Why Do the Lights Go Out?

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How do we get electricity?

- Generation
- Transmission
- Distribution
- Load

Power System
How is a Power System Structured?

One-line diagram representation
Generating units

Multiple generators are connected to the system
Transmission network

Multiple path across the transmission network
Distribution network

Single path across the distribution network
Distribution network is radial
Faults

• Breakdown of the insulation around the electric cable
• Creates a short circuit
• Large current that must be interrupted quickly
  – Safety
  – Destroy the equipment
What causes faults?

• People digging up the street
• Rats chewing up cables
• Aging of the insulation
• Branches flying into the lines
• Squirrels jumping from one conductor to another
What causes faults?

Wind…
What causes faults?

Lightning...
What causes faults?

Snow and ice...
What causes faults?

Too much current…
Fault in the distribution network

Because distribution network is radial, a single fault makes the lights go out
Getting the power back on

The utility company re-energizes the blacked out part of the system by closing a normally open switch.

Normally open switch
Fault in the transmission network
Fault in the transmission network

Because the transmission network is meshed (multiple paths), a single fault does not cause the lights to go out.
What if it happens on a day when the load is high?

The current that was flowing in the faulted line goes through the remaining lines.
What if it happens on a day when the load is high?

The overloaded line is disconnected
The system is split in two parts
Will the lights stay on?
Balancing consumption and production

Conservation of energy:

Power input = power output
Analogy: Bicycle on a Hill

Power input: human effort

Power output: climbing the hill

Speed of the bike: stored kinetic energy
Analogy: Bicycle on a Hill

- **Power input**: human effort
- **Power output**: climbing the hill
- **Power produced by generators**: stored kinetic energy
- **Power consumed by loads**: stored kinetic energy

**Speed of the bike**: stored kinetic energy

**Frequency of the ac voltage**: stored kinetic energy
Bicycle in steady state

Human effort = rate of climb  speed is constant

Generation = load  frequency is constant
Slope suddenly gets steeper...

Human effort < rate of climb  speed decreases  
  (until human effort increases)

Generation < load  frequency decreases  
  (until generation increases)
Slope suddenly gets less steep...

Human effort > rate of climb speed increases
(until human effort decreases)

Generation > load frequency increases
(until generation decreases)
Cyclist suddenly start pedaling less hard...

Human effort < rate of climb → speed decreases
(until human effort increases)

Generation < load → frequency decreases
(until generation increases)
Extending the analogy to multiple generators

Each cyclist is like a generator
The transmission system is like the chain on the bike
Generator failure

Generator failure equivalent to cyclist stopping to pedal

Generation < load    frequency decreases
What happens when the speed of a bicycle decreases too much?
What happens when the frequency decreases too much?
Frequency limits

- The power system is much less stable than a bike
- Normal frequency: 60 Hz
- Normal limits: 59.5 Hz to 60.5 Hz
- Emergency limits: 59 Hz to 61 Hz
- System collapse: 57.5 Hz
How do we prevent blackouts?

• Mostly preventive security
  – Operate the system with a safety margin big enough to handle the loss of one component
  – N-1 security criterion
  – Loss of one generator $\rightarrow$ reserve generation capacity
  – Loss of one transmission line $\rightarrow$ limit on the flow allowed on each line

• On-line contingency analysis
  – Check all N-1 conditions using a power flow calculations
  – Adjust operating conditions if needed
Failure of a large generating unit

National Grid managed to increase the output of the remaining generators fast enough
European incident of 4 November 2006
European incident of 4 November 2006

Line disconnected to let the ship pass safely

Other lines disconnected
European incident of 4 November 2006
Frequency in the Western part

Frequency Curve "West" on November 4, 2006, 22:00 - 23:00 hours
(Gauging: EnBW Transportnetze)

Automatic Load Shedding
European incident of 4 November 2006

• Bad news
  – 15 million consumers disconnected
  – In Italy, France, Spain, Belgium, Netherlands

• Good news
  – All consumers reconnected in 45 minutes
  – The system did not collapse... but it was close!

• If the system had collapsed, reconnecting it would probably have taken a day or so...
North East US Blackout of 2003

- Normal summer day
- State estimator at control center in Cleveland stops working
  - Operators lose “situation awareness”
- Operators do not realize that the state estimator is not working
- One line overloads and trips
- Other lines overload and trip
- System collapses, dragging down all of the North East USA
DMSP F15
15 August 2003
0114Z
~7 hrs after Blackout
Consequences of the blackout of 15 August 2003

• 50 million people affected
• Restoration not completed for 4 days
• Cost: ~ $5 to $11 billion
Getting the power back on after a blackout

• Can’t just reclose the switch
• All of the power plants have shut down to avoid damage
• They all need to be restarted
• But to restart a power plant... you need electricity!
• Where do you get it?
  – Small diesel generators
  – Hydro power plants
  – Neighboring power systems
• Slow and complex process
• Takes at least 8 hours to complete for a large system
Research directions

• Why do we get blackouts even when the system is “N-1 secure”?  
  – Use Monte Carlo simulations  
  – Understand blackout mechanisms  
  – Develop a proper measure of risk

• Develop techniques to implement corrective security measures  
  – React after a fault has taken place  
  – Cheaper and more flexible

• Understand impact of information failures
Conclusions

• We have gotten used to a high level of reliability from the power system
• Very costly, large scale incidents can still happen
• Keeping the lights on remains a big challenge
• A good example of “systems engineering”
  – Study the various components
  – Study how they fit together
  – Mathematical modeling