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- The opinions expressed in this presentation are those of Robert W. Cummings from 45 years of experience in the electric power industry:
  - 6 years – Central Vermont Public Service (System Planning – Gen. and Transmission)
  - 8 years – Public Service Company of New Mexico (Operations Engineering and Wide Area Planning)
  - 8 years – East Central Area Reliability Coordination Agreement (ECAR – Manager of Transmission Services)
  - 23 years – North American Electric Reliability Corp. (NERC – retired in 2020 as Senior Director of Engineering and Reliability Initiatives)

Energy Conversion – What We Need…Yesterday

Reliability Concerns for the Future

The Power Electronics and Energy Conversion Workshop

Robert W. Cummings 2 August 2023

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The Changing Grid

Where we ~~are~~ were

- The electric grid of North America is a system of central generating stations with large rotating machines – we've had over 100 years to learn how the physics works
- Load consisting of synchronous motors, resistive loads, and incandescent lights

Where we are going

- A system of smaller distributed resources, **largely connected through inverters (IBRs)**
- A large portion of resources are variable (wind and solar) *with much lower capacity factors*
- Energy storage systems will be essential to continuous power availability
- **Variable speed drive motors** connected by power electronics
- Lighting rapidly moving to LEDs – far less incandescent, CFL, or mercury vapor lights
- Chargers for everything from phones to electric vehicles
- *Quantum increases in power and energy requirements for electrifying everything – this is where you come in!!*

So…how do we get from here to there without adversely effecting reliability?

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Grid of the Future

Questions

- What will it look like?
- Will we have 100% renewable resources?
- Will all resources be connected through power electronics?
- What will the load look like?
- Will we still have a grid and transmission lines?
- How will micro grids interact?

Transition issues

- Transition to higher penetrations of inverter-coupled renewables may be painful…and not without surprises
- Reductions in inertia and synchronizing torque – a more brittle system
- How to dispatch variable resources with lower capacity factors?
- IBR plant and unit interoperability
- Potential for inverter controls interaction – what kind of oscillations will there be?
- Cyber Security for IBR controls

Brutal Facts About the Electric System

- Stuff will happen
- Things will blow up
- People will make mistakes
- Your load forecast is wrong
- All models are wrong – but some are useful in certain situations
- You don't know when stuff will happen
- You don't have enough money to keep stuff from happening
- With new systems, things will happen that we've never seen

System Operational Threats Observed

What are we facing NOW?

Threats to Reliability from Inverter-Based Resources

- Observed threats to reliability – What we have seen
  - **Behavior of Inverters on Utility Scale**
  - **Forced oscillations** caused by digital control system and their INTERACTION
  - **Lack of accurate models** for IBRs – Models do NOT reflect reality
    - Shades of BAD MODELING of synchronous machines before the 1996 Western Blackout (9 States)
- What don't we know yet
  - **Inexperience** of the Industry with IBRs and their control systems
  - How the **inter-area oscillations** will be changed by IBRs supplanting synchronous generation – what are the new modes and mode shapes?
  - IBR controls interaction
  - Locating source of forced oscillations

Known Threats Facing the New System

- Normally Cleared Faults 2.5 to 10 Cycles – being addressed in IBR standards like IEEE 2800-2022
- Protracted Faults
  - Often caused by protection failures – protection systems need to be hardened against single points of failure
  - Voltage depressions or spikes
  - Legacy (Pre IEEE-2800-2022 Standard) IBRs not designed to ride through such events
  - Fault-Induced Delayed Voltage Recovery (FIDVR) – unknown performance with IBRs and new load characteristics
- Switching surges
- Relay Loadability – largely solved on EHV system, but possible problems on HV and LV systems as resources are more dispersed
- UFLS interaction with lower amounts of inertia, higher ROCOF, and lower nadirs

New Operational Challenges

- Angular separation problems – moving points of concern for standing angles across open breakers
  - Reclosing across wide angles and high voltage differentials
- New variants on Inter-Area Oscillations
  - New, unstudied frequency oscillation modes and shapes
  - Control system interactions – with other IBRs, DC Ties, SVCs, etc.
  - Potential for control failures with more IBRs
  - Forced oscillations more prevalent
    - How to detect them
    - How to find their sources
    - How to stop them
- Blackstart capabilities are eroding!
  - Anything developed with IBS MUST have Grid Forming Capabilities!

New Operational Challenges

- Changes to Oscillation Modes and Mode Shapes – new players in the oscillation game
  - Loss of synchronous machines participation
  - New lines (impedance matrix changes) and new injection points change natural oscillation modes
  - Unknown oscillatory behavior of IBRs
    - Not tied to today's natural mode frequencies – not related to physics of rotating machinery
    - Outside of expected ranges
    - Potential for IBR control interactions

Modeling Issues

Whatever you build, it MUST be able to be modeled!!

Whatever systems you develop, they MUST be able to be modeled!

- If something in not modeled, how can you predict system behavior or interaction????
- Positive sequence models are insufficient to deal with high penetrations of IBR Plants
  - Powerflow, transient, and dynamic stability models MUST be available.
- New types of modeling must be used
  - Electromagnetic Transient (EMT) analysis must be employed
  - Composite load model representation in stability programs
  - Hardware-in-loop (HIL) testing of IBR plant controls
- Models lacking for legacy wind and solar plants
- Lack of knowing where DER plants are located
- Security-Constrained Aggregation and Dispatch
  - Must be done for at time of aggregation for both resources and direct-controlled demand management to properly protect system from overloads, voltage problems, and stability problems

Tenets of Modeling and Predictive Studies

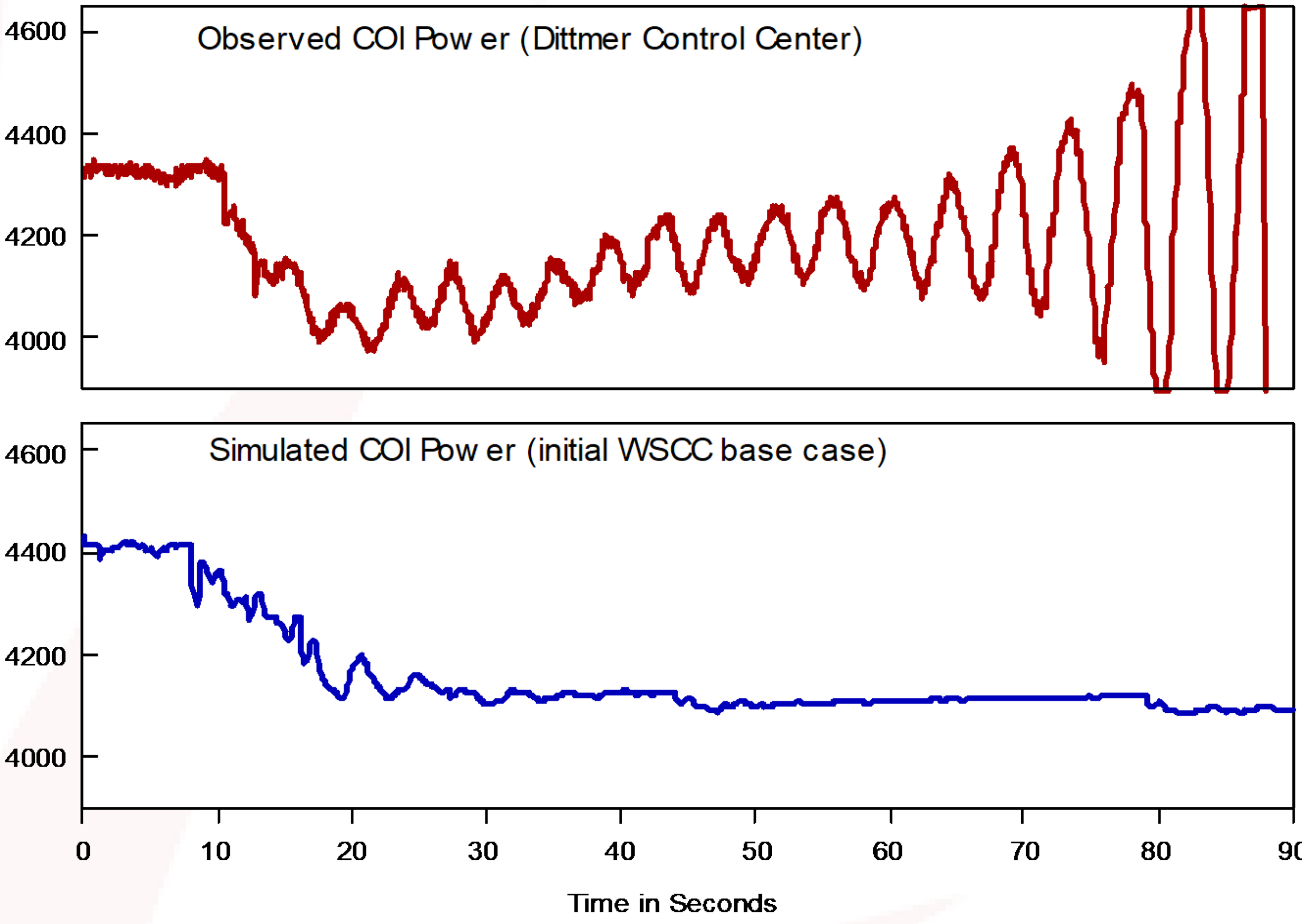
- To predict performance, you must able to understand the system's behavior.
- To understand the system's behavior, you must observe and measure its actual behavior.
- Once you understand the system's behavior, you must be able to model it – All models MUST be validated for fidelity to actual system behavior.
- Once you are able to model the system's behavior, you can predict its performance.

10 August 1996 WSCC Disturbance

- Don’t be overly dependent on models!

Real event

Dynamic simulations



No confidence in dynamics database

Challenges in Energy Conversion

Exciting time for research

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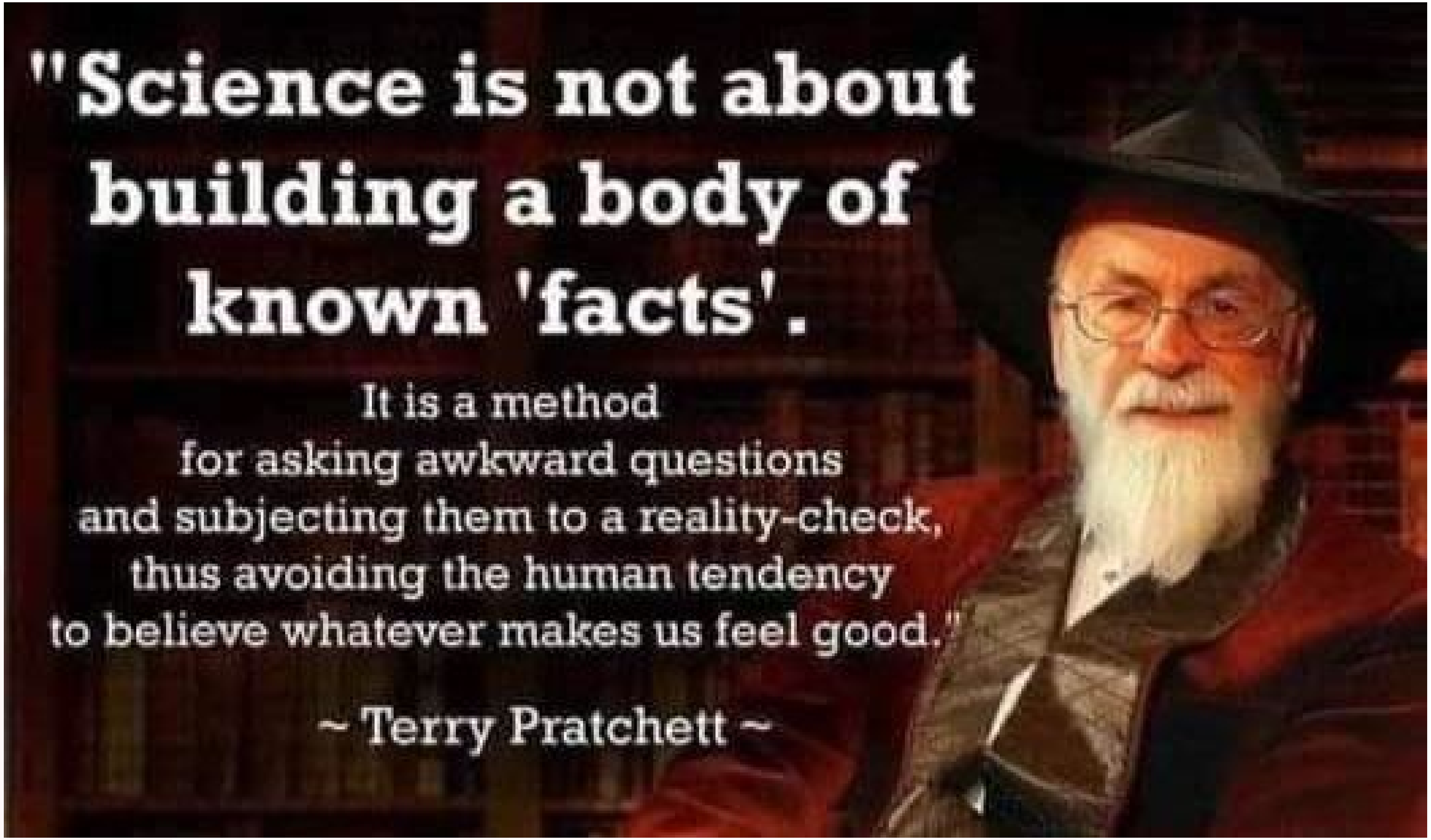

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Concentrate on the Short-Term Needs <u>First</u>

- Research needs to be bifurcated into:
  - Short-term/Immediate technology needs
  - Longer-term – in nascent development or not expected to be ready for several years
- Short-term needs
  - Retire, but not dismantle fossil generation plants – resiliency is being destroyed by lack of resource choices in operations
  - Implementation and use of proven energy storage technologies – advanced pumped storage
  - Definition of needed reliability attributes
    - Reliable capacity of variable resources – time-of-day based and sometimes site specific (wind patterns)
    - Fuel diversity/security and deliverability
    - Fast Frequency Response – IBR answer to reduced inertia for both over- and under-frequency events
    - Synchronizing torque from PMU-driven, IBR-coupled energy storage systems (with some capacity dedicated) – substitution for synchronous condensers
  - Common set of analyses for differing IBR plant properties
  - Develop common set of tools/terms that can be used across the industry
    - Powerflow, Transient Stability, and Electromagnetic Transient analysis (EMT)
  - Detection of and analyses to prevent controls interaction of IBS and other power electronics

Concentrate on the Short-Term Needs First

- Intermediate technology needs
  - Alternatives to Battery Energy Storage
  - To-scale proofs of concept for Hydrogen technologies
    - Hydrogen production and hydrogen-fueled generators co-located at retired fossil plant sites – transmission already there!
    - Co-location of solar, wind, and storage
  - Development of resources choices in system operations for resiliency
    - How do you replace capacity of large off-shore wind farms during a hurricane?
    - Quick-start natural gas-fired generation
  - Promote aggregation of distributed energy resources and direct-controlled demand management
    - Security-Constrained Aggregation and Dispatch to known nodes on distribution and transmission that can be modeled
- Longer-term technologies
  - Small Modular Reactors – may be key to achieving electrification of long-haul trucking
  - Other technologies that are in nascent development or not expected to be ready for several years

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The Math of Renewable Penetration

A Massive Re-training is Needed

Resource Adequacy in the New World

Traditional Resources Adequacy

- Known installed and operational capacity compared to load projections
  - Is my operational capacity adequate to support expected loads
    - Based on relatively few generating resources
    - Predicated on known effective forced outage rates of resources and capacity factors of those generators
    - Predictable load patterns
    - Predictable weather patterns
  - Can be done for peak conditions on a day-ahead basis

New Resource Adequacy Analysis

- Variable operating capacity with heavy links to weather and time of day
  - Virtually unknown (or new) forced outage rates
  - Capacity limitations based on time and previous operating conditions (state of charge of batteries)
  - New, highly influential weather conditions
  - Completely new load characteristics and changing load patterns heavily influenced by vehicle charging and BTM solar and batteries
- Must be done for every hour of every day, often more often

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Renewable Integration Possibilities and The Math Problem

- What is higher penetration?
- The reported penetration MATH is wrong:
  - The values is from 1 SCADA scan cycle – 4 seconds!
  - The load value is in the denominator – lower loads make the % higher.
  - You must consider all of the timeframes – on peak, off peak
- Displacement of fossil resources – synchronous generators
  - Lower operating reserves possible
  - Not relying on idling gas turbines to provide primary frequency response
  - Incredible fast frequency response with zero carbon footprint
- Presents challenges to system operators due to variability
  - Extremely high ramp rates
  - Often weather dependent
  - Incredible fast frequency response with zero carbon footprint
- Several mandates for higher penetration

Resource Capability Comparison

- 500 MW capacity of different resources are NOT equal
- Note: Battery Energy Storage Systems are not included – they do not generate electricity, just storage and must be charged from other resources

Generation Source	Size (MW)	Capacity Factor	Annual MWh
Coal unit	**500**	**87%**	**3,810,600**
Natural Gas	**500**	**95%**	**4,161,000**
Wind Plant	**500**	**32%**	**1,401,600**
Solar Plant	**500**	**28%**	**1,226,400**

Resource Equal Equality Comparison

- To produce the same amount of annual energy as a coal-fired generator, the other resources would have to have far different capacity ratings (size)

Generation Source	Annual MWh	Size (MW)	Capacity Factor
Coal unit	3,810,600	500	87%
Natural Gas	3,810,600	458	95%
Wind Plant	3,810,600	1,359	32%
Solar Plant	3,810,600	1,554	28%

- Note: Battery Energy Storage Systems are not included – they do not generate electricity, just storage and must be charged from other resources

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Questions?

Future Topics?

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