Announcements

• Homework 7 is due on Nov 24
• Associated with Homework 7 there can be optional student presentations on Nov 24
  • Let me know if you would like to present
Inertia and Governor Power Flows

- In the regular power flow a single slack bus is used so total load + losses = total generation.
- The slack bus is characterized by having a fixed voltage magnitude and angle.
  - A slack bus is needed for each island though nothing precludes having multiple slack buses in an island.
- If an area is on AGC then the outputs for the other generators can be changed either before or during the power flow solution.
- This does not match the initial change in the generator output following a contingency.
Inertia and Governor Power Flows

• Following a generation and/or load contingency the changes in the generator outputs will be
  – Initially determined by the generator’s inertia
  – After several seconds the output will be determined by the generator’s governor response, which takes into account limits
  – After dozens of seconds to minutes the AGC will respond

• A governor or an inertia power flow seeks to match this initial response
Generator Output Example

- Example shows the generator outputs following the loss of a 250 MW generator (at Kyle138)
Generator Output Example, cont.

- Graph shows the normalized change in output, with the initial value based on the inertia then on the governor.
Inertia and Governor Power Flows

• The inertia and governor power flows seek to match this response by including in each real power balance equation an additional term that the allocates this power mismatch to each generator in proportion to its relative percentage inertia or relative percentage governor response

• This is a distributed slack approach since the allocation occurs inside the power flow iteration

• There is still a slack bus to provide an angle reference
Inertia Power Flow

- In an inertia power flow let $\alpha$ be the accelerating power. Then at each generator bus $i$ the generator output is
  \[ P_{Gi} = P_{0,Gi} + \frac{H_i}{H_T} \alpha \]
  where $P_{0,Gi}$ is the initial power output for the bus $i$ generators,
  $H_i$ is the inertia constant for all the generators at bus $i$ and
  $H_T$ is the total inertia constant for all the generators
  (both values are per unit on the system MVA base)

- The accelerating power can just be included as a solution variable

- Real power flow equations are then written for all the buses, but the slack angle is not a solution variable
Two Bus DC Power Flow Example

- Assume a two bus system with the buses connected with a lossless line with $X=0.1$. Let bus 2 be the slack with $\theta_2=0$, generators at both buses with $P_{G1}=1$ and a single load (at bus 1) with $P_{L1}=3$. Assume equal inertia for the generators.

- In a traditional dc power flow there is one equation

\[ P_{G1} - P_{L1} = 1 - 3 = 10\theta_1 \]
Two Bus DC Power Flow Example

• With the inertia approach there would be two equations and the power is specified at both buses (say \( P_{G2} = 1.5 \))

\[
P_{G1} - P_{L1} + 0.5\alpha = 10\theta_1
\]
\[
P_{G2} + 0.5\alpha = 10\theta_1
\]

• Solving gives

\[
\begin{bmatrix}
10 & -0.5 \\
-10 & -0.5
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\alpha
\end{bmatrix}
= 
\begin{bmatrix}
-2 \\
1.5
\end{bmatrix}
\Rightarrow
\begin{bmatrix}
\theta_1 \\
\alpha
\end{bmatrix}
= 
\begin{bmatrix}
-0.175 \\
0.5
\end{bmatrix}
\]
Power System Restoration

- Power system restoration or black start (or blackstart)
  - A procedure to restore power in the event of a partial or total shutdown of the power system
  - A highly complex decision problem
- Object is to serve the load as soon as possible without violating operating constraints
  - Actions are time critical
- Primarily manual work by operators
- Offline restoration planning usually based on simulations
Power System Restoration

- Common characteristics of restoration (even though strategies are different)
  - Immediate resupply of station service
  - Time consuming nature of switching operation
  - Start-up timings of thermal units
  - Voltage rise problems of energizing unloaded transmission lines
  - Frequency response of prime movers to a sudden load pickup
  - Cold load inrush, power factors and coincident demand factors
System Restoration Efforts - IEEE

- After 1977 New York City blackout, DOE required operating companies to develop a power system restoration plan, train personnel, regularly update and maintain the plan.

- In response to this requirement in 1978, the Power System Operation Committee established the Power System Restoration (PSR) Task Force (TF) within the System Operation Subcommittee of the Power System Engineering Committee.

- A few years later, the PSR TF was upgraded to PSR working group (WG)
System Restoration Efforts - IEEE

• In 1993 a 110 page brochure was prepared by PSR WG and published by the IEEE PES

• Includes:
  – 14 IEEE Committee Reports
  – 5 SRWG member papers in IEEE publication
  – 13 related IEEE transaction papers
In 2000 a 700 page book was prepared by PSRWG and published by Wiley-IEEE Press.

Includes 87 papers including 14 papers in the original 1993 collection.
System Restoration Efforts - IEEE

- In 2014 40 IEEE papers by 110 authors including 42 panelists of Restoration Dynamics Task Force

- Covers:
  - Real power balance and control of frequency
  - Reactive power balance and control of voltages
  - Critical tasks (time sensitive functions)
  - Analyses and simulations
Mahmood Mike Adibi (1924 – 2018)

- The godfather of power system restoration
- B.S.E. in 1950 from University of Birmingham, U.K.
- M.S.E in 1960 from Polytech Institute of Brooklyn, NY
- IEEE Life Fellow
- Founder and chairman of the IEEE System Restoration Working Group in 1979
  - A great review book of IEEE papers between 1987 and 1999
- Developed restoration plans for over a dozen utilities
Other Good References

- PJM Manual 36: System Restoration
NERC Standards on Restoration

- NERC System Restoration and Black Start standards
  - EOP-005-2 & EOP-005-3
    - System Restoration from Black Start Resources
    - Ensure plans, Facilities, and personnel are prepared to enable System restoration from Black Start Resources to assure reliability is maintained during restoration and priority is placed on restoring the Interconnection
  - EOP-006-2 & EOP-006-3
    - System Restoration Coordination
    - Ensure plans are established and personnel are prepared to enable effective coordination of the System restoration process to ensure reliability is maintained during restoration and priority is placed on restoring the Interconnection.
Common Issues during Restoration

• Active power balance and frequency control
  – Need to maintain system frequency within limits by system stability and protection settings
  – Can be accomplished by picking up loads in increments

• Reactive power balance and overvoltage control
  – Energizing few high voltage lines
  – Operating generators at minimum voltage levels
  – Deactivating switched shunt capacitors
  – Connecting shunt reactors
  – Adjusting transformer taps
  – Picking up reactive loads
Common Issues during Restoration

- **Transient switching voltages**
  - Switching surges occur when energizing equipment

- **Self-excitation**
  - When the charging current is high relative to the size of generators
  - When opening a line at the sending end but leaving the line connected to a large motor
  - This causes overvoltage and damages equipment

- **Cold load pickup**
  - When load has been de-energized for several hours or more
  - Inrush current can be as high as 8 – 10 times of the normal value
Common Issues during Restoration

• System stability
  – Voltage should be within limits
  – Angle stability have to be maintained
  – Frequency is the main issue in stability assessment

• Protective systems and load control
  – Continuous change in system configuration and in operating conditions may trigger undesirable operation of relays
  – Load shedding can be useful in case of low frequency conditions
Common Issues during Restoration

• Partitioning system into islands
  – Necessary to speed up the process, especially for large systems
  – NERC standards
    • Each islands must have sufficient black start capability
    • Each islands should have enough cranking paths to gens and loads
    • Each islands should be able to match generation and load within prescribed frequency limits
    • Each islands should have adequate voltage controls
    • All tie points must be capable of synchronization with adjacent subsystems
    • All islands should share information with other islands
Generic Restoration Steps

• Preparation stage (1 – 2 hours)
  – Evaluate pre- and post-disturbance conditions
  – Define the target system
  – Restart generators and rebuild transmission network

• System restoration stage (3 – 4 hours)
  – Energize transmission paths
  – Restore load to stabilize generation and voltage
  – Synchronize islands and reintegrate bulk power system

• Load restoration stage (8 – 10 hours)
  – Load restoration is the governing control objective
  – Load pickup is scheduled based on generation availability
  – Load restoration is effected in increasingly larger steps
System Restoration Tasks

• Know the status of the grid
• List and rank critical loads by priority
• List and rank initial sources of power by availability
  – Maximize generation capabilities with the available black start resources
• Determine the most effective ways of bringing the two together
  – Schedule tasks and resources during restoration
  – Establish transmission capability and paths while meeting operating constraints
Initial Power and Load

- Initial source of power

<table>
<thead>
<tr>
<th>Type</th>
<th>Time (min)</th>
<th>Success probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-of-the-River Hydro</td>
<td>5-10</td>
<td>High</td>
</tr>
<tr>
<td>Pump-Storage Hydro</td>
<td>5-10</td>
<td>High</td>
</tr>
<tr>
<td>Combustion Turbine</td>
<td>5-15</td>
<td>Medium</td>
</tr>
<tr>
<td>Tie-line with Adjacent Systems</td>
<td>Short</td>
<td></td>
</tr>
</tbody>
</table>

- Initial critical loads

<table>
<thead>
<tr>
<th>Type</th>
<th>Priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranking drum-type units</td>
<td>High</td>
</tr>
<tr>
<td>Pipe-type cables pumping plants</td>
<td>High</td>
</tr>
<tr>
<td>Transmission stations</td>
<td>High to Medium depending on location</td>
</tr>
<tr>
<td>Distribution stations</td>
<td>High to Medium depending on location</td>
</tr>
<tr>
<td>Industrial loads</td>
<td>Medium to low</td>
</tr>
</tbody>
</table>
Electric Grid Visualization

- Electric grid models can be quite complex and large
  - There are commonly many assumptions and automatic control actions embedded in these models.
- Oftentimes engineers do studies associated with these grids, not always fully understanding these embedded assumptions or how the models can fail.
- Electric grid visualization is focused on helping people understand what occurred when the engineer “pushed the button.”
Visualization Software Design

• Key question: what are the desired tasks that need to be accomplished?
  – Needs for real-time operations might be quite different than what is needed in planning

• Understanding the entire processes in which the visualizations are embedded is key

• Software should help humans make the more complex decisions, i.e., those requiring information and knowledge
  – Enhance human capabilities
  – Alleviate their limitations (adding up flows into a bus)
Some Useful General References

- Claus Wilke, *Fundamentals of Data Visualization*, 2019
Example: Visualization and Cholera in Central London, 1854

Dr. John Snow helped to end an epidemic by noting that the deaths were clustered about the Broad Street Water pump.

Images source: http://www.datavis.ca/gallery/historical.php
Graph used to determine whether to launch Challenger in 1986; shows O-ring failure vs. temperature but neglects launches with no failures.

A better graphic including all data. Would you launch at 32°F?
Visualization Cautions!

- Just because information can be shown graphically, doesn’t mean it should be shown.
- Three useful design criteria from 1994 EPRI visualization report:
  1. Natural encoding of information
  2. Task specific graphics
  3. No gratuitous graphics


Tufte: “may well be worst graphic ever”
Visualization and User Familiarity

• Visualizations do not exist in a vacuum; the prior experience of the users is a key consideration
  – QWERTY keyboard arrangement is a classic example, in which a design that was originally setup in the 1870’s to prevent mechanical problems is still used today

• Using existing visual metaphors in new designs help them seem more familiar (like a folder)
  – A skeuomorphic design retains no longer needed structures that were inherent in the original, usually to make them more familiar (using gauges, sliders, buttons and analog clocks in visualizations are examples)
Decision Making, Data, Information, Knowledge

- Ultimate goal is to help humans make better decisions
- Competing definitions for the process of taking raw “data” and producing something useful
  - Understanding, decisions, wisdom
- Data: symbols, raw, it simply exists
- Information: Data that is given meaning, often in a relational context; some how processed
- Knowledge: Application of information to answer “how.” Connecting patterns.
- Understanding, and/or wisdom at top
The Visualization Process

Figure 1.2 The visualization process.

Understanding the Entire Process is Key

• Understanding the entire processes in which the visualizations are embedded is key.
  – What is the “information access” cost?
  – How will the information be used and shared?
  – Is it raw data, or derived values?
  – Should the visualizations sit on top of a model, or is a standalone process sufficient?
  – Ultimately, what are the desired tasks that need to be accomplished?

• We’ll start with a brief coverage of some traditional approaches (tabular, graphs and onelines, then go into some newer ones)
Example: Tabular Displays

- In many contexts, tabular displays (particularly with interactive features such as sorting, filtering, drill-down, and the ability to enter data) can be a great way to show data.
Use of Color

• Some use of color can be quite helpful
  – 10% of male population has some degree of color blindness (1% for females)

• Do not use more than about ten colors for coding if reliable identification is required

• Color sequences can be used effectively for data maps (like contours)
  – Grayscale is useful for showing forms but not values
  – Multi-color scales (like a spectrum) have advantages (more steps) but also disadvantages (effectively comparing values) compared to bi-color sequences

The book by Colin Ware is a great resource
Graphs

- Graphs are also a great way to show information, particularly for time-variation.
- The number of curves needs to match the task.

A few curves, detail of each visible, key can identify objects (several thousand values)

Envelope of response for the 80k bus, 40,000 substation frequencies (24 million values)
Onelines

- Widely used and can be quite effective for showing substations (or local regions) or smaller grids; can be slow on larger systems
Visualization Background: Preattentive Processing

• When displaying large amounts of data, take advantage of preattentive cognitive processing
  – With preattentive processing the time spent to find a “target” is independent of the number of distractors

• Graphical features that are preattentively processed include the general categories of form, color, motion, spatial position
Preattentive Processing Examples

All are preattentively processed except for juncture and parallelism; however too many can defeat their purpose.

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Fig 5.12
Preattentive Processing with Color & Size

42 Bus Case
Metric: Unserved MWh: 0.00
Unserved Load: 0.00 MW

Apple
Oak
Palm
Tiger
Prairie
Eagle
Sugar
Lake
Ram
42%
268%
88%
28%
66%
Detecting Patterns

• A large portion of information visualization is associated with detecting patterns

• Gestalt (German for “pattern”) Laws
  – Proximity
  – Similarity (we didn’t discuss color)
  – Connectedness
  – Common Fate (flows)
Proximity, Similarity, Connectedness,

Connectedness is stronger than proximity, color, shape

Similarity makes all perceived as rows

Source: Information Visualization (Fourth Edition) by Colin Ware, Chapter 6 Images
Common Fate: Patterns in Motion

- Motion can be a very effective means for showing relationships between data
- People perceive motion with great sensitivity
- Motion can also be used to convey causality (one event causing another)
- However, too much motion can be a distractor
Scattered Data Interpolation (Colored Contouring)

• For wide-area visualization, contours can be effective for showing large amounts of spatial data
  – Takes advantage that as humans we perceive the world in patterns (sometimes even when none exist!)
  – Now widely used

• Scattered data interpolation algorithms are needed to take the discrete power system data and make it spatially continuous
  – Various algorithms can be used include a modified Shephard’s and Delaunay triangulation

• A color mapping is needed
Shepard’s Algorithm, Blue/Red Discrete Color mapping

42 Bus Case

Unserved Load: 0.00 MW

Apple
Oak
Eagle
Tiger
Prairie
Palm
Sidney
Badger
Bear
Valley
Lake
Ram

Hickory138
Elm138
Lark138
Monarch138
Willow138
Homer138
Owl138
Walnut138
Parkway138
Spruce138
Ash138
Peach138
Rose138
Steel138

电压/单位
-1.02 pu
-0.95 pu
-0.88 pu

电压
-1.02 pu
-0.95 pu
-0.88 pu

-1.02 pu
-0.95 pu
-0.88 pu

42 Bus Case

Unserved MWh: 0.00

Unserved Load: 0.00 MW
Delaunay Algorithm, Spectrum Continuous Color mapping

The color in this contour is too intense!
Some General Thoughts on Power System Visualizations

• While the previous techniques can be quite helpful, there is often just too much data to display.

• Interactive visualizations, taking advantage of the underlying geographic information, can be quite effective, particularly if the displays can be rapidly customized to show different sets of information.

• Also, much of the data should first be pre-processed using potentially quite sophisticated algorithms.
Geographic Data Views

- One way to make visualizations more interactive is to use underlying geographic information to quickly auto-create displays
  - Known as geographic data views (GDVs)
- GDVs can be used either on individual objects (like generators, buses, or substations), or on aggregate objects (like areas and zones)
- The GDV display attributes (e.g., size, color) can be used to show object data
- The GDV displays can be saved for later use and links to the underlying objects allow for drilldown
80,000 Bus System Area GDV Example

Size is proportional to the area’s generation, while the color is based on the amount of exports.
Texas 2000 Substation GDV

Size is proportional to the substation MW throughput, while the color is based on the amount of substation generation.
Pseudo-Geographic Mosaic Displays

• GDVs can be quite useful, but there is a tradeoff between geographic accuracy and maximum display space usage
  – Much of the electric grid is concentrated in small (primarily urban) areas

• Pseudo-Geographic Mosaic Displays (PGMDs) utilize a tradeoff of geographic accuracy to maximize display space
80,000 Bus System Area PGMD

GDVs are as before (size = area gen MW, color = interchange); the percentages show the amount of transition
Some Techniques for Dealing with Time-Varying Data

• Need to keep in mind the desired task!
• Tabular displays
• Time-based graphs (strip-charts for real-time)
• Animation loops
  – Can be quite effective with contours, but can be used with other types of data as well
• Data analysis algorithms, such as clustering, to detect unknown properties in the data
  – There is often too much data to make sense without some pre-processing analysis!
Animation loops

- Animation loops trade-off the advantages of snapshot visualizations with the time needed to play the animation loop
  - A common use is in weather forecasting
- In power systems applications the length/speed of the animation loops would depend on application
  - In real-time displays could update at either SCADA or PMU rates
  - Could be played substantially faster than real-time to show historical or perhaps anticipated future conditions
Wide-Area Contours Can be Quickly Created Using GDVs

Image shows a substation GDVs with 40,000 subs; when making the contour the GDV size is shrunk so they are invisible.
When making movies we use the Delaunay contours because they are so fast.
80K-Bus Frequency Variation (Substation Contour; Time = 8.0 Seconds)
When showing values like voltage magnitudes it is often better to show the deviation from the initial values.