

# **How Transmission Grids Fail**

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**Prepared for**  
**NARUC Staff Subcommittee on**  
**Accounting and Finance**  
**Spring 2004 Meeting**

**Scottsdale, Arizona**  
**March 22, 2004**



# Agenda

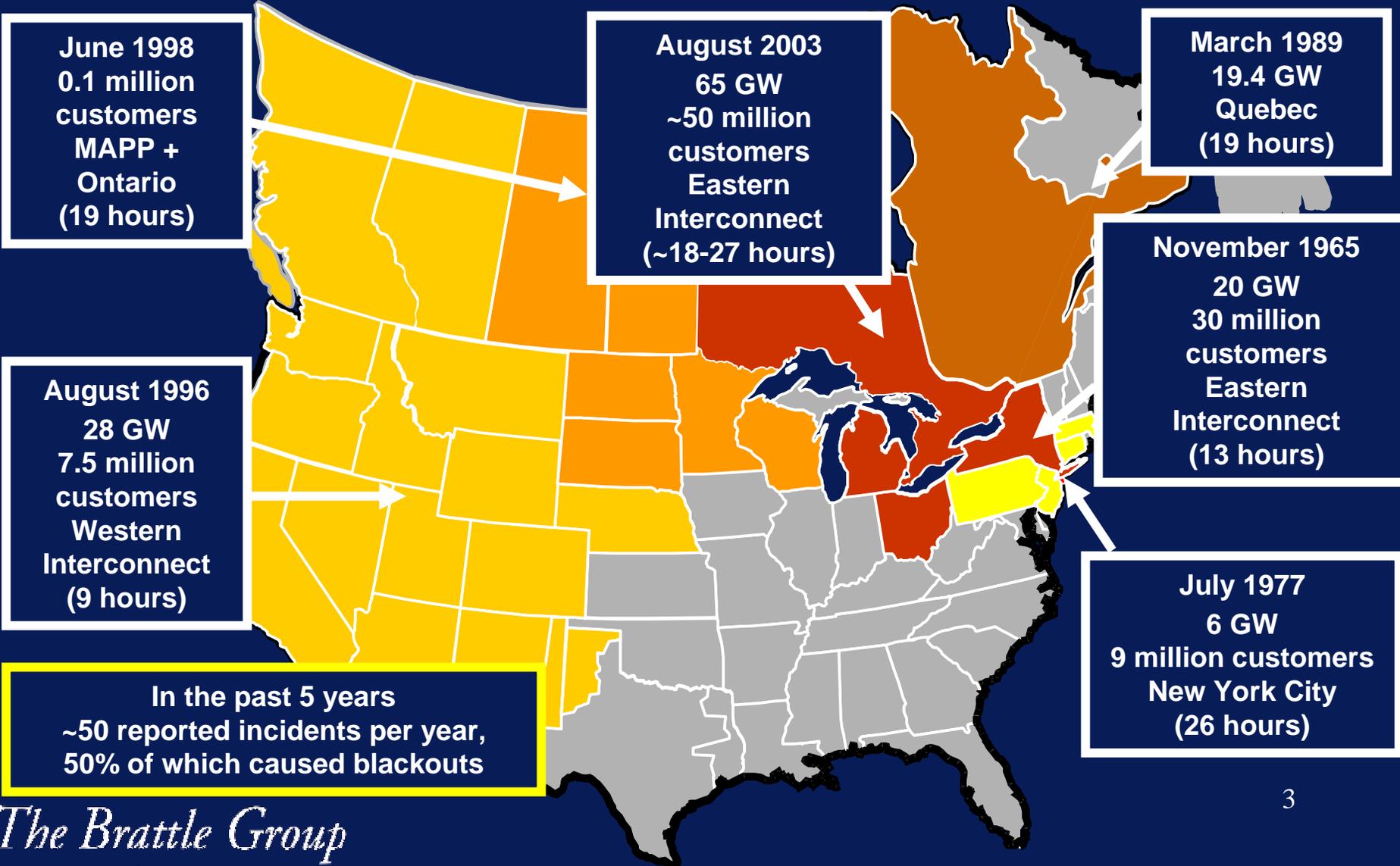
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The August 14, 2003 blackout in the Northeast made it clear that transmission reliability is both important and complex. This presentation provides an introduction to what transmission engineers can (and cannot) do to prevent such events, in order to assist in resolving questions of vulnerability and liability.

- ▶ History of U.S. grid performance
- ▶ Rudiments of power flow
- ▶ Measuring and monitoring transmission capacity
- ▶ How transmission grids fail
- ▶ Improving transmission grid performance



# Major Outages in North America





# Scale and Cost of the NE Blackout

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- **Load lost: Approximately 60,000 – 65,000 MW of load initially interrupted.**
  - ▶ **PJM – 4,000 MW**
  - ▶ **Midwest ISO – 18,500 MW**
  - ▶ **Hydro Quebec – 100 MW**
  - ▶ **Ontario IMO – 21,000 MW**
  - ▶ **ISO-New England – 2,500 MW**
  - ▶ **New York ISO – 24,400 MW**
- **531 generating units shut down at 263 plants.**
- **A few cities experienced lost power for up to three days.**
- **Rough estimates place social costs of the outage at ~ \$6 billion or more.**



# Pursuing Improvements in the Grid

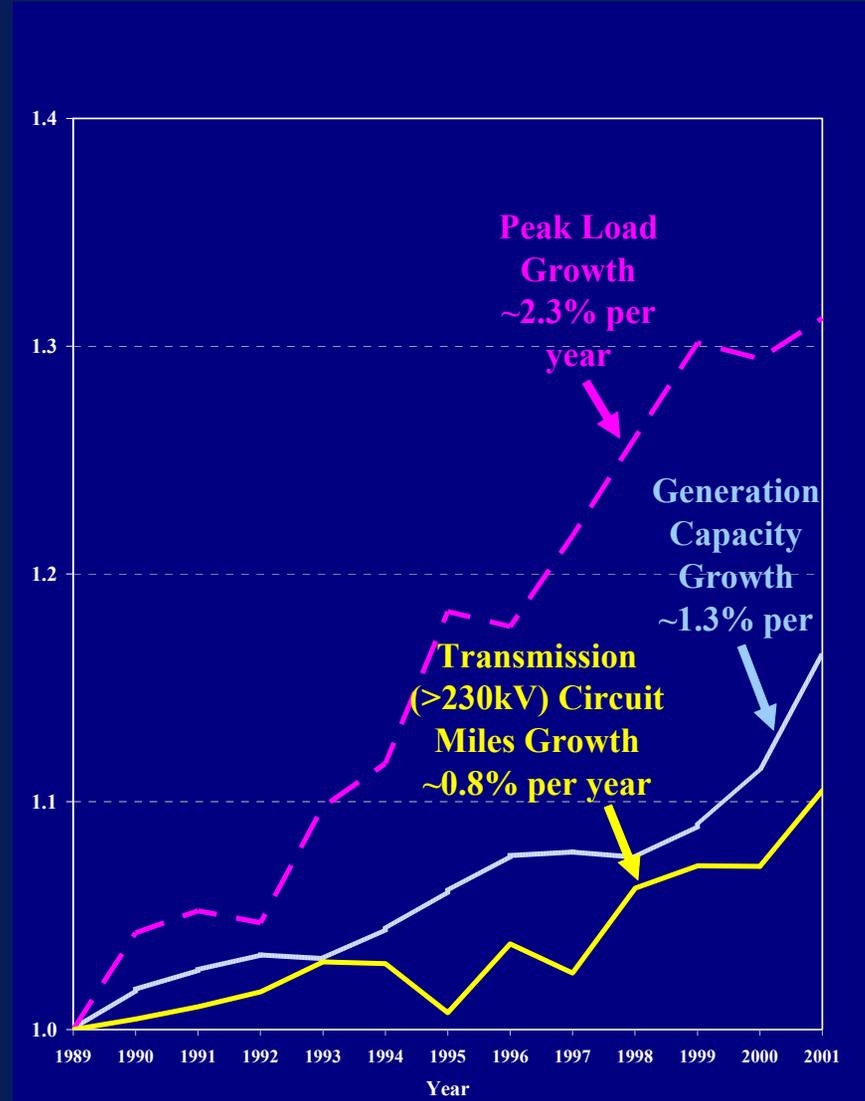
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- Often, many technical and economic improvements to grid structure and use are possible.
- Not simple to find the socially optimal solutions – most typically have unequal incidence of costs, benefits and risks – in part because of complex grid system dynamics
- Likely to be lots of conflicts over merits of new standards, pricing, funding, policies, and expansion proposals
- Process needs to be informed by solid technical understanding of how proposed solutions likely to affect various market participants.



# Expansion Has Been Limited

- Transmission capacity growth rate has been ~1/3 of peak load
- However, proportional growth in transmission may not be necessary
  - ▶ Recent generation located closer to load
  - ▶ Increasing flow capability on existing lines



Source: NERC ES&D data



# What is Power?

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- Power is the instantaneous rate of ability of the electrical system to deliver energy. It is measured in watts, or more commonly megawatts.
  - ▶ Light bulb = 100 watts
  - ▶ Average home = 2-5 kilowatts
  - ▶ Homes for 1,000,000 people  $\approx$  1,000 megawatts = 1 or 2 large baseload plants
  - ▶ U.S. total power demand  $\approx$  700,000 megawatts
- Power depends on voltage and current
  - ▶ Voltage  $\approx$  pressure
  - ▶ Current  $\approx$  volume of electric charge being conveyed
  - ▶ Power = voltage x current



# What is Power?

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- **Our system delivers AC power, in which the direction of current flow oscillates back and forth 60 times per second.**
  - ▶ **In contrast to DC flow, which is continuously in same direction**
  - ▶ **AC power is easier to generate and step up or down in voltage.**
- **Two kinds of power:**
  - ▶ **Real Power: does useful work, e.g. creating light, heat, driving motors (units of Watts)**
  - ▶ **Reactive Power: alters voltage of supplied power (units of Volt-Amps reactive, or VARs)**



# Power Flow – Kirchoff's Laws

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- Power cannot be directed along a particular path, unless that is the only path available to it.
- Instead, it tends to spread out and use all available paths, in proportion to their capacity and ease of use (lack of resistance or impedance)
  - ▶ Similar to water flowing from reservoirs to cities via a series of interconnected canals or pipes
  - ▶ Released water will use each canal, but in proportion to its size (diameter) and ease of flow
  - ▶ Like water, if one or more canals (wires) is disabled, the balance will try to spill over to adjacent canals (wires), potentially overloading them as well.



# Power Flow – Kirchoff's Laws

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- Unlike canals, transmission wires (and generators) are equipped with self-protection devices to cut their exposure to overloads; under extremes, this can result in “cascading outages.”
  - ▶ Under-frequency automatic load shedding
  - ▶ Impedance-monitoring relays on major lines
  - ▶ Generator relays that trip if low frequencies



# Power System Balancing

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- **Real power (MW) must be balanced (or nearly so) at all times.**
  - ▶ **Generation = load plus losses**
  - ▶ **Imbalances show up as changes in 60 Hz frequency**
- **Reactive power (MVAr) must be balanced at all times.**
  - ▶ **Suppliers = generators, capacitors, transmission lines**
  - ▶ **Users = loads, transmission lines, transformers, reactors**
  - ▶ **Too much reactive supply creates high voltages; too little reactive supply leaves voltages low**
  - ▶ **Reactive power does not travel well; local balancing needed**



# **Power Systems Synchronization**

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- **All the generators in an alternating current (AC) interconnection must operate in synchronism.**
  - ▶ **Spin in unison while producing 60 Hertz power**
  - ▶ **Very tight tolerance critical; systems usually controlled to deviations of a few hundredths of a cycle (.01 Hz)**
- **Three synchronous regions in U.S. – Eastern Interconnection, ERCOT (most of Texas), WECC (western U.S.)**



# Measuring and Monitoring Transmission “Capacity”

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Transmission systems are not described in term of “capacity” (unlike power plants) but rather in terms of *transfer capability*.

- Because power distributes itself over all available paths, the amount of slack capacity to add more power at one point and take it off elsewhere depends on:
  - ▶ Location of those injection and withdrawal points (hence point-to-point FTRs, or Firm Transmission Rights)
  - ▶ Size and pattern of prevailing flows already occurring on the system



# Measuring and Monitoring Transmission “Capacity”

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The physically feasible amount of Available Transfer Capability (“ATC”) between two points can vary (considerably) from minute to minute on the system, as loads, supplying generation, and wheeling varies throughout the day.

- “Contract Path” capacities or ATC capacities were attempts to simplify/ignore this reality using conservative estimates of what would generally be feasible, e.g. on peak.
- Under competition, much more dynamic, real-time measurements of physical capability (not contractual) are needed and reported by RTOs and control areas.



# How Grids Fail — Constraint Violations

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There are three kinds of flow limitations that can arise on a transmission network: thermal, voltage, and dynamic stability.

Thermal limits — As lines are used more, they tend to heat up (just like light bulbs get hotter).

- Higher temperature causes the wire to expand and sag, at some point possibly touching grounded objects, such as trees, and causing a short-out.
- Shorter, lower voltage lines are more prone to this problem.
- 9/28/03 blackout in Italy started this way.



# How Grids Fail — Constraint Violations

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Voltage limits — As lines become more heavily loaded (carrying more power), they tend to create their own electromagnetic fields that alter flows.

- Voltages typically rise at very low loadings; fall at very high loadings.
- As voltages decline, current must increase (to carry the same amount of power) causing a worsening of the voltage adequacy problem.
- At some point, voltage collapses precipitously to zero and the line goes out of service (spilling its load to other lines).



# How Grids Fail — Constraint Violations

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Dynamic stability limits — Power supply is provided by generators whose output is managed by “governors” that detect the system frequency.

- If load increases to exceed supply, the frequency drops (slightly) below 60 Hz.
- This signals generators on “regulation” (an RTO ancillary service) to increase their output.
- If they should over-shoot the needed supply slightly, e.g., due to lags in response, then the reverse situation begins: frequencies rise and governors tell generating units to reduce their output.



# How Grids Fail — Constraint Violations

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- If many widely dispersed units are sharing this regulation responsibility, they can (rarely) get slightly out of phase and begin see-sawing the supply of current and/or voltage at some non-60 Hz cycle.
  - ▶ This can be difficult to detect and remedy.
  - ▶ Often worsened if a major imbalance elsewhere is suddenly isolated (islanded)
  - ▶ If amplitudes become too large, system can collapse.



# Many Examples of Security-Constrained Operating Limits Exist

- NERC has identified 1340 flowgates for monitoring.\*
- WECC monitors flows on 79 paths.\*
- ERCOT currently monitors flows between four congestion zones and in 10-15 local areas.\*
- Every ISO and control center monitors flows on hundreds of other local lines and interfaces.
  - ▶ Grid operators assess security every few minutes
  - ▶ Set flow limits to withstand 1 or 2 major losses of plants or lines.

\*As of 11/03



# August 14 Northeast Blackout — Problems of Every Kind

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- 1. Thermal:** “The events that led to Thursday’s blackout began when several high-voltage transmission lines near Cleveland failed. . .” (NYTimes 08.17.03)
- 2. Monitoring:** “There were early reports of line outages coupled with a disabled/ malfunctioning alarm screen function in FirstEnergy’s control center.” (NYTimes, 08.17.03)
- 3. Coordination:** “There were reports of communications lapses among utilities and grid operators...” (NYTimes, 09.03.03)  

“... a FirstEnergy controller told a counterpart at MISO: ‘We have no clue. Our computer is giving us fits too.’”  
(NYTimes, 09.04.03)
- 4. Voltage:** “Experts now think that on Aug. 14, northern Ohio had a severe shortage of reactive power...” (NYTimes 09.23.03)
- 5. Dynamic Stability:** “. . . what one official called [an] eastward-pulsing “shock wave” . . . triggered the wider failure.” (NYTimes 09.18.03)



# Market Pressures

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- Existing transmission assets are currently being taxed in unprecedented ways.
  - ▶ New generation facilities have been added or planned almost anywhere an attractive site exists, often even where transmission is insufficient.
  - ▶ Volatilities in the commodities markets (electricity and fuels) lead to large swings in power flow patterns.
- Significant new transmission investment may be needed, but it has long lead times and lots of opposition.
  - ▶ Investment in many more short lead-time upgrades
  - ▶ Ever-growing list of contingency response plans



# **Locational Marginal Prices (LMPs)**

- **Locational Marginal Prices (LMPs) are increasingly being used to manage congestion and force those creating it to bear the costs.**
  - ▶ **Spot (5 minute), location-specific (1000s of nodes in PJM) price signals for efficient re-dispatch around grid constraints**
  - ▶ **Use of transmission paths priced at the difference between LMPs at receipt & delivery points**
  - ▶ **Can add to volatility and make load-pocket locations much more expensive**
- **Controversy over whether LMPs create more problems than they cure – opposition to FERC SMD**



# Long-Run Consequences

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- The system is increasingly becoming a collection of local congestion zones interconnected with security constrained interfaces/flowgates/paths.
  - ▶ Leading to increasing dependence on reliability must-run generating units, out-of-merit dispatch, use of Transmission Loading Relief (TLR) protocols, and increased congestion costs
  - ▶ Exacerbating local market power problems
- The system is harder to operate.
- The risk of cascading failures is increased.
- The efficiency gains of expanded competition and commerce in electricity are diminished.
- The result will be more congestion and higher congestion costs.



# Improving Grid Performance – Engineering

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There is no single/simple way to improve grid performance, assuming it is not woefully inappropriate for its typical duties.

- **Almost every problem has multiple solutions, e.g.,**
  - ▶ Adding more lines, reinforcing existing lines (e.g., with voltage management devices),
  - ▶ Collecting better state information,
  - ▶ Adding new generation at points requiring high transmission loading,
  - ▶ Demand-side management, *etc.*



# Improving Grid Performance – Engineering

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- A problem is not necessarily best solved where its symptoms are felt, e.g., flows in Ohio may cause problems in Michigan or New York.
- There are significant scale and scope economies, so that enhancements larger than are immediately needed may be preferred socially (but be hard to recover privately).
- Expanding ties between regions to support more traffic?
  - ▶ Lower risk of modest problems, but greater max potential problem
  - ▶ Like tying mountain climbers together – good if only 1-2 fall, else brings down the entire team!



# Improving Grid Performance – Economics

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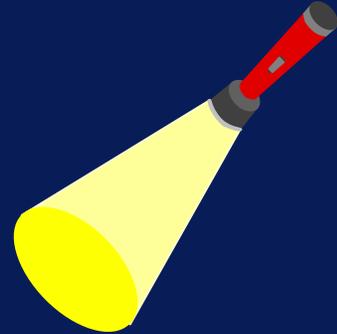
- **Scale economics and multiple solutions create many “externalities” to grid enhancements**
- **Marginal shares of expansion benefits very difficult and costly to quantify**
- **Sometimes dramatic increases in costs under efficient pricing from LMPs and localized ICAP requirements**
- **Incentives not established for how transcos can share in improved up and downstream performance**
- **Complex interactions among multiple requested upgrades**



# Where Does This Leave Us?

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- Lucky the lights are on?
- Many unresolved problems
- Lots of conflict and experimentation ahead
  - ▶ RTO Procedures
  - ▶ Genco upgrades for plants sited without transmission considerations
  - ▶ Attempts to localize responsibilities
  - ▶ Pressure for expedited authority to expand
- Reasons will abound for challenging how standards and solutions are interpreted, enforced, and observed





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