ECE 422
Power System Operations & Planning
1 – General Background

Spring 2015
Instructor: Kai Sun
Outline

• Overview of power system reliability and NERC guidelines
• Introduction of power system stability (basic concepts, definitions and examples)
• Materials
  – Part I (Chapters 1&2) of Kundur’s book
  – Glossary of Terms Used in NERC Reliability Standards, Dec 21, 2012
Structure of an AC Power System

- **Generation**
  - Low voltages <25kV due to insulation requirements

- **Transmission system**
  - Backbone system interconnecting major power plants (11-35kV) and load center areas
  - 161kV, 230kV, 345kV, 500kV, 765kV, etc.

- **Sub-transmission system**
  - Transmitting power to distribution systems
  - Typically, 35/69kV-138kV

- **Distribution system**
  - Typically, 4kV-34.5kV

Bulk Power System (Bulk Electric System)

- NERC definition
  - The bulk electric system is a term commonly applied to the portion of an electric utility system that integrates “the electrical generation resources, transmission lines, interconnections with neighboring systems, and associated equipment, generally operated at voltages of 100 kV or higher.”
  - Radial transmission facilities serving only load with one transmission source are generally not included in this definition

- For short, a bulk electric system is the part of the transmission/sub-transmission system connecting
  - power plants,
  - major substations, and
  - HV transmission lines

- Most of power system reliability concerns are about bulk electric systems
NERC (North American Electric Reliability Corporation)

• As a non-government organization, formed by the electric utility industry in 1968 to promote the reliability of bulk power systems in North America.

• Initially membership was voluntary and member systems followed the reliability criteria for planning and operating bulk power systems to prevent major system disturbances following severe contingencies.

• As of June 2007, FERC (U.S. Federal Energy Regulatory Commission) granted NERC the legal authority to enforce reliability criteria with all users, owners, and operators of the bulk power systems in the U.S.

• NERC Membership is now mandatory and member systems comply with NERC’s Reliability Standards (approved by FERC) to both promote reliable operations and to avoid costly monetary penalties if caught non-compliant. Every system operator should read, understand and follow NERC’s Reliability Standards. (Visit http://www.nerc.com for more information on NERC.)
NERC Functional Model Diagram

Standards and Compliance Functions
- Standards Development Standards Developer
- Compliance Enforcement Compliance Enforcement Authority
- Reliability Assurance Reliability Assurer

Reliability Service Functions
- Operating Reliability Reliability Coordinator
- Transmission Service Transmission Service Provider
- Planning Reliability Planning Coordinator
- Interchange Interchange Coordinator
- Balancing Balancing Authority

Planning and Operating Functions
- Transmission Ownership Transmission Owner
- Generator Operations Generator Operator
- Transmission Operations Transmission Operator
- Load Serving Load-Serving Entity
- Purchasing-Selling Purchasing-Selling Entity
- Distribution Distribution Provider
- Market Operations Market Operator
- Resource Planning Resource Planner
NERC Balancing Authorities

- EI has about 90 BAs, which range in load size up to 130GW peaks.
- WI (WECC) has about 30 BAs.
- ERCOT and Hydro Quebec are each operated as single BAs.
Reliability of Bulk Power Systems

• Power systems should be built and operated to **ACHIEVE A RELIABLE ELECTRIC POWER SUPPLY AT THE MOST ECONOMICAL COST**

• Reliability is defined using two terms:
  
  – **Adequacy (planning)**: The ability of the electric systems to supply the **aggregate electrical demand and energy requirements** of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.
  
  – **Security (operation)**: The ability of the electric systems to withstand **sudden disturbances** such as electric short circuits or unanticipated loss of system elements.
Reliability of Bulk Power Systems (cont’d)

• Important requirements of a reliable electric power service
  – Voltage and frequency must be held within close tolerances
  – Synchronous generators must be kept running in parallel with adequate capacity to meet the load demand
  – Maintain the “integrity” of the bulk power network (avoid cascading outages)
  – Others
Example of NERC’s Reliability Standards: Performance under Normal and Emergency Conditions

Table I. Transmission System Standards – Normal and Emergency Conditions

<table>
<thead>
<tr>
<th>Category</th>
<th>Contingencies</th>
<th>System Limits or Impacts</th>
<th>Loss of Demand or Curtained Firm Transfers</th>
<th>Cascading Outages</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No Contingencies</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>B</td>
<td>Event resulting in the loss of a single element.</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Single Line Ground (SLG) or 3-Phase (30) Fault, with Normal Clearing:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1. Generator</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>2. Transmission Circuit</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>3. Transformer</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Loss of an Element without a Fault</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Single Pole Faults, Normal Clearing:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>4. Single Pole (dc) Line</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>C</td>
<td>Event(s) resulting in the loss of two or more (multiple) elements.</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>SLG Fault, with Normal Clearing:</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1. Bus Section</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>2. Breaker (failure or internal fault)</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>SLG or 30 Fault, with Normal Clearing:</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>3. Category B (B1, B2, B3, or B4) contingency, manual system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Bipolar Block, with Normal Clearing:</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>4. Bipolar (dc) Line Fault (non 30), with Normal Clearing:</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>5. Any two circuits of a multiple circuit tournielle</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>SLG Fault, with Delayed Clearing (stuck breaker or protection system failure):</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>6. Generator</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>7. Transformer</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>8. Transmission Circuit</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>9. Bus Section</td>
<td>Yes</td>
<td>Planned/Controlled</td>
<td>No</td>
</tr>
</tbody>
</table>

**d)** A number of extreme contingencies that are listed under Category D and judged to be critical by the transmission planning entity(ies) will be selected for evaluation. It is not expected that all possible facility outages under each listed contingency of Category D will be evaluated.

30 Fault, with Delayed Clearing: (stuck breaker or protection system failure):
1. Generator
2. Transformer
3. Transmission Circuit
4. Bus Section

5. Breaker (failure or internal fault)

- Loss of load with three or more circuits
- All transmission lines on a common right-of-way
- Loss of a substation (one or more transmission lines plus transformers)
- Loss of a switching station (one or more transmission lines plus transformers)
- Loss of all generating units at a station
- Loss of a large load or major load center
- Failure of a fully redundant Special Protection System (or Remedial Action Scheme) in response to an event or abnormal system condition for which it was not intended to operate
- Impact of severe power swings or oscillations from disturbances in another Regional Reliability Organization.

Evaluate for risks and consequences:
- May involve substantial loss of customer demand and generation in a widespread area or area.
- Portions or all of the interconnected systems may or may not achieve a new, stable operating point.
- Evaluation of these events may require joint studies with neighboring systems.
### Summary of NERC Contingencies

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Stability</th>
<th>Loss of load</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No contingencies</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>B</td>
<td>N-1 (loss of 1 element)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>C</td>
<td>Loss of $\geq 2$ elements (local events)</td>
<td>Yes</td>
<td>Planned or controlled</td>
</tr>
<tr>
<td>D</td>
<td>Extreme events (loss of a transmission path, substation, power plant or major load, cascading outages, etc.)</td>
<td>Selecting contingencies for evaluation</td>
<td></td>
</tr>
</tbody>
</table>
Contingencies to be studied

• Normal Design Contingencies (Categories A, B and C)
  – Have a significant probability of occurrence
  – Following any of these contingencies, the system is secure (stability is maintained, and voltages and line and equipment loadings are within applicable limits.)
    • All facilities are in service, or
    • A critical generator, transmission circuit, or transformer is out of service, assuming that the area generation and power flows are adjusted between outages by use of a reserve.

• Extreme Contingencies (Category D)
  – After the analysis and assessment of selected extreme contingencies, measures are developed to reduce the frequency of occurrence of such contingencies or to mitigate the consequences that are indicated by the simulations of such contingencies
NECR Contingencies

- Most utilities manually select NERC Category D contingencies to simulate:
  - Loss of a key substation
  - Loss of tie lines
  - Outages close to a generation/load pocket

<table>
<thead>
<tr>
<th>Consequences</th>
<th>Frequency of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

- Unlikely but with Extreme Impacts
- Not Existing in Well-designed Systems
- Credible and Acceptable
- Needless to study

Frequency may increase when system is stressed (e.g. Storm Approaching)
How are reliability standards used?

• In Planning:
  – Reliability standards should never be violated in designing the system.

• In Operations:
  – Reliability standards should never be intentionally violated
  – Sometimes, violations occur due to mis-operations or delayed awareness of the real-time situation
Related Terms

• **Operating quantities**: Physical quantities (measured or calculated) that can be used to describe the operating conditions of a power system, e.g. real, reactive and apparent powers, RMS values/phasors of alternating voltages and currents.

• **Steady-state operating condition** of a power system: An operating condition of a power system in which all the operating quantities that characterize it can be considered to be constant for the purpose of analysis.
• In designing and operating an interconnected power system, its dynamic performance subjected to changes (i.e. contingencies, small or large) is considered.

• It is important that when the changes are completed, the system settles to new operating conditions without violation of constraints.

• In other words, not only should the new operating conditions be acceptable (as revealed by steady-state analysis) but also the system must survive the transition to those new conditions. This requires dynamic analysis.
Related Terms (cont’d)

• **Disturbance**: a sudden change or a sequence of changes in one or more parameters or operating quantities of the power system.

• **Small disturbances** vs. **large disturbances**
  
  – _a small disturbance_ if the equations describing the dynamics of the system may be linearized for the purpose of accurate analysis, e.g. a load change. (We don’t care what that disturbance is)

  – _a large disturbance_ if the equations that describe the dynamics of the system cannot be linearized for the purpose of accurate analysis, e.g. a short circuit and loss of a generator or load. (We do need to know what exactly that disturbance is in order to estimate the following system trajectory)
• **Synchronous operation:**
  – A machine is in synchronous operation with another machine or a network to which it is connected if its average electrical speed \((\omega p/2)\) is equal to the electric speed of the other machine or the angular frequency \((\omega)\) of the ac network.
  – A power system is in synchronous operation if all its connected synchronous machines are in synchronous operation with the ac network and with each other.

• **Asynchronous operation:** loss of synchronism or out of step
Stability of a Dynamical System

Consider a nonlinear dynamical system

\[ \dot{x} = f(t, x) \]  

Assume origin \( x=0 \) is an equilibrium, i.e. \( f(t, 0) = 0, \forall \ t \geq 0 \)

The equilibrium point \( x=0 \) is **stable in the sense of Lyapunov** if, for each \( \varepsilon > 0 \), there is \( \delta = \delta(\varepsilon, t_0) > 0 \) such that

\[ \|x(t_0)\| < \delta \Rightarrow \|x(t)\| < \varepsilon, \quad \forall \ t \geq t_0 \geq 0 \]  

In other words, the system variable will stay in any given small region (\( \varepsilon \)) around the equilibrium point once becoming close enough (\( \delta \)) to that point.
Power System Stability

• **Power system stability** is the ability of a power system, for a given initial operating condition, to regain an acceptable state of operating equilibrium (i.e. the new condition) after being subjected to a disturbance

• Considering an interconnected power system as a whole
  – The stability problem with a multi-machine power system is mainly to maintain synchronous operation of the machines (generators or motors)

• Considering parts of the system
  – A particular generator or group of generators may lose stability (synchronism) without cascading instability of the main system.
  – Motors in particular loads may lose stability (run down and stall) without cascading instability of the main system.
Some Terms Related to System Dynamic Performance

Secure (vs. Insecure)
Not violating given security criteria

Stable (vs. Unstable)
A system is able to regain an equilibrium following a disturbance.

(A stable power system may not be secure if the equilibrium or the transition to the equilibrium violates security criteria)

Oscillatory
An operating quantity repetitively changes at some frequency around a central value (equilibrium).

(When oscillation becomes uncontrollable to damage generators and other equipment, the system will become insecure and even unstable)
Example: FIDVR (Fault-Induced Delayed Voltage Recovery)

NERC/WECC Planning standards require that following a Category B contingency,

- voltage dip should not exceed 25% at load buses or 30% at non-load buses, and should not exceed 20% for more than 20 cycles at load buses
- the post-transient voltage deviation not exceed 5% at any bus
Stability Classification

• Power system stability is essentially a single problem; however, the various forms of instabilities that a power system may undergo cannot be properly understood and effectively dealt with by treating it as such.

• Because of high dimensionality and complexity of stability problems, it helps to make simplifying assumptions to analyze specific types of problems using an appropriate degree of detail of system representation and appropriate analytical techniques.

• Analysis of stability, including identifying key factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories.
Stability Classification


- The classification of power system stability considers:
  - The physical nature of the resulting mode of instability as indicated by the main system variable (angle, frequency or voltage) in which instability can be observed.
  - The size of the disturbance (small or large) considered, which influences the method of calculation and prediction of stability.
  - The devices, processes and time span that must be taken into consideration in order to assess stability. Typical ranges of time periods
    - Transient or short-term: 0-10s
    - Mid-term: 10s to several minutes
    - Long-term: several to tens of minutes
Stability Classification

- Rotor Angle Stability
  - Small-Disturbance Angle Stability
  - Transient Stability
- Frequency Stability
  - Short Term
  - Long Term
- Voltage Stability
  - Large-Disturbance Voltage Stability
  - Small-Disturbance Voltage Stability

Physical nature
Disturbance size
Time span
Rotor Angle Stability

- **Rotor Angle Stability** refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance.
- **Phenomenon of instability**: increasing angular swings of some generators leading to their loss of synchronism with others.
- It depends on the ability to maintain/restore equilibrium between electromagnetic and mechanical torques of each synchronous machine in the system.
For a simple power system consisting of a generator tied to a load bus, **only when both sides have rotating mass**, rotor angle stability can be a concern.
“Dynamic Stability”

• The term “dynamic stability” also appears in the literature as a class of rotor angle stability.
  – In the North American literature, it has been used mostly to denote small signal stability.
  – In the European literature, it has been used to denote transient stability.

• Both CIGRE and IEEE have recommended that it not be used.
Voltage Stability

- **Voltage stability** refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition.

- The term **voltage collapse** is also often used. It is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system.
Relationship between rotor angle instability and voltage instability

• Typical systems vulnerable to two stability problems
  
  – Rotor angle stability
  
  – Voltage stability

• However, two problems often occur together
  
  – For example, as rotor angles between two groups of generators approach 180°, the loss of synchronism causes rapid drop in voltages at intermediate points in the network.
  
  – Loss of synchronism of some generators may result from the outages caused by voltage collapse or from operating conditions that violate generator field current limits
• Establish most economical operating conditions under “normal” circumstances
• Operate the system such that if an unscheduled event occurs, it does not result in uncontrolled (or cascading) outages
• Establish “Safe Operating Limits” for all situations
• Meet reliability criteria
  – Voltage limits
  – Line and component loading limits (thermal limits)
  – Stability
  – Dynamic performance
Normal
Secure with sufficient margin; able to withstand a contingency

Alert
Secure with insufficient margin; Contingency may cause overloading

Emergency
Insecure; system is still intact

Restorative
Transition due to control action

Emergency control

Corrective control

Cascading events

Transition due to disturbance

Preventive control

Restorative control

Extreme
Power outages; system separates

Preventive control

Corrective control

Restorative control

Emergency control

Cascading events

Normal
Secure with sufficient margin; able to withstand a contingency

Alert
Secure with insufficient margin; Contingency may cause overloading

Emergency
Insecure; system is still intact
Design and Operating Criteria for Stability

Design and operating criteria play an essential role in preventing major system disturbances following severe contingencies.

• The use of criteria ensures that, for all frequently occurring contingencies (i.e. credible contingencies, e.g. Categories B and C), the system will, at worst, transit from the normal state to the alert state, rather than to a more severe state such as the emergency state or the extreme state.

• When the system enters the alert state following a contingency, operators can take actions to return the system to the normal state.
Structure of a Power System and Associated Controls
Homework #1

• Learn the IEEE paper “Definition and Classification of Power System Stability”

• Select 1 journal/conference paper published by IEEE since 2010 that introduces or addresses some stability problems
  – Keywords: e.g. “power system” + “stability” or “control”
  – The paper should be about bulk power systems, not microgrid or distribution systems

• Write a 1-2 pages essay (not Q&A’s):
  – Title, authors, source of the paper
  – Background:
    • What stability problem is concerned? (Which IEEE categories?)
    • Why is the problem significant? (Any real-world stories?)
  – Approach
    • What new approach or technique is proposed? (Outline of the procedure or steps)
    • How does the new approach perform?
  – Remark
    • Any conclusions from the work, or any room for further work

• Give a 3-5 minutes talk on your chosen paper and hand in your essay in the class of Jan 20 (Tuesday). Please email me the paper title by Jan 19 (Monday) 5pm