Distributed Control, Protection, and Automation of Modern Electric Power Systems

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Making Electric Power Safer, More Reliable, and More Economical®

Thesis

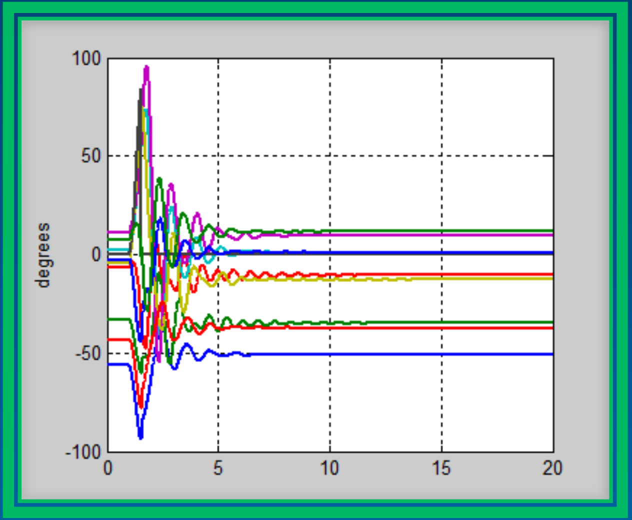
Electric power systems deliver energy at the speed of light!

- Legacy power systems had a lot of margin.
- Today, there is less margin, and we must look for new, faster, robust control solutions, like feedback control.
- I believe we will DISTRIBUTE and AUTOMATE control, as we do protection.

Power Systems Are Changing

Less control over sources

Faster dynamics

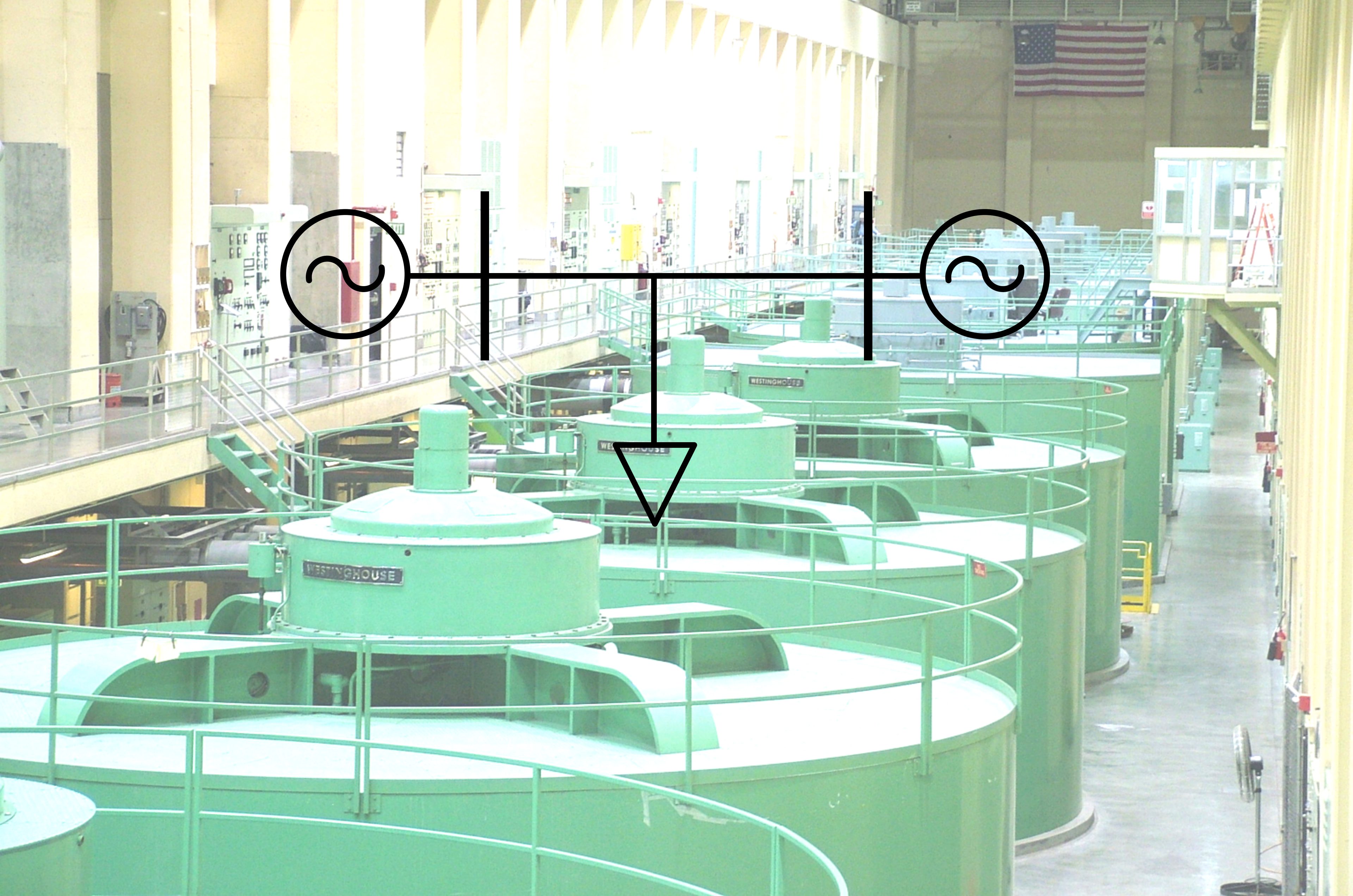


Increasing dependence on electric power

Characterizing SCADA

- *Asynchronous* Measurements
- *Asynchronous* Communications
- *Centralized and Slow* Data Gathering
- *Control by Operators…* No Automation
- *Slow State Estimation…* May not Converge

Traditional Generation Has MASS!

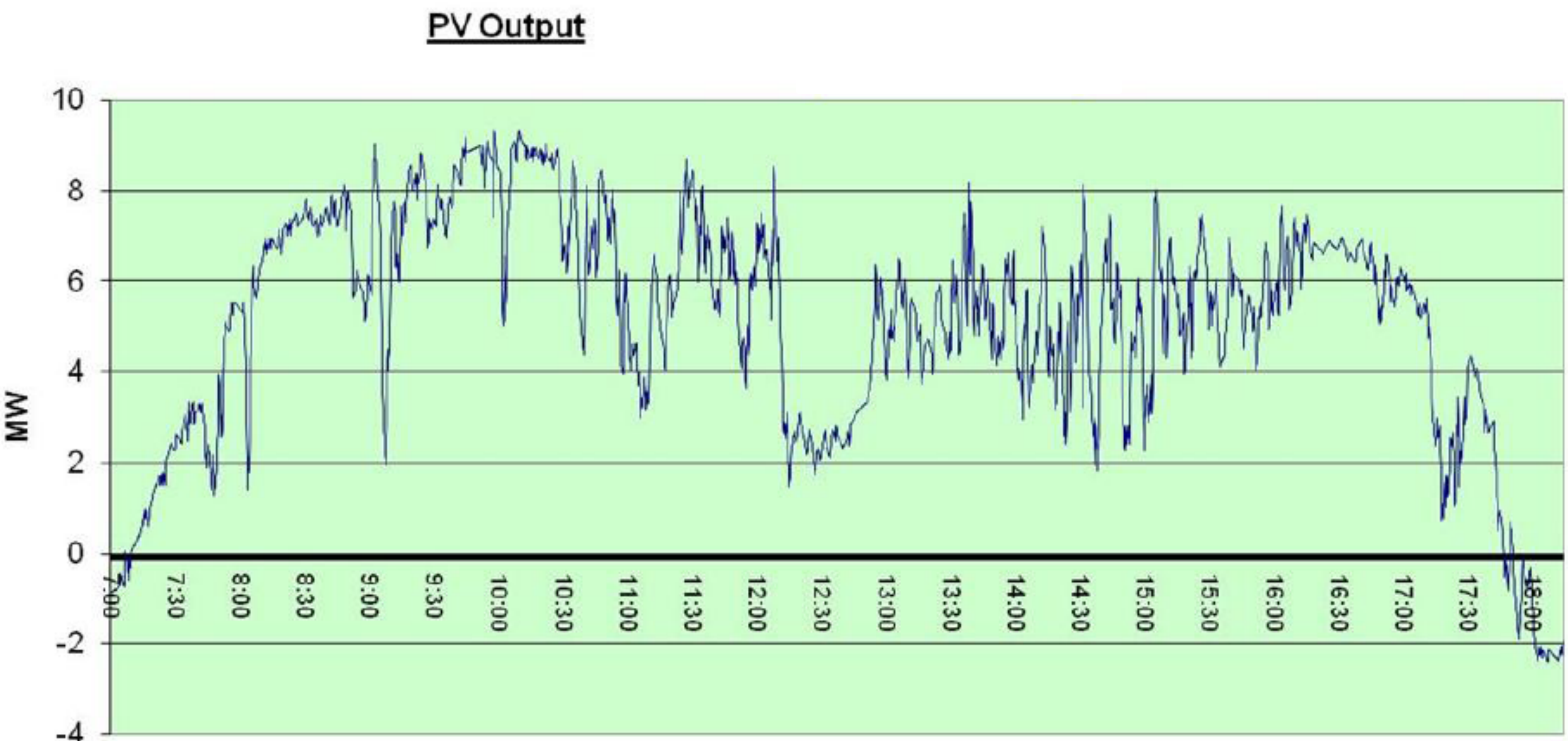


Electronic Sources Have Lower “Mass”

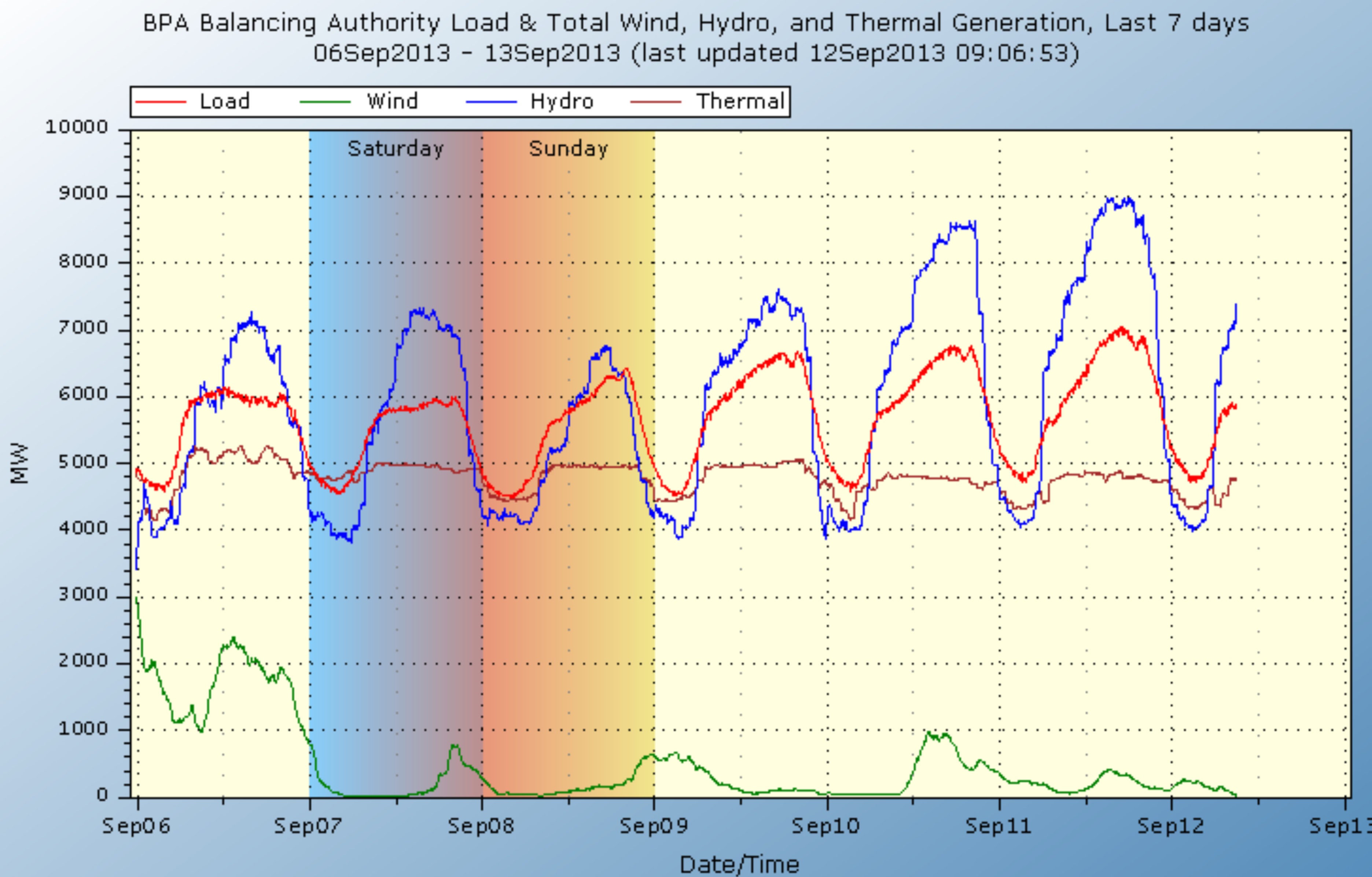
“Twitchier” Power Systems

- Photovoltaic generation
- Wind farms
- Less energy stored in capacitors than in rotating masses of traditional generators
- Lower “mass” => faster power swings
- Faster swings => better react faster!
- Why not PREDICT trajectory, instead of just reacting to it?

PV Output: Very Rapid Changes



2013: Hydro Picks Up When Wind Stops

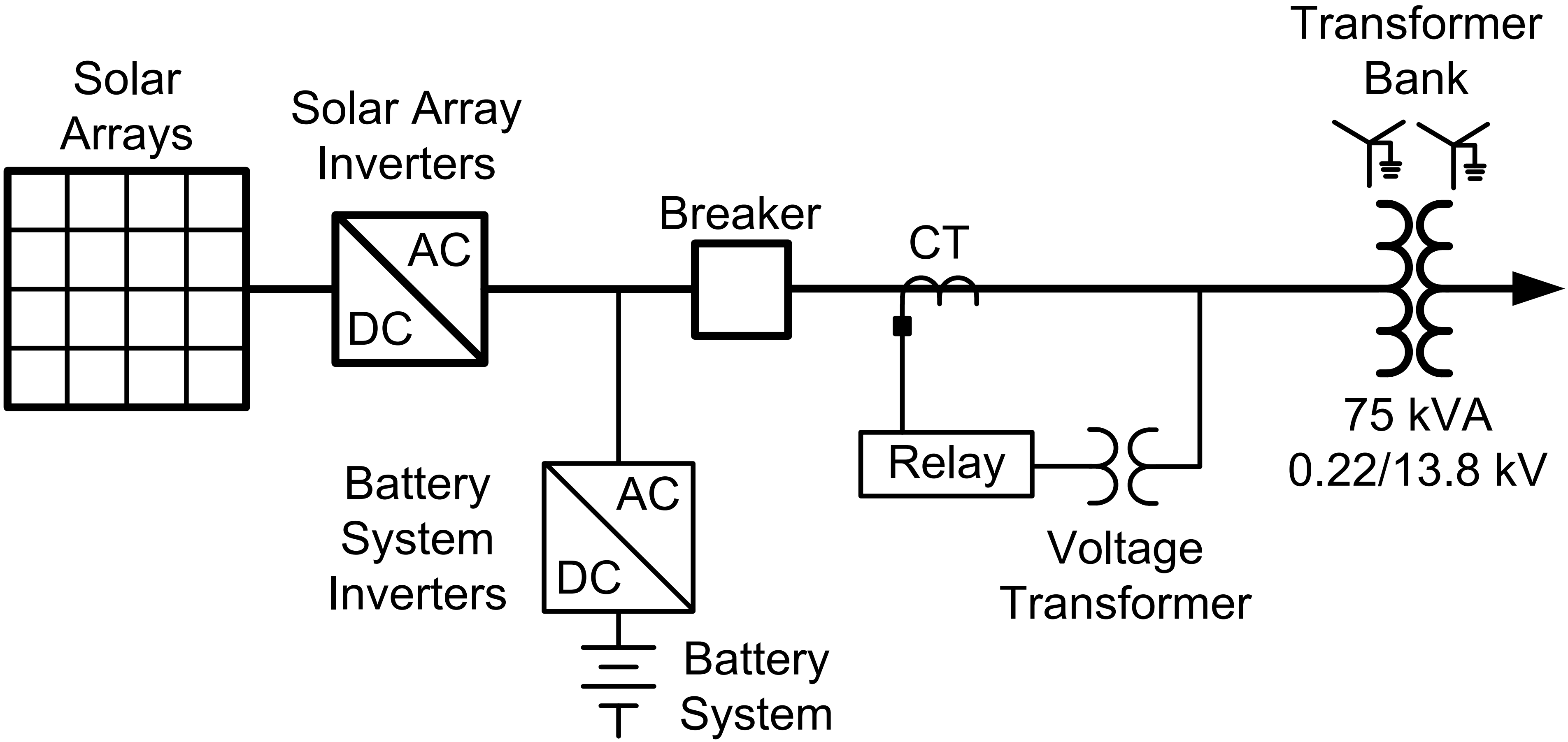


Guásimas del Metate (Nayarit)

Electrifying the remaining 2%

Solar Panels

Microgrid System for Reliability

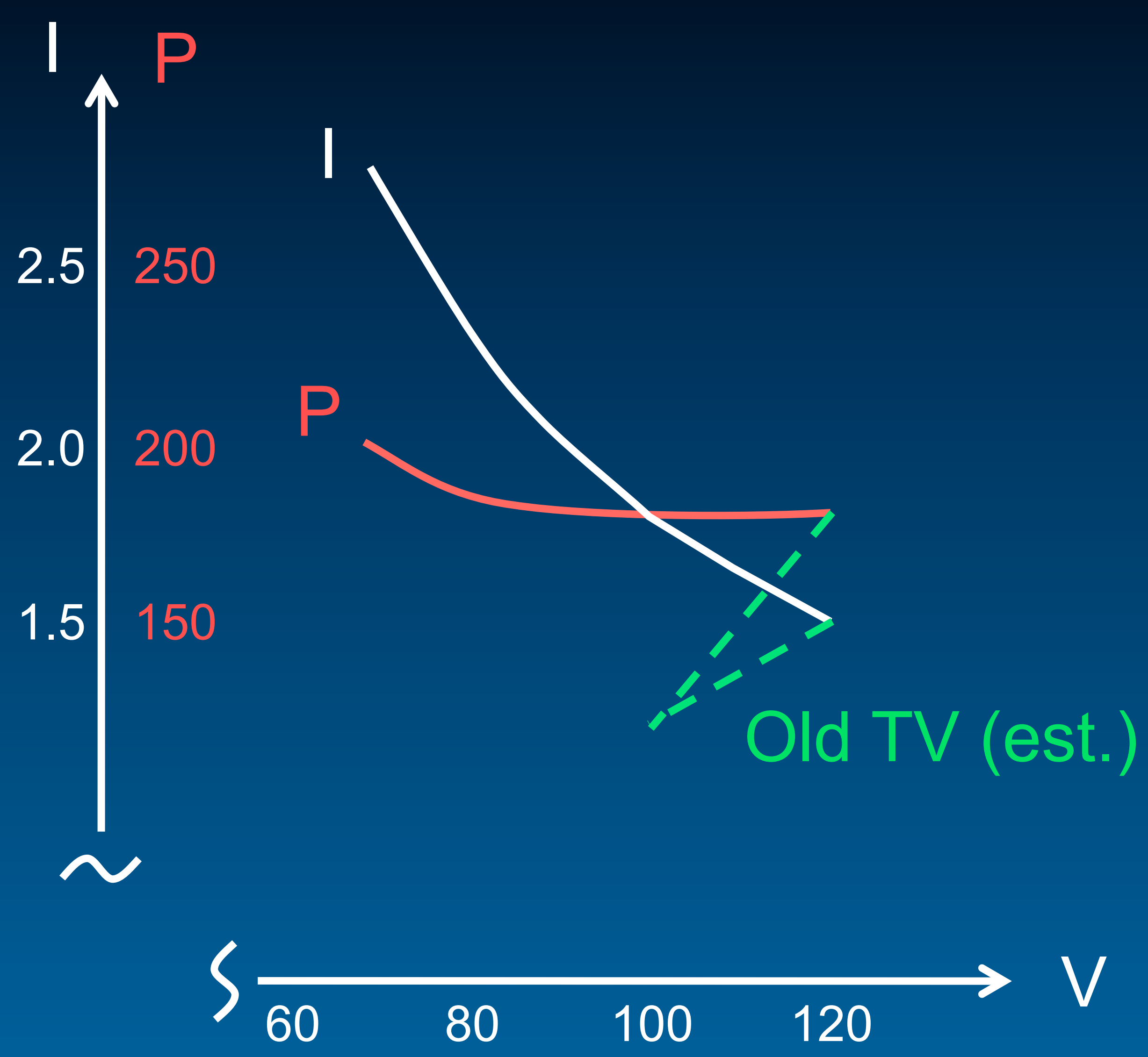


Stores energy for two days.

Load Trends Over Time

- Fewer resistive loads ($P = V^2/R$)
- More switchers (P = const.)
  - Electric car chargers
  - Data centers
- More “brittle” systems increase risk of voltage collapse
- Conservation voltage reduction (brownout) is less effective today…and may even be counter-productive!

50” Flat-Panel TV Test



How Do We Automate Wide-Area Control Today?

- Model the system
- Analyze contingencies for various operating conditions
- Decide if special protection or control systems are needed
- Build systems that respond to contingencies in ways that depend on the operating conditions at that moment

Problem With Predicting Contingencies

- Consider IEEE 39-bus 45-line system
- Number of k line outages = $\binom{45}{k}$

- Doesn't even include other failure cases

High k Contingencies

- Traditionally rare
- But they cause the largest outages
- Intermittent resources increase k
- Generation and load flow can change quickly today.
- Intentional attacks are “high k”

Contingency-Based Control Problems

- It’s hard, and getting harder, to know all the contingencies and operating conditions.
- Each contingency must be carefully analyzed and understood for every operating condition.
- The controller turns out to be a list of “if-then-else” actions, per contingency, and methods of identifying if and what contingency occurred.

Distribution Feeders as Buses

- Looped feed, pilot protection
  - Instantaneous tripping
  - Virtually no loss of service
- Accept generation anywhere
  - Rooftop solar, small wind, fuel cells
  - Integrate and dispatch backup gensets
- Islands ?microgrids? match load to source, and control frequency and voltage

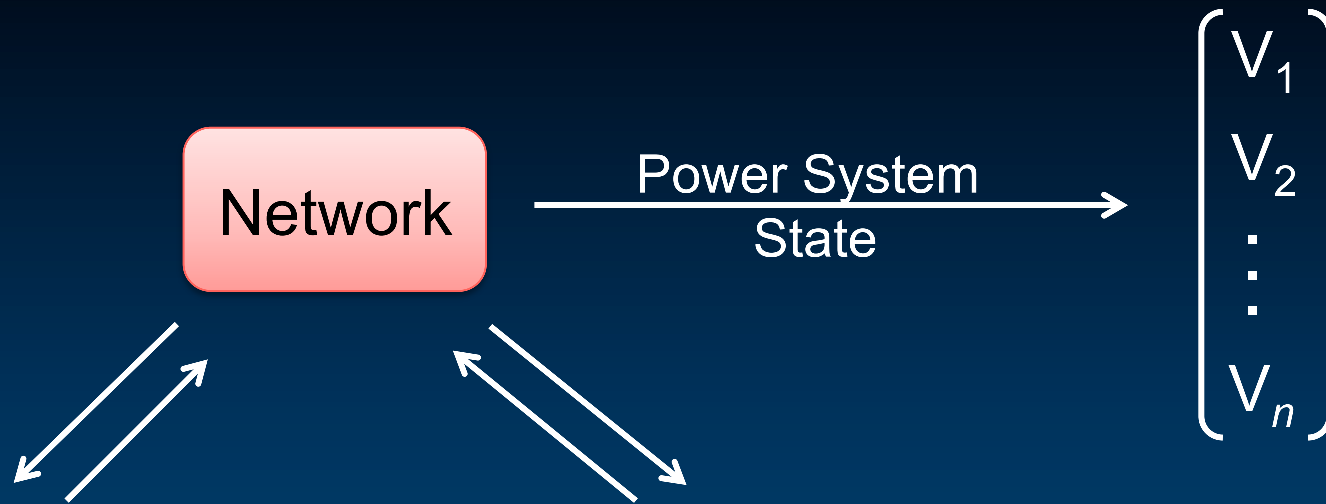
Closed Loop Control

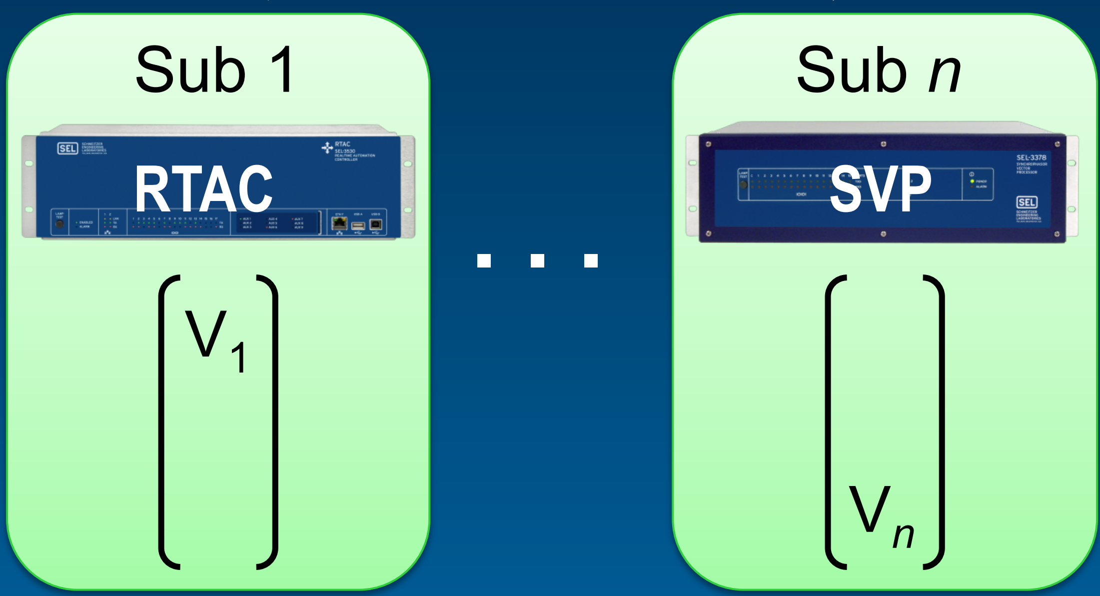
- …instead of predicting contingencies,
- Directly measure the state
- Predict the state evolution
- Take anticipatory control actions

What Is the “State” of the Power System?

- A vector of the complex voltages at every node, measured at the same time
- Either estimate state using “state estimator”
- …Or directly measure state:
  SYNCHROPHASORS

Directly Measure the State





- Detect bad data
- Average measurements
- Determine topology
- Calculate V at adjacent stations: $V' = V + ZI$

Relay-Speed Processing, Anywhere

- State Equations: Stability, Thermal

$$\dot{\underline{x}} = A\underline{x} + B\underline{u}$$

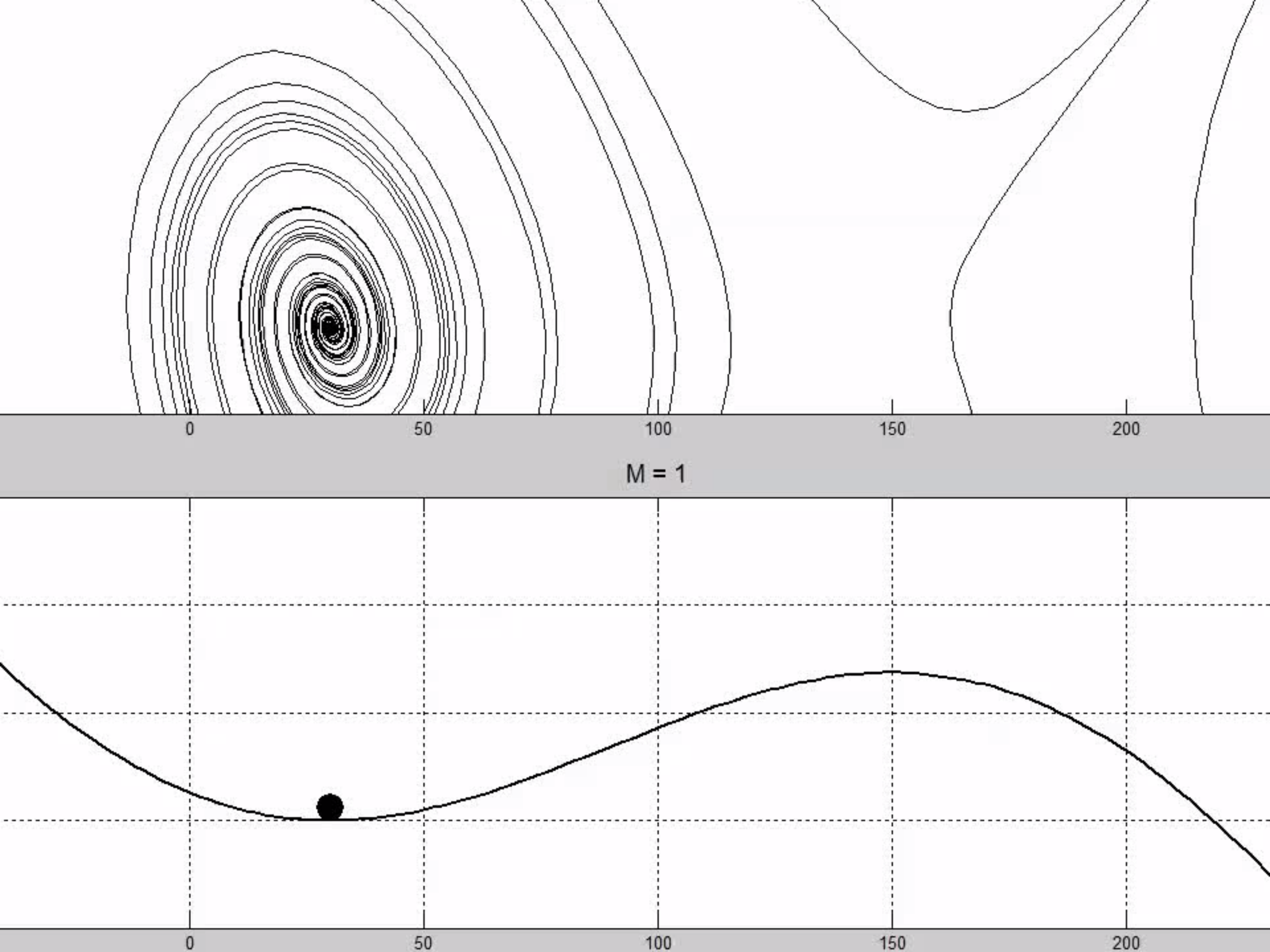
$$\underline{y} = C\underline{x} + D\underline{u}$$

- Phasor Math: Self-Checks, Interpolation

$$\dot{V}_m = \dot{V}_n + Z_{mn}\dot{I}_n$$

Maintain Load and Generation Balance

- View system as interconnected regions.
- Directly measure *state* in each region and share with neighbors, and master.
- When asset is lost, system starts to move from present state to predictable new one.
- If prediction is undesirable, act quickly to preserve as much generation and load as possible.


0
50
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M = 1
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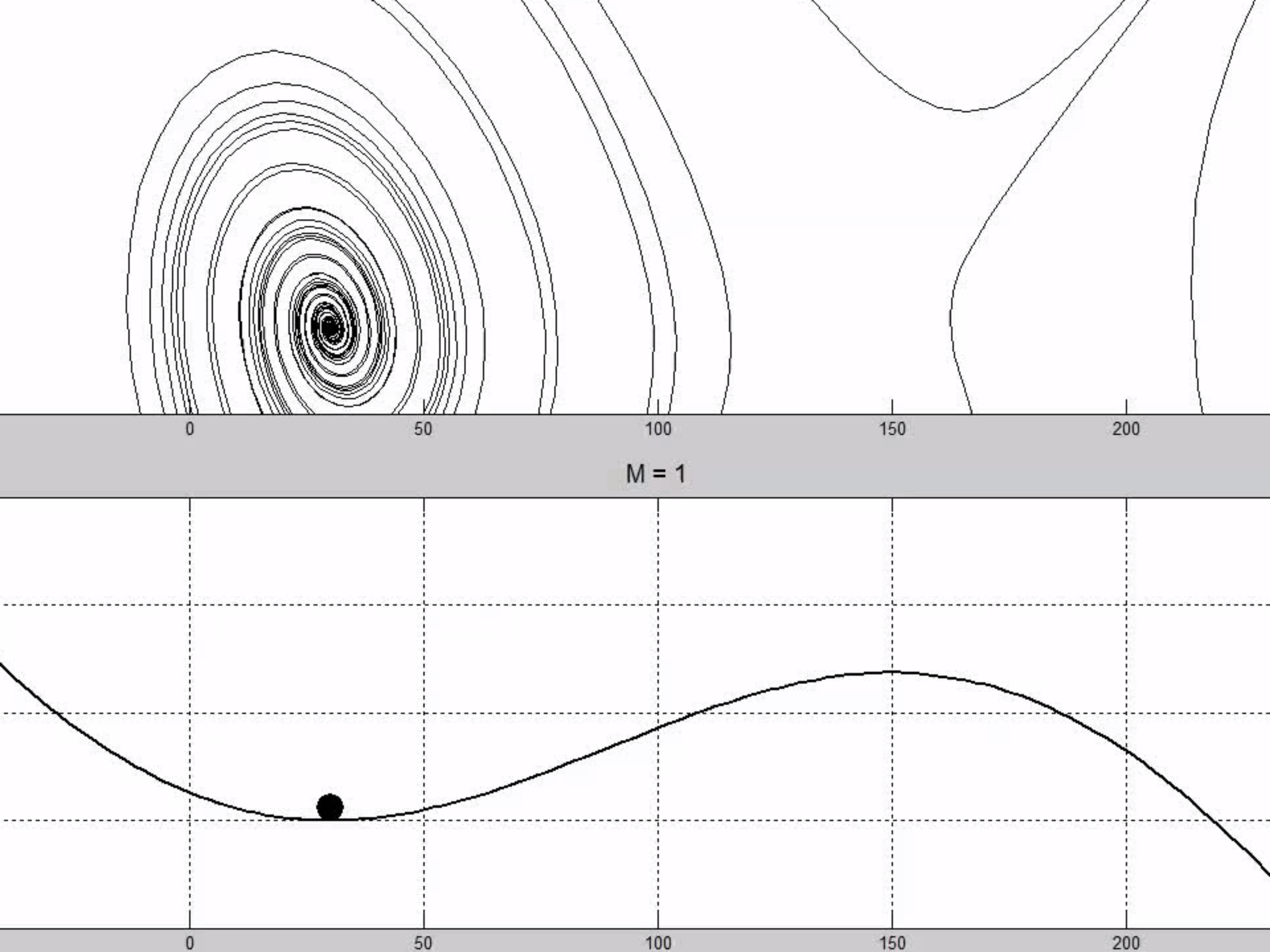
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M = 1
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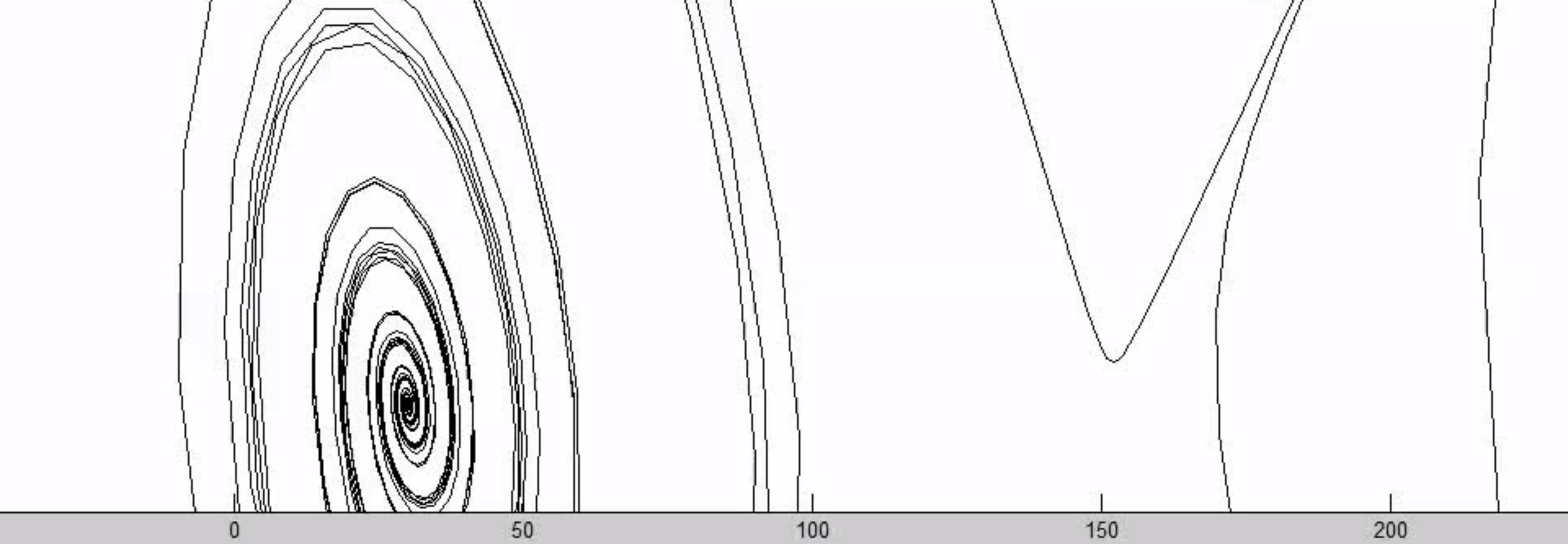
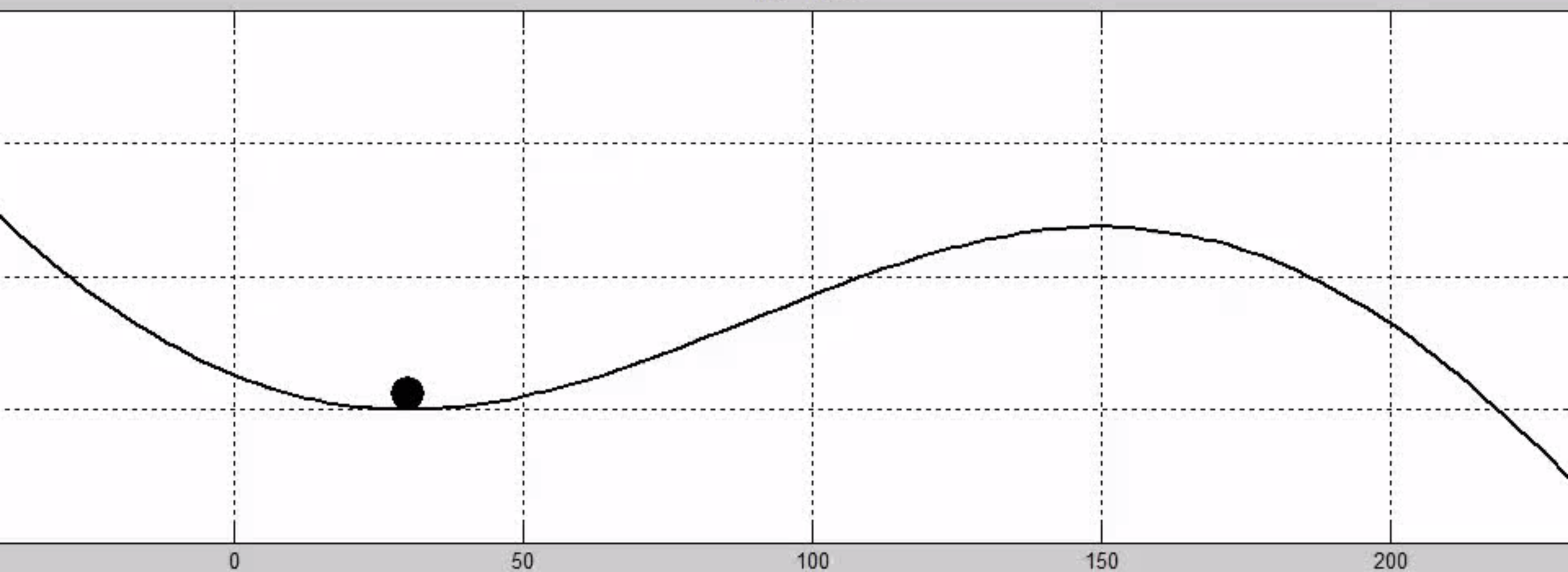
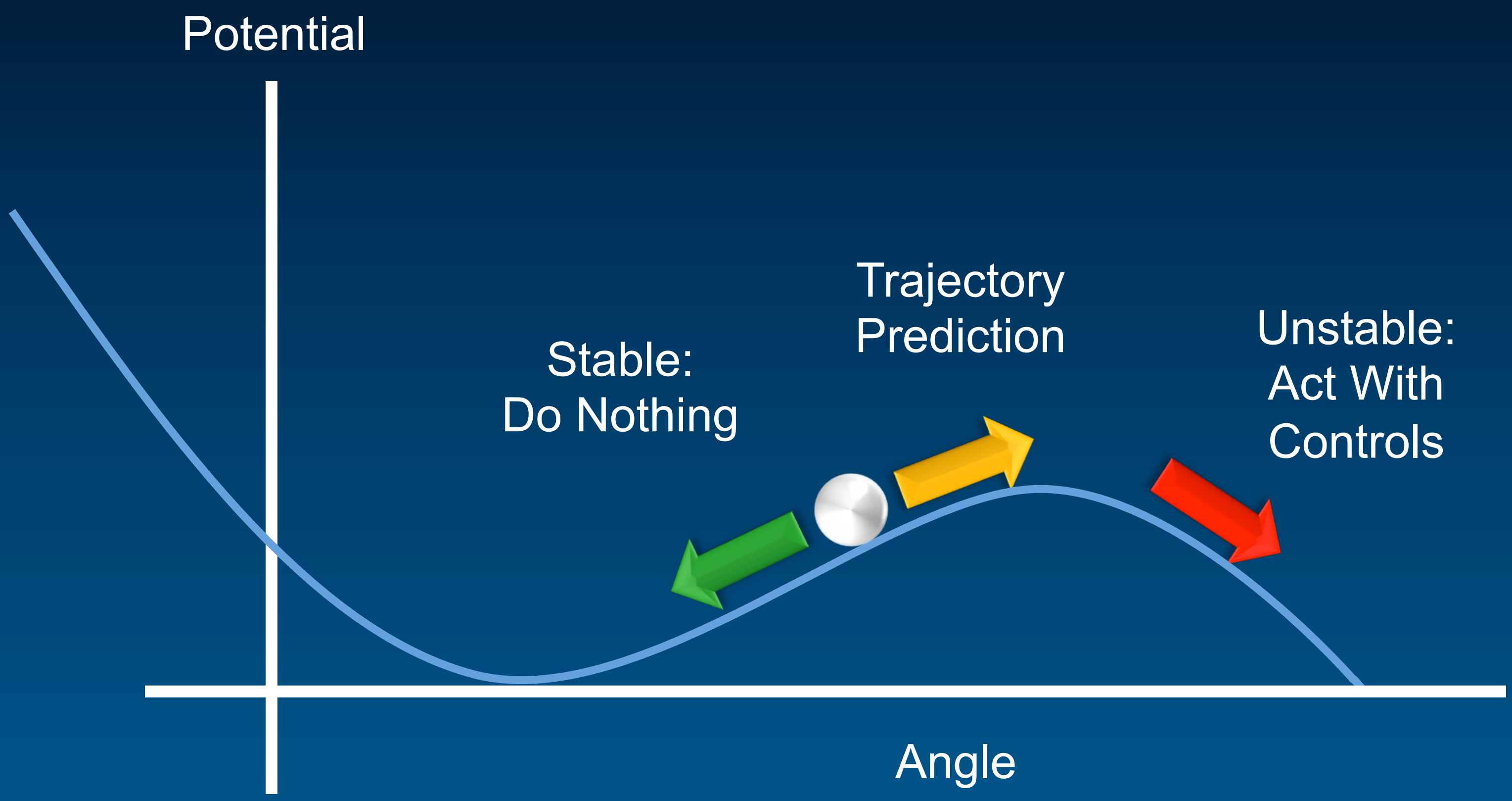


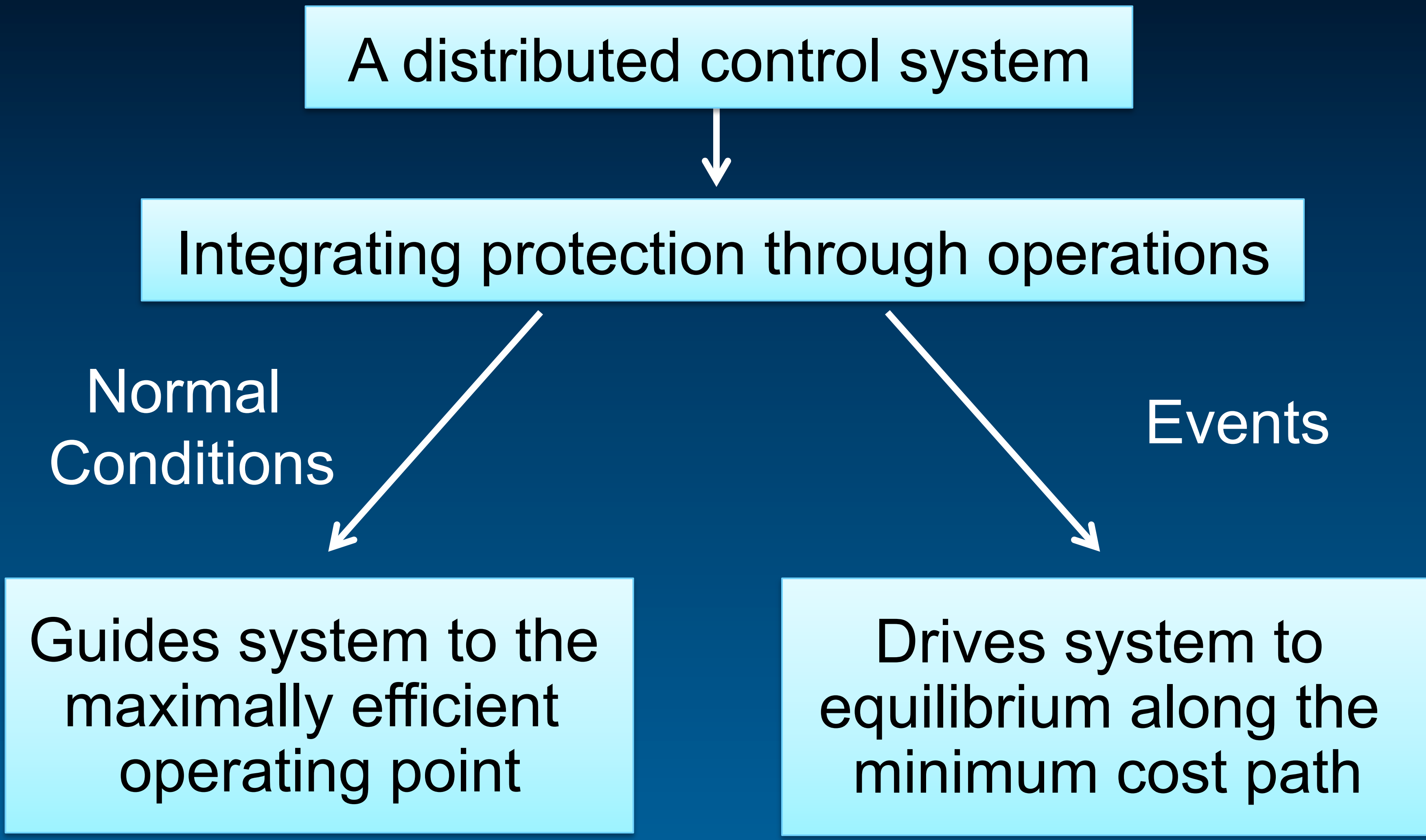
M = 0.3



Predict and Respond Before Instability



Control for Normal and the Unpredicted



Moving Forward

- Changes in sources, loads, expectations
- Systems may require automated controls
- General solutions too complex for RAS
- Feedback control will be simpler and better
- DISTRIBUTED control for reliability
- We have the theory and tools today