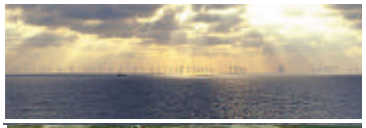
Welcome to Electric Power Systems

Wind farm



HVDC

www.iea.lth.se/eks

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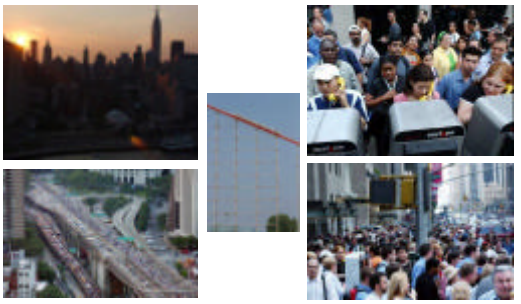
This lecture

- What is a blackout?
  1. Initial fault
  2. New power flow situation
  3. Loads and generators disconnected
  4. Restoration
- About the course
- Single line diagram
- Per unit normalization

Blackout!



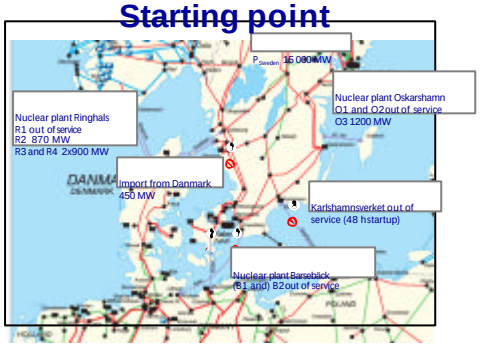
What is a blackout?

- Initiating event
  - Fault (short-circuit) or malfunction
  - Disconnection of faulted part
- Problem spreads
  - Lines overload and disconnect
- Collapse and blackout
  - Stability limit is reached
- Restoration

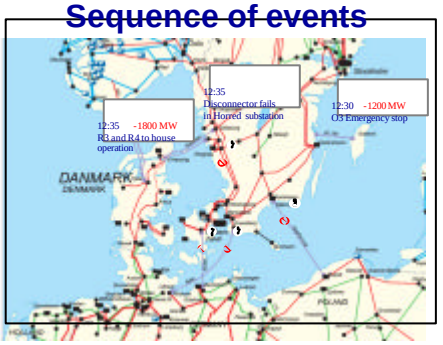
Sweden 23 September 2003

- Initiating event
  - Two-phase short-circuit at substation
- Final stage
  - Voltage collapse
- 4 Million people affected
- Restoration time 1.5-6.5 h

Starting point



Sequence of events



Blackout!

System frequency

Pantograph type disconnector

Open:

isolate for maintenance

visual open-circuit

Closed:

carry load current

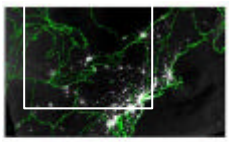
Restoration

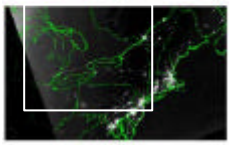
USA 14 August 2003

- Initiating event
  - Generator shutdowns
- Final stage
  - Voltage collapse
- 50 Million people affected
- Restoration time up to 30 h

System split into islands

Area hit by blackout





Italy 28 September 2003

- Initiating event
  - Two lines trip in stormy weather
- All lines into Italy lost one by one
- Final stage unknown
- 58 Million people affected
- Restoration time 16.5 h

Italy blackout

Famous blackouts

- USA 2 July 1996
  - Line into tree, voltage collapse, report 2 August
- USA 10 August 1996
  - Line into tree, angle instability, 7.5 million
- Sweden 27 December 1983
  - Disconnector failed, voltage collapse
- USA 1965 ”The great blackout”
  - Generator trip, angle instability, 30 million
  - See Textbook chapter 13

Post mortem analysis

- Pre-fault operating state
  - Generator and line status
- Sequence of events
  - Digital fault recorders
  - Time of breaker openings
  - Time uncertainty
- Large amounts of information
- Sweden: Windpower trips cause/effect?

Video 10 August 1996

- Hot weather
- Line sags into tree
- Other lines overload
- 4 island networks

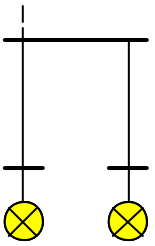
- Fast analysis with new tools

Fault handling

- Detect fault
- Isolate fault
  - Isolate fault and minimum part of the system
  - Neighboring parts back to normal
  - Component can fail, larger area affected
- Remove fault and repair damage
  - Lightning strikes only temporary
- Restore service

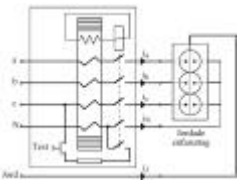
Events at fault

- Fault occurs
- Isolate fault
- Remove fault
- Restore service
- Automatic reclosing
  - Light back in <1s



Detect fault current

- Relay protection
  - Measures U and I
  - Detects fault
  - Controls breaker
- Earth fault protection
  - ~ Relay protection + small breaker



Interrupt current

- Moving contacts apart not enough
  - Arc current flows through arc (ionized air)
  - Extinguish arc, AC current passes zero
- Fuse
  - Measures current!
  - Manually replaced
- Circuit breaker
- Disconnector

Disconnector

Arcing at opening of disconnector carrying too large current

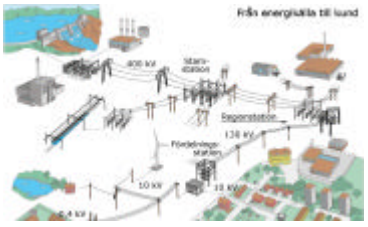
- For small current, cannot extinguish arc
- Manual control
- Visual open-circuit for safety
- Challenge: Open construction unprotected

Circuit breaker

Source: Nicklasson

- Interrupts large current
  - Cooling
  - Pressurized air, oil
- Remote control
  - Protection
  - Control center
- Hidden breaking point
- Challenge: Several kA

Transmission and distribution



Source: vattenfall.se

Generation
|
Transmission
|
Distribution
|
Consumption

Bridging distances

Transmission
- Hundreds of km
- Hundreds of MW
- Economical V~ $15\sqrt{P}$
- SE: 130, 220, 400 kV
- High reliability
- Meshed network

Reach addresses

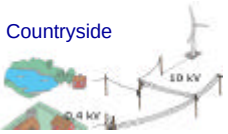
Distribution
- Distance few km
- SE: 10, 20, 50 kV
- Radial network

Line length SE 1996

400 kV	9851 km
130- 220 kV	19740 km
30-70 kV	21100 km
10-20 kV	152000 km
400 V	280000 km

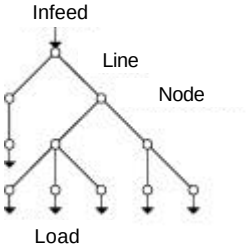
City

Countryside

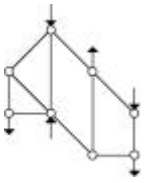


Radial network

- Distribution
- Tree shape
  - Single infeed
  - Many supply points
- Reliability
  - Single fault interrupts service



Meshed network



- Transmission
- Meshing
  - Many infeeds
  - Many supply points
  - Many paths for power
- Reliability
  - N-1 criterion

N-1 reliability criterion

- Intact system has N components
- Withstand loss of any single
  - Generator
  - Line or cable
  - Transformer
  - Busbar (interconnection point)
- No overload on remaining components
- Major outages: N-1 turns into N-2…

Power flow in PowerWorld

Stability limits

- Angle instability
  - Active power imbalance
  - Mechanical generator dynamics excited
  - Generator loses synchronism
  - Generator disconnected
- Voltage instability
  - Lack of reactive power
  - Overload of power lines
  - Loads disconnected

Restoration

- Blackstart generating units
  - Batteries and diesel for starting
- Energizing lines
  - Careful with voltage
- Adding little load
  - Limited control capacity
- Adding generation and load
- Restoration important, how to practice?

Blackout and course modules

- Problem spreads
  - 1. Load flow
- Blackout when stability limit is reached
  - 2. Voltage stability, power system control
  - 3. Angle stability, synchronous generators
- Short-circuits initiate problems
  - 4. Relay protection and symmetrical faults
  - 5. Unsymmetrical faults

A course module

- Tuesday: Lecture
- Thursday: Hand exercise
  - Work in pairs
  - Small system in detail by hand
- Monday: Computer exercise
  - Work in pairs
  - Large system in detail with computer
  - Large system simplified by hand

Learning sequence

- Demonstrate need for knowledge
- Learn theory
  - Lecture
- Practice principle
  - Hand exercise
- Practice principle in practice
  - Computer exercise

Other activities

- Laboratory exercises
  - Power in AC networks
  - Synchronous generator
- Study visits
  - Real-time simulator, Malmö Högskola
  - Substation in Lund
- Current topics lecture

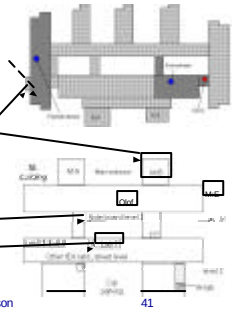
Schedule

W	Monday	Tuesday	Thursday
1	L1	L2	E1
2	SV1	L3	E2
3	C1	L4	E3
4	C2	L5	E4
5	C3	L/E5	L/E6
6	C4	L/E7	L/E8
7	C5	SV2	L6

Lecture
Exercise
Computer
Study Visit

Rooms

- Mondays 13-15
  - M:E
  - E:Neptunus, E:Pluto
- Tuesdays 15-17
  - M:B
- Thursdays 13-15
  - E:1406 this week
  - M:E other weeks
- Notice board
- Lab 7



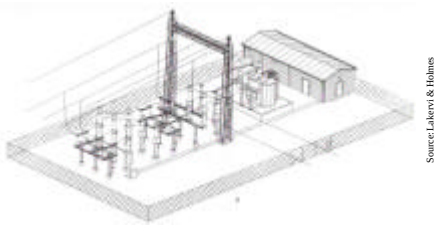
Textbook

- J. D. Glover & M. Sarma: *Power System Analysis and Design*
- Brooks-Cole, US, 2002
- 3rd ed, ISBN 0-53495-367-0
- Akademibokhandeln today Internet cheap but slow
- PowerWorld CD included

Assumed knowledge

- Parts of a power system
  - Generator, line, transformer
- Three-phase voltage and currents
- AC power
- Electric machinery basics
- Matlab/Simulink

Substation



Source: Lakervi & Holmes

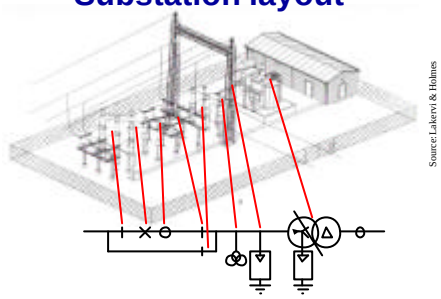
Substation functions

- Voltage transformation (reduction)
  - Power transformer
- Switchyard for network configuration
  - Busbars, circuit breakers, disconnectors
- Monitoring point for control center
  - Potential and current transformers
- Fuses and other protection

Single line diagram symbols

Three-phase component	Comment
Busbar	No impedance
Three-phase line	Line with impedance
Power transformer	US:
Generator	
Load	
Circuit breaker	US: Open Closed
Disconnector	
Surge arrester	Overvoltage protection
Current transformer	
Potential transformer	

Substation layout



Source: Lakervi & Holmes

Per unit normalization

- Normalize to nominal value
- Example: 11 kV at 10 kV bus
  - $V_{p.u.}=V_{actual}/V_{base}$=11kV/10kV=1.1p.u.
- p.u. indicates if situation is normal
- Voltage levels comparable
- Simplifies transformer calculations

Per unit base values

- Theoretically
  - Any two of S, V, I and Z
- Practically
  - System MVA base + *One* voltage base
  - Three-phase: $S_{base}/(v3V_{base}) => I_{base}$
  - $V_{base}^2/S_{base} => Z_{base}$
- Transformer turns ratio => voltage base on other side of transformer