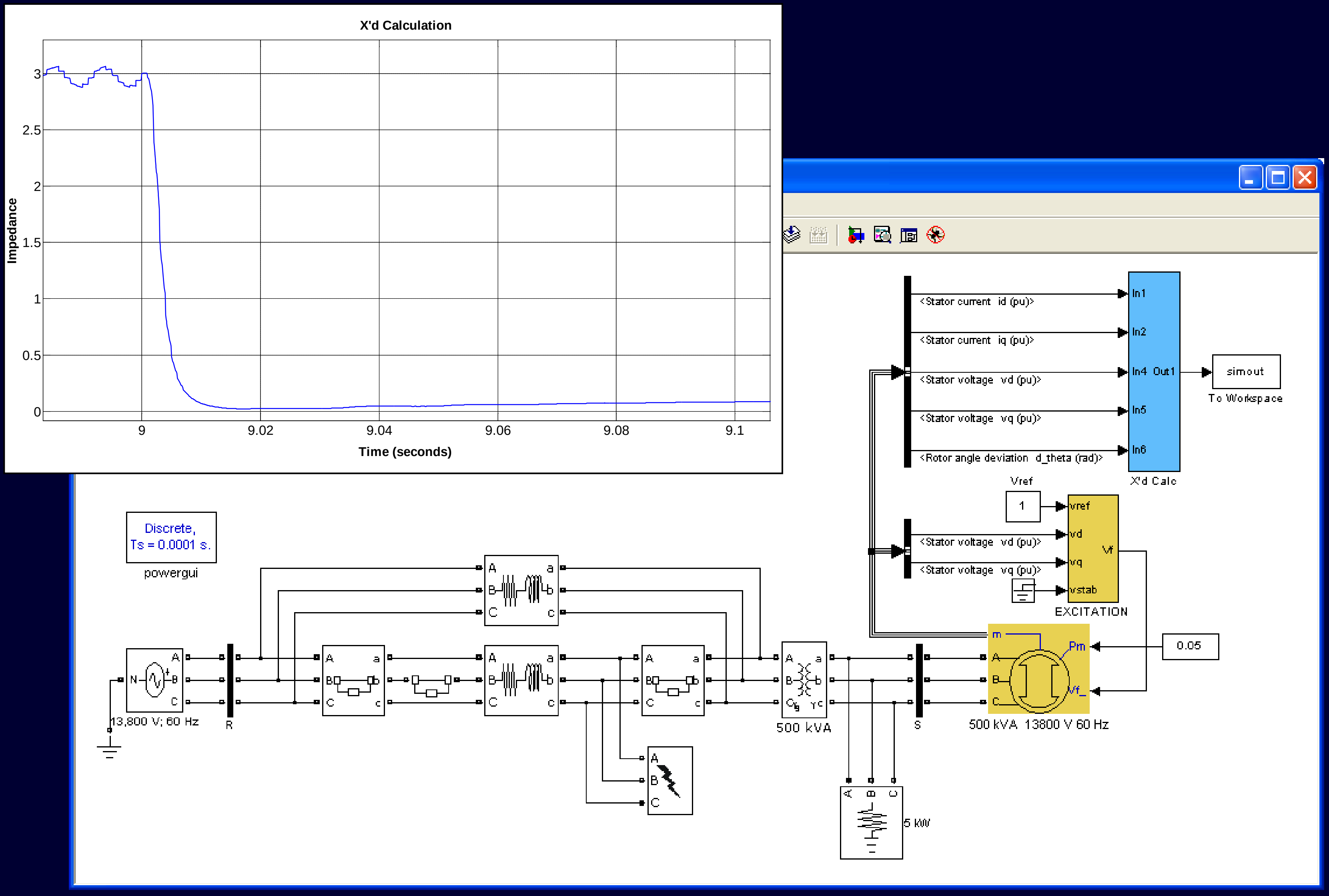
$$jX'_d I e^{j\phi} = E' e^{j\theta} - V e^{j\delta}$$

Solving:

$$X'_d = -\frac{V \bullet \sin(\delta - \theta)}{I \bullet \cos(\varphi - \theta)}$$

$$E' = V\cos(\delta - \theta) + V\sin(\delta - \theta)\tan(\phi - \theta)$$

Simulink Model



Transient Stability Control
RAS Scheme

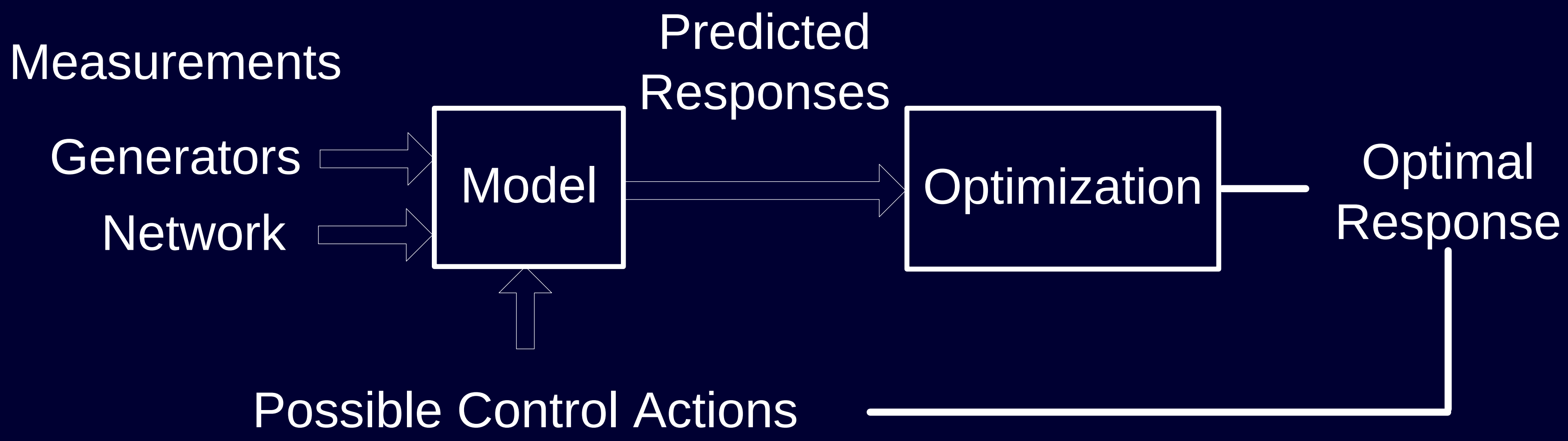
- Is a preplanned control action for a system event
  - Identify the contingency
  - Determine the system response
  - Select an appropriate control action

Modeling is done off-line

Transient Stability Control

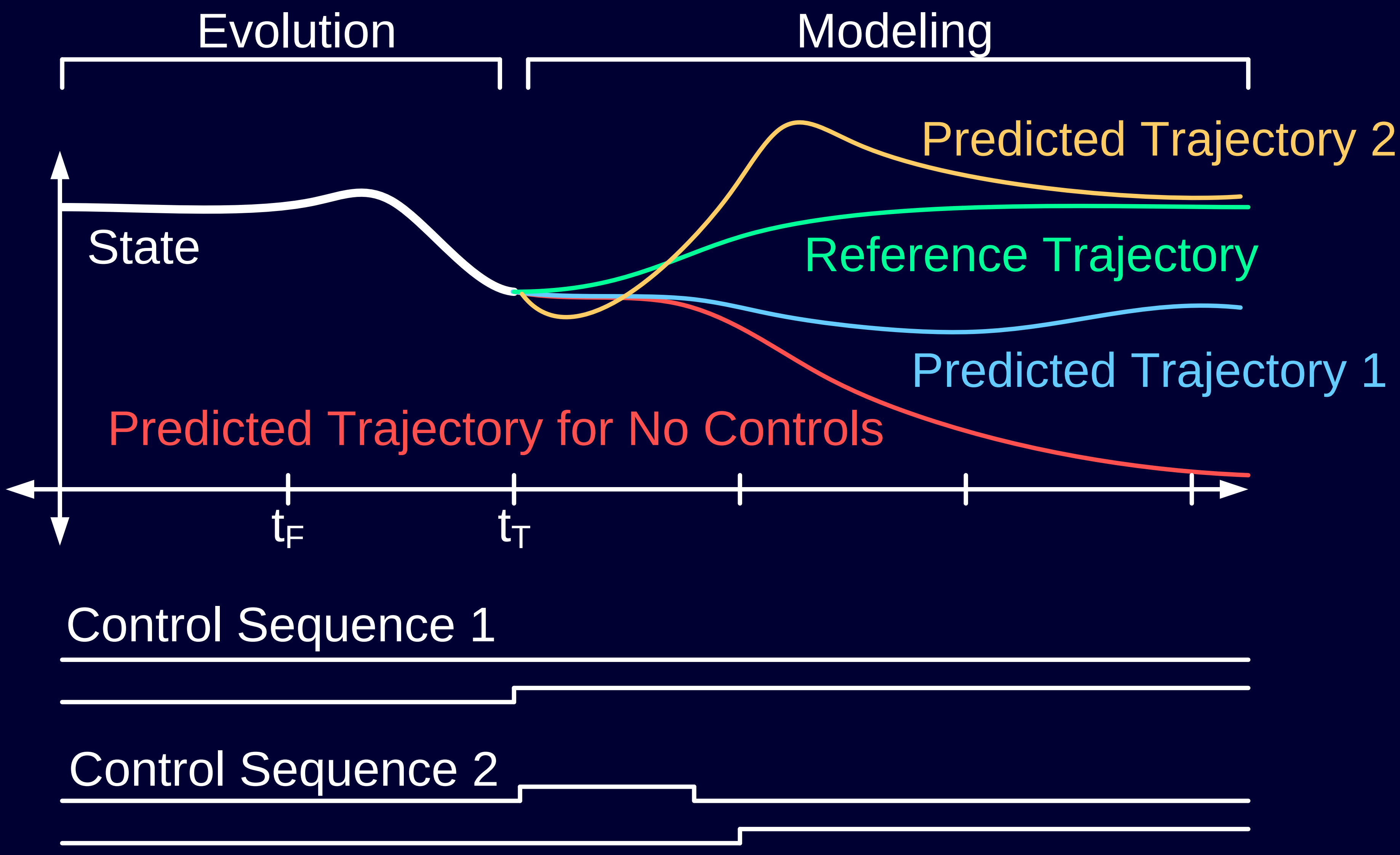
Model-Based Scheme

Determines optimal system response for a number of available control actions



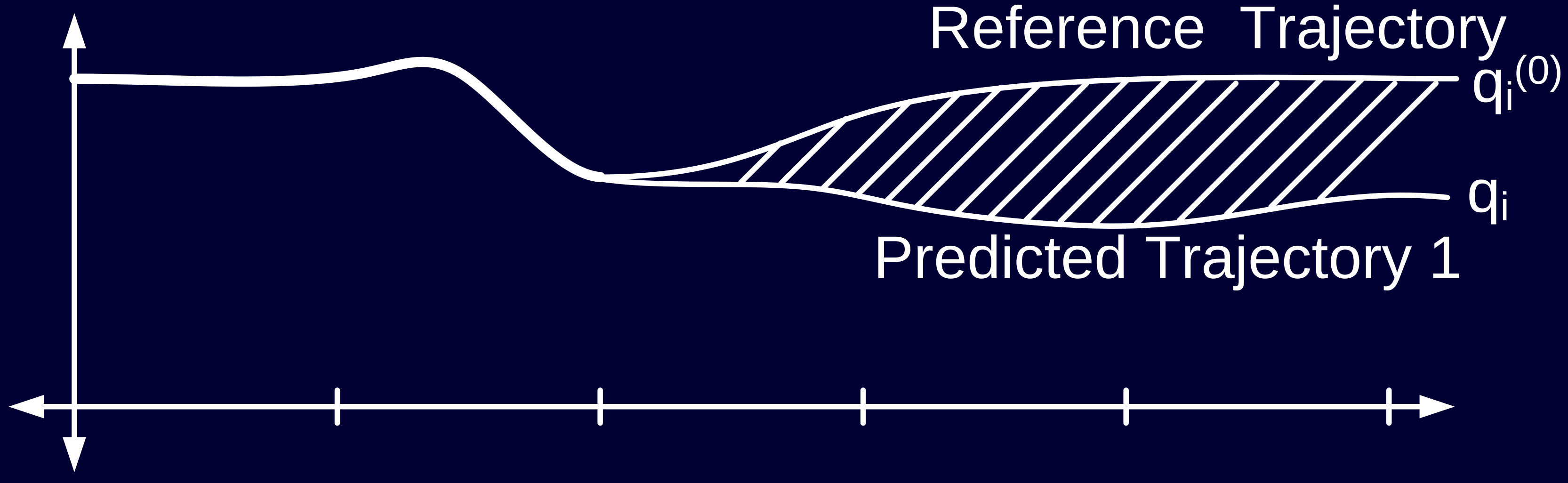
Modeling is done in real-time

Model-Based Transient Stability Control



Minimizing an Objective Function

- *Q* measures deviation
- *C* is the control cost



$$\min_{u}\left\{\left(\sum_{i=k+1}^{k+K'} Q\left(q_i - q_i^{(o)}\right)^2\right) C\left(u_{k+1},\ldots,u_{k+K}\right)\right\}$$

Control Costs

- Are relative (allow prioritization)
- Selected according to predicted stability

Control	Cost	
	Stable	Unstable
No Action	1	2
Generator Shedding	∞	3
Capacitor Switching	2	1

Control Costs

- Costs are time-dependent
- A generator can only be shed once
- Other controls can be included, such as load shedding

Control	Cost	
	Stable	Unstable
No Action	1	2
Generator Shedding	∞	3
Capacitor Switching	2	1

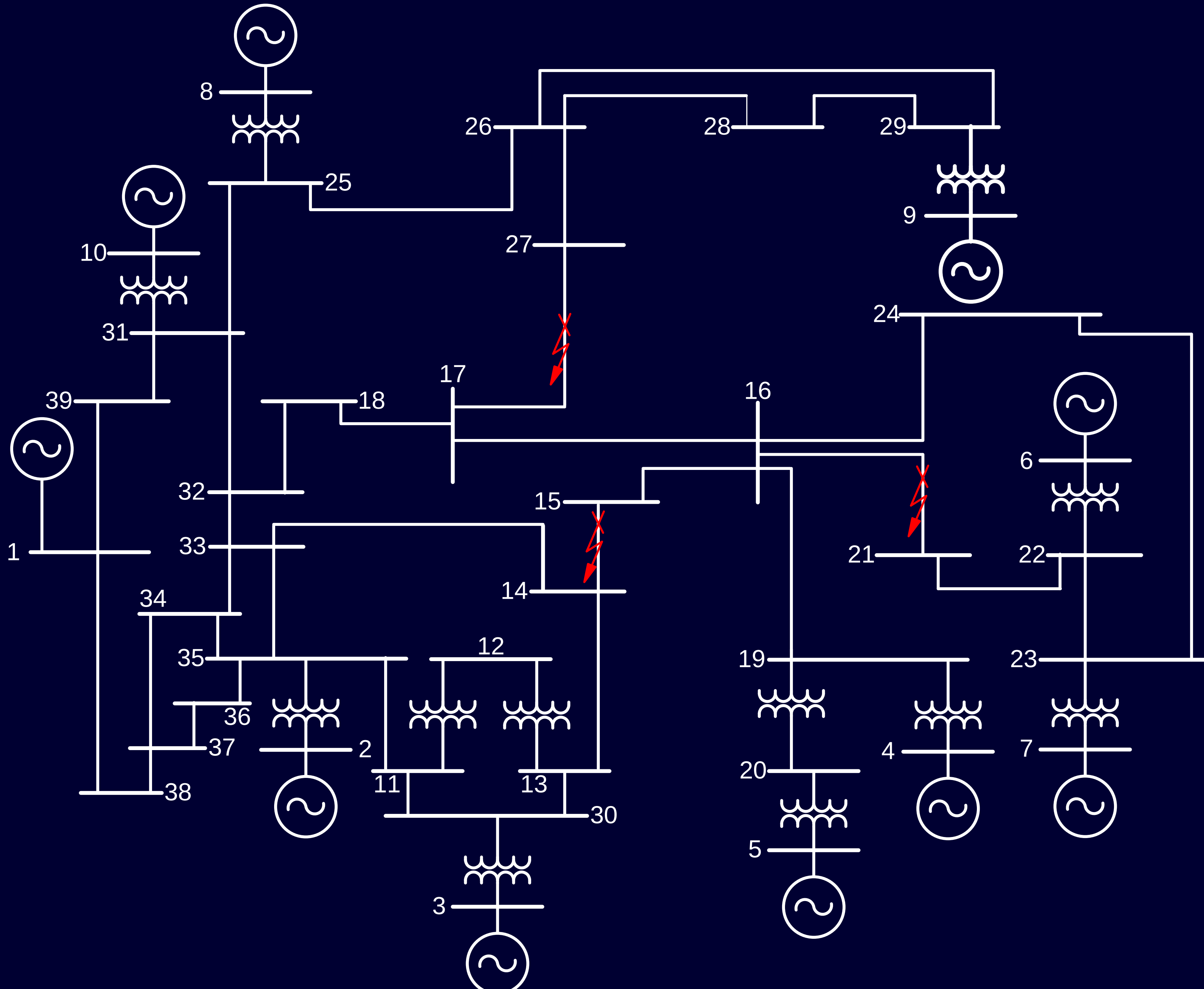
Adding Shaft Angle Improves the Modeling Process

Measurements

Generator Network

$$\dot{x} = f(x, y)$$ ← Two-axis generator equations

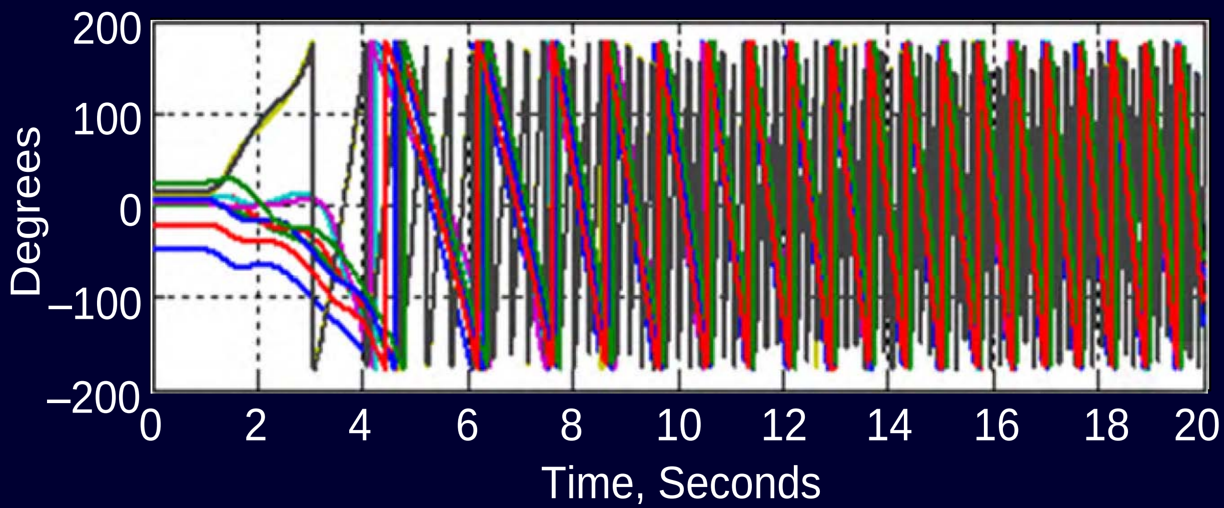
$$0 = g(x, y)$$ ← Network power flow equations



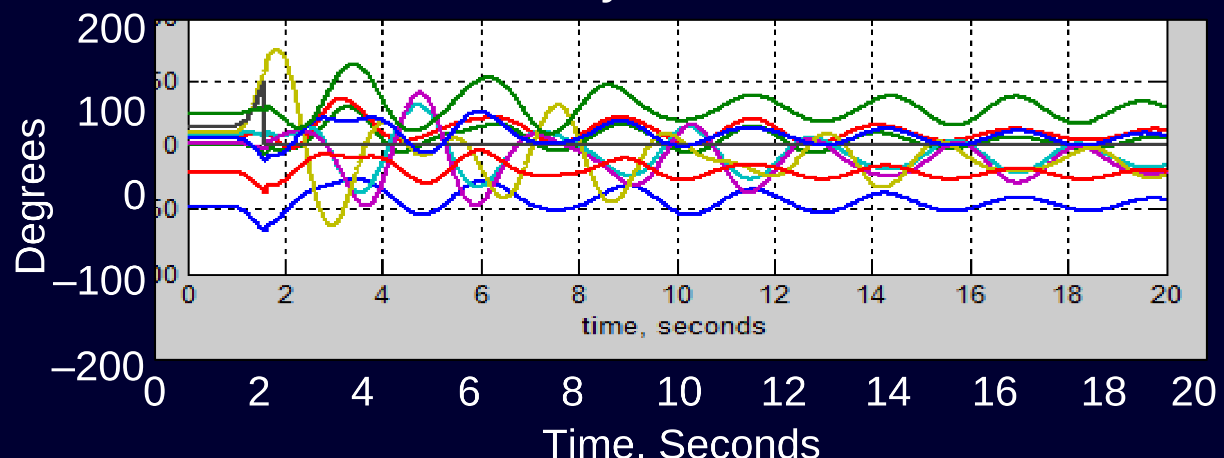
8
25
26
28
29
9
10
27
31
24
39
17
18
16
32
6
15
1
33
21
22
14
34
12
35
19
23
36
37
2
4
7
11
13
20
38
30
5
3

System Response

Without control, Generators 6 and 7 lose synchronism



With control, only Generator 7 is shed



Conclusion

- Shaft angle measurements enable new schemes for monitoring, protection, and control
- Adding shaft angle to generator relays leverages existing measurements and synchrophasor capabilities


T5001
JACKET WATER
JACKET WATER
JACKET WATER
JACKET WATER
VENT

Questions?