# Data and metrics for power grids and energy supply sustainability

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# A quick review of power systems and important data

*The traditional quantities of interest are:*

- Voltage, current, power, frequency, Phasor Measurement Units (PMUs)
- Circuit breaker status (network topology)
- Locational marginal prices ($/MWH)
- Oil temperature, pressures, $NO_x$ and $SO_x$ and $CO_2$

*We now add:*

- Computer server status
- Communication network status
- Control system status

# Voltage

- Voltage is the separation of charge (Insulators and air keep charges separated)

- Electric fields "due to voltage"

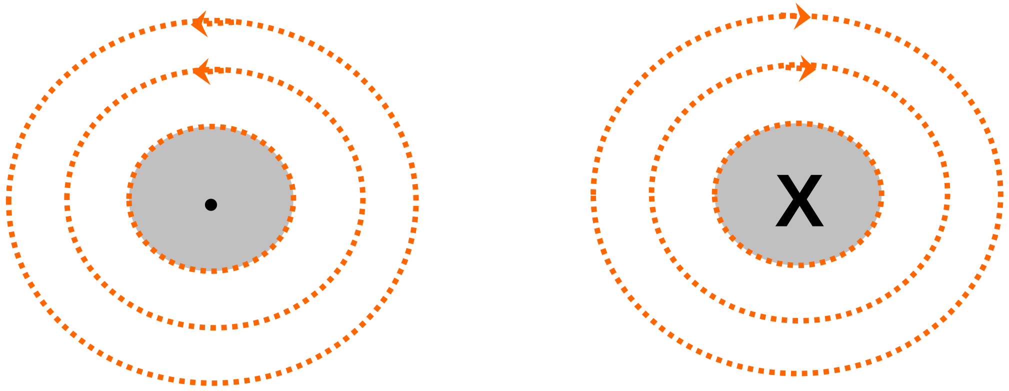

- Voltage is like pressure in a water system

# Voltage

- In the cornfields, the voltage is high (345 to 765 kV) – (OH – bare)
- In our neighborhoods and cities, the voltage is medium (12 to 69 kV) – (OH – bare, UG – insulated)
- In our houses the voltage is low (120 or 240 Volts) – (OH – insulated, UG – insulated)

# Current

- Current is the movement of charge
- In our houses, current flows in the wires when something is turned on




- Magnetic fields "due to current "
- Current is like water flow in a water system

# How are voltage and current related?

- Voltage is created by a "source" - perhaps a battery or a generator.
- Current flows when a "load" is switched across a voltage source – perhaps a light bulb or phone charger.
- The amount of current depends on the "Resistance" of the path or load.

# Power

- Power (Watts) is Voltage (Volts) times Current (Amps)
- A typical oven can heat up to 12,000 Watts - this would draw up to 50 Amps at 240 Volts
- A 60 Watt light bulb connected to 120 Volts draws 0.5 Amps

- NOTE:  High voltage means low current and low voltage means high current (all for the same power)

# Fundamental Laws

- Kirchhoff's voltage law: The sum of voltage drops around a closed path is equal to zero.

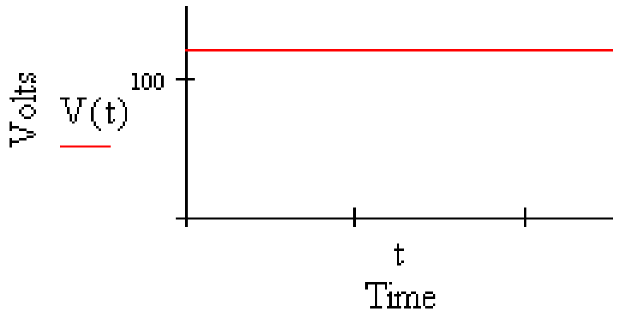
- Kirchhoff's current law: The sum of currents entering a point (called a "bus") is equal to zero.

- Ohm's law: The ratio of voltage divided by current is the "resistance" of the load.

# Types of Electricity

- DC
  - Batteries
  - Fuel cells

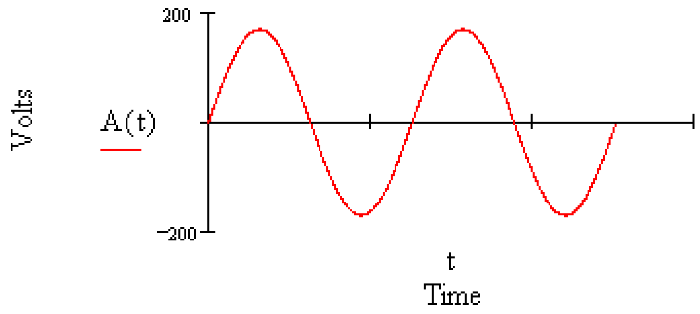
| Average = 120 Volts |
| --- |
| Peak = 120 Volts |
| RMS = 120 Volts |




DC Power

- AC
  - Rotating machines
  - Electronic converters
  - 60 Hertz in the US

| Average = 0 Volts |
| --- |
| Peak = 170 Volts |
| RMS = 120 Volts |



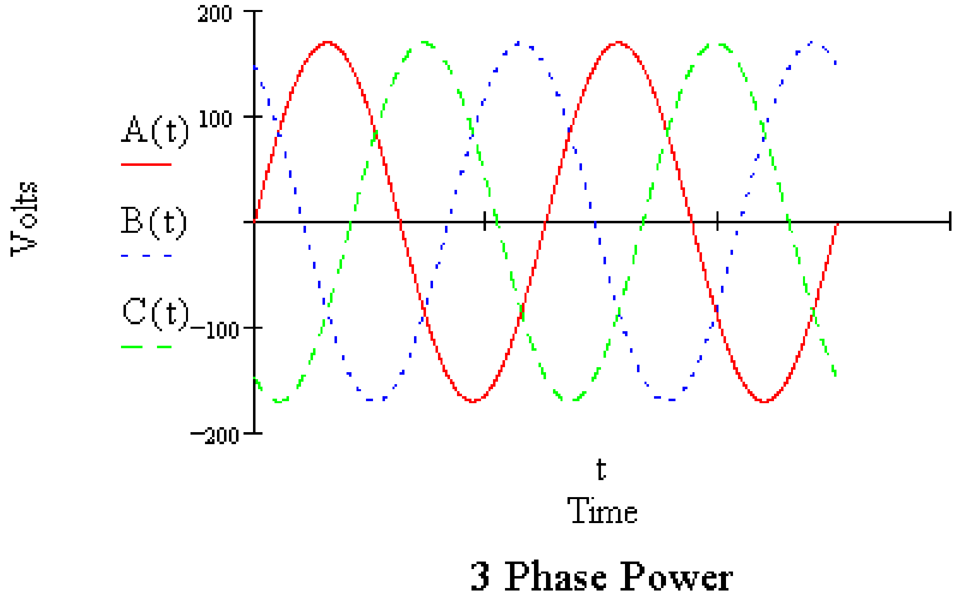

Single Phase Power

# The early years (1900)

- DC
  - –Thomas Edison (GE)
  - –Could not change voltage levels
  - –Could not go long distances
  - –Stuck with the DC motor
- AC
  - –George Westinghouse
  - –Nikola Tesla
  - –Could change voltage levels (the transformer)
  - –Could go long distances (high voltage)
  - –Invented the induction motor and three-phase

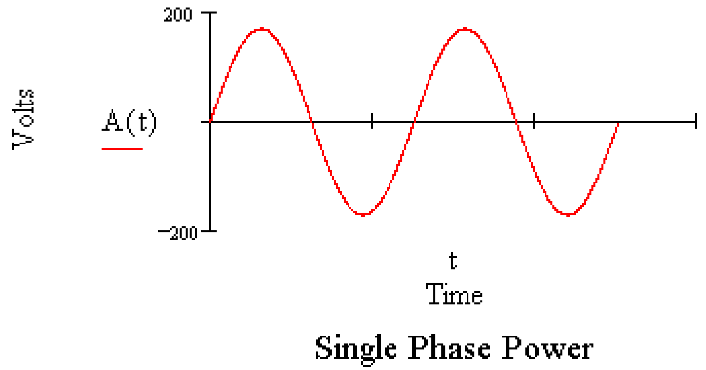
# 3-Phase AC

Bulk power generation/transmission and commercial use



# Frequency

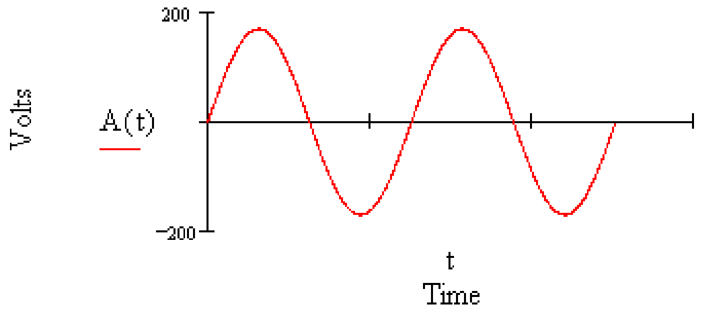
- The number of "cycles" per second
  - Zero for DC
  - Many options for AC




- Unit is Hertz
  - 60 in the US
  - 50 in Europe

# Why is frequency important?

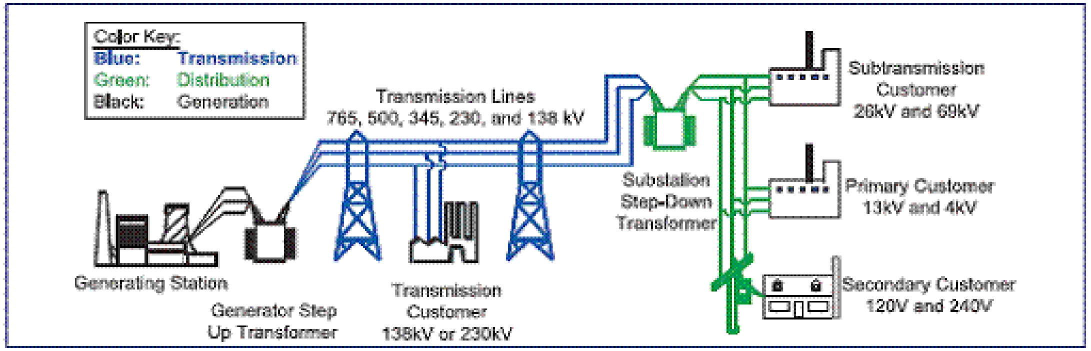
- It decides the speed of motors
- If it is too low, lights will flicker on and off
- Synchronism requires identical frequency between units




Single Phase Power

# Components of the Grid

- Generation – Sources of electricity
- Load – Consumers of electricity
  - Consumers are in complete control of the switch; utilities must supply enough power to meet load
- Transmission – Transporters of electricity
  - 115,000 Volts to 765,000 Volts
- Distribution – Distributors of electricity
  - 4,000 Volts to 69,000 Volts




http://www.nerc.com/AboutNERC/Documents/Understanding%20the%20Grid%20AUG13.pdf

# The North American Electric Grid

- One of the largest and most complex man-made objects ever created
- Consists of four large 60 Hertz synchronous AC Systems
  - Eastern Interconnect
  - Western Interconnect (WECC)
  - Texas (ERCOT)
  - Quebec
- Small amounts of power can be transferred between subsystems using AC-DC-AC ties

(More about this later)

# Protection systems

- **What happens when a short circuit (fault) occurs?**

- i.e. suppose your kid sticks a two-pronged fork in the outlet of your house!

- **The fault must be detected quickly.**
- **The fault must be isolated quickly.**
- **Possible fault current values are an important metric.**

# How do things trip?

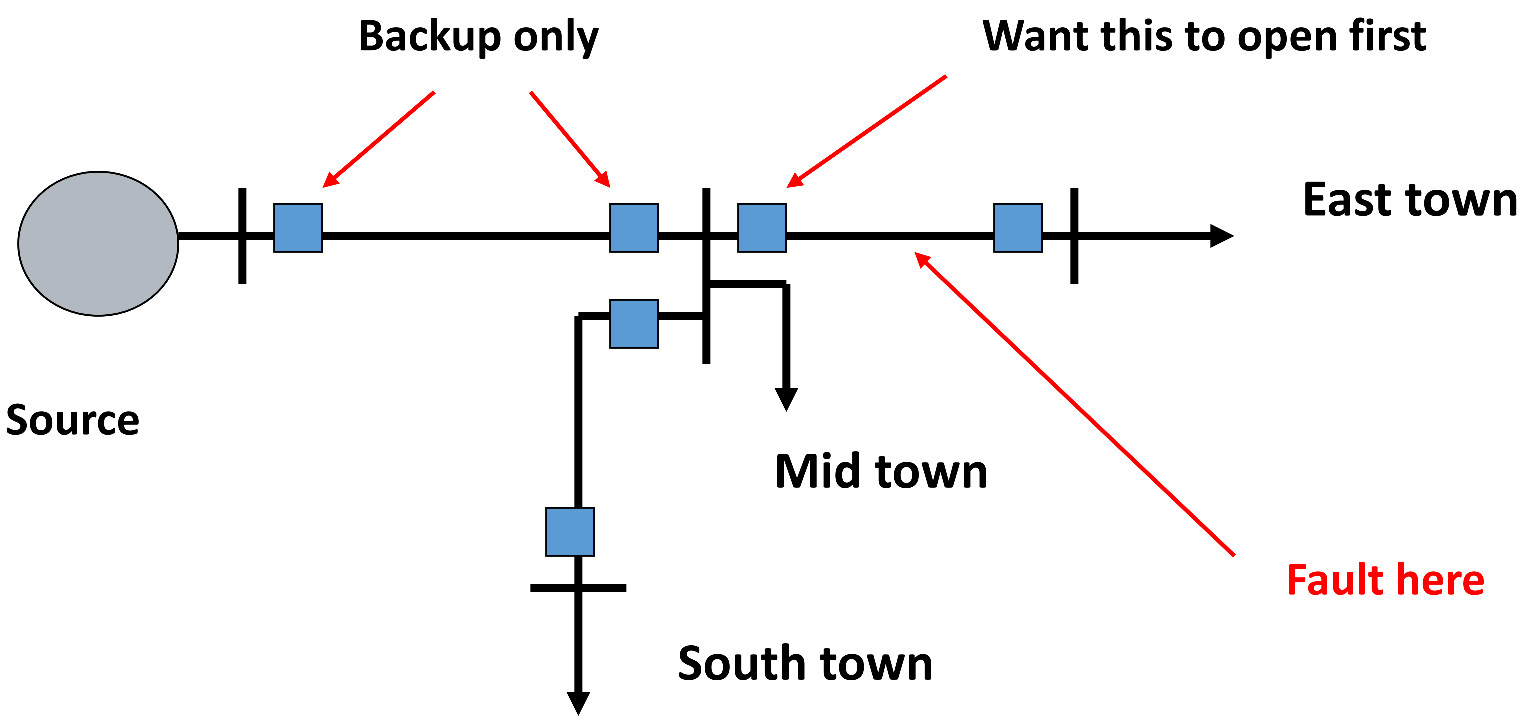
- **Fuses** detect abnormal conditions in lines and trip by melting a wire element.  Must be replaced.

- **Relays** detect abnormal conditions through sensors and send signals to tell the circuit breakers to “trip”.  Settings can be changed.

- **Circuit breakers** open up lines.  Can be reused.  Can also be remotely “tripped”.

# Trip coordination

**The right fuses and or circuit breakers need to operate at the right place and right time.**



# Time evolution of substation devices and tools

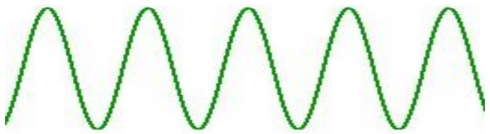
1900 —— 1950 —— 2000 ——

| 1900 | 1950 | 2000 |
|---|---|---|
| Electromechanical (Screwdrivers) | Solid state (Solder guns) | Digital (Laptops) |

# Physical constraints

**Thermal** -- things get hot when overloaded

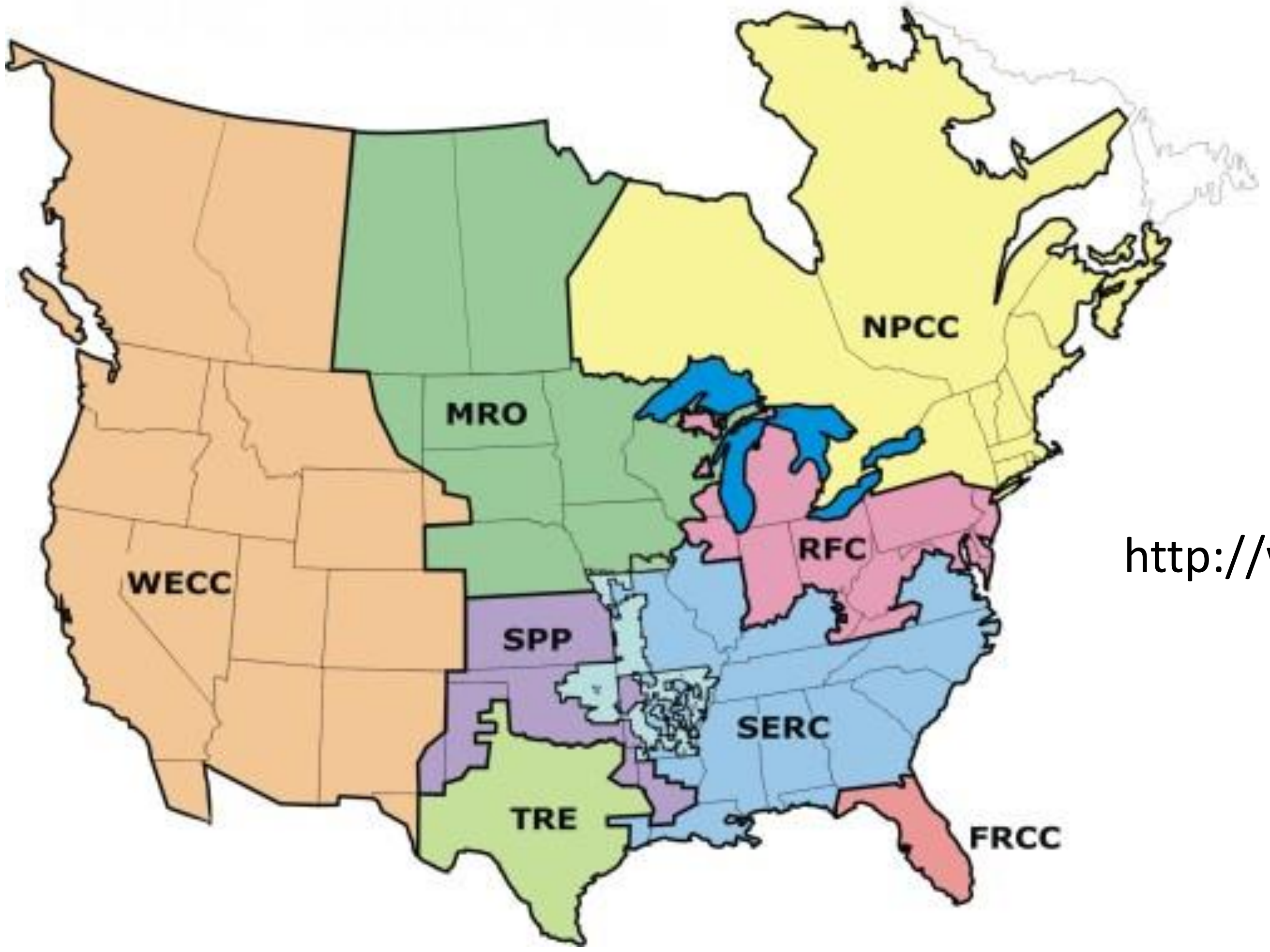
**Voltage** -- the quality of the grid service (60 Hz)

**Stability** -- maintaining order 

# Who is in charge?

- Federal Energy Regulatory Commission (FERC)
- North American Electric Reliability Corp. (NERC)
- State legislatures
- Regional reliability councils
- ISOs and RTOs
- State commerce commissions
- Control area (Balancing Authority) operators

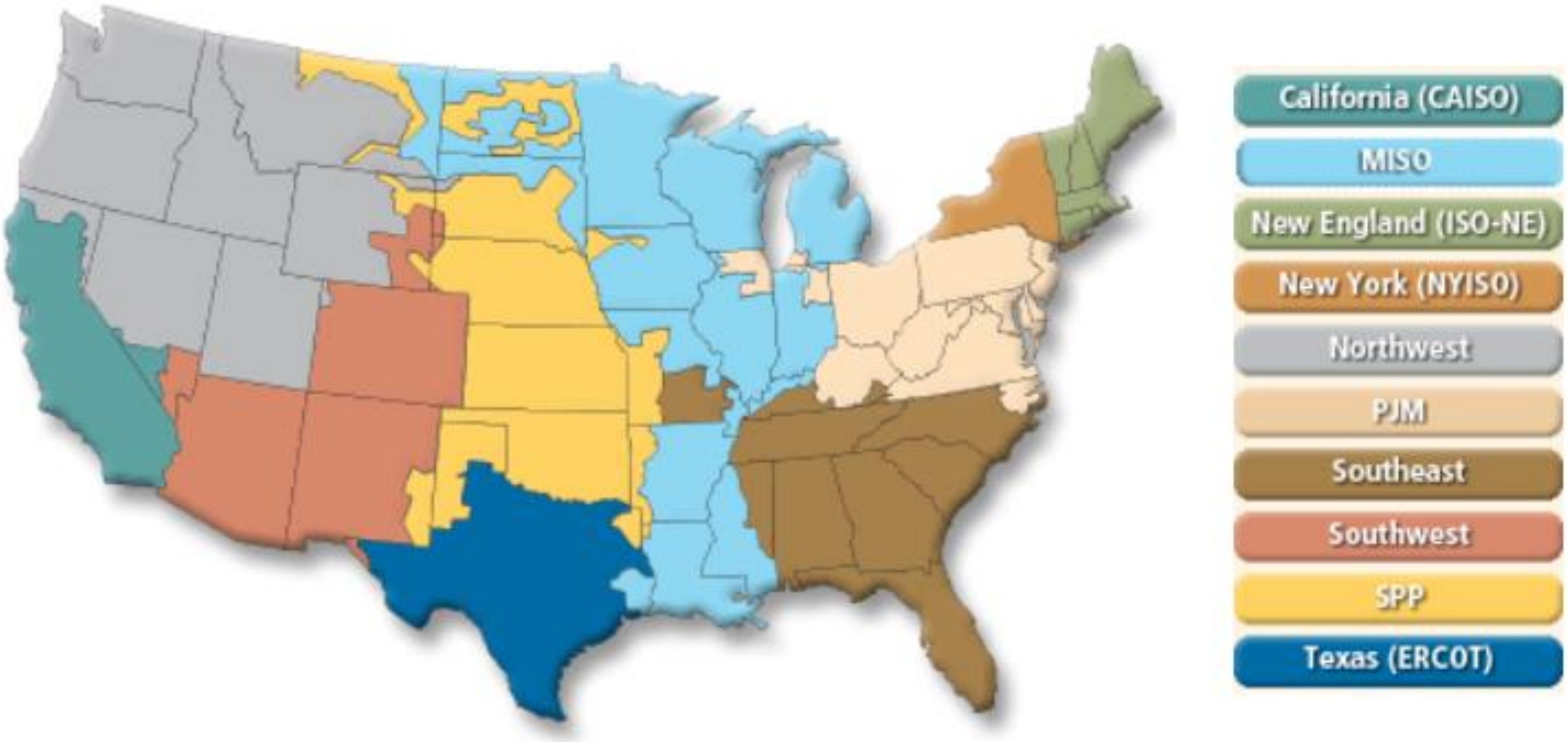
# North American Electric Reliability Corporation (NERC)




NERC publishes the Electricity Supply and Demand Data base (many years available) - Download for free at:

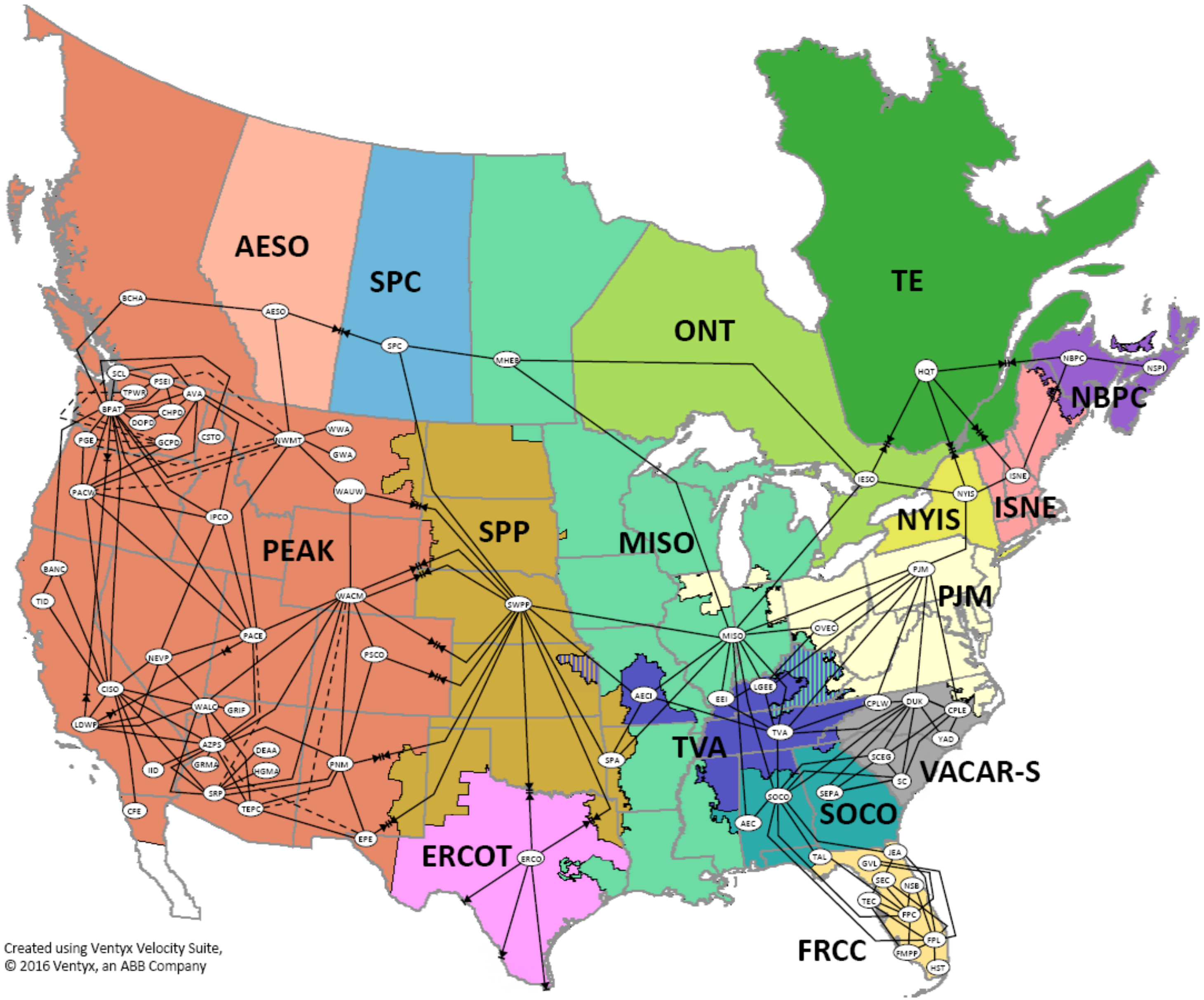
http://www.nerc.com/pa/RAPA/ESD/Pages/default.aspx

## Electric Power Markets: National Overview



# NERC Balancing Authorities

As of October 1, 2015




Dynamically controlled generation

Back-to-Back DC Converter

Submit changes to balancing@nerc.com

# Control centers

# Energy storage is a problem with the AC grid

- **There is no mechanism to efficiently store a large amount of electrical energy**
  - A small amount of kinetic energy is stored in the spinning masses
  - One small exception is a “pumped storage” hydro plant
  - Natural gas pipelines have storage fields and pipelines
  - In a telephone system you have a busy signal
  - In a computer system things just slow down

- **This mean the generator outputs must match the consumer loads *at all times – just in time manufacturing***

- **How is this possible?**
  - Does the power company send a signal from your house every time you turn on a light bulb? No.

# Operation of a power system

- How does it all work?
- What can go wrong?
- What is protecting it?
- What data and/or metrics are important?

# What happens when you turn on a light bulb?

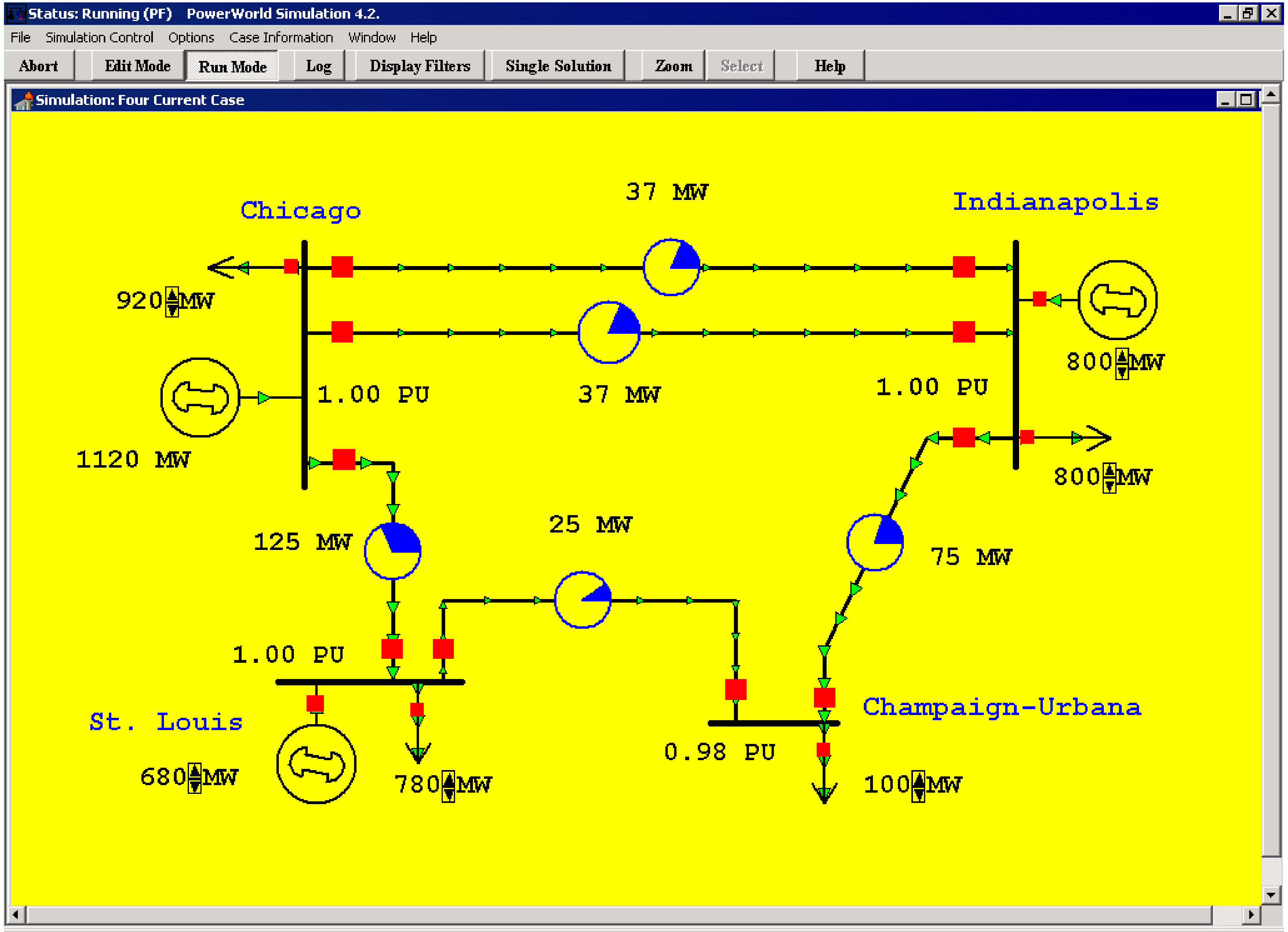
## Here is the general feedback mechanism

- Turn on a light bulb
- Current is delivered to the bulb at the speed of light
- The increase in current is felt by the generators immediately
- The generator slows down a little bit to meet this load
- A control system recognizes the slowed spinning
- A control system tells the turbine to increase its speed by opening the steam valve a little bit
- When the steam pressure drops (because of the additional steam going out), another control system tells the fuel supply to add more fuel to make more steam.

# No direct control of power flow

- If a telephone or computer network circuit is overloaded, you just switch to use another route (That is the job of the “router”)
- Natural Gas pipelines have valves to control flow.  They also tend to be more radial in nature
- With a few expensive exceptions, there is no mechanism to directly control power flow in the electric power grid

# Power flows in a network



## Java Applets -- how power systems work

http://tcip.mste.uiuc.edu/applet1.html

http://tcip.mste.uiuc.edu/applet2.html

# Weather Caused Outages

- **Direct damage from wind and lightning (wind blows wire or the wire sags into a tree)**
- **Worst outages are caused by ice storms**
  - Ice builds up on tree branches and lines - adding weight
  - Eventually the branches or lines just break or touch something
  - Protective devices take you off-line
  - Physical damage must be fixed to get the system back up

# Reliability (In the eyes of NERC)

- **Adequacy:** The ability of the system to supply the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

- **Security (now called "Operational Reliability"):** The ability of the system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

- **N-1 criteria:** Must be able to survive the loss of any single element.

# Generation reserve margins

- **Short term (contingency reserve):** If a major generating unit is lost, is there enough excess generation on line (spinning) to accommodate the lost unit? An important metric.

- **Long term (operational reserve):** Will there be enough generation in case there is a very high demand period?

- **Loss of Load Probability**

# Contingencies

**Disturbances that might happen on a power system:**

- Loss of a line
- Loss of a transformer
- Loss of a generating station
- Loss of a major load

# Causes of contingencies

- Storms (knock down lines)
- Tree growth (touch bare wires)
- Breakdown with age (insulation fails)
- Squirrels and snakes (touch things)
- Poor or careless maintenance (mistakes)
- Sabotage (disgruntled employees or terrorists)
- Other contingencies (cascading outages)

# What does it mean to survive a contingency?

- **Thermal:** all power flows are within acceptable range (rated)
- **Voltage:** all points are within acceptable range (rated plus or minus 5%)
- **Stability:** all generators remain in synchronism (near speed for 60 HZ)

There are mathematical models and equations (metrics) for all of these.

# Static Contingency Analysis

Change in steady-state solution after the loss of a line, generator, or load

- Physical laws:  Kirchhoff voltage and current laws plus load/generator powers

Commercial software – first developed in the 60s

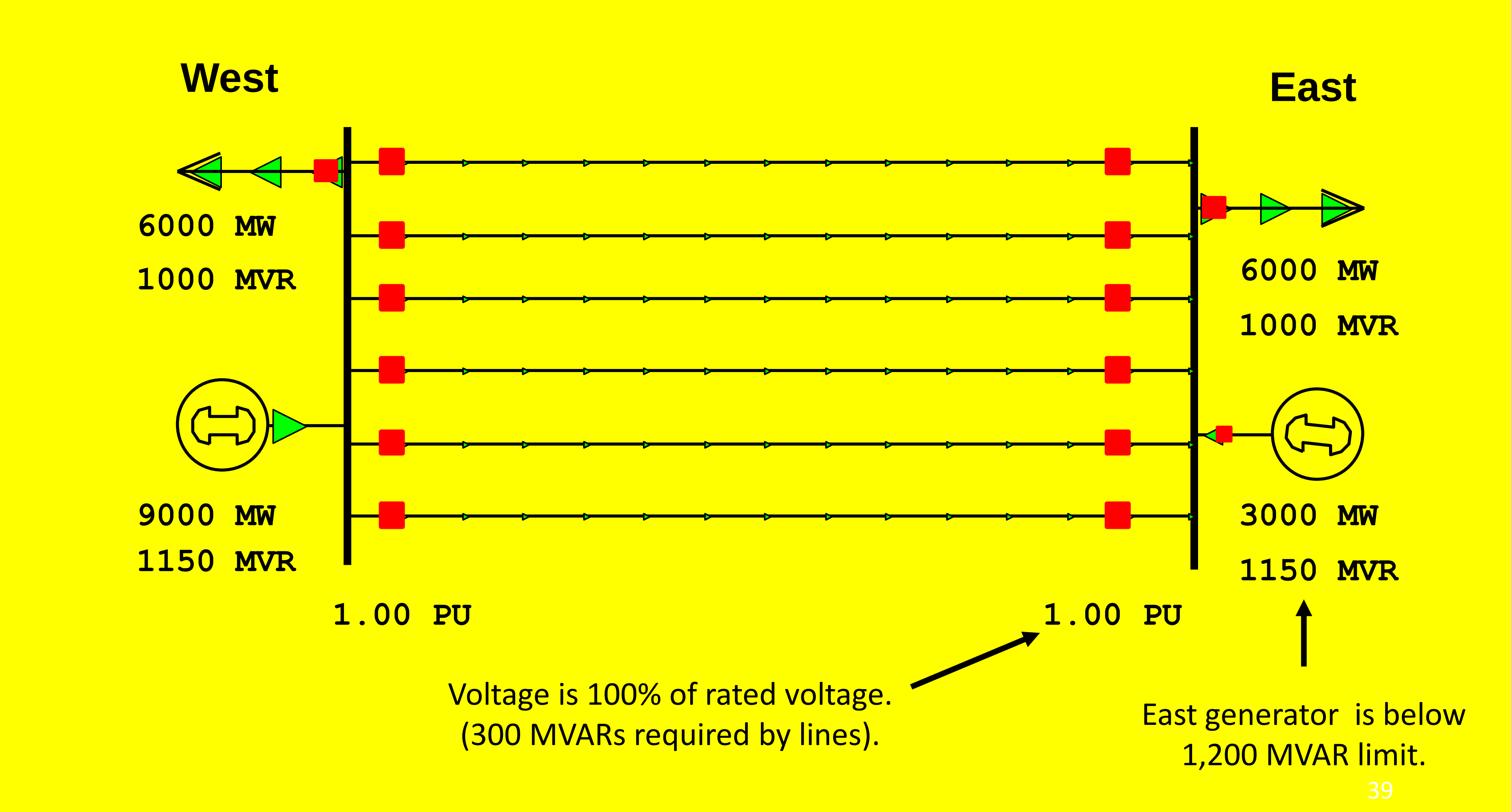
- PSS/E, PSLF, ABB, Alstom, Siemens, OSII, PowerWorld

Calculations (the power flow equations)

- I = YV  (n vectors and nxn admittance matrix) plus  $S_i = V_i I_i^* = P_i + jQ_i$   (i = 1 , , , , n)
- These result in nonlinear problems with multiple solutions (i.e. what does P = Q = 0 mean?  **Answer – open circuit or short circuit – both are possible!**)
- Linear solutions - large-change sensitivities – current dividers – line flow distribution after line loss or injected power change

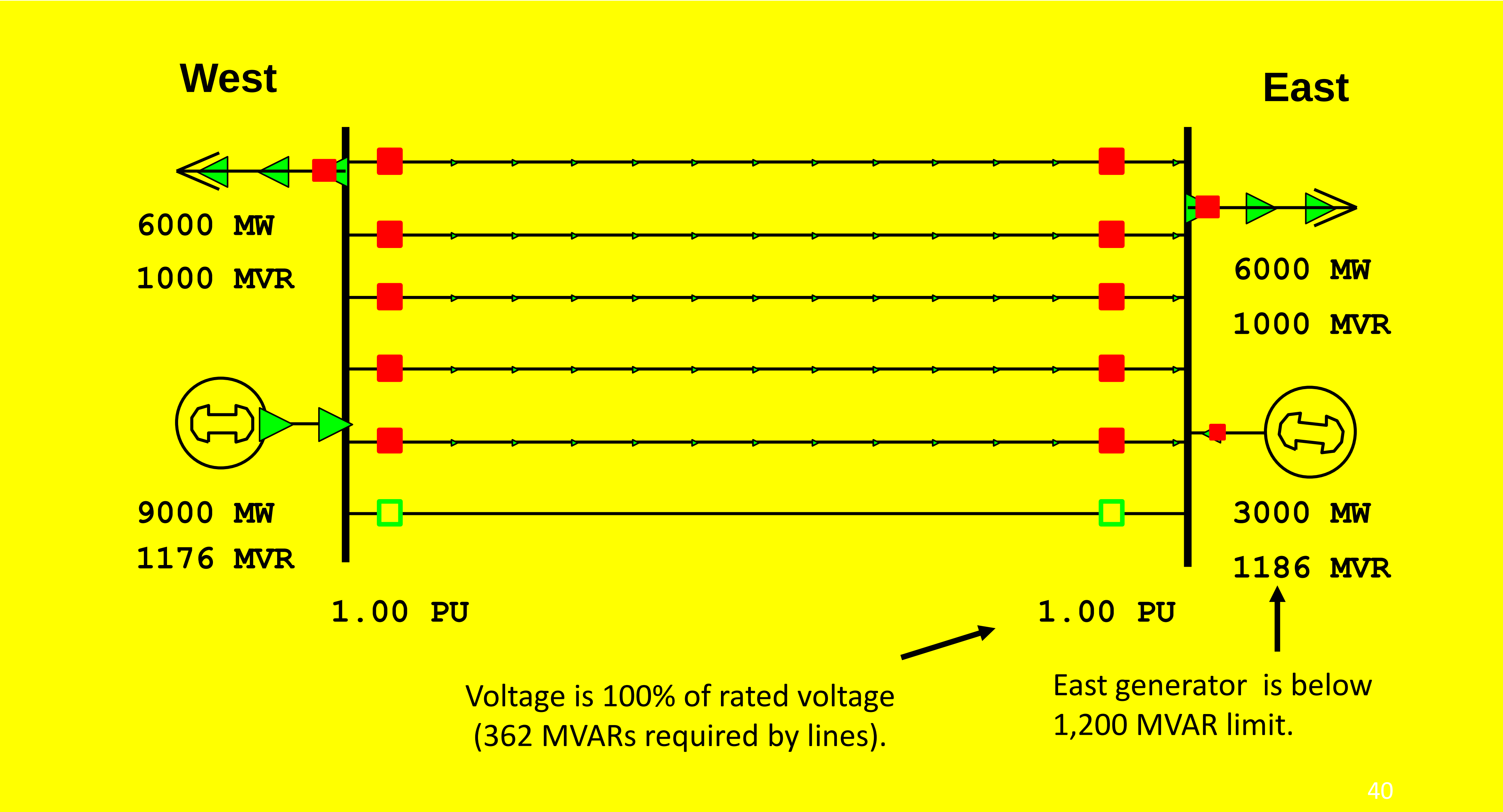
# Case 1: All Lines In-Service

## 3,000 MW transfer – 500 MW per line



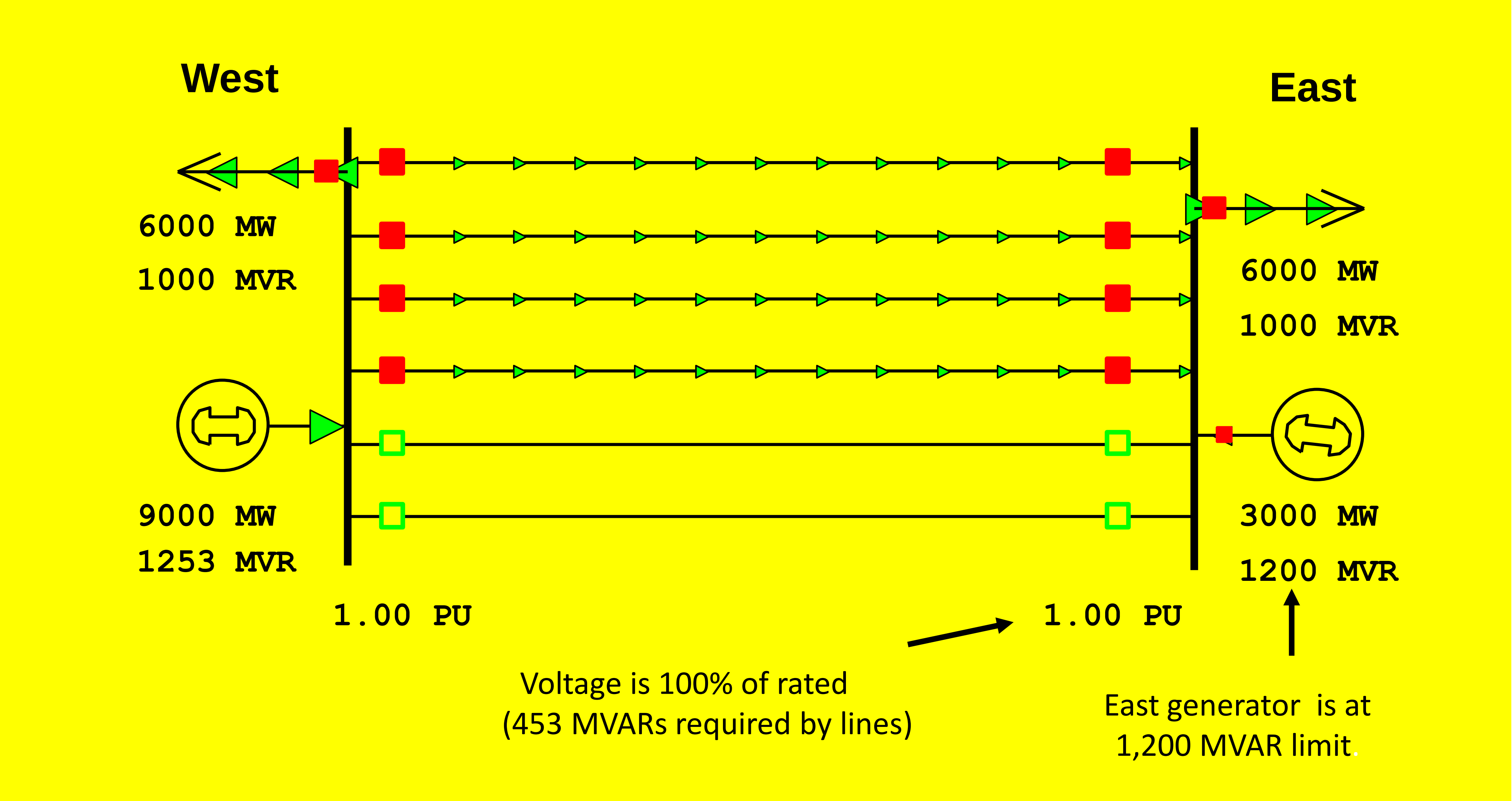
# Case 2: One Line Out

## 3,000 MW transfer – 600 MW per line



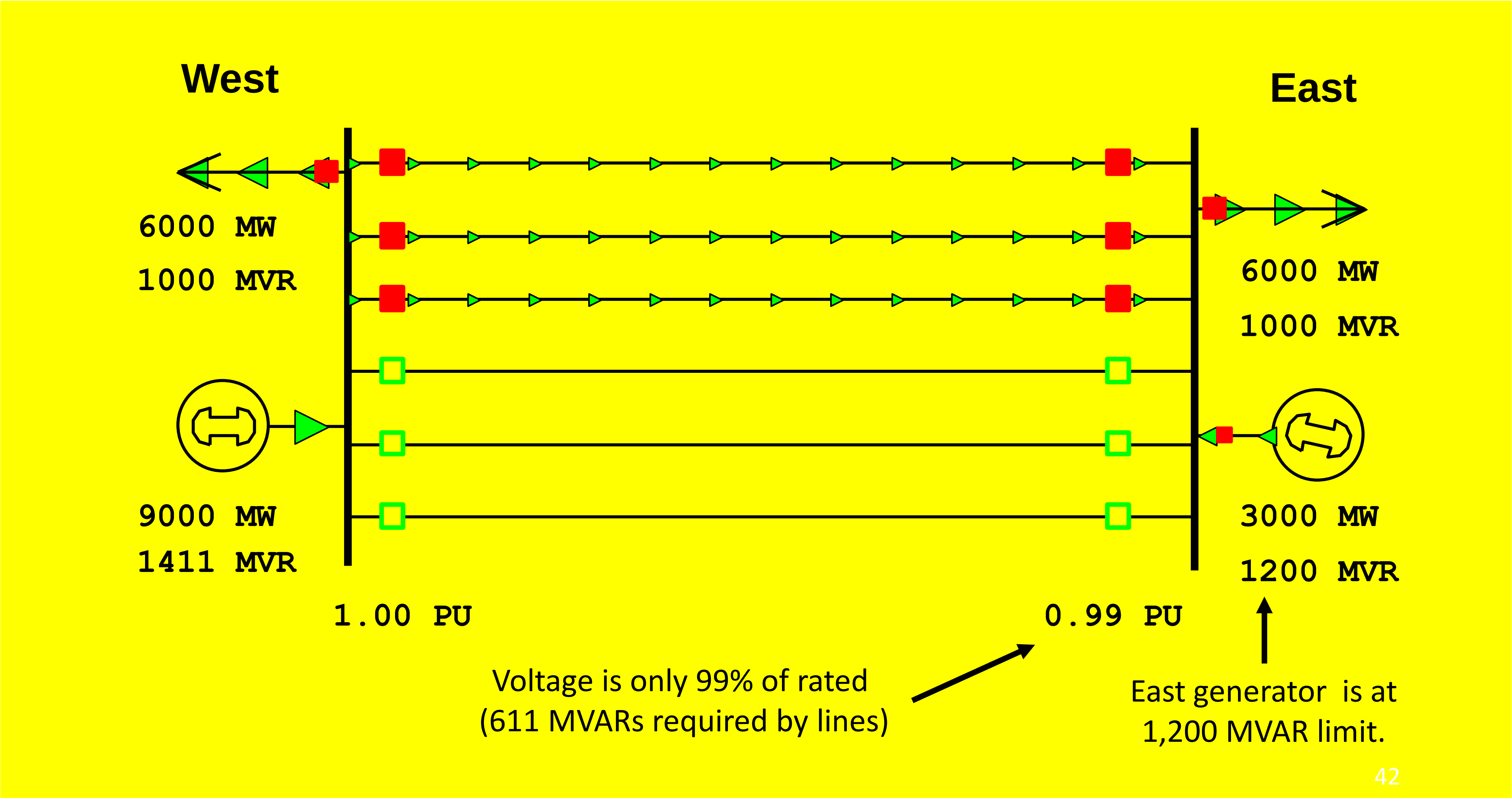
# Case 3: Two Lines Out

3,000 MW transfer – 750 MW per line



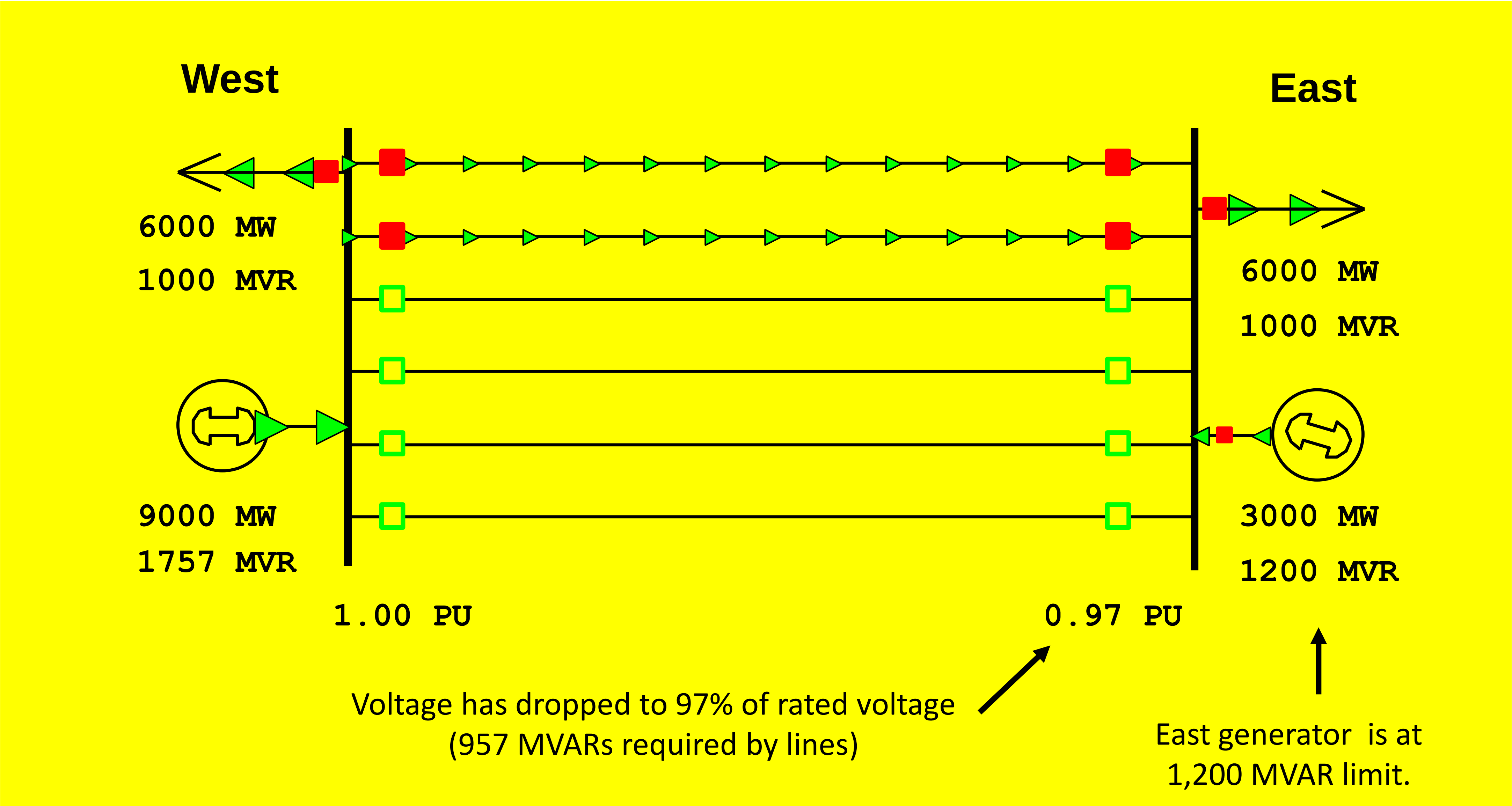
# Case 4: Three Lines Out

## 3,000 MW transfer – 1,000 MW per line



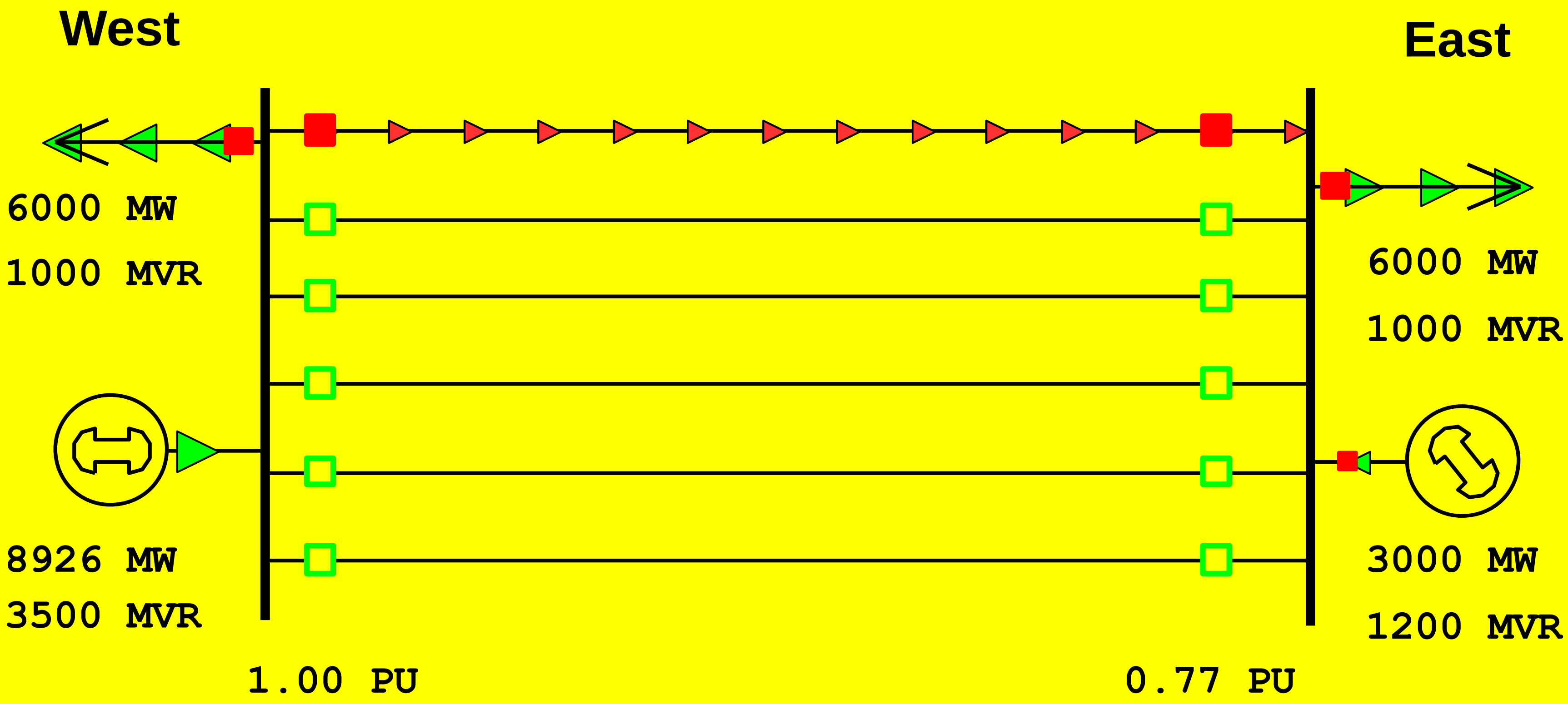
# Case 5: Four Lines Out

## 3,000 MW transfer – 1, 500 MW per line



# Case 6: Five Lines Out

## Voltage Collapse (One line cannot transfer 3,000 MW)




This simulation could not solve the case of 3,000 MW transfer with five lines out. Numbers shown are from the model's last attempt to solve. The West generator's unlimited supply of VARs is still not sufficient to maintain the voltage at the East bus.

# Dynamic Contingency Analysis

Loss of stability or loss of acceptable conditions after the loss of a line, generator, load, or short circuit

- Laws: Kirchhoff voltage and current laws plus load/generator powers plus Newton's laws of motion and control laws

Commercial software – first developed in the 70s

- PSS/E, PSLF, ABB, Alstom, Siemens, OSII, PowerWorld

Calculations (the power flow and dynamic equations)

- $I = YV$ (n vectors and nxn admittance matrix) plus $S_i = V_i I_i^* = P_i + jQ_i$ $(i = 1, , , , n)$
- Plus $dx/dt = f(x,y)$ and $0 = g(x,y)$ (The algebraic equations are from fast transients)
- Full nonlinear simulation of dynamics, or linearize and compute eigenvalues

# An islanded system (micro grid)

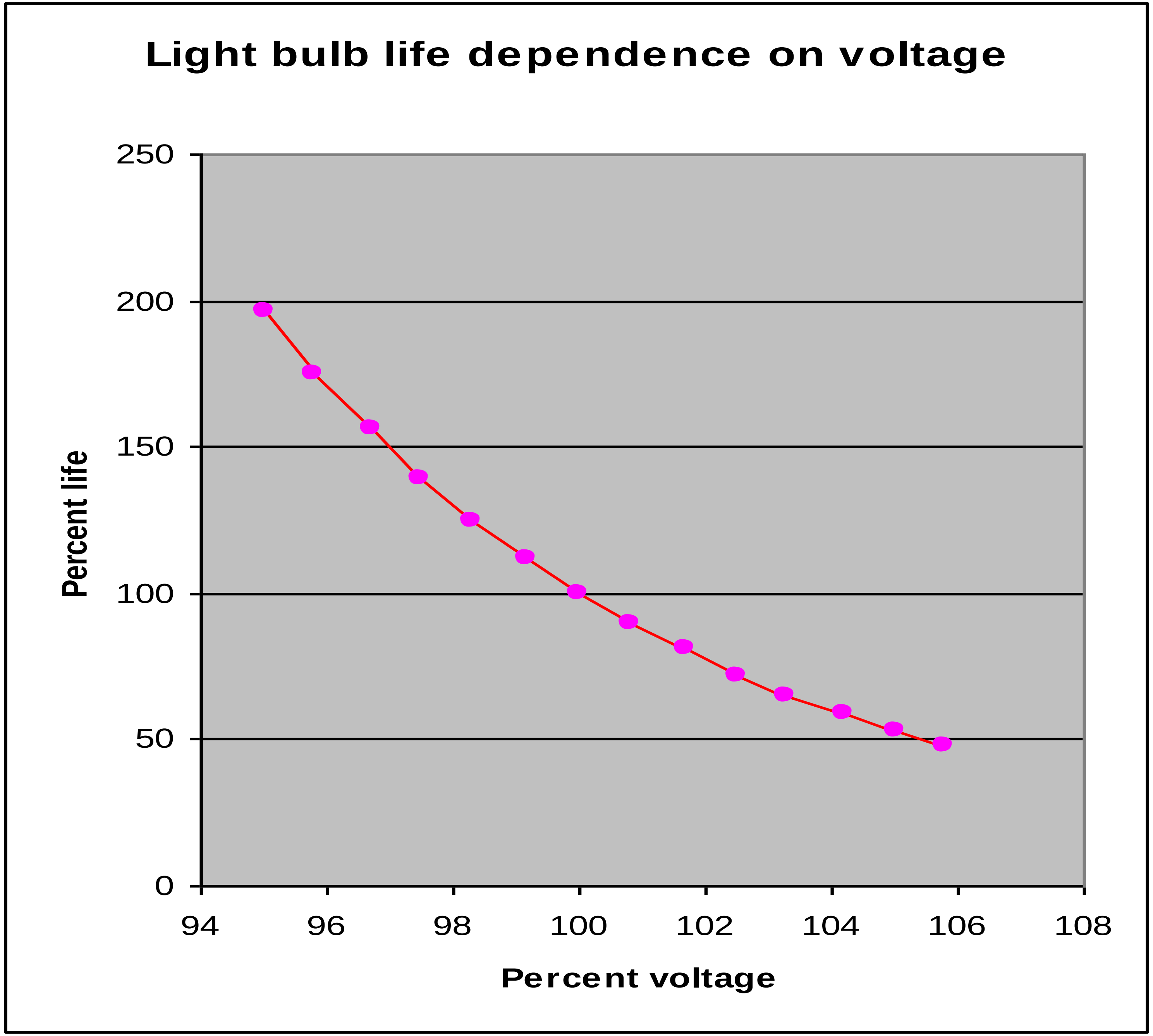
- **When the grid fails, some systems can switch off the grid to a backup grid (also called a micro-grid). This could be as simple as a standby generator – engine running on gasoline. Hospitals have these.**

- **It could be as complicated as a "fast transfer" to an "uninterruptible power supply (UPS)" with batteries – critical loads have these.**

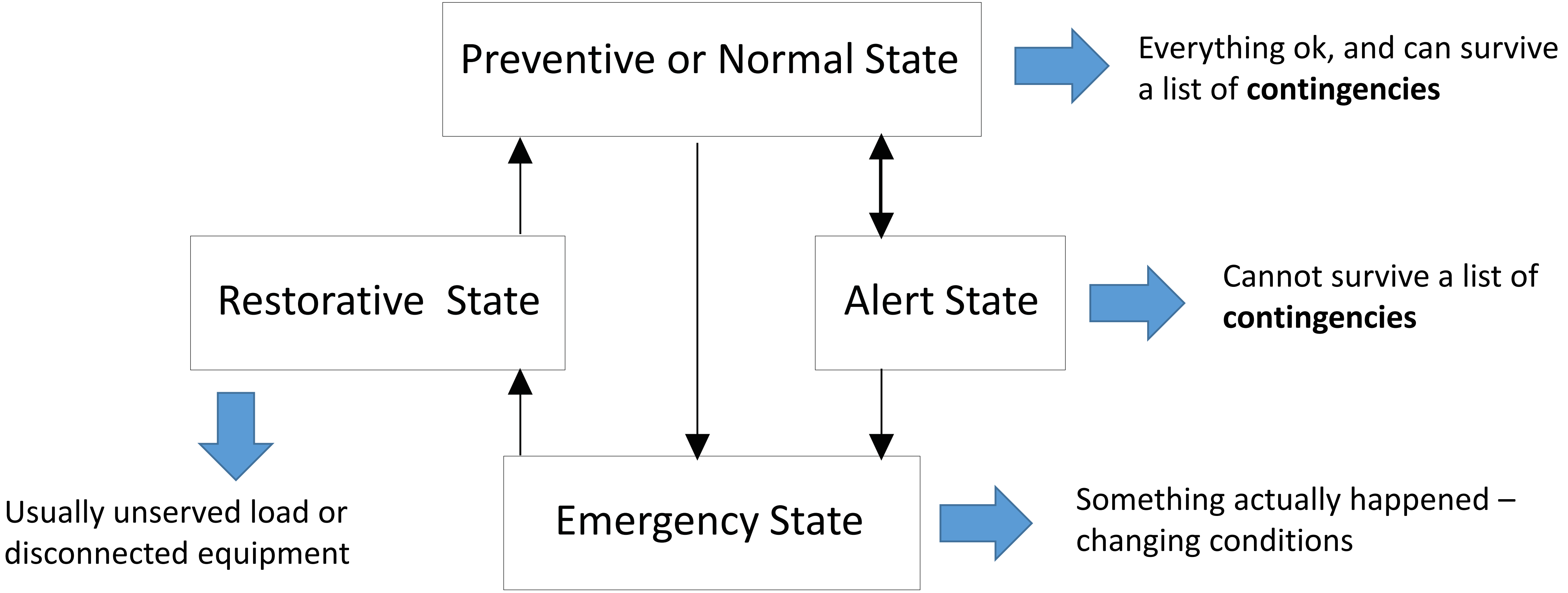
# Power Quality

- **In addition to energy, we really pay for our voltage waveform also**

- **Poor quality when:**
  - Outage – complete loss of power
  - Sags (voltage drops below rated)
  - Swells (voltage goes above rated)
  - Harmonics (persistent distortion)


Light bulb life dependence on voltage
250
200
150
100
50
0
Percent life
94
96
98
100
102
104
106
108
Percent voltage

# Traditional Power System Operating States




See Lamine Mili, "Taxonomy of the Characteristics of Power System Operating States," Proceedings, NSF Virginia Tech RESIN workshop, 2011, http://www.nvc.vt.edu/lmili/docs/RESIN_Workshop_2011-White_Paper-Mili.pdf

# Monitoring is the Data Acquisition part of SCADA

Situational awareness requires knowing the current conditions on the grid

- System Frequency
- Voltage magnitude at each bus (relative to ground) – PTs
- Current flow magnitude on all lines/transformers – CTs
- Power flow on all lines/transformers (real and reactive)
- Circuit breaker status (Open or Closed)
- Positions of TCUL taps
- Phase angles of voltages and currents

Measurement sensors can have errors (and time skew) every 5 seconds

- Need estimation of real grid conditions (every 5 to 10 minutes)
- Need bad data detection
- Observability and redundancy

# State Estimation provides the conditions and bad data

## Weighted Least Squares

z is the vector of measurements and x is the vector of states being sought

**z = h(x) + w** h(x) is the vector of physical relationships between x and z

w is the vector of measurement errors or bad equipment described as Normal

Given the measurements z and the statistics of w (mean and covariance), find the statistics of x (mean and covariance).

Consider the linear case where h(x) = Hx (about some initial guess of x)

Minimize (over x) $J = (z-Hx)^t \; R^{-1} \, (z-Hx)$ where R is the assumed covariance of w

The solution for the estimate is: $\hat{x} = (H^t R^{-1} H)^{-1} H^t R^{-1} z$

The residual is: $z - h(\hat{x})$ (used to find bad data – or hackers changing numbers)

# Supervisory Control is the "SC" part of SCADA

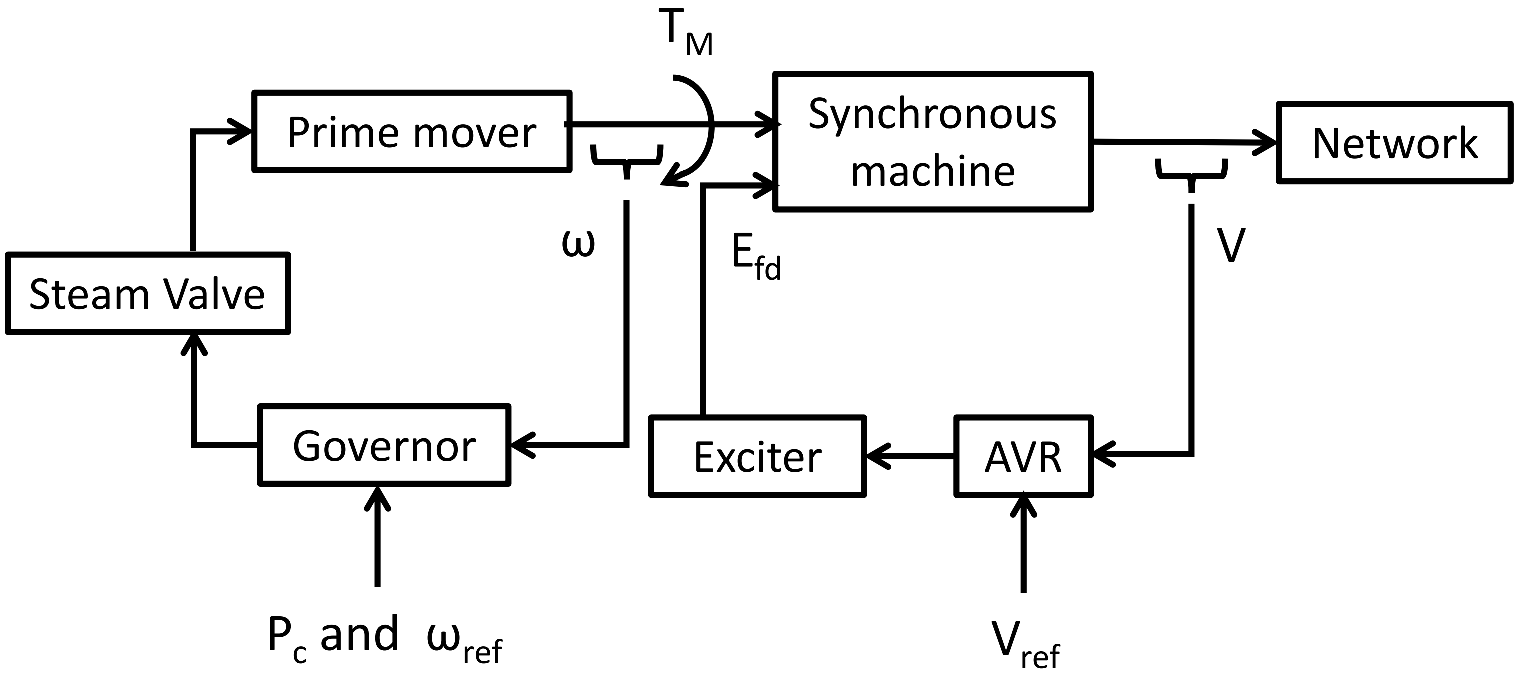
Things that can be controlled

- Frequency of the system (or generator speed)
- Voltage at certain locations
- Power flow on lines/transformers
- Stability of the generators (synchronization)
- Environmental quantities

Sensors that are available

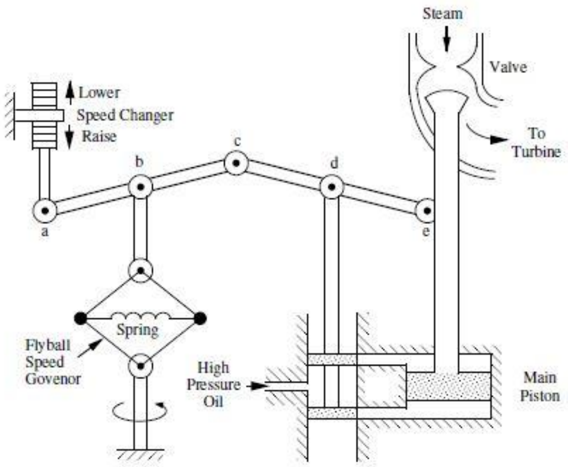
- Frequency meter, PMU, or relay
- Voltage from PT
- Current form CT and power from Wattmeter
- Out of step relays, synchronizing relays, breaker status sensors
- Emissions

# Two traditional automatic controls (Frequency and Voltage)




$$(P,\theta) \qquad (Q,V)$$

# Frequency (or speed) control




- Inertia response to imbalance caused by instantaneous change in currents (milliseconds)
- Primary Control also called Frequency Response (seconds)
  - Governor action and frequency dependent loads
  - NERC standard FRS-CPS1
- Secondary Control also called Regulation, or Load Frequency Control (minutes) - Balancing Services – ACE - Part of Automatic Generation Control – NERC Standards CPS1-CPS2-DCS-BAAL
- Tertiary Control also called reserve deployment (tens of minutes to hours) – includes Economic Dispatch and other generation shifts – return to normal state – NERC Standards BAAL-DCS
- Time Control (Time error corrections – make up for lost time) – NERC Standard TEC

# Automatic Generation Control (AGC)

- Load Frequency Control (LFC) and Area Control Error (ACE)
  - "What you have done" – Positive ACE means to lower generation – this is NERC

    $ACE = Pexport_{act} – Pexport_{sch} – 10B(f\text{-}60)$ (B is negative MW/O.1Hz)

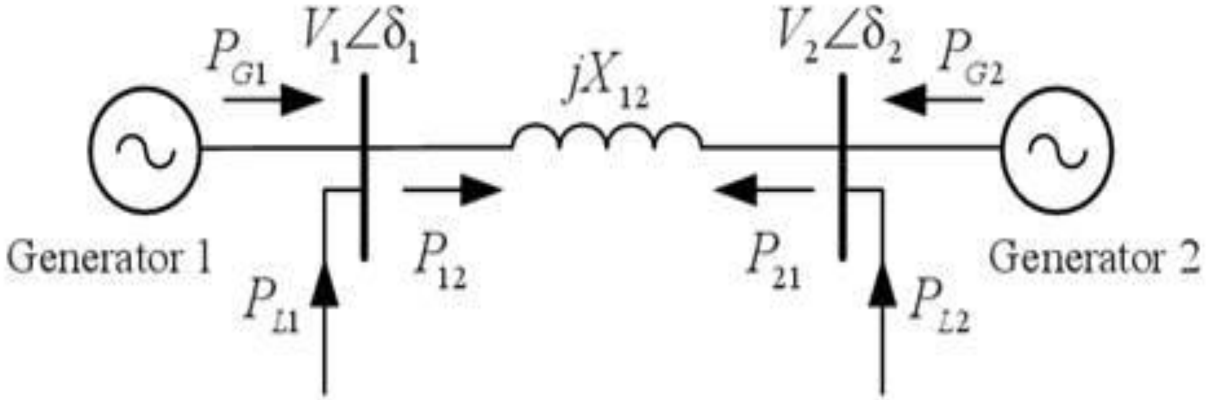
  - "What should you do" – Positive ACE means to increase generation (opposite sign)
- The dynamics of AGC control are assumed to be (using the NERC ACE):

  $dZ/dt = – ACE$ (one ACE per area)

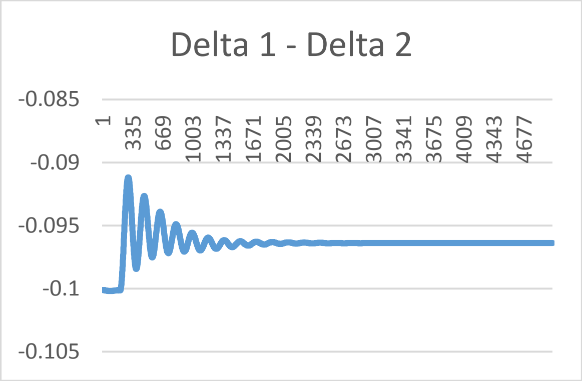
- The generation set points are:

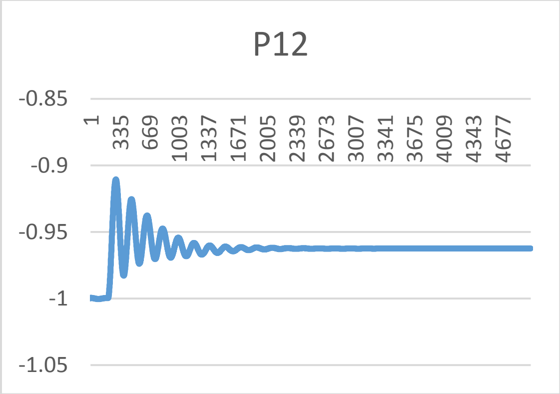
  $P_{Ci} = P_{CiED} + pf_i Z$ where $pf_i$ is the participation factor of unit i (sum to 1.0) estimates the economic split between units and the "ED" subscript means Economic Dispatch

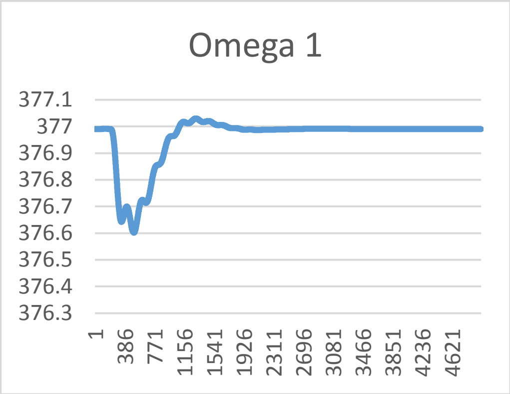
# AGC simulation (two machines, one area)

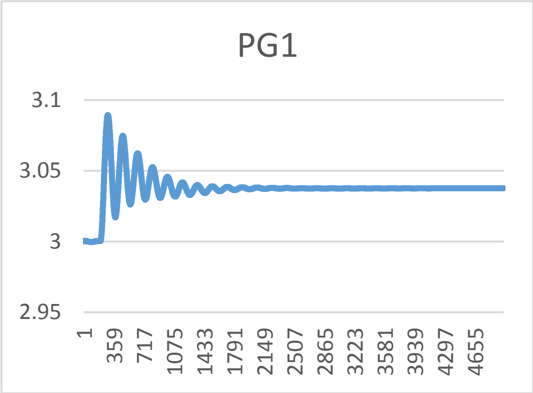


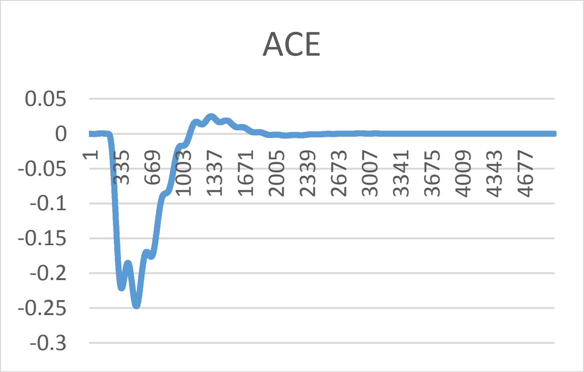
# AGC simulation – one area, two machines

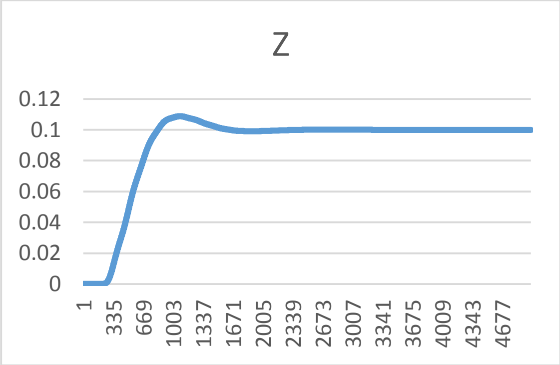


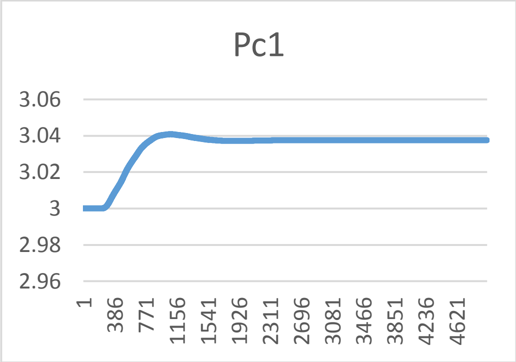



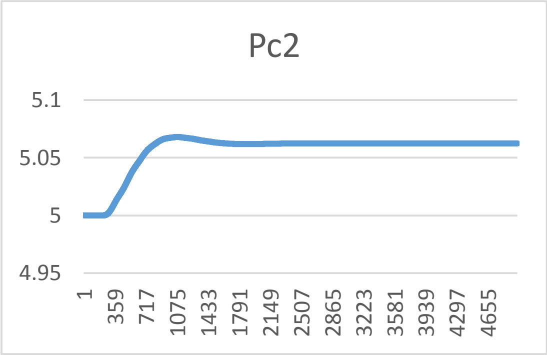



# Voltage Control

- Voltage and VAR regulation services for ISO
- Generator excitation control (AVR) – including synchronous condensers
- Tap Changing Under Load (TCUL) transformers (16 taps above and 16 below)
- Switched reactors during light load
- Switched capacitors during heavy load
- Static VAR compensators
- Flexible AC Transmission System (FACTS) devices

# Power Flow Control

- Simplest - Topology Control (line switching) – old method - discrete events – newly "approved"

- Traditional - Phase-Shifting Transformers – add phase shift to turns ratio

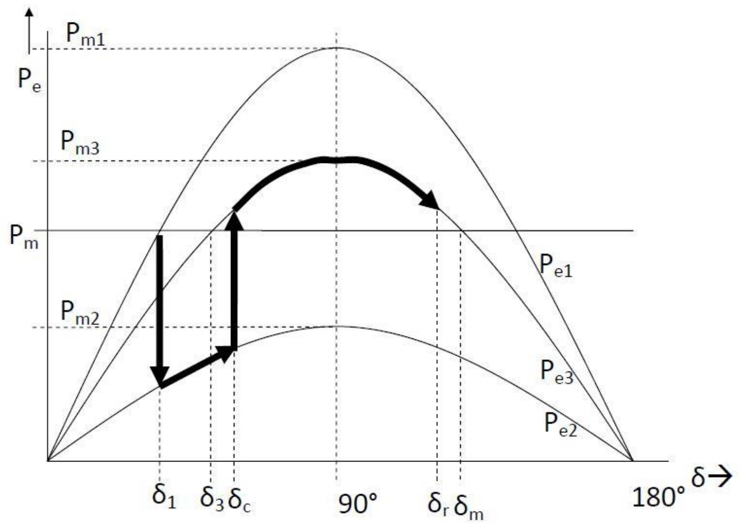
- Fairly new - Variable Frequency Transformer – wound rotor induction machine

- Expensive - HVDC and FACTS devices (UPFC) – Big wire power electronic converters

HVDC Inter-Island project – North and South New Zealand

# Stability Control

Equal area criteria: "Clear" fault in time (fuse or relay/breaker)
Fast Valving: Close steam valve to slow down turbine
Breaking Resistors: Switch shunt resistors in to slow down turbines




Under Frequency Load Shedding: Senses low frequency and opens breakers
Out-of-step relays: Senses loss of synchronism and trips unit
FACTS devices: HVDC modulation, UPFC, SVC
Islanding: Open tie lines to neighbors

# Other things

Remedial action schemes (RAS) or Special Protection Systems (SPS)

- Predefined actions that are ready to do after predefined disturbance
- "Arming", "trigger condition", "operate"

Series capacitors increase transfer capability

- Long lines are limited by inductive reactance of the line

$$\frac{V_1 V_2}{X_{12}} \sin\left(\theta_1 - \theta_2\right)$$

# Environmental Control

Emissions monitoring and control

- Run-time constraints
- Carbon emissions cap
- $NO_x$ , $SO_x$ , and $CO_2$

Acid rain

- From Nitrogen and Sulfur Oxides from factories, cars and homes
- Primarily harm to forests and lakes

Emissions markets

- Carbon credits
- Can be traded or sold

# Electricity markets in the good old days

ComEd operator calls up the IP operator and says “My average cost of generation is \$37/MWH” (which is \$0.037/KWH).

IP operator says “My average cost is \$31/MWH” (which is \$0.031/KWH).

ComEd operator says “how about if you sell me 100 MW for the next hour at \$34 per MWH?” (split the difference)

IP operator says “Deal” – IP makes \$300 per hour profit and ComEd saves \$300 per hour

# How is the trade done?

ComEd operator lowers his generation by 100MW for an hour at a specified time.

IP operator raises his generation by 100MW for an hour at a specified time.

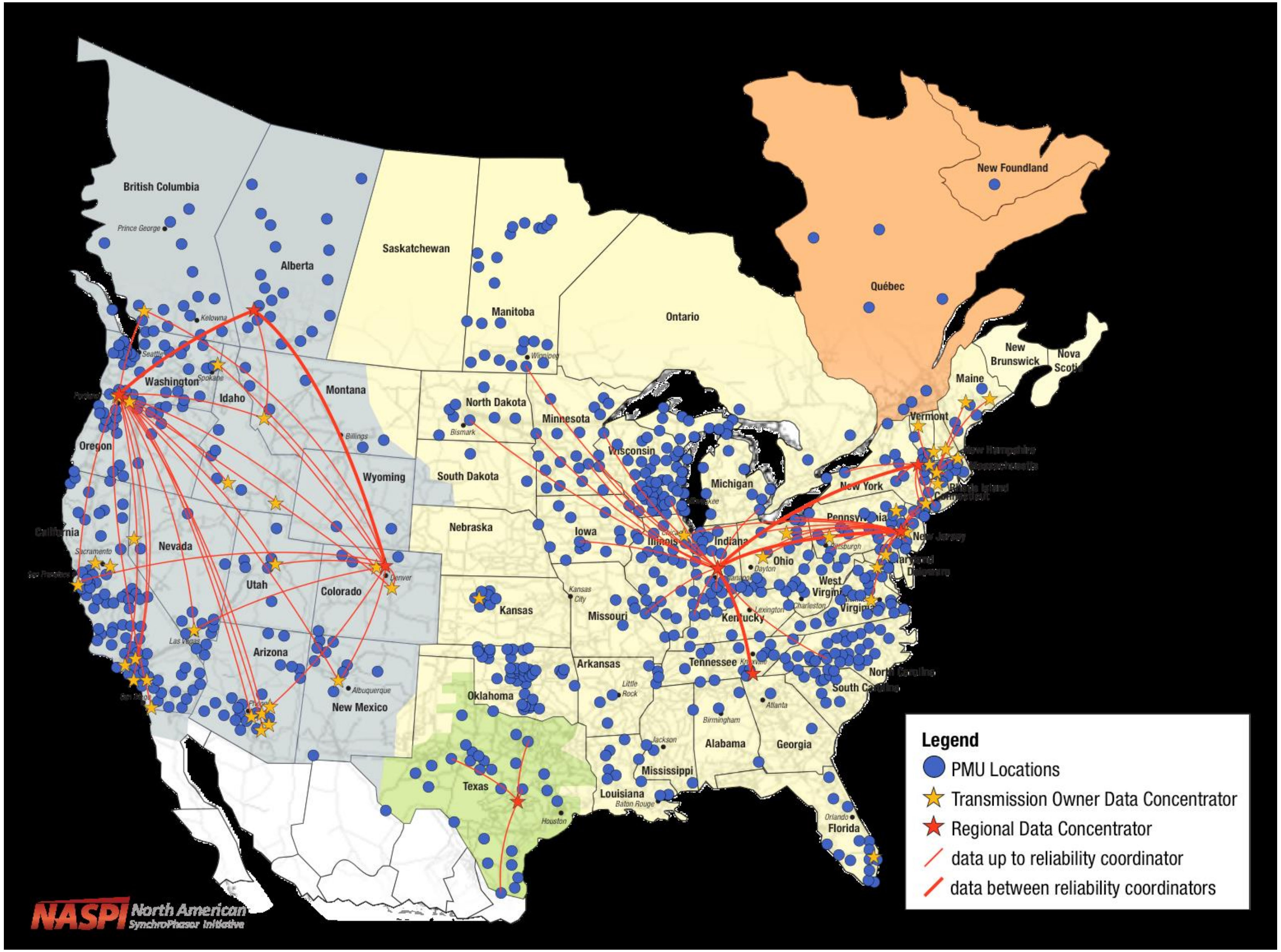
The scheduled interchange is entered into the ACE computation of the AGC and computers and governors do the rest.

# Phasor Measurement Units (PMUs)

- **Current Transformer (CT):** measures current in a wire (line)
- **Potential Transformer (PT):** measures voltage between wires (lines)
- **Global Positioning System:** provides a time stamp of when the measurements were taken

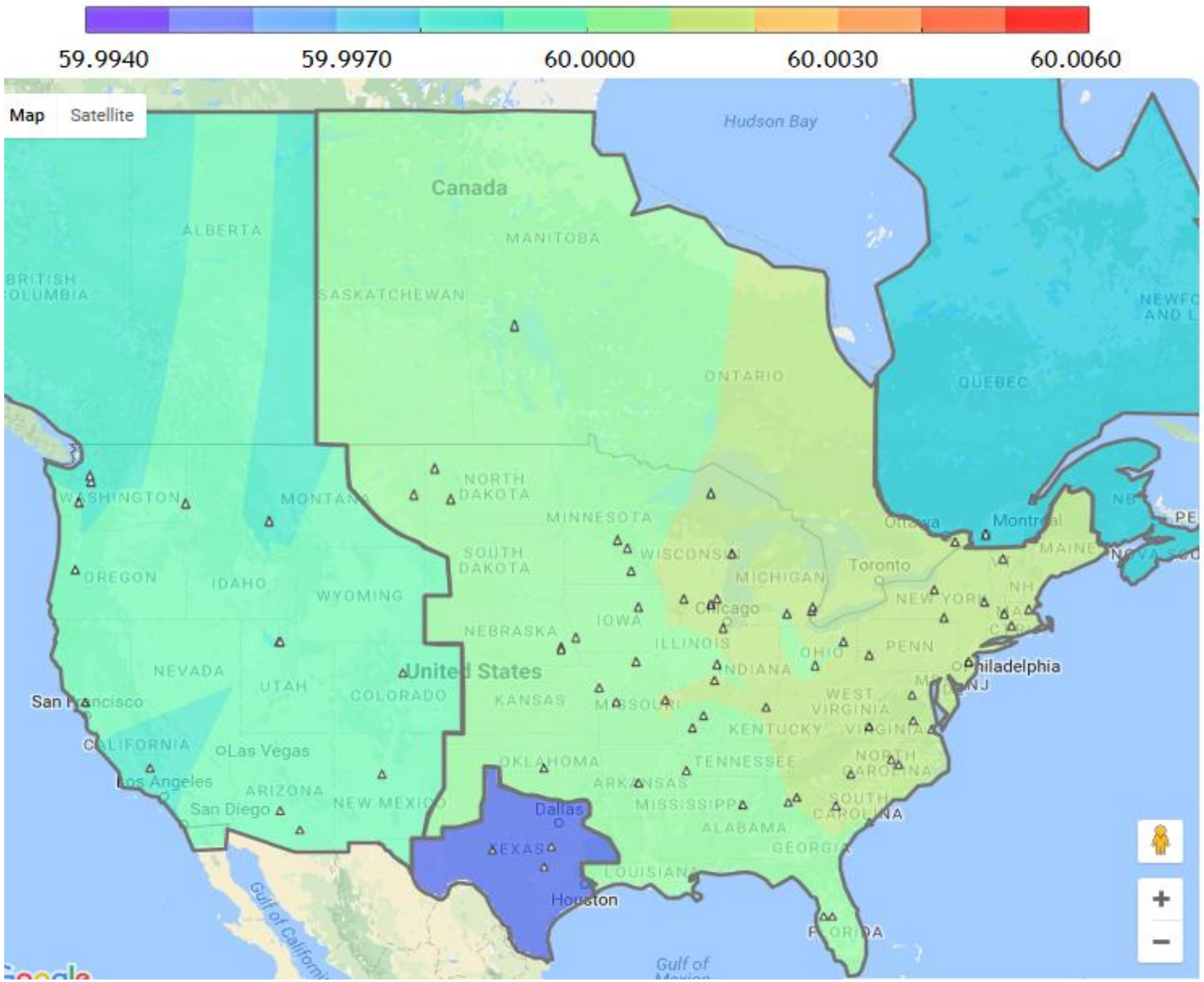
The PMU device takes these three inputs and provides data metrics for evaluating operational reliability.

# Phasor Measurement Units (PMUs)



# Frequency – fnet.com

May 21st 2017, 9:35:41 pm



# Metrics for evaluating operational reliability

- Fit the CT, PT, and GPS readings to a fundamental frequency cosine wave to determine the phasor magnitude and angle (relative to the time stamp).
- The magnitude of the current phasor reflects the acceptability of the current – related to thermal limits
- The magnitude of the voltage phasor reflects the acceptability of the voltage – related to collapse limits
- The relative angles of the current and voltage reflect the acceptability of power transfer – related to stability limits.

# Other Data and Metrics

- Meter data and associated data analytics?
- Intrusion detection  - abnormal data?
- Quality assessment – voltage limit violations, harmonics (CBEMA curves)?
- Power factor limits – and correction

# SAIDI, SAIFI and CAIDI

- **System Average Interruption Duration Index (SAIDI):** measured in units of time over one year (8760 hours) – about **1.5 hours/year** in North America
- **System Average Interruption Frequency Index:** measured in units of interruptions per customer over one year (8760 hours) – about **1.1 interruptions/customer** in North America
- **Customer Average Interruption Duration Index:** measured in units of time over one year (8760 hours) - about **1.36 hours/year** in North America – equal to SAIDI/SAIFI (like an average restoration time)