Real-world Operating Challenges of Increasing Renewable Penetration Scenarios on the Electric System

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Closing Plenary Session – Future Trends and Needs and International Collaboration

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Real-world Operating Challenges

March 2018

CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:

This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:

In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered “non-GAAP financial measures” under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

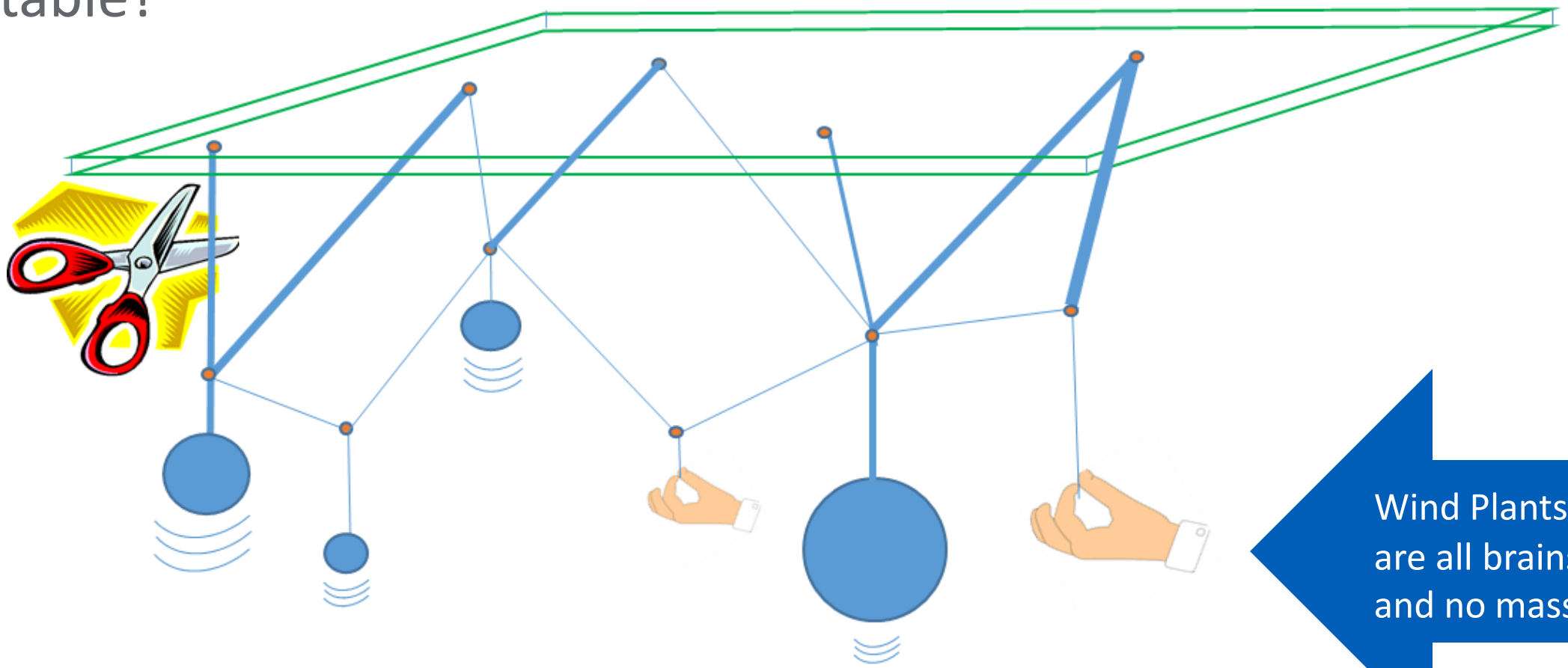
- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE’s cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity.

GEE, What could go wrong?

- Long list follows…. That's why we're here
- I'll focus on three ~~two~~ one:

- Is it stable?
- ~~Seasonality of renewables: can we make it thru the calm/cloudy/dry season?~~

Is it stable?

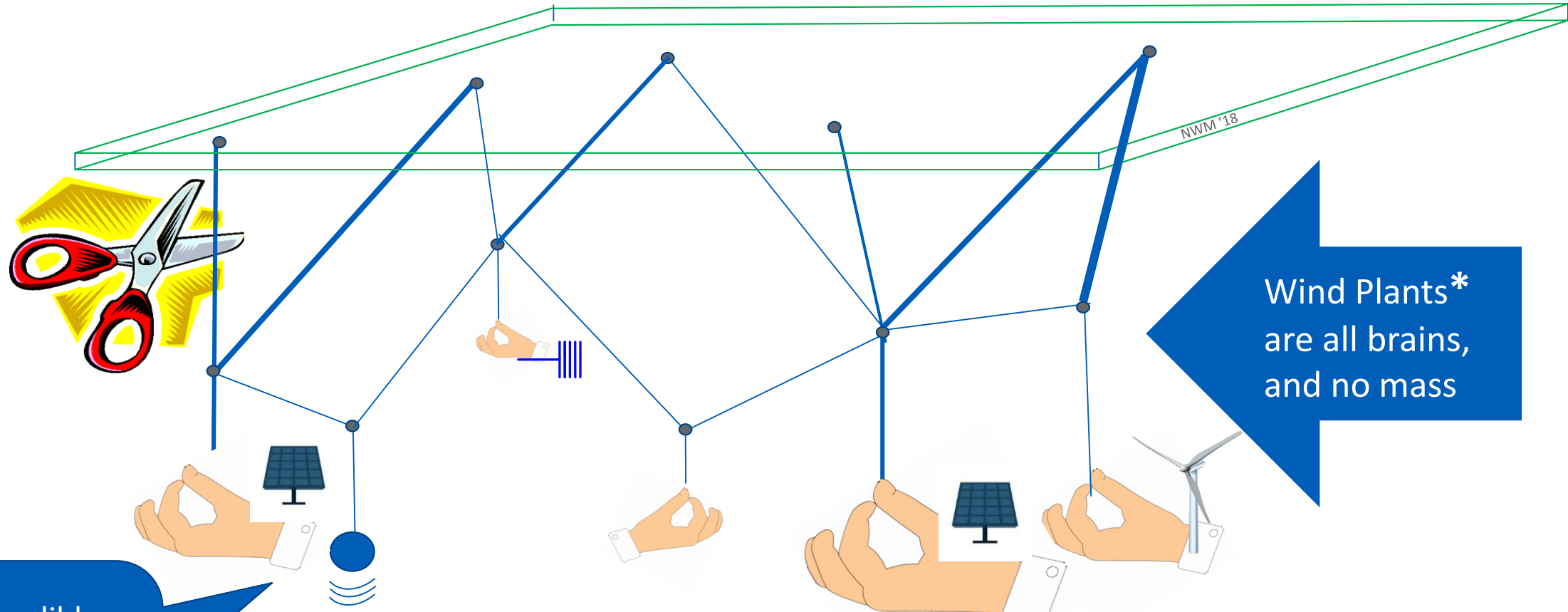


Wind Plants* are all brains, and no mass

* And all other inverter-based resources, including solar PV and batteries

Source: NREL/GE WWSIS 3a Derived from original figure by Elgerd

Is it stable when the vast majority, but not 100%, are inverters?



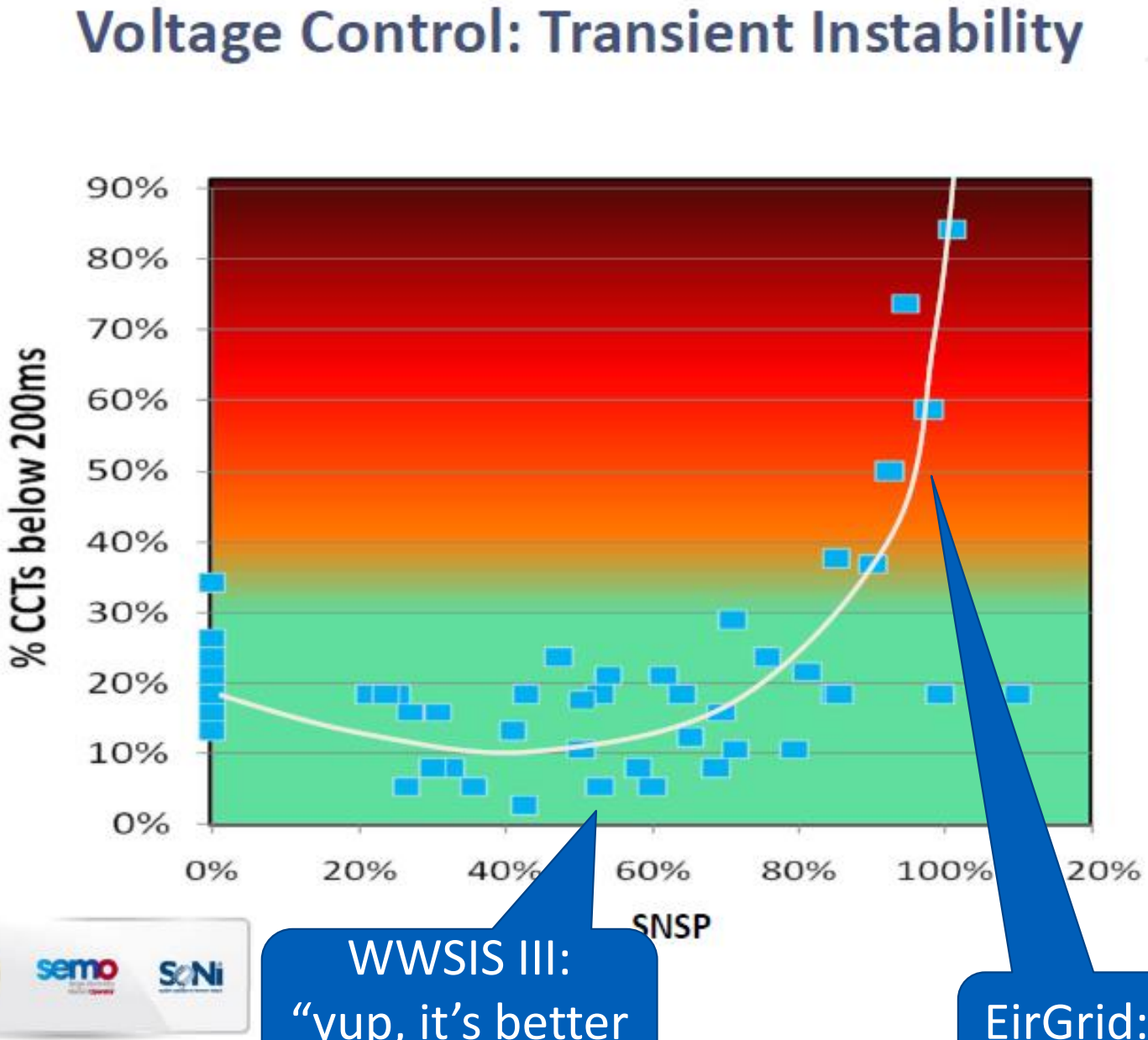
Wind Plants* are all brains, and no mass

Is there a credible future for large systems in which there is ***never*** synchronous machines? Really?

* And all other inverter-based resources, including solar PV and batteries

EirGrid & Jon O

- In the near term, big systems up to (say) 75% are being found to be manageable, even well behaved.
- But, things get funky somewhere between 75% and 100% (Jon O' has been telling us that for years…we're catching up).
- And, yes there are times when we (Xcel, SSP, ERCOT, …) are closing in on the 75% level.

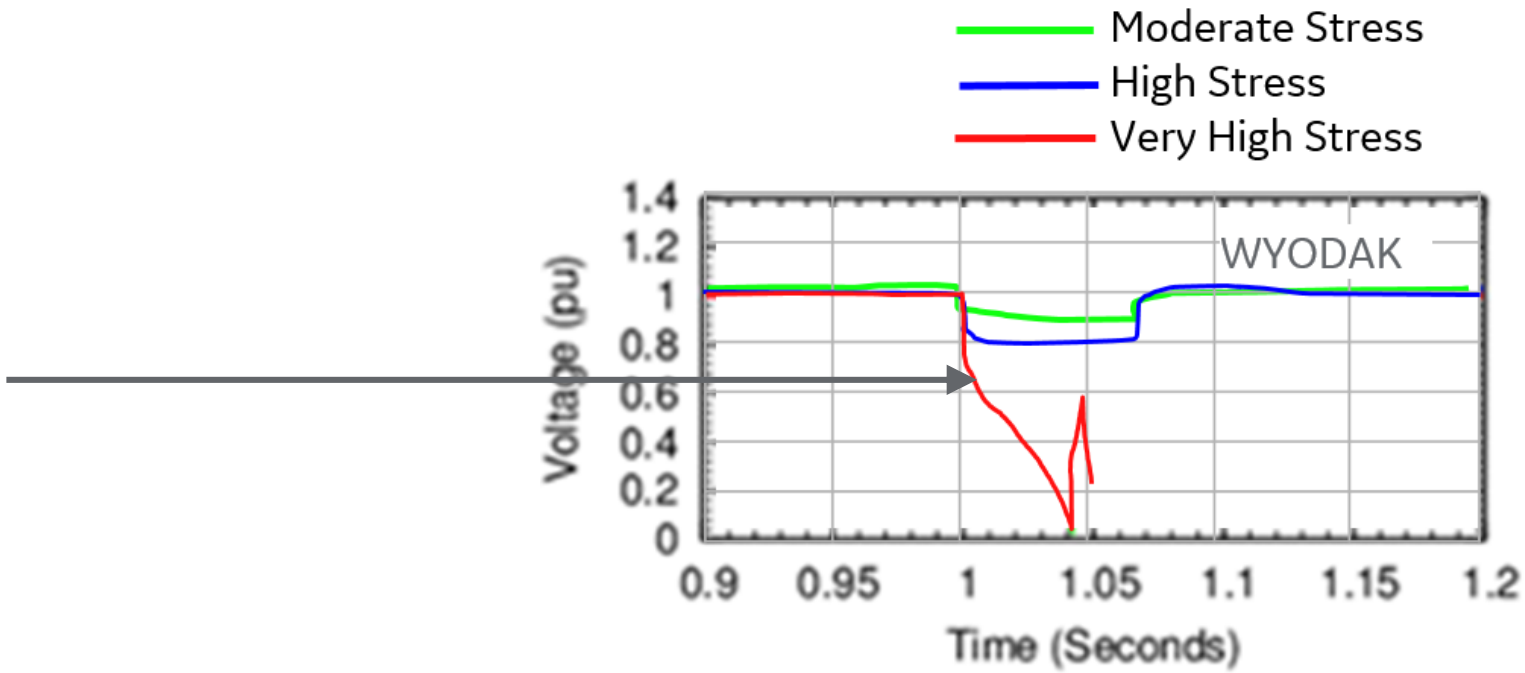


Source: EirGrid, Jon O'Sullivan c. 2013

Paradoxically: Grids are both stronger and more brittle.

Stability limits tend to be **higher – that is good for reliability and economy.**

But, when the grid fails, it **fails faster and with less warning**



We need better :

- Understanding
- WTG (and inverter) controls
- Simulation tools
- Predictive tools and metrics

The world looks different as we a*pproach* "Zero Inertia Systems" … we aren't ready

Source: NREL/GE WWSIS 3a

Are we using the right metrics?

Voltage dips, Onion curves, Proximity indicators and other oddities….

Western Electricity Coordinating Council

RELIABILITY CRITERIA

APRIL 2003

This would have given no indication of risk for the fail on the previous slide.

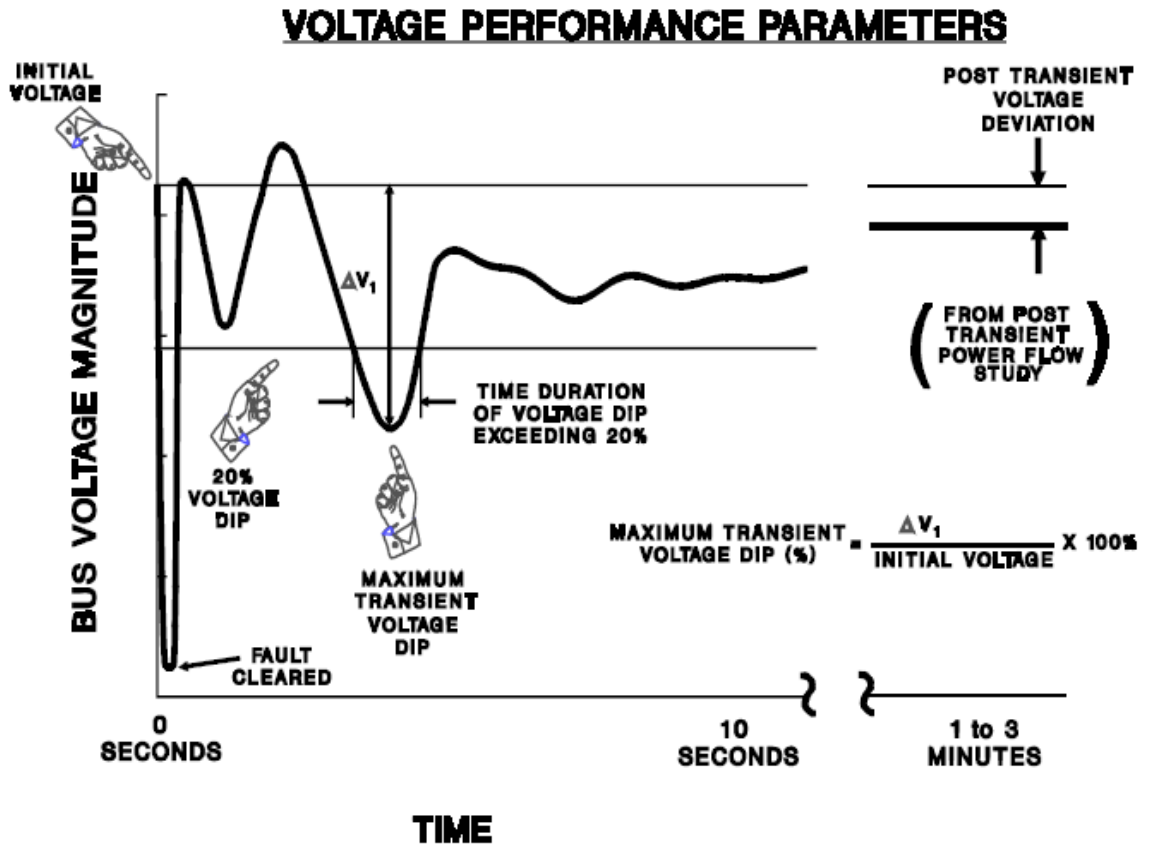
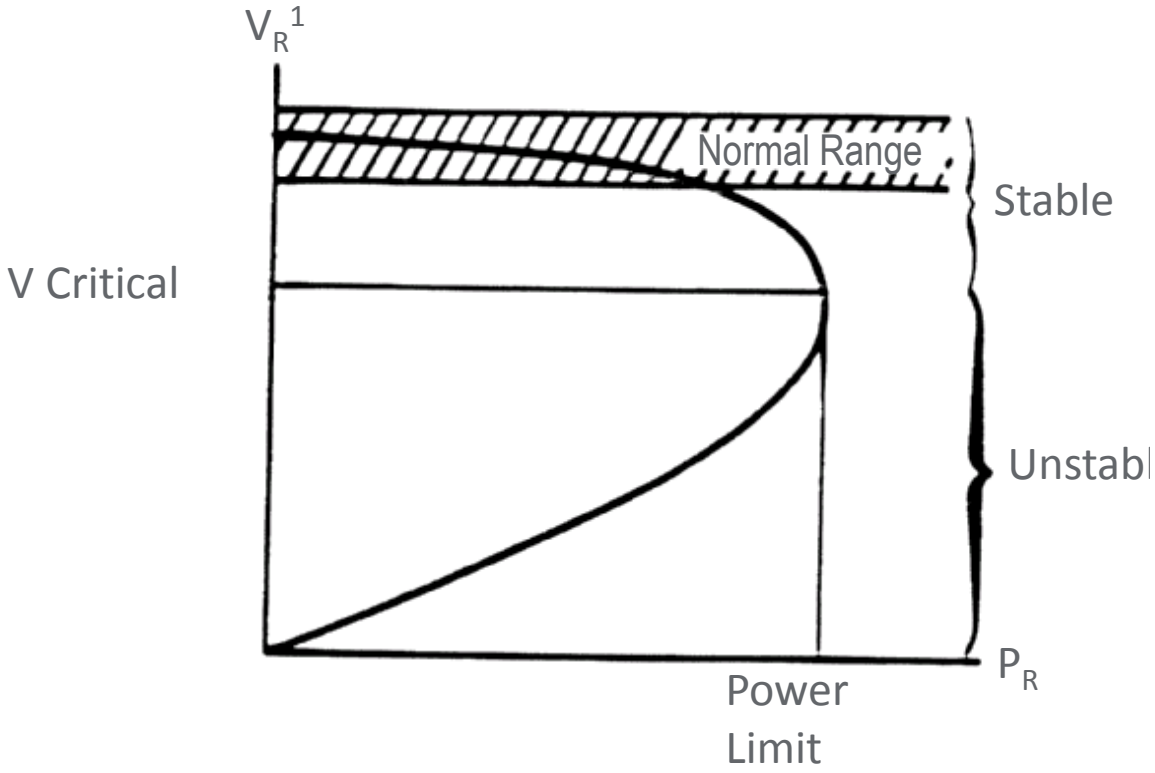


Figure W-1

Classical Power Limit Curve
"Nose Curves"



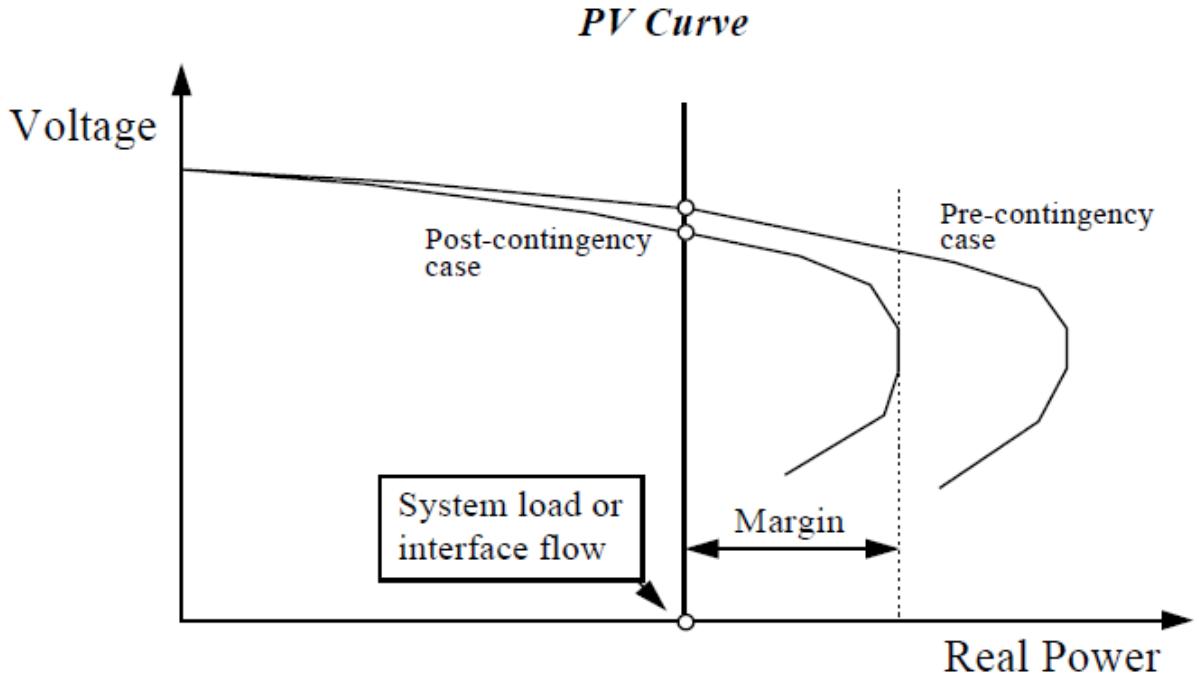


Figure 8.1 - P-V Curve

VOLTAGE STABILITY CRITERIA,
UNDERVOLTAGE LOAD SHEDDING STRATEGY, AND
REACTIVE POWER RESERVE MONITORING
METHODOLOGY

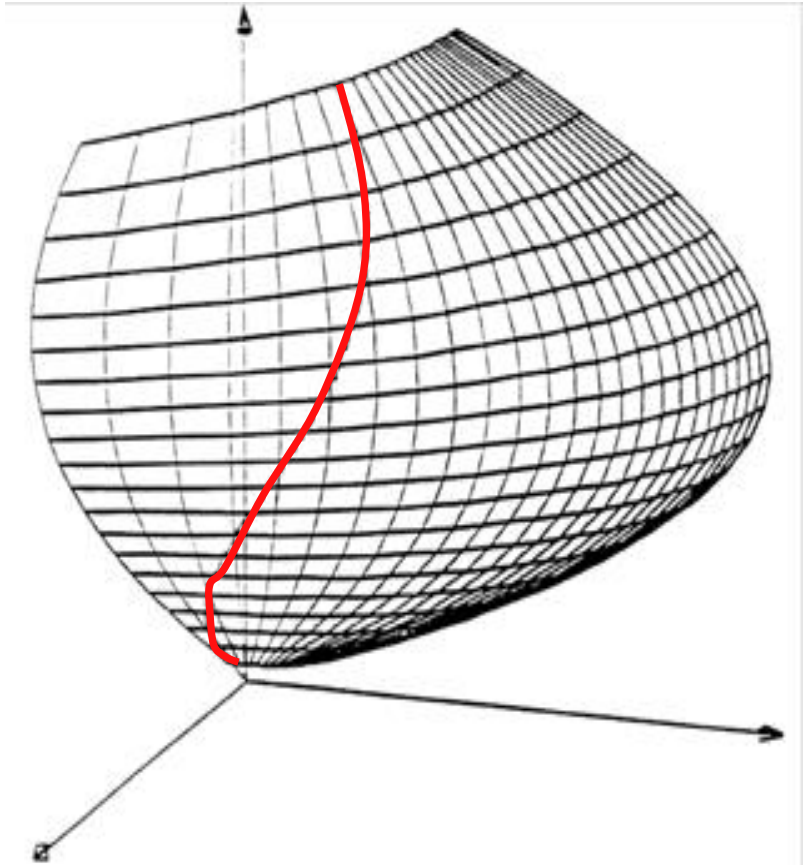
Final Report – May 1998

These are static, and segregate P from Q…. Sufficient?
Not obviously so.

Time to revisit concepts of dynamic voltage stability?

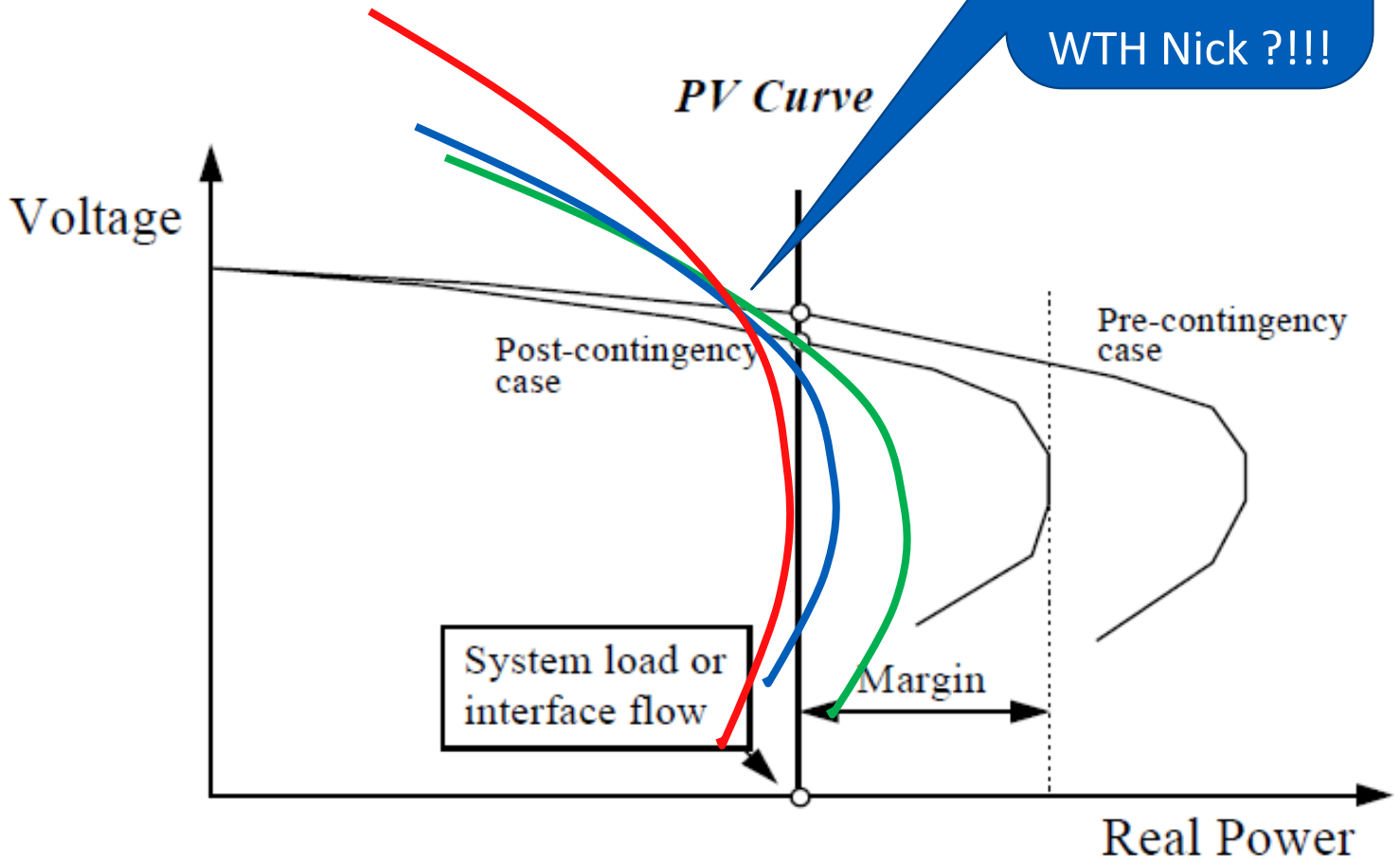
System and Load

* Trajectory *

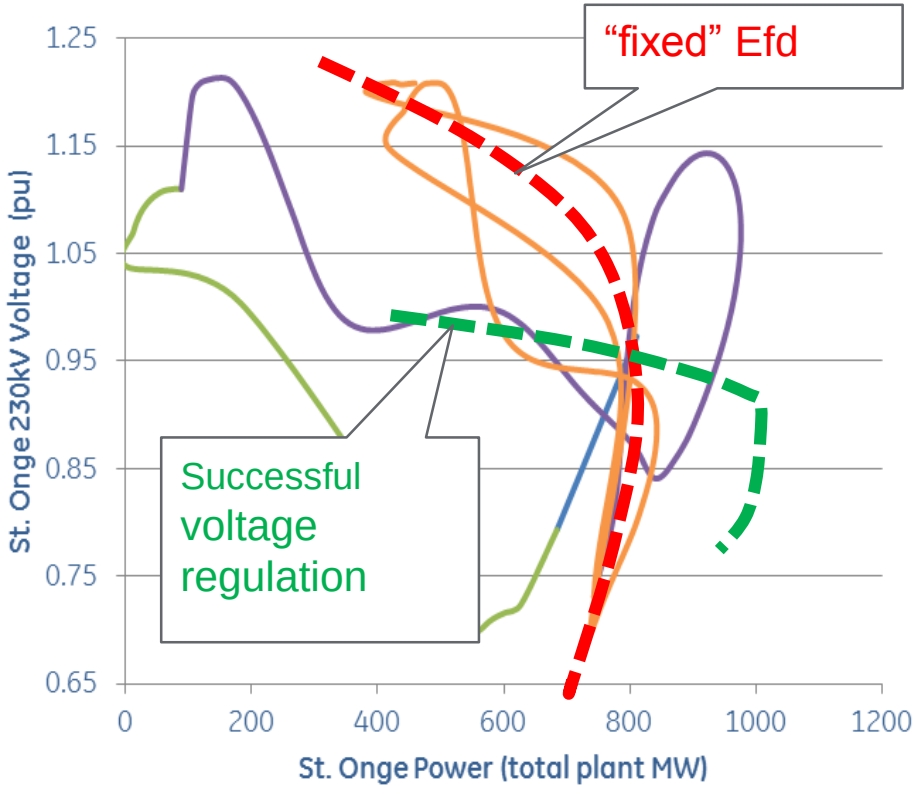


Dynamic, during fault, nose curves …

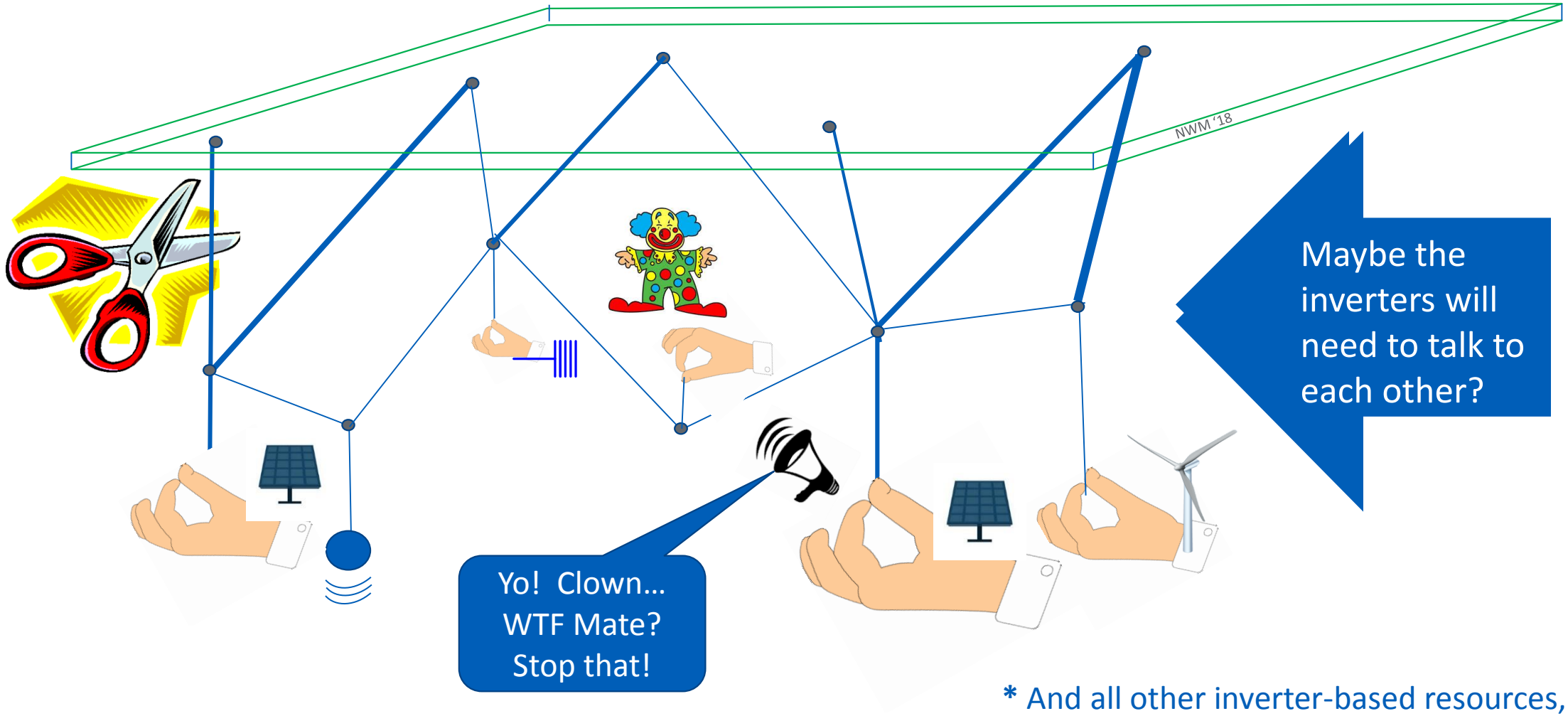
WTH Nick ?!!!



The reality is dynamic… and much faster than we're accustomed to be worrying about



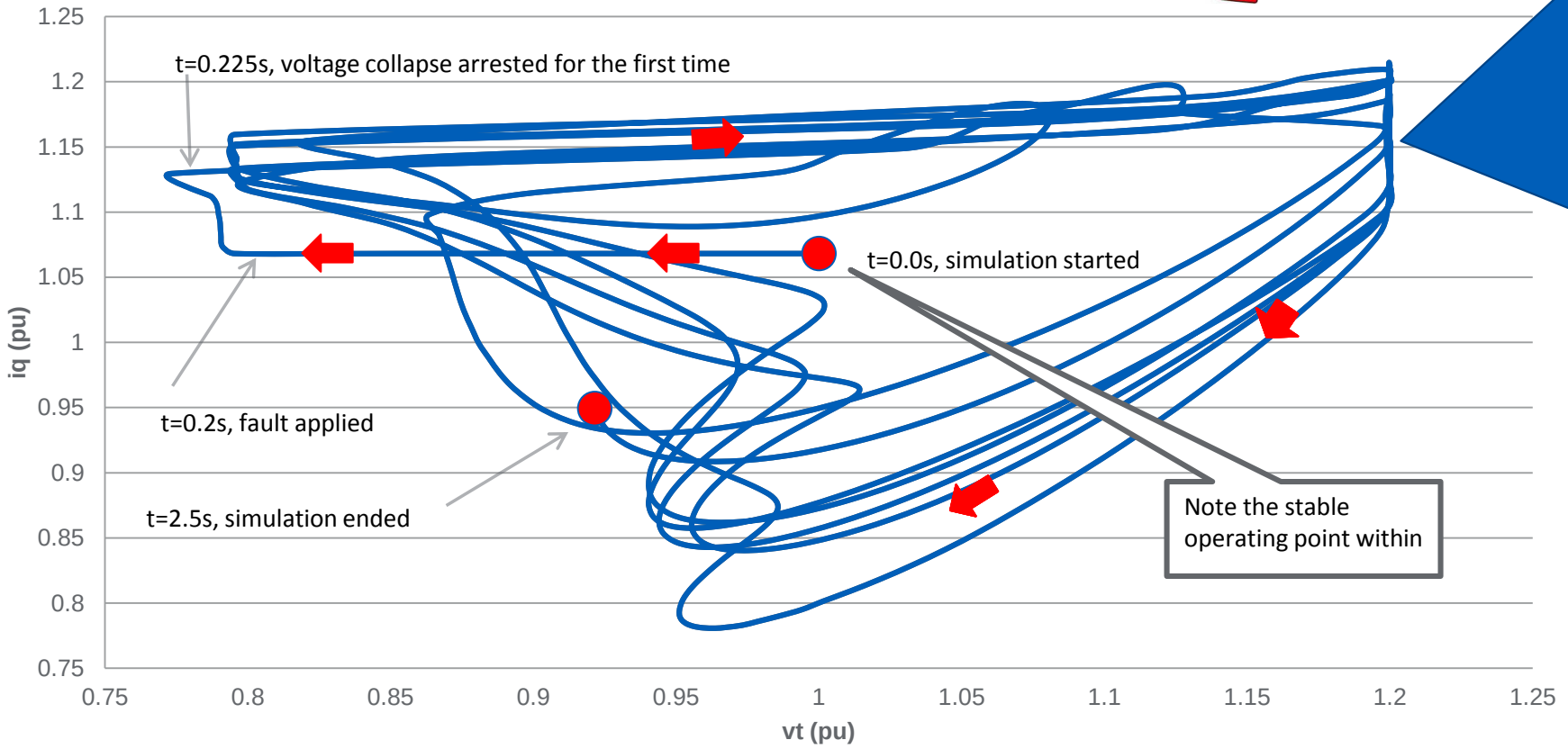
Is it stable when “someone” misbehaves?



* And all other inverter-based resources, including solar PV and batteries

We're not in Kansas anymore Dorothy…

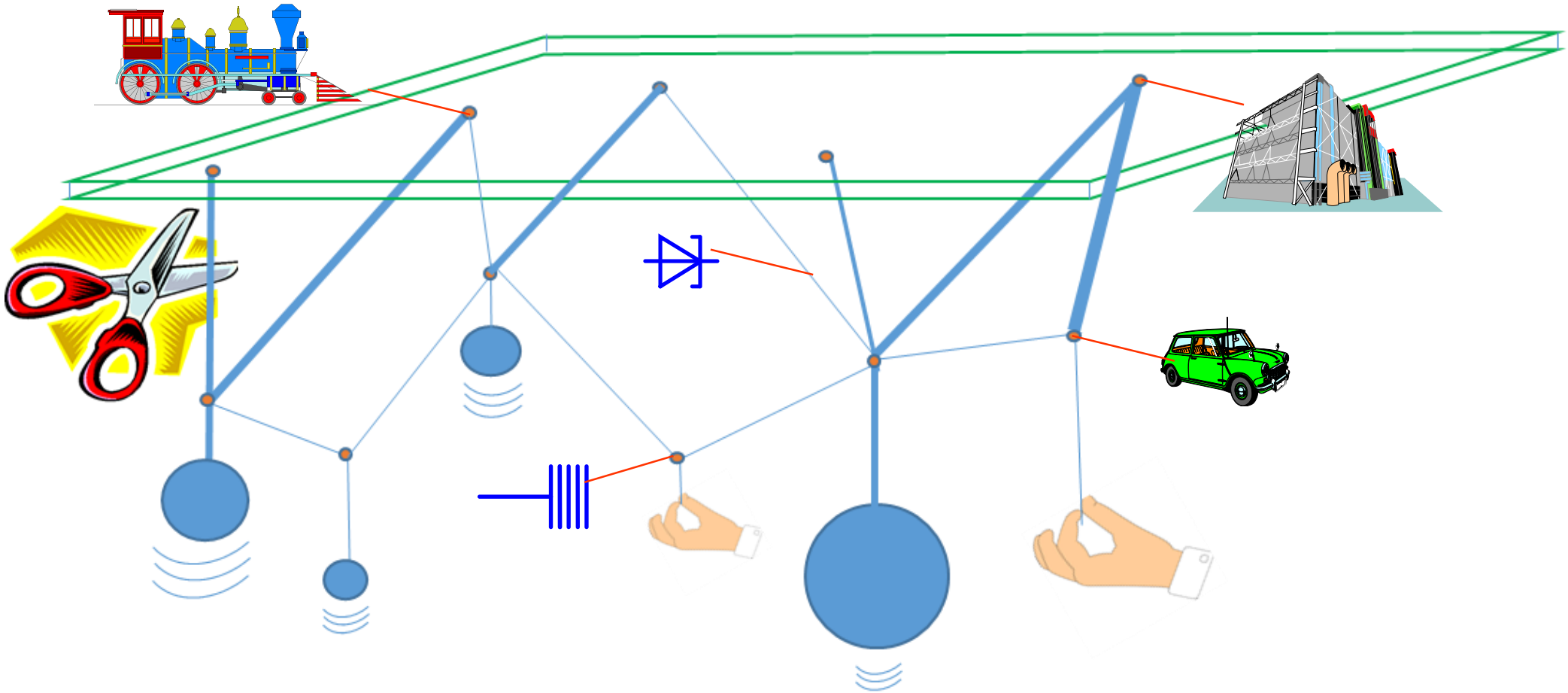
(well, actually, maybe we are…and it's really windy)



Things can get weird in a hurry…

This is an instability between V Q and P regulators

Is it stable in the future with massive ESI?



Derived from original figure by Elgerd

"Positive sequence fundamental frequency simulations don't cut it with inverter based systems. We'll just model the whole system with point-on-wave tools like EMTP/PSCAD/…"*

REALLY?

- Consider :
  - Dynamics cover 1000s of miles, 1000s of generator, 100k state variables in positive sequence.
  - What do you throw away, and at what cost?
  - How do you initialize with realistic boundary conditions… we can barely get production simulations to talk to stability programs. Progress is being made, but long way to go. New, exciting developments in validation from reality (e.g. Peak, Slaven Kincic)
  - Getting POW simulations that are meaningful for relatively small, simple systems is HARD. Garbage results are common.
- Solution: learn from POW work, use POW carefully & selectively, improve the stability programs and how we use them. Stability analysis will continue to be the main workhorse for bulk power system dynamics.

* "stability programs, e.g. PSS/e, PSLF, …

Take-Aways

The future Grid is only as reliable as it is stable

- Reliability must be and can be as good or better, with well designed systems.
- Flexibility, flexibility, flexibility
- The dynamics we are accustomed to are being replaced with “new” ones

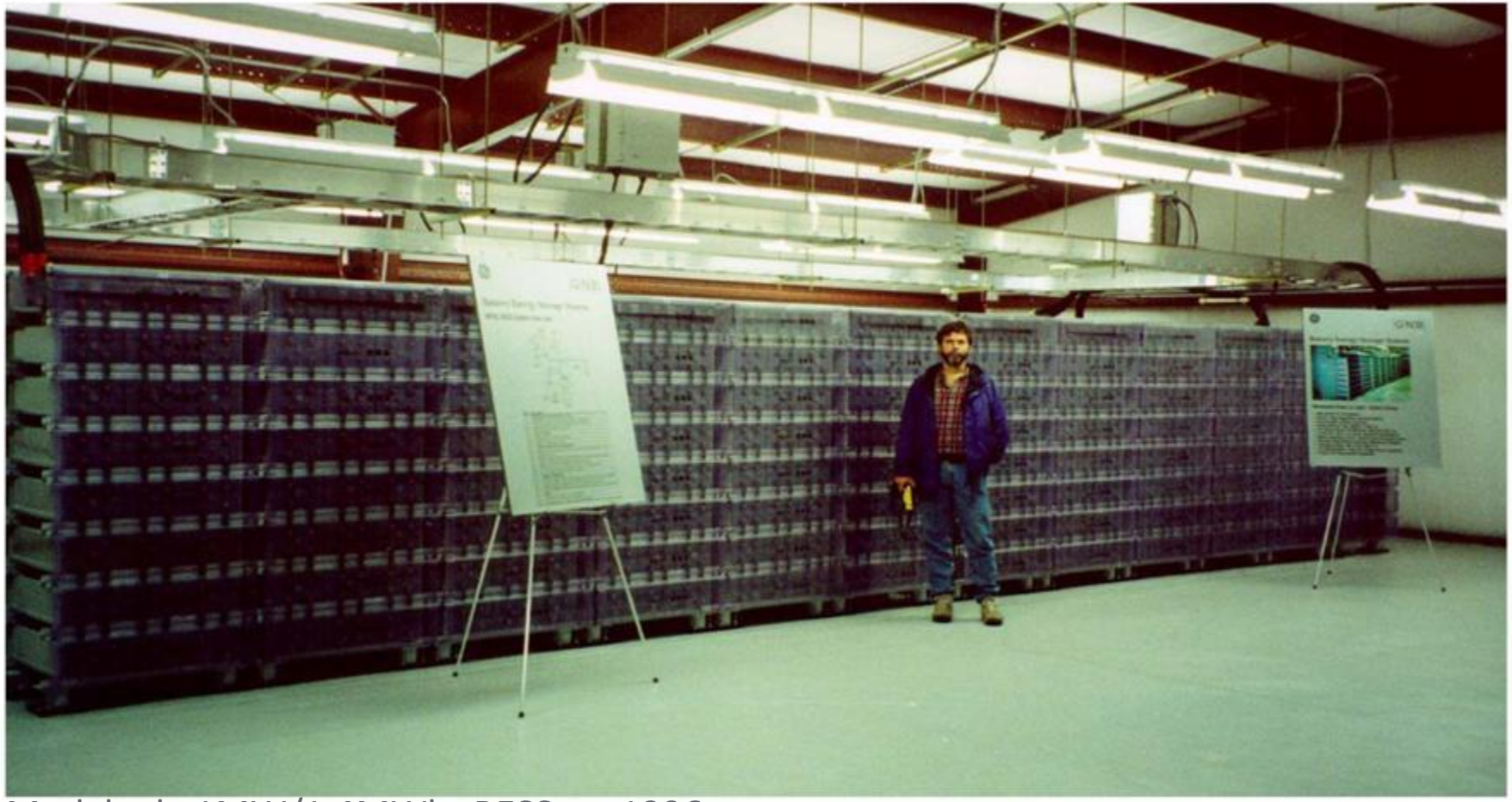
System Dynamics are already complex, and getting more so.

- Understanding and tools must evolve
- Super high wind and solar penetration brings a whole new layer of complexity and opportunity

Using the actual power system as a simulator is uneconomic and irresponsible

- We’ve got more research to do, and we’d better get to it!

This is 1.4MWh of batteries. Multiply by ~10 million. Hmmm…



Metlakatla 1MW/1.4MWhr BESS. c. 1996

Doesn’t look like batteries alone will do it.

Back to the future: PSH is alive and well… w/ very cool per

Power	1000 MW
Energy	34 GWh
Stored water	25 Mio. m3
Equivalent number of containers	28'500

And ONLY need 500 of these, not 10 million. Yeeeha!

Thanks …

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