Electric Power Group Presents
Operationalizing Phasor Technology

Phase Angle Differences

What They Mean and How to Use Them For Operations

September 17, 2013

Presented by:

John Ballance

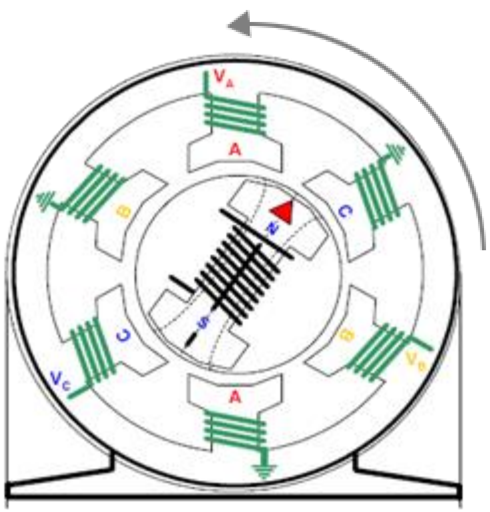
Electric Power Group

Webinar Outline

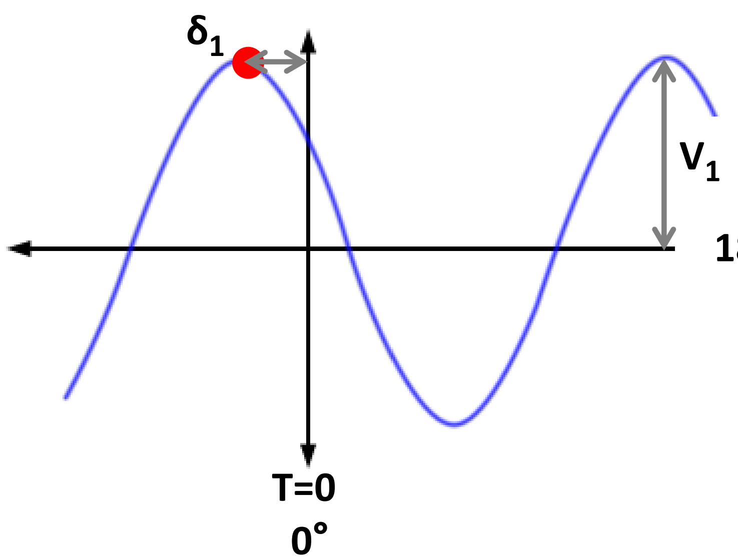
- July 16 Webinar - System Events- Deciphering the Heartbeat of the Power Grid
- Aug 20 Webinar - Using Synchrophasor Technology For Real-Time Operations and Reliability Management
- Today's Topic: Phase Angle Differences - What They Mean and How To Use Them in Operations
  - Phase Angles - Introduction
  - Use of Phase Angles in Control Rooms - Monitor, Diagnose and Act
  - Power Flow Model - Using 8 Bus System to Illustrate Use of Phase Angles
    - Base Case
    - Line Trip
    - Load Trip
    - Generator Trip
    - Cascade
  - Power Flow Model Representation of Sources and Sinks - Examples
  - Phase Angles - Recap
  - Phase Angles - Key Takeaways
- Schedule of Upcoming Webinars
- Appendix: Power Flow Model – 8 Bus System

What is a Voltage Phasor?

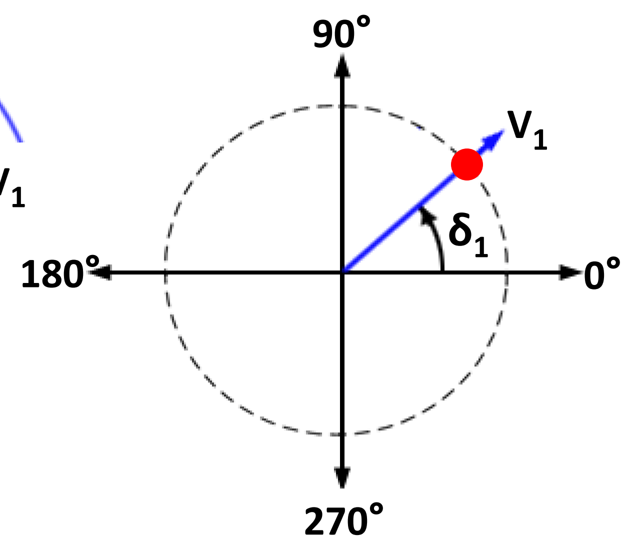
- A Phasor is a rotating vector
- Voltage Phasor is defined by magnitude V_1 and angle δ_1
- Angle is measured with respect to universal time (T=0 top of a second)
- Phasor rotates counter clockwise, similar to rotating magnetic field in a synchronous generator
- A Synchrophasor is a Phasor referenced to 60 Hz with angle referenced to universal time (T=0 top of second)



AC Circuits

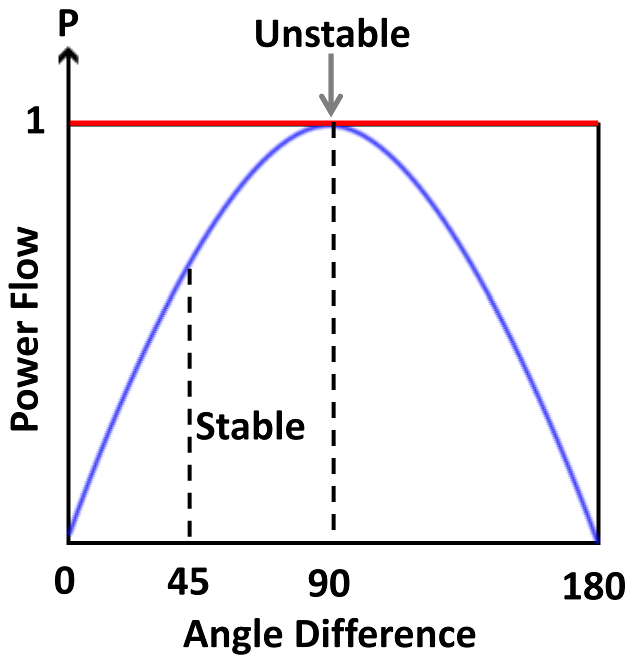


Sinusoidal Waveform

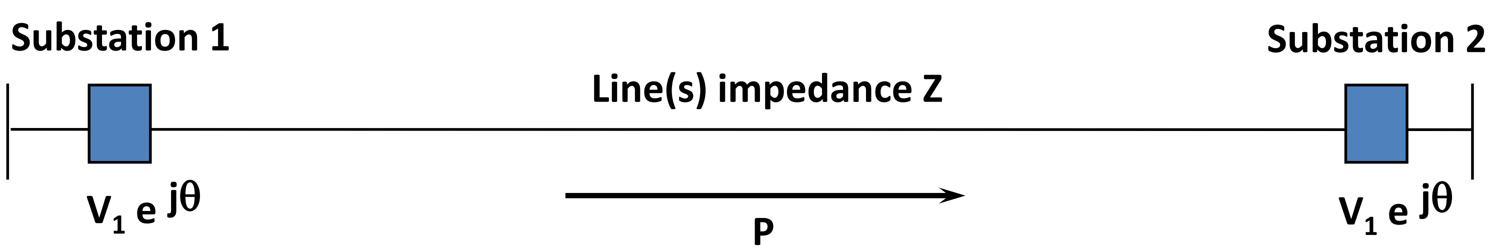


Phasor Representation

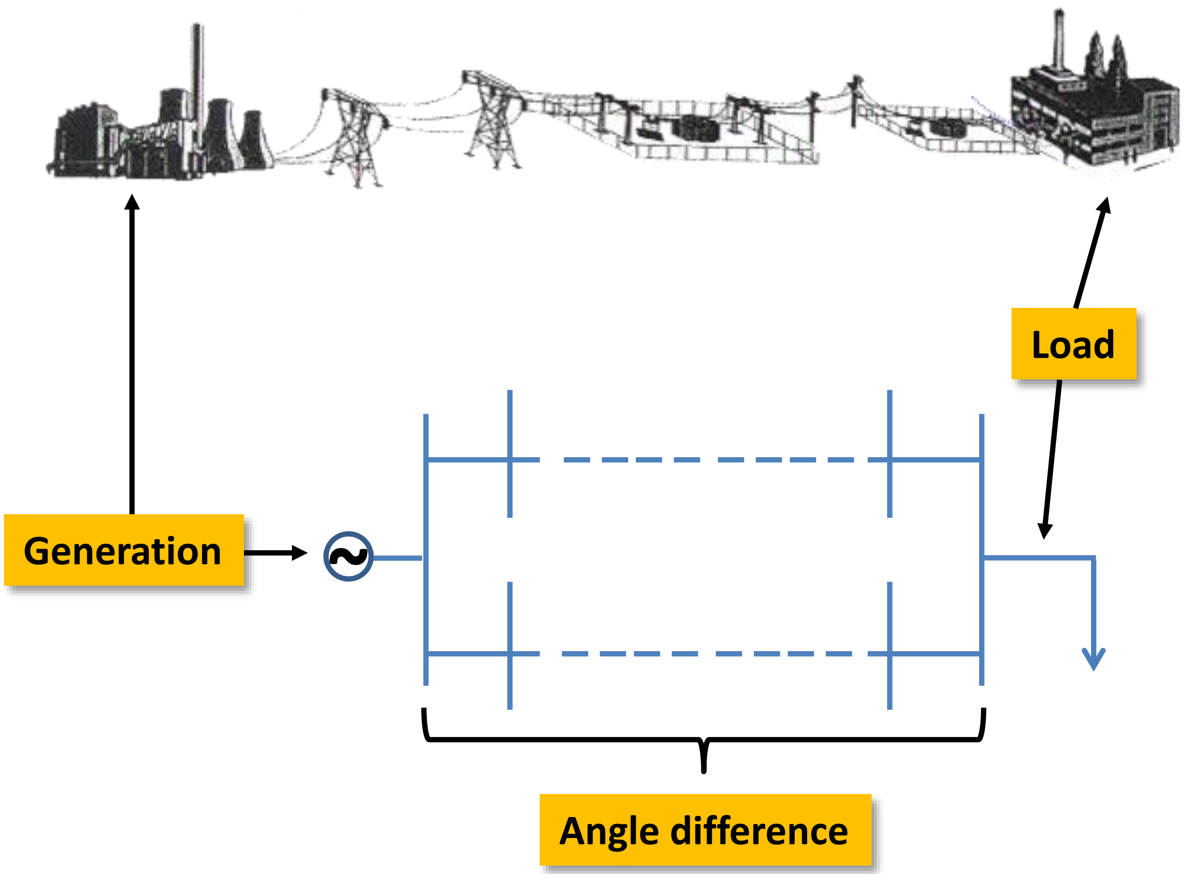
Power Flow Is a Function of Phase Angle Difference



- **Power *flows* from high to low Voltage in DC systems**
- **Power *flows* from high Voltage Angle to low Voltage Angle in AC systems**
  - Power flow equation:
    $P = V_1\ V_2 \sin(\theta - \phi)/Z$, where θ is greater than ϕ
- **Synchrophasor angles are correlated to universal time (UTC) and 60 Hz**
  - Allows comparison over wide area
- **The Voltage Angle difference between two substations correlates with the power being transferred across the grid between them**
- **The Current Angle paired with Voltage Angle describes real and reactive power on any line**



Power Flow & Phase Angles



- **AC Power System:** Power *flows* from a point of high voltage angle to a point of low voltage angle
- Voltage Angles across a network change when something happens (e.g. line outage, generation trip, or load change)
- Increasing Voltage Angle differences across a network indicates increasing stress

Phase Angle Difference

Screenshot of RTDMS® – Real Time Dynamics Monitoring System

Phase angle differences between two distant PMUs can indicate the relative stress across the grid, even if the PMUs are not directly connected to each other by a single transmission line.

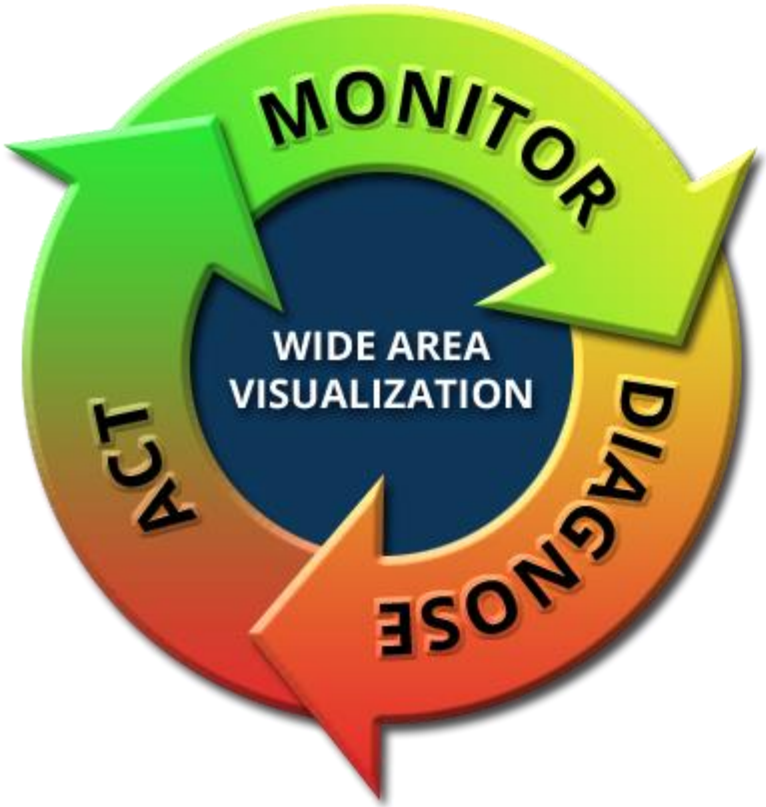
Use of Phase Angles in Control Rooms

Monitor, Diagnose and Act

Phase Angle Difference = *Grid Stress*

Operator Actions for Stability:

- Redispatch Generation
- Shed Load
- Provide Voltage Support



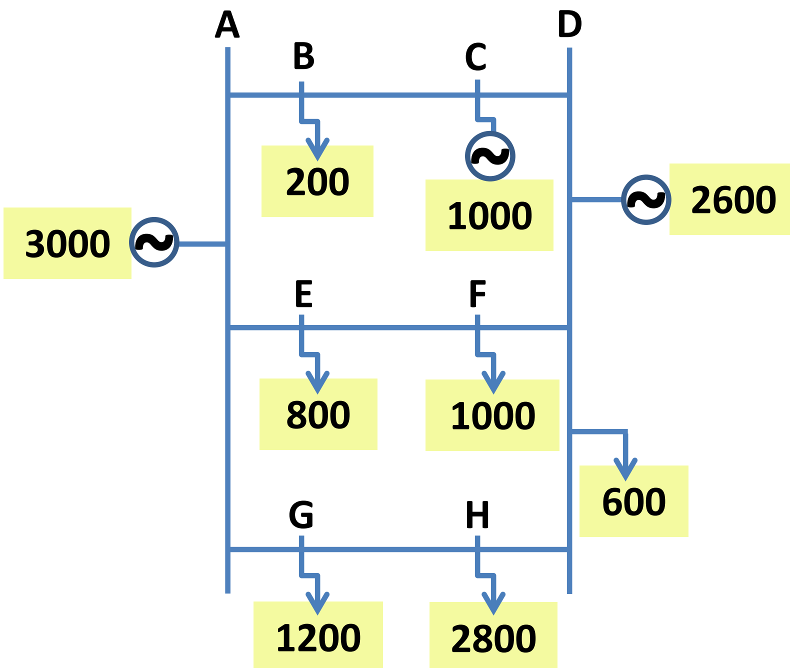
Grid Stress Diagnostics:

- Line Trip
- Load Trip
- Generation Trip
- Cascade
- Wide Area, Regional or Local

Power Flow Model - 8 Bus System

Base Case

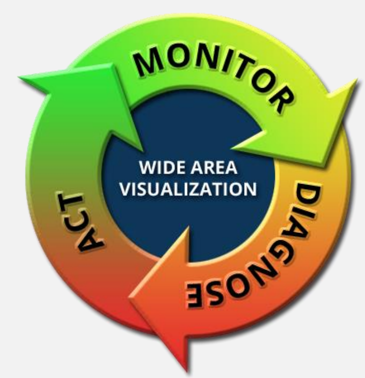
System Stable



No Change
Event
Mitigation

- Load: 6600 MW (Buses B, D, E, F, G and H)
- Generation: 6600 MW (Buses A, C and D)
- Key Phase Angle Paths:

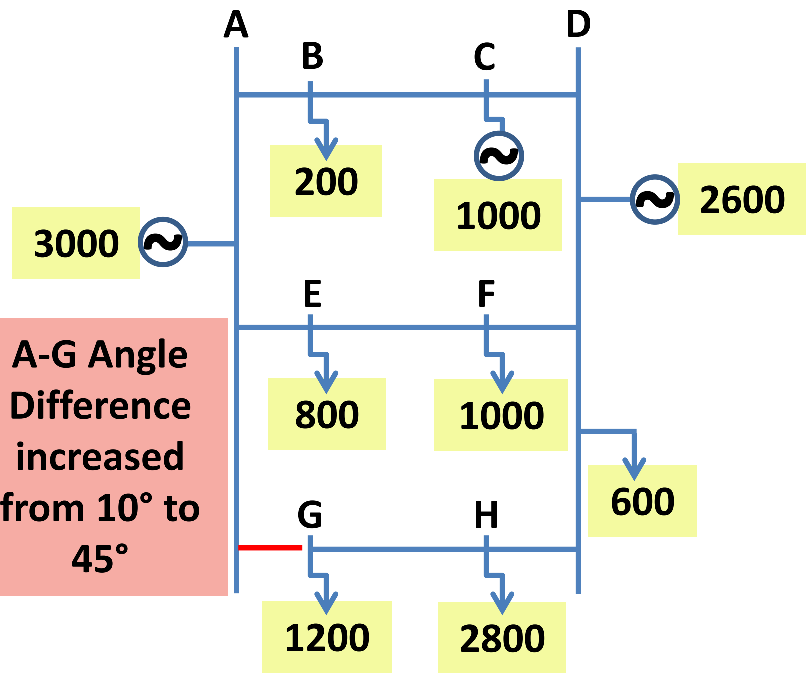
PHASE ANGLE	BASE
A-G	10°
A-E	7°
A-D	6°



Power Flow Model - 8 Bus System

Line Trip

Event: Line Trip (A-G)



A-G Angle Difference increased from 10° to 45°

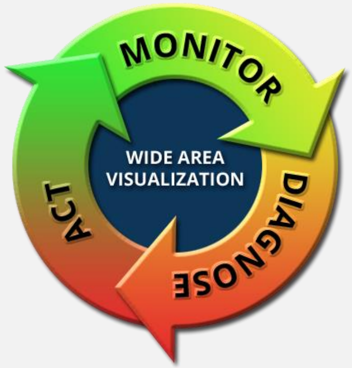
- No Change
- Event
- Mitigation

- Load: 6600 MW (Buses B, D, E, F, G and H)
- Generation: 6600 MW (Buses A, C and D)
- Key Phase Angle Path Changes:

PHASE ANGLE	BASE	LINE TRIP
A-G	10°	45°
A-E	7°	16°
A-D	6°	24°

A-G Phase Angle increases to 45°

ACTION: Redispatch

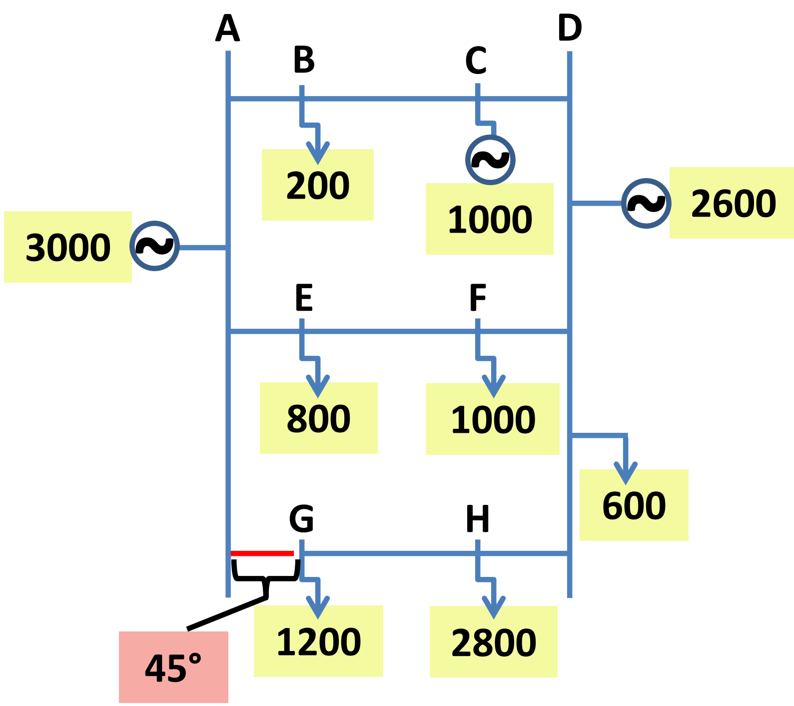


Line Trip

Power Flow Model - 8 Bus System

Line Trip - Mitigation

Line Trip: Mitigation



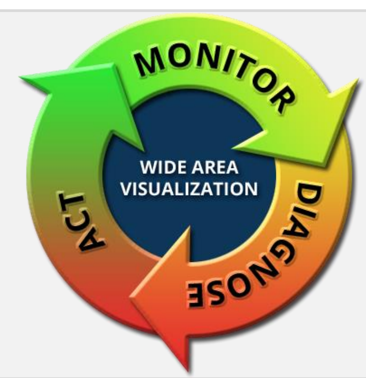
No Change
Event
Mitigation

*Gen A adjusted to balance network load

- **Issues:**
  - A-G Angle at 45°
  - Assume 30° needed to close CB
- **Options for Redispatch:**

ACTION	SENSITIVITY X°/100MW
Reduce G Load	2.60°
Reduce H Load	1.85°
Reduce D Load and Increase D Gen	1.28°
Increase C Generation	1.10°

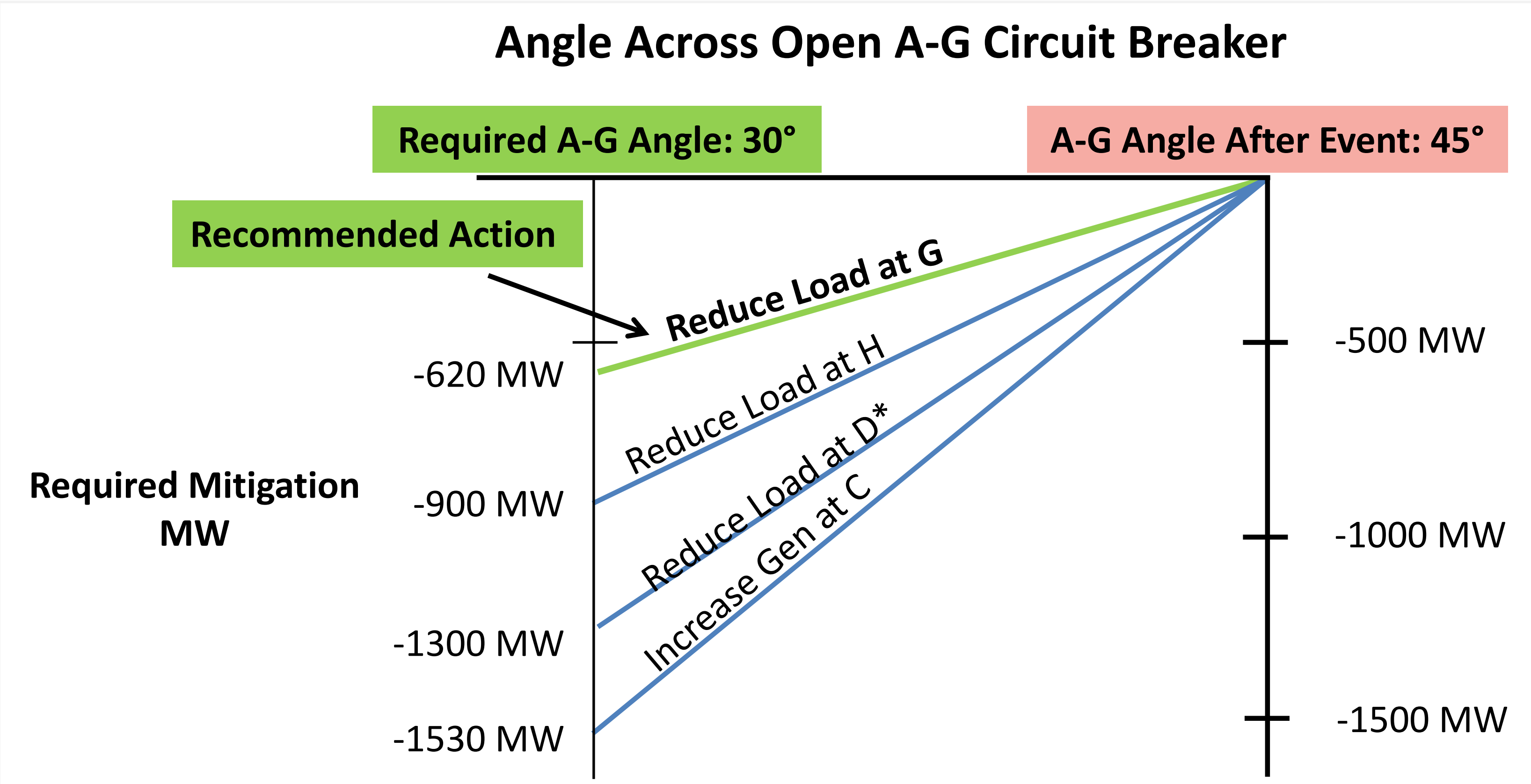
REQUIRED ACTION:
Reduce angle across A-G to 30° to permit CB closing



Power Flow Model - 8 Bus System

Line Trip – Mitigation Options and Effectiveness

Effectiveness of Mitigation Options In Reducing A-G Angle



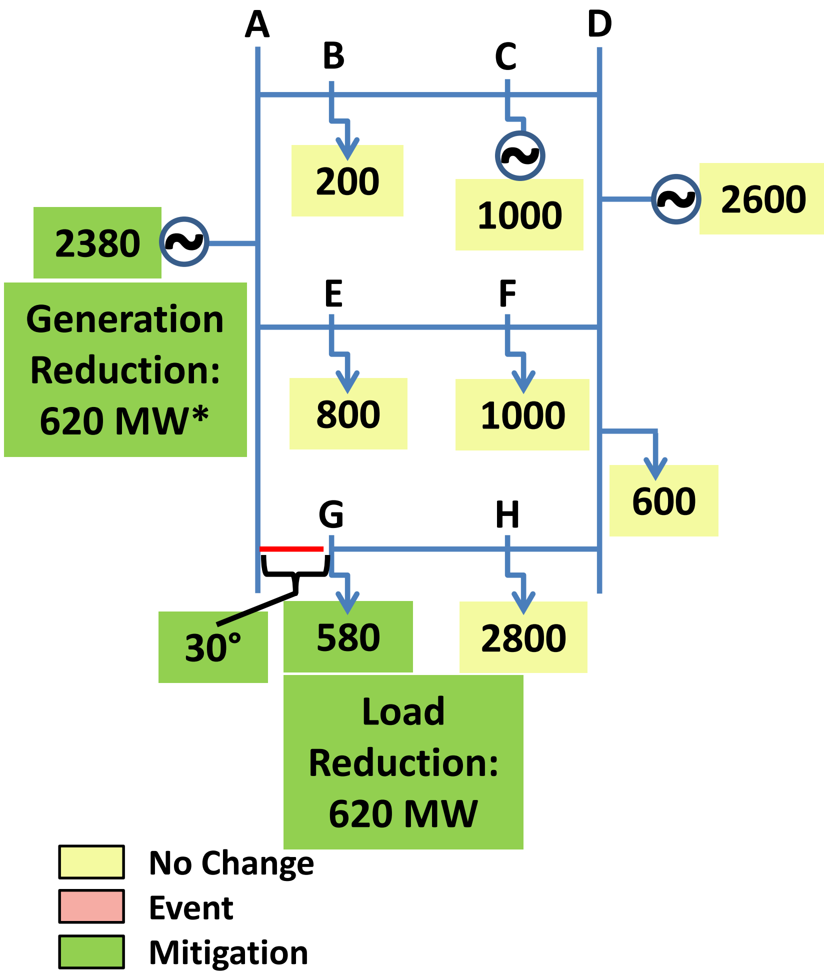
*Reduce load, then increase generation to mitigate

Back to Case Index

Power Flow Model - 8 Bus System

Line Trip - Mitigation

Line Trip: Mitigation

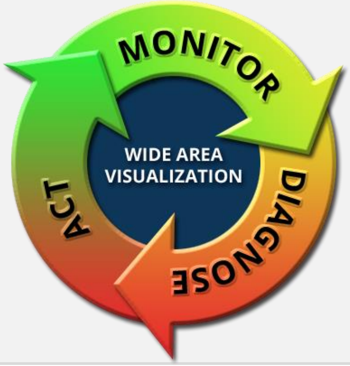


*Gen A adjusted to balance network load

- **Issues:**
  - A-G Angle at 45°
  - Assume 30° needed to close CB
- **Options for Redispatch:**

ACTION	SENSITIVITY X°/100MW	RESULT: A-G ANGLE
Reduce G Load by 620 MW	2.60°	30°
Reduce H Load by 900 MW	1.85°	30°
Reduce D Load by 600 MW & Increase D Gen by 700 MW	1.28°	30°
Increase C Generation by 1530 MW	1.10°	30°

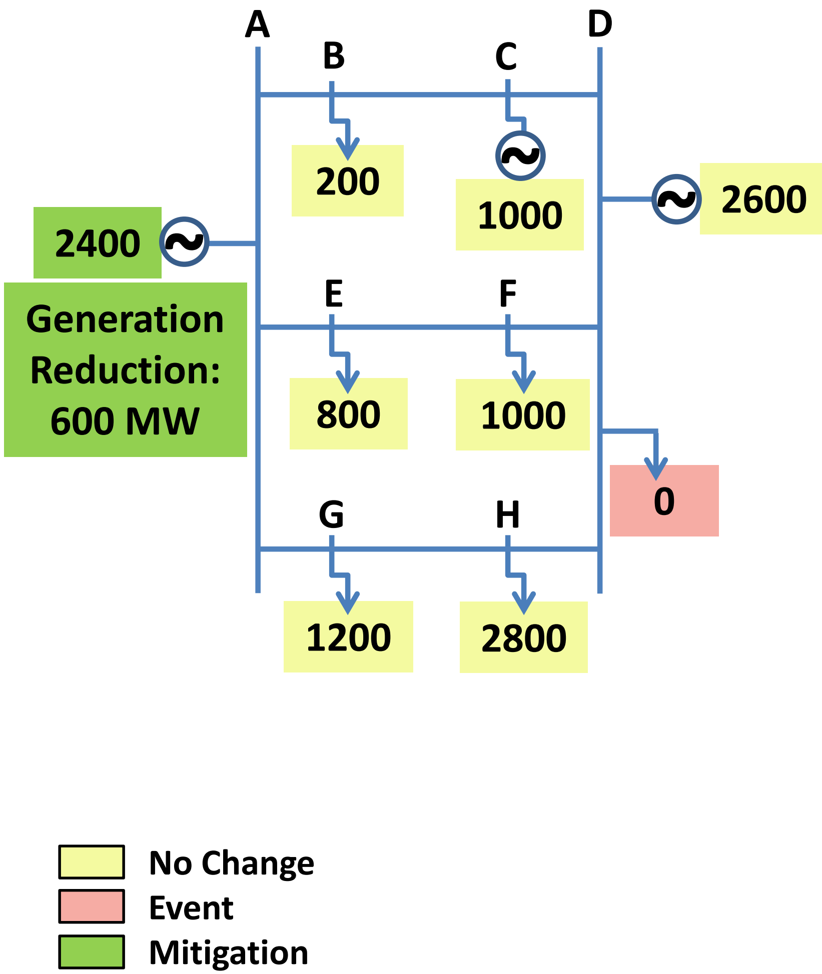
RECOMMENDED ACTION:
To enable CB closing at 30°, reduce G load and A generation by 620 MW, restore line and restore G load



Power Flow Model - 8 Bus System

Load Trip

Event: 600 MW Load Loss at D

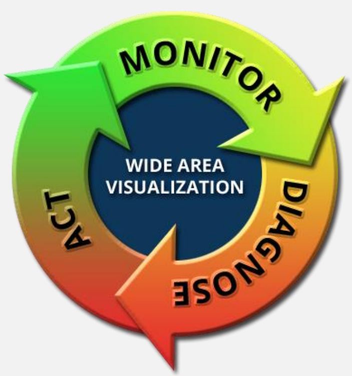


- Load: 6000 MW (Buses B, D, E, F, G and H)
- Generation: 6000 MW (Buses A, C and D)
- Key Phase Angle Paths:

PHASE ANGLE	BASE	LOAD TRIP
A-G	10°	8°
A-E	7°	5°
A-D	6°	3°

A-D Phase Angle decreases from 6° to 3°

ACTION: Generation Redispatched

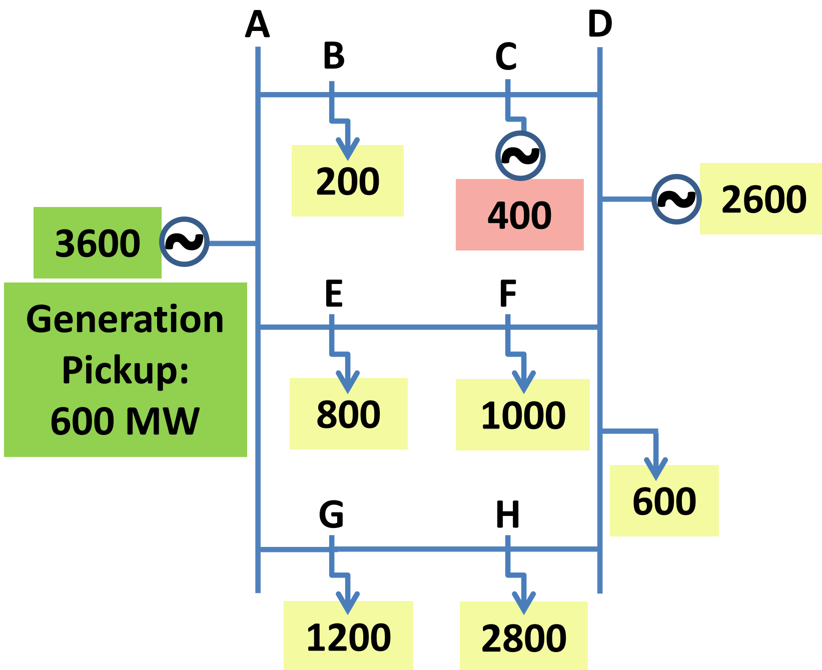


Load Trip

Power Flow Model - 8 Bus System

Generation Trip

Event: 600 MW Gen Loss at C



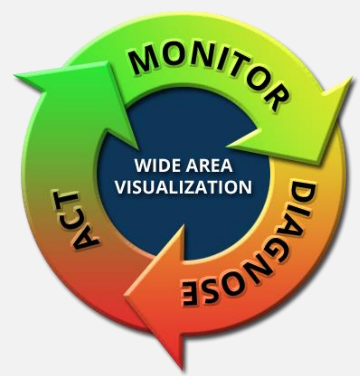
- No Change
- Event
- Mitigation

- Load: 6600 MW (Buses B, D, E, F, G and H)
- Generation: 6600 MW (Buses A, C and D)
- Key Phase Angle Paths:

PHASE ANGLE	BASE	GEN TRIP
A-G	10°	11°
A-E	7°	8°
A-D	6°	9°

A-D Phase Angle increases from 6° to 9°

ACTION:
Redispatch



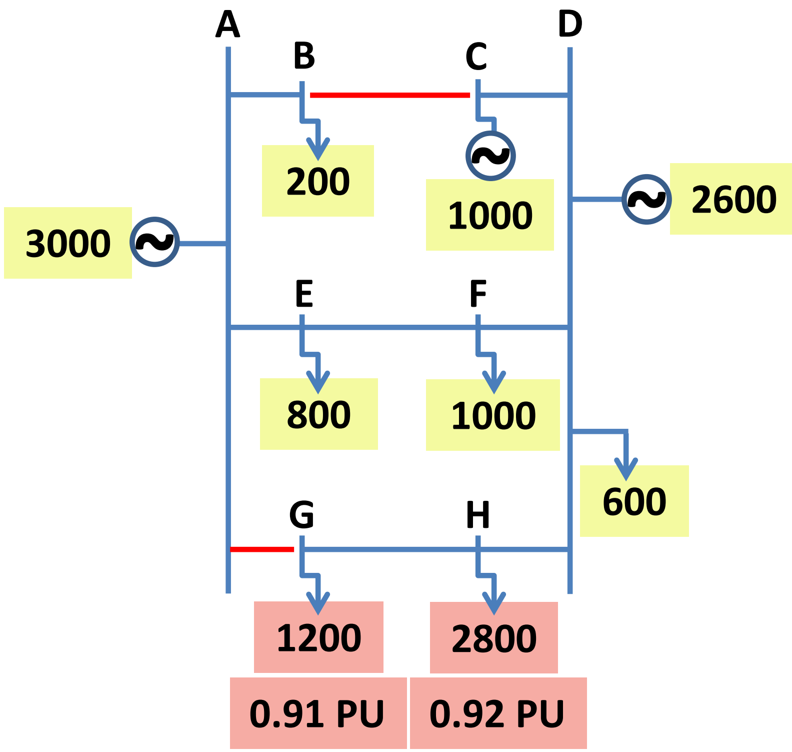
Gen Trip

Back to Case Index

Power Flow Model - 8 Bus System

Cascade – Loss of A-G and B-C Lines

Event: 2 Lines Tripped



No Change
Event
Mitigation

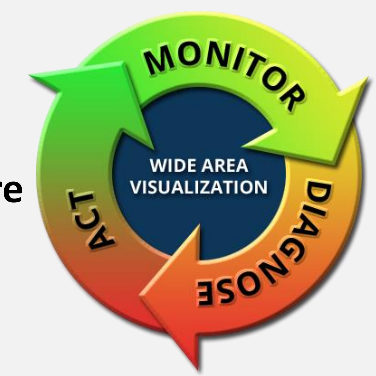
- Load: 6600 MW (Buses B, D, E, F, G and H)
- Generation: 6600 MW (Buses A, C and D)
- Key Phase Angle Paths:

PHASE ANGLE	BASE	CASCADE
A-G	10°	48°
A-E	7°	17°
A-D	6°	26°

- Voltage at Bus G drops to 0.91 PU

A-G Phase Angle difference increased by 38° to 48°; Voltage at G drops to 0.91 PU

ACTION:
Reduce load or add voltage support to restore voltage and prevent further cascading

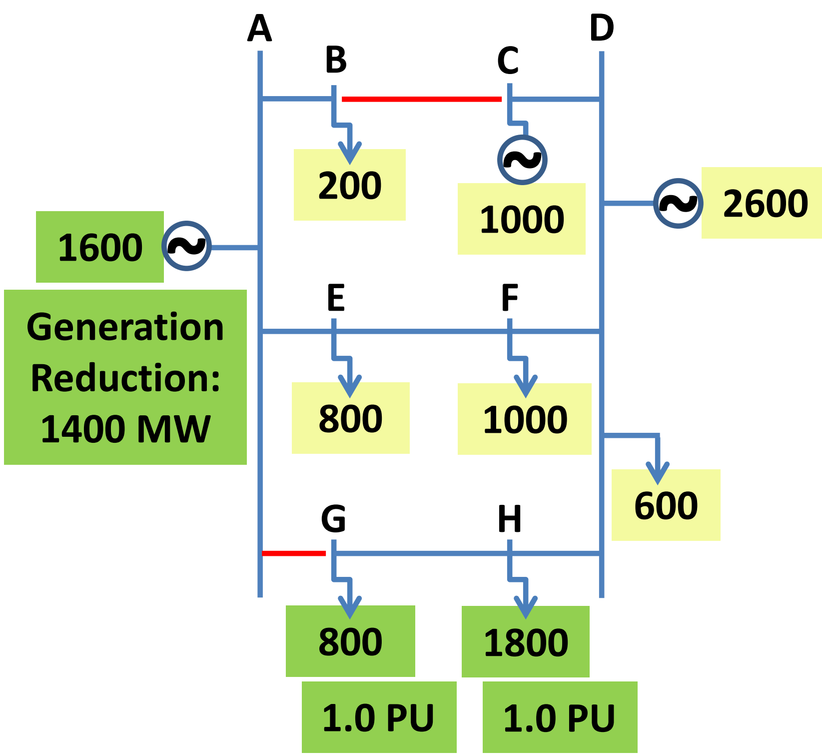


A-G and B-C Tripped

Power Flow Model - 8 Bus System

Cascade – Mitigation – Load Shed

Event: 2 Lines Tripped



Load Reduction: 400 MW at G, 1000 MW at H

- No Change
- Event
- Mitigation

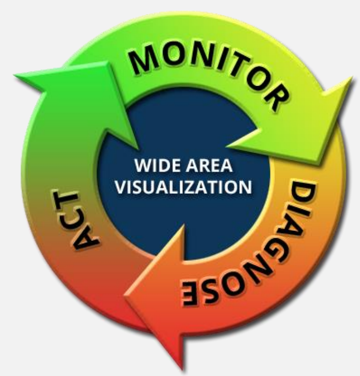
- Load: 6600 MW (Buses B, D, E, F, G and H)
- Generation: 6600 MW (Buses A, C and D)
- Key Phase Angle Paths:

PHASE ANGLE	CASCADE	MITIGATION
A-G	48°	21°
A-E	17°	10°
A-D	26°	9°

- Voltage at Bus G drops to 0.91 PU

A-G Phase Angle difference increased by 38° to 48°; Voltage at G drops to 0.91 PU

ACTION:
Reduce load at G and H to restore voltage, restore A-G line, restore load

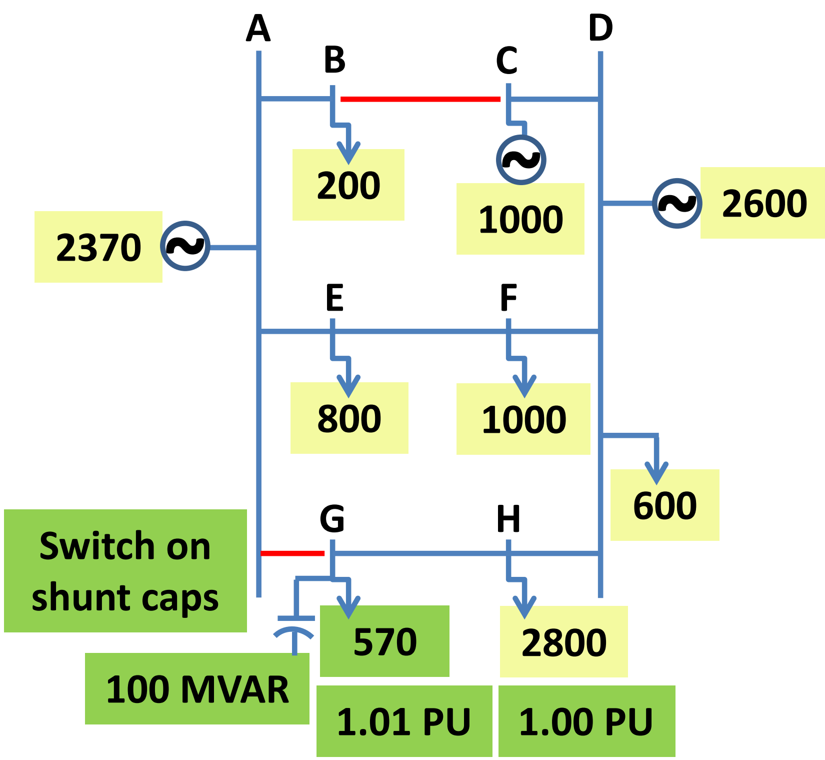


A-G and B-C Tripped

Power Flow Model - 8 Bus System

Cascade - Mitigation - Switch Shunt Caps and Shed Load

Event: 2 Lines Tripped



- No Change
- Event
- Mitigation

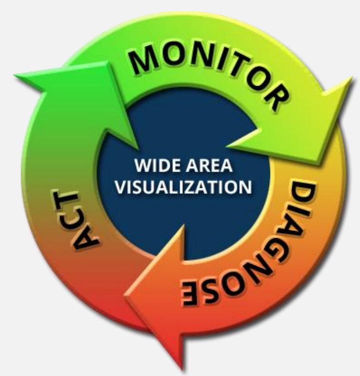
- Load: 6600 MW (Buses B, D, E, F, G and H)
- Generation: 6600 MW (Buses A, C and D)
- Key Phase Angle Paths:

PHASE ANGLE	CASCADE	MITIGATION
A-G	48°	30°
A-E	17°	12°
A-D	26°	17°

- Voltage at Bus G drops to 0.91 PU

A-G Phase Angle difference increased by 38° to 48°; Voltage at G drops to 0.91 PU

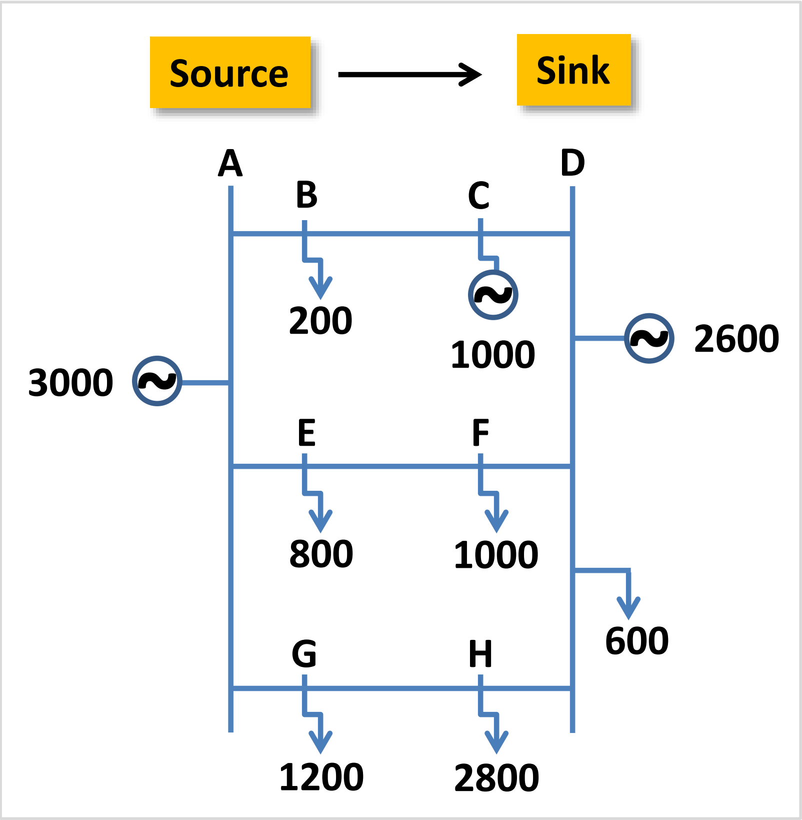
ACTION:
Switch in 100 MVAR at G to restore voltage, reduce 630 MW load, restore A-G line, restore load

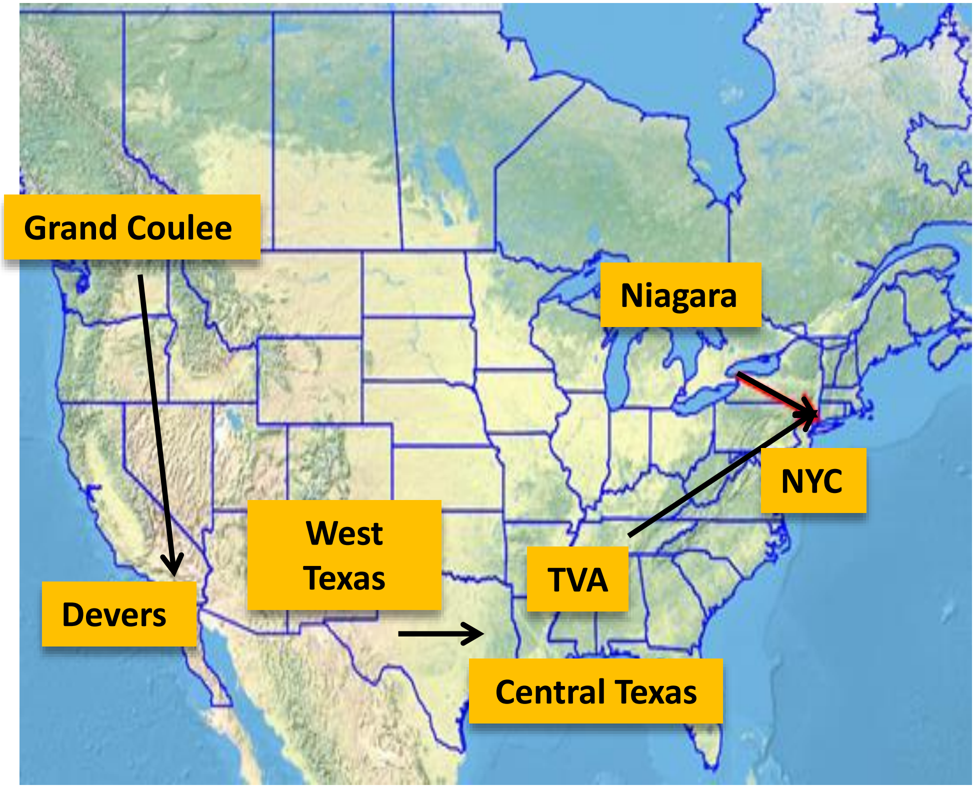


A-G and B-C Tripped

Wide Area Monitoring

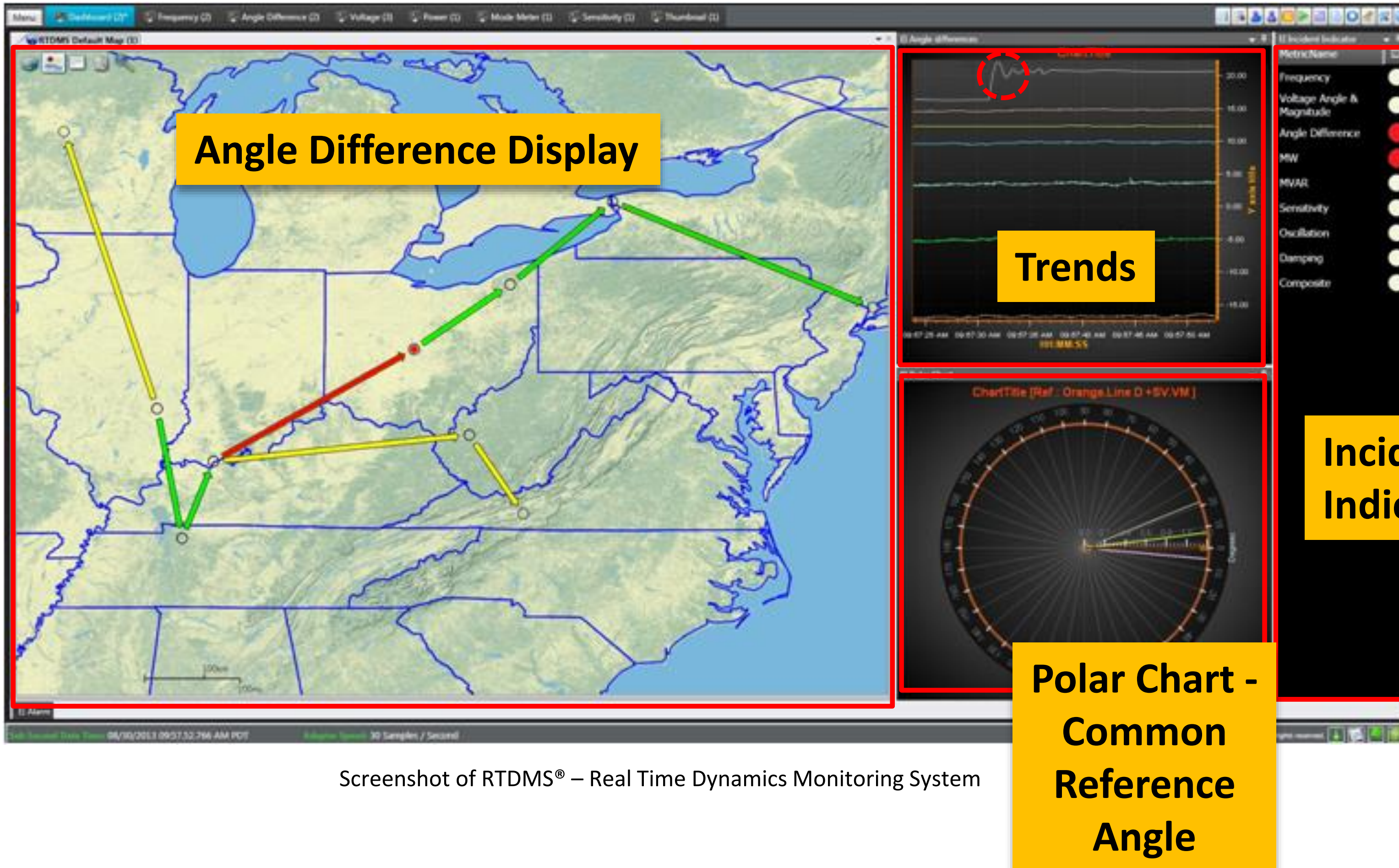
Focus On Phase Angle Difference Between Sources and Sinks





Wide Area Monitoring – Phase Angle Displays

Focus On Phase Angle Difference Between Sources and Sinks

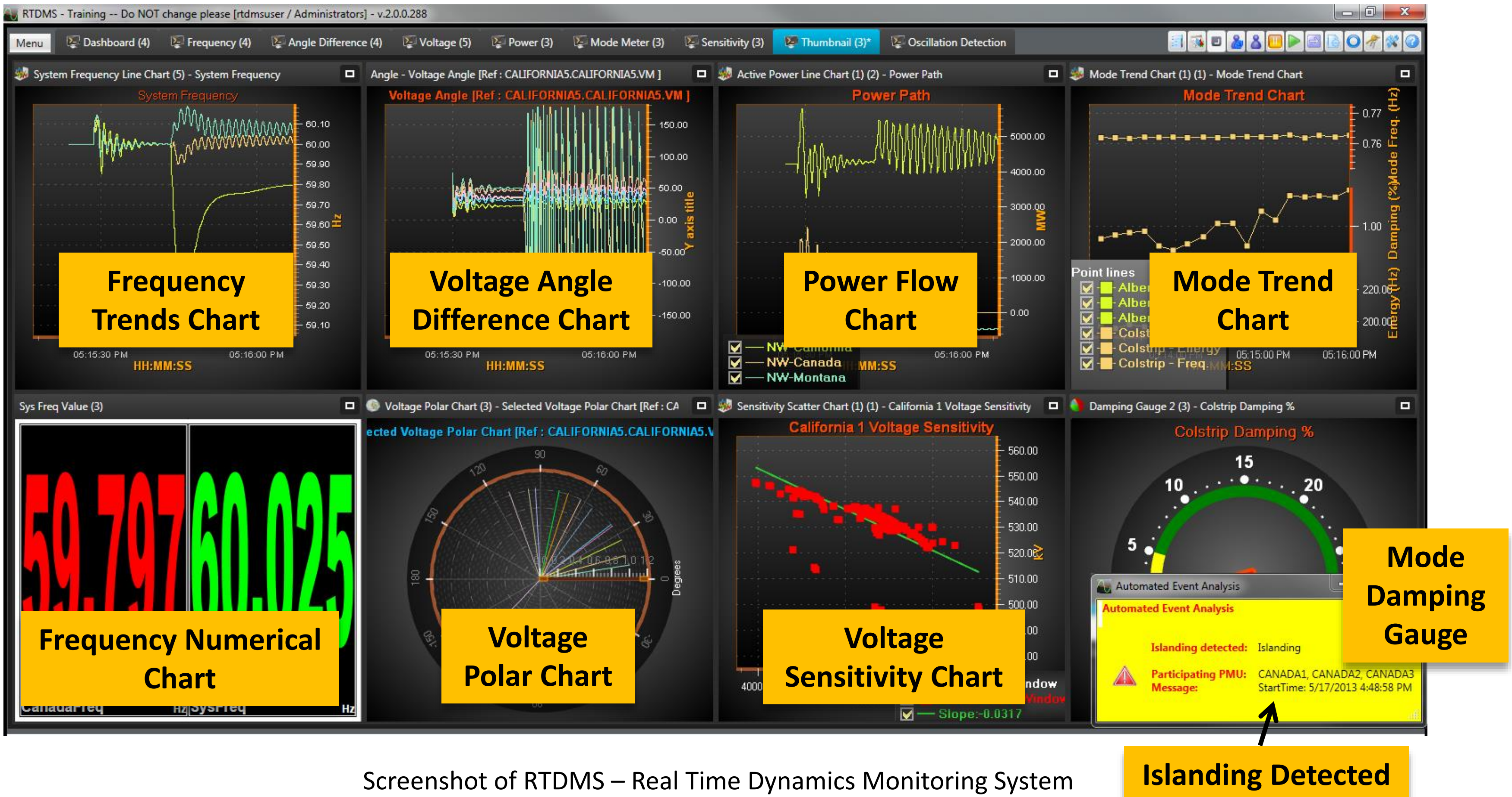


Screenshot of RTDMS® – Real Time Dynamics Monitoring System

Arrow shows Phase Angle Difference between two PMUs – may not represent a transmission line

Wide Area Diagnostics in Real Time

RTDMS – Real Time Dynamics Monitoring System - Used in Control Rooms at ISOs and Utilities



Screenshot of RTDMS – Real Time Dynamics Monitoring System

Phase Angles
Recap

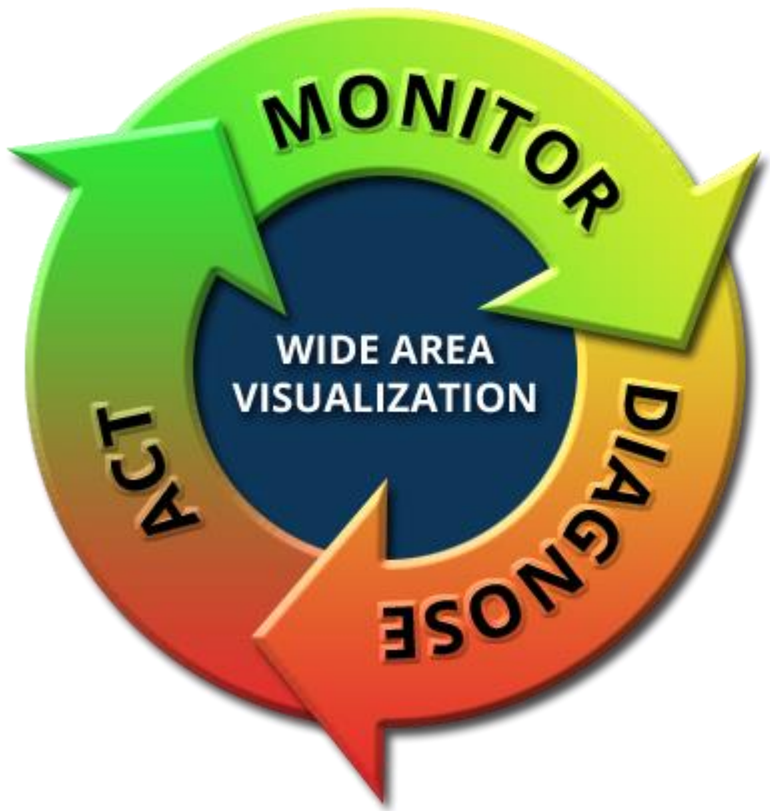
- **What is a Voltage Phasor?**
- **What is an Angle Difference?**
- **Why are Phase Angles important?**
- **What do Phase Angle differences tell me about system stress?**
- **How do I use Phase Angle in real-time monitoring?**
- **What is the difference between Voltage Angle and Current Angle?**
- **What can be diagnosed from monitoring Phase Angles? (Losing synchronization, power flow direction change, change in grid stress)**

Phase Angles
Key Takeaways

Use Phase Angles In Operations to Monitor, Diagnose and Act

Phase Angle Difference = Grid Stress

Operator Actions for Stability:
- Redispatch Generation
- Shed Load
- Provide Voltage Support



Grid Stress Diagnostics:
- Line Trip
- Load Trip
- Generation Trip
- Cascade
- Wide Area, Regional or Local

EPG WEBINAR SERIES

Webinars are planned monthly, on the third Tuesday of each month from 11 a.m. to 12 Noon Pacific. The initial webinar topic list includes:

- System Events - Deciphering the Heartbeat of the Power Grid (Jul 16)
- Using Synchrophasor Technology For Real-Time Operation and Reliability Management (Aug 20)
- **Phase Angle Differences – What They Mean and How to Use Them For Operations (Sep 17)**
- **Establishing Alarm Limits For Use in Operations (Oct 8) NOTE DATE CHANGE**
- **Phasor Simulations – How Can They Be Used in Operations? (Nov 19)**
- **Using Synchrophasor Technology to identify Control System Problems(Dec 17)**
- **Model Validation (Jan 21, 2014)**
- **Data Diagnostics (Feb 17, 2014)**

Feedback

Your feedback and suggestions are important!
PLEASE do let us know…

Q&A

Thank You!

For questions, please contact **Frank Carrera**:
carrera@ElectricPowerGroup.com

Or if you prefer, call and tell us directly:
(626)685-2015

Electric Power Group

201 S. Lake Ave., Suite 400
Pasadena, CA 91101
(626)685-2015
www.ElectricPowerGroup.com

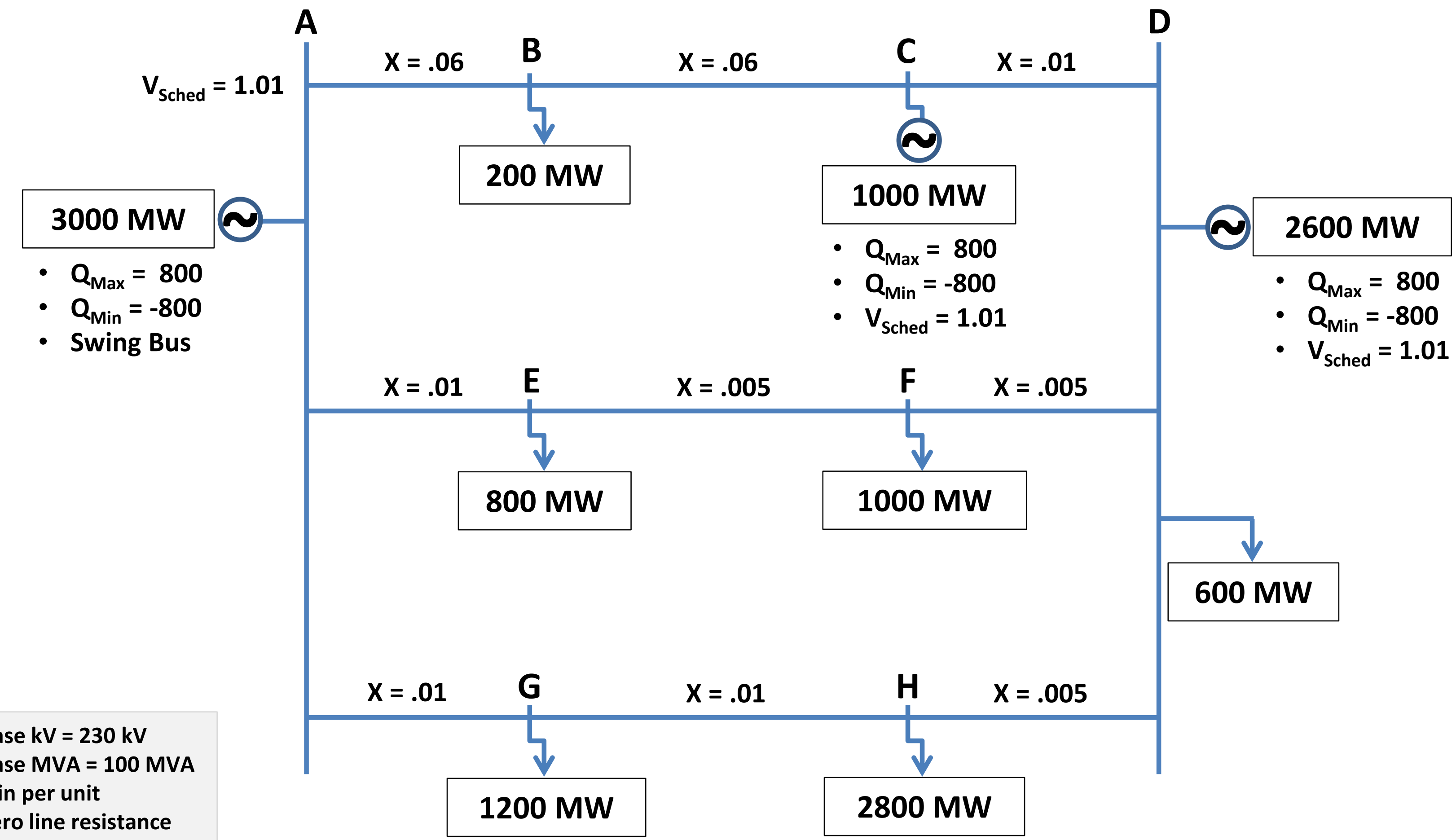
Index

Power Flow Model - 8 Bus System

Appendix

Power Flow Model - 8 Bus System

Used In EPG's Sep 17, 2013 Webinar on Phase Angle Differences by John Ballance



- Base kV = 230 kV
- Base MVA = 100 MVA
- X in per unit
- Zero line resistance
- Zero line charging