Engineering, Economics & Regulation of the Electric Power Sector

ESD.934, 6.974

Session 2. Monday February 8, 2010

Module A.2

Power system operation & management *(2 of 2)*

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Outline

- Background
- The technological perspective
- **The economic & managerial perspectives**
  - Economic data & orders of magnitude
  - Time scales
    - Expansion planning
    - Operation planning
    - Operation
    - Protection & control

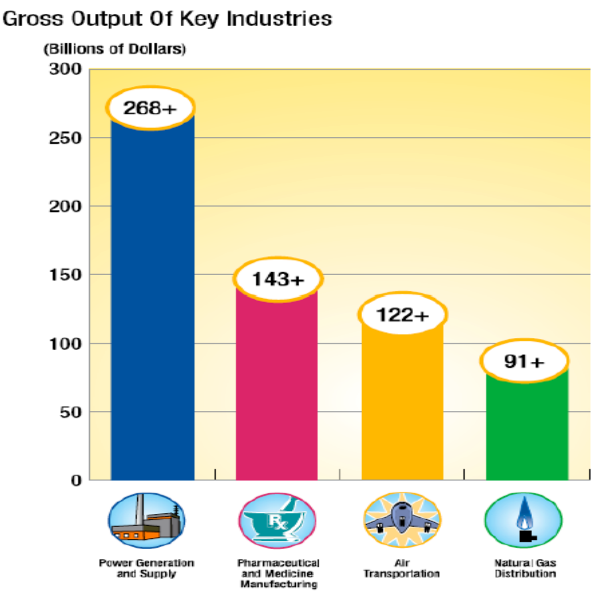
Economic data & orders of magnitude

Energy units & conversion factors

To:	TJ	Gcal	Mtoe	MBtu	GWh
From:	*multiply by:*				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

- Source: International Energy Agency (IEA), US DOE, The Atlas of Climate Change

Economic relevance of the power sector in the US



Source: U.S. Department of Commerce, Bureau of Economic Analysis, 2004.

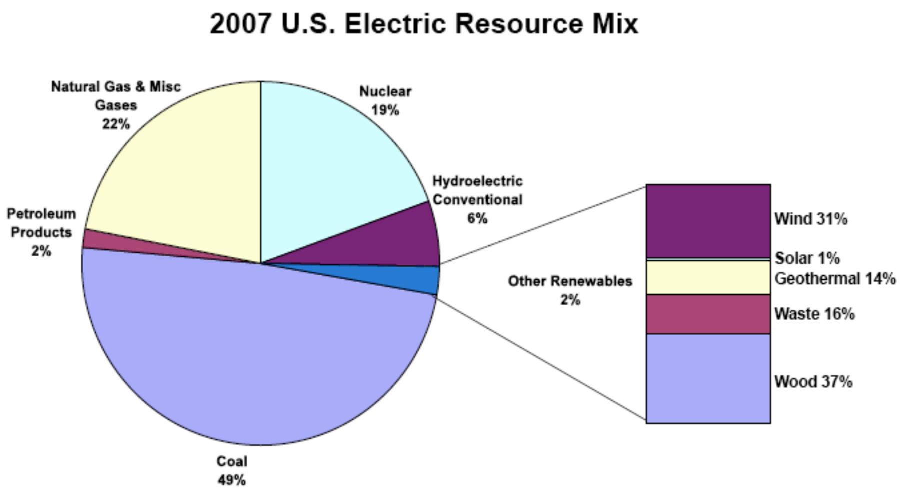
The power sector in the US *(1 de 3)*

- Accounts for 42% of primary energy consumption
- Accounts for 35% of U.S. fossil fuel consumption
- Uses almost no petroleum
- Accounts for 40% of U.S. CO2 emissions
- Relies mainly on North America for fuel
- Consumption is expected to grow faster than the rate of energy consumption

The power sector in the US *(2 de 3)*

- Annual revenues (from consumers) > b$250
- Total asset value > b$800
  - Generation 60%, Distribution 30%, Transmission 10%
- Ownership *(3100 entities)*
  - 213 Investor Owned Utilities: 74% consumers
    - IOU ownership of generation was 71% of capacity in 1996 and 38% now
    - While IPP ownership has increased from 8% to 41%
  - 2000 Public Owned Utilities: 15% consumers
  - 930 cooperatives: 11% consumers

The power sector in the US *(3 de 3)*



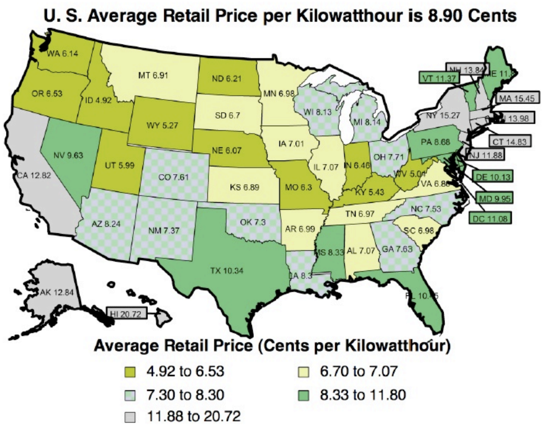
Price of electricity

US Electricity Market in numbers

	Retail Prices (c/kwh)	# Customers
Residential	10.65	123,949,916
Commercial	9.65	17,377,219
Industrial	6.39	793,767
Transportation	9.7	750
Total	9.13	142,121,652

- Average Residential Monthly Use: 936 kWh
- Average Residential Monthly Bill: $99.70

US Electricity Market in numbers



Note: Data is displayed as 5 groups of 10 States and the District of Columbia. Sourc
Information Administration, Form EIA-861, "Annual Electric Power Industry Report."

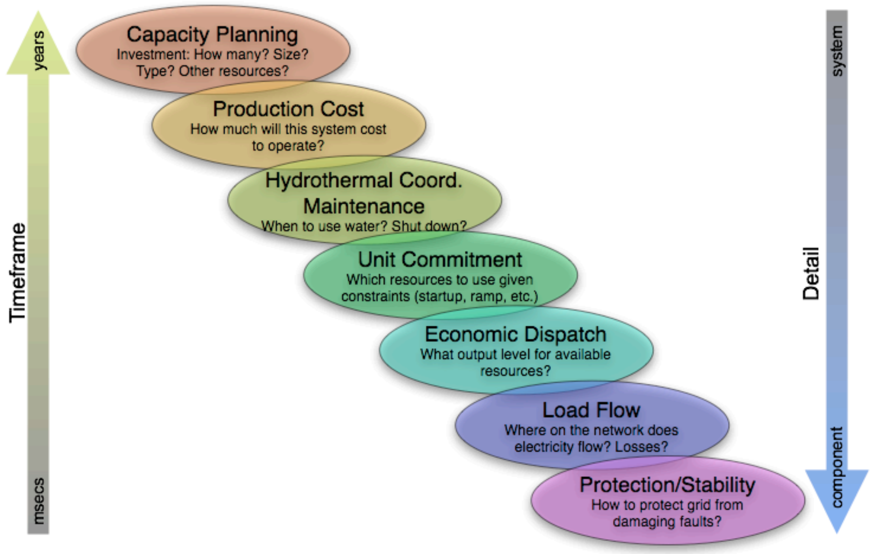
Time scales in power systems management

The question

- How can it be possible to meet the demand at any time **efficiently** and **reliably**, for an infinite time horizon and under **uncertainty**?

The answer: Use a temporal hierarchy of decisions
- – Decision functions hierarchically chained
- – Each function optimizes its own decisions subject to
  - Its own constraints
  - Constraints that are imposed from "upstream"

The temporal hierarchy of decisions



Source: Bryan Palmintier

Time scales (1)

	Horizon	Functions
Expansion Planning	Very long term up to 25 years	• Expansion of generation & network facilities • New power plants & lines / Retirement of existing plants
Operation Planning	Long term 2 to 5 years	• Establish long-term contracts • Nuclear fuel management • Management of multi-year reservoirs
	Medium term from 1 month to 2 years	• Maintenance scheduling • Annual management of reservoirs • Production cost & reliability models

Time scales (2)

	Horizon	Functions
Planificación Operación	Short term 1 to 4 weeks	• Pumping storage plants • Schedule weekly shut-downs & start-ups of thermal plants
	Very short term < 1 week	• Unit commitment of all generation units • Detailed decisions of starting-up & shuting-down plants
Operación	Real time < 1 hour	• Economic dispatch • Load/frequency & voltage control • Protection

Representative functions & models

- Analysis of electromagnetic transients
- Protection coordination
- Short circuit analysis
- Stability analysis
- Load flow
- State estimation
- Security / contingency analysis
- Load forecasting
- Economic dispatch
- Optimal load flow
- Unit commitment
- Hydrothermal coordination
- Reliability / adequacy analysis
- Risk assessment
- Investment (generation / transmission) planning

Regulatory paradigms

- Two regulatory paradigms
  - Centralized – **Traditional, regulated monopolies**
  - Decentralized – **De-regulated, market-oriented**
- Both regulatory approaches seek to achieve the **same basic objective**
  - in theory they only condition the decision-making process, but not the outcome
  - in practice they condition the outcome of planning and operation

Traditional regulation – context

- Monopolies with geographic franchises
- Vertically integrated businesses
- Centralized operation and expansion
  - Cost minimization
- Cost of service-based remuneration
  - Fixed investment costs (plant, line construction...) €/MW
  - Variable operating costs (fuel consumption, maintenance, ...) €/MWh
- Tariff-based prices for users; utilities subject to mandatory supply obligations
- Minimum (cheap) risk assumed by consumers

Liberalized regulation - context

- De-regulate activities
  - Freedom to invest and operate
    - Attract private, international investment
    - Allow new and more efficient initiatives
  - Decentralization
  - Introduce competition to
    - Lower costs
    - Encourage demand-side participation
- Unbundle business activities
  - Competitive: generation and retailing
  - Natural monopolies: transmission and distribution

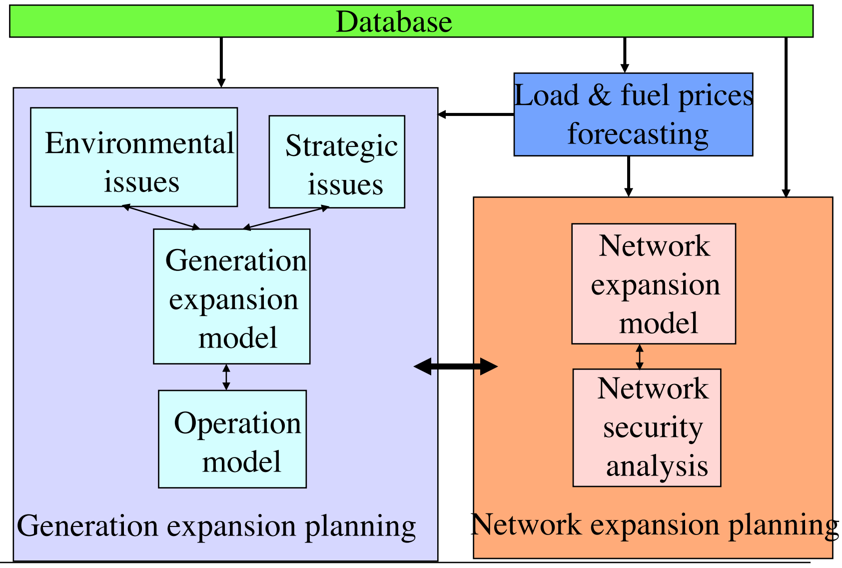
Liberalized regulation - context

- **Market mechanisms** govern **generation** investment and operating decisions
  – supply-demand balance sets **prices & amounts**
    - Wholesale Market
  – **remuneration** based on the competitive sale of the "electricity product" €/MWh
    - Short-term sales (pool – balancing markets)
    - Long-term sales (OTC contracts)
  – higher (expensive) **risk,** assumed by **investors**
  – **maximized** individual **profit** and market balance

Liberalized regulation - context

- **Market mechanisms** govern power **retailing** decisions
  – Distinction between the "wire" business (likened to roads) and the business of selling power (likened to tomatoes), distributed across wires
  – Notion of **customer**
  – Absence of tariffs
  – Retailing valued for the **added value** offered to customers

Expansion planning: Centralized environment



Generation expansion planning

(in a liberalized regulatory framework)

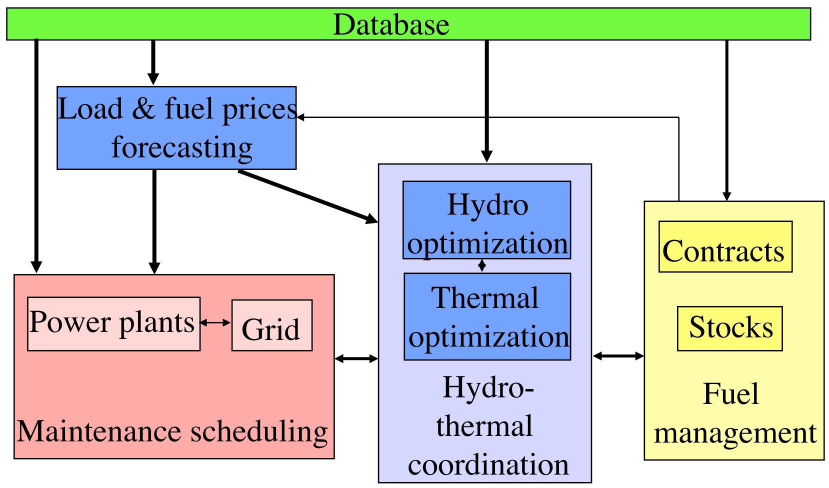
- Every agent decides by itself
- It is a typical investment planning decision under uncertainty
  - Key point is the evaluation of future market behavior
    - market price
    - new investments of competitors
    - fuel prices
    - demand growth

Network expansion planning

(in a liberalized regulatory framework)

- No radical changes with traditional regulation
- Transmission
  - Generation expansion is unknown ➔ uncertainty
  - Most frequent: centralized planning under supervision of regulator and cost-of-service remuneration
- Distribution
  - Distributor decides network expansion in its franchised territory
  - Distributor is subject to quality of service conditions
  - Diverse remuneration schemes are possible

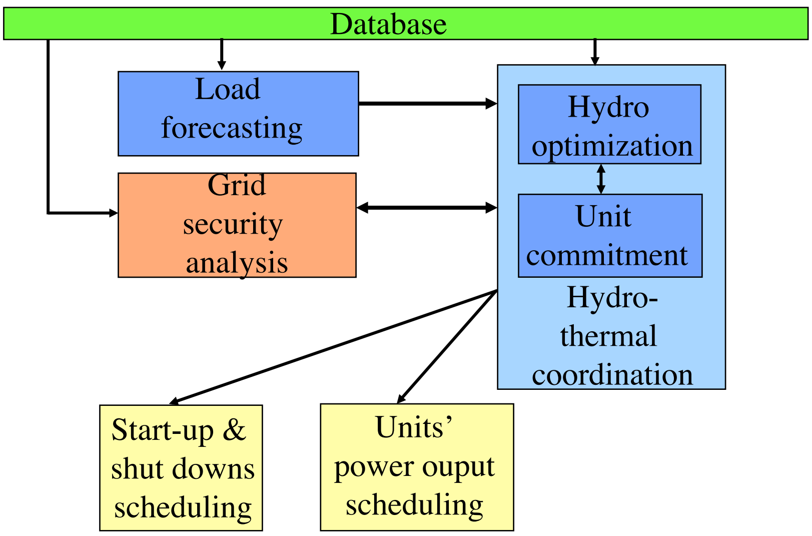
Operation planning (medium term): Centralized environment



Operation planing (Medium term):
(in a liberalized regulatory framework)

- Medium term economic forecasts
- Strategies for profit maximization
  - Contracts, maintenance of facilities, reservoir management
  - Guidelines for preparation of bids: Limited energy plants
    - The economic value of water
- New issues in power system models
  - Strategic behavior of each firm, impact of stranded cost recovery on market strategies, subsidies or domestic fuel quotas, market price caps, etc.

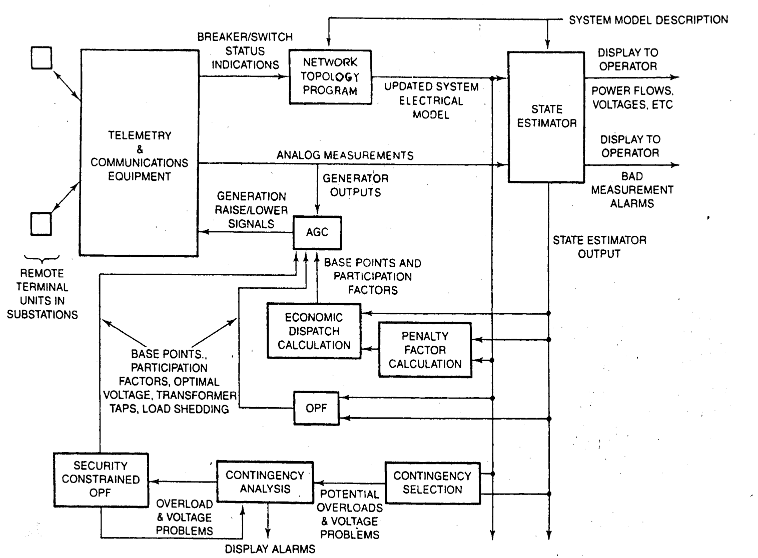
Operation planning (short term): Centralized environment



Operation planning (Short term)
(in a liberalized regulatory framework)

- Preparation of bids for the daily market
  - Selling & purchasing bids are grouped into supply & demand curves and matched using some kind of algorithm to yield the market marginal price
- Issues
  - Internalization of strictly non variable costs
  - Inter-temporal couplings
  - Estimation of the strategic behavior of competitors

Real time operation: Centralized environment



Real time operation
(in a liberalized regulatory framework)

- Most security / monitoring activities are the same as in the centralized framework
- Changes in the new open market environment
  - Existence of short-term markets
    - Intra-daily markets
    - Regulation markets
  - Unbundled &/or market-oriented ancillary services

Ancillary services

Ancillary services
Definition

- Activities (may be associated to generation, transmission or distribution) that are needed to guarantee security, quality & efficiency in electricity supply
- Main ancillary services
  - Load-frequency control
    - Primary regulation
    - Secundary reserves
    - Tertiary reserves
  - Voltage control
  - System restoration
    - Black start capability

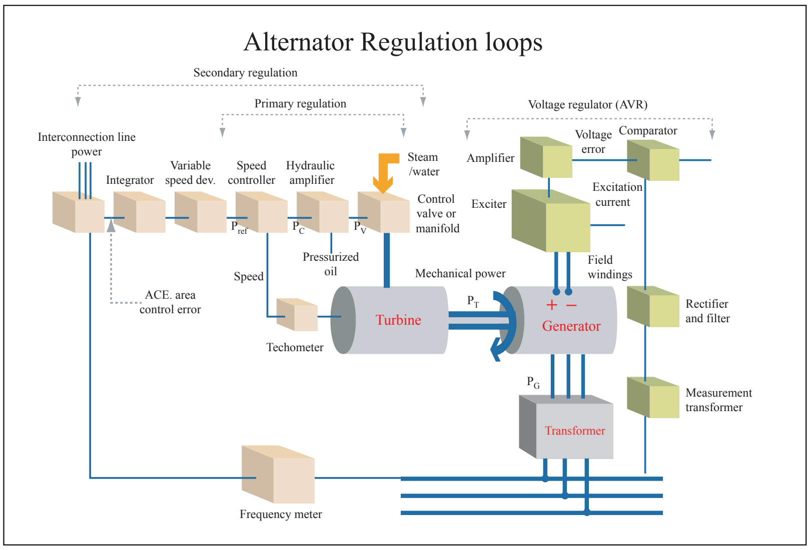
Ancillary services
Traditional & market oriented approaches

- Tradicional regulation: Fully integrated in the generation or transmission activity
- Market oriented regulation: Unbundled & with own scheme (some times market-oriented) of provision & remuneration
  - Provision of ancillary services usually results in extra costs for the suppliers & an increase in the expected price of energy
- SO establishes required volume of service

Load frequency control (LFC)
Primary control

- Primary control
  - Makes use of the governor in the generator
    - Time constant of about 1 second
  - Objective: to prevent frequency deviations
  - Each machine has a specific response to frequency deviations
  - The primary control cannot completely recover the nominal frequency value or eliminate errors in scheduled power exchanges

Alternator regulation loops



Source: O. Elgerd

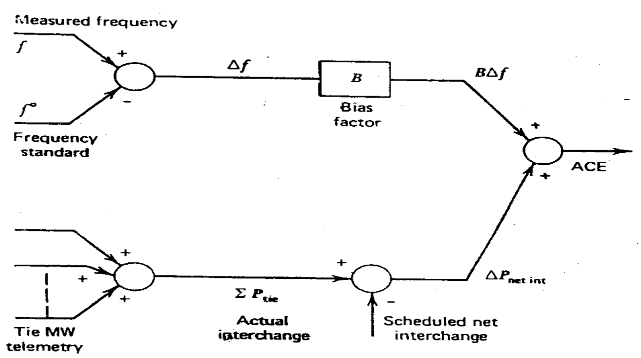
Image by MIT OpenCourseWare.

Load frequency control (LFC)
Secundary & tertiary controls

- Secundary control
  - This is the Automatic Generation Control, **AGC**
    - Time response ~ 1 minute
  - Restores frequency & power exchanges to preset values
    - It cancels the **Area Control Error** ACE, which combines both objectives
- Tertiary control
  - This is an **economic generation dispatch** that recomputes the set points of generators & restores secundary reserves
    - Time response ~15 minutes

Secondary LFC

Computation of the area control error (ACE)



$$ACE = (P_{INT} - P_{PR}) + B \cdot \Delta f$$

P_{INT} ≡ POTENCIA DE INTERCAMBIO CON OTRAS AREAS

P_{PR} ≡ POTENCIA DE INTERCAMBIO PROGRAMADA

Voltage (reactive power) control

- Primary control
  - Voltage regulator in the generating machine
    - Time response of less than 1 second (depending on the type of excitation system: DC, AC, static)
  - It keeps a constant voltage in the generator's output
- Secundary & tertiary controls *(less structured than for AGC)*
  - Objectives
    - Maintain voltage at preset values at some chosen nodes
    - Keep the balance in reactive power allocation
    - Minimize losses
  - Resources
    - Generators, Transformer taps , Capacitors, SVC's

Security analysis and control

Major threats to the power system

- Lack of generation output to meet demand
  - Either at global system level or locally (because of network constraints)
- Lack of operating generation reserves to respond to plausible changes in demand or production
- Overload of network components
- Violation of voltage limits
- Loss of (or proximity to loose) system stability conditions
  - transient (large scale) instability
  - long-term (frequency response) instability
  - oscillatory (low frequency) instability
  - voltage collapse

Security functions

- **State estimation:** Assign best possible values to the state variables of the power system from the available measurements
- **Contingency analysis:** Evaluation of the impact on the system (line overloads, voltages out of range, loss of stability, etc) of potential failures of components
  - generators
  - lines
  - combined failures

Power Grid Evolution

- Phase I: Network analyzer *(Pre 1950)*
- Phase II: Digital computer *(1950+)*
- Phase III: Control ,system theory, optimization impact *(1970+)*
- Phase IV: Environmental concerns, HVDC,FACTS + markets *(1990+)*
- Phase V: advanced communication, sensors, active demand response, distributed generation *(2010+)*

Protections

- Every piece of equipment is protected against faults, short-circuits in particular
  - Contact (an electric arc, usually) between two conductors or between a conductor & ground
    - Why? Electric, mechanic, atmospheric or human
    - Very large currents are produced ➔ thermal problems &/or mechanical stresses
- It is necessary to **detect** & **eliminate** the fault very quickly & then to **isolate** the faulted element so that it can be repaired
    - Relays detect, power breakers eliminate the fault & disconnect switches isolate the faulted element

Types of Protection relays

- Most common types of protection relays
  - **Overcurrent** relay
  - **Directional** overcurrent relay
    - for selectivity
  - **Distance** relay
    - Response time proportional to distance to the fault
  - **Overvoltage / undervoltage** relays
  - **Differential** relay
    - Comparison of two theoretically equal magnitudes
- **Time delay relays**
  - Selectivity may also be attained by timing relays

Protection for people

- Earthing system
  - Electrical facility designed so that, at any accessible point, people would be subject at most to non-hazardous **pass** and **contact** voltage.
- **Pass** voltage
  - Voltage between two points on the ground, 1 metre from one another.
- **Contact** voltage
  - Voltage between an accessible conductor and a point on the ground 1 metre away

Thank you for your attention

ESD.934 / 6.695 / 15.032J / ESD.162 / 6.974 Engineering, Economics and Regulation of the Electric Power Sector
Spring 2010