

# 9 | Principles of System Operation

# Course Outline

1. Introduction to WECC
2. Fundamentals of Electricity
3. Power System Overview
4. Principles of Generation
5. Substation Overview
6. Transformers
7. Power Transmission
8. System Protection
9. Principles of System Operation

# Overview

- **The Principles of Power System Operation module presents the following topics:**
  - Balancing Authorities
  - AGC and Energy Balance
  - Interconnected Operations
  - Automatic Generation Control
  - Operating Limits
  - Power System Stability
  - Computer System Functions
  - And a few more topics of interest

# Balancing Authority Overview

- Definition
- Basic Responsibilities
- WECC Balancing Authorities
- Industry Restructuring

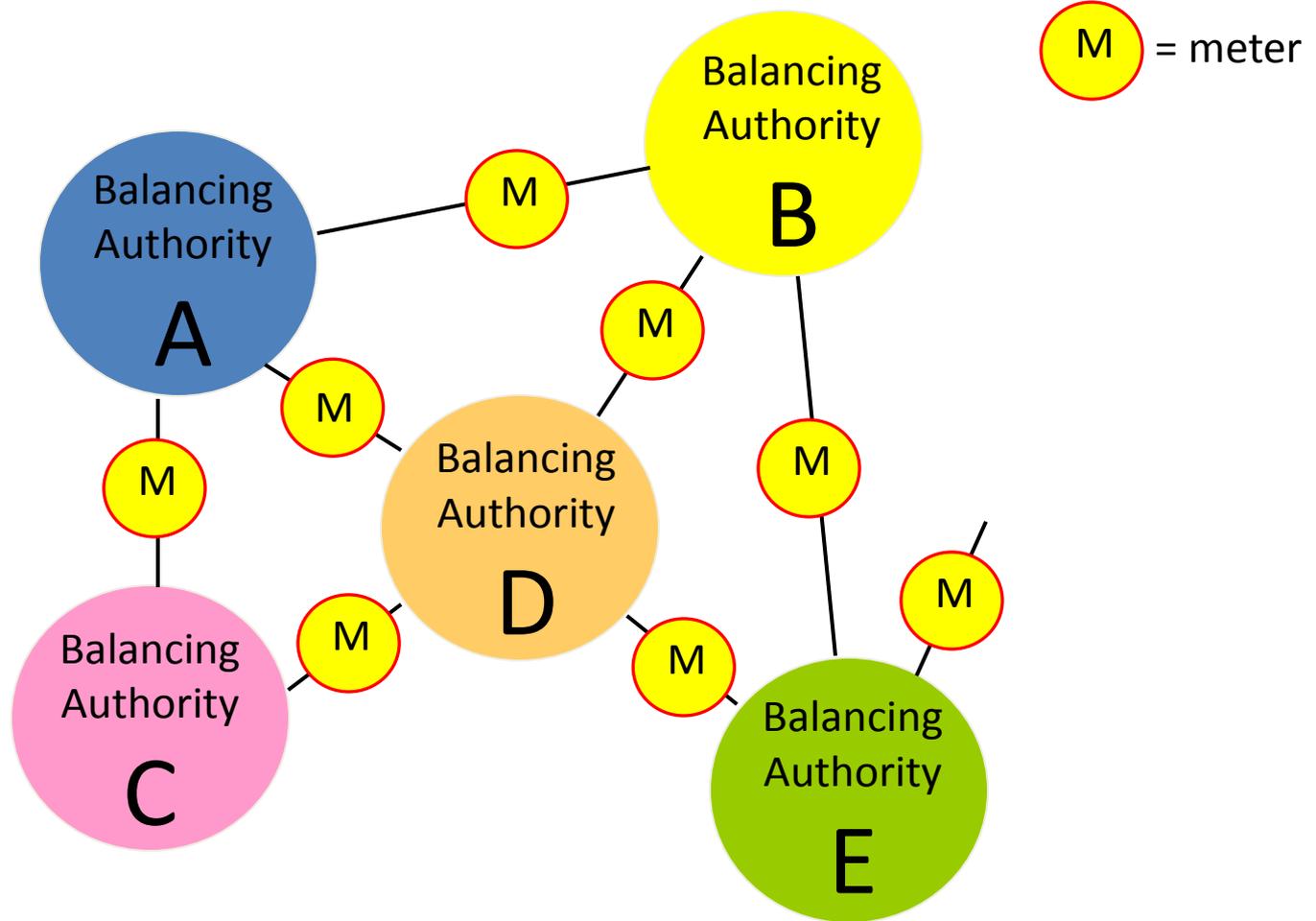
# Balancing Authority Overview

## Definition

### What Is A Balancing Authority (BA)?

- A Balancing Authority is defined by a set of resources and interchange meters.
- Traditional Balancing Authorities have dispatchable generation, load, and interchange.

# Balancing Authorities



# Balancing Authority Overview

## Basic Responsibilities

### Why Balancing Authorities Are Needed:

- Load and Generation Balancing
- Required for good control of frequency
- Short term balancing called “load-frequency regulation.”
- Longer term balancing is called “load following.”
- Balancing Authorities and their AGC systems coordinate this control.

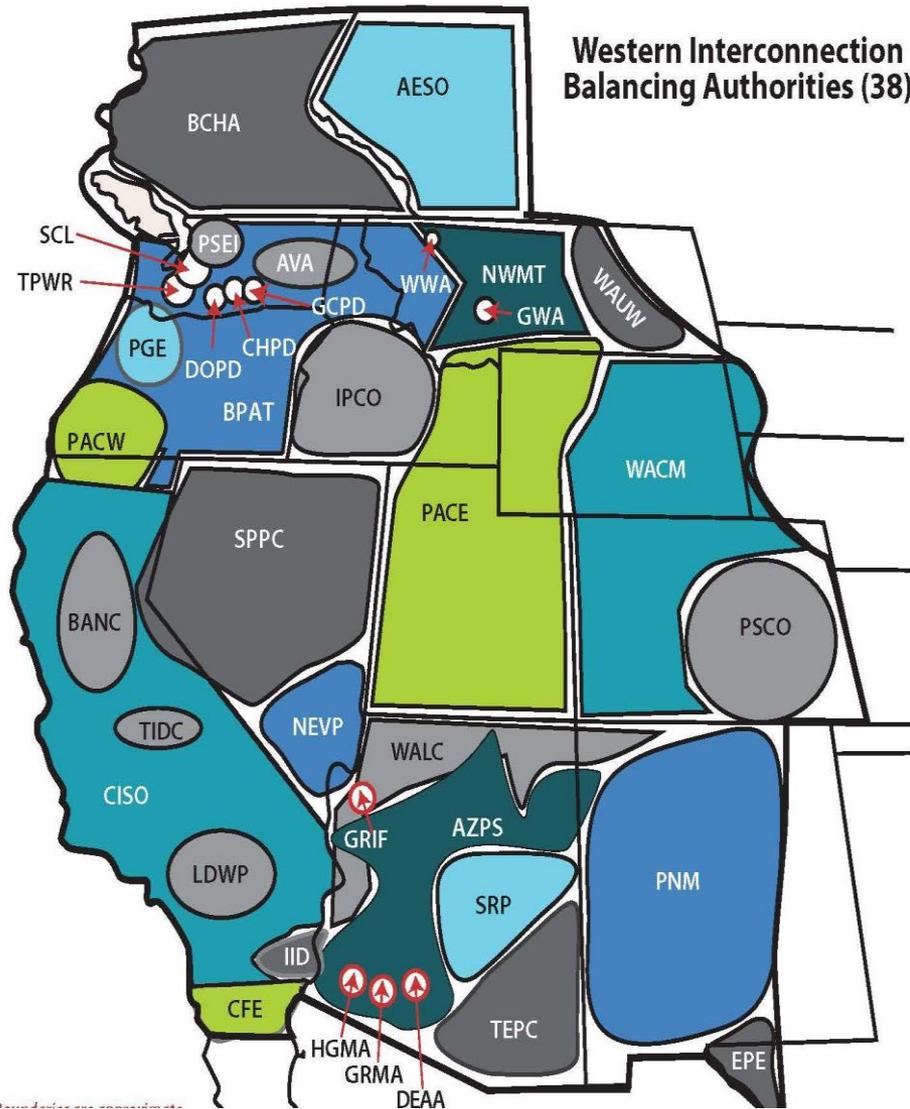
# Balancing Authority Overview

## Basic Responsibilities

- Balance Load, Generation, and Net Interchange.
- Control Frequency and Time Error.
- Implement Interchange Transactions.

# Balancing Authority Overview

## WECC Balancing Authorities



# Balancing Authority Overview

## Industry Restructuring

- Balancing Authorities
- Reliability Coordinators
- Interchange Coordinators
- Transmission Operators
- Independent System Operators (ISO)
- Regional Transmission Organizations (RTO)



# Check Your Knowledge: Balancing Authority Overview

1. How many Balancing Authorities are in the Western Interconnection?
2. What do BAs balance?
3. How does a generation-only BA balance load and generation?

# Automatic Generation Control (AGC) Basics

- Scheduled and Actual Interchange
- Turbine Governor Controls
- Area Control Error
- Sample Automatic Generator Control Response
- NERC / WECC Control Criteria
- Time Error

# Automatic Generation Control (AGC) Basics

## Scheduled Interchange

### How Do We Do Interchange?

How do we get 100 MW of power to flow from Balancing Authority **A** to **B**?

### Scenario:

**A** generates 100 MW more than its load.

**B** generates 100 MW less than its load.

Excess MW from **A** serves the deficiency in **B**.

# Automatic Generation Control (AGC) Basics

## Scheduled Interchange

### What is Scheduled Interchange?

- An agreement to exchange a specified amount of power for an agreed upon period of time.
- Balancing Authorities implement the schedule in a coordinated manner.

# Automatic Generation Control (AGC) Basics

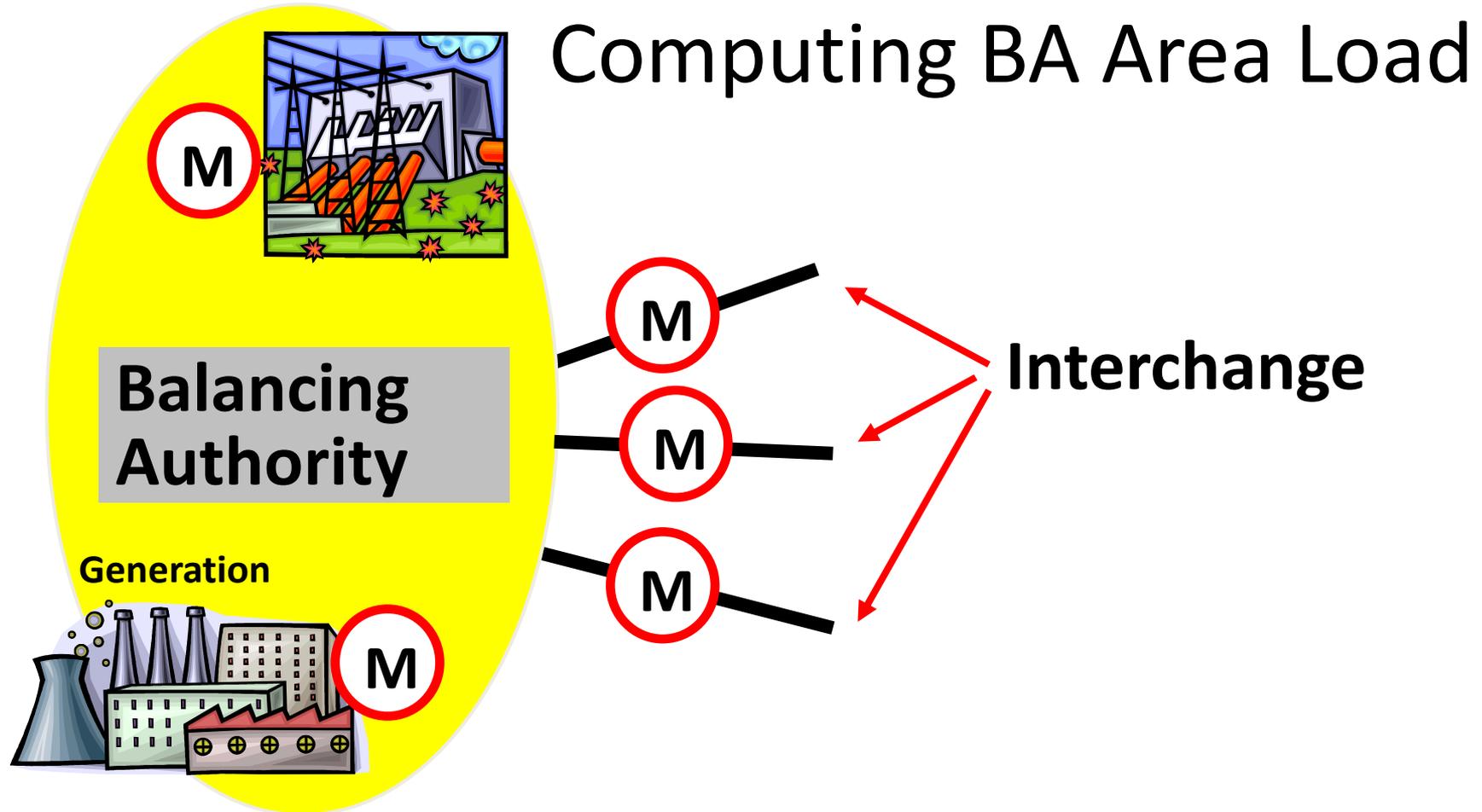
## Actual Interchange

### What is Actual Interchange?

- Measured MW flow between balancing authorities.
- Uses interchange meters on lines establishing the balancing authority boundaries.
- Flows are not always intentional

# Automatic Generation Control (AGC) Basics

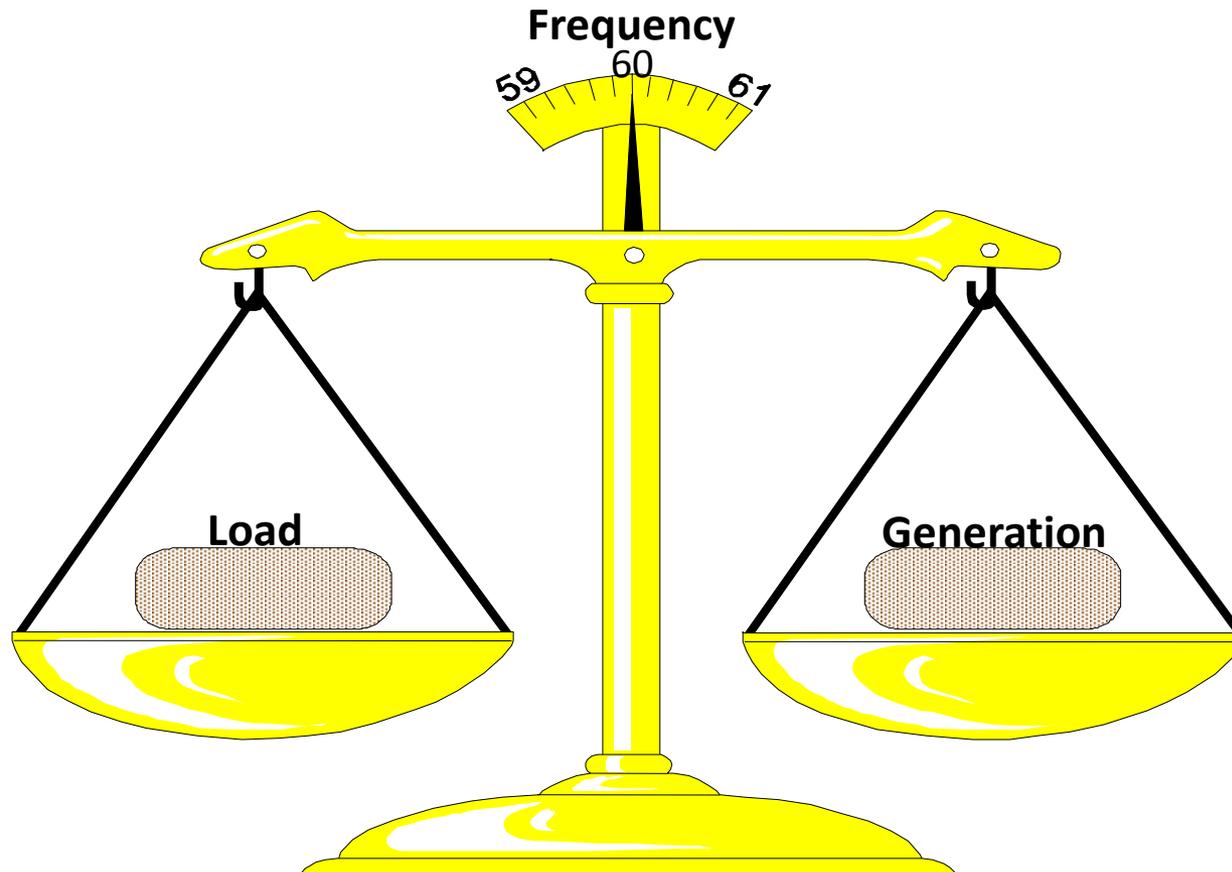
## Actual Interchange



$$\text{BA Load} = (\text{Generation}) - (\text{Net Interchange})$$

# Automatic Generation Control (AGC) Basics

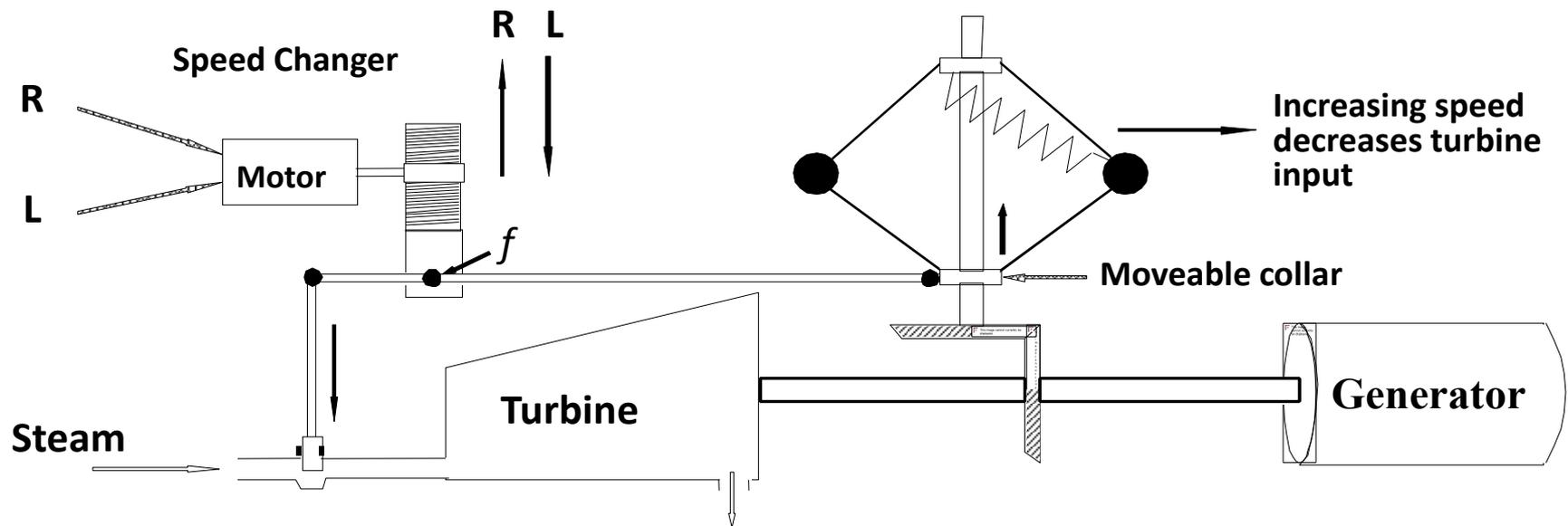
## A Matter of Balance



# Automatic Generation Control (AGC) Basics

## Turbine Governor Controls

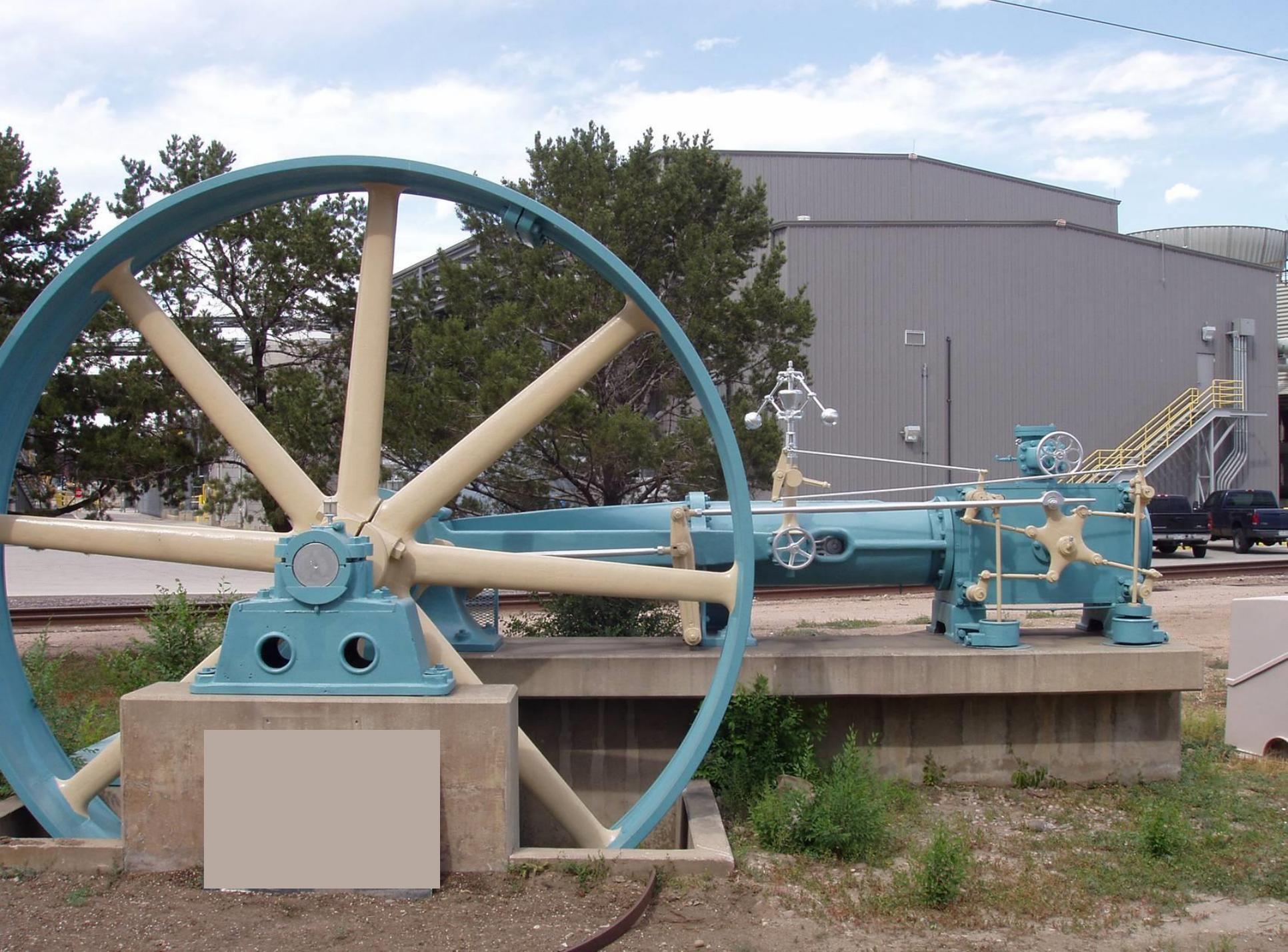
### Generating Unit Controls



A generator will increase output when it sees low frequency

A generator will decrease output when it sees high frequency

Governor action takes place without control center instruction.



# Automatic Generation Control (AGC) Basics

## Area Control Error (ACE)

- Measures whether Balancing Authority is properly generating its MW requirements.
- Factors in required actions to help control interconnection frequency.

# AGC Control Modes

- ***Tie line bias control is the normal mode used. It uses both frequency and tie-line power flow to calculate ACE.***
- A more descriptive term for this control mode is constant net interchange with frequency bias. It recognizes the following:
- If frequency decreases and the power leaving the system increases (or power entering the system decreases), then the need for power is outside the Balancing Authority.
- If frequency decreases and the power leaving the system decreases (or power entering the system increases), then the need for power is inside the Balancing Authority.

# AGC Control Modes

- ***Flat frequency*** control responds only to frequency changes. It does not respond to power flow changes on tie lines. This mode is used only on an isolated system, since it could lead to overloading tie lines while correcting frequency in an interconnected system.
- ***Flat tie line*** control responds only to changes in power flow on tie lines. It does not respond to changes in frequency. To prevent large frequency deviations, it is used only for brief periods when a frequency measurement is not available.

# Automatic Generation Control (AGC) Basics

## ACE Equation

$$ACE = (NI_A - NI_S) - (10B \times (F_A - F_S))$$

Tie-line error  
factor

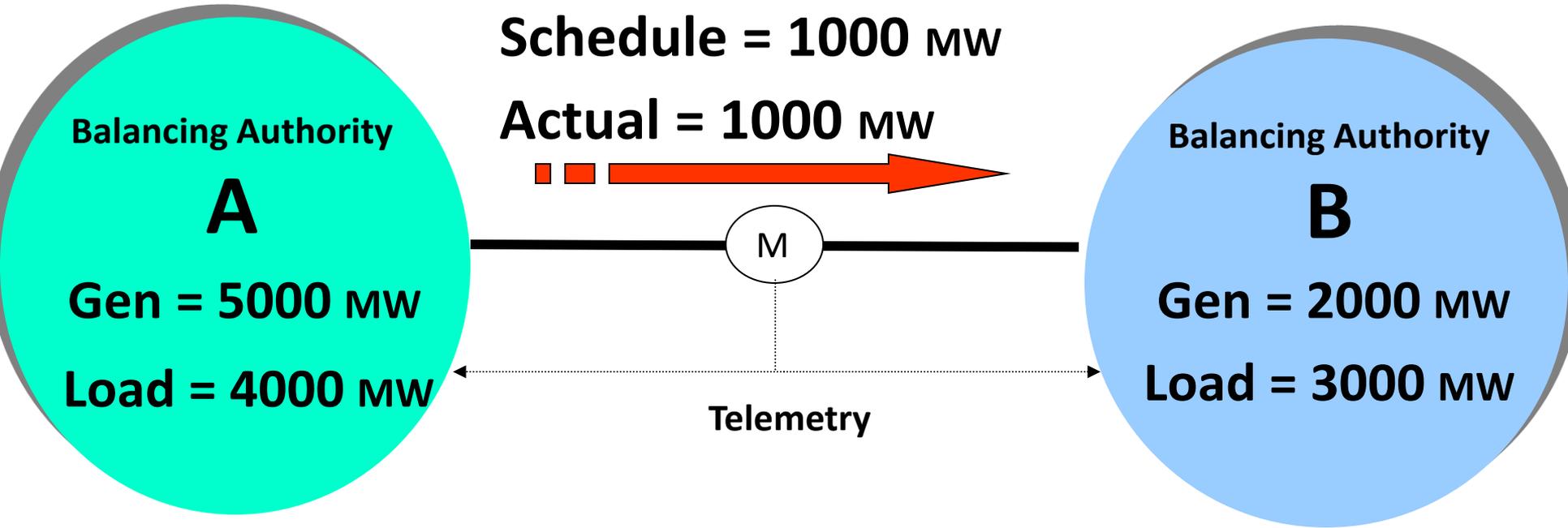
Frequency  
error factor

- Negative ACE = under-generation
- Positive ACE = over-generation

# 1 Initial Conditions

Frequency **OK**

Tie Line Error? **NO**



A's control action due to:

**Tie Line Error**

**NONE**

**Frequency Error**

**NONE**

B's control action due to:

**Tie Line Error**

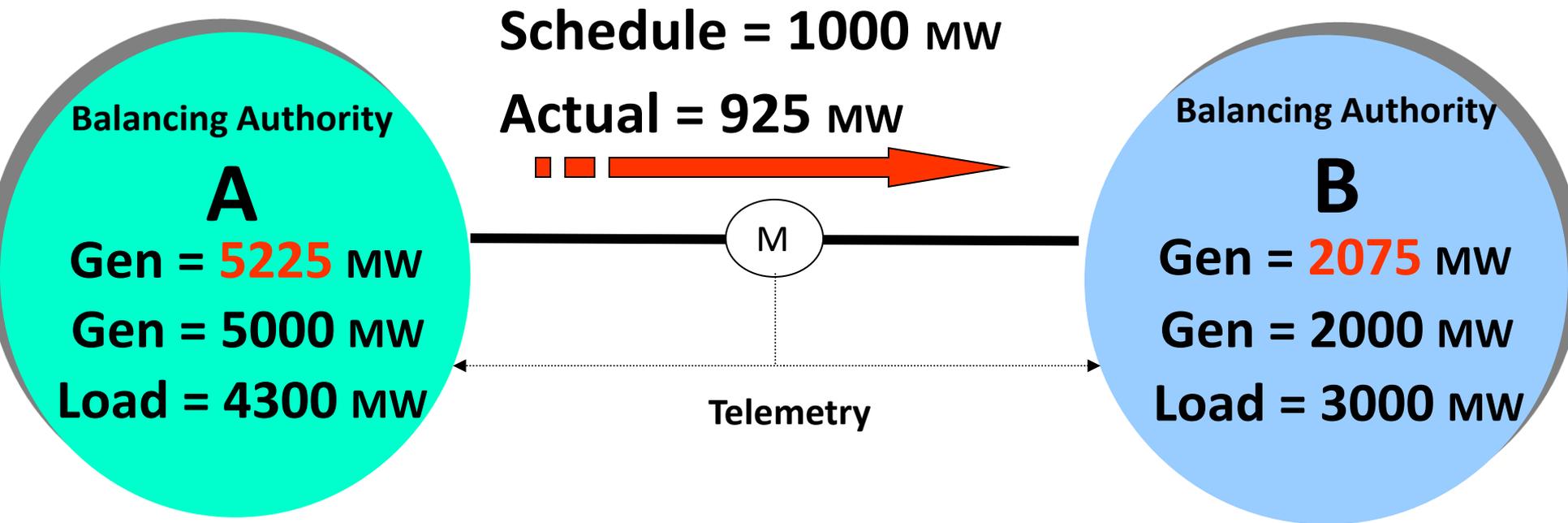
**NONE**

**Frequency Error**

**NONE**

# 2 Load Jumps 300MW in Balancing Area A

Frequency **Low**  
Tie Line Error? **Yes**



A's control action due to:

Tie Line Error



Frequency Error



B's control action due to:

Tie Line Error



Frequency Error

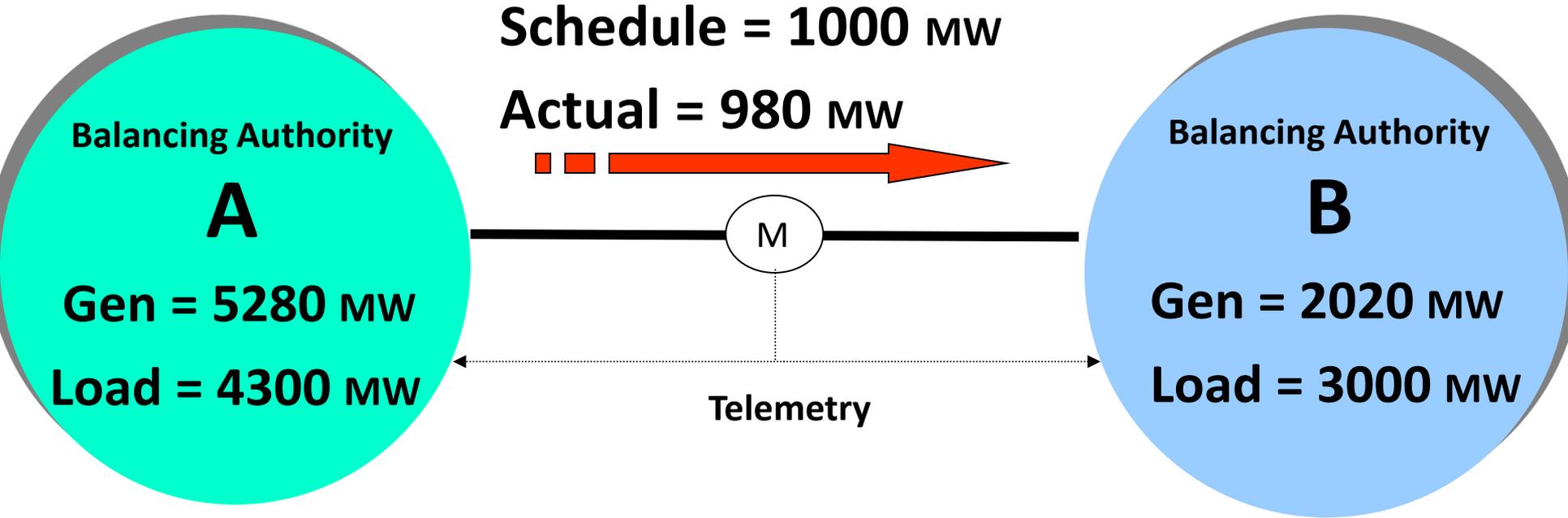


 =increase generation

 =decrease generation

# 3 Nearing new steady state

Frequency **Low**  
Tie Line Error? **Yes**



A's control action due to:

Tie Line Error



Frequency Error



=increase generation

B's control action due to:

Tie Line Error



Frequency Error

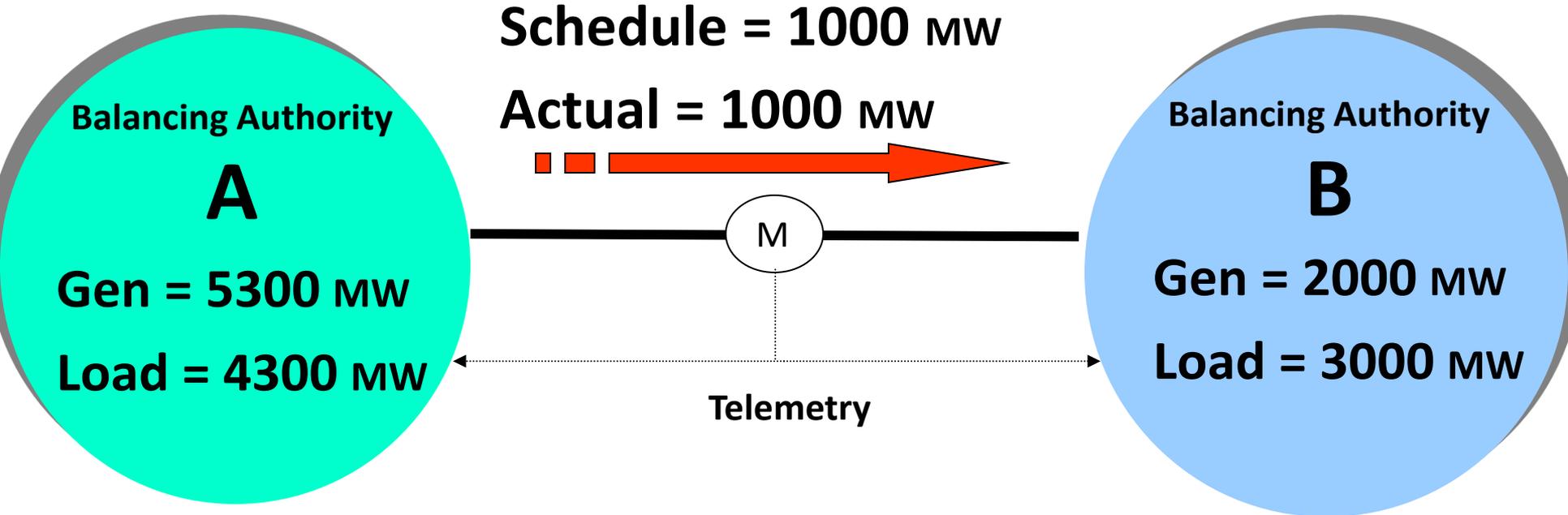


=decrease generation

# 4 New steady state

Frequency **OK**

Tie Line Error? **NO**



A's control action due to:

Tie Line Error

**NONE**

Frequency Error

**NONE**

 =increase generation

B's control action due to:

Tie Line Error

**NONE**

Frequency Error

**NONE**

 =decrease generation

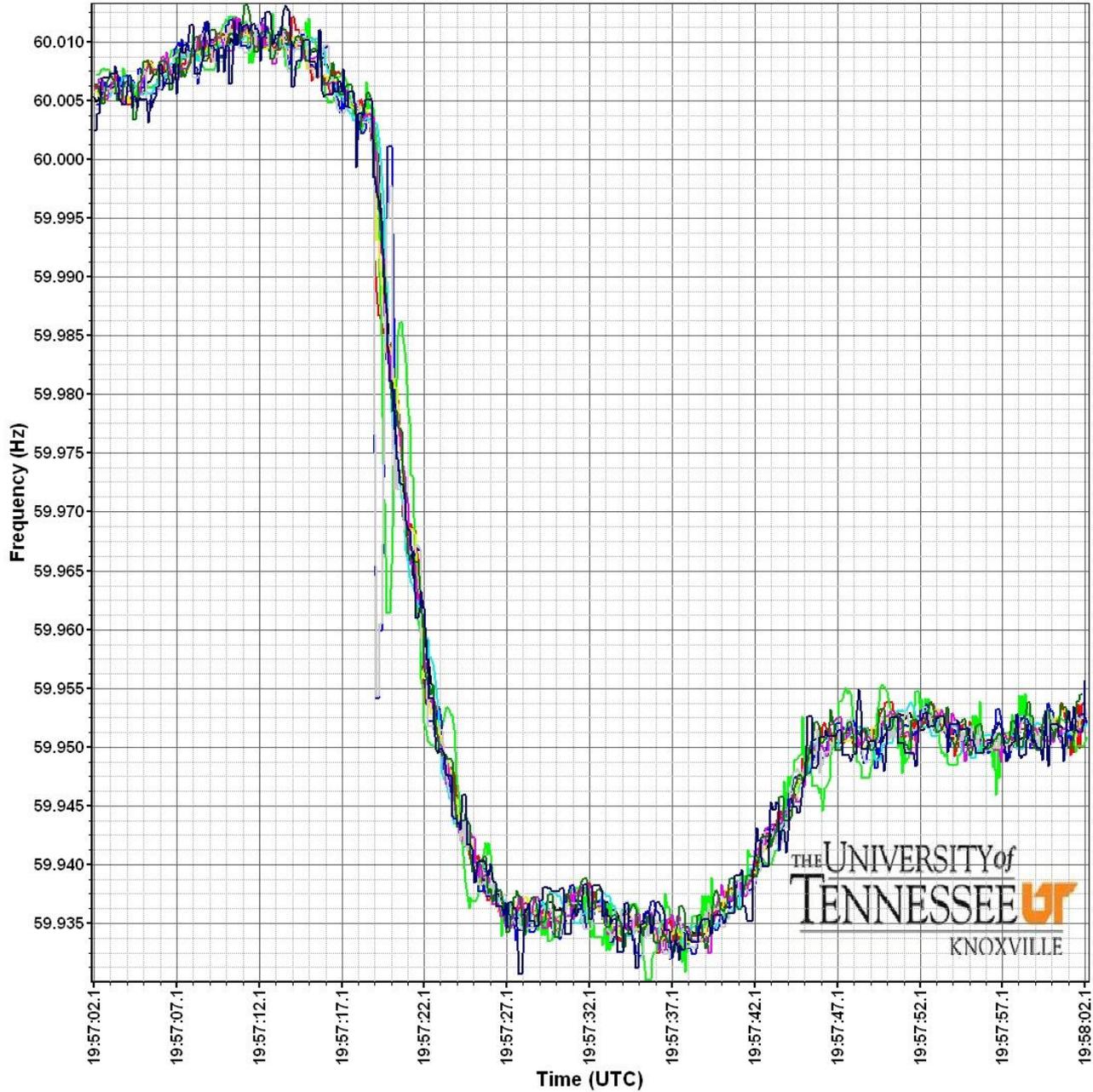
# Automatic Generation Control (AGC) Basics

## Sample Automatic Generator Control Response

### Frequency Disturbance Sequence

- Somewhere in the system, a generator trips.
- Stored energy (inertia) from all rotating mass in system replaces lost generation.
- Increased MW output without increased mechanical input slows the interconnected system (frequency drops).
- All generator governors act to stop frequency decline.
- AGC of deficient system eventually reacts to restore frequency.

2014/10/28 19:57:17(UTC) WECC(5-point median filter)



- UsCaSacramento732
- UsMtMtu757
- UsCoGolden764
- UsUtLayton766
- UsCaSanDiego768
- UsWaPullman798
- UsWaCentralia871
- UsUTLayton879
- UsOrPortland996
- UsCaEureka1012

THE UNIVERSITY of  
**TENNESSEE** UT  
KNOXVILLE

(2014-10-28 19:57:17 UTC)

( 42.7784, -109.8075)  
WECC Generator Trip:560(MW)

# Automatic Generation Control (AGC) Basics

## NERC / WECC Control Criteria

- Measures a Balancing Authority's control performance over time
  - Non-compliance can result in monetary penalties
  - Two Control Performance Standards serve as measures
    - ◆ CPS1
    - ◆ CPS2

# Automatic Generation Control (AGC) Basics

## NERC / WECC Control Criteria

### CPS1 – Helping or hurting frequency?

- Control errors of moderate magnitude are acceptable
- Control errors helping frequency are good.  
(over-generating when frequency is low,  
under-generating when frequency is high)
- Control errors hurting the frequency are bad.  
(over-generating when frequency is high,  
under-generating when frequency is low)

# Automatic Generation Control (AGC) Basics

## NERC / WECC Control Criteria

### CPS1 – Help the Frequency!

Starting with a nominal value of 200%, your score goes up when you help the frequency, and your score goes down when you hurt the frequency.

- At 200% your frequency is on schedule and your ACE is zero.
- 100% is the minimum acceptable control average.

# Automatic Generation Control (AGC) Basics

## NERC / WECC Control Criteria

### CPS2 – Magnitude of ACE over time

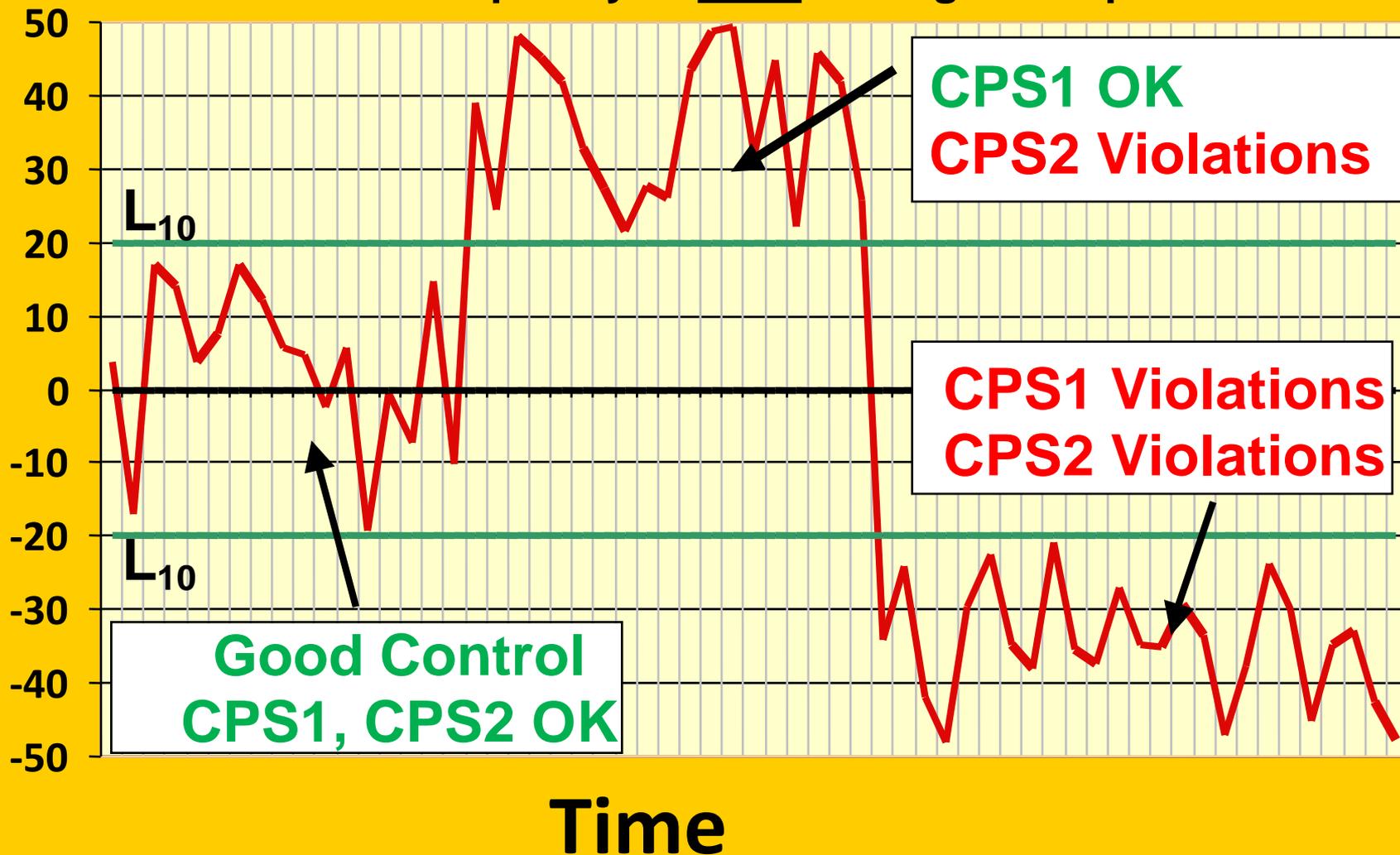
Over a 10-minute period, the average ACE may not exceed a threshold value called  $L_{10}$ .

- $L_{10}$  values are unique to each Balancing authority

# Control Performance Example

Note: Assume Frequency is LOW during entire period

ACE- mW



# Automatic Generation Control (AGC) Basics

## Time Error

- Operation at other than 60Hz results in time error
  - Low frequency-time is “slow”
  - High frequency-time is “fast”

Large time error accumulations are a sign of poor Interconnection control performance.

# Automatic Generation Control (AGC) Basics

## Time Error

- Scheduled frequency altered
  - ◆ 60.02 Hz to correct “slow” time
  - ◆ 59.98 Hz to correct “fast” time
- Automatic time error (ATEC)
  - ◆ Added component to ACE equation



# Check Your Knowledge:

## AGC Basics

1. What does AGC stand for?
2. How does the system know you plugged your vacuum in?
3. How do different types of generation respond to AGC?

# Operating Reserves

- Purpose and type of operating reserves
- Standards
- Current issues
- Reserve Sharing Groups

# Operating Reserves

## Purpose and Types

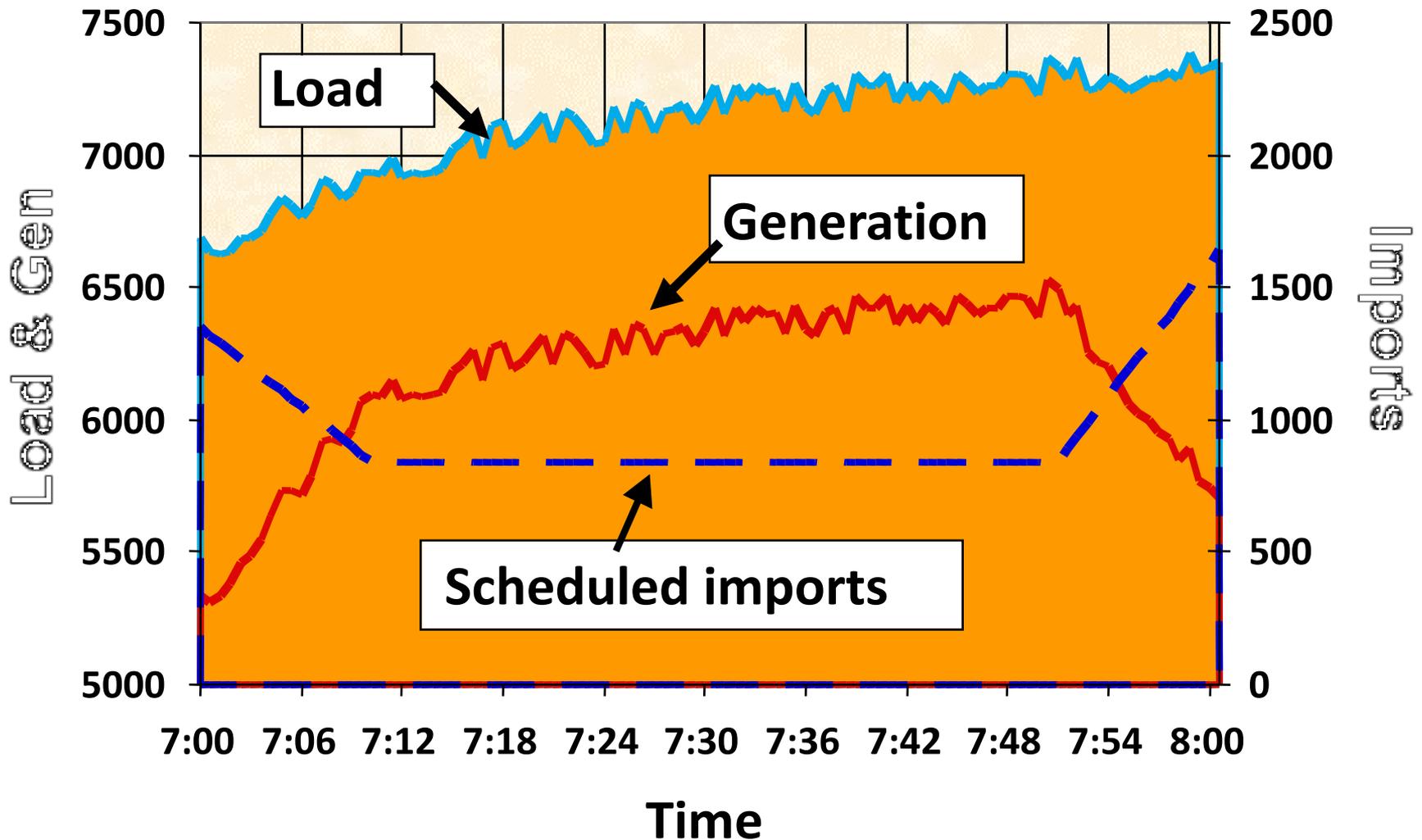
- Electricity production is an “real-time” process.
- Extra generating capacity needs to be readily available.
- Operating reserves are needed to replace lost generation and supply load increases.
- All in the name of good frequency control

# Operating Reserves

## Purpose and Types

- Regulating reserve
  - Needed for moment to moment load balancing
  - Used to meet CPS1 and CPS2
- Standard
  - ◆ Must be spinning
  - ◆ Responsive to AGC
  - ◆ Have enough to meet CPS1 and CPS2

# Regulating Reserves For Moment To Moment Load Regulation



# Operating Reserves

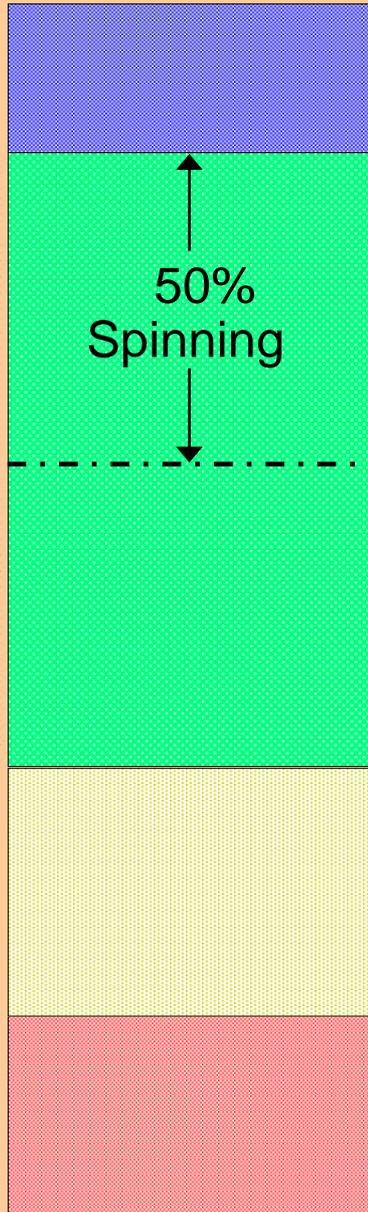
## Purpose and Types

- **Contingency Reserve**
  - Used to replace lost generation
  - Used to meet the Disturbance Control Standard (DCS)
  - Systems can meet requirements collectively
    - Create Reserve Sharing Groups

# Purpose and Types Operating Reserves

- **Contingencies**
  - e.g. generation failures
  - load forecast errors
- **Regulation**
  - Frequency
  - ACE

# OLD - TOTAL OPERATING RESERVE



Regulating Reserve

Spinning - Meet NERC Criteria

Contingency Reserve =  
Greater of:

1) Greatest Single Contingency

OR

2) 5% Load Responsibility on  
Hydro PLUS 7% of Load  
Responsibility on Thermal

Plus

Additional for Interruptible Imports

Plus

On Demand Obligations

# Operating Reserves

## Purpose and Types

### New Standard-How much?

Greater of:

- MW loss from single most severe contingency.

-or-

- 3% of hourly integrated load  
plus  
3% of hourly integrated generation

# Operating Reserves Standards

## New BAL-002-WECC-2 Standard

**R1.** Each Balancing Authority and each Reserve Sharing Group shall maintain a minimum amount of Contingency Reserve, except within the first sixty minutes following an event requiring the activation of Contingency Reserve, that is: [Violation Risk Factor: High] [Time Horizon: Real-time operations]

1.1 The greater of either:

The amount of Contingency Reserve equal to the loss of the most severe single contingency;

The amount of Contingency Reserve equal to the sum of three percent of hourly integrated Load plus three percent of hourly integrated generation.

# Operating Reserves Standards

New BAL-002-WECC-2 Standard

**1.2** Comprised of any combination of the reserve types specified below:

Operating Reserve – Spinning

Operating Reserve - Supplemental

Interchange Transactions designated by the Source Balancing Authority as

Operating Reserve – Supplemental

Reserve held by other entities by agreement that is deliverable on Firm  
Transmission Service

A resource, other than generation or load, that can provide energy or  
reduce energy consumption

Load, including demand response resources, Demand-Side Management  
resources, Direct Control Load Management, Interruptible Load or  
Interruptible Demand, or any other Load made available for curtailment by  
the Balancing Authority or the Reserve Sharing Group via contract or  
agreement.

All other load, not identified above, once the Reliability Coordinator has  
declared an energy emergency alert signifying that firm load interruption is  
imminent or in progress.

# Operating Reserves Standards

## **Disturbance Control Standard (DCS)**

- **The ACE must return either to zero or to its pre-disturbance level within fifteen minutes following the start of the disturbance.**
- **Disturbance control standard compliance**
  - **Each BA or reserve sharing group shall meet the Disturbance Control Standard (DCS) 100% of the time for reportable disturbances.**
- **Reportable disturbance reporting threshold**
  - **events that cause ACE to change by 35% of Most Severe Single Contingency.**

# Operating Reserves

## Providing Reserves

- Self supply
- Market structure
  - California ISO
- Reserve sharing groups
  - Northwest Power Pool
  - Desert Southwest Reserve Sharing Group
  - Rocky Mountain Reserve Group



# Check Your Knowledge: Operating Reserves

1. What is the purpose of Operating Reserves?
2. What are 3 types of Operating Reserves?

# Operating Limits

- Electric current flowing from the generators to the loads follows all available paths.
- Most current flows over paths that offer the least impedance through conductors, transformers, and other power system components.
- On well-designed power systems, natural load flows are such that no lines are overloaded under normal circumstances.
- In some cases, phase-shifting transformers may be required to alter the natural current flows on the transmission system.

# Operating Limits

- If a transmission line is opened for any reason, such as a fault, current flows almost instantaneously redistribute over the remaining transmission system.
- Power systems are generally designed to handle contingencies, such as a line tripping, without overloading any facility.
- However, this is not always possible, particularly when other lines are already out of service. Therefore, system operators may be required to implement emergency switching actions or arm special remedial action schemes during certain contingencies to prevent equipment loadings from exceeding emergency ratings.

# Thermal Limits

- To avoid excessive heating, utilities assign thermal limits or ratings to devices.
- These limits should not be exceeded.
- The ratings are based on the amount of heat the device can carry and dissipate. Ratings are expressed in amps, MW, or MVA.
- Ratings vary with season and the amount of time the device is exposed to the high current.

# Thermal Limits

- Each energized device (a circuit breaker, the bus work, transformer, conductor, etc.) has an individual rating. When multiple devices in series (e.g., a transmission line and a series capacitor) have different thermal limits, the most restrictive rating applies to the combination of facilities.
- Conductor and transformer ratings are typically the most restrictive factors.

# Annealing

- The reduction of conductor strength due to annealing over the life of the conductor (***annealing is the process of heating and cooling the conductor***)
- The increase in conductor sag due to thermal expansion at high temperatures (minimum conductor-to-ground clearances must be maintained at all times)
- There are usually several ratings, tailored to local loading and weather conditions that apply to a given line.

# Normal, Peak & Emergency Ratings

- ***Normal rating*** is the maximum current that can flow on a continuous basis.
- ***Peak rating*** is the current that can be tolerated for a limited time period, usually four hours. In general, the peak rating is higher than the normal rating.
- ***Emergency rating*** is the highest rating of the line. This rating is the maximum current that is permissible for a short period of time, usually one hour or less. Utilities may operate at the emergency rating during abnormal power system conditions.

# Voltage Limits

- Voltage limits provide upper and lower voltage boundaries for operating the equipment and overall power system. The purpose of voltage limits is to maintain voltage levels on both transmission and customer connections.
  - Exceeding the high-voltage limit may lead to overheating and over-excitation of the equipment.
  - Operating the equipment below the low-voltage limit may cause motor loads to stall and may lead to voltage collapse.

# Stability

- ***Stability*** is a power system property that enables the synchronous machines of the system to respond to a disturbance so as to return to a steady-state condition. It is determined by the power system's ability to adjust its generators so that they remain synchronized following a power system load change or disturbance, such as the loss of a major transmission line, generator, or load.

# Synchronism

- You may recall from previous modules that ***synchronism*** occurs when connected AC systems, machines, or a combination of the two operate at the same frequency and the voltage phase angle differences between systems or machines are stable at less than  $90^\circ$ .
- In an unstable system, load changes or disturbances cause generators to speed up or slow down and consequently, to fall out of synchronism with the rest of the system. When a generator loses synchronism, it has to be tripped and re-synchronized, which places additional burden on the remaining generators.

# Stability Problems

- Changes in the mechanical forces that drive generators occur much more slowly than power system electrical changes resulting from disturbances. When a disturbance occurs, the generating station's mechanical components have to play "catch up" to make the required adjustments.
- We know that the power delivered to the system by a generator depends on the relative phase angle between the generator voltage and the system voltage.

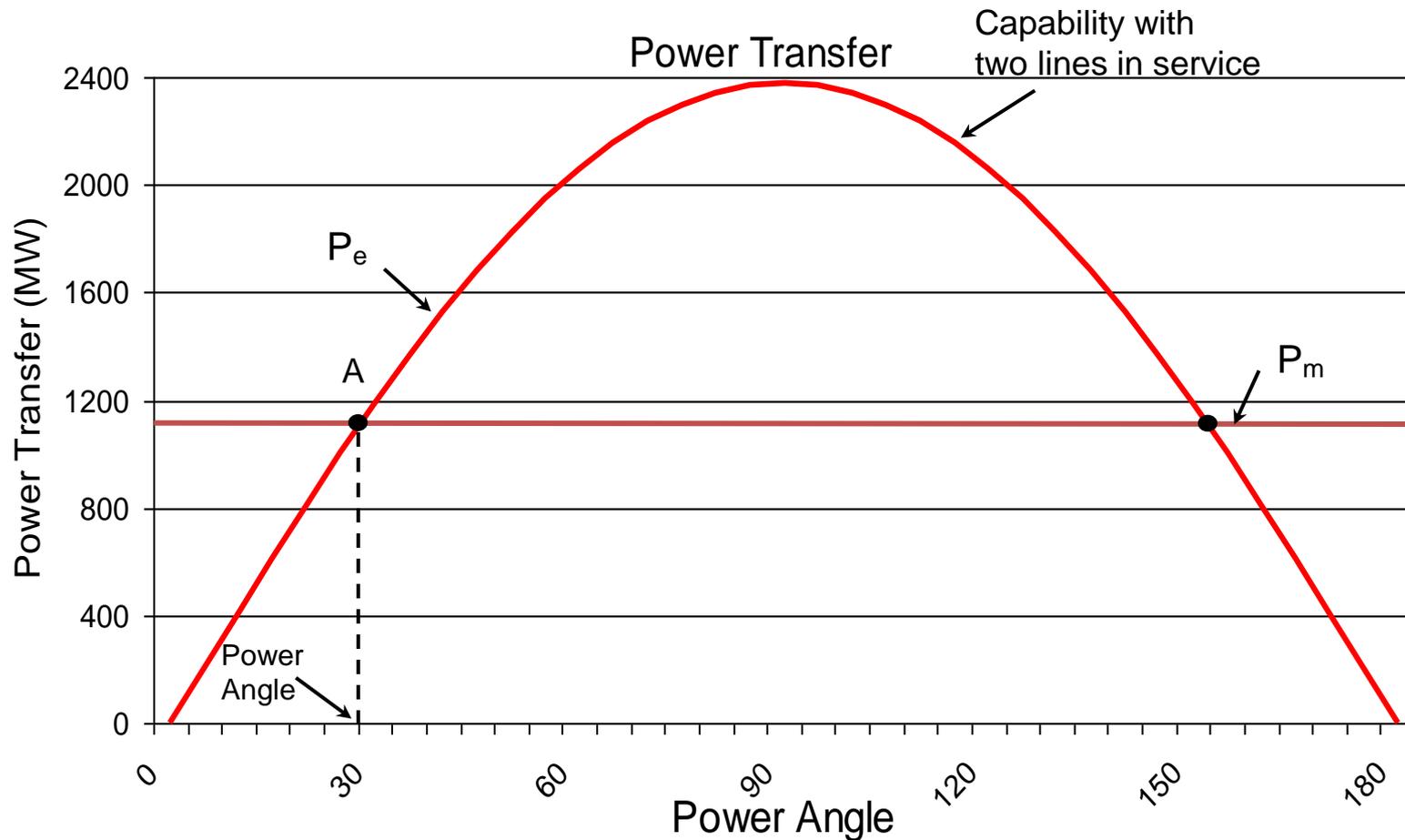
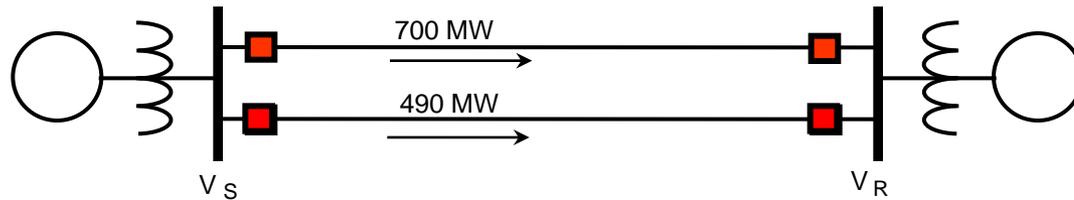
# Stability Problems

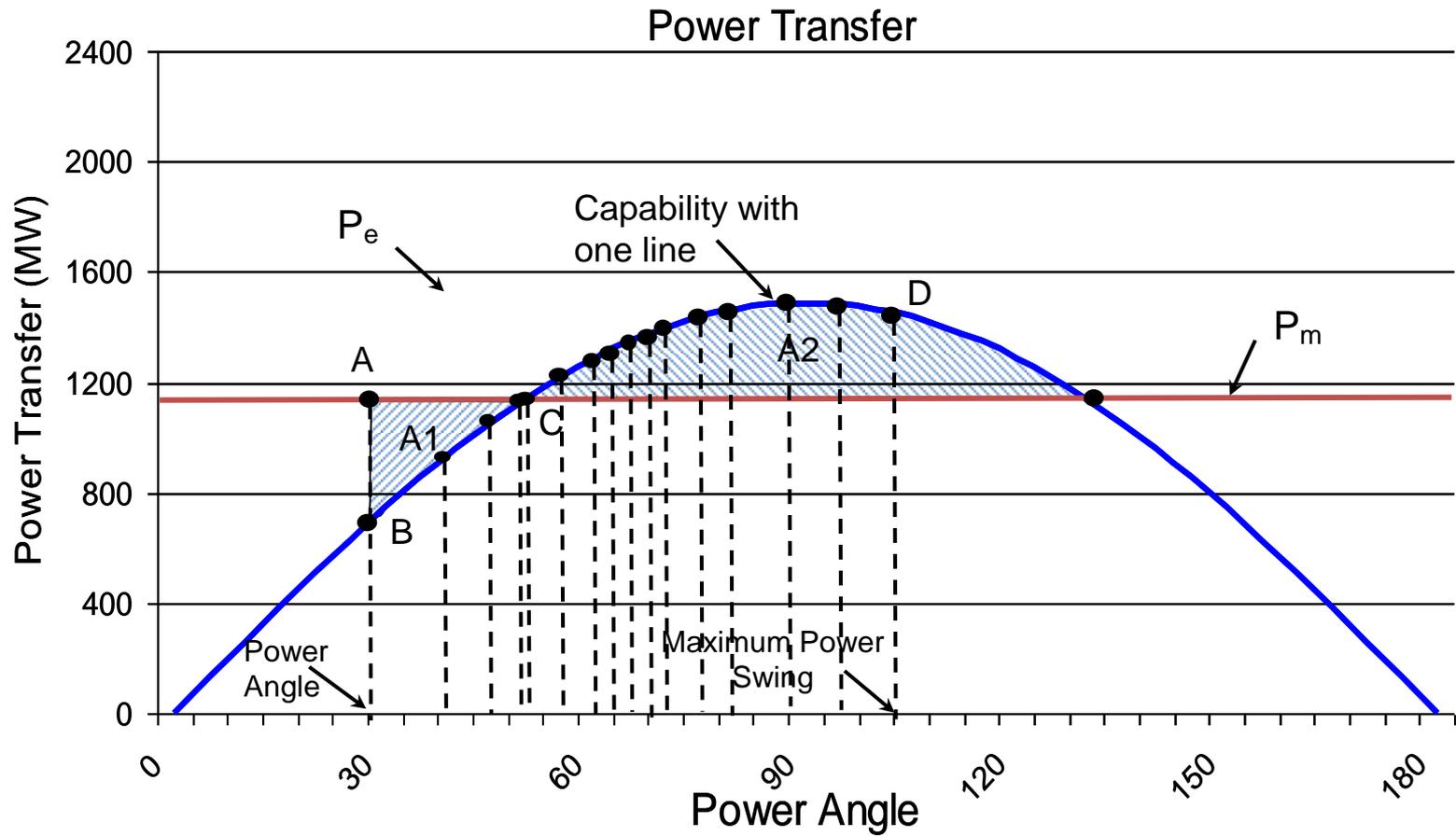
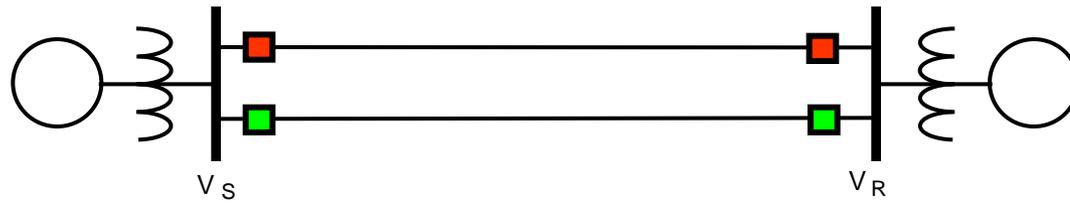
$$\text{Power} = \frac{V_s V_r}{X} \sin \phi$$

# Stability Problems

- If the phase angle increases slightly, the power flow increases.
- Decreasing the phase angle causes the electrical power flow to decrease.
- However, under fault conditions, even though the phase angle may increase, power transfer may decrease on the line. This is due to an increase in reactance and a decrease in voltage.
- When the relative phase angle reaches  $90^\circ$ , the electrical output of a generator starts to decrease as the angle increases. This is a key point in understanding the process of generator stability.

$$P = \frac{V_S V_R}{X} \text{Sine } \phi$$





# Stability Limit

- The maximum amount of power that can be transferred across a system is called the ***stability limit***.
- If the power transfer is below the stability limit, the system is stable.
- If the power transfer is above the stability limit, the system is unstable.

# Stability Conditions

- Three stability conditions exist:
  - steady-state
  - transient
  - dynamic
- It is beyond the scope of this class to cover each of the stability conditions in detail. Instead we provide general definitions of each. These classes are covered in detail in the WECC System Operator Training EOPS/System Restoration class.

# Stability Conditions

- ***Steady-state stability*** is a power system's ability to maintain synchronism between parts of the system during normal load changes. It also refers to the power system's ability to damp out any oscillations caused by such changes.
- ***Transient stability*** is a power system's ability to maintain synchronism between system parts when subjected to a fault of specified severity.
- ***Dynamic stability*** is a power system's ability to maintain synchronism between system parts after the initial swing (during the transient stability period) until the system settles down to a new, steady-state condition.

# Suggested Operating Guidelines

- Adhere to actual line loading limits and path scheduling limitations (i.e., the maximum scheduled interchange is not greater than the transfer capability).
- Use series compensation methods, as appropriate.
- Monitor system conditions, including line loadings, generation changes, and line conditions.
- Carefully analyze the effect of planned equipment outages and adjust system operations accordingly.

# Suggested Operating Guidelines

- Keep remedial action schemes and protection schemes in-service as much as possible.
- Keep power system stabilizers in-service.
- Follow established operating procedures.
- Be prepared to shed load, as necessary.
- Exchange operating information with adjacent systems.

# Subsynchronous Resonance

- The Series Capacitors capacitance may interact (resonate) with the transmission line's inductance and produce electrical oscillations with frequencies between 10 and 50 Hz.
- These oscillations are called subsynchronous since they are less than the normal 60 Hz frequency of the rotating machine. When these electrical resonances occur on the system, currents at the subsynchronous frequency flow into the stators of the generators. These currents produce torsional stresses in the generating unit shafts.

# Subsynchronous Resonance

- If the damping from the electrical resistance in the system and steam in the turbines is insufficient, or if the electrical system is heavily stressed, the subsynchronous oscillations build up. This is called ***subsynchronous resonance***. Shearing of the turbine-generator shaft can occur as a result of subsynchronous resonance.

# Subsynchronous Resonance



# Subsynchronous Resonance

- Utilities use several methods to prevent and/or control subsynchronous resonances, including: minimizing the use of series capacitors by implementing other methods of improving power system stability  
implementing operating procedures that bypass series capacitors when the power system is in a contingency condition
- Installing special relays or filtering devices that block low frequency currents from entering a generator
- Installing a NGH Damping scheme at the series capacitor installation site

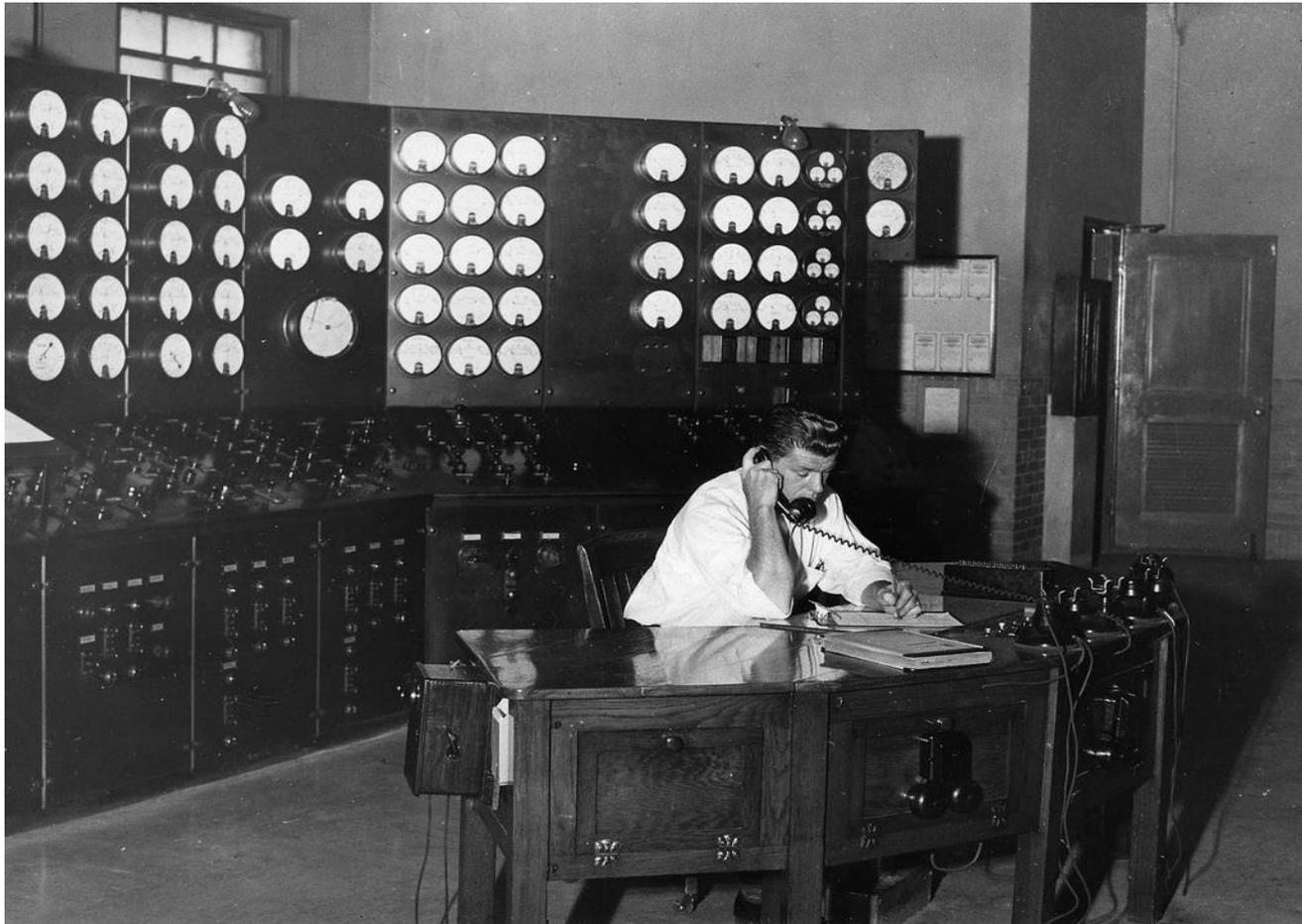
# Computer System Function

- SCADA
- AGC
- Economic Dispatch
- Interchange Transaction Scheduling
- Hydroelectric Coordination
- Hydrothermal Coordination
- Power System Analysis
- Information Storage and retrieval
  
- **AND ALL OF THIS INFO IS BROUGHT INTO THE SYSTEM OPERATORS DESK & the S.O. must monitor and determine what actions need to be taken....**

# Computer System Function



# Computer System Function- the “Good Old Days”



# Interchange Scheduling Introduction

- Scheduling Fundamentals
- Scheduling Day

# Power Markets

## Decentralized Market

- Used to be most common
- Individual sellers deal with individual buyers
- Marketers & Brokers facilitate deals
- Analogous to a Real Estate Market

# Power Markets

## Centralized Market

- Becoming more common.
- Sellers & Buyers converge in a “marketplace.”
- Marketplace designs vary.
- May include ancillary services.
- Analogous to a Stock Market.

# Day in the Life of a Market

## Generation Market (producers)

- Assesses Market Conditions
- Submits an “asking price” (bid)
- Looks for a buyer

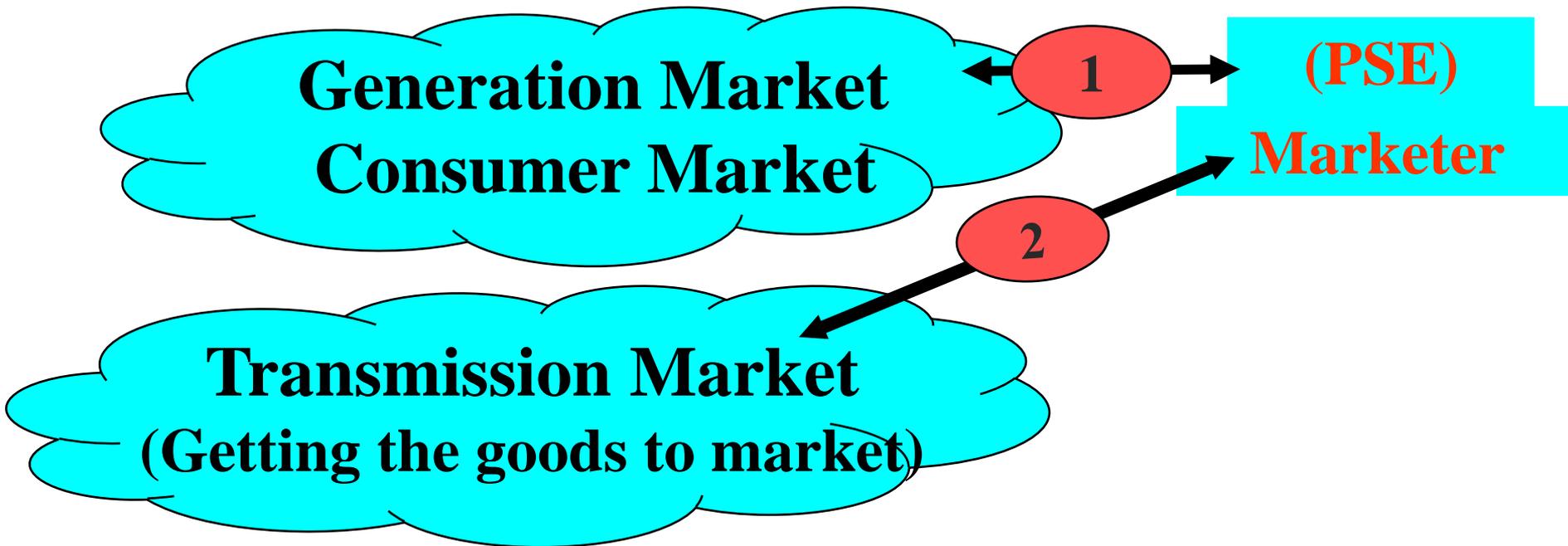
## Consumer Market (loads)

- Assesses Market Conditions
- Assesses needs
- Submits a “willing to purchase price”
- Looks for a seller



# Marketing / Operations Interface

## Supply & Demand



# Transmission Service

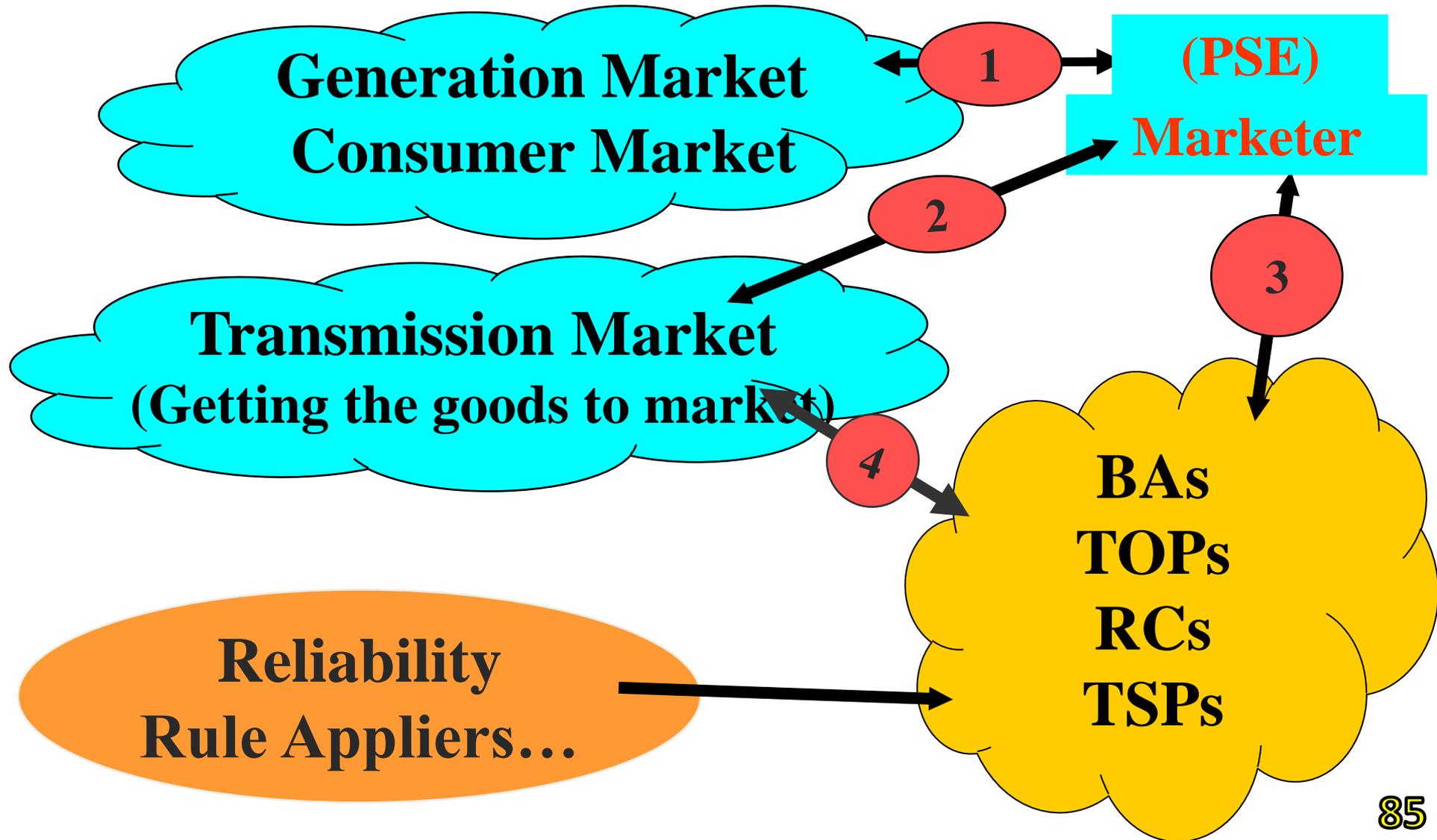
- **FERC Orders 888/889**
  - Requires functional separation of merchant & transmission functions.
  - Transmission service equally available to all market players.
  - Transmission marketed via an OASIS (Open Access Same-time Information System).

# Ancillary Service

- Scheduling & Dispatch.
- Reactive supply & voltage control.
- Load regulation & frequency control.
- Energy imbalance.
- Operating Reserves.
- Energy loss compensation.

# Marketing / Operations Interface

## Supply & Demand



# MARKETING / OPERATIONS INTERFACE

**Supply & Demand**

**Market Rule Applier...**

**Generation Market  
Consumer Market**

**(PSE)  
Marketer**

**Transmission Market**

**(Getting the goods to market)**

**BAs  
TOPs  
RCs  
TSPs**

**Reliability  
Rule Appliers...**

1

2

3

4

# Common Power Types in the Market

- **Firm**
  - **Highest level of delivery priority**
  - **Backed-up by system-wide resources**
  
- **Contingent**
  - **Delivery contingent on availability of certain resources**
  - **Cut before any firm deliveries**

# Common Power Types in the Market

- **Non-firm / Interruptible**
  - **Lowest level of priority**
  - **Highest likelihood of being cut**

# Power Scheduling

- **Power transactions are implemented by use of hourly schedules**

Hour 	1	2	3	4
Import A	50	50	25	35
Export B	35	42	55	80

≈

21	22	23	24
75	45	25	0
62	75	30	25

# Power Scheduling

- Hour 2 is understood as the 60 minute period ending at 2:00 AM (Hour Ending 0200)

Hour 	1	2	3	4
Import A	50	50	25	35
Export B	35	42	55	80

≈

	21	22	23	24
	75	45	25	0
	62	75	30	25

# Power Scheduling

- Values shown are the MWh hours to be delivered or received for the hour

Hour 	1	2	3	4
Import A	50	50	25	35
Export B	35	42	55	80

≈

	21	22	23	24
	75	45	25	0
	62	75	30	25



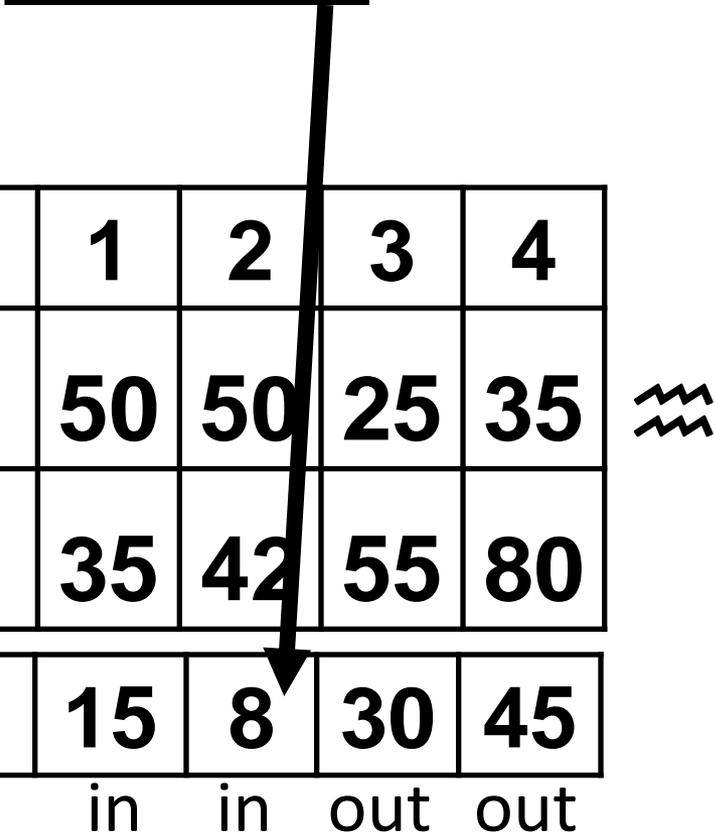
# Power Scheduling

- Imports are netted against exports to determine a net schedule

Hour 	1	2	3	4
Import A	50	50	25	35
Export B	35	42	55	80
Net	15	8	30	45
	in	in	out	out

≈

21	22	23	24
75	45	25	25
62	75	30	0
13	30	5	25
in	out	out	in

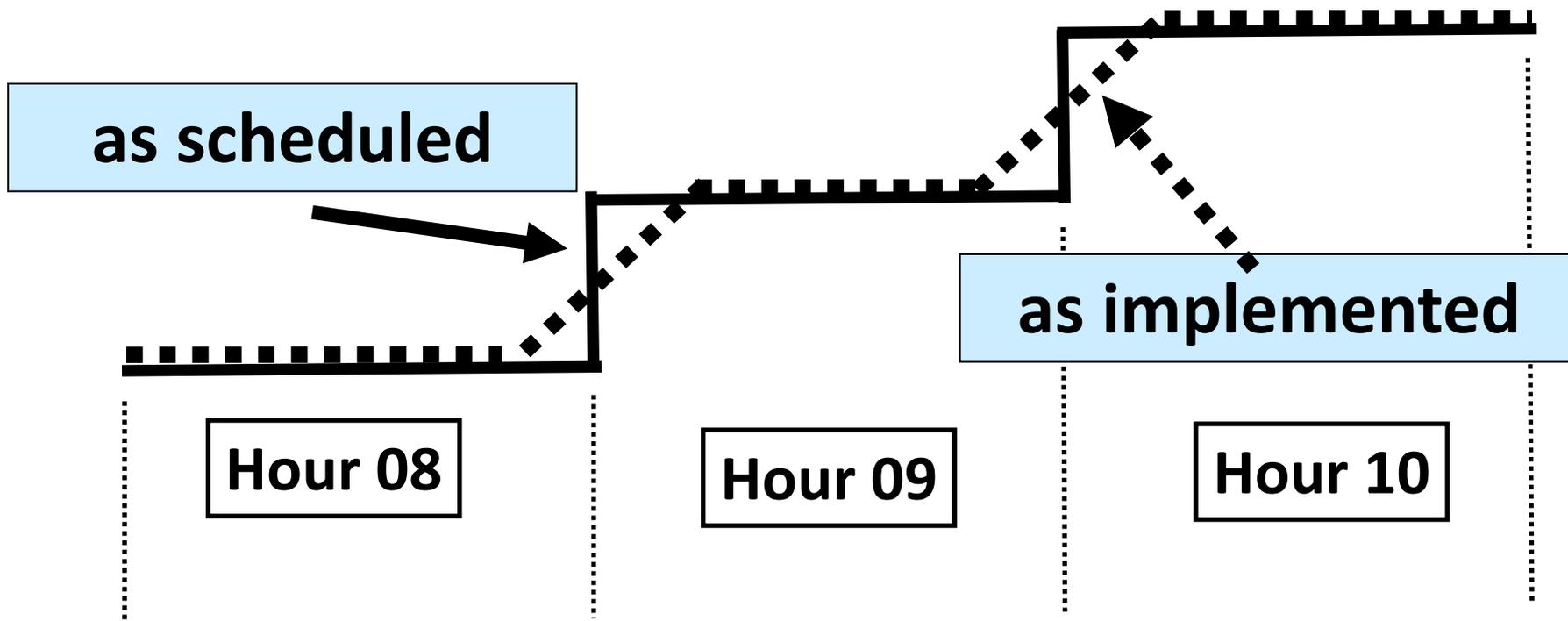


# Power Scheduling

- Schedulers exchange schedules (the preschedule) with transaction partners & balancing authorities each day for the next day's operation
- Operators make real-time schedule adjustments, as needed

# Power Scheduling

- In real-time, hourly schedule changes are ramped to smooth out abrupt changes



# Inadvertent Interchange

- When actual interchange differs from scheduled interchange we get inadvertent flow
- Causes
  - Schedule errors
  - Poor unit control
  - Frequency control
  - Ramp skew
  - Metering error

# Transaction Tagging

- The number of power transactions has grown tremendously
- Electronic Tagging (E-tag)
  - Allows each transaction to be uniquely identified
  - Identifies all parties & transmission arrangements
  - Facilitates timely schedule cuts if problems arise



# Unscheduled Flow

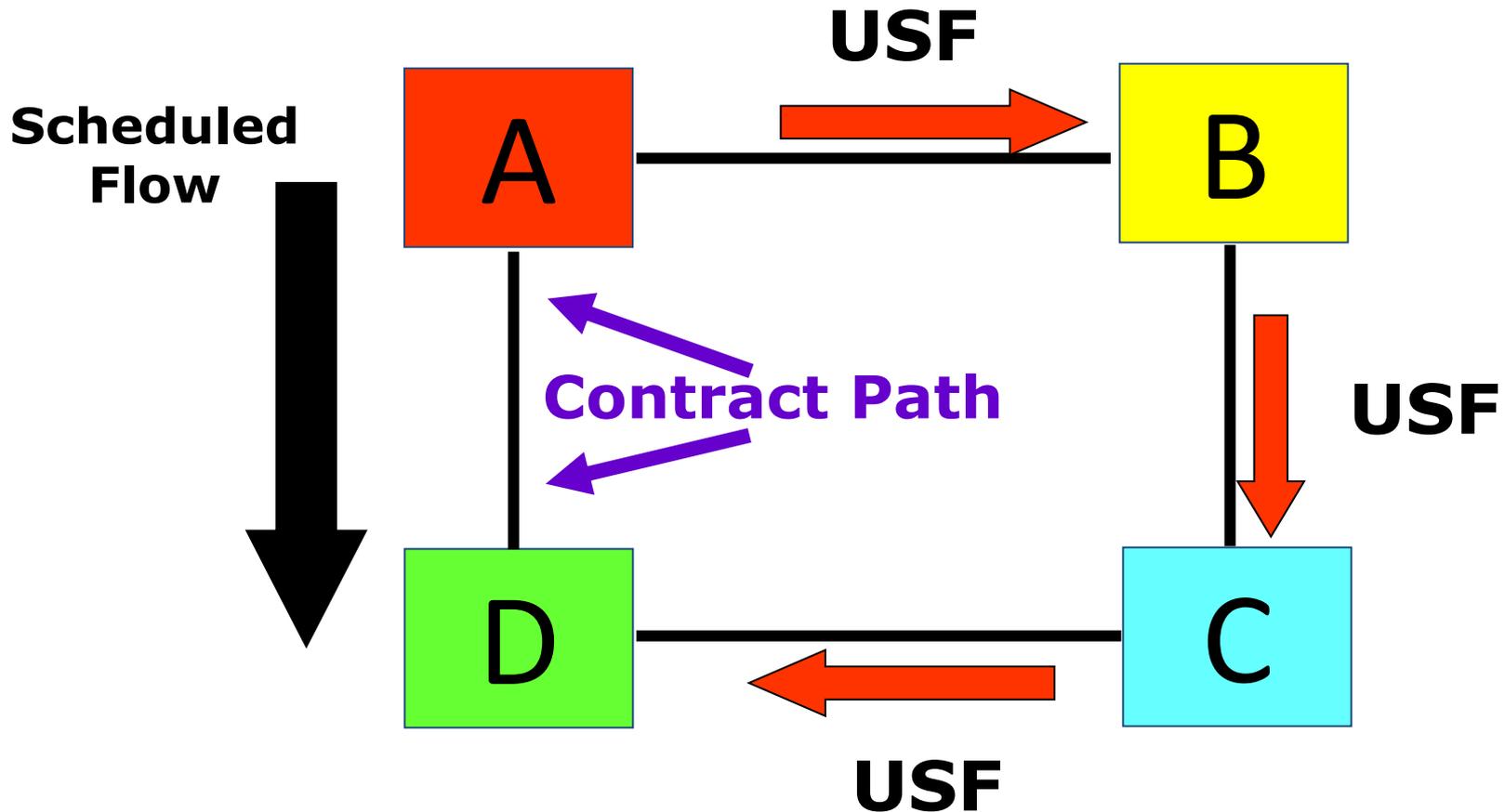
- What is Unscheduled flow?
- Why is it a problem?
- Managing USF
  - WECC USF Procedures

# Unscheduled Flow

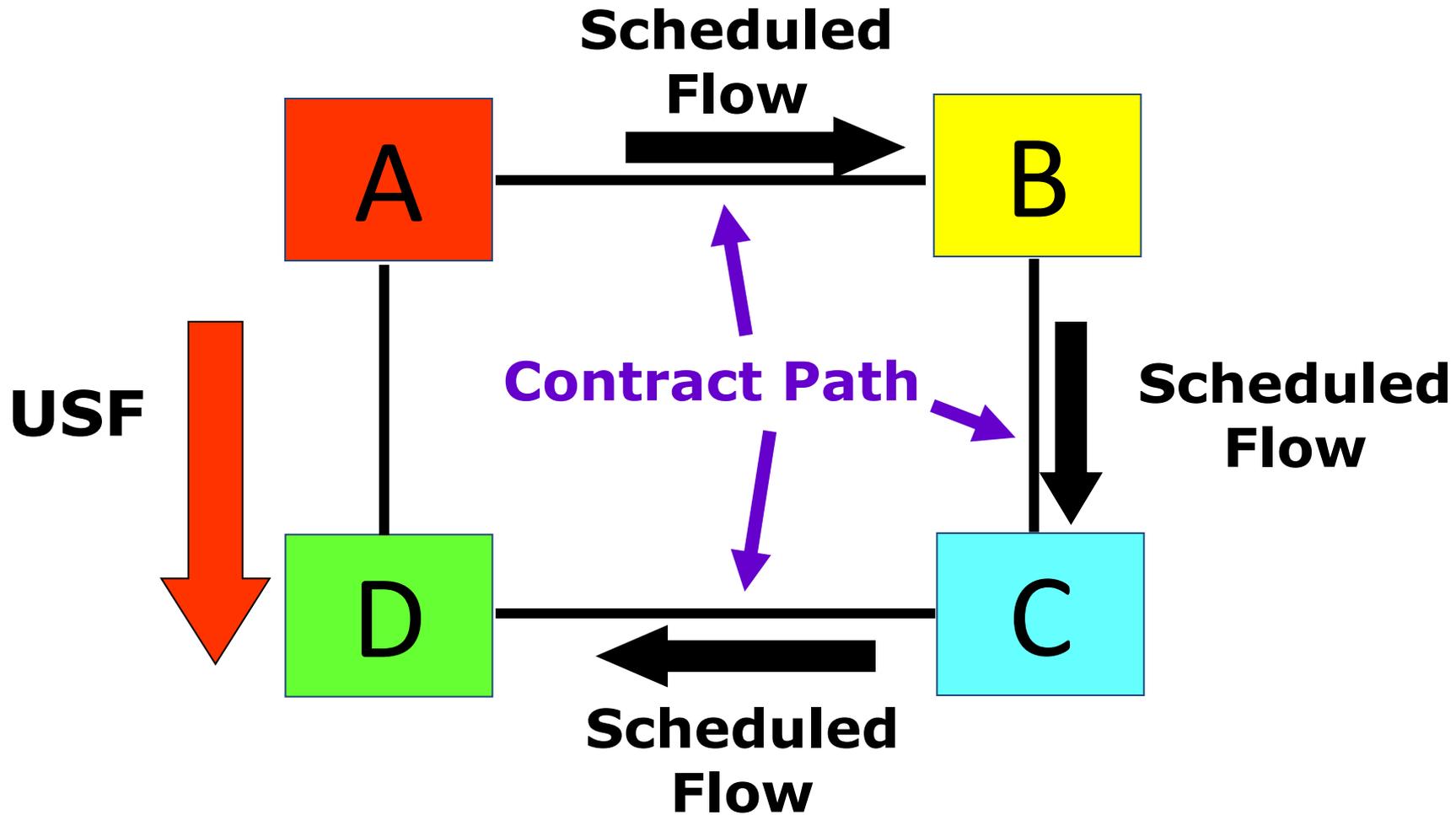
- Inherent in interconnected system operation
- Power flows in all parallel paths
- Scheduled path will not carry all the power
- USF creates problems for others...

# Scheduled & Unscheduled Flow

## Schedule from A to D



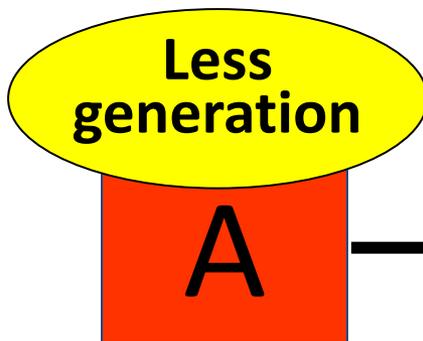
# Scheduled & Unscheduled Flow



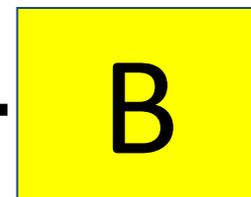
# How Schedule Cuts Relieve USF

## Affected Path from A to D

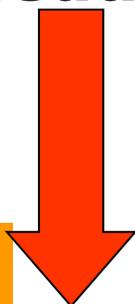
Sender  
reduces  
export  
schedule  
Decreases  
generation



Scheduled  
Flow



Unscheduled  
Flow



Affected  
Path



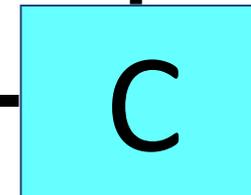
D



Contract  
Path



Scheduled  
Flow



Scheduled  
Flow



# Managing Unscheduled Flow

- Use phase shifters, DC line, series capacitors in the path
- Accommodate some USF
- Coordinate phase shifters WECC-wide
- Curtail schedules causing USF

# After-the-Fact Accounting

- Actual operation differs from the original plan
- Accounting and billing actual deliveries
- Every day, energy accounting personnel unravel the myriad changes from the prescheduled operation



# Check Your Knowledge:

## Interchange Scheduling Introduction

1. What is the relation between scheduling power and actual power?
2. What is the primary contributor to unscheduled flows?
3. Is it better to generate close to load or far away?

# Off-Nominal Frequency Plan

- Load/Generation Balance
- Generator Under-frequency Protection
- Why Coordinate Load-Shedding?
- Plan Overview

# Off-Nominal Frequency Plan

## Load/Generation Balance

### Frequency Control

- Frequency is stable when load and generation match
- Frequency drops when load is higher than generation
- Frequency rises when generation is higher than load

# Off-Nominal Frequency Plan

## Load/Generation Balance

### **Frequency Control**

- Many types of utility and customer equipment will be damaged if operated at abnormal frequencies
- Generators will trip

# Off-Nominal Frequency Plan

## Generator Under-Frequency Protection

### Generator Frequency Trip Settings

<u>Under-Frequency Limit</u> <u>(Hz)</u>	<u>Over-Frequency Limit</u> <u>(Hz)</u>	<u>Time Delay Before</u> <u>Tripping</u>
60.0-59.5	60.0-60.5	NA (normal)
59.4-58.5	60.6-61.5	3 minutes
58.4-57.9	61.6-61.7	30 seconds
57.8-57.4		7.5 seconds
57.3-56.9		45 cycles
56.8-56.5		7.2 cycles
<56.4	>61.7	Instant. trip

# Off-Nominal Frequency Plan

## Generator Under-Frequency Protection

### Controlling Frequency

- AGC
- Operator action
  - Routine generation changes
  - Interruptible load curtailments
  - Manual load shedding

# Off-Nominal Frequency Plan

## Generator Under-Frequency Protection

### Controlling Frequency

- Automatic relay action
  - Under-frequency load shedding
  - Over-frequency load restoration

# Off-Nominal Frequency Plan

## Generator Under-Frequency Protection

### Under-frequency Load Shedding

- Block of load is set to trip if frequency dips below a pre-set point.
- Multiple blocks are used.
- Settings are coordinated throughout WECC.

# Off-Nominal Frequency Plan

## Generator Under-Frequency Protection

### Under-Frequency Load Shedding

LOAD SHED BLOCK	% of LOAD TO DROP	RELAY TRIP FREQUENCY
1	5.3	59.1 Hz
2	5.9	58.9 Hz
3	6.5	58.7 Hz
4	6.7	58.5 Hz
5	6.7	58.3 Hz

# Off-Nominal Frequency Plan

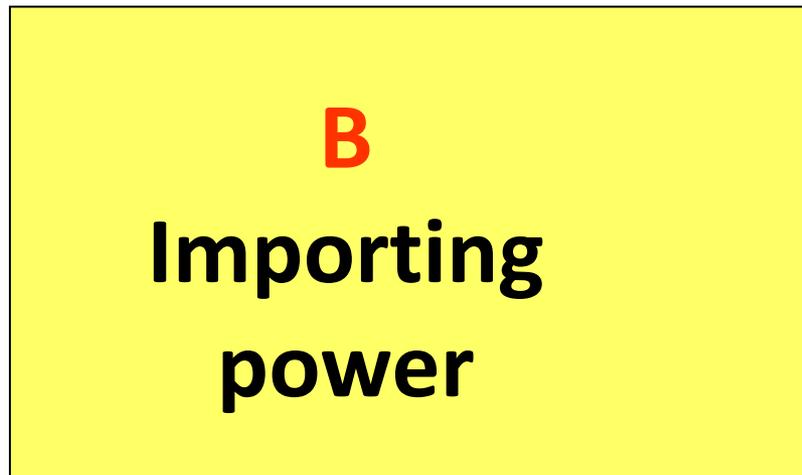
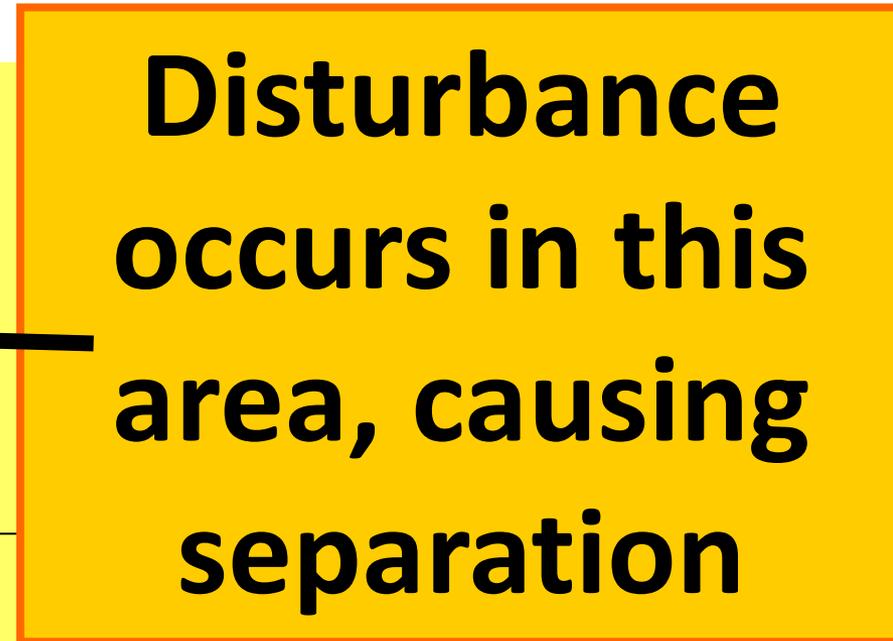
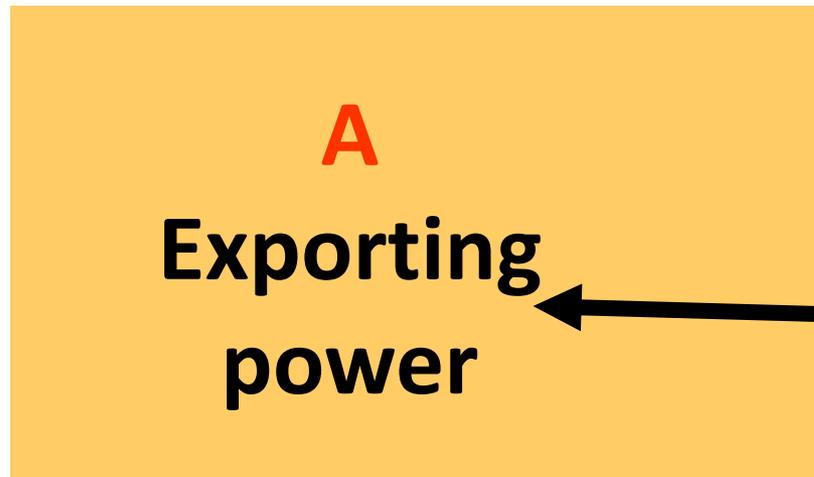
## Why Coordinate Load Shedding?

### XYZ Interconnection

<p><b>A</b></p> <p><b>Exporting power</b></p>	<p><b>C</b></p> <p><b>Exporting power</b></p>
<p><b>B</b></p> <p><b>Importing power</b></p>	<p><b>D</b></p> <p><b>Importing power</b></p>

# Off-Nominal Frequency Plan

## Why Coordinate Load Shedding?



# Off-Nominal Frequency Plan

## Why Coordinate Load Shedding?

**A**

**Exporting  
power**

**High frequency**

**C**

**Exporting  
power**

**B**

**Importing  
power**

**Low frequency**

**D**

**Importing  
power**

# Off-Nominal Frequency Plan

## Why Coordinate Load Shedding?

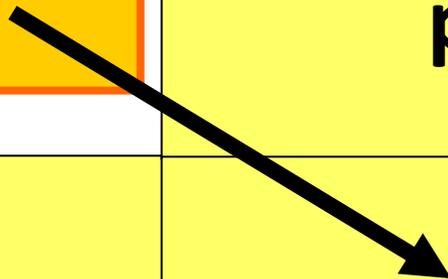
Load shedding in area D is set to trip at higher frequencies than area B. Island sheds load-all in area D

**C**  
Exporting power

**B**  
Importing power

**D**  
Importing power

Low frequency



# Off-Nominal Frequency Plan

## Why Coordinate Load Shedding?

**A further  
separation  
occurs**

**B**  
**Importing  
power**

**Low frequency**

**C**  
**Exporting  
power**

**D**  
**Importing  
power**

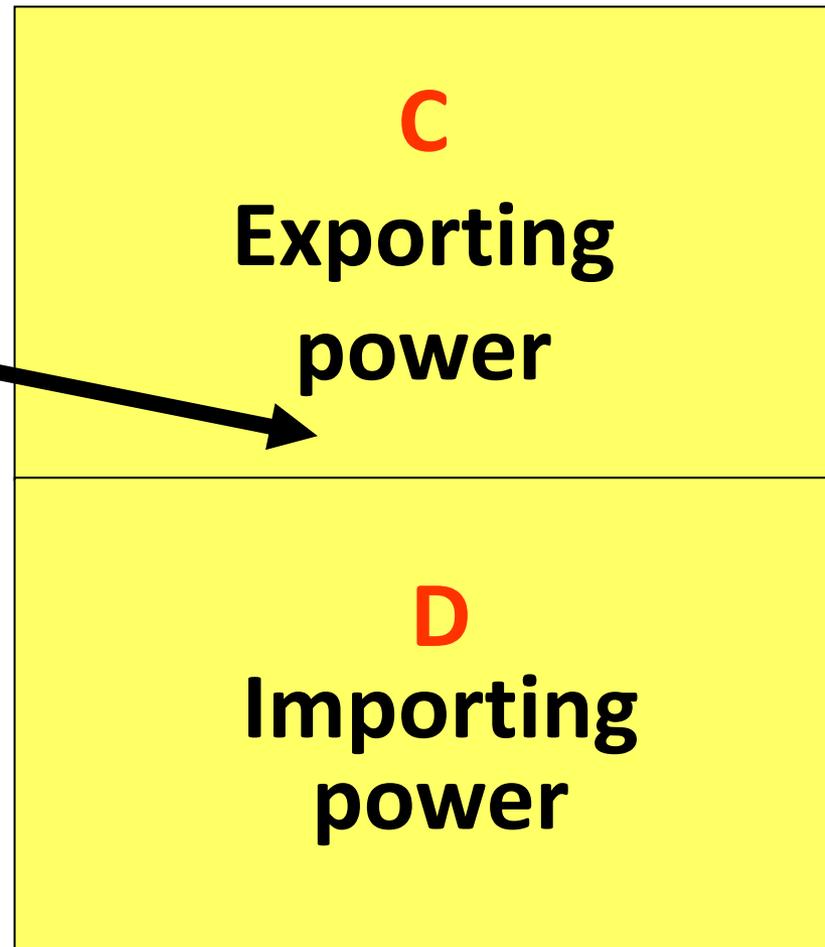
**High frequency**

# Off-Nominal Frequency Plan

## Why Coordinate Load Shedding?

**Way too much generation, units trip on high frequency.**

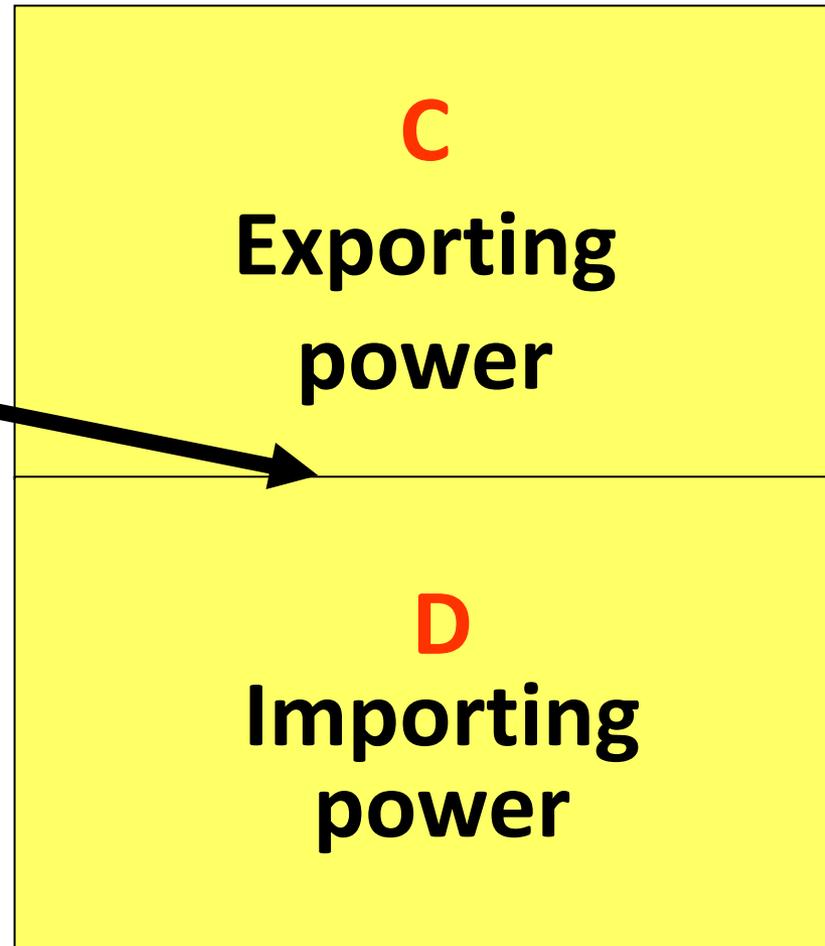
**Then, frequency goes low again & more load trips**



# Off-Nominal Frequency Plan

## Why Coordinate Load Shedding?

**If all areas had same UF trip points, this island would have been much less affected by the initial disturbance**



# WECC Off-Nominal Frequency Load Shedding & Restoration Plan

## Coordinates:

- Trip levels for UF load shedding-normal and stall.
- Generation UF/OF tripping levels-trip load first.
- Automatic load restoration levels-limits frequency overshoot.

# WECC Off-Nominal Frequency Load Shedding & Restoration Plan

## Also Specifies:

- Relay types and response times.
- Tie-line tripping guidelines.
- Loads unacceptable for UF tripping.



## Check Your Knowledge: Off-Nominal Frequency Plan

1. How does the power system protect itself when the frequency is moving too far away from the target?
2. What frequency is used at your house? In your state? In the interconnection?

# System Restoration

- Major Disturbances
- Operator Challenges
- Building from the Black
- 2003 Eastern Blackout
- 2011 Pacific Southwest Blackout

# Major System Events

- Islanding
- Load shedding
- Trip of generation
- Full or partial blackout

# Causes of Major System Events

- Storms
- Earthquakes
- Equipment malfunction
- Operating errors
- Sabotage (intentional or not)

# Operator Challenges In Restoration

- Communication
  - Many alarms & phone calls
  - Non-routine conversations
  - Many demands for information
- Battery power limited

# Operator Challenges In Restoration

- Full extent of problem often unknown.
- Availability and training of field personnel.
  - Mobilization difficulties.
  - Un-staffed facilities.

# Building From Black

- Blackstart units
  - Few units can blackstart
  - Testing/training important



# Building From Black

- Initial system very fragile
  - Frequency control critical
  - High voltage a problem
  - Cold load pickup



# Key Findings of 2003 Blackout Report

1. Poor Vegetation Management
2. Poorly Trained Operators
3. Poor Operator Tools
4. Need Mandatory Rules

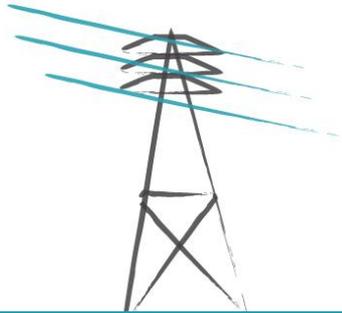
# Improved Vegetation Management

## Before Trimming



## After Trimming





# WECC

September 2011  
Pacific Southwest  
Disturbance

# September 8, 2011

- A disturbance occurred on the afternoon of September 8, 2011 which led to cascading outages and loss of load.
- SDG&E, IID & CFE had complete system outages.
- APS and WALC lost some load.

# September 8, 2011

- This disturbance occurred on a heavily loaded summer day.
- Load interrupted:
  - SDG&E      4293 MW
  - CFE            2150 MW
  - IID            929 MW
  - APS            389 MW
  - WALC         74 MW

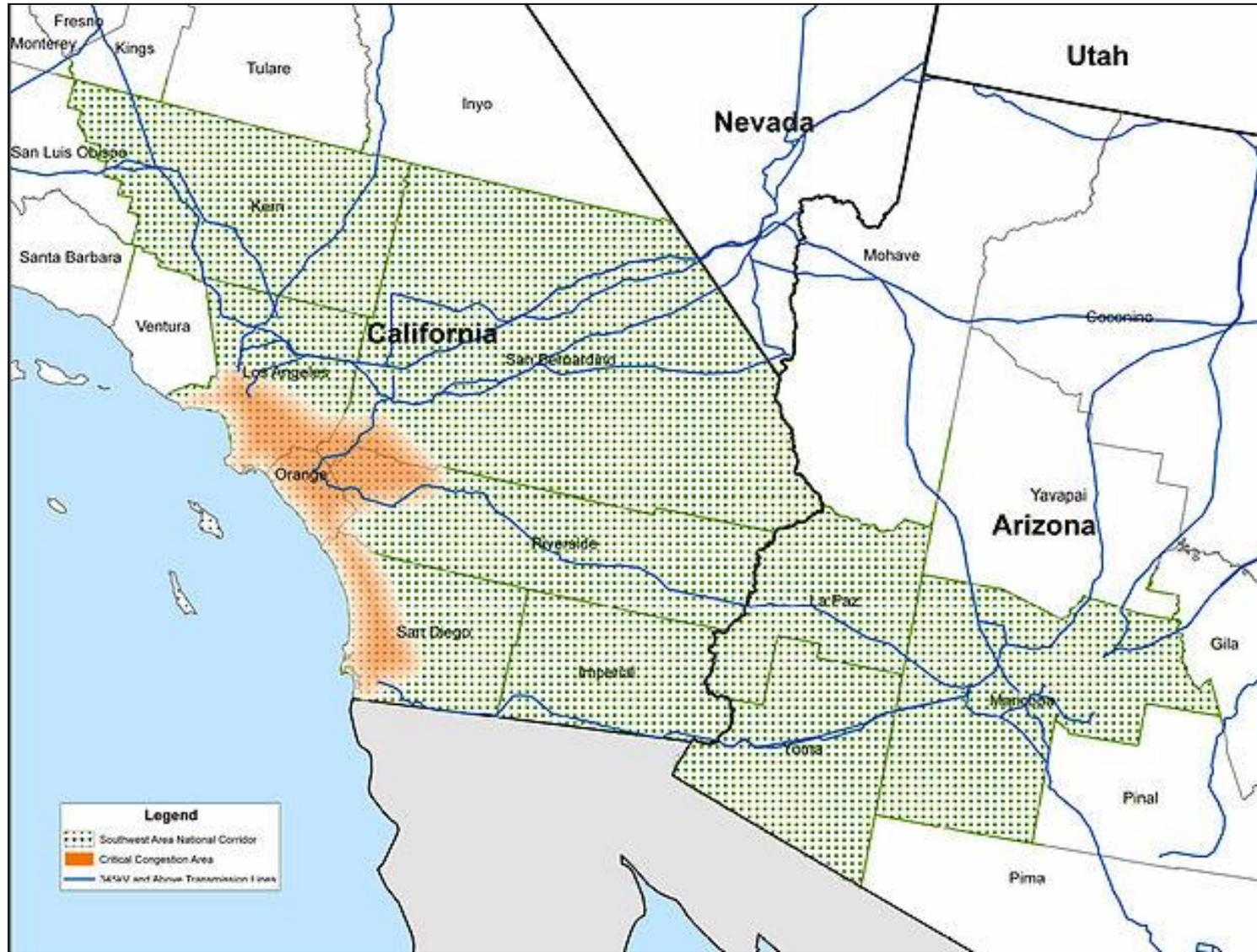
# September 8, 2011

- FERC / NERC Report findings: System was not being operated in a secure state for an N-1 outage due to:
  - Lack of information sharing between entities.
  - Lack of adequate studies.
  - Sub 100 kV facilities not adequately considered in next-day studies.
- Initiating event: Loss of APS Hassayampa-North Gila 500 kV Line due to an operating error.
- All load was restored in approximately 12 hours.

# Some NERC Standards Violated

- **COM-002-2, R2**
  - Issue directives in a clear & concise manner
  - Three-part communication
- **EOP-001-2.1b**
  - Developing, maintaining & implementing emergency plans
- **EOP-003-2**
  - Shed load rather than risking uncontrolled failure or cascade
- **EOP-005-2**
  - Returning system to normal following a disturbance
- **EOP-006-2**
  - Coordination with Reliability Coordinator
- **TOP-004-2**
  - Operate so that instability, uncontrolled separation, or cascading outages will not occur as a result of the most severe single contingency



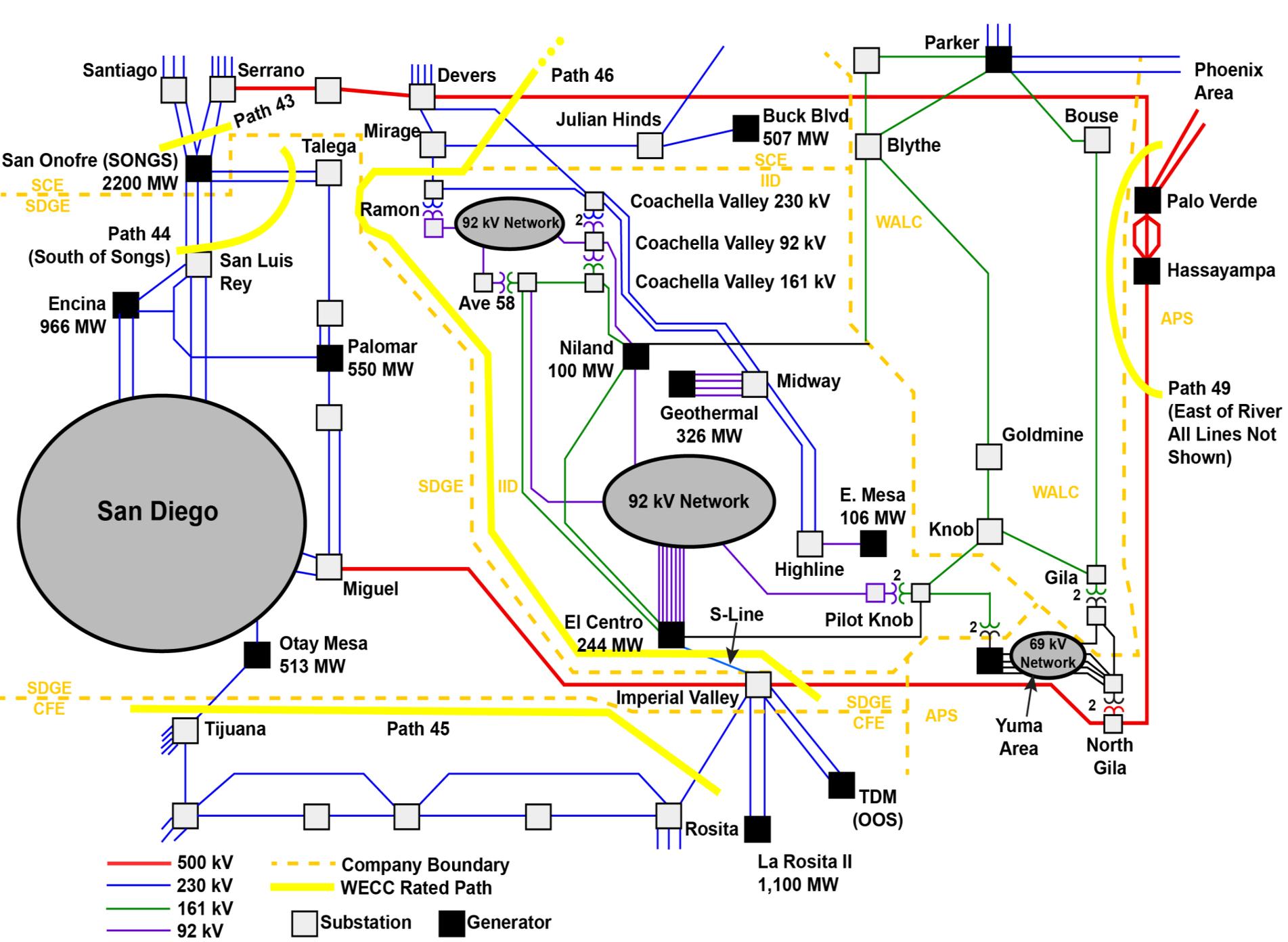


# Sequence of Events – 1

- At 1527, APS Hassayampa-North Gila 500 kV line relayed due to switchmen error.
- Loss of 500 kV line caused overload on area's lower voltage system as power sought alternate route into San Diego area.
- IID's 92 kV system started to collapse within 40 seconds of initial 500 kV line trip.

## Sequence of Events – 2

- IID lost 230/92 kV transformers at Cochella Valley and Ramon.
- CFE lost generation in Mexico.
- IID experienced a voltage collapse in its service area and lost 50% of load when UVLS operated.

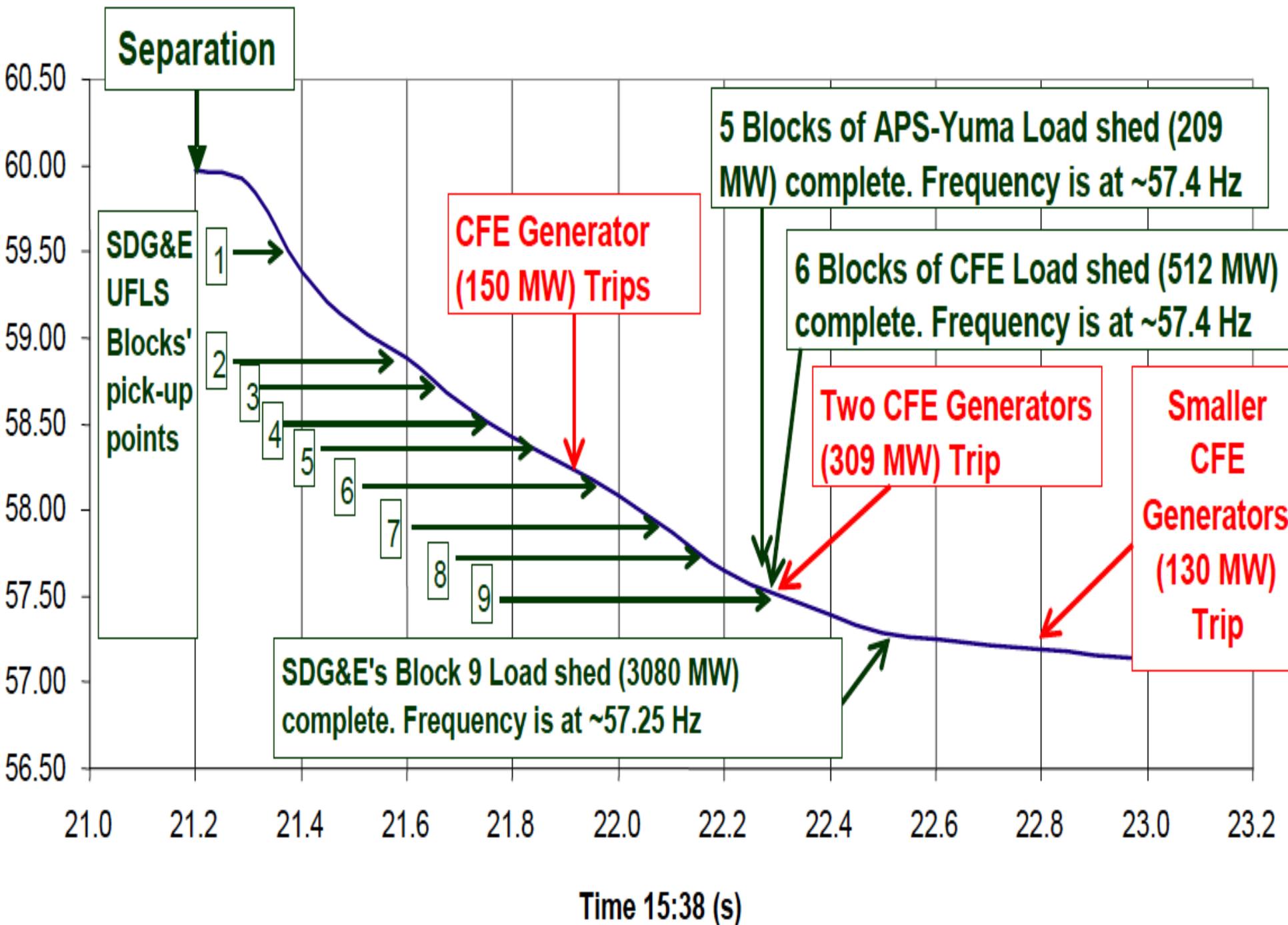


- 500 kV
- 230 kV
- 161 kV
- 92 kV
- Company Boundary
- WECC Rated Path
- Substation
- Generator

# Sequence of Events - 3

- As IID, WAPA and APS lower voltage system collapsed the 230 kV system on the coast loaded heavier and heavier.
- A protection scheme associated with path 44 operated separating the San Diego, IID, and CFE systems.
- Load was much greater than generation so system collapsed.
- UFLS operated but too little too late.
- Entire event took only 11 minutes.





*Questions?*

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# Things left to do????

## ✓ REVIEW

- **Collect Pre-test & Simulator Modules**
- **Complete course evaluation**
- **Take final exam**

**FLY A KITE**

JUMP IN PUDDLES

WISH ON DANDELIONS

LIE IN THE GRASS

**DREAM BIG**

PLAY DRESSUPS

RUN BAREFOOT

HOST A TEA PARTY

**DANCE IN THE RAIN**

REACH FOR THE STARS

**IMAGINE**

TREAD GENTLY

SLEEP SOUNDLY

# TEST TIME...



Closed Book!

# You Endured to the End!

Please turn in your Class evaluations and plastic badge holders.



*Thank you!*

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