POWER SYSTEM DYNAMICS (STABILITY) AND CONTROL
Introduction
Lecture Notes 1

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Lecture Content

- Introduction to power system dynamics and control
- Small-signal stability
- Transient stability and equal area criteria (Single-Machine Infinite-Bus System)
- Transient stability of multi-machine power systems
- Voltage stability analysis
- Economic dispatch of power generation
- Control of active power: Load frequency control and automated generation control
- Control of reactive power: Excitation systems and Power System Stabilizer
- Delay-Dependent Stability Analysis of Time-Delayed Dynamical systems: Direct method and Rekasius Substution
- Delay-Dependent Stability Analysis of Load Frequency Control Systems: EVs and Demand Response
- Stability Boundary Locus Method and Controller Design for Load Frequency Control Systems with Time Delay
- Virtual Inertia and Damping

References

- H. Saadat, Power System Analysis, McGraw-Hill, 1999.
- P. Kundur, Power System Stability and Control, (EPRI Power System Engineering, 1994
- P. W. Sauer and M. A. Pai, Power System Dynamics and Stability, Prentice Hall, 1998.
- J. Machowski, J. W. Bialek and J. R. Bumby, POWER SYSTEM DYNAMICS: Stability and Control
- K. R. Padiyar, POWER SYSTEM DYNAMICS Stability and Control, BS Publication

Grading

	Numbers	Total Weighting (%)
Midterm Exam (Take Home)	1	50
Homework	5	50
Application		
Projects		
Practice		
Quiz		
Percent of In-term Studies (%)		60
Percentage of Final Exam (Take Home+Project) to Total Score (%)	1	40

Power System Components

- **Power generation**
- **Power transmission**
- **Power distribution**

An Overview of Power and Energy Systems

Power System Analysis, Computing and Economics

Computing applications
Distribution system analysis
Economics, market organization, cost structures, pricing, and risk management
Intelligent system applications
Reliability, uncertainty, and probability and stochastic system applications

Power System Dynamic Performance

Power system dynamic modeling: components and systems
Power system stability: phenomena, analysis, and techniques
Power system stability controls: design and applications
Power system dynamic measurements
Power system interaction with turbine generators
Dynamic security assessment: techniques and applications, risk-based methods

Power System Operations

Power system dynamic modeling: components and systems
Power system stability: phenomena, analysis, and techniques
Energy control centers
Distribution operation
System control
Operating economics and pricing

An Overview of Power and Energy Systems

Power System Planning & Implementation

Generation system resource planning
Transmission system planning
Distribution system planning
Integrated resource planning and distributed resource planning
Load forecasting
Customer products and services planning and implementation
Industry restructuring planning and policy issues

Insulated Conductors

Construction and design of cables (materials and manufacturing)
Construction, design and testing of cable accessories (cable terminations and joints)
Construction, operation, and testing of cable system
Assembly, operation, and testing of station, control (including fiberoptic), and utilization cables (no
transmission and distribution cables)

Power Engineering Education

New instruction methods (software/ internet / laboratory / combined with research)
Virtual classrooms/laboratory
Distance education
Life-long learning

An Overview of Power and Energy Systems

Electric Machinery

DC Machines
Permanent magnet machinery systems
Switched and variable reluctance machines
Integral horsepower induction machinery
Wound rotor induction machinery
Single phase induction motors
Electronic drives for electric machinery
Induction generators for grid and isolated applications
Synchronous generators
Motor/generator sets for pumped storage
Synchronous motors materials to electric machinery
Electrical machinery theory
Numerical analysis of electric machinery
Power processing equipment
Insulation for electric machinery
Application of magnetic materials to electric machinery
Application of superconducting

Power System Communications

Communication systems
Communication media
Communication protocols
Communication standardization
Home automation and communication

An Overview of Power and Energy Systems

Power System Instrumentation and Measurements

Digital technology for measurements
Electricity metering
High voltage testing
Measurement techniques for impedance elements

Power System Relaying

Digital protection systems
Adaptive protections
Power system protection
Protection of electrical equipment
Relaying communications
Relaying for consumer interface

Substations

Substation automation
Intelligent electronic devices (IEDs)
Programmable logic controllers (PLCs)
Substation design
High voltage power electronics stations
Gas insulated substations (GIS)

An Overview of Power and Energy Systems

Surge Proctective Devices

Design/testing of high voltage surge protective devices (>1000V)
Application of high voltage surge protective devices (>1000V)
Design/testing of low voltage surge protective devices (<1000V)
Application of low voltage surge protective devices (<1000V)

Nuclear Power Engineering

Nuclear power plant controls
Modeling, simulations and control
monitoring and instrumentation

Transformer

Power and instrument transformers
Insulating fluids
Dielectric testing
Audible noise and vibration
Transformer modeling techniques

An Overview of Power and Energy Systems

Transmission and Distribution

AC transmission and distribution facilities
Lightning phenomena and insulator performance
Overhead line conductors: thermal and mechanical aspects
Corona, electric, and magnetic fields
Towers, poles, and hardware
Capacitors, shunt and series capacitor banks, and harmonic filter banks
HVDC transmission and distribution, FACTS and power electronic applications to ac transmission
Harmonics and power quality
Transients, switching surges, and electromagnetic noise
Maintenance and operation of overhead lines
Work procedures, safety, tools, and equipment
Superconductivity analysis and devices
Distributed resources

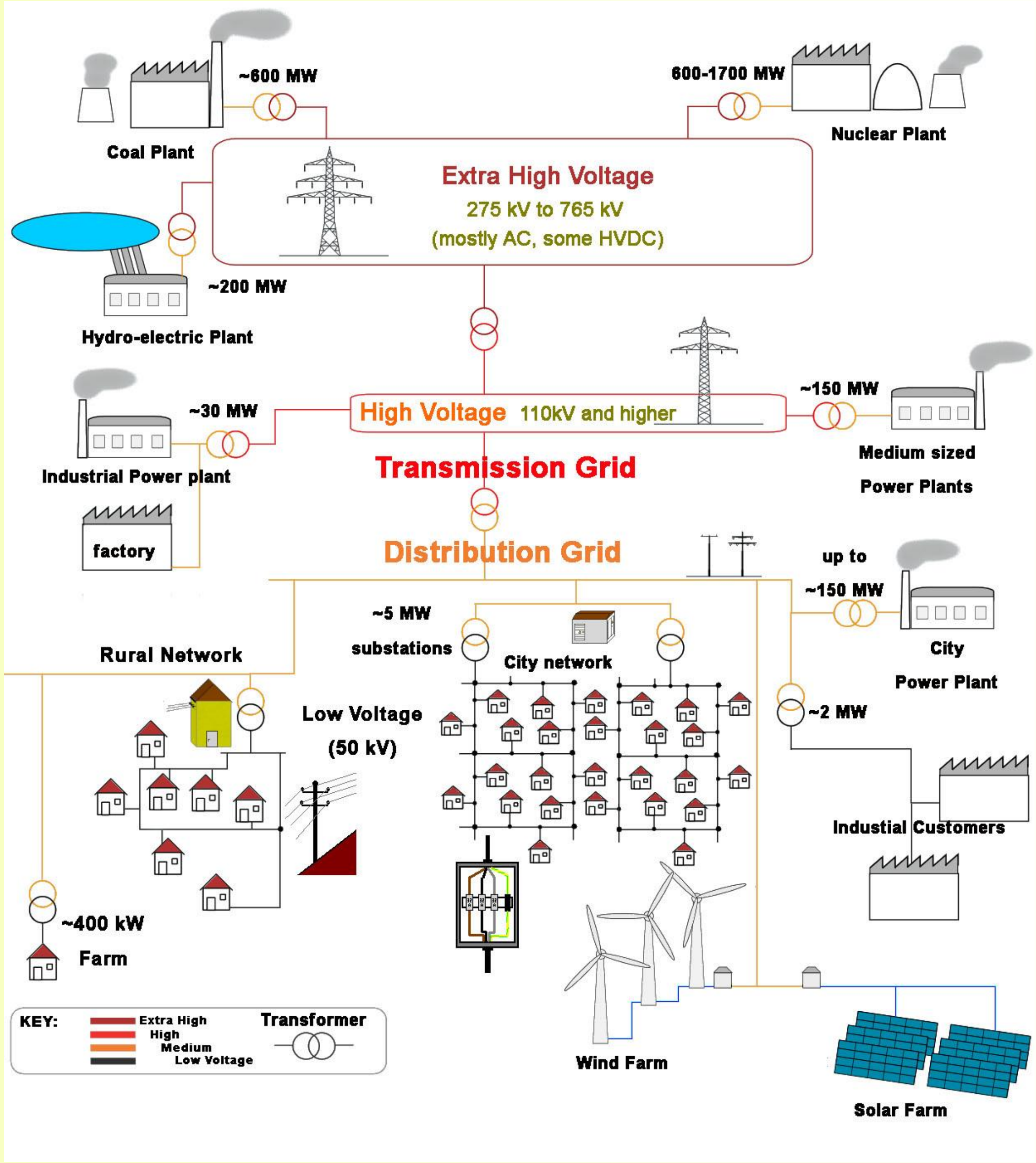
Energy Development and Power Generation

Excitation systems
Power system stabilizers
Advanced energy technologies, Renewable energy technologies
Station design, operations, and control
Modeling, simulation and control of power plants
Monitoring and instrumentation of power plants
Control of distributed generation
Hydroelectric power plants, Power plant scheduling, Engineering economic issues
International practices in energy development

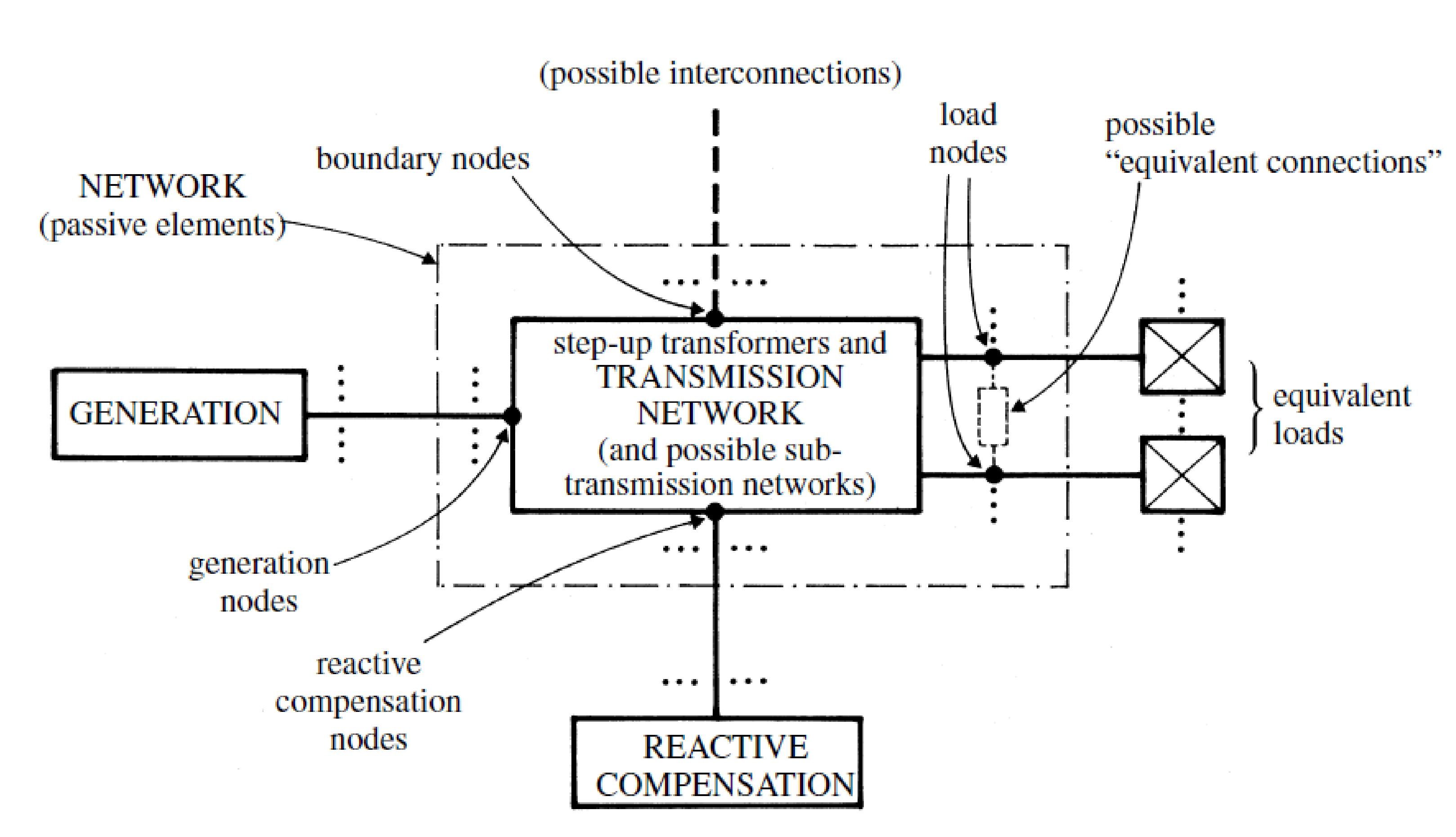
Electric Power System Operation

- **Operational objectives of a power system have been to provide a continuous quality service with minimum cost to the user. These objectives are:**
  - **First Objective:** **Supplying the energy user with quality service, i.e., at acceptable voltage and frequency**
  - **Second Objective:** **Meeting the first objective with acceptable impact upon the environment.**
  - **Third Objective:** **Meeting the first and second objectives continuously, i.e., with adequate security and reliability.**
  - **Fourth Objective:** **Meeting the first, second, and third objectives with optimum economy, i.e., minimum cost to the energy user.**
- **The term "continuous service" can be translated to mean "secure and reliable service"**

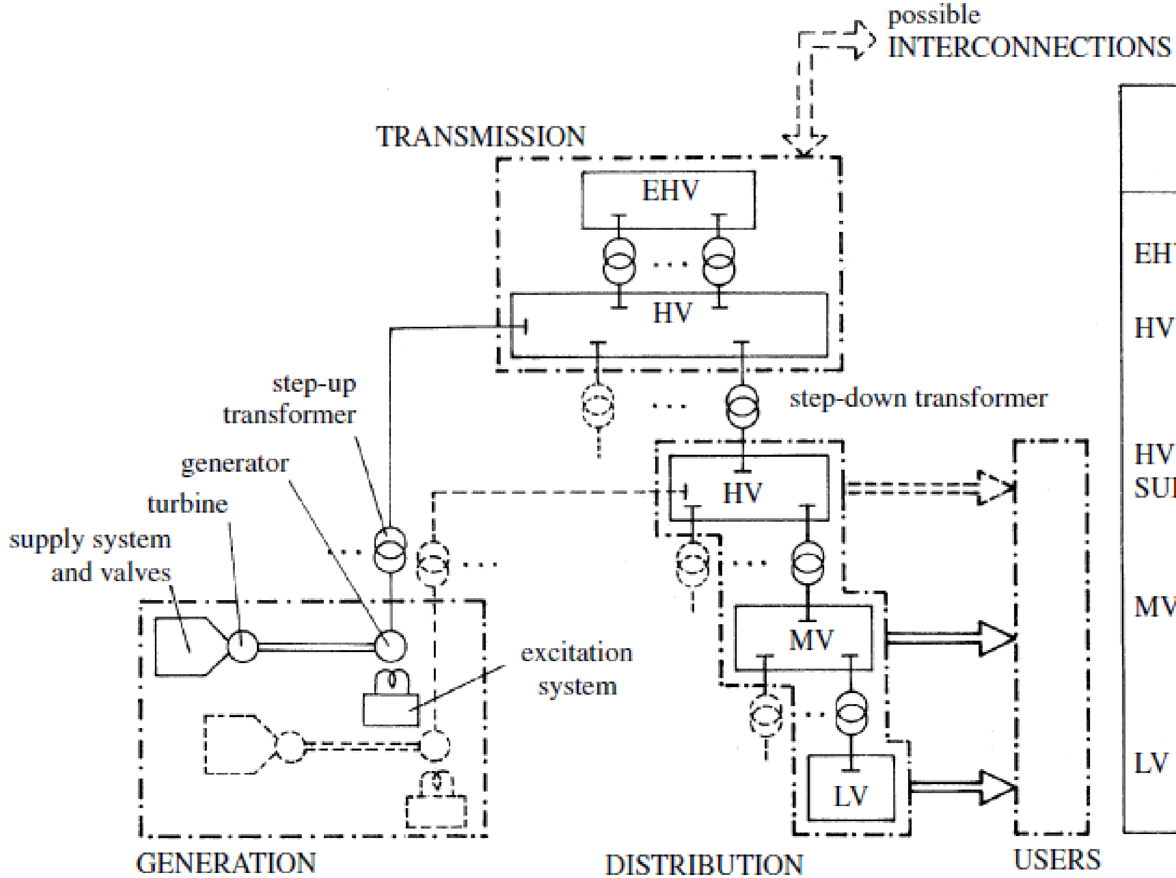
General Structure of Power Systems



Schematic Representation

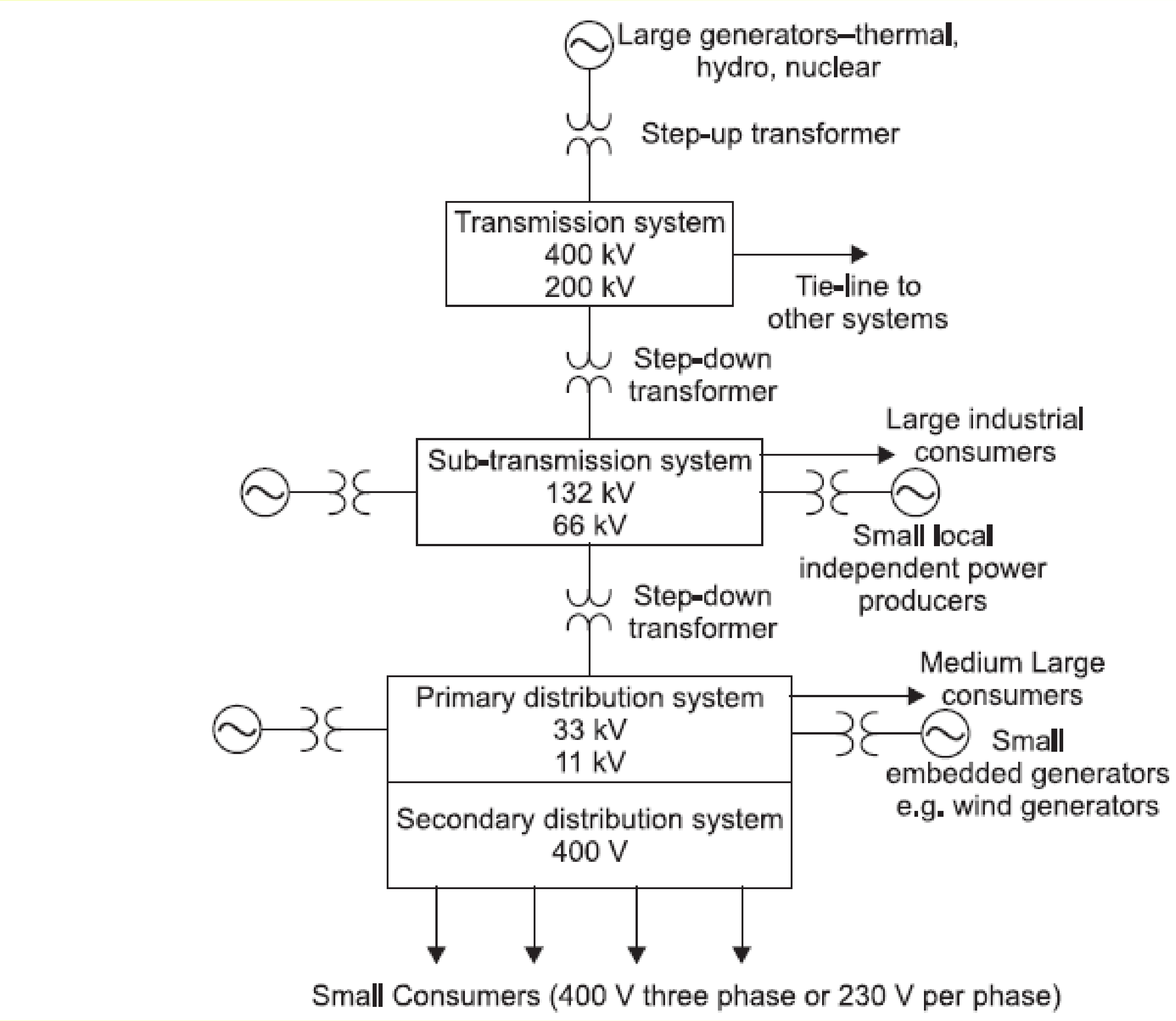


Basic Elements of an Electric Power System

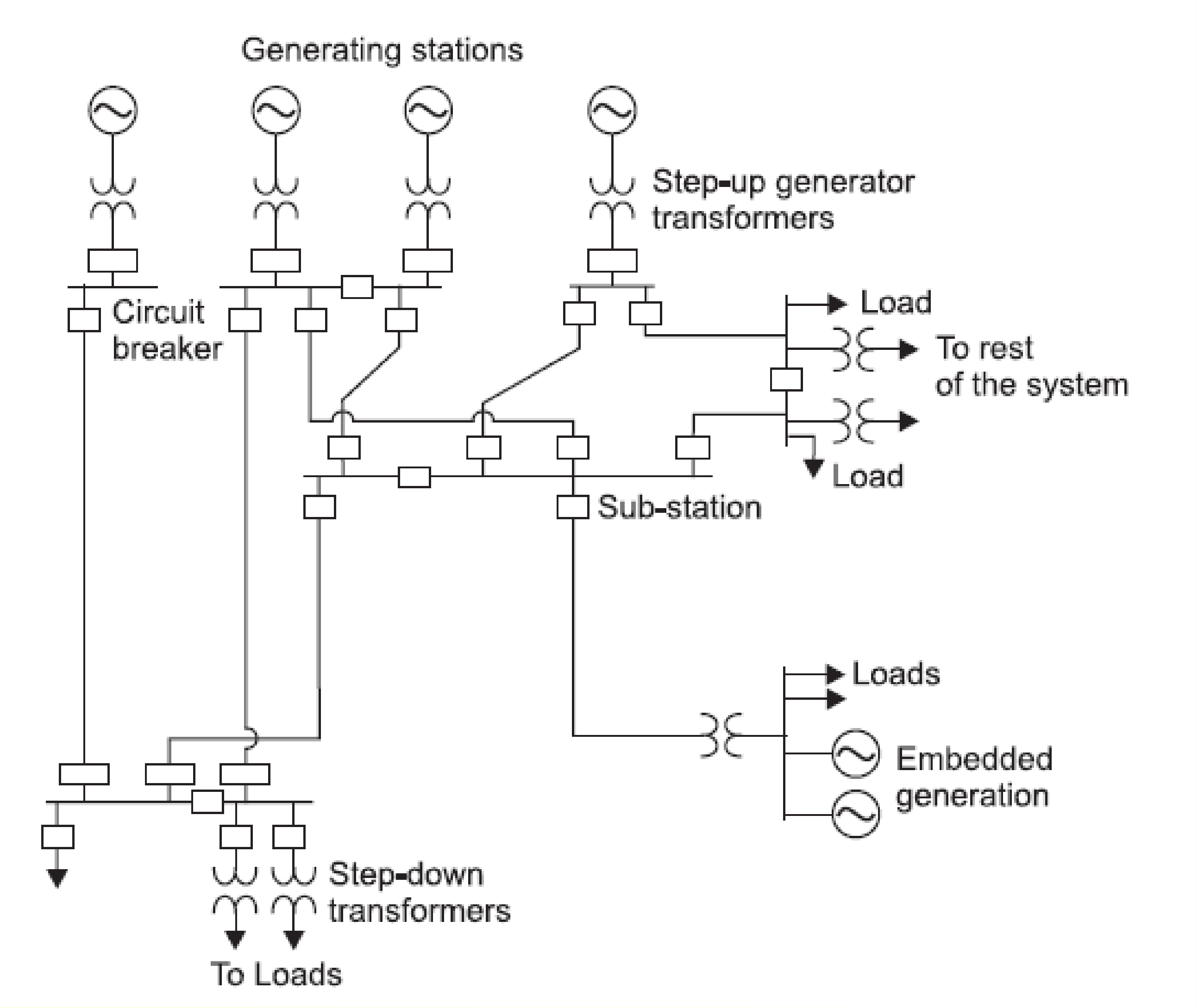


examples of nominal line-to-line voltages	
EHV TRANSMISSION	...
HV TRANSMISSION	380 kV 220 kV
HV DISTRIBUTION (or SUBTRANSMISSION)	150 kV 132 kV 60 kV
MV DISTRIBUTION	30 kV 20 kV 15 kV 10 kV
LV DISTRIBUTION	380 kV 220 kV

Basic Elements of an Electric Power System



One-Line (Single-Line) Diagram



Classification of Dynamics

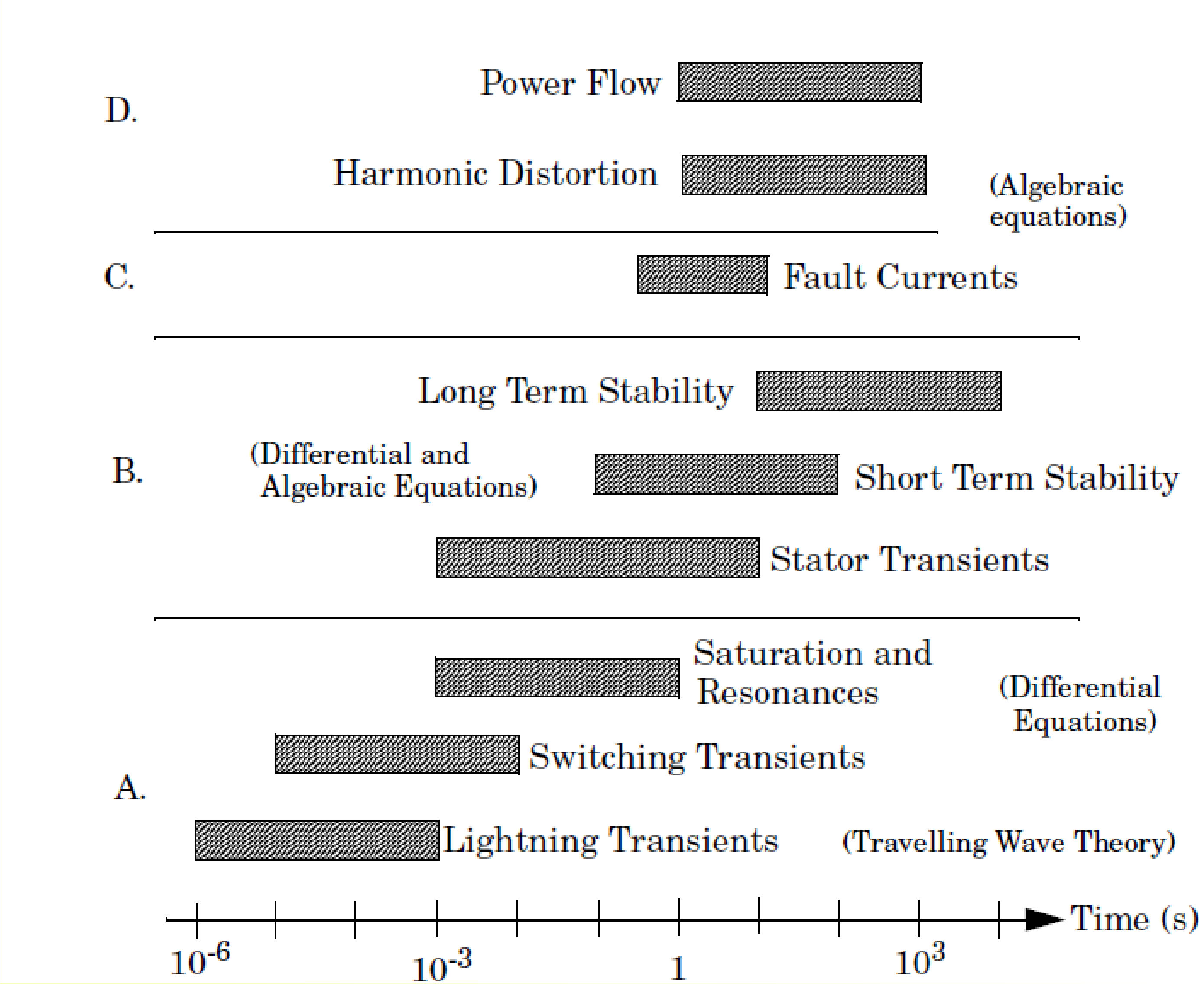
Dynamic phenomena in power systems are usually classified as

- Fast (electro-magnetic) transients (100 Hz - MHz)
- Electro-mechanical swings (rotor swings in synchronous machines) (0,1-3 Hz)
- Non-electric dynamics, e.g. mechanical phenomena and thermodynamics (up to tens of Hz)

A Simple Dynamic Sequence

- One single initial event in the power system can give rise to dynamics in all the three groups above.
- A **lightning stroke** in a power line can induce so high over-voltages that the insulation fails, causing **a earth fault.**
- The earth fault can cause **rotor swings** in synchronous machines with high amplitudes.
- This can trigger **protections to disconnect generators**, so that **an unbalance between produced and consumed power** in the system arises.
- The frequency in the system drops and generators participating in **the frequency control** compensate this by increasing their power outputs.
- Thus the initial lightning stroke has initiated dynamics in all the three groups above.

Time Frame of Dynamic Phenomena



Power System Stability

- Power System Stability Overview
- Power System Stability: A Proposed Definition
- Need of Stability Classification
- Power System Stability Classification
  - Rotor Angle Stability
  - Voltage Stability
  - Frequency Stability
- Rotor Angle Stability vs. Voltage Stability

Power System Stability Overview

- Power system is defined as a network of one or more generating units, loads and power transmission lines including the associated equipments connected to it.

- The stability of a power system is its ability to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium.

- Power system stability problem gets more pronounced in case of interconnection of large power networks.

Power System Stability: A Proposed Definition

- 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.

Two Important Comments

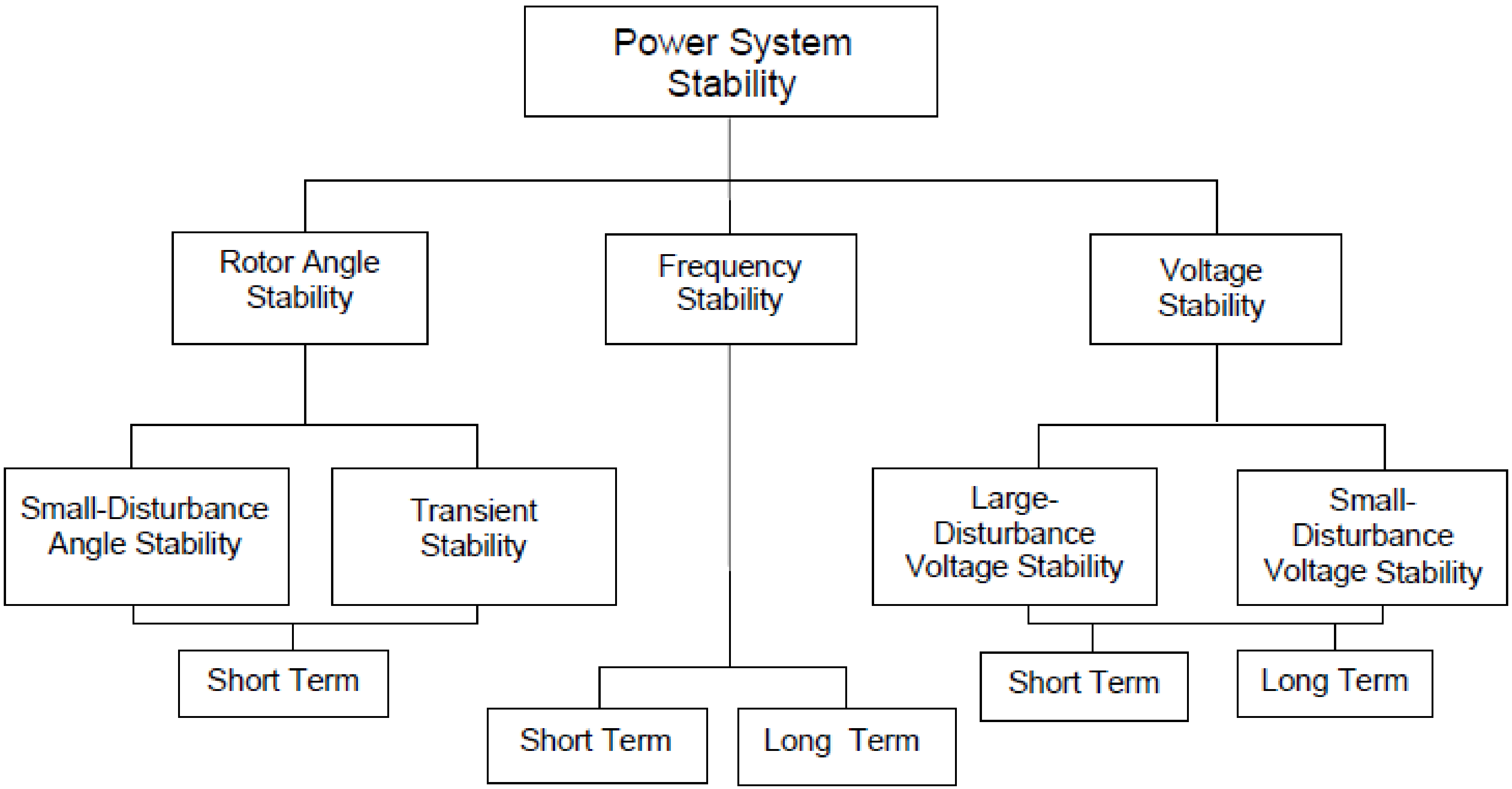
- It is not necessary that the system regains the same steady state operating equilibrium as prior to the disturbance. This would be the case when e.g. the disturbance has caused any power system component (line, generator, etc.) to trip. Voltages and power flows will not be the same after the disturbance in such a case. Most disturbances that are considered in stability analyses incur a change in system topology or structure.

- It is important that the final steady state operating equilibrium after the fault is steady state acceptable. Otherwise protections or control actions could introduce new disturbances that might influence the stability of the system. Acceptable operating conditions must be clearly defined for the power system under study.

Need of Stability Classification

- Power system stability is essentially a single problem; however, the various forms of instabilities that a power system may undergo cannot be properly understood and effectively dealt with by treating it as such.
- Because of high dimensionality and complexity of stability problems, it helps to make simplifying assumptions to analyze specific types of problems using an appropriate degree of detail of system representation and appropriate analytical techniques.
- Analysis of stability, including identifying key factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories
- Classification, therefore, is essential for meaningful practical analysis and resolution of power system stability problems. understanding of different power system instabilities.

Power System Stability Classification



Power System Stability Classification

- Rotor angle stability
  - Small disturbance angle stability
  - Transient stability

- Voltage stability
  - Small disturbance voltage stability
  - Large disturbance voltage stability

- Frequency stability
  - Short term frequency stability
  - Long term frequency stability

Rotor Angle Stability

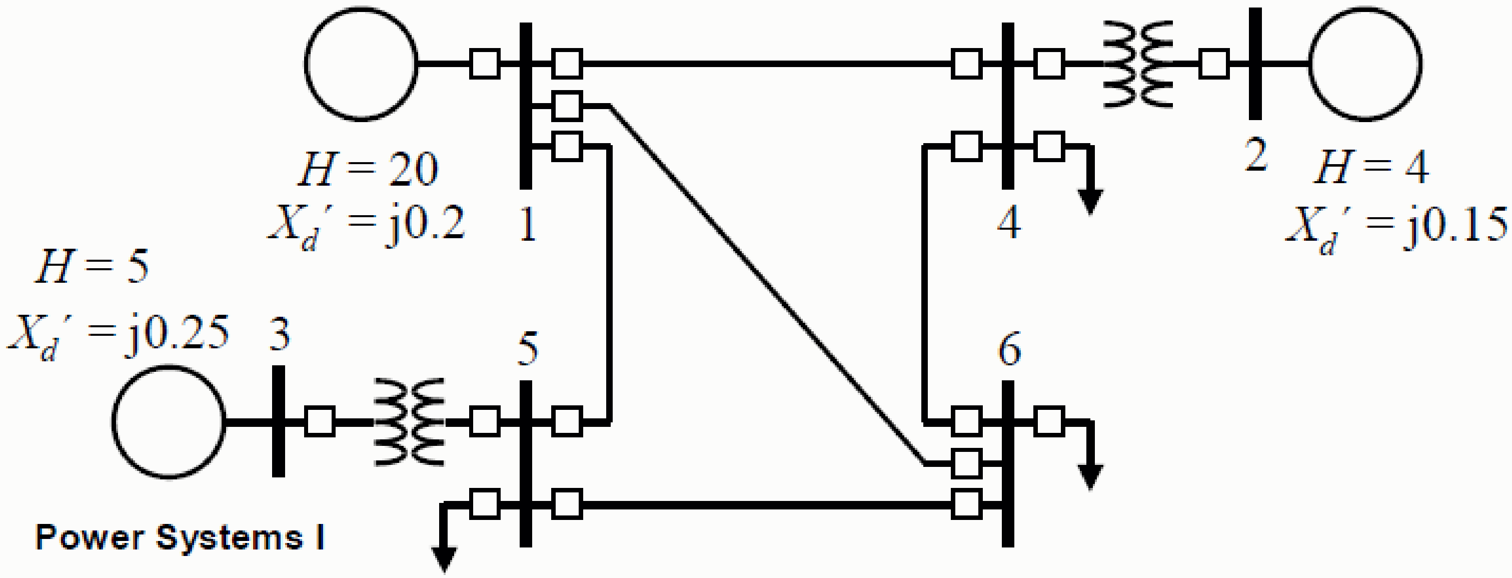
- The total active electrical power fed into the power system by the generators is always equal to the active power consumed by the loads including the losses in the system.
- On the other there is not always a similar balance between the loads and the power fed into the generators by the prime movers, e.g. the hydro and steam turbines.
- If such an imbalance develops the rotating parts of the generators, and other rotating machines, will act as energy buffer, and the kinetic energy stored in these will decrease or increase as a result of the imbalance.
- **Rotor angle stability refers to the ability of synchronous machines of a power system to remain in synchronism after a disturbance.**
- Rotor angle instability occurs due to angular swings of some generators leading to their loss of synchronism with other generators.

Rotor Angle Stability (contd.)

- If the disturbance is local and substantial, e.g. an earth fault close to an generator, the generator can fall out of step since it has been accelerated during the fault.
- As quite big currents will flow in the generator windings in such a case, it must be disconnected to avoid that it is damaged.
- Typical time scale for such an instability to develop is a second to a couple of seconds.
- This kind of instability is called **transient instability**, and, instability is usually in form of aperiodic angular separation due to lack of synchronizing torque.
- This form of instability is also referred to as **large-disturbance rotor angle instability.**

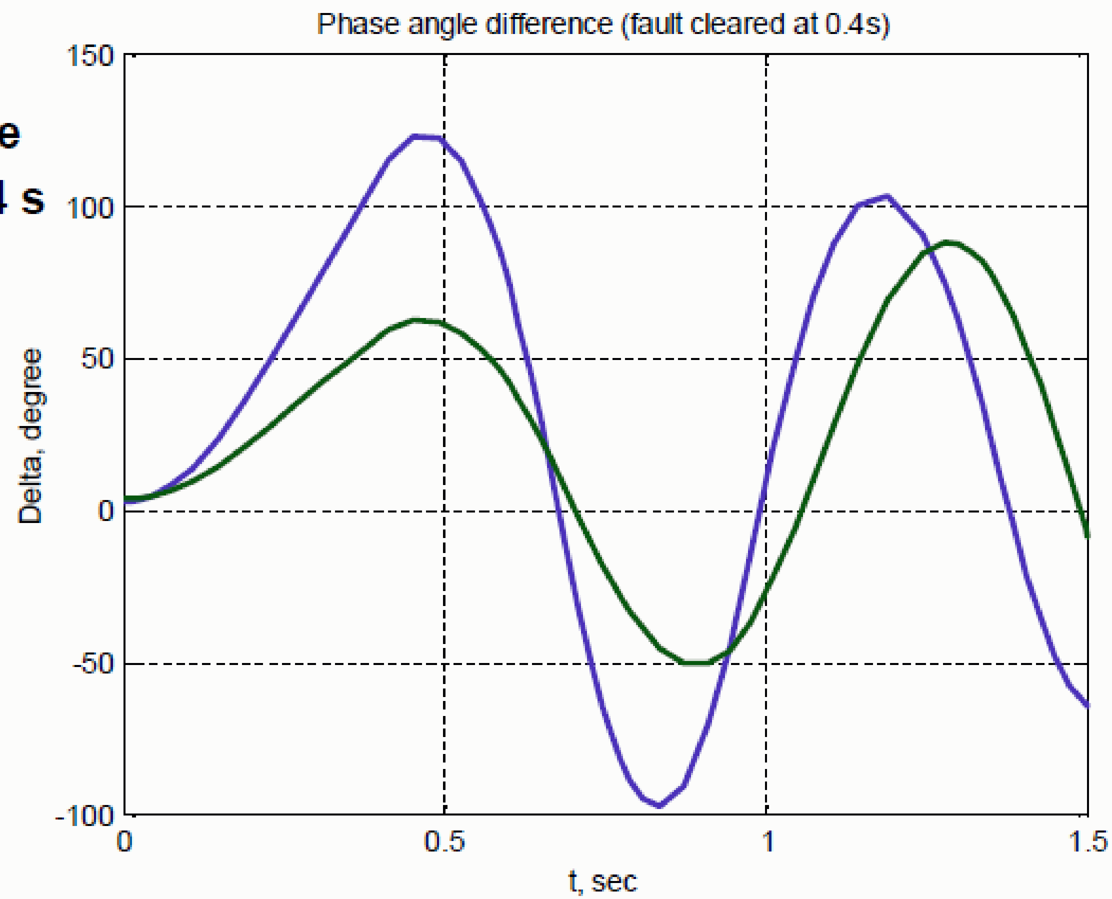
Example

- **Consider the 3 machine system below**
  - select generator #1 as the swing machine with a constant angle of 0 degrees
  - determine the system stability when a fault on the line 5-6 near bus 6 is cleared in 0.4 and 0.5 seconds



Example

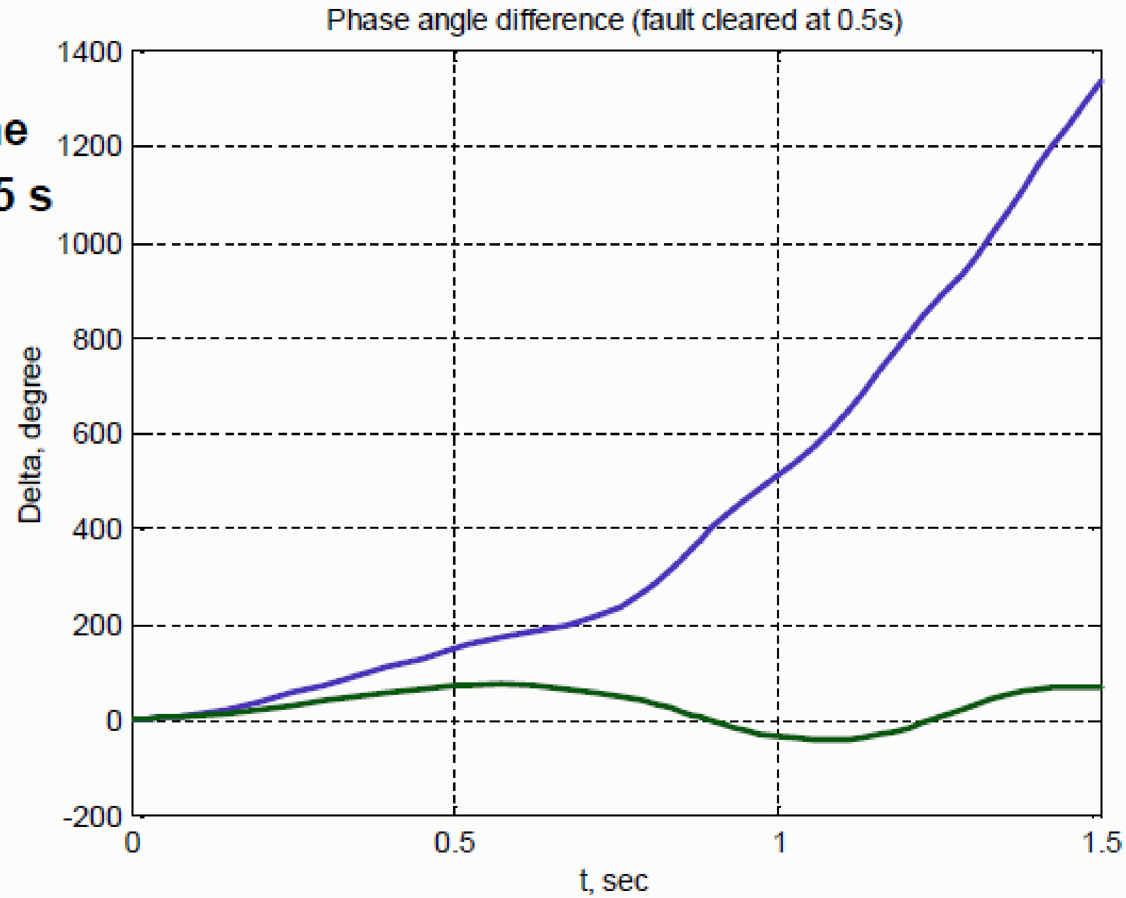
Power angle / time fault clearing in 0.4 s



Power Systems I

Example

Power angle / time
fault clearing in 0.5 s



Power Systems I

Small Disturbance Rotor Angle Stability

- It is the ability of the power system to maintain synchronism under **small disturbances**.
- Disturbances are considered to be sufficiently small such that the linearization of system equations is permissible for purposes of analysis.
- The time frame of interest in small-disturbance stability studies is of the order of 10 to 20 seconds following a disturbance.

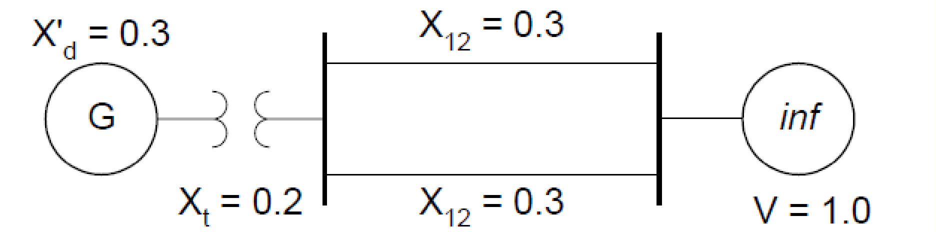
Small Disturbance Rotor Angle Stability

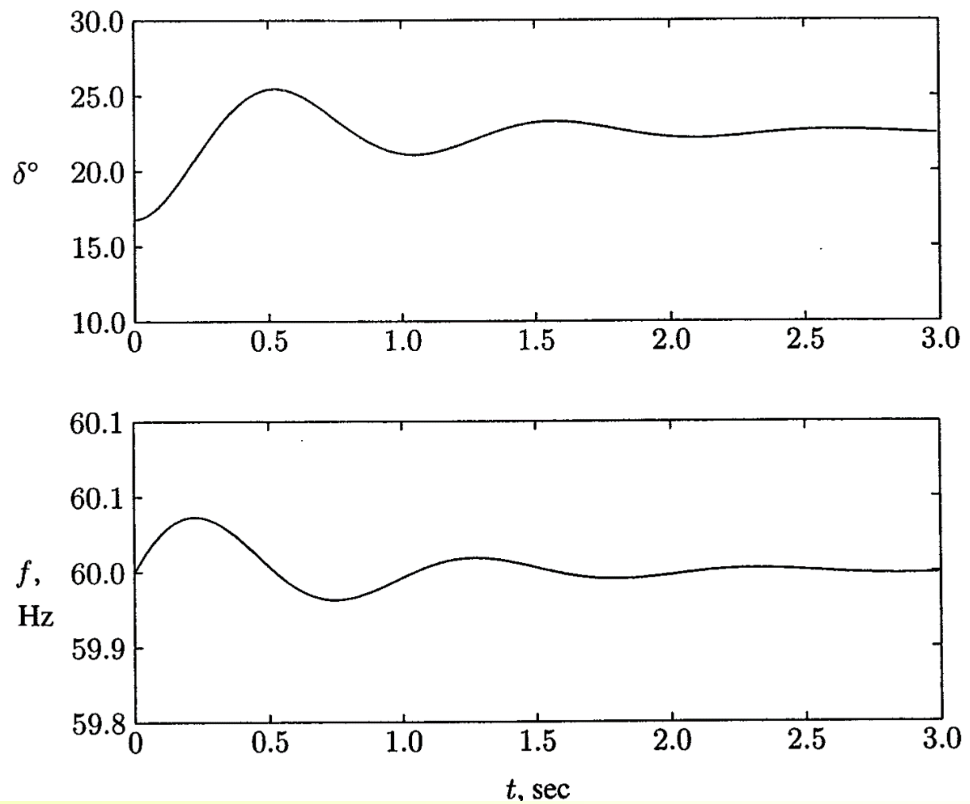
- Small-disturbance stability depends on the **initial operating state** of the system.
- Instability that may result can be of two forms:
  - increase in rotor angle through **a nonoscillatory or aperiodic mode due to lack of synchronizing torque,**
  - rotor oscillations of increasing amplitude due to lack of sufficient damping torque.
- In today's power systems, small-disturbance rotor angle stability problem is usually associated with insufficient damping of oscillations.
- The aperiodic instability problem has been largely eliminated by use of continuously acting generator voltage regulators; however, this problem can still occur when generators operate with constant excitation when subjected to the actions of excitation limiters (field current limiters).

Small Disturbance Rotor Angle Stability

- Small-disturbance rotor angle stability problems may be either local or global in nature.
- Local problems involve a small part of the power system, and are usually associated with rotor angle oscillations of a single power plant against the rest of the power system.
- Such oscillations are called ***local plant mode oscillations*****.**
- Stability (damping) of these oscillations depends on the strength of the transmission system as seen by the power plant, generator excitation control systems and plant output.
- Global problems are caused by interactions among large groups of generators and have widespread effects.
- They involve oscillations of a group of generators in one area swinging against a group of generators in another area.
- Such oscillations are called ***inter-area mode oscillations***. Their characteristics are very complex and significantly differ from those of local plant mode oscillations.
- Load characteristics, in particular, have a major effect on the stability of interarea modes

Example


X'd = 0.3
G
X12 = 0.3
inf
Xt = 0.2
X12 = 0.3
V = 1.0


30.0
25.0
δ°
20.0
15.0
10.0
0
0.5
1.0
1.5
2.0
2.5
3.0
60.1
60.1
f, Hz
60.0
59.9
59.8
0
0.5
1.0
1.5
2.0
2.5
3.0
t, sec

Large Disturbance Rotor Angle Stability: Transient Stability

- It is the ability of the power system to maintain synchronism under a **severe disturbance**, such as a short circuit on a transmission line.
- Disturbances are large so that the linearization of system equations is **not permissible** for purposes of analysis.
- The time frame of interest in small-disturbance stability studies is of the order of 3 to 5 seconds following a disturbance.
- It may extend to 10–20 seconds for very large systems with dominant inter-area swings.

Large Disturbance Rotor Angle Stability: Transient Stability

- Transient stability depends on both **the initial operating state of the system and the severity of the disturbance.**
- Instability is usually in the form of **aperiodic angular separatio**n **due to insufficient synchronizing torque, manifesting as *first swing instability*.**
- However, in large power systems, transient instability may not always occur as first swing instability associated with a single mode; it could be a result of superposition of a slow inter-area swing mode and a local-plant swing mode causing a large excursion of rotor angle beyond the first swing.
- It could also be a result of nonlinear effects affecting a single mode causing instability beyond the first swing.

Dynamic Stability

- The term ***dynamic stability*** also appears in the literature as a class of rotor angle stability.
- However, it has been used to denote different phenomena by different authors.
- In the North American literature, it has been used mostly to denote **small-disturbance stability in the presence of automatic controls (particularly, the generation excitation controls)** as distinct from the classical "steady-state stability" with no generator controls.
- In the European literature, it has been used to denote transient stability.

Voltage Stability Definitions

- Voltage stability is the ability of a power system to maintain steady voltages after a disturbance. Must maintain or restore equilibrium between connected load, and load supply from the power system. Instability is progressive fall or rise of voltages at some buses:
  - Parallel definitions for angle and frequency stability. What must be in equilibrium?
  - The driving force for voltage instability is usually the loads. After a disturbance, load power restoration is attempted by motor slip adjustment, tap changing, and thermostats.
  - Short-term, long-term voltage instability
  - Instability is runaway, positive feedback phenomena

Voltage Stability Definitions

- A power system at an operating state is *voltage stable* if following a disturbance, voltages near loads approach stable post-disturbance equilibrium values:
  - Within region of attraction of post-disturbance equilibrium after switching and control actions
  - Stability may be due to destabilizing controls reaching limits, or other actions such as load disconnection
  - Voltage instability may cause voltage collapse or abnormally high voltages

Voltage Stability Definitions

- A power system undergoes *voltage collapse* if post-disturbance equilibrium voltages are below acceptable limits:
  - Voltage collapse may be total (blackout) or partial
  - Voltage collapse may be due to voltage or angle instability
  - Inadequate voltage support may cause angle instability
- Underside of *P-V* curve is partial voltage collapse with *power uncontrollability*
  - Adding load reduces voltage (normal), but reduces total power (abnormal)
  - Stable operation possible with voltage-sensitive loads
- Distinguish between load power at nominal voltage and load power consumed at actual voltage

Voltage Stability

- Causes of voltage instability
  - Insufficient reactive capability support in load areas
    - Especially dynamic VAr sources
  - Loads exceeding system capability
    - Size and power factor
  - Excessive use of shunt capacitor banks in the load area
  - Increased power transfers
  - Lower reactive support capability of newly installed generators
  - Reactive power transfer capability of the system is very limited by its nature
    - Voltage is a local problem
      - Controlled at a limited number of nodes
      - Remaining voltages are function of controllable voltages and system conditions

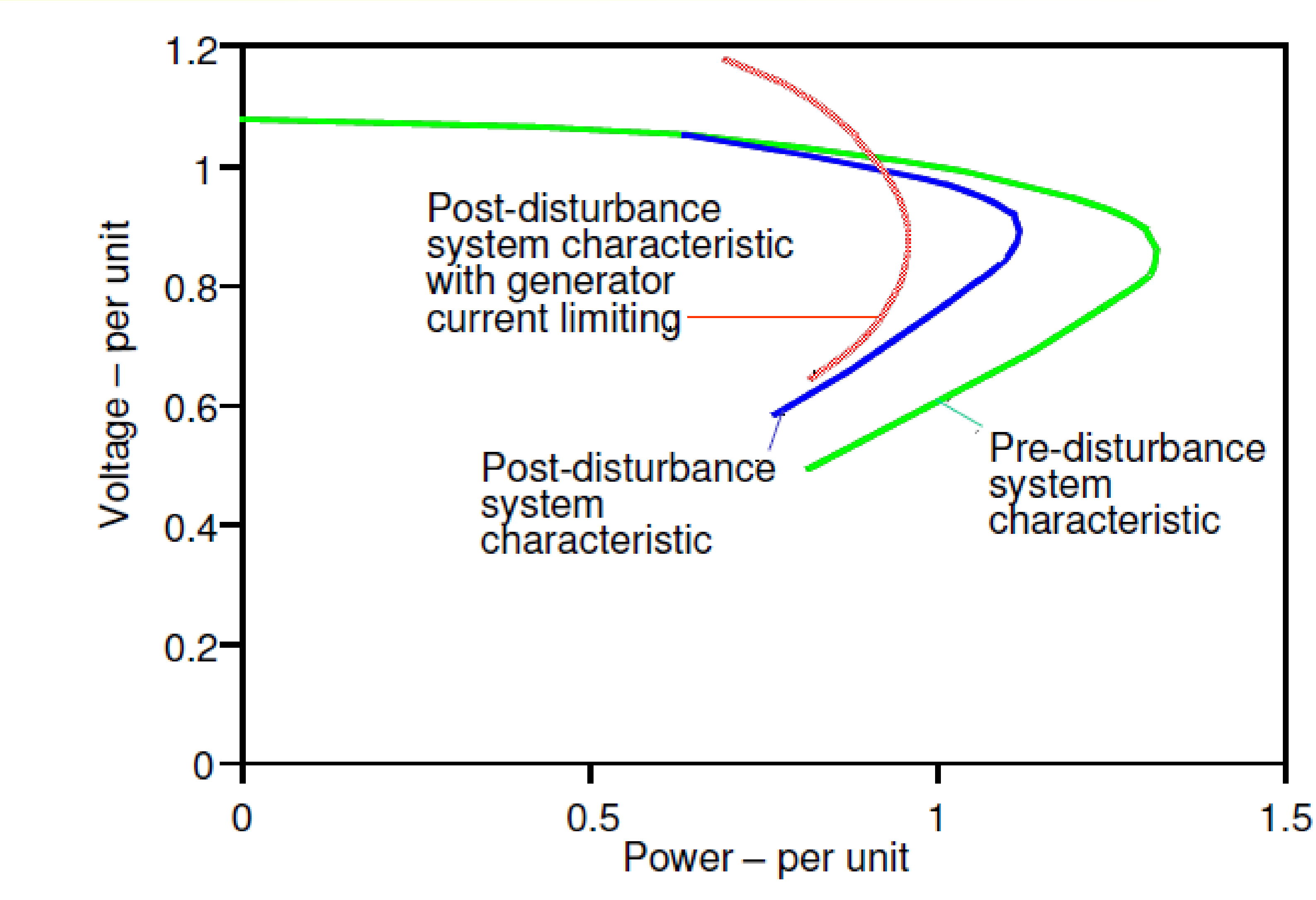
Voltage stability

- Voltages have to be within 95% and 105% of the rated value under normal system conditions

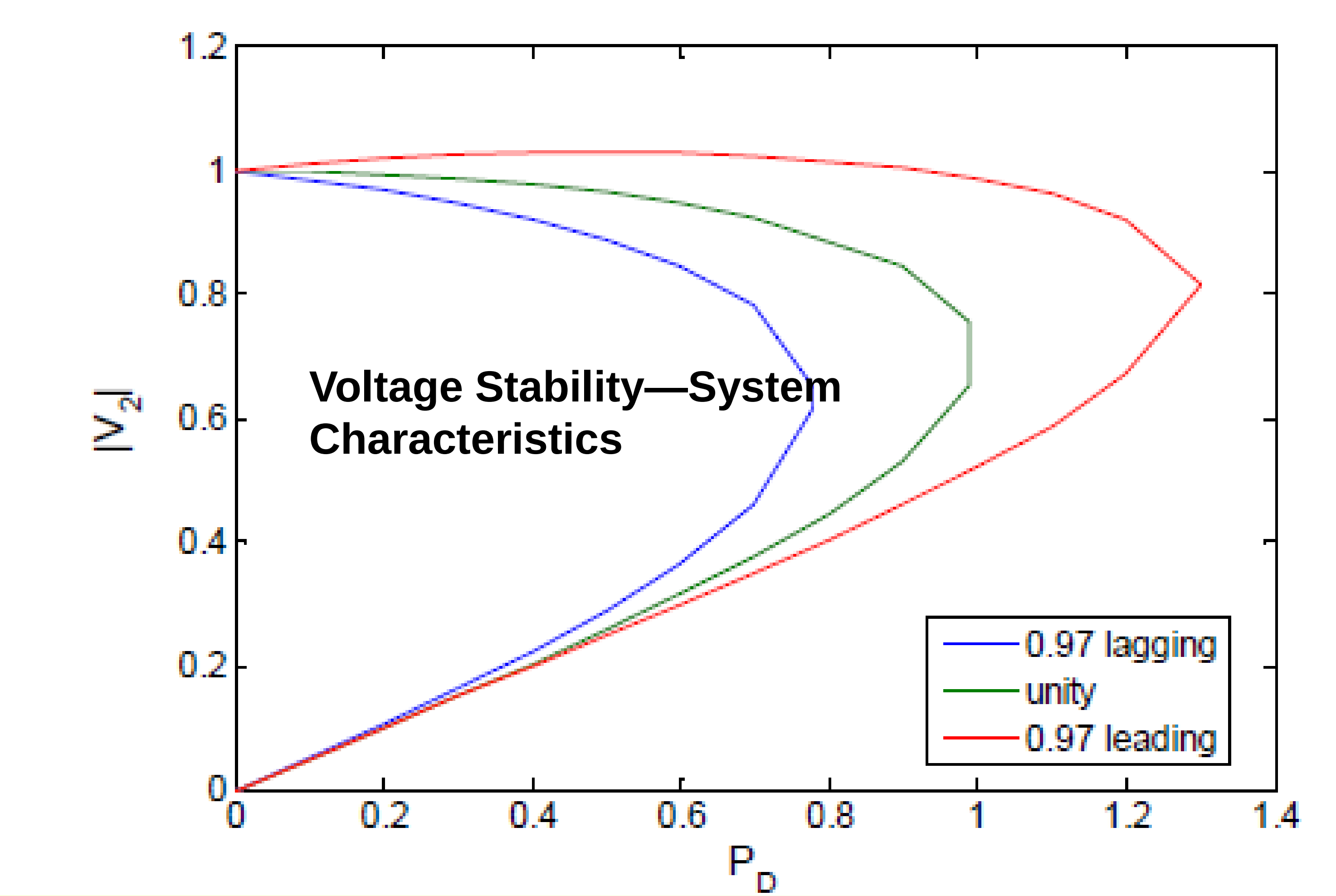
- Lower voltage causes
  - Higher transmission losses
  - Equipment malfunctions
    - i.e. motor's stall, overheat or damage
  - Quadratic reduction of reactive power output of capacitors
  - Tripping of generating units

- Higher voltage causes
  - Damage major equipment – insulation failure
  - Automatically trip major transmission equipment

Voltage Stability—System Characteristics

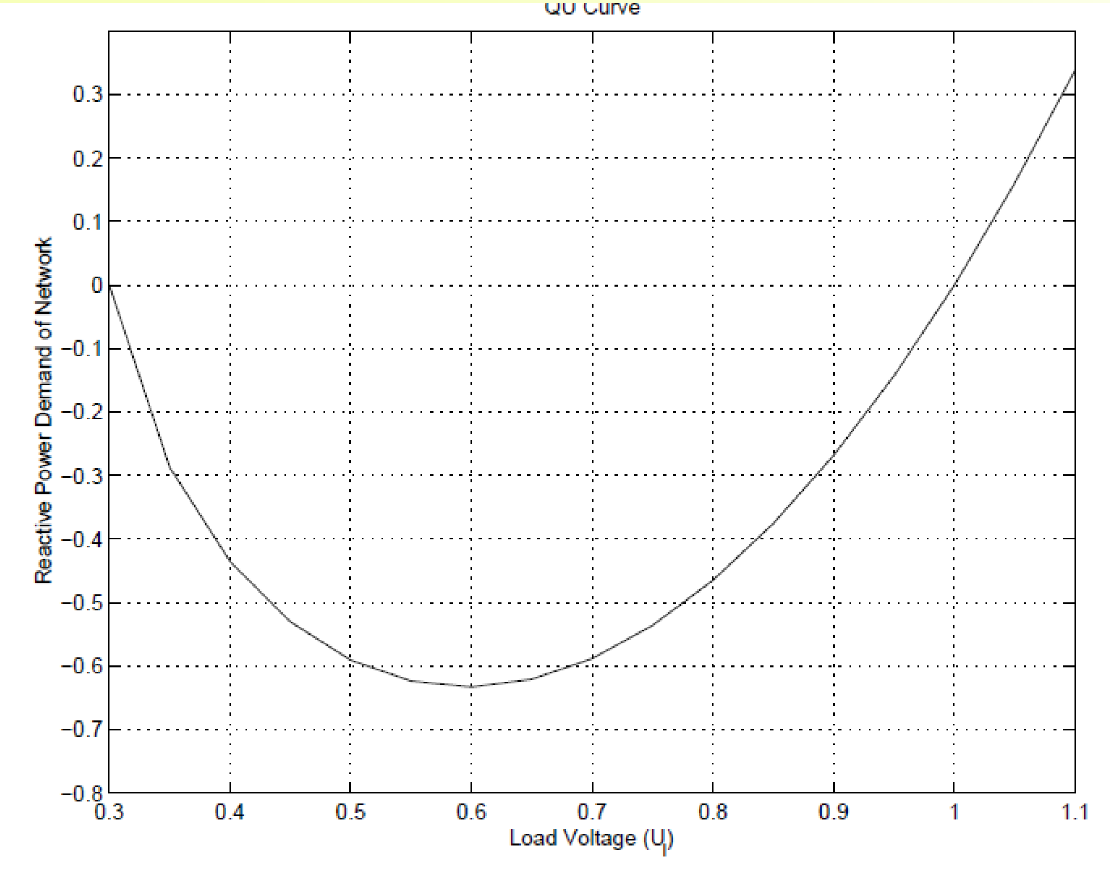


PV Curves



Voltage Stability—System Characteristics
$|V_2|$
P_D
0.97 lagging
unity
0.97 leading
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4

QV curves



- The *V SF* criterion for stability says that an reactive power injection should result in a higher voltage.
- In the *QV* curve this corresponds to a positive derivative, which are for load voltages higher than ≈ 0.6 p.u.

***QV* curve for the system (U_N = 1.044, X_e = 0.3 p.u., P_l = 1.0 p.u.)**

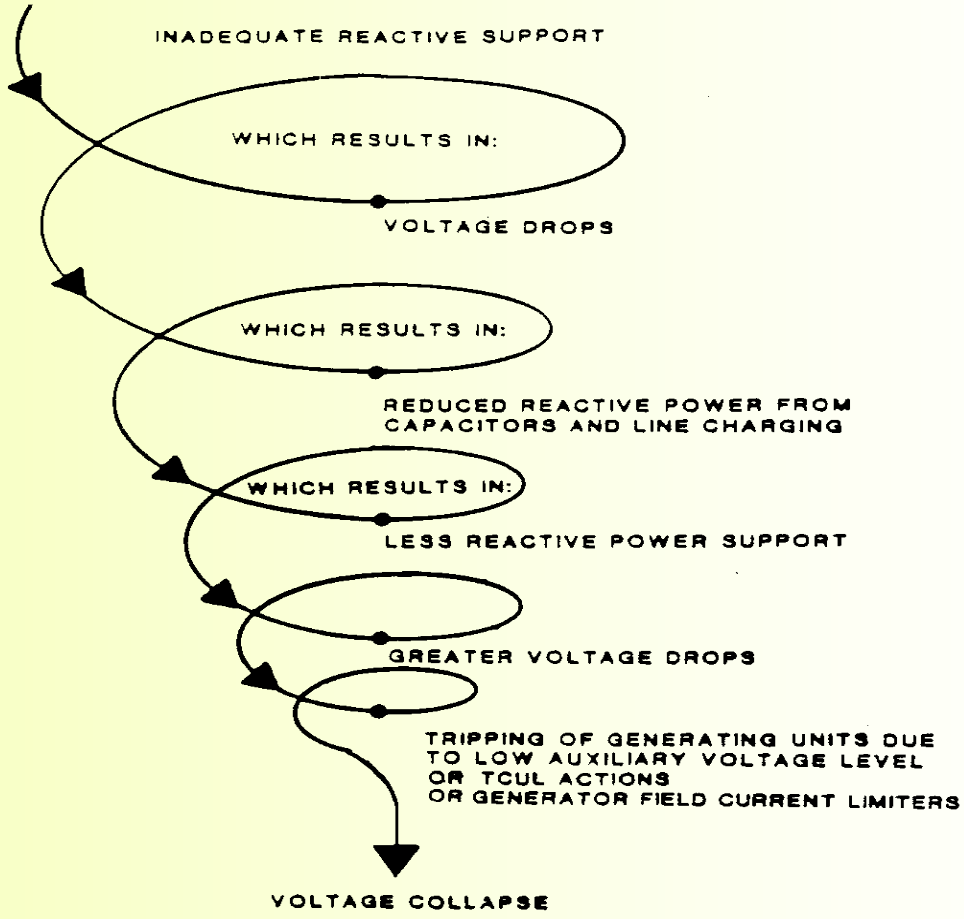
Voltage Collapse

- Large scale effect of voltage instability leads to **Voltage collapse.** It is a process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system.

- The driving force for voltage instability is usually the loads.

- Voltage stability problems is also experienced at terminals of HVDC links connected to weak ac systems.

Voltage Collapse Phenomenon



Voltage Instability

- The driving force for voltage instability is usually the loads.
- In response to a disturbance, power consumed by the loads tends to be restored by the action of motor slip adjustment, distribution voltage regulators, tap-changing transformers, and thermostats.
- Restored loads increase the stress on the high voltage network by increasing the reactive power consumption and causing further voltage reduction.
- A run-down situation causing voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation.

Small Disturbance Voltage Stability

- Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small disturbances such as incremental changes in system load.
  - This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining, at any instant, how the system voltages will respond to small system changes.
  - With appropriate assumptions, system equations can be linearized for analysis thereby allowing computation of valuable sensitivity information useful in identifying factors influencing stability
  - A combination of both linear and non-linear techniques are used for analysis.

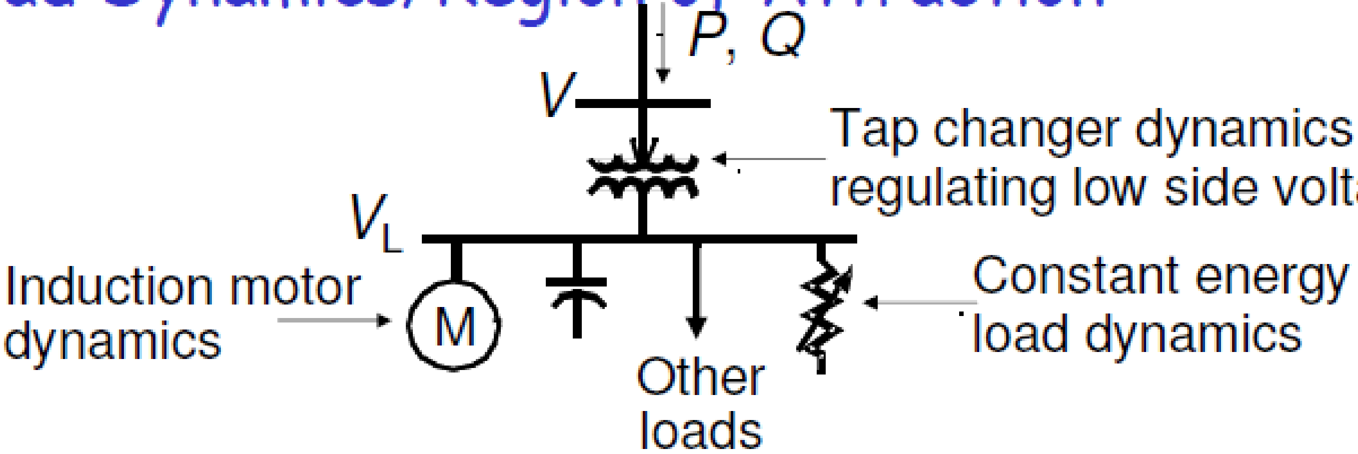
Large Disturbance Voltage Stability

- Large-disturbance voltage stability refers to the system’s ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.
- The study period of interest may extend from a few seconds to tens of minutes.

Short-Term Voltage Stability

- ***Short-term voltage stability*** involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters.
- The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations; this is similar to analysis of rotor angle stability.
- Dynamic modeling of loads is often essential.
- In contrast to angle stability, short circuits near loads are important.
- It is recommended that the term ***transient voltage stability*** not be used.

Load Dynamics/Region of Attraction



Load dynamics are basically first order

$$2H\omega\frac{ds}{dt} = P_o - P_e$$ Motor

$$T_T\frac{dn}{dt} = P_o - P_o\left[\frac{V_L}{V_o}\right]^{\alpha}$$ Tap changer

$$T_E\frac{dG}{dt} = P_o - G_o\left[\frac{V_L}{V_o}\right]^{2}$$ Constant energy

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Long-term Voltage Stability

- ***Long-term voltage stability*** involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters.
- The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance .
- Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance.
- Instability is due to the loss of long-term equilibrium (e.g., when loads try to restore their power beyond the capability of the transmission network and connected generation), post-disturbance steady-state operating point being small-disturbance unstable
- The disturbance could also be a sustained load buildup (e.g., morning load increase).
- In many cases, static analysis,can be used to estimate stability margins, identify factors influencing stability, and screen a wide range of system conditions and a large number of scenarios.

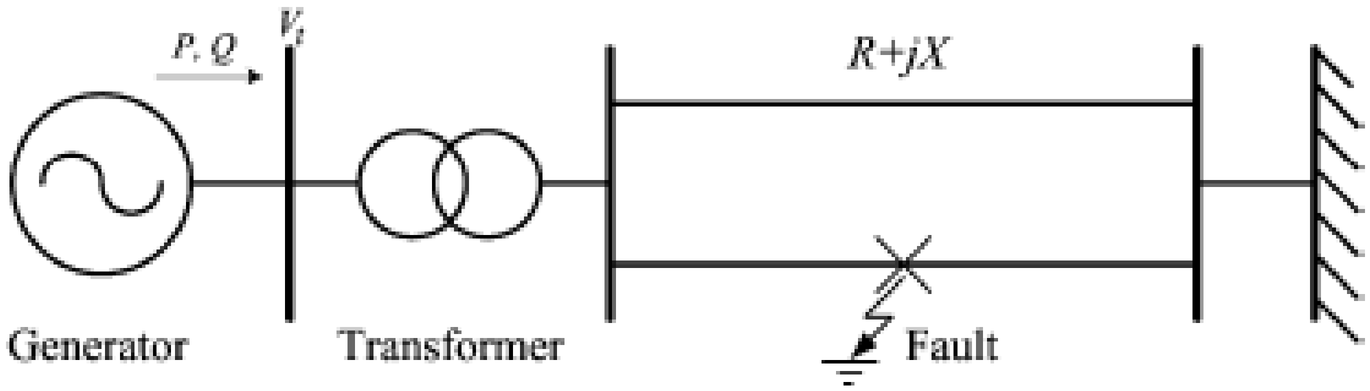
Rotor Angle Stability vs. Voltage Stability

- Rotor angle stability is basically a generator stability while voltage stability means load stability.

- Rotor angle stability is mainly interlinked to real power transfer whereas voltage stability is mainly related to reactive power transfer.

Power System Dynamics

Single-machine infinite-bus (**SMIB**) power system



Swing Equations

$$\frac{d\delta}{dt} = \omega$$

$$M\frac{d\omega}{dt} + D\omega = P_m - P_e$$

$$P_e = \frac{E_g E_b}{x_g - x_e} sin\,\delta$$

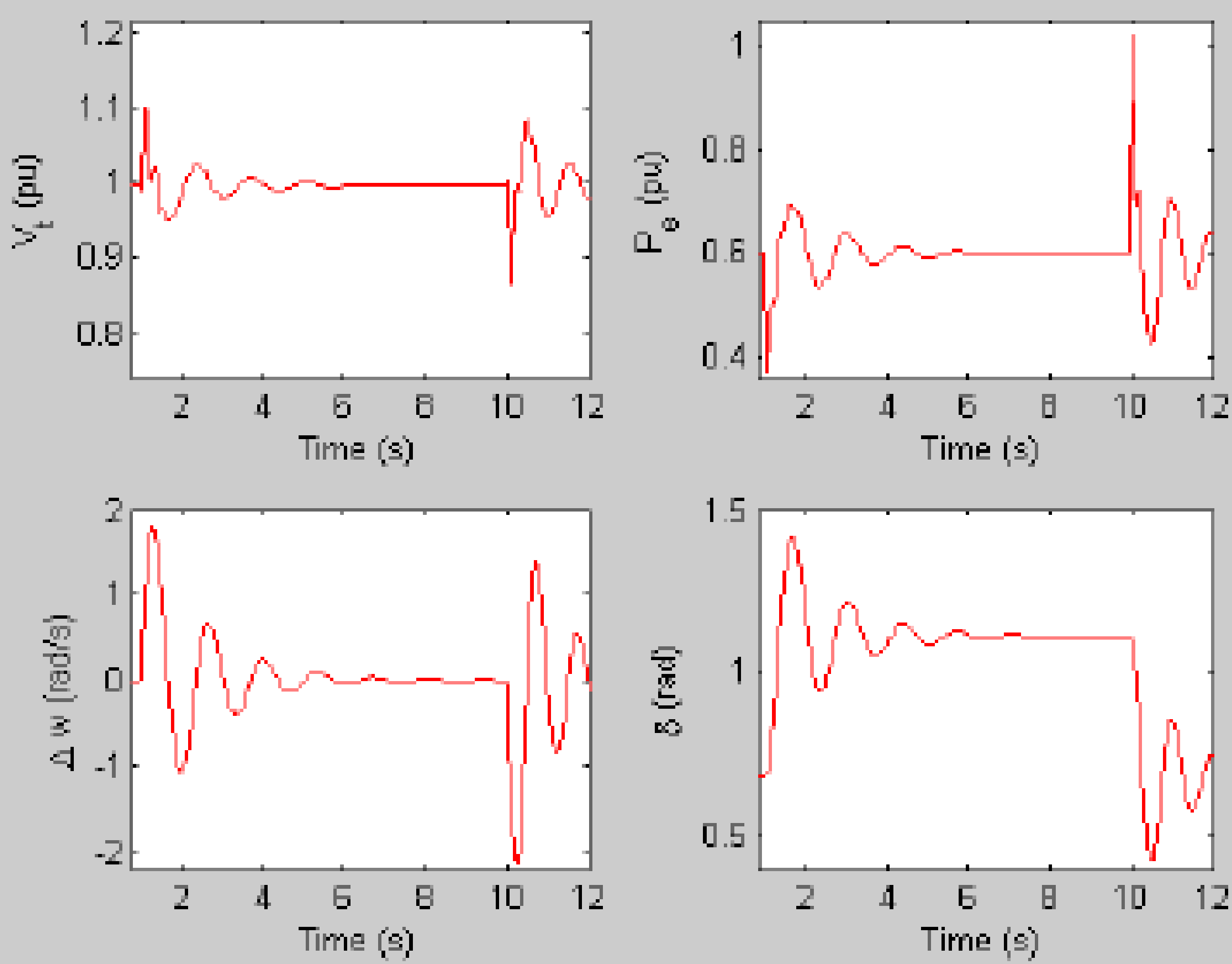
ω , δ , E: Frequency, rotor angle and voltage (at gen. or Infinite bus)

P_m , P_e : Mechanical and electrical powers

x_g , x_e : Generator and other (external) reactance

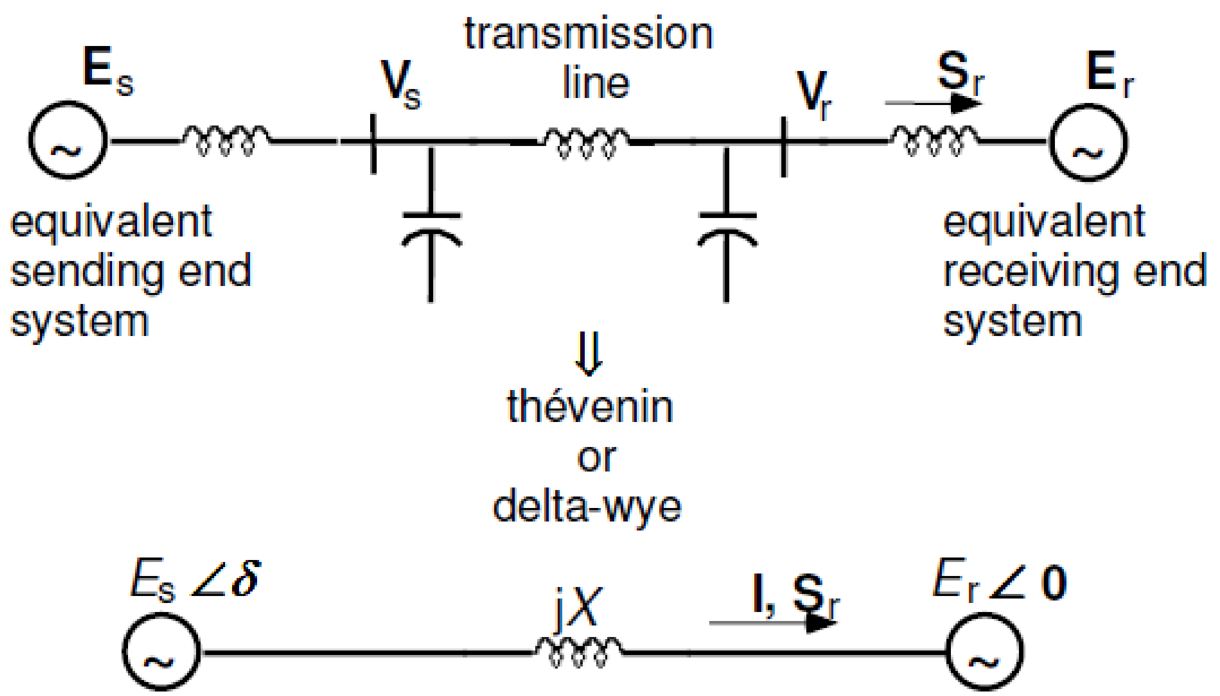
M , D: Inertia and damping coefficients

Swing Equations



System response for a fault during 1 to 10 seconds

Bacis Power Transmission



- δ is "load angle"
- Draw phasor diagram

Bacis Power Transmission

$$S_r = P_r + jQ_r = E_r I^*$$

$$= E_r \left[\frac{E_s \cos\delta + jE_s \sin\delta}{jX} \right]$$

$$= \frac{E_s E_r}{X} \sin\delta + j \frac{E_s E_r \cos\delta - E_r^2}{X}$$

$$P_r = P_s = \frac{E_s E_r}{X} \sin\delta$$

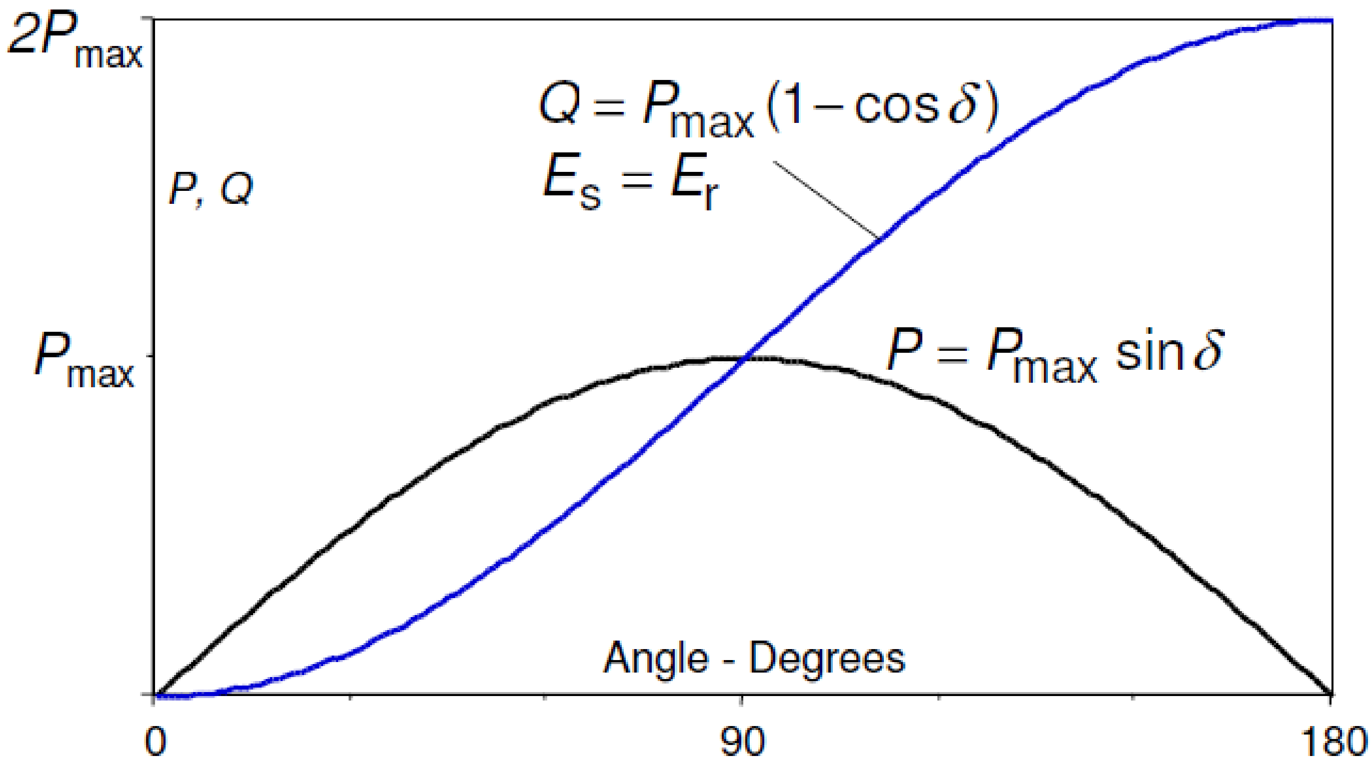
$$Q_r = \frac{E_s E_r \cos\delta - E_r^2}{X}$$

$$Q_s = \frac{E_s^2 - E_s E_r \cos\delta}{X}$$

Bacis Power Transmission

$$P = \frac{E_s E_r}{X} \sin\delta = P_{max} \sin\delta$$

$P_{max} \propto E^2$ Maximum power at 90°



Bacis Power Transmission

$$P = P_{\max} \sin\delta \cong P_{\max}\delta \qquad \delta < 30^\circ$$

Real or active power transfer depends mainly on load angle.

Steady-state angle across a transmission path between "voltage secure" busses normally less than 45°.

Bacis Reactive Power Transmission

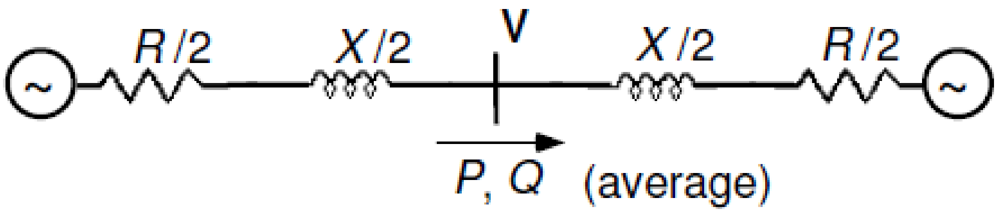
$$Q_r = \frac{V_s V_r \cos\delta - V_r^2}{X} \cong \frac{V_r(V_s - V_r)}{X}$$

$$Q_s = \frac{V_s^2 - V_s V_r \cos\delta}{X} \cong \frac{V_s(V_s - V_r)}{X}$$

Reactive power transfer depends mainly on voltage magnitudes and flows from highest voltage to lowest voltage.

- P and δ are closely coupled
- Q and V are closely coupled
- Can reactive power be transferred long distances?
- What happens to Q_s and Q_r at large angles?

Transmission Losses



$$I^2 = \left[\frac{P + jQ}{V}\right]\left[\frac{P - jQ}{V}\right] = \frac{P^2 + Q^2}{V^2}$$

$$P_{loss} = I^2 R = \frac{P^2 + Q^2}{V^2} R$$

$$Q_{loss} = I^2 X = \frac{P^2 + Q^2}{V^2} X$$

- Effect of reducing Q transfer?
- Effect of voltage?
- Real and reactive power losses dominated by *P* transfer

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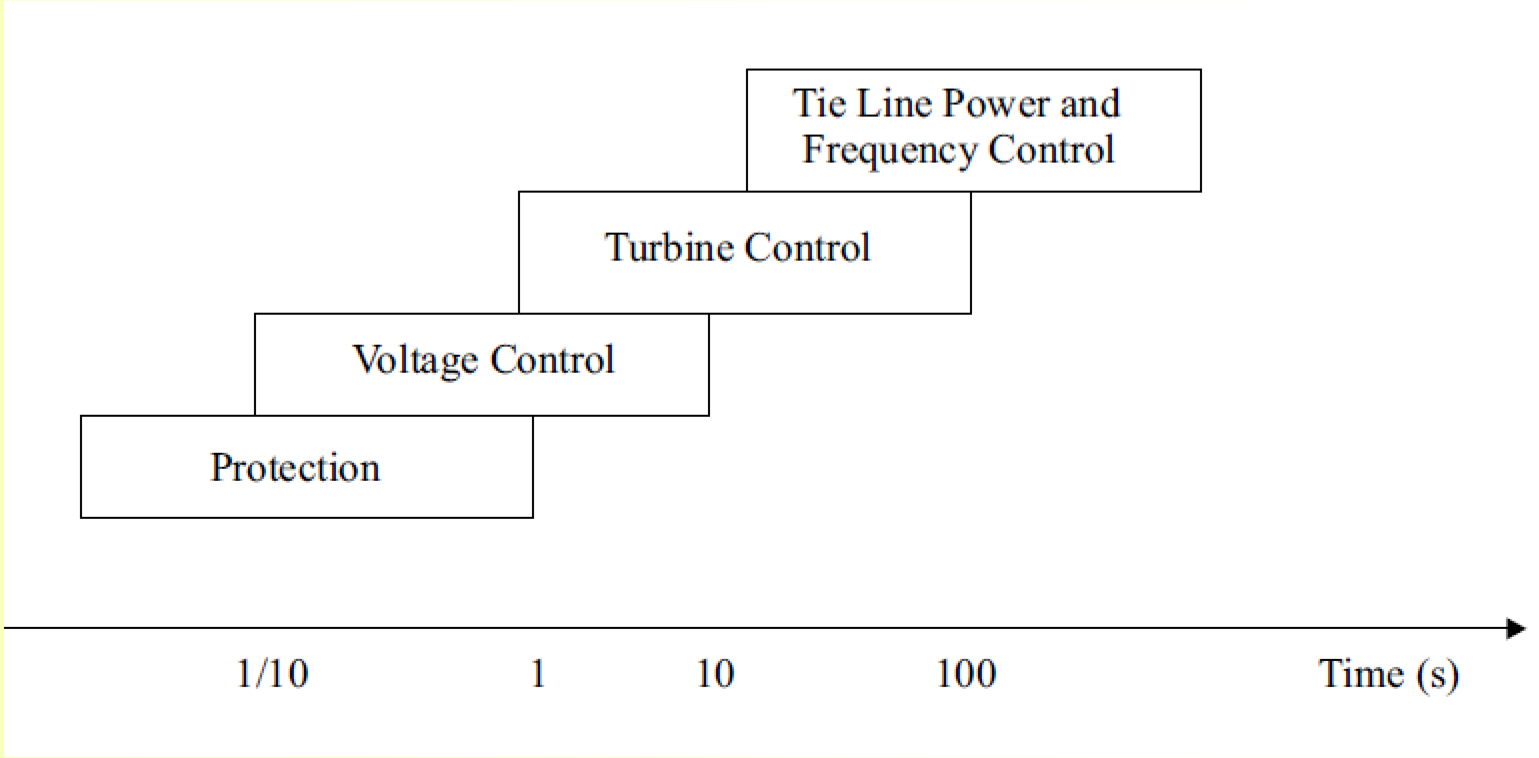
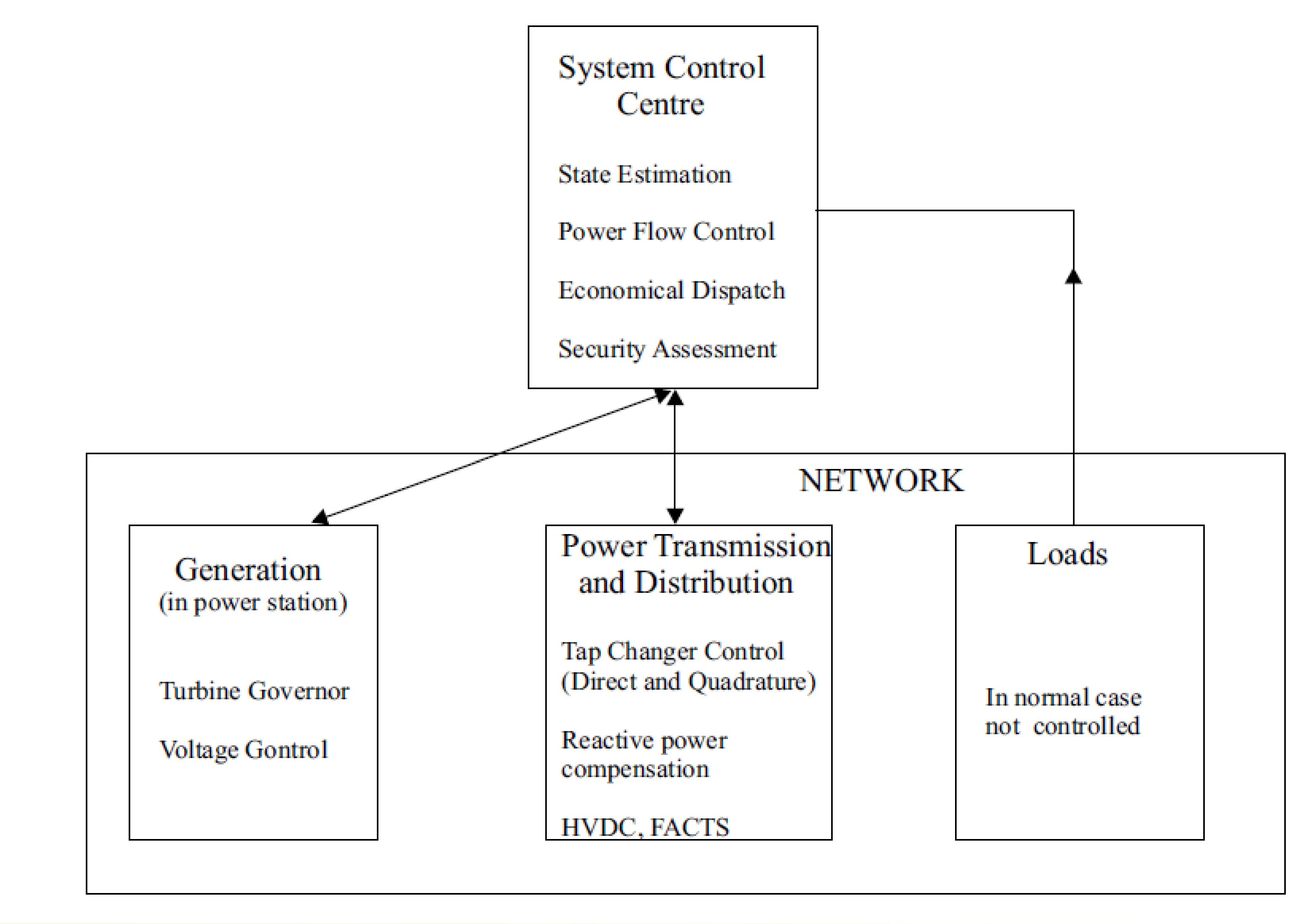
Power System Control

- Power systems comprises the subsystems **Electricity Generation, Transmission, Distribution, and Consumption (Loads)**
- The associated control system has a hierarchic structure. This means that the control system consists of a number of nested control loops that control different quantities in the system.
- In general the control loops on lower system levels, e.g. Locally in a generator, are characterized by smaller time constants than the control loops active on a higher system level.
- As an example, the **Automatic Voltage Regulator (AVR),** which regulates the voltage of the generator terminals to the reference (set) value, responds typically in a time scale of a second or
- less, while **the Secondary Voltage Control**, which determines the reference values of the voltage controlling devices, among which the generators, operates in a time scale of tens of seconds or minutes.
- That means that these two control loops are virtually de-coupled.
- This is also generally true for other controls in the systems, resulting in a number of de-coupled control loops operating in different time scales.

Schematic diagram of dierent time scales of power system controls



The structure of the Hierarchical Control Systems of a Power System



Control Tasks of Power Systems

- The overall control task in an electric power system is to maintain the balance between the electric power produced by the generators and the power consumed by the loads, including the network losses, at all time instants.
- If this balance is not kept, this will lead to frequency deviations that if too large will have serious impacts on the system operation.
- A complication is that the electric power consumption varies both in the short and in the long time scales.
- In the long time scale, over the year, the peak loads of a day are in countries with cold and dark winters higher in the winter, so called winter peak, while countries with very hot summers usually have their peak loads in summer time, summer peak.
- Examples of the former are most European countries, and of the latter Western and Southern USA.

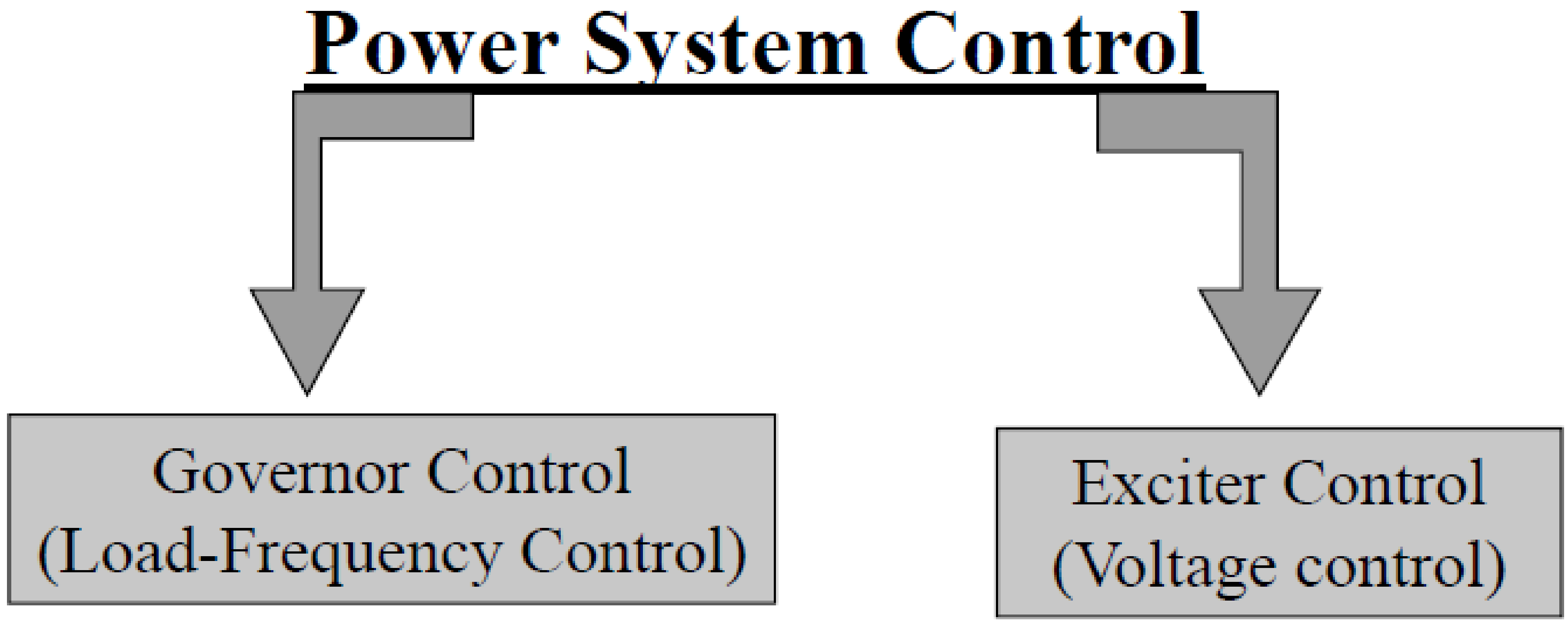
Control Tasks of Power Systems

- In addition to keeping the above mentioned balance, the delivered electricity must conform to certain quality criteria.
- This means that the voltage magnitude, frequency, and wave shape must be controlled within specified limits.
- If a change in the load occurs, this is in the first step compensated by the kinetic energy stored in the rotating parts, rotor and turbines, of the generators resulting in a frequency change.
- If this frequency change is too large, the power supplied from the generators must be changed, which is done through the frequency control of the generators in operation.
- An unbalance in the generated and consumed power could also occur as a consequence of that a generating unit is tripped due to a fault.
- The task of the frequency control is to keep the frequency deviations within acceptable limits during these events.
- Minimization of costs over the year
- Minimization of fuel costs and start/stop costs

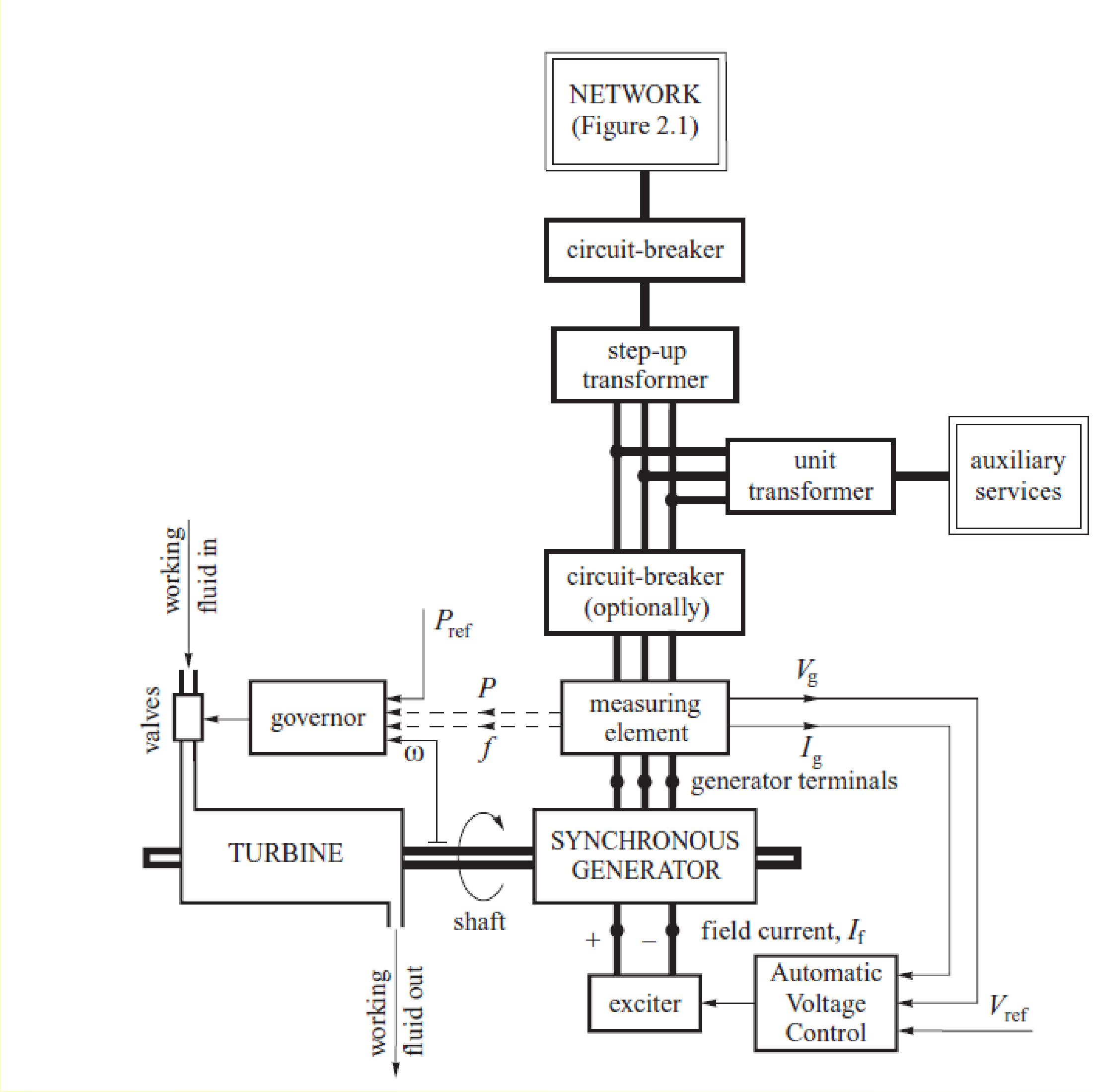
Frequency Stability

- Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.
- Frequency instability leads to tripping of generating units and/or loads.
- Frequency stability may be a short-term phenomenon or a long-term phenomenon.

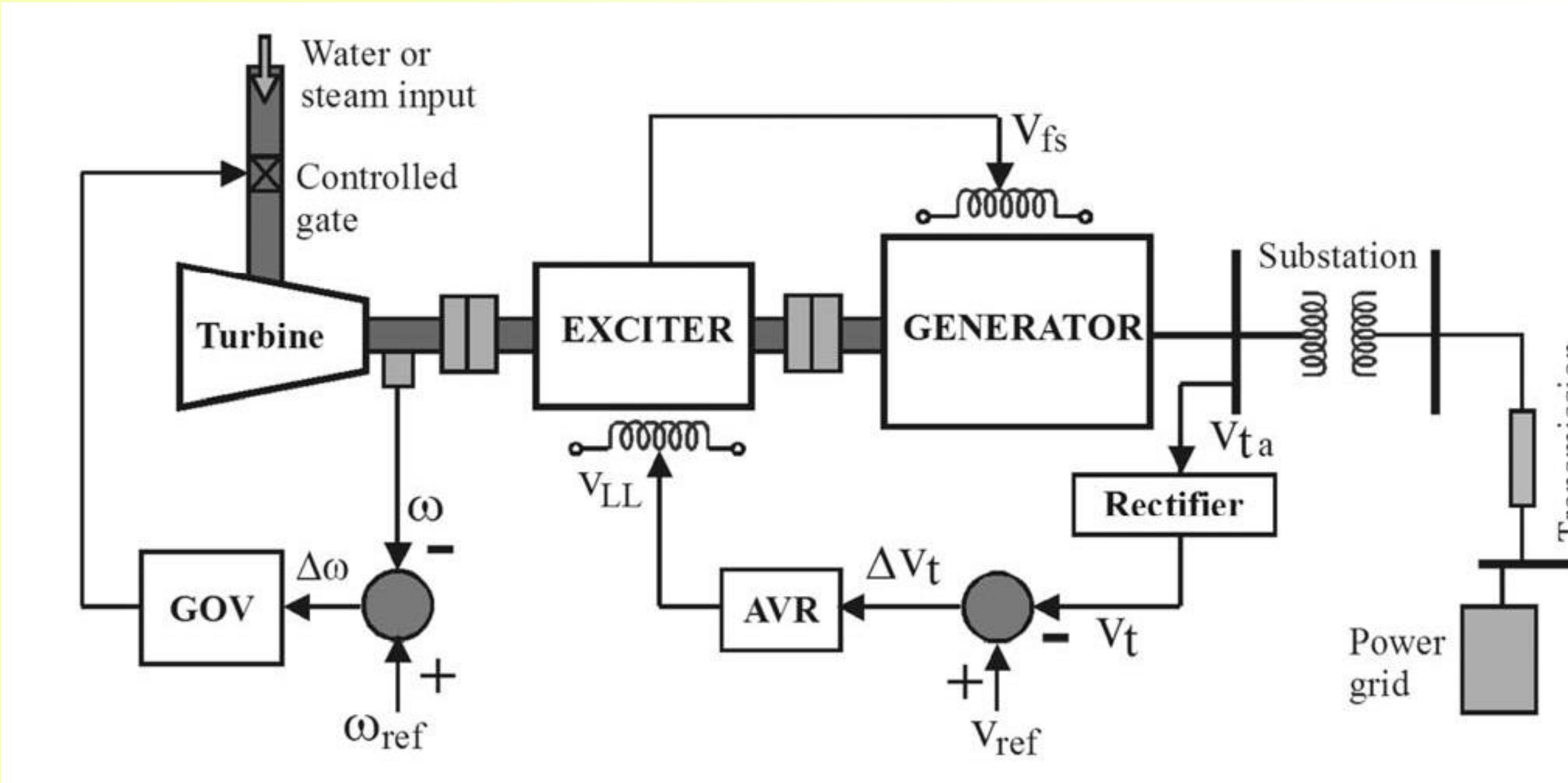
Power System Control



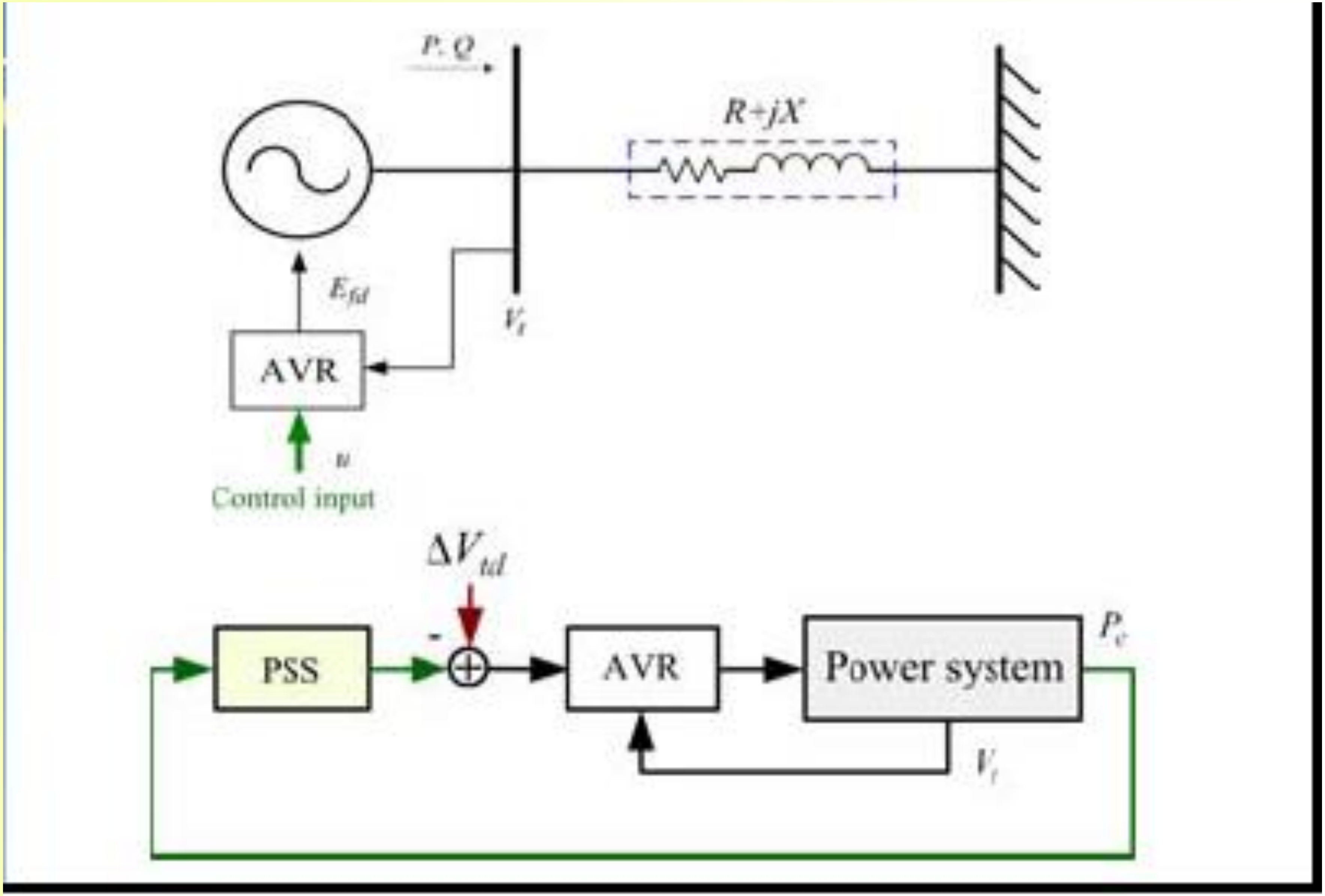
Block diagram of a power generation unit



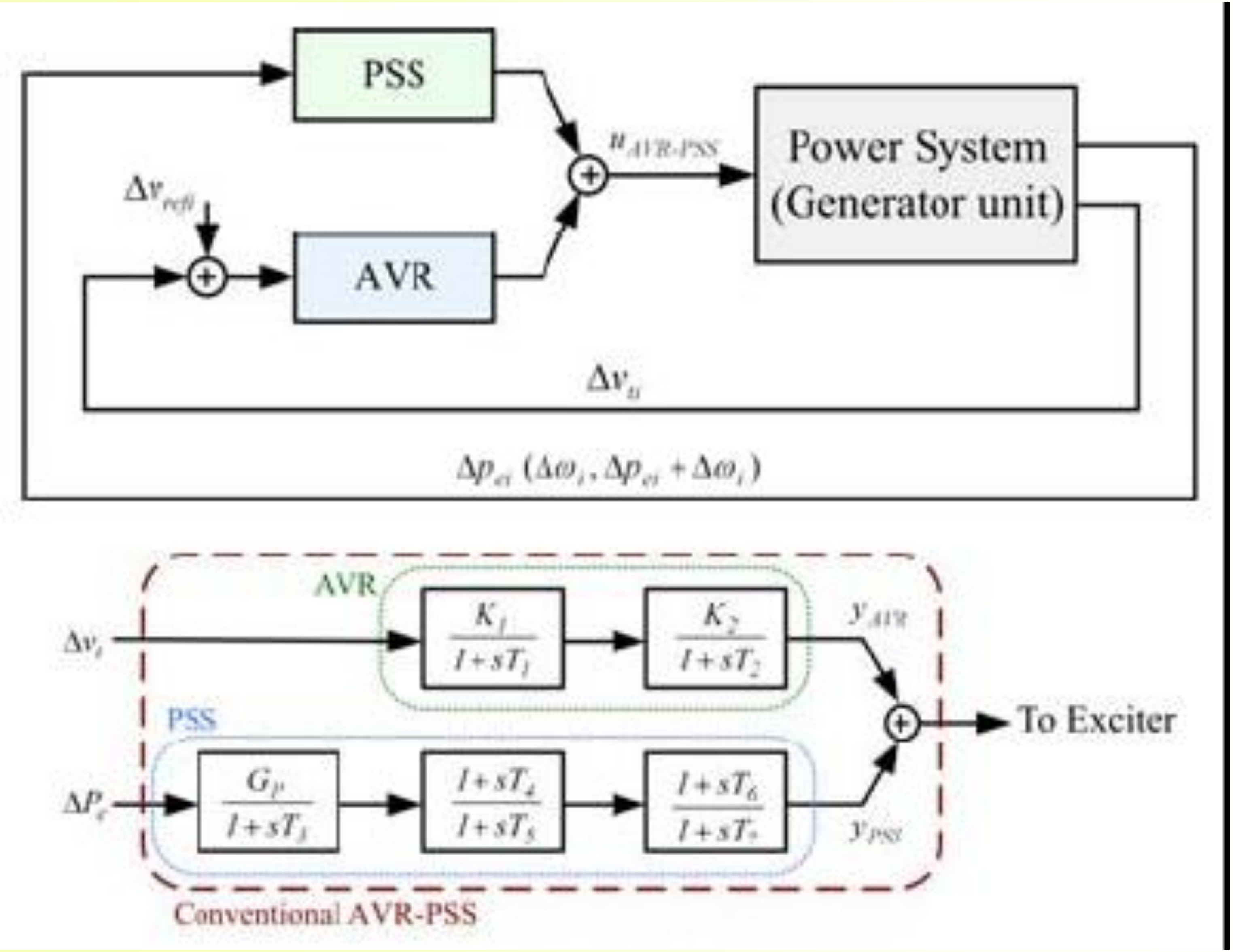
Control Block Diagram of the Power System



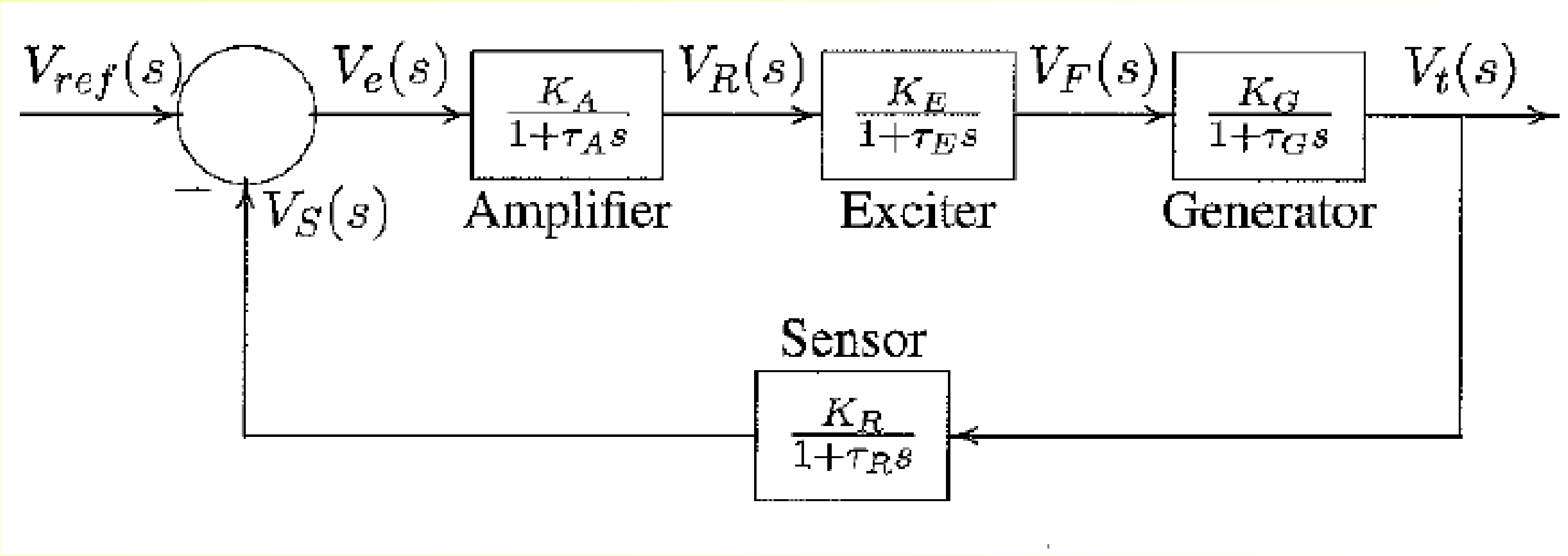
SMIB Power System Comtrol



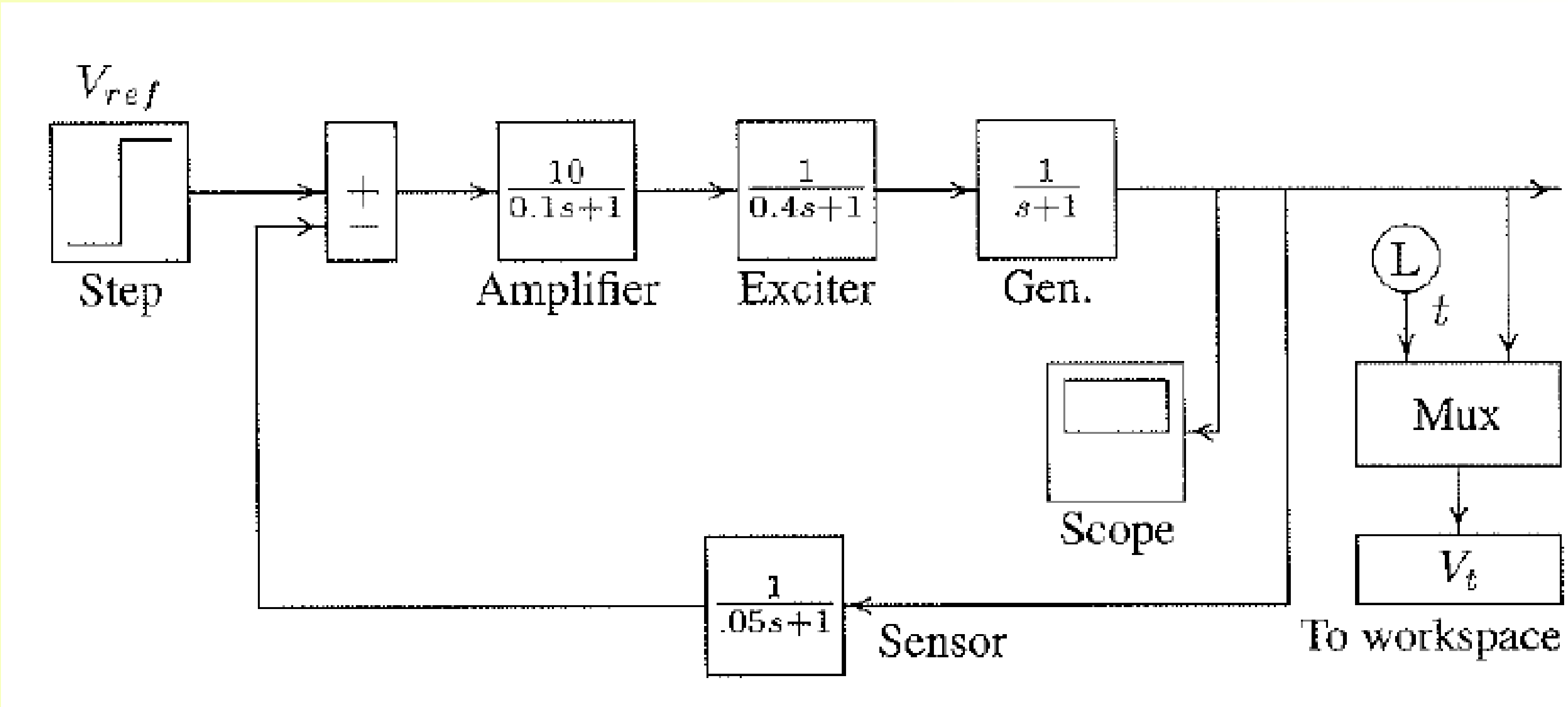
Conventional AVR-PSS Scheme



AVR Block Diagram

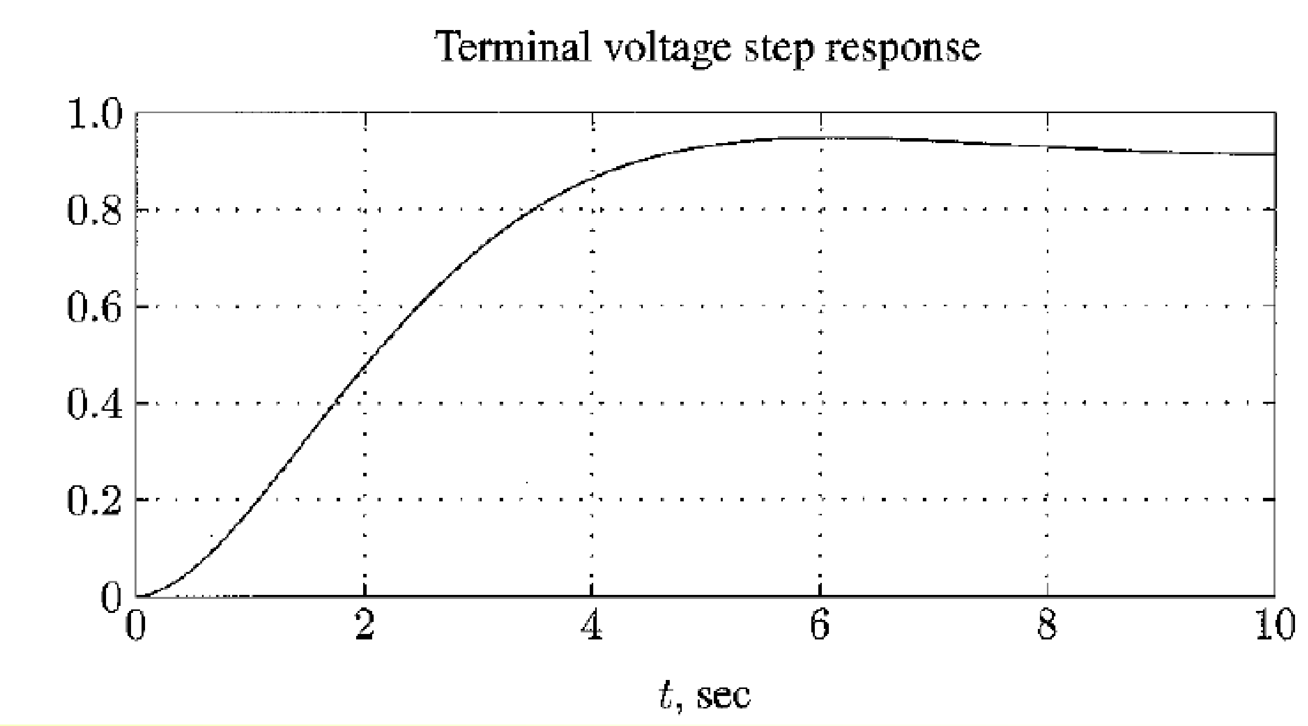


SIMULINK MODEL



Step response and the time-domain performance

```
numc=250*[1 45 500];
denc=[1  58.5  13645  270962.5  274875 137500];
t=0:.05:10;
c=step(numc, denc, t); plot(t, c), grid
timespec(numc, denc)
```



Automatic Generation Control

- To maintain power balance in the system.
- Make sure that operating limits are not exceeded:
  - Generators limit
  - Tie-lines limit
- Make sure that system frequency is constant (not change by load).

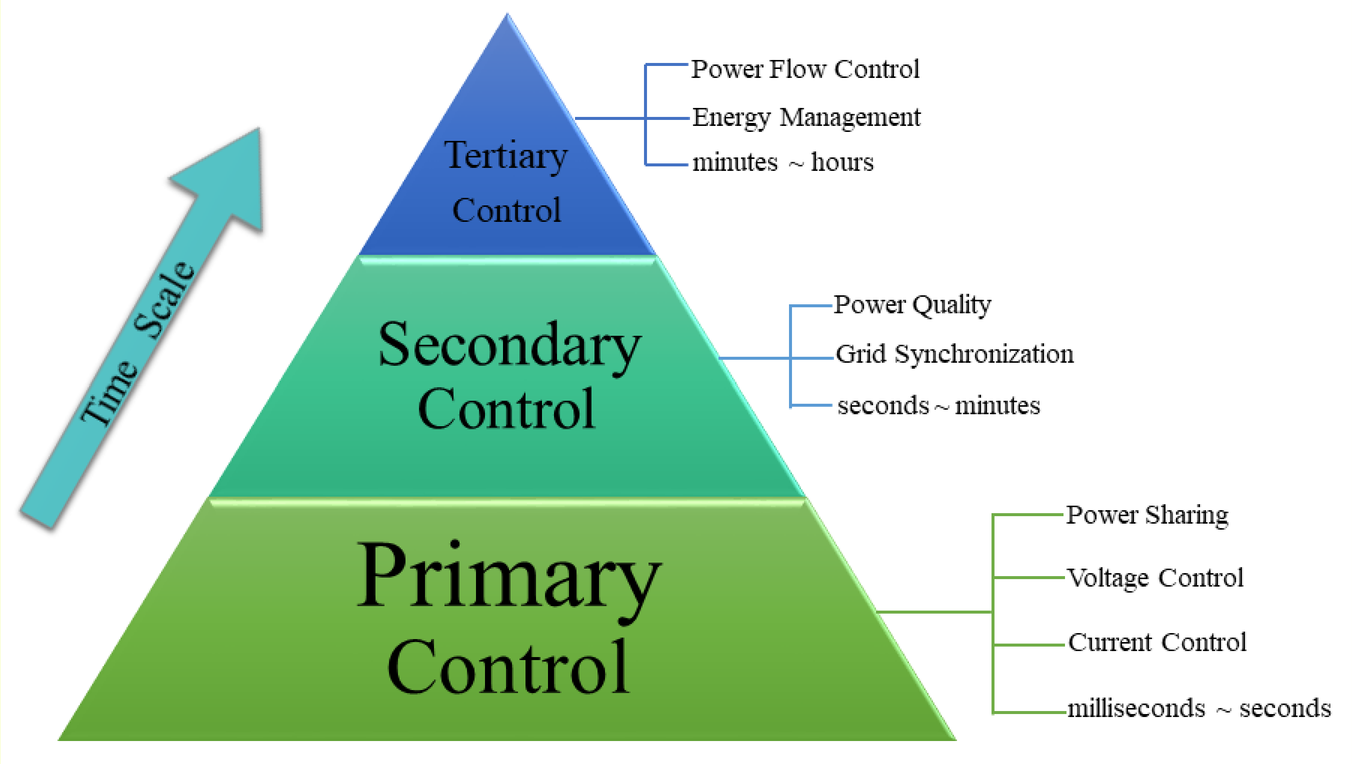
Overview of AGC

- Load is always changing.
- To maintain power balance, generators need to produce more or less to keep up with the load.
- When Gen < Load (Gen > Load), generator speed and frequency will drop (rise).
- => We use this generator speed and frequency as control signals!

3 Components of AGC

- **Primary control**
  - Immediate (automatic) action to sudden change of load.
  - For example, reaction to frequency change.
- **Secondary control**
  - To bring tie-line flows to scheduled.
  - Corrective actions are done by operators.
- **Economic dispatch**
  - Make sure that the units are scheduled in the most economical way.
- This presentation covers only primary and secondary control of AGC.

Load Frequency Control



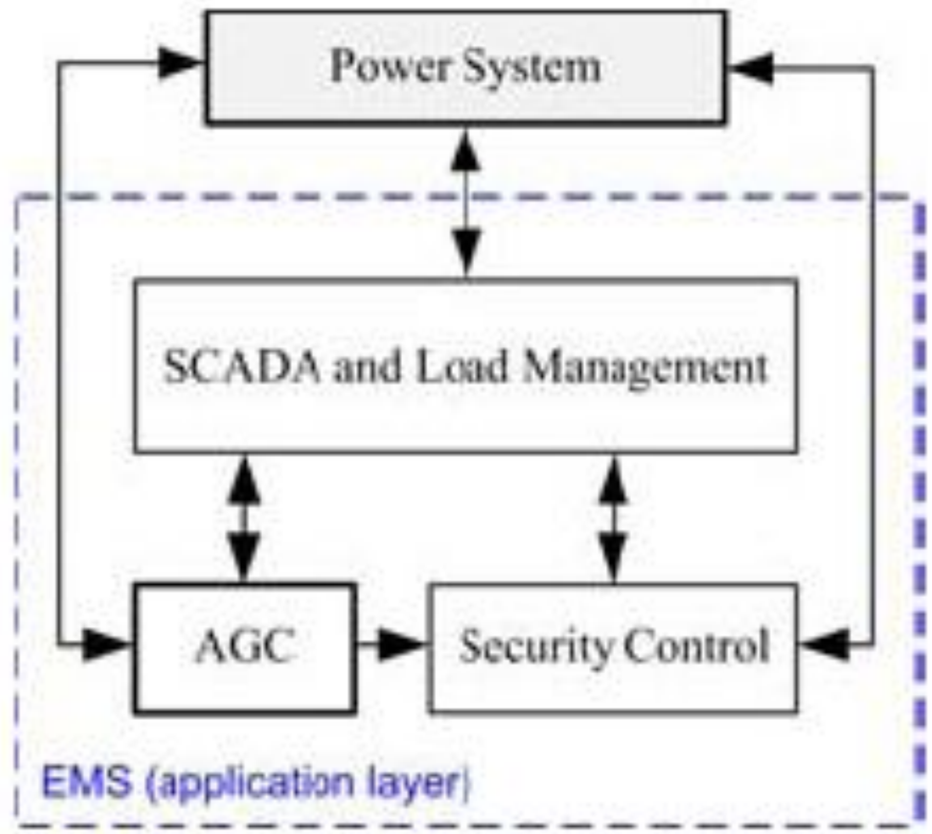
Targeted operating conditions: 49.8 Hz ≤ f ≤50.2 Hz

Acceptable operating conditions: 49.5 Hz ≤ f < 49.8 Hz and 50.2 Hz < f ≤ 50.5 Hz

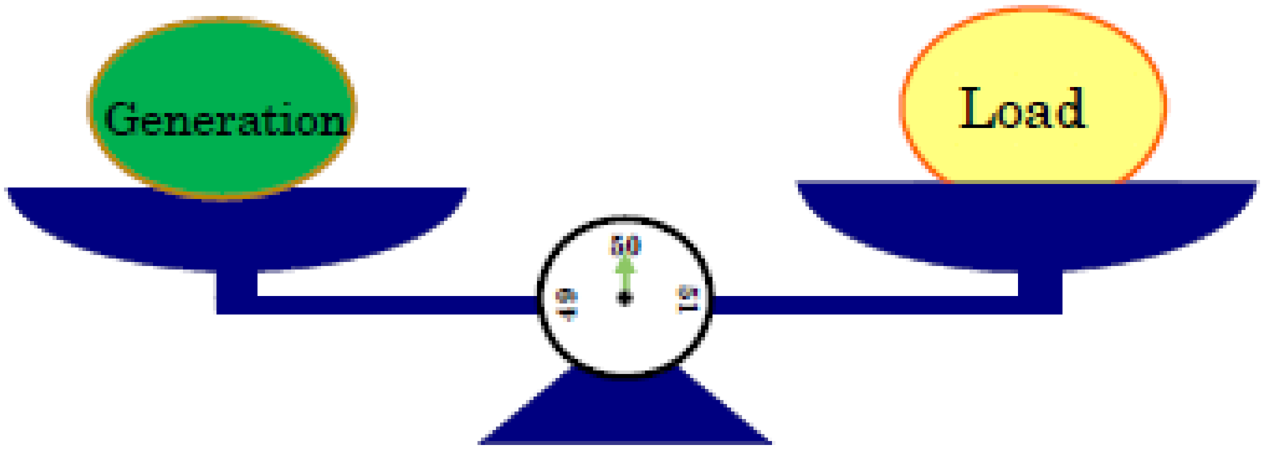
Critical operating conditions: 47.5 Hz ≤ f < 49.5 Hz and 50.5 Hz < f ≤ 52.5 Hz

Unstable operating conditions: f < 47.5 Hz and 52.5 Hz < f

AGC in a Modern Power System

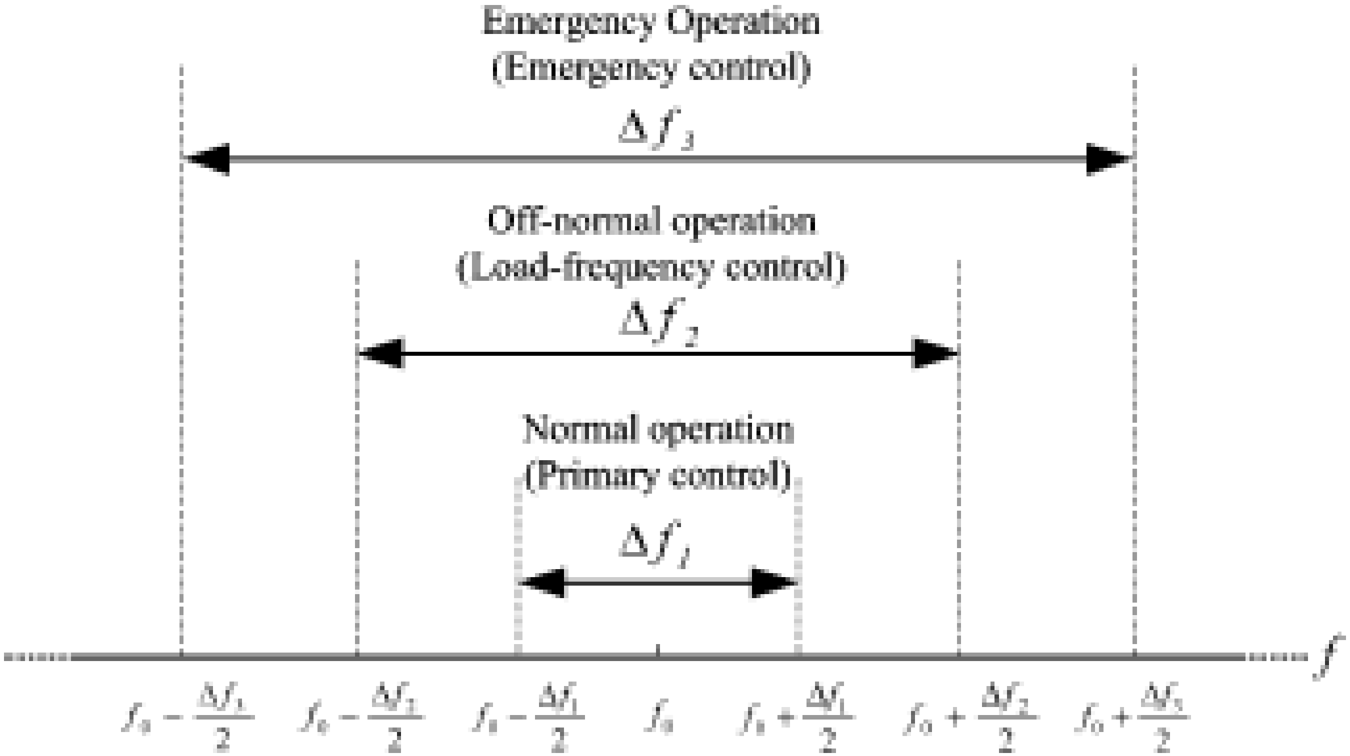


Load-generation balance



$$\Delta P_m(t) - \Delta P_L(t) = 2H\frac{d\Delta f(t)}{dt} + D\Delta f(t)$$

Frequency Control



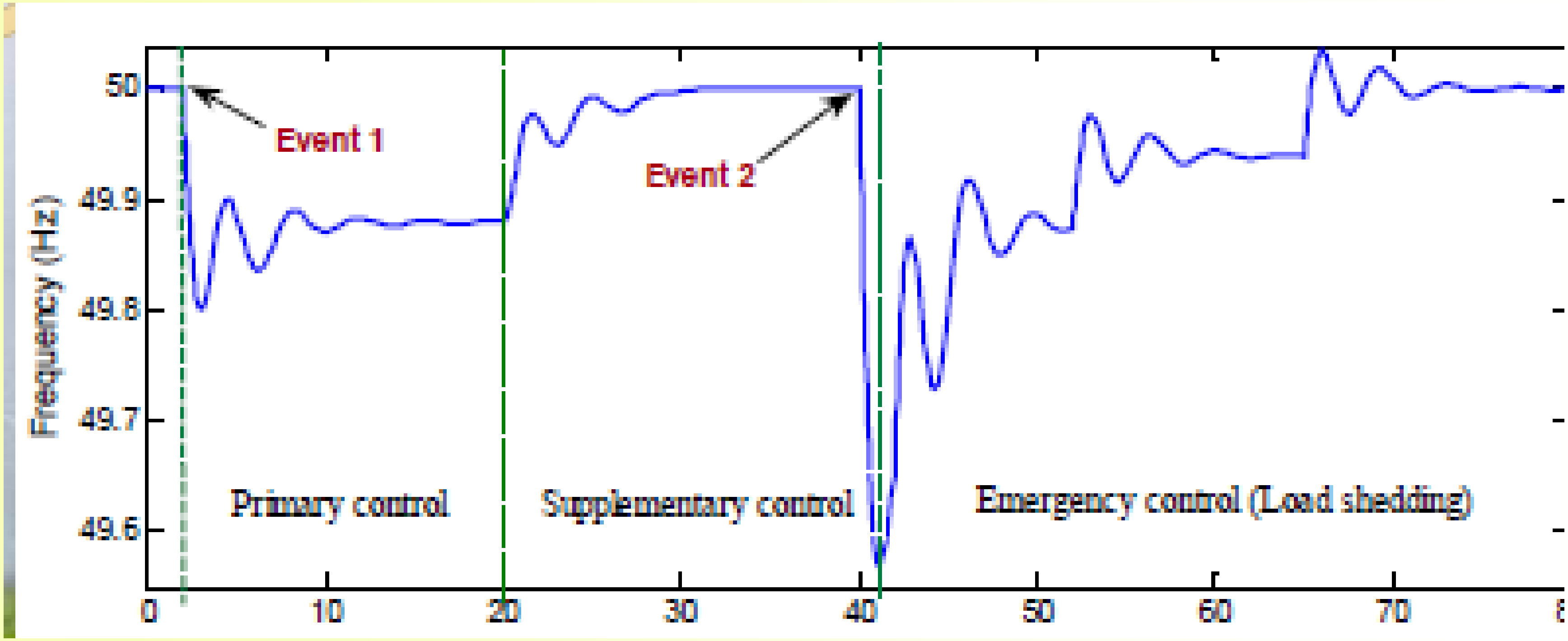
Frequency deviations and associated operating controls

Frequency operating standards

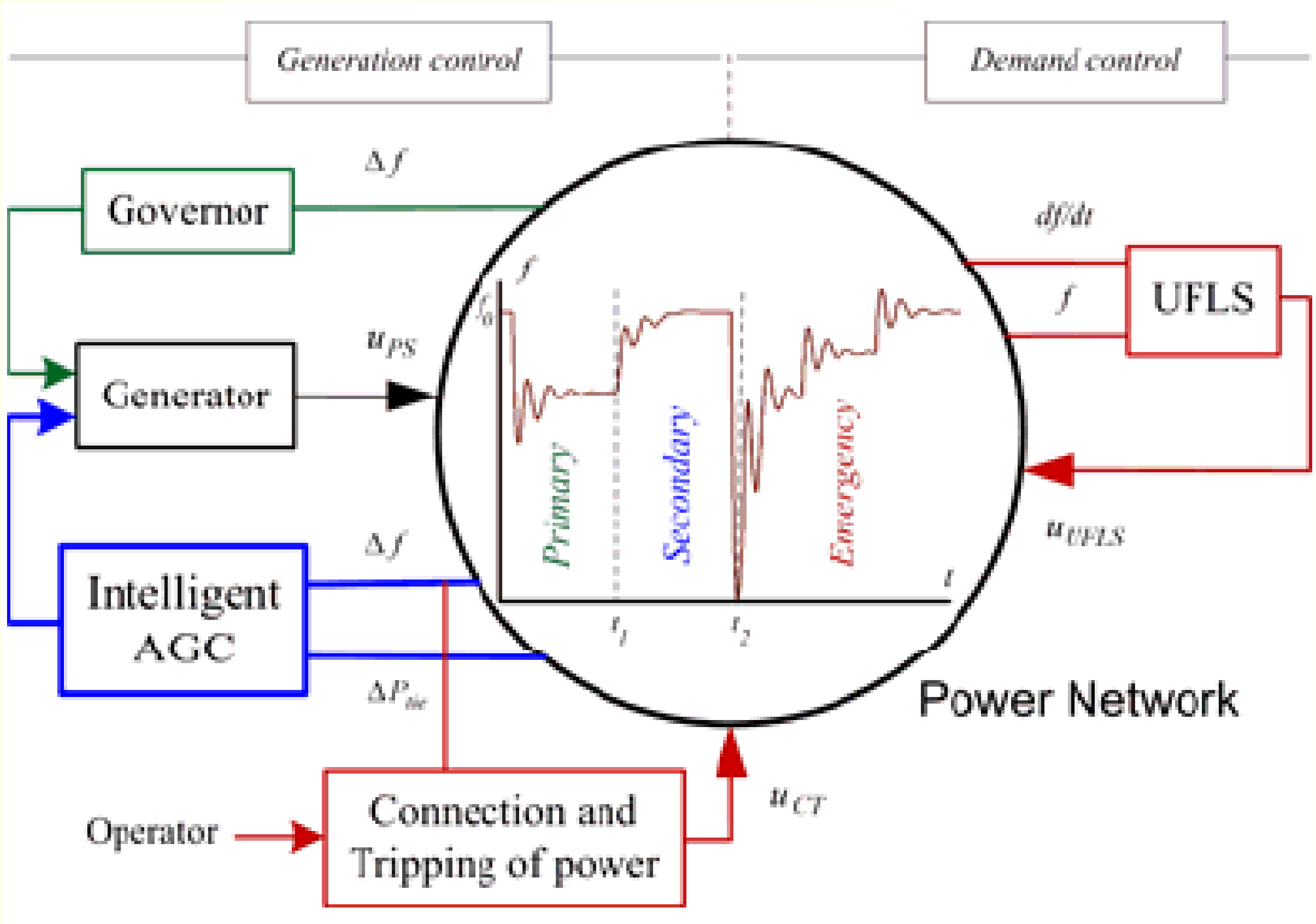
Frequency operating and control actions

Frequency deviation range	*Condition*	*Control action*
Δf_1	No contingency or load event	Normal operating
Δf_2	Generation/load or network event	LFC operating
Δf_3	Separation event	Emergency operating
Δf_4	Multiple contingency event	Emergency operating

Frequency Control

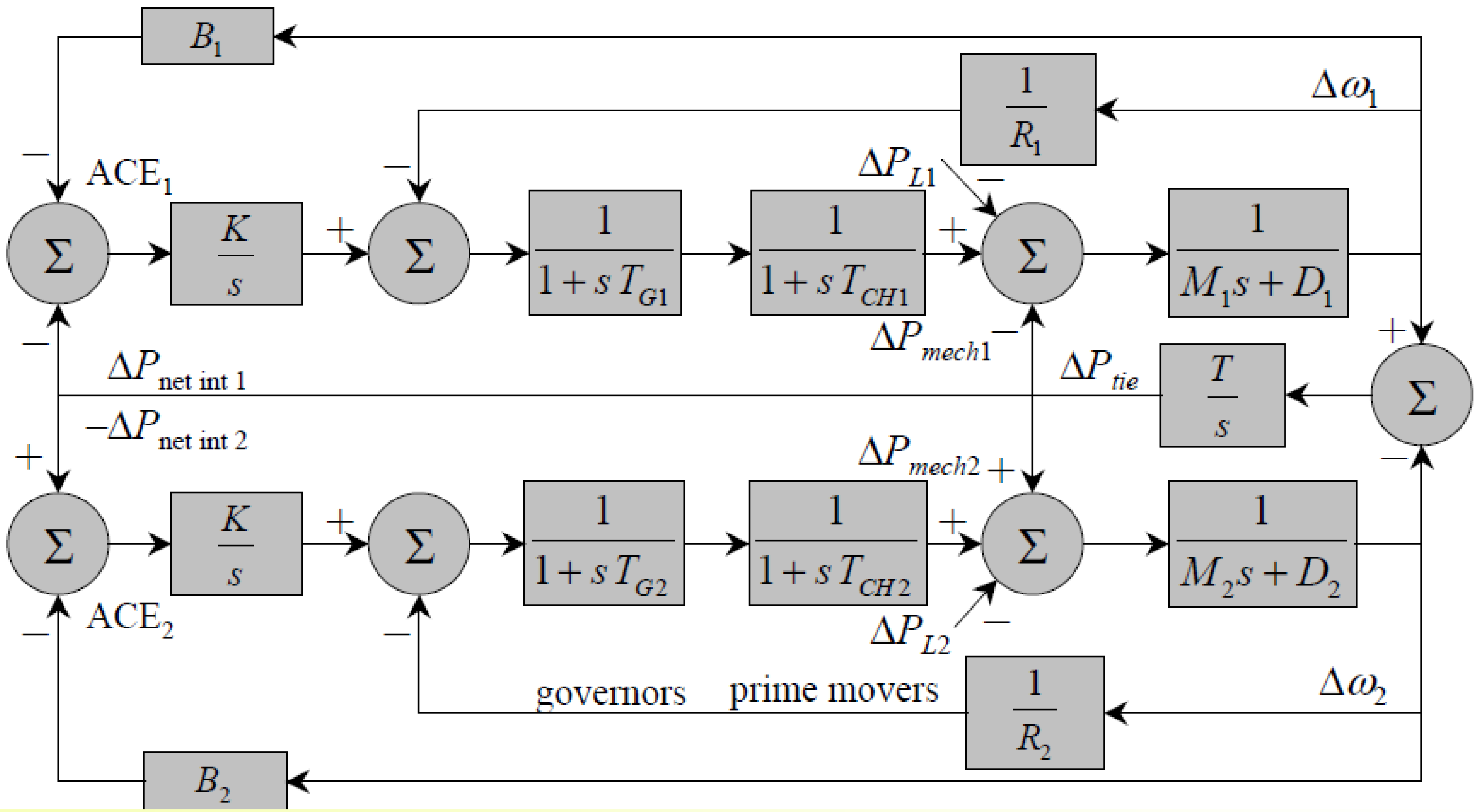


Frequency Control

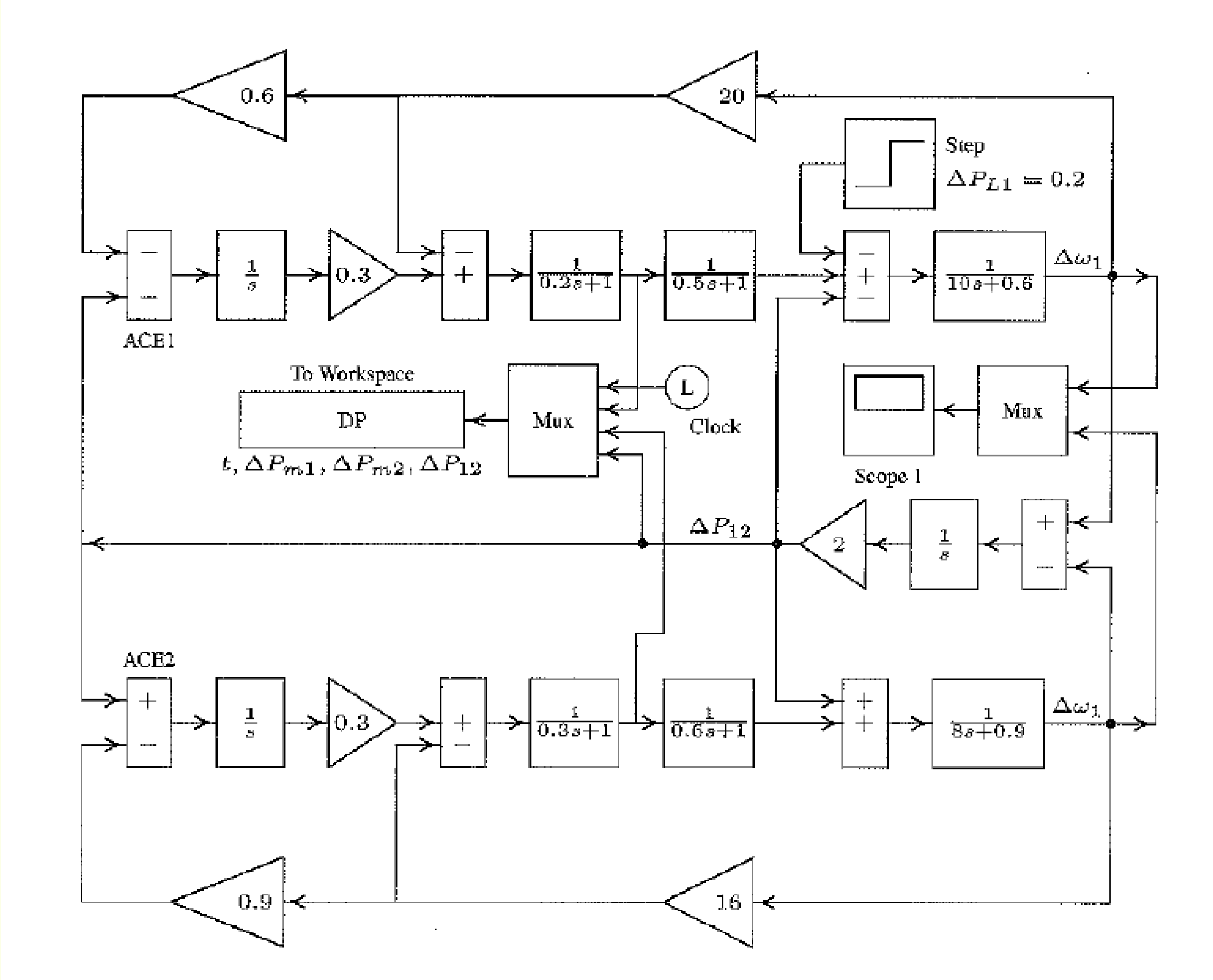


AGC for 2-Area with Tie-line Bias Control: Block Diagram

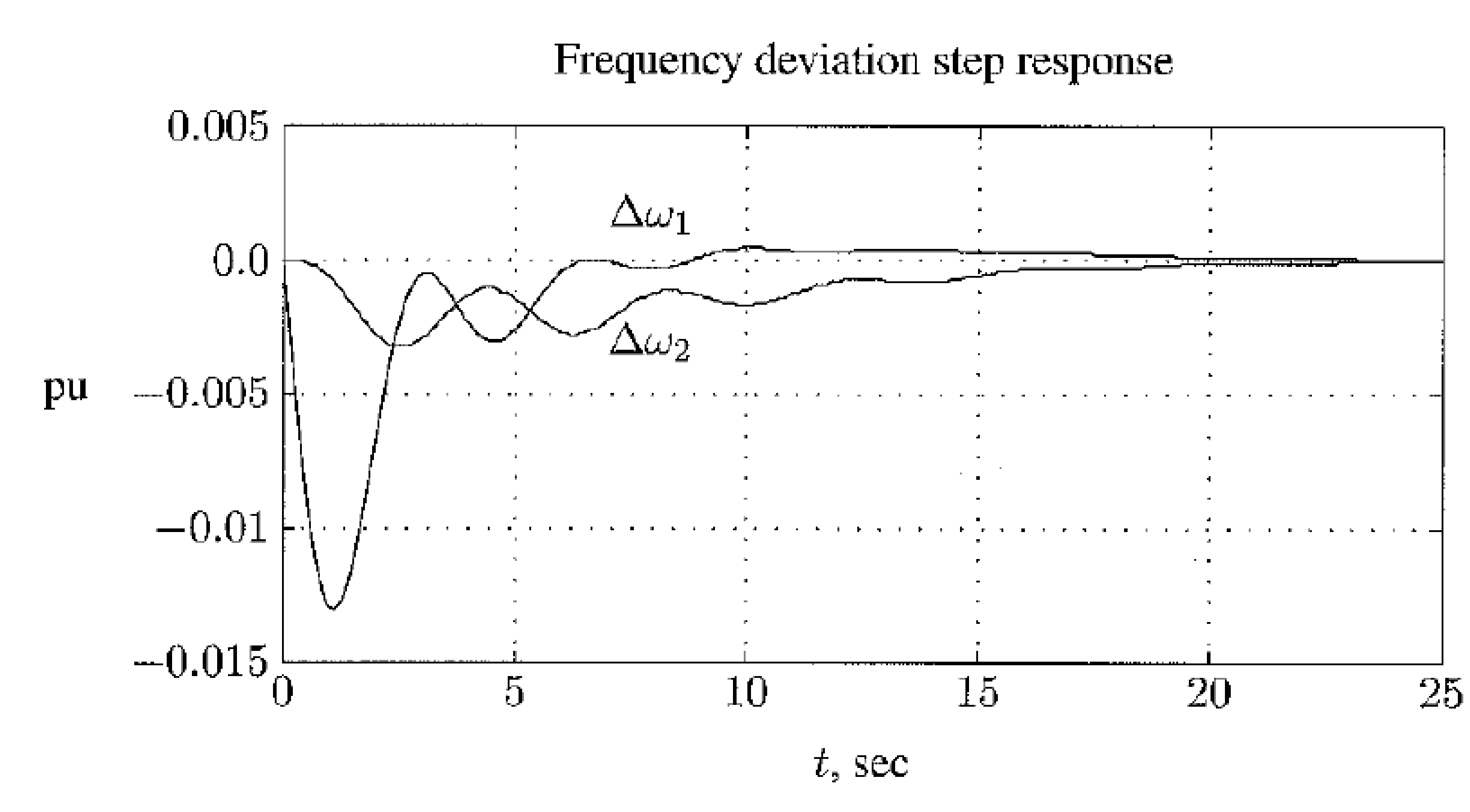
- Tie-line bias supplementary control for two areas



AGC IN THE TWO-AREA SYSTEM SIMULINK MODEL



Frequency Deviation Step Response



BACKGROUND NEEDED

- Laplace Transform
- Linear Algebra: Eigenvalue and eigenvectors
- Linear and nonlinear system theory: Equilibrium, stability
- Matlab and Simulink
- Basic Control Theory:
  - Stability
  - Routh-Hurwitz Stability Criterion
  - Root-locus Analysis
  - Steady-State Errors
  - Step Response
  - PID Controller