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 $\delta_1$
- 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)
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: \( P = \frac{V_1 V_2 \sin(\theta - \phi)}{Z} \), where \( \theta \) is greater than \( \phi \)
- 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

Substation 1

\[ V_1 e^{j\theta} \]

Substation 2

\[ V_2 e^{j\theta} \]

Line(s) impedance \( Z \)
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 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.

Screenshot of RTDMS® – Real Time Dynamics Monitoring System
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

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

<table>
<thead>
<tr>
<th>PHASE ANGLE</th>
<th>BASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-G</td>
<td>10°</td>
</tr>
<tr>
<td>A-E</td>
<td>7°</td>
</tr>
<tr>
<td>A-D</td>
<td>6°</td>
</tr>
</tbody>
</table>

**System Stable**

- A - G: 3000
- A - E: 200
- A - D: 1000
- B - E: 800
- C - F: 1000
- G - H: 600
- E - F: 200
- C - D: 2600

**No Change**

- Event
- Mitigation

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Power Flow Model - 8 Bus System

Line Trip

Event: Line Trip (A-G)

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

<table>
<thead>
<tr>
<th>PHASE ANGLE</th>
<th>BASE</th>
<th>LINE TRIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-G</td>
<td>10°</td>
<td>45°</td>
</tr>
<tr>
<td>A-E</td>
<td>7°</td>
<td>16°</td>
</tr>
<tr>
<td>A-D</td>
<td>6°</td>
<td>24°</td>
</tr>
</tbody>
</table>

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

ACTION: Redispatch
**Power Flow Model - 8 Bus System**

**Line Trip - Mitigation**

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

**Options for Redispatch:**

<table>
<thead>
<tr>
<th>ACTION</th>
<th>SENSITIVITY X°/100MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce G Load</td>
<td>2.60°</td>
</tr>
<tr>
<td>Reduce H Load</td>
<td>1.85°</td>
</tr>
<tr>
<td>Reduce D Load and Increase D Gen</td>
<td>1.28°</td>
</tr>
<tr>
<td>Increase C Generation</td>
<td>1.10°</td>
</tr>
</tbody>
</table>

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

*Gen A adjusted to balance network load
Effectiveness of Mitigation Options In Reducing A-G Angle

Required Mitigation MW

-620 MW
-900 MW
-1300 MW
-1530 MW

Recommended Action

Reduce Load at G
Reduce Load at H
Reduce Load at D*
Increase Gen at C

Required A-G Angle: 30°
A-G Angle After Event: 45°

*Reduce load, then increase generation to mitigate

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**Power Flow Model - 8 Bus System**

**Line Trip - Mitigation**

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

**Options for Redispatch:**

<table>
<thead>
<tr>
<th>ACTION</th>
<th>SENSITIVITY X°/100MW</th>
<th>RESULT: A-G ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce G Load by 620 MW</td>
<td>2.60°</td>
<td>30°</td>
</tr>
<tr>
<td>Reduce H Load by 900 MW</td>
<td>1.85°</td>
<td>30°</td>
</tr>
<tr>
<td>Reduce D Load by 600 MW &amp; Increase D Gen by 700 MW</td>
<td>1.28°</td>
<td>30°</td>
</tr>
<tr>
<td>Increase C Generation by 1530 MW</td>
<td>1.10°</td>
<td>30°</td>
</tr>
</tbody>
</table>

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

*Gen A adjusted to balance network 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:**

<table>
<thead>
<tr>
<th>PHASE ANGLE</th>
<th>BASE</th>
<th>LOAD TRIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-G</td>
<td>10°</td>
<td>8°</td>
</tr>
<tr>
<td>A-E</td>
<td>7°</td>
<td>5°</td>
</tr>
<tr>
<td>A-D</td>
<td>6°</td>
<td>3°</td>
</tr>
</tbody>
</table>

**ACTION:**

- **Generation Redispached**

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

**No Change**

- **Generation Reduction:** 600 MW

**Load Trip**
Power Flow Model - 8 Bus System
Generation Trip

Event: 600 MW Gen Loss at C

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

<table>
<thead>
<tr>
<th>PHASE ANGLE</th>
<th>BASE</th>
<th>GEN TRIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-G</td>
<td>10°</td>
<td>11°</td>
</tr>
<tr>
<td>A-E</td>
<td>7°</td>
<td>8°</td>
</tr>
<tr>
<td>A-D</td>
<td>6°</td>
<td>9°</td>
</tr>
</tbody>
</table>

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

ACTION: Redispatch

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### Power Flow Model - 8 Bus System

**Cascade – Loss of A-G and B-C Lines**

**Load:** 6600 MW (Buses B, D, E, F, G and H)

**Generation:** 6600 MW (Buses A, C and D)

**Key Phase Angle Paths:**

- 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

**Event: 2 Lines Tripped**

- A-G
- B-C

**PHASE ANGLE**

<table>
<thead>
<tr>
<th></th>
<th>BASE</th>
<th>CASCADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-G</td>
<td>10°</td>
<td>48°</td>
</tr>
<tr>
<td>A-E</td>
<td>7°</td>
<td>17°</td>
</tr>
<tr>
<td>A-D</td>
<td>6°</td>
<td>26°</td>
</tr>
</tbody>
</table>

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

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Event: 2 Lines Tripped

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

Key Phase Angle Paths:

<table>
<thead>
<tr>
<th>PHASE ANGLE</th>
<th>CASCADE</th>
<th>MITIGATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-G</td>
<td>48°</td>
<td>21°</td>
</tr>
<tr>
<td>A-E</td>
<td>17°</td>
<td>10°</td>
</tr>
<tr>
<td>A-D</td>
<td>26°</td>
<td>9°</td>
</tr>
</tbody>
</table>

- Voltage at Bus 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**

- **Load**: 6600 MW (Buses B, D, E, F, G and H)
- **Generation**: 6600 MW (Buses A, C and D)

**Key Phase Angle Paths**:

<table>
<thead>
<tr>
<th>PHASE ANGLE</th>
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<th>MITIGATION</th>
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<tr>
<td>A-G</td>
<td>48°</td>
<td>30°</td>
</tr>
<tr>
<td>A-E</td>
<td>17°</td>
<td>12°</td>
</tr>
<tr>
<td>A-D</td>
<td>26°</td>
<td>17°</td>
</tr>
</tbody>
</table>

- **Voltage at Bus G drops to 0.91 PU**

- **Switch on shunt caps**: 100 MVAR

**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**

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Wide Area Monitoring
Focus On Phase Angle Difference Between Sources and Sinks

Source → Sink

- A
- B: 200
- C: 1000
- D: 2600
- E
- F
- G: 800
- H: 1000
- 1200
- 2800
- 3000

Map:
- Grand Coulee
- Niagara
- NYC
- West Texas
- TVA
- Central Texas
- Devers
Wide Area Monitoring – Phase Angle Displays
Focus On Phase Angle Difference Between Sources and Sinks

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

**Angle Difference Display**

**Trends**

**Incident Indicator**

**Polar Chart - Common Reference Angle**

Screenshot of RTDMS® – Real Time Dynamics Monitoring System
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

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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)
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

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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)
Your feedback and suggestions are important! PLEASE do let us know...
Thank You!

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

Or if you prefer, call and tell us directly:
(626)685-2015
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Power Flow Model - 8 Bus System

• **Base Case** (Slide 9)
• **Line Trip** (Slides 10-13)
• **Load Trip** (Slide 14)
• **Generation Trip** (Slide 15)
• **Cascade** (Slides 16-18)
Appendix
Power Flow Model - 8 Bus System

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

- **A**
  - Voltage Scheduled (V_sched) = 1.01
  - 3000 MW
  - Q_max = 800
  - Q_min = -800
  - Swing Bus

- **B**
  - X = 0.06
  - 200 MW

- **C**
  - X = 0.06
  - 1000 MW
  - Q_max = 800
  - Q_min = -800
  - V_sched = 1.01

- **D**
  - X = 0.01
  - 2600 MW
  - Q_max = 800
  - Q_min = -800
  - V_sched = 1.01

- **E**
  - X = 0.01
  - 800 MW

- **F**
  - X = 0.005
  - 1000 MW

- **G**
  - X = 0.01
  - 1200 MW

- **H**
  - X = 0.005
  - 2800 MW

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