# Monitoring and Control of Electric Power Systems

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CREDC

# CYBER RESILIENT ENERGY DELIVERY CONSORTIUM

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Pacific Northwest
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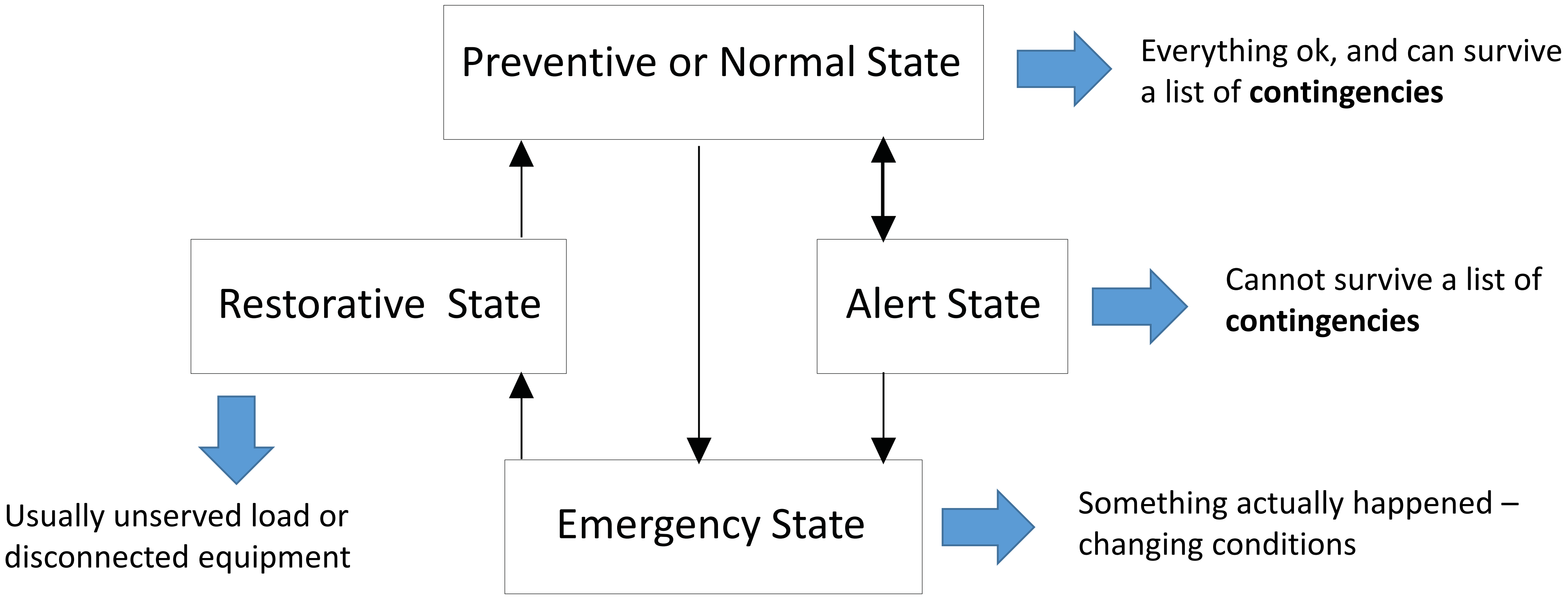
Argonne
NATIONAL LABORATORY

OLD DOMINION
UNIVERSITY
IDEA FUSION

# Control centers

# 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

# Contingencies are Considered in Planning and Operations

Disturbances that might happen on a power system:

Loss of a line, transformer, generating station, 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)

Hackers (cyber attacks)

# 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

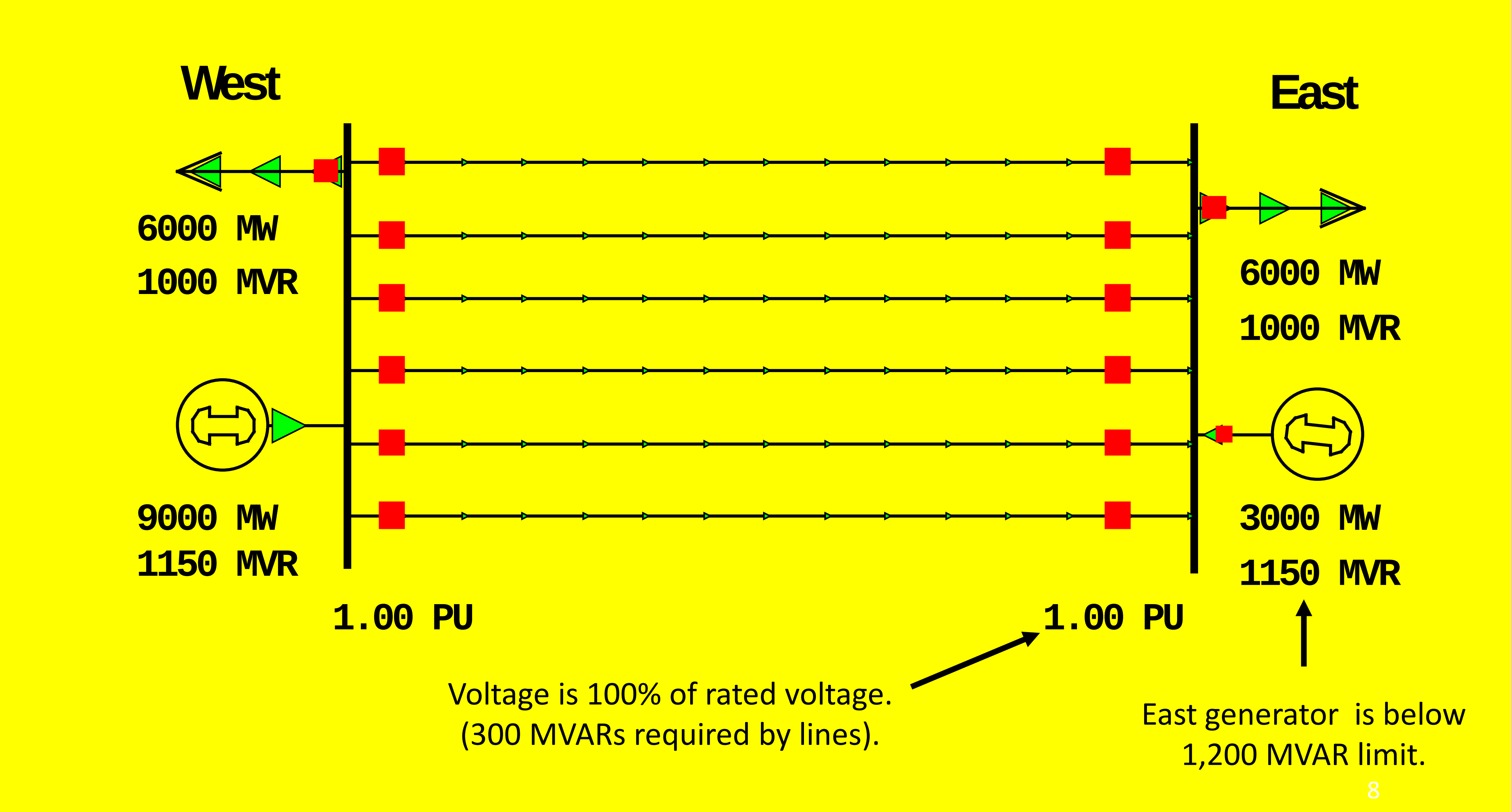
- PSS/E, PSLF, ABB, Alstom, Siemens, OSII, PowerWorld

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

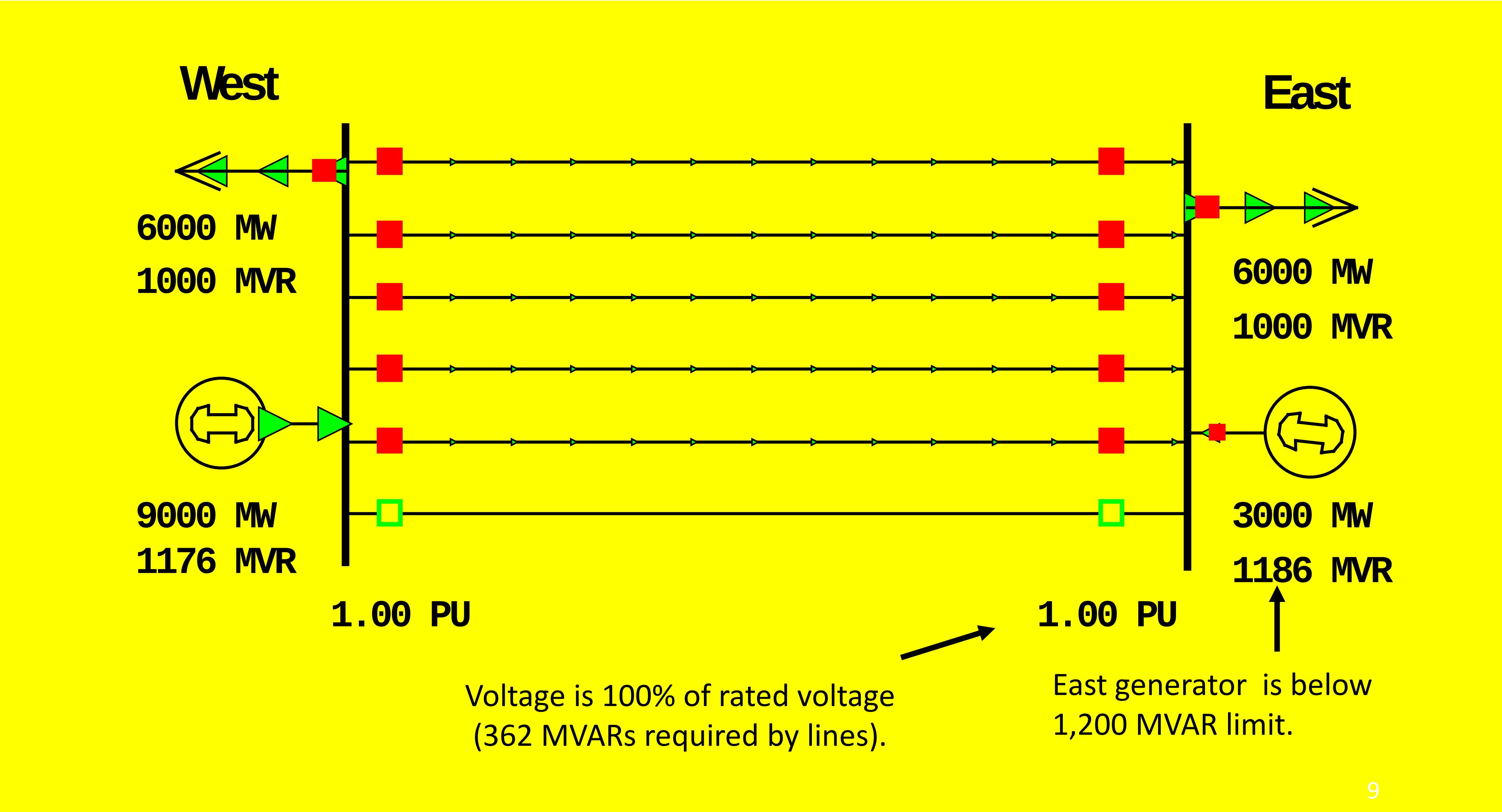
# Case 1: All Lines In-Service

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



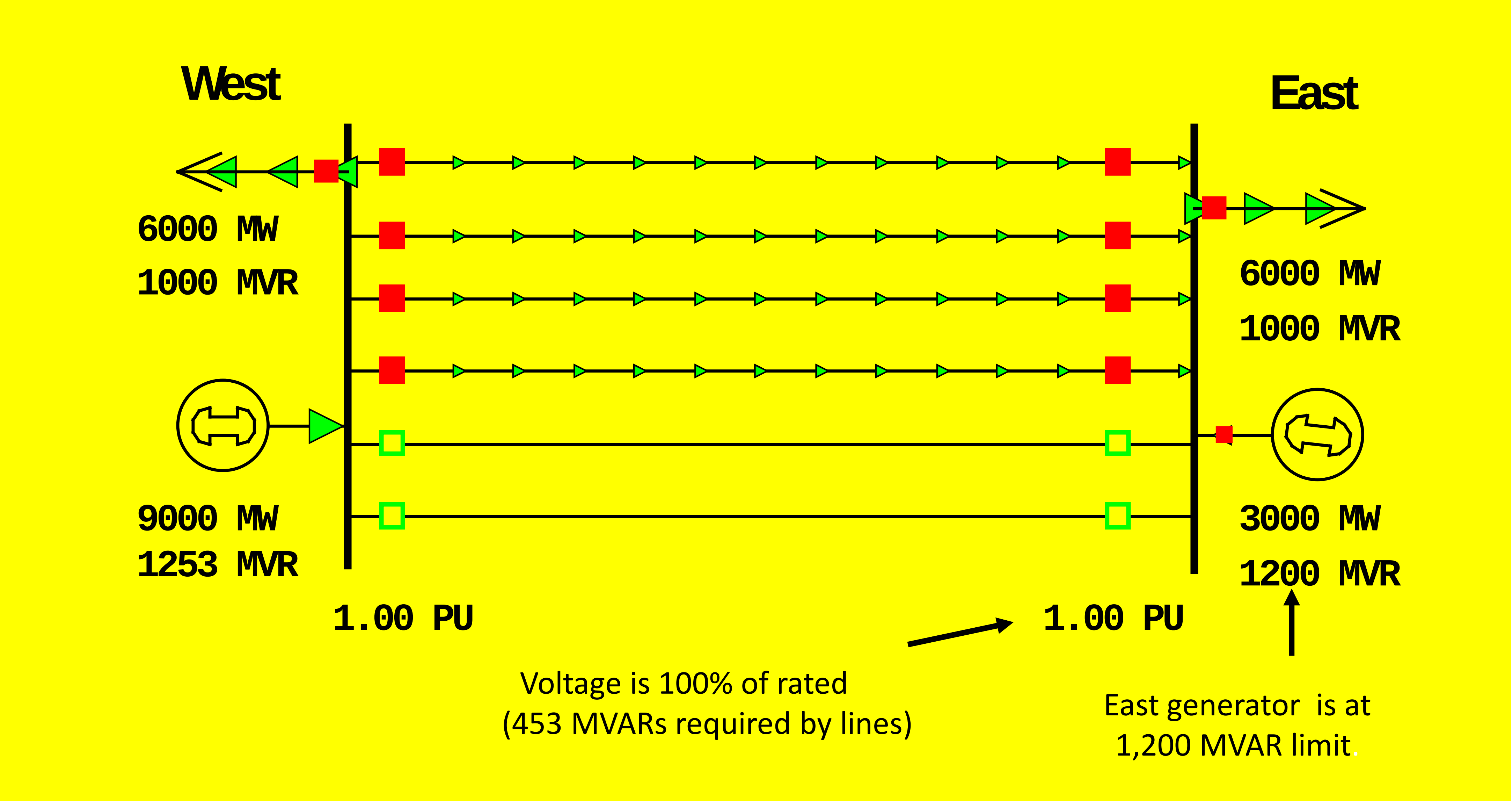
# Case 2: One Line Out

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



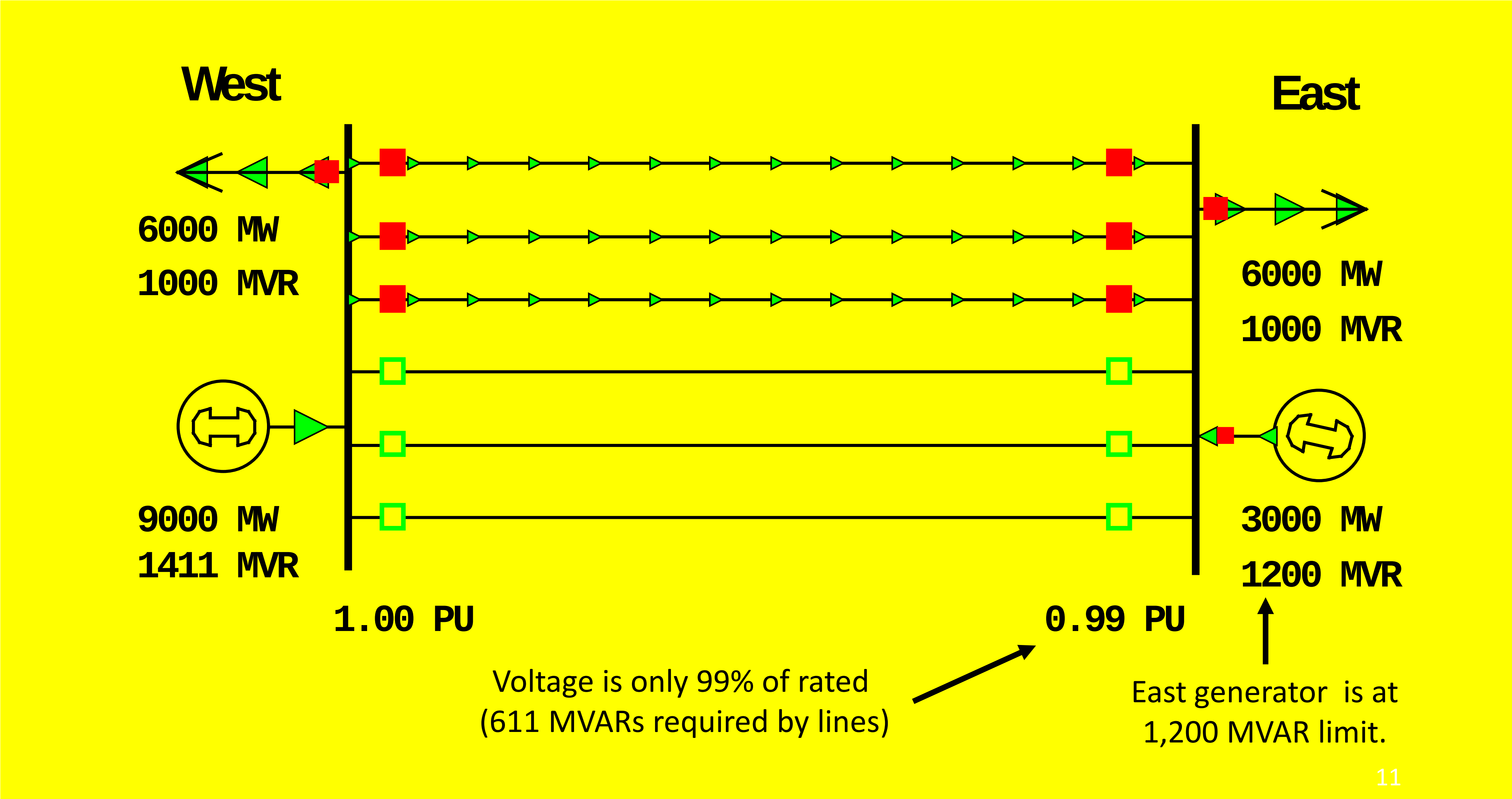
# Case 3: Two Lines Out

## 3,000 MW transfer – 750 MW per line



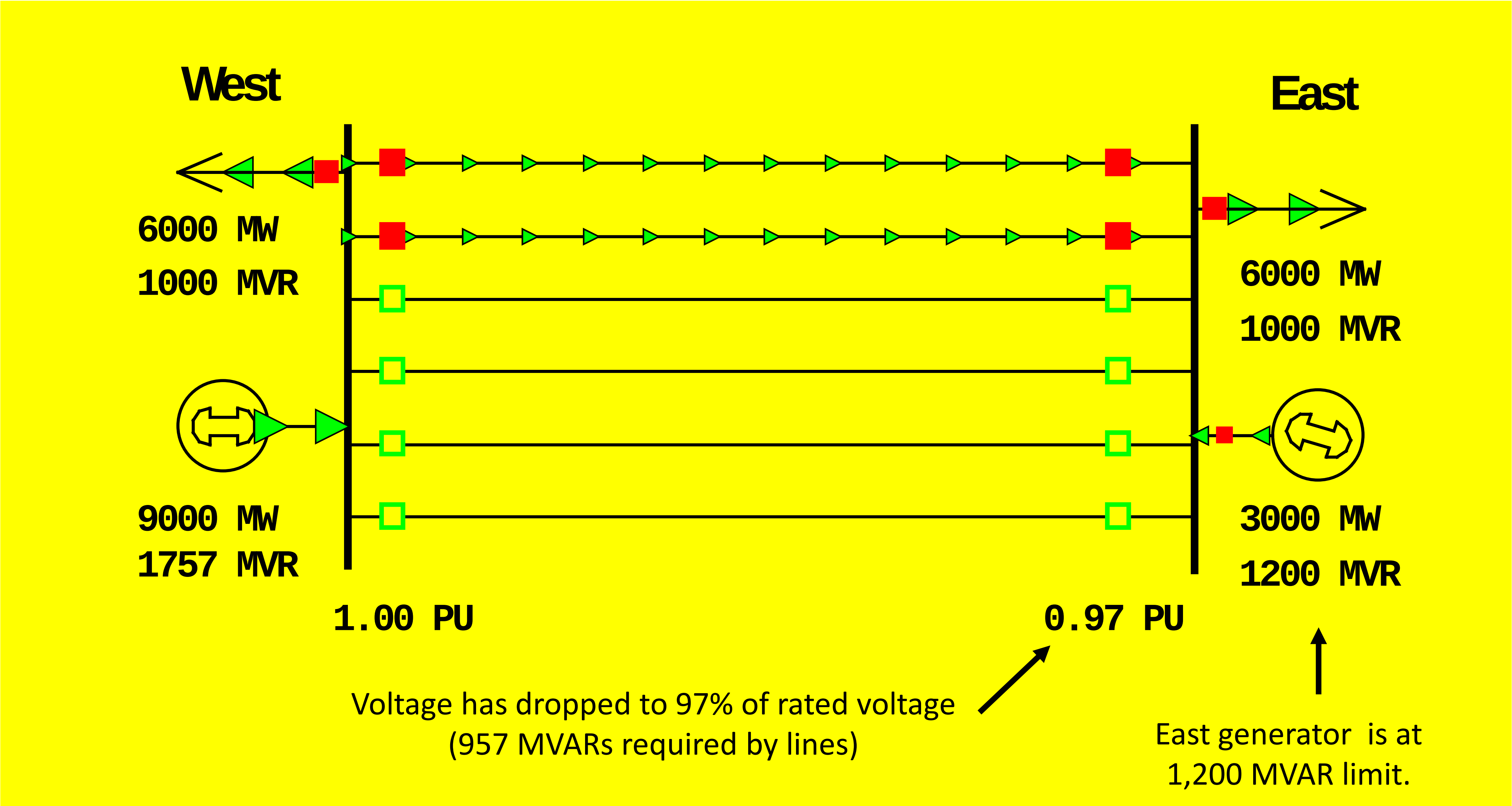
# Case 4: Three Lines Out

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



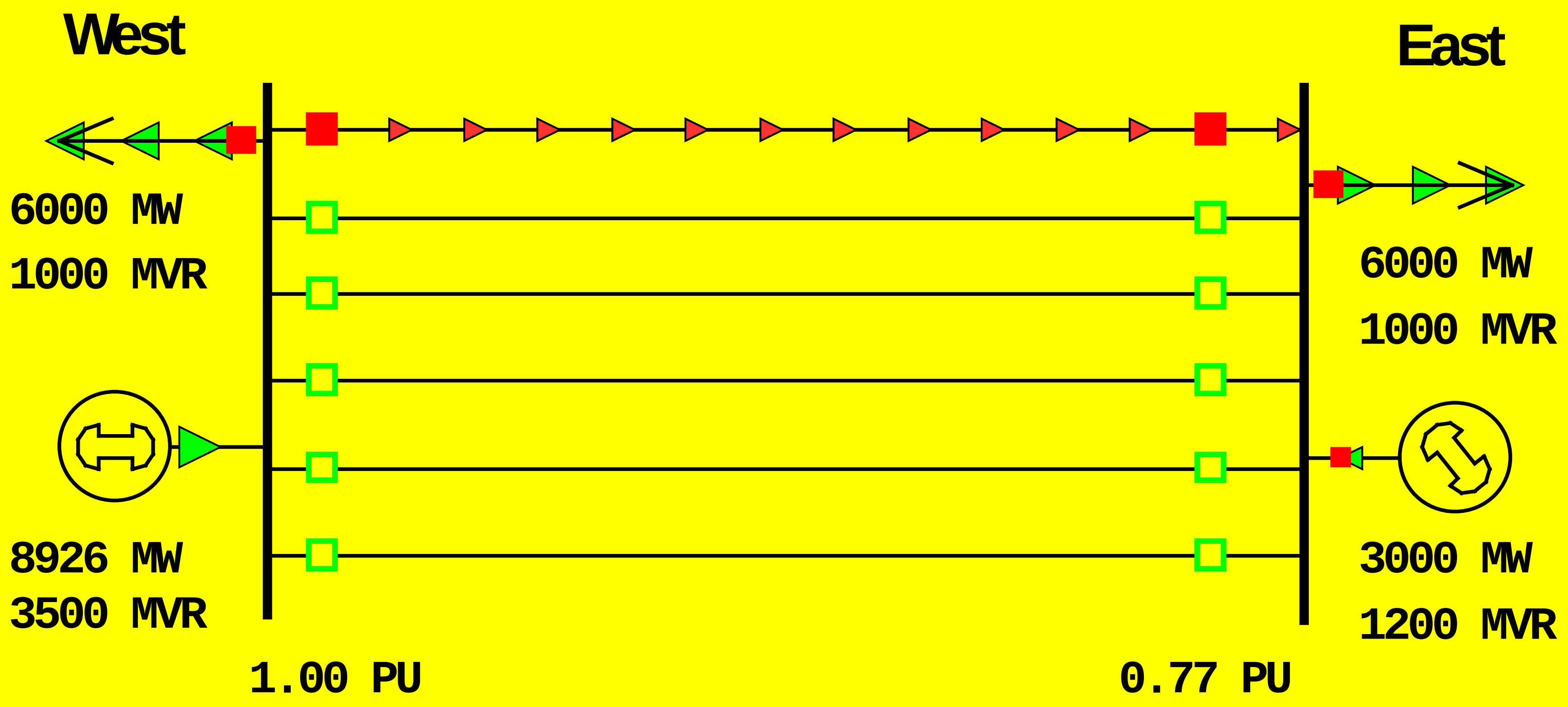
# Case 5: Four Lines Out

## 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

# 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)

# Control is the “C” part of SCADA

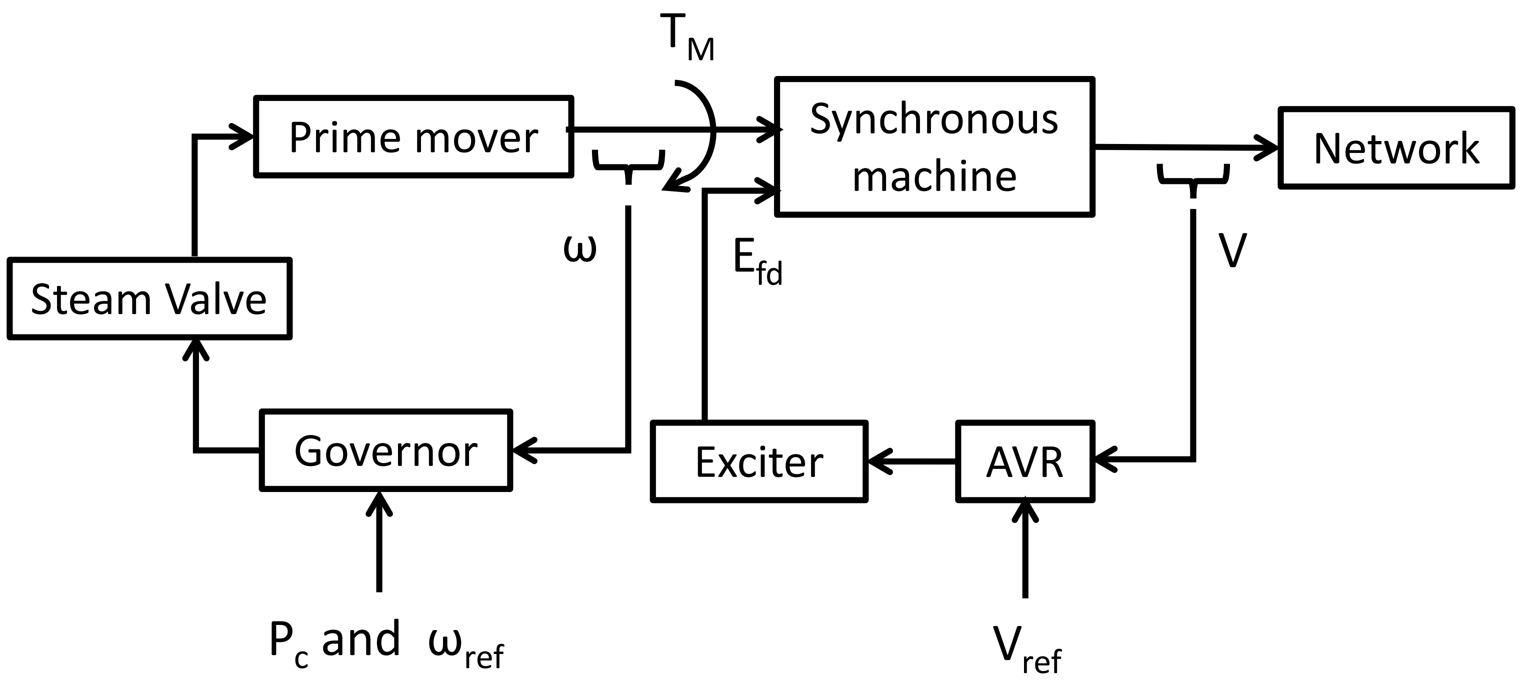
Things that can be controlled

- 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)

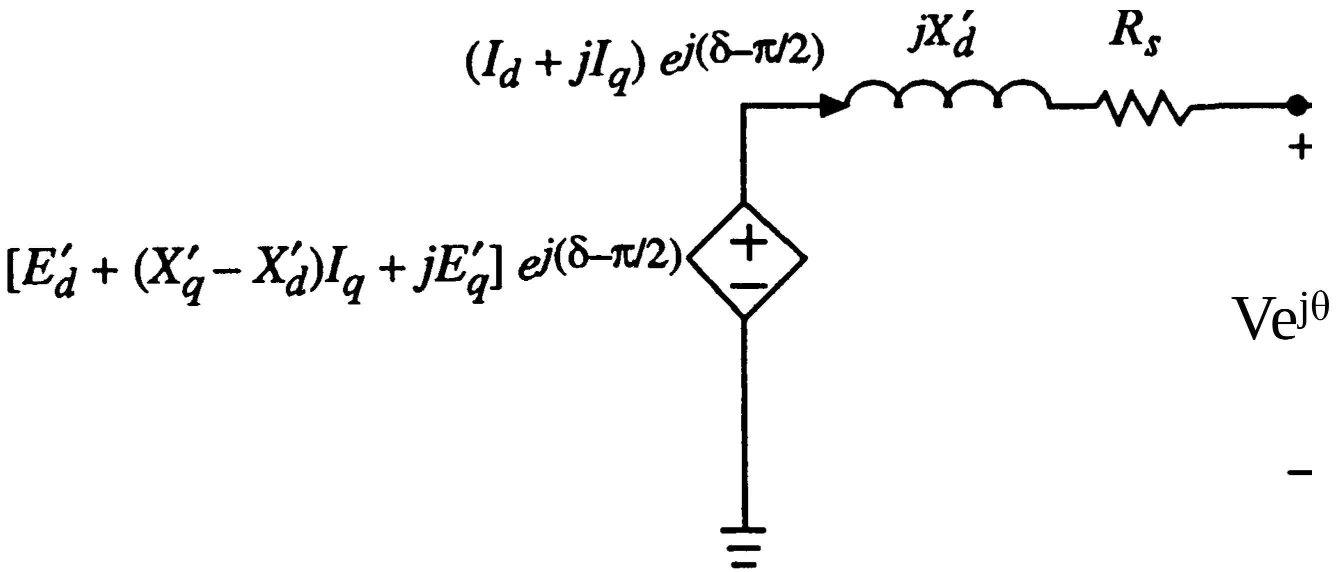



$(P,\theta)$ $(Q,V)$

# Synchronous Machine (Detailed Model)

$$T'_{do}\frac{dE'_q}{dt} = -E'_q - \left(X_d - X'_d\right)I_d + E_{fd}$$

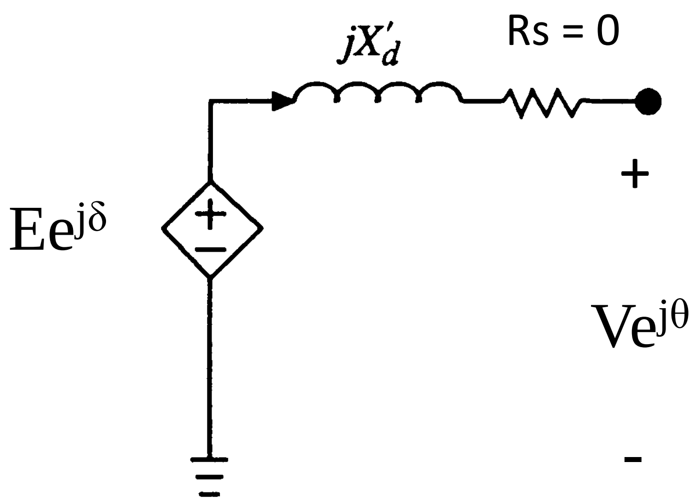
$$T'_{qo}\frac{dE'_d}{dt} = -E'_d + \left(X_q - X'_q\right)I_q$$




$$\frac{d\delta}{dt} = \omega - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_M - E'_d I_d - E'_q I_q - \left(X'_q - X'_d\right)I_d I_q - T_{FW}$$

# Synchronous Machine (Simple Classical Model)




$$\frac{d\delta}{dt} = \omega - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_M - \frac{EV}{X'_d}\sin\left(\delta - \theta\right) - D(\omega - \omega_s)$$

(Same as a damped pendulum)

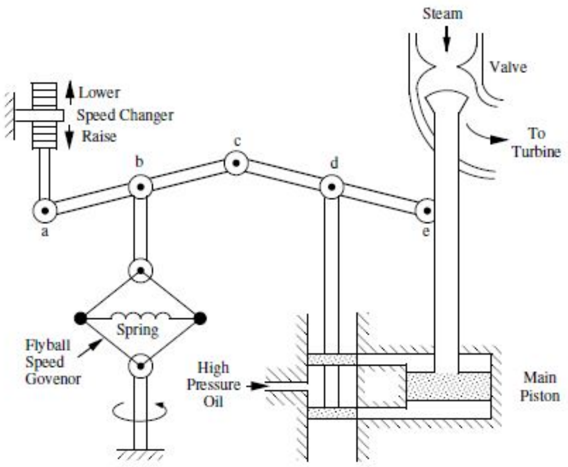
# Turbine/Governor

$$T_{CH}\frac{dT_M}{dt} = -T_M + P_{SV}$$

$$T_{SV}\frac{dP_{SV}}{dt} = -P_{SV} + P_C - \frac{1}{R_D}\frac{\omega - \omega_s}{\omega_s}$$

Generator output power set-point – determines frequency

# 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)

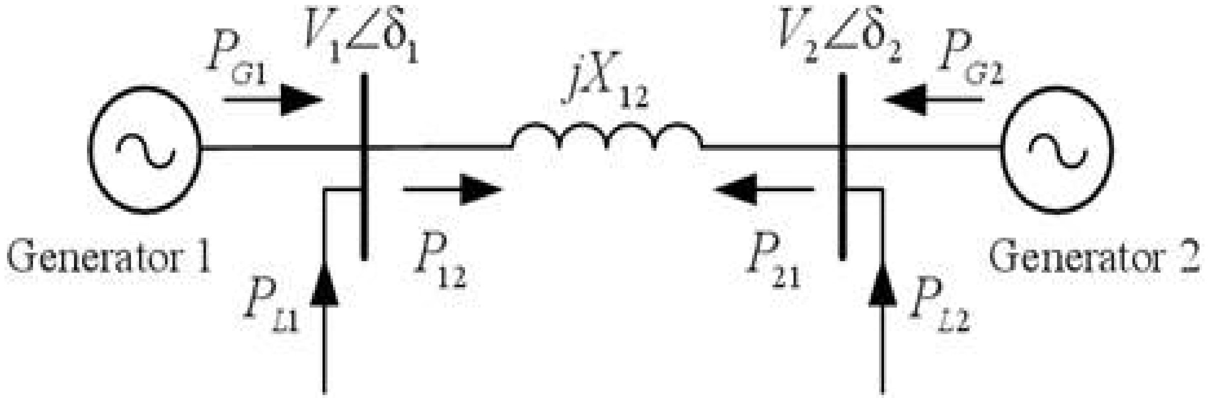
- Load Frequency Control (LFC) and Area Control Error (ACE)
  - "What you have done" – Positive ACE means to lower generation – this is NERC

    $ACE = Pexport_{act} - Pexport_{sch} - 10B(f\text{-}60)$ (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)

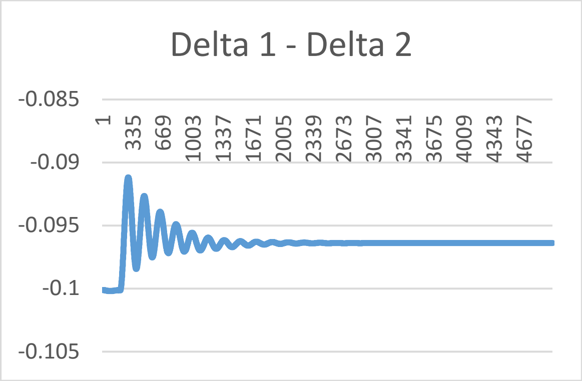


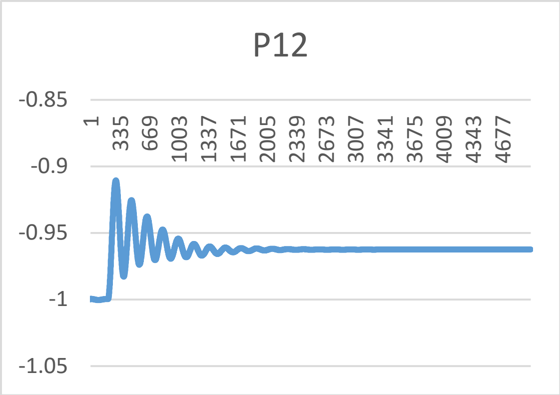
# AGC simulation data (two machines, one area)

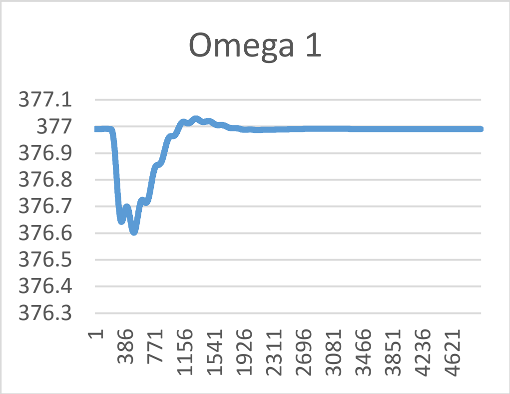
System data initial conditions (t=0) using the simple classical model plus Turbine/Governor

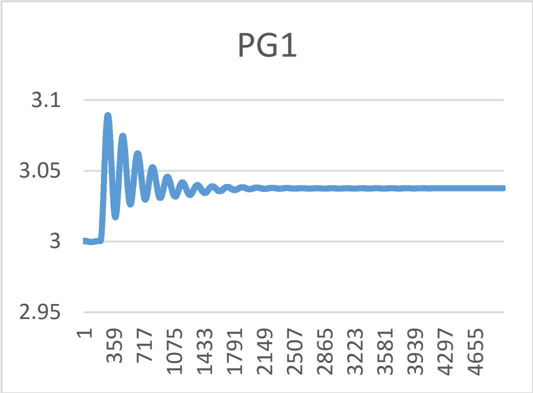
- $Pexport_{act} - Pexport_{sch} = 0$ (no scheduled or actual export from single area)
- f = 60 Hz and the speed of each machine is $2\pi 60$ rad/sec
- V = 1.0 pu for both buses, H = 3.0 sec for each machine, and D = 0.1 sec for each machine
- B = - 40 MW/0.1Hz for each machine (10B = -400MW/Hz)
- $P_{C1ED} = 3.0$ pu and $P_{C2ED} = 5.0$ pu (assumed Economic Dispatch values at time zero)
- $P_{L1} = -4.0$ pu (injected), $P_{L2} = -4.0$ pu (injected), and all loads are unity power factor
- $T_{M1} = P_{SV1} = P_{C1} = P_{G1} = 3.0$ pu, $T_{M2} = P_{SV2} = P_{C2} = P_{G2} = 5.0$ pu
- $pf_1 = 0.375$ and $pf_2 = 0.625$ (unit 1 is expensive and unit 2 is cheap)
- Turbine/governor time constants are 0.1 sec each for each machine
- $R_{D1} = R_{D2} = .05$ (This is 5% droop)
- $R_{12} = 0$ and $X_{12} = 0.1$ pu Ohms
- ACE=0 and Z (integral of –ACE) = 0 pu
- The load at bus 2 is suddenly increased from 4.0 to 4.1 pu at t=0.2 sec
- Total simulation time is 5 seconds using Euler's method with a time step of 0.001 sec
- The Base power (three-phase) is 100MW

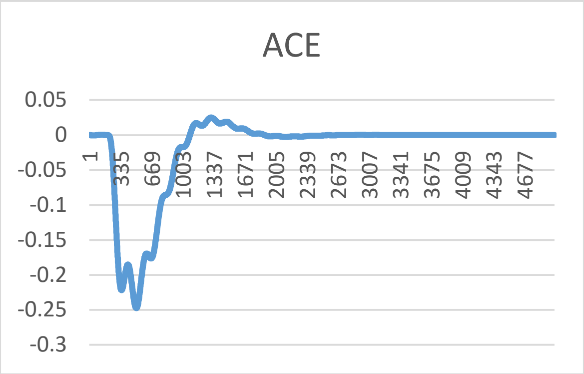
# AGC simulation – one area, two machines

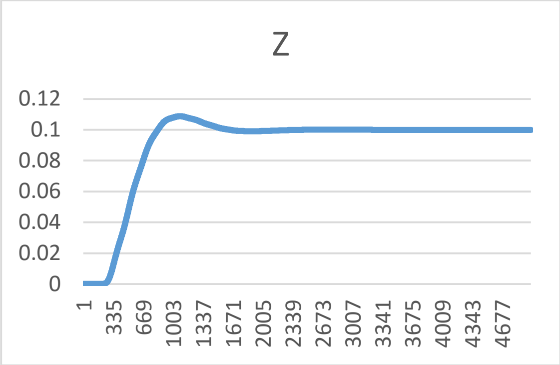


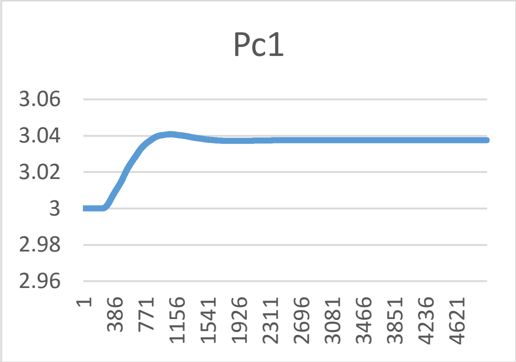



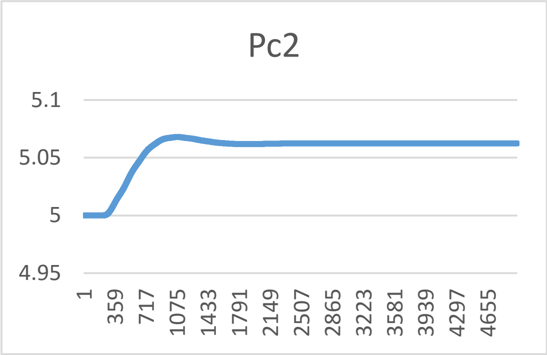



# Exciter and Automatic Voltage Regulator (AVR)

$$T_E \frac{dE_{fd}}{dt} = -\left(K_E + S_E\left(E_{fd}\right)\right)E_{fd} + V_R$$

$$T_F \frac{dR_f}{dt} = -R_f + \frac{K_F}{T_F} E_{fd}$$

Generator voltage set-point – not needed in the simple classical model

$$T_A \frac{dV_R}{dt} = -V_R + K_A R_f - \frac{K_A K_F}{T_F} E_{fd} + K_A\left(V_{ref} - V_t\right)$$

# 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

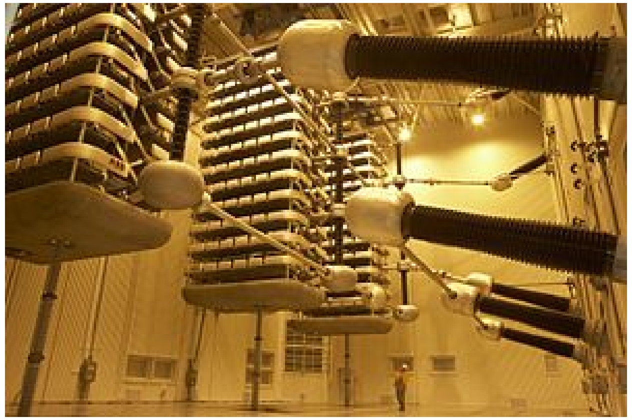
# Power Flow Control

- 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



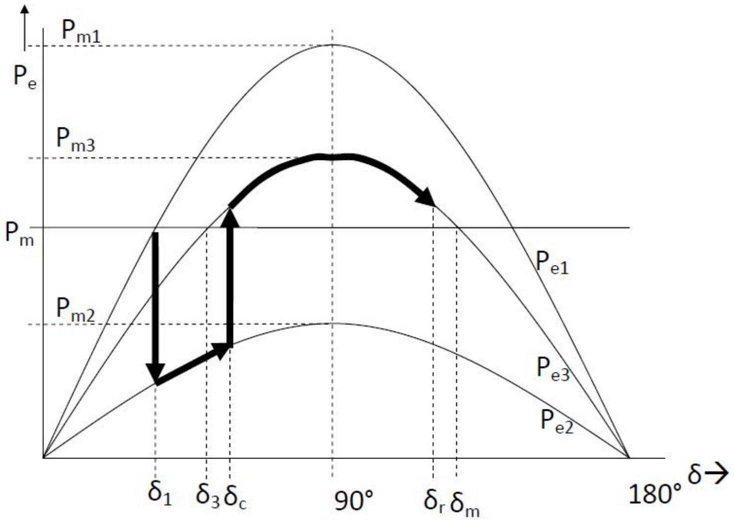
HVDC Inter-Island project – North and South New Zealand

# 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)

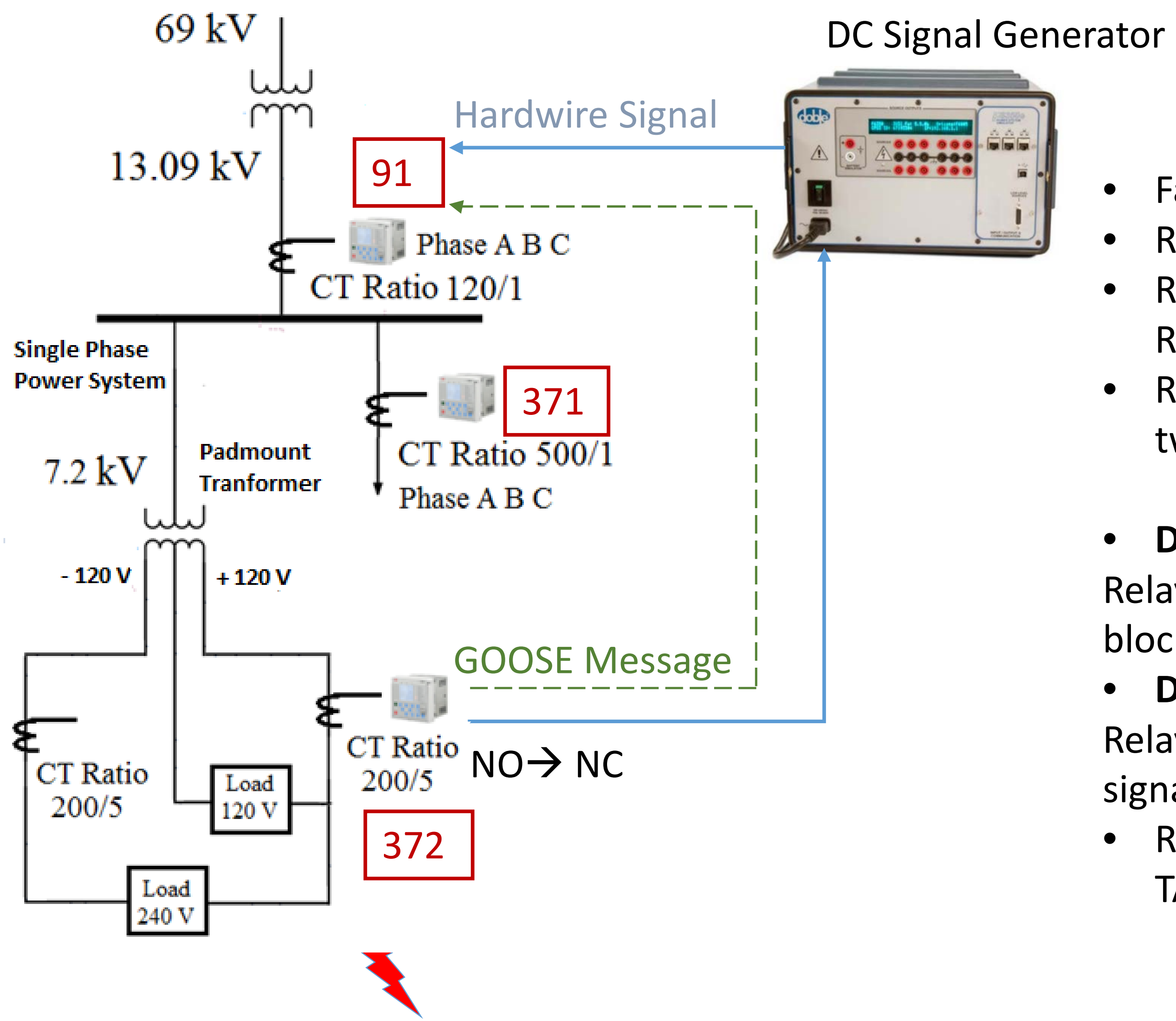
- Predefined actions that are ready to do after predefined disturbance
- “Arming”, “trigger condition”, “operate”

Series capacitors increase transfer capability

- Long lines are limited by inductive reactance of the line

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

# Reverse Blocking – TAC Setup for DOE CODEF project




- Fault on Feeder 372
- Relays 372 and 91 pick up
- Relay 372 initiates block signal for Relay 91
- Record blocking time for following two demos individually.

- **Demo Run 1:**

Relay 372 → Relay 91 Goose message blocking signal

- **Demo Run 2:**

Relay 372 → Relay 90 Hardwire blocking signal

- Relays 91 and 372 are both inside the TAC building.

# Environmental Control

Emissions monitoring and control

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

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