INTRODUCTION

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INTRODUCTION

1. The Bulk Power Supply

- Elaborate, complex, interconnection of power components which make up an interconnected power system.

- When we talk about reliability and security of power systems, we are interested in what we call “THE BULK POWER SUPPLY SYSTEM”

- The part of the network which connects the power plants, the major substations, and the main EHV/HV lines.

- Interruptions in the bulk power supply are very serious
  - Many users are affected by these interruptions
  - They can be costly

- They are to be avoided, and much effort is spent to do that
2. RELIABILITY

Power Systems are built and operated with the following goal:

*TO ACHIEVE A RELIABLE and ECONOMIC ELECTRIC POWER SUPPLY.*

For the consumer to have a reliable and economic electric power supply, a complex set of engineering analysis and design solutions need to be implemented.

Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period.

- IEEE Paper on Terms & Definitions, 2004
Reliability has two components

**Security** is the ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

Focus of our course

**Security** of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances. (IEEE TermsDefs’04)

**Adequacy** is 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 outage of system elements.
An operator’s view of “security”

“Any consequence of a credible disturbance that requires a limit”

Static security

- Overload Security
  - Transformer Overload
  - Line Overload

- Voltage Security
  - Low Voltage
  - Unstable Voltage

Dynamic security

- Angle/Frequency security
  - Frequency instability
  - Rotor angle instability
Another View of “Security”

Security = dynamic security

Adequacy = static security

This view is strongly held by engineers that have been deeply involved with “reliability” assessment tools for planning such as TRELLS, Tplan, etc., which compute probabilistic indices based on static security assessment. They will tell you that their tools are concerned with adequacy, not security.

You must note the person’s background who uses the term “Security” in order to understand the meaning being implied.
3. REQUIREMENTS OF A RELIABLE ELECTRIC POWER SERVICE

- Steady-state and transient voltages and frequency must be held within close tolerances
- Steady-state flows must be within circuit limits
- 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)

NERC, North American Electric Reliability Corporation: Mission is to ensure reliability of the bulk power system in North America. They develop/enforce reliability standards; assess reliability annually via 10-year and seasonal forecasts; monitor the bulk power system; evaluate users, owners, and operators for preparedness; and educate, train, and certify industry personnel. NERC is a self-regulated organization, subject to oversight by the U.S. Federal Energy Regulatory Commission & governmental authorities in Canada. It is composed of 9 regional reliability councils & encompasses virtually all power systems in US & Canada. NERC’s activities play an essential role in preventing contingencies and mitigating their consequences.
Interconnections

NERC INTERCONNECTIONS

WESTERN INTERCONNECTION

WECC

TRE

ERCOT INTERCONNECTION

EASTERN INTERCONNECTION

FRCC

SERC

RFC

NPCC

MRO

SPP

QUEBEC INTERCONNECTION

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4. System Dynamic Performance

In designing and operating the interconnected power network, system dynamic performance is taken into account because:

• The power system is subjected to changes (small and large). It is important that when the changes are completed, the system settles to new operating conditions such that no constraints are violated.

• Not only should the new operating conditions be acceptable (as revealed by steady-state analysis) but also the system must survive the transition to these conditions. This requires dynamic analysis.

ONE ASPECT OF SYSTEM SECURITY IS THE ABILITY OF THE SYSTEM TO “STAY TOGETHER.” THE KEY IS THAT THE GENERATORS CONTINUE TO OPERATE “IN SYNCHRONISM,” OR NOT TO “LOSE SYNCHRONISM” OR NOT TO “GO OUT OF STEP.” THIS IS THE PROBLEM OF “POWER SYSTEM STABILITY”
Importance of Power System Stability

- Generators must be kept in synchronism; if their relative motion begins to change too much, uncontrollable oscillations may appear in the grid causing damage to generators and to equipment.
- Therefore, relays are used to detect this condition and trip generators before the damage occurs. Although tripping prevents the damage, it results in under-frequency, and possibly load interruption, and in the worst case, cascading outages and blackout.
Definitions

• **Power System**: A network of one or more electrical generating units, loads, and/or power transmission lines, including the associated equipment electrically or mechanically connected to the network.

• **Operating Quantities of a Power System**: Physical quantities, measured or calculated, that can be used to describe the operating conditions of a power system. Operating quantities include real, reactive, and apparent powers, & rms phasors of alternating voltages & 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.
Definitions

• **Synchronous Operation:**
  – **Synchronous Operation of a Machine:** A machine is in synchronous operation with a network or another machine(s) to which it is connected if its average electrical speed (product of its rotor angular velocity and the number of pole pairs) equals the angular frequency of the ac network or the electrical speed of the other machine(s).
  – **Synchronous Operation of a Power System:** 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.
Definitions

• Asynchronous or nonsynchronous operation:
  – Asynchronous Operation of a Machine: A machine is in asynchronous operation with a network or another machine to which it is connected if it is not in synchronous operation.

  – Asynchronous Operation of a Power System: A power system is in asynchronous operation if one or more of its connected synchronous machines are in asynchronous operation.

• Hunting of a Machine: A machine is hunting if any of its operating quantities experience sustained oscillations.
Definitions

- **Disturbance in a Power System**: A disturbance in a power system is a sudden change or a sequence of changes in one or more parameters of the system, or in one or more of the operating quantities.
  - _Small Disturbance In a Power System_: A small disturbance is a disturbance for which the equations that describe the dynamics of the power system may be linearized for the purpose of accurate analysis.
  - _Large Disturbance In a Power System_: A large disturbance is a disturbance for which the equations that describe the dynamics of the power system cannot be linearized for the purpose of accurate analysis.

- **Steady-State Stability of a Power System**: A power system is steady-state stable for a particular steady-state operating condition if, following any _small_ disturbance, it reaches a steady-state operating condition which is identical or close to the pre-disturbance operating condition. This is also known as _Small Disturbance Stability of a Power System_. It should NOT be called “dynamic stability.”

- **Transient Stability of a Power System**: A power system is transiently stable for a particular steady-state operating condition _and for a particular disturbance_ if, following that disturbance, it reaches an acceptable steady-state operating condition.
Definitions

• **Power system stability**: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

• ...Stability of a power system... refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance.

• An equilibrium set of a power system is stable if, when the initial state is in the given starting set, the system motion converges to the equilibrium set, and operating constraints are satisfied for all relevant variables along the entire trajectory.

• If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.
  – Anderson & Fouad, pg. 5.
Differences between reliability, security, and stability

• Reliability is the overall objective in power system design and operation. To be reliable, the power system must be secure most of the time. To be secure, the system must be stable but must also be secure against other contingencies that would not be classified as stability problems e.g., damage to equipment such as an explosive failure of a cable, fall of transmission towers due to ice loading or sabotage. As well, a system may be stable following a contingency, yet insecure due to post-fault system conditions resulting in equipment overloads or voltage violations.

• System security may be further distinguished from stability in terms of the resulting consequences. For example, two systems may both be stable with equal stability margins, but one may be relatively more secure because the consequences of instability are less severe.

• Security and stability are time-varying attributes which can be judged by studying the performance of the power system under a particular set of conditions. Reliability, on the other hand, is a function of the time-average performance of the power system; it can only be judged by consideration of the system’s behavior over an appreciable period of time.

- IEEE Paper on Terms and Definitions, 2004
The Disturbance-Performance Table is the heart of reliability criteria

<table>
<thead>
<tr>
<th>Category</th>
<th>Contingencies</th>
<th>System Stable and both Thermal and Voltage Limits within Applicable Rating*</th>
<th>Loss of Demand or Curtailed Firm Transfers</th>
<th>Cascading Outages</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>All Facilities in Service</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
| B        | Event resulting in the loss of a single element | Single Line Ground (SLG) or 3-Phase (3Ø) Fault, with Normal Clearing:  
1. Generator 
2. Transmission Circuit 
3. Transformer 
4. Loss of an Element without a Fault | Yes | No* | No |
|         | Single Pole Block, Normal Clearing*:  
4. Single Pole (dc) Line | Yes | No* | No |
| C        | Event(s) resulting in the loss of two or more (multiple) elements | SLG Fault, with Normal Clearing*:  
1. Bus Section 
2. Breaker (failure or internal fault) | Yes | Planned/Controlled* | No |
|         | SLG or 3Ø Fault, with Normal Clearing*, Manual System Adjustments, followed by another SLG or 3Ø Fault, with Normal Clearing*:  
3. Category B (B1, B2, B3, or B4) contingency, manual system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency | Yes | Planned/Controlled* | No |
|         | Bipolar Block, with Normal Clearing*:  
4. Bipolar (dc) Line Fault (non 3Ø), with Normal ** | Yes | Planned/Controlled* | No |
|         | Any two circuits of a multiple circuit transmission | Yes | Planned/Controlled* | No |
|         | SLG Fault, with Delayed Clearing* (tripped breaker or protection system failure):  
6. Generator | Yes | Planned/Controlled* | No |
<p>|         | 7. Transformer | Yes | Planned/Controlled* | No |
|         | 8. Transmission Circuit | Yes | Planned/Controlled* | No |
|         | 9. Bus Section | Yes | Planned/Controlled* | No |</p>
<table>
<thead>
<tr>
<th>Extreme event resulting in two or more (multiplex) elements removed or Cascading out of service.</th>
<th>30 Fault, with Delayed Clearing* (stuck breaker or protection system failure):</th>
<th>Evaluate for risks and consequences.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Generator</td>
<td>3. Transformer</td>
<td>- May involve substantial loss of customer Demand and generation in a widespread area or areas.</td>
</tr>
<tr>
<td>2. Transmission Circuit</td>
<td>4. Bus Section</td>
<td>- Portions or all of the interconnected systems may or may not achieve a new, stable operating point.</td>
</tr>
<tr>
<td>30 Fault, with Normal Clearing*:</td>
<td>5. Breaker (failure or internal fault)</td>
<td>- Evaluation of these events may require joint studies with neighboring systems.</td>
</tr>
<tr>
<td>6. Loss of transmission with three or more circuits</td>
<td>7. All transmission lines on a common right-of-way</td>
<td></td>
</tr>
<tr>
<td>8. Loss of a substation (one voltage level plus transformers)</td>
<td>9. Loss of a switching station (one voltage level plus transformers)</td>
<td></td>
</tr>
<tr>
<td>10. Loss of all generating units at a station</td>
<td>11. Loss of a large Load or major Load center</td>
<td></td>
</tr>
<tr>
<td>12. Failure of a fully redundant Special Protection System (or remedial action scheme) to operate when required</td>
<td>13. Operation, partial operation, or misoperation 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</td>
<td></td>
</tr>
<tr>
<td>14. Impact of severe power swings or oscillations from Disturbances in another Regional Reliability Organization.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Applicable rating refers to the applicable Normal and Emergency facility thermal Rating or system voltage limit as determined and consistently applied by the system or facility owner. Applicable Ratings may include Emergency Ratings applicable for short durations as required to permit operating steps necessary to maintain system control. All Ratings must be established consistent with applicable NERC Reliability Standards addressing Facility Ratings.

b) Planned or controlled interruption of electric supply to radial customers or some local Network customers, connected to or supplied by the Faulted element or by the affected area, may occur in certain areas without impacting the overall reliability of the interconnected transmission systems. To prepare for the next contingency, system adjustments are permitted, including curtailments of contracted Firm (non-recallable reserved) electric power Transfers.

c) Depending on system design and expected system impacts, the controlled interruption of electric supply to customers (load shedding), the planned removal from service of certain generators, and/or the curtailment of contracted Firm (non-recallable reserved) electric power Transfers may be necessary to maintain the overall reliability of the interconnected transmission systems.

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.

e) Normal clearing is when the protection system operates as designed and the Fault is cleared in the time normally expected with proper functioning of the installed protection systems. Delayed clearing of a Fault is due to failure of any protection system component such as a relay, circuit breaker, or current transformer, and not because of an intentional design delay.

f) System assessments may exclude these events where multiple circuit towers are used over short distances (e.g., station entrance, river crossings) in accordance with Regional exemption criteria.
5. HOW ARE RELIABILITY CRITERIA USED?

A) In System Planning or Design
   – Make decisions on size, type and timing of new generation and transmission facilities
   – Design transmission network to withstand normal & prescribed abnormal conditions
   – The latter includes such things as short circuits (faults) followed by loss of major components (to isolate the fault).

B) In System Operation
   – Establish most economic operating conditions under “normal” conditions
   – Operate the system such that if an unscheduled event occurs, it does not result in violation of reliability criteria.
   – Establish “Safe Operating Limits” for all situations
The most salient feature of reliability criteria is a philosophy captured by the following statement taken from theWSCC criteria for transmission system planning, which describes its disturbance-performance table:

“The table is based on the planning philosophy that a HIGHER level of PERFORMANCE is required for disturbances generally having a higher frequency of occurrence.”

Or stated another way,

“The table is based on the planning philosophy that a LOWER level of SEVERITY is required for disturbances generally having a higher frequency of occurrence.”

Considering risk \( \sim \) frequency \( \times \) severity, we see that the criteria suggests a uniform maximum risk for different kinds of contingencies.
RELIABILITY CRITERIA SHOULD NEVER BE VIOLATED IN DESIGNING THE SYSTEM.

RELIABILITY CRITERIA SHOULD NEVER BE INTENTIONALLY VIOLATED IN OPERATING THE SYSTEM.

SOMETIMES, VIOLATIONS OCCUR IN OPERATIONS.
Power system operational “states” & actions

- Normal (secure)
  - Restorative
    - Extreme emergency. Separation, cascading delivery point interruption, load shedding
  - Alert, Not secure
    - Other actions (e.g. switching)
    - Off-economic dispatch
  - Emergency
    - Controlled load curtailment
Some comments about the previous slide:

• The use of criteria ensures (and the diagram illustrates that), for all **credible** contingencies, 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 *in extremis* state.

• If a system is operated according to criteria, the system can transition from normal state to emergency or *in extremis* state only for a non-credible (extreme) contingency.

• When the alert state is entered following a contingency, operators can take actions to return the system to the normal state, but such actions should not include load shedding.

• Load shedding should only be performed under emergencies.
Extreme Contingency Assessment (category D)

Extreme contingency assessment recognizes that the interconnected bulk power system can be subjected to events that exceed in severity the normal design contingencies. The effect of these contingencies on system performance should be determined in order to obtain an indication of the system strength and to identify the extent of a widespread disturbance. After analysis and assessment of 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.
6. Types of Stability Studies

A. Steady-state instability

Use linear system analysis techniques to study modal system response. Calculation input: (a) pre-disturbance system conditions (the power flow solution); (b) the dynamic models.

Typical purpose of such studies:

- Obtain safe operating limits and guidelines
- Identify poorly damped modes of oscillation
- Setting of controls (e.g., exciters, power system stabilizers)
B. Transient instability

- Use of non-linear system analysis tools to study the system response to (large) disturbances.
  - Traditional method is to use time-domain simulation to “track” the evolution of system states & parameters during the transient.
  - Simulation input: (a) pre-disturbance system conditions (the power flow solution), (b) the dynamic models. (c) the switching sequence.
  - Simulation results: short-term (2-20 seconds) trajectory of all system parameters and final (post-disturbance) conditions.
  - Any change in input WILL change the results, the question that one needs to answer based on judgment is “how much?”
Transient instability....

**Switching sequences**

- The simplest switching sequence is “no-disturbance.” Why would we ever want to do that?
- The next simplest is:
  - 0 cycles: remove circuit 10-29
  - 10 seconds: end simulation
- The next simplest, and most common, is:
  - 0 cycles: apply fault at bus 2339
  - 4 cycles: clear fault
  - 4 cycles: remove circuit 2339-2337
  - 10 seconds: end simulation
- The most complicated (ever?) is the WECC islanding scheme – 44 steps.
Transient instability....

• “First-swing” or “early-swing” (1-5 secs) is a standard problem for which analysis is performed where a large disturbance (fault) is applied to see if the system remains in synchronism during first one or two swings. But often, large disturbances also create damping problems (oscillatory instability) which require 10-20 seconds of simulation time.

• Why not run simulations for 3 minutes of simulation time?
  – Build-up of numerical error for most common type of integration technique
  – Usually, models are for short-term analysis only and do not include, for example, boiler dynamics, thermostatic load models, load tap changers, AGC, etc.
  – If you eliminate numerical error from integration scheme, and use appropriate models, you can perform mid- or long-term simulation (EUROSTAG)
Many books use the word “study” to denote a single “run” on the computer.

I use “simulation” (time-domain simulation) and “calculation” (steady-state stability) for this.

I use the word “study” to denote a set of simulations/calculations from which one draws a relevant conclusion.
• Typical purpose of such studies

  – New generation studies (to meet reliability criteria)

  – Transmission planning studies (to analyze plans for future transmission expansion, and to meet reliability criteria)

  – Operations planning studies (to check that a given system configuration (and operations schedule) meets reliability criteria)

  – Special control to maintain stability (e.g., generation tripping, braking resistor insertion, etc.)

  – Severe disturbance (extreme contingency) studies

  – Special purpose studies (e.g., verifying known system upsets, and system restoration.)
Frequency instability is the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.
7. Stability Implications of Changing Conditions

A. Stability is now considered a problem for system operations in many systems
Here is a quote from a recent paper by B.C. Hydro Engineers about their on-line dynamic security assessment scheme:

“Conventionally, dynamic security assessment has been performed using off-line calculations. In this process, detailed stability analysis is conducted for each credible contingency under a variety of operating conditions. In real system operations, conditions frequently do not match those studied off-line. Consequently, the guidelines and limits produced are usually provided on the conservative side. Power system networks nowadays operate more and more in a stressed state where conservative operation often results in significant financial consequences. A more effective approach is to assess only those contingencies likely to cause dynamic violations for the operating condition encountered in real time. The new B.C. Hydro EMS system offered an opportunity for implementation of an on-line transient stability assessment (TSA).
The need is to enable on-line dynamic security analysis. It is not enough to just say a particular contingency is acceptable or not – we also need to know the “limit.”

Thus we need to:

• Use faster or more computers
  – Parallelization
  – Continuous computing

• Enhance algorithm computational efficiency
  – Direct methods
  – “Smarter” integration schemes

• Limit contingencies to be analyzed
  – Filtering techniques
Important approximations inherent to all that we will do:

- Network electromagnetic transients (DC and higher harmonics) are neglected; we are therefore only interested in current and voltage variations associated with the fundamental (60 Hz).
- We use phasor representation of voltages and currents. Thus, we regard the network, during the electromechanical (as opposed to electromagnetic) transient conditions, as though it were passing directly from one electromagnetic steady-state to another. In other words, we consider only the variations in the amplitude-envelope of the fundamental.
- Impedances:
  - are represented using lumped (not distributed) parameter models
  - are independent of frequency variation (computed at 60 Hz).
- We may model different fault types, but we study the effects of disturbances on only the positive sequence network, therefore the network is modeled as a per-phase network.
B. Context of Stability Analysis May Change

- The nature of the problems, and the required answers required may change
  - Enhance modeling (e.g., wind!)
  - Mid-term and long-term analysis: need extended models for this (boiler, tap changers, thermostatic loads, induction motors)
  - Large disturbance voltage instability
  - New types of answers are required (e.g., if a new transaction is requested the stability implications, consequences, and the amount of additional flow which can reliably be transacted will need to be known in a relatively short interval of time)
  - Very fast computational capability is needed

- Reliability criteria as they exist today are deterministic
  - To relieve the constraints of conservative limits obtained from deterministic criteria, it may be essential to incorporate concepts of probability and risk.
  - New criteria involving probability and risk would have to be translated into meaningful operating guidelines in order to find acceptance with system operators.
C. Your and my goals

Your goal is to obtain a clear understanding of the physical aspects of each phenomena, be able to use the appropriate representation of the power system to analyze the phenomena, and apply new or existing tools in an original and creative manner to provide needed answers.

My goal in this course is to motivate and channel your thought process towards your goal and provide the various building blocks, tools, and relevant reference material you will need.