Power System Operation

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What do we need to model in the power system?
Electrical Infrastructure
Electrical infrastructure

• Generation
• Transmission
• Distribution
• Consumption (a.k.a. load)
Generation

• Transform primary energy into electrical energy
• Operating cost
• Flexibility
  – Ability to increase or decrease power output quickly
  – Ability to start and shutdown quickly

Flexible plants are usually more expensive to run
Transmission

- Transport electrical energy over long distances
- Lines and transformers $\leftrightarrow$ branches of the graph
- Substations $\leftrightarrow$ nodes of the graph
What’s in a substation?

• Bus or busbar:
  – Connection point

• Switching devices:
  – Interrupt fault currents
  – Reconfigure the topology of the network
Distribution

• Radial network connecting each consumer to the transmission grid
Consumption - Loads

- Consider in aggregated form
- Varies over the day/week/year
Information and Control Infrastructure

- Protection
- Remedial action schemes
- Measurement
- Communication
- Control centers
- Automatic control systems
Protection: Relays

• Detect faults and other dangerous conditions
• Trigger the disconnection of a component
  – line, generator, transformer
• Occasionally fail to operate when they should
• Sometimes operate when they should NOT
• Intended to protect the components
• Not intended to protect the system
Remedial action schemes

• Intended to protect the system or some components by taking drastic action
  – Disconnect load, generation
• Driven by event or LOCAL conditions
• Can be very effective
• Can make matters worse because they don’t take into account the condition of the overall system

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Measurements

• Types of measurements:
  – Position of switching devices (open/closed)
  – Voltages
  – Active and reactive power flows in the lines
  – Active and reactive power output of generators
  – Active and reactive loads
  – A few phase angle measurements (Phasor Measurement Units – PMUs)
  – Others (e.g. transformer temperature)
Communications

• Bi-directional:
  – Measurement from the power plants and substations to the control center
  – Control signals from the control center to the power plants and substations
• Dedicated communication system
• Scan rate: ~ 3-5 seconds
• PMUs: ~30 samples per second
• Also control center to control center
Control Center

- Supervisory Control and Data Acquisition (SCADA)
- Sophisticated Graphical User Interface (GUI)
- Various simulation-based software applications to check security and optimize economics
- One control center can be responsible for a very large area (e.g. California, most of Texas..)
Human Infrastructure

Information & Control Infrastructure

Electrical Infrastructure
Human Infrastructure

• Real-time operation
• Operational planning
  – 1-day to a few years ahead
  – With existing infrastructure only
• System planning
  – Up to 30-40 years ahead
  – New infrastructure
What do operators do?

• Under normal circumstances:
  – Monitor that things are happening according to the operational plan

• Events:
  – Sudden disconnection of a generating plant
  – Sudden disconnection of a line

• After such an event:
  – Take action to stabilize the system
  – Return it to a secure condition
What’s in the operational plan?

• Balance load and generation
• Keep the network within safe operating limits
  – Steady state
  – Stability

Balancing the greed and the fear
Balancing load and generation

California ISO May 11, 2012
Balancing load and generation

- Kinetic energy stored in rotors of generators provides a (small) buffer
- If $P_{\text{loads}} > P_{\text{generators}} \rightarrow$ frequency decreases
- If $P_{\text{loads}} < P_{\text{generators}} \rightarrow$ frequency increases
- If frequency deviates too much from nominal, generating plants shut down automatically

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Balancing load and generation

• Small deviations are handled automatically using generators that are on-line (Automatic Generation Control – AGC)

• Large changes require that generating units be connected or disconnected from the grid

➤ Unit commitment program to do that at minimum cost
Unit Commitment

• Schedules the startup and shutdown of generating units to meet a load profile over a 24-hour horizon at minimum cost

• Large Mixed Integer Linear Programming problem

• Includes commitment of reserve capacity to protect the system against the loss of the largest unit or similar disturbance
  – N-1 security

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Reserve generation capacity

[Graph showing reserve generation over time]

California ISO May 11, 2012
What about the network?

• Network should always be operated within its operating limits:
  – Branch flows should be below safe operating limit
  – Voltages should be within a ± 5% band of nominal
  – Faults or other major events should not make the system unstable
    • Angular stability (a.k.a. transient stability)
    • Voltage stability
Tools (1)

• Power Flow (PF):
  – Check that all flows and voltages are within limits for given topology, generations and loads

• Contingency Analysis:
  – Runs a power flow for all N-1 contingency conditions to check whether the system would be in an acceptable operating state post-contingency

• Optimal Power Flow (OPF):
  – Determine the lowest cost generation dispatch that keeps all flows and voltages within limits for the current conditions
Tools (2)

• Security Constrained Optimal Power Flow (SCOPF):
  – Determine the lowest cost generation dispatch that keeps all flows and voltages within limits for the current conditions AND all N-1 contingency conditions

• Security Constrained Unit Commitment
  – Same as SCOPF but looks 24 hours ahead and can turn generating plants on and off

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Tools (3)

• Stability analysis tools
  – Used to check whether the system would remain stable following a contingency
  – Hard to check in real-time
  – System operators tend to use conservative limits calculated off-line when stability is an issue
Conclusions on operational planning

• Best practice if for the power system to be operated based on a detailed and risk-averse process plan
  — This is sometimes not the case (e.g. San Diego)
• As long as the operators follow the plan, the power system should continue operating after any N-1 contingency
• This should give enough time to the operator to take action to bring it back to an N-1 secure state
Classical security framework

- Normal state is stable and secure
- In the abnormal state, system is vulnerable or unstable
- Operator must keep the system or return it to the normal state
- Considers only the “electrical” part of the system
- Considers only “electrical” events
  - Failures in the “electrical” infrastructure
- Assumes that the operator has a perfect knowledge and understanding of the state and behavior of the system

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Failures in the other infrastructures

- Malfunctions of protection relay
- Incorrect or unavailable measurement
- Failure of a remote control command
- Non-convergence of state estimator program
- Loss of a communication link
- Software crash
- Misinterpretation of situation by an operator
- Miscommunication between operators
Arizona-Southern California Outages on September 8, 2011

Causes and Recommendations

Prepared by the Staffs of the

Federal Energy Regulatory Commission
and the
North American Electric Reliability Corporation

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What is the state of the system?

Actual State

Reported State

Perceived State
Human Infrastructure

Information & Control Infrastructure

Electrical Infrastructure
This is the basic power system. As shown, this system is unstable because of the unpredictable load fluctuations and faults and failures. The resources here are the units that are committed to meet the load. The control variables are the unit dispatch and settings of the various other controllable devices (voltage setpoints, transformer taps, capacitor banks).
To make the system stable, some automatic controls are used in all modern power systems. For the sake of simplicity, these controls are represented by a single (conceptual) control loop.
With this control loop, the system remains stable as long as the load does not change too much. Being a non-linear system, it is not globally stable but has a region of stability.
Because of the fluctuations in the load and the possibility of faults and failures, we need an operator to monitor the state of the system and to adjust the resources and the control variables to keep the system within this region of stability. Let us model this using a second (slower) control loop.
Operators do not behave like an automatic control system. They do not monitor all the state variable on a continuous basis. Let us represent this limitation by the block labeled “Real-Time Filter” in the second control loop.

The Real-Time Filter models the data that is available to the operator through the SCADA/EMS and the processing done on this data by the security functions of this EMS (static, dynamic, voltage, etc...)
This model is a suitable framework for studying why a particular blackout happened in a particular system. For example:
- The fault, failures or load fluctuations may have been so severe that they took the system outside its region of stability
- The limitations of the real time filter may have prevented the system operator from detecting a problem in due time
- The operator may not have been paying sufficient attention

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The operational planner gets information about the expected state of the system but this information is limited (i.e. filtered).
The system development filter provides statistical information about the behavior of the system.
Summary

• Each loop has its stability domain. The goal of the outer loops is to keep the inner loops within their stability domain most of the time.

• Relation between stability region and security criteria