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

4) 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.
# Summary of NERC Contingencies

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Impacts / Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No contingencies</td>
<td>Stable: Yes, Loss of Load: No</td>
</tr>
<tr>
<td>B</td>
<td>N-1 (loss of 1 element)</td>
<td>Stable: Yes, Loss of Load: No</td>
</tr>
<tr>
<td>C</td>
<td>Loss of ( \geq 2 ) elements (local events)</td>
<td>Stable: Yes, Loss of Load: 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>Select contingencies to evaluate for risks and consequences</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

Some extreme events may happen more often 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
Stability of a General Dynamical System

Consider a nonlinear dynamical system
\[ \dot{x} = f(t, x) \]  \hspace{1cm} (1)

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
\[ \|x(t_0)\| < \delta \Rightarrow \|x(t)\| < \varepsilon, \quad \forall t \geq t_0 \geq 0 \]  \hspace{1cm} (2)

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.
Stability of a Power System

• **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) and be disconnected without causing major instability of the main system.
  – Motors in particular loads may lose stability (run down and stall) without causing instability of the main system.

*Stability of a power system is about the state variables that are defined*
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.
Why dynamic analysis is needed

• 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)
Related Terms (cont’d)

• **Synchronous operation:**
  – A machine is in *synchronous operation* with another machine or a network to which it is connected if its *average electrical speed* \((=\omega \cdot p/2)\) is equal to the *electric speed* of the other machine or the *angular frequency* 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
Some Terms Related to System Dynamic Performance

**Secure (vs. Insecure)**
No violation of given security criteria

**Stable (vs. Unstable)**
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)*
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
Classification of Power System Stability

• 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.
Classification of Power System Stability (cont’d)


• 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
Classification of Power System Stability (cont’d)

- Rotor Angle Stability
  - Small-Disturbance Angle Stability
  - Transient Stability
    - Short Term
    - Long Term

- Frequency Stability
  - Large-Disturbance Voltage Stability
    - Short Term
  - Small-Disturbance Voltage Stability
    - Long Term

- Voltage Stability

Physical nature
Disturbance size
Time span
Rotor Angle Stability (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.

\[ T_m = \text{Mechanical Input Torque} \]
\[ T_e = \text{Electrical Output Torque} \]
\[ T_m - T_e = T_a = \text{Accelerating Torque} \]
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
System Operation

• 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

Restorative

Emergency
Insecure; system is still intact

Extreme
Power outages; system separates

Cascading events

Restorative control

Emergency control

Corrective control

Preventive control

Transition due to control action

Transition due to disturbance
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 one IEEE PES journal/conference paper published after 2014 that studies or controls some stability problems of 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 5-minute presentation (3-5 slides) on your chosen paper and hand in your essay in the class of Jan 24 (Tuesday).