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Power System Stability

Development of Energy Education in the Mekong area

DEEM Trainings on March 2019

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Source: Prabha Kundur, Power System Stability and Control. McGraw-Hill 1994. ISBN 0-07-035958-X

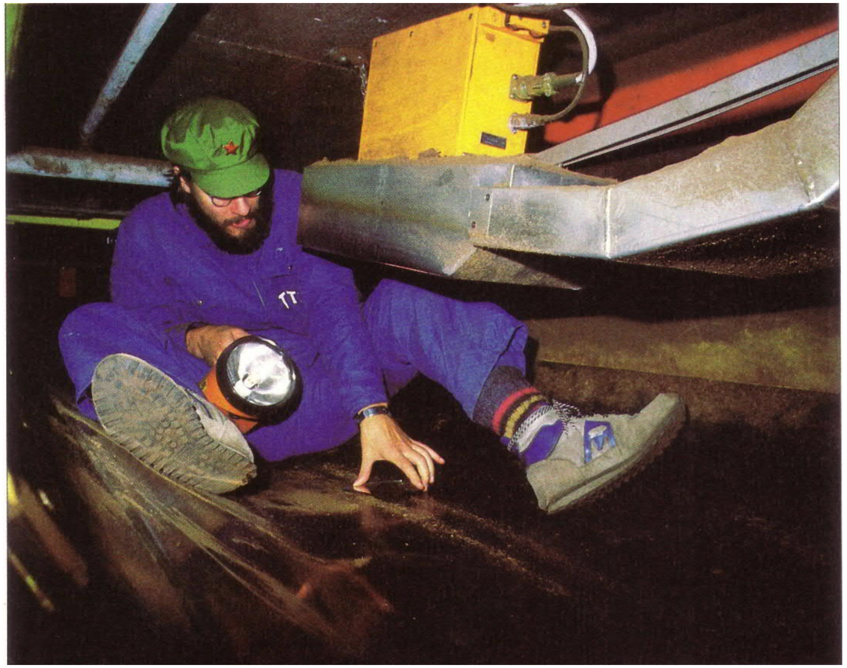
Introduction

Yrjö Majanne

Position: Research manager

Special expertise:

- Power generation and control of power systems
  - Control and Instrumentation
  - Dynamic modelling
  - Process optimization
  - Environmental systems, efficiency, LCA,
- Industrial automation
  - Automation systems (normal & safety related)
  - Field instrumentation
- City energy systems
  - Distributed generation
  - Energy intelligent buildings
  - IoT



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Outline

- Short Introduction to Power System Control
  - Generating unit Controls
    - Load control, Frequency control
  - Transmission Controls
    - Reactive power and voltage
    - Optimal power flow
- Design and Operating criteria for Stability
- Basic concepts and defnitions
  - Rotor Angle Stability
  - Voltage Stability
- Mid-Term and Long-Term stability
- Classification of stability

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Power System Control

A properly designed and operated power system should meet the following fundamental requirements:

- The system must be able to meet the continually changing load demand for active and reactive power.
  - Unlike other types of energy, electricity cannot be conveniently stored in sufficient quantities.
  - Therefore, adequate "spinning" reserve of active and reactive power should be maintained and appropriately controlled at all times.

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Power System Control

- The system should supply energy at minimum cost and with minimum ecological impact.
- The "quality" of power supply must meet certain minimum standards with regard to the following factors:
  - constancy of frequency
  - constancy of voltage
  - level of reliability

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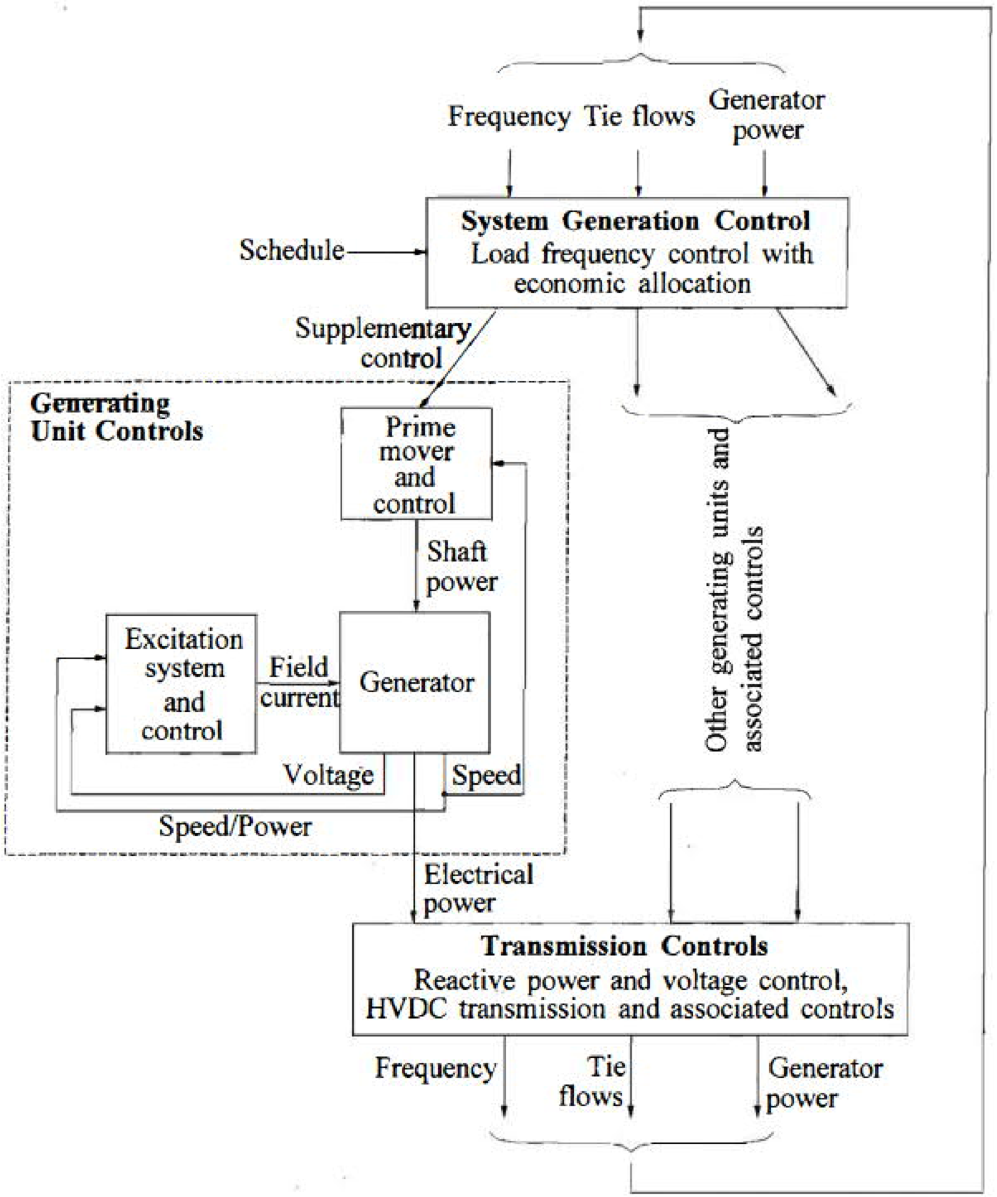
Power System Control

- System Generation Control
  - **Coordinates** operation of both generating and transmission systems
    - Unit Commitment and Economic dispatching
    - Frequency control
    - Optimal power flows (tie flows)
- Generating Unit Controls
  - Prime mover controls (boiler – turbine) for power generation
    - Combustion power, steam pressure and temperature, etc.
  - Generator excitation control
    - Voltage and reactive power
- Transmission controls
  - Reactive power and voltage controls
    - Static VAR compensators, switched capacitors and reactors, tap-changing transformers, etc.



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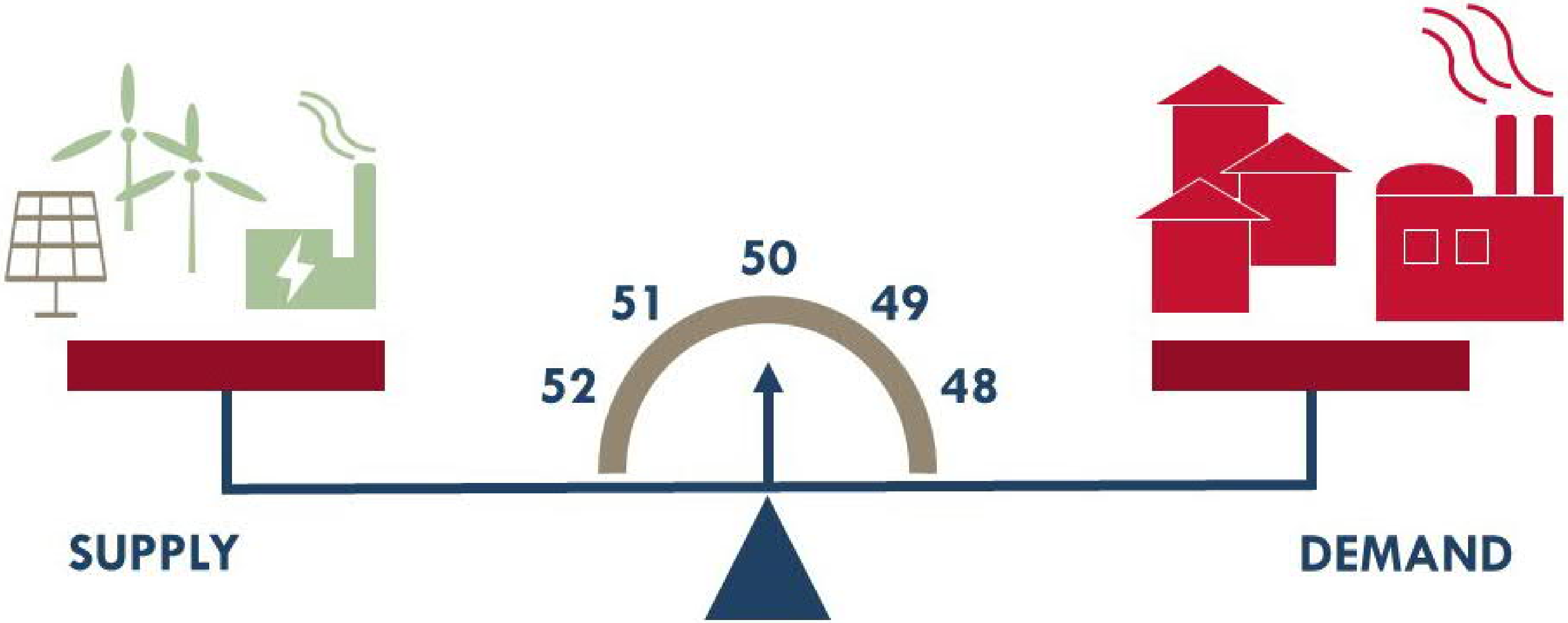
Power System Control



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Design and Operating Criteria for Stability

- The design of a large interconnected system to ensure stable operation at minimum cost is a very complex problem.
- The economic gains to be realized through the solution to this problem are enormous.
- From a control theory point of view, the power system is a very high-order multivariable process, operating in a constantly changing environment.
  - It is essential to make simplifying assumptions and to analyze specific problems using the right degree of detail of system representation.
  - This requires a good grasp of the characteristics of the overall system as well as of those of its individual elements.

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Design and Operating Criteria for Stability

- The power system is a highly nonlinear system whose dynamic performance is influenced by a wide array of devices with different response rates and characteristics.
- System stability must be viewed not as a single problem, but rather in terms of its different aspects.

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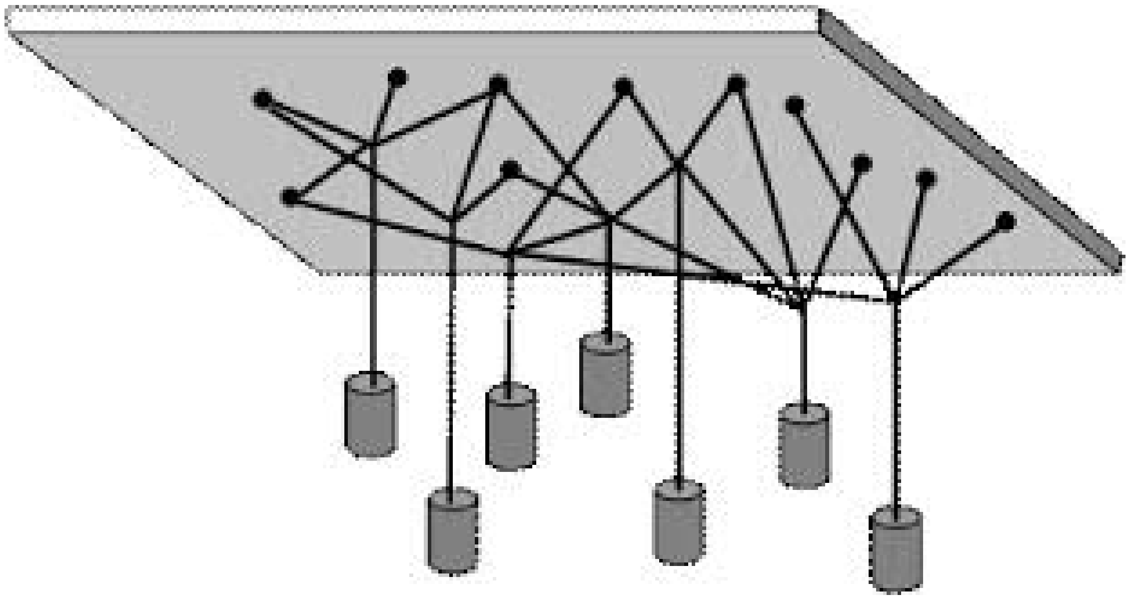
Basic Concepts and Definitions

- Stability enables power system to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.



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Basic Concepts and Definitions

- Traditionally, the stability problem has been one of maintaining synchronous operation.
  - Power systems still rely on synchronous machines for generation of electrical power
  - Necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism or "in step."
  - This aspect of stability is influenced by the dynamics of generator rotor angles and power-angle relationships.
- Instability may also be encountered without loss of synchronism.
  - For example, a system consisting of a synchronous generator feeding an induction motor load through a transmission line can become unstable because of the collapse of load voltage.
  - This form of instability can also occur in loads covering an extensive area supplied by a large system.

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Basic Concepts and Definitions

- The system response to a disturbance involves much of the equipment.
  - a short-circuit on a critical element followed by its isolation by protective relays will cause variations in power transfers, machine rotor speeds, and bus voltages
  - the voltage variations will actuate both generator and transmission system voltage regulators
  - the speed (system frequency) variations will actuate prime mover governors
  - the change in tie line loadings may actuate generation controls
  - the changes in voltage and frequency will affect loads on the system in varying degrees depending on their individual characteristics

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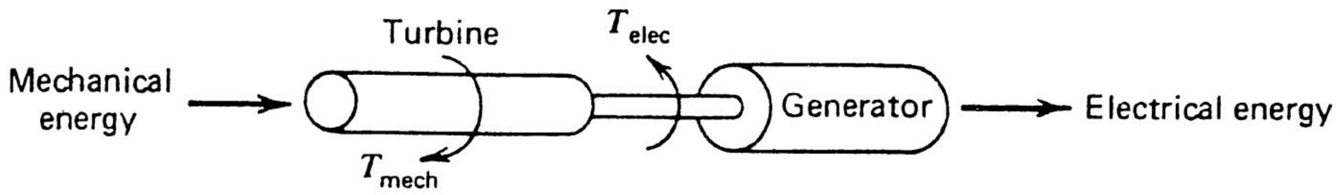
Rotor Angle Stability

- Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism.
- The stability problem involves the study of the electromechanical oscillations inherent in power systems.
- A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotors oscillate.

$$J\frac{d^2\theta_m}{dt^2}=T_a=T_m-T_e$$



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Rotor Angle Stability
Synchronous machine characteristics

- A synchronous machine (generator) has two essential elements: the field and the armature.
  - Normally, the field is on the rotor and the armature is on the stator
- The field winding is excited by direct current.
- When the rotor is driven by a prime mover (e.g steam turbine), the rotating magnetic field of the field winding induces alternating voltages in the three-phase armature windings of the stator.
- The frequency of the induced alternating voltages and of the resulting currents that flow in the stator windings, when a load is connected, depends on the speed of the rotor.

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Rotor Angle Stability
Synchronous machine characteristics

- The frequency of the stator electrical quantities is thus synchronized with the rotor mechanical speed: hence the designation "synchronous machine."
- When two or more synchronous machines are interconnected, the stator voltages and currents of all the machines must have the same frequency and the rotor mechanical speed of each is synchronized to this frequency.
  - Therefore, the rotors of all interconnected synchronous machines must be in synchronism.
- The physical arrangement (spatial distribution) of the stator armature windings is such that the time-varying alternating currents flowing in the three-phase windings produce a rotating magnetic field that, under steady-state operation, rotates at the same speed as the rotor.

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Rotor Angle Stability
Synchronous machine characteristics

- The stator and rotor fields react with each other and an electromagnetic torque results from the tendency of the two fields to align themselves.
- In a generator, this electromagnetic torque opposes rotation of the rotor, so that mechanical torque must be applied by the prime mover to sustain rotation.
- The electrical torque (or power) output of the synchronous generator is changed only by changing the mechanical torque input by the prime mover.
- The effect of increasing the mechanical torque input is to advance the rotor to a new position relative to the revolving magnetic field of the stator. Conversely, a reduction of mechanical torque or power input will retard the rotor position.

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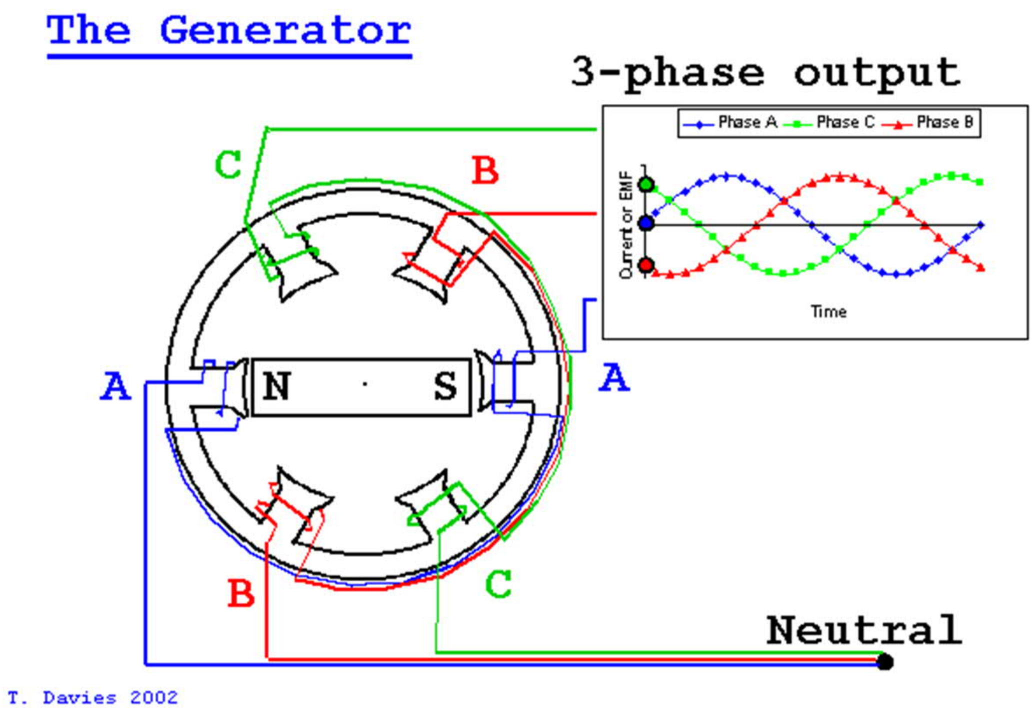
Rotor Angle Stability
Synchronous machine characteristics



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Rotor Angle Stability
Synchronous machine characteristics

- Under steady-state operating conditions, the rotor field and the revolving field of the stator have the same speed. However, there is an angular separation between them depending on the electrical torque (or power) output of the generator.
- The terms torque M and power P have been used interchangeably. This is common practice, since the average rotational velocity ω of the machines is constant even though there may be small momentary excursions above and below synchronous speed.
  - The per unit values of torque and power are, in fact, very nearly equal.

$$P = M\omega$$

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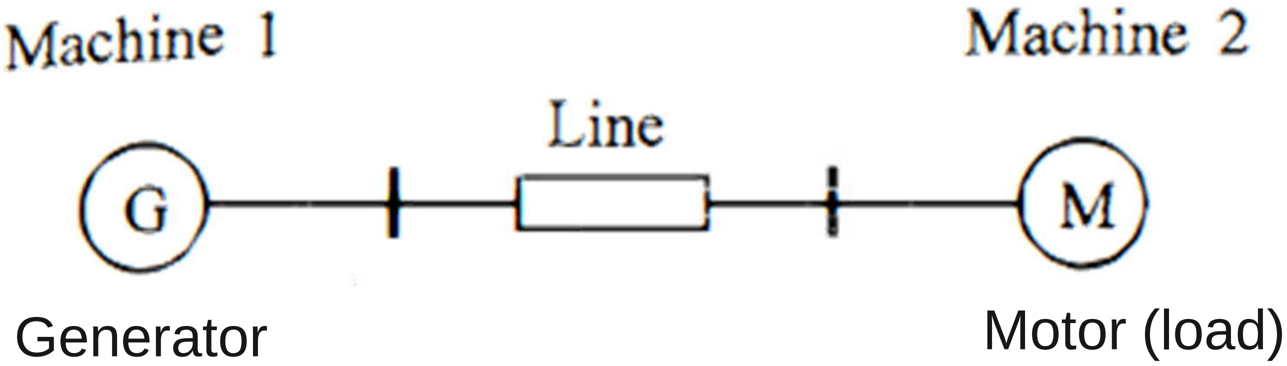
Rotor Angle Stability
Synchronous machine characteristics

- An important characteristic that has a bearing on power system stability is the relationship between interchange power and angular positions of the rotors of synchronous machines.
- To illustrate this let us consider the simple system shown below. It consists of two synchronous machines connected by a transmission line having an inductive reactance Xr but negligible resistance and capacitance.



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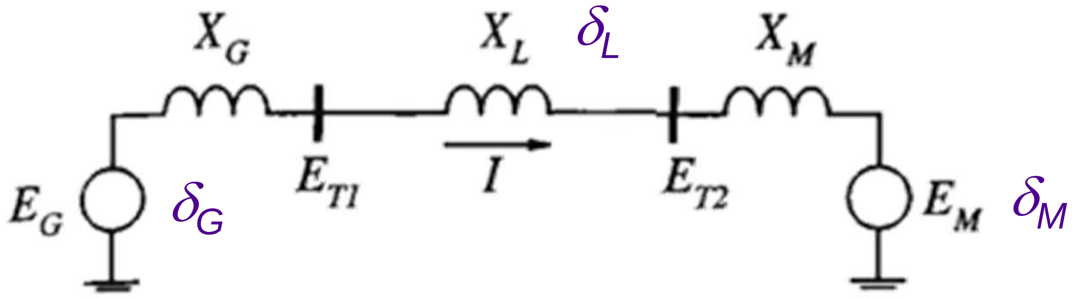
Rotor Angle Stability
Synchronous machine characteristics

- The power transferred from the generator to the motor is a function of angular separation (δ) between the rotors of the two machines.
- This angular separation is due to three components:
  - generator internal angle δ_G (angle by which the generator rotor leads the revolving field of the stator)
  - angular difference δ_L between the terminal voltages of the generator and motor (angle by which the stator field of the generator leads that of the motor)
  - the internal angle δ_M of the motor (angle by which the rotor lags the revolving stator field).



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Rotor Angle Stability

Synchronous machine characteristics

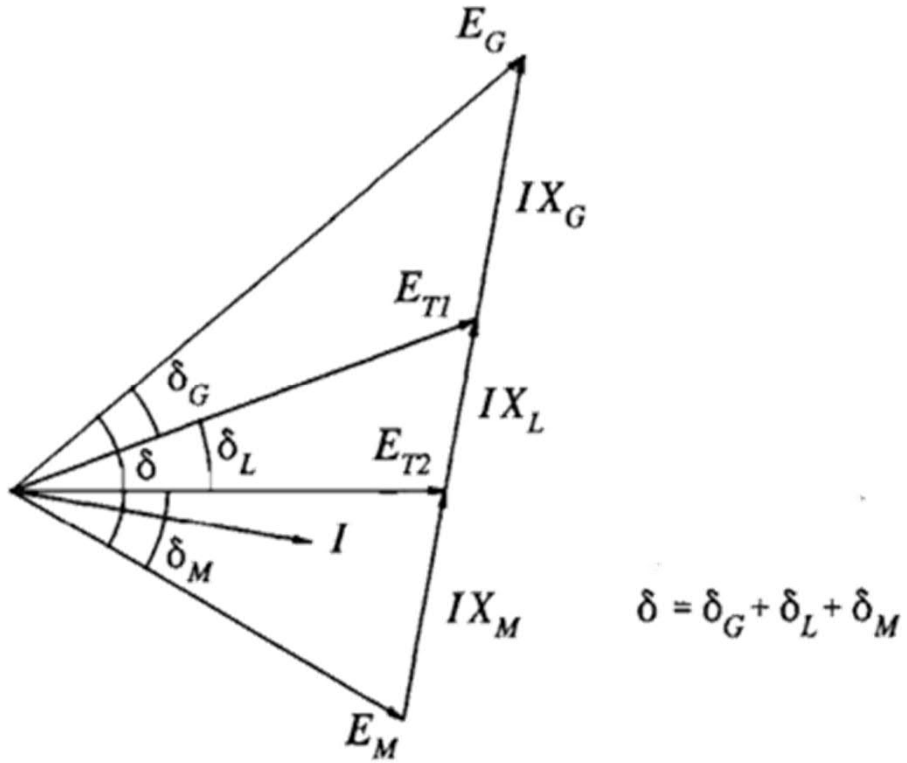
- A phasor diagram identifying the relationships between generator and motor voltages is shown below

- The power transferred from the generator to the motor is given by

$$P = \frac{E_G E_M}{X_T} \sin \delta$$

where

$$X_T = X_G + X_L + X_M$$



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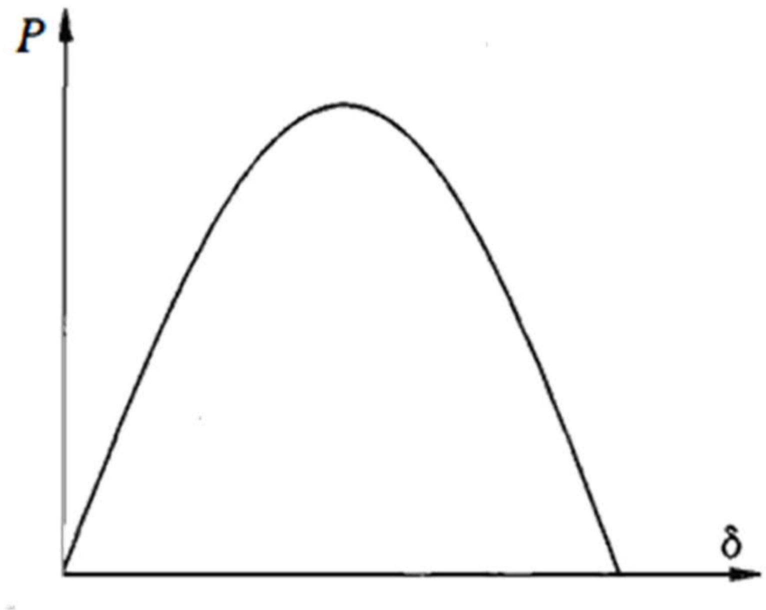
Rotor Angle Stability

Synchronous machine characteristics

- The corresponding power *P* versus angle δ relationship is plotted below
- With the somewhat idealized models used for representing the synchronous machines, the power varies as a sine of the angle.
- As the angle is increased, the power transfer increases up to a maximum.
- After a certain angle, nominally 90°, a further increase in angle results in a decrease in power transferred.
- The magnitude of the maximum power is directly proportional to the machine internal voltages and inversely proportional to the reactance between the voltages
  - includes reactance of the transmission line connecting the machines and the reactances of the machines.



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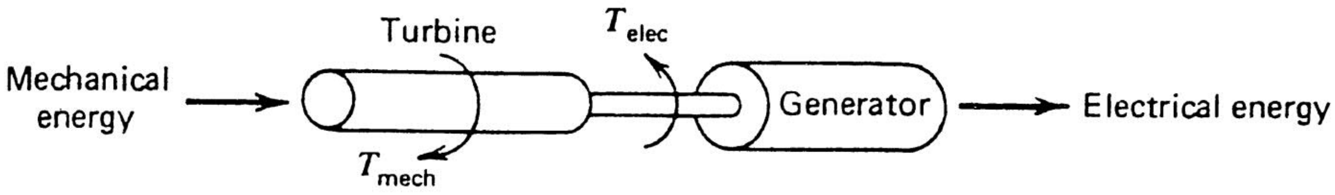
Rotor Angle Stability
The Stability Phenomena

- Stability is a condition of equilibrium between opposing forces.
- The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machines.
- Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant.

$$J\frac{d^2\theta_m}{dt^2}=T_a=T_m-T_e$$



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Rotor Angle Stability
The Stability Phenomena

- If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body.
  - If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance, and the resulting angular difference transfers part of the load from the slow machine to the fast machine.
- Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer
  - this increases the angular separation further and leads to instability

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Rotor Angle Stability
The Stability Phenomena

- When a synchronous machine loses synchronism or "falls out of step" with the rest of the system, its rotor runs at a higher or lower speed than that required to generate voltages at system frequency.
- The "slip" between rotating stator field (corresponding to system frequency) and the rotor field results in large fluctuations in the machine power output, current, and voltage
  - this causes the protection system to isolate the unstable machine from the system.

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Rotor Angle Stability
The Stability Phenomena

- With electric power systems, the change in electrical torque T_e of a synchronous machine following a perturbation can be resolved into two components.

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega$$

where

- $T_S\Delta\delta$ is the component of torque change in phase with the rotor angle perturbation $\Delta\delta$ and is referred to as the synchronizing torque component; T_S is the synchronizing torque coefficient.
- $T_D\Delta\omega$ is the component of torque in phase with the speed deviation $\Delta\omega$ and is referred to as the damping torque component; T_D is the damping torque coefficient.

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Rotor Angle Stability
The Stability Phenomena

- Small-signal (or small-disturbance) stability is the ability of the power system to maintain synchronism under small disturbances.
  - Such disturbances occur continually because of small variations in loads and generation
  - Instability that may result, can be of two forms:
    - steady increase in rotor angle due to lack of sufficient synchronizing torque
    - rotor oscillations of increasing amplitude due to lack of sufficient damping torque
  - For a generator connected radially to a large power system, in the absence of automatic voltage regulators (i.e., with constant field voltage), the instability is due to lack of sufficient synchronizing torque
    - This results in instability through a non-oscillatory mode
  - With continuously acting voltage regulators, the small-disturbance stability problem is one of ensuring sufficient damping of system oscillations.
    - Instability is normally through oscillations of increasing amplitude.

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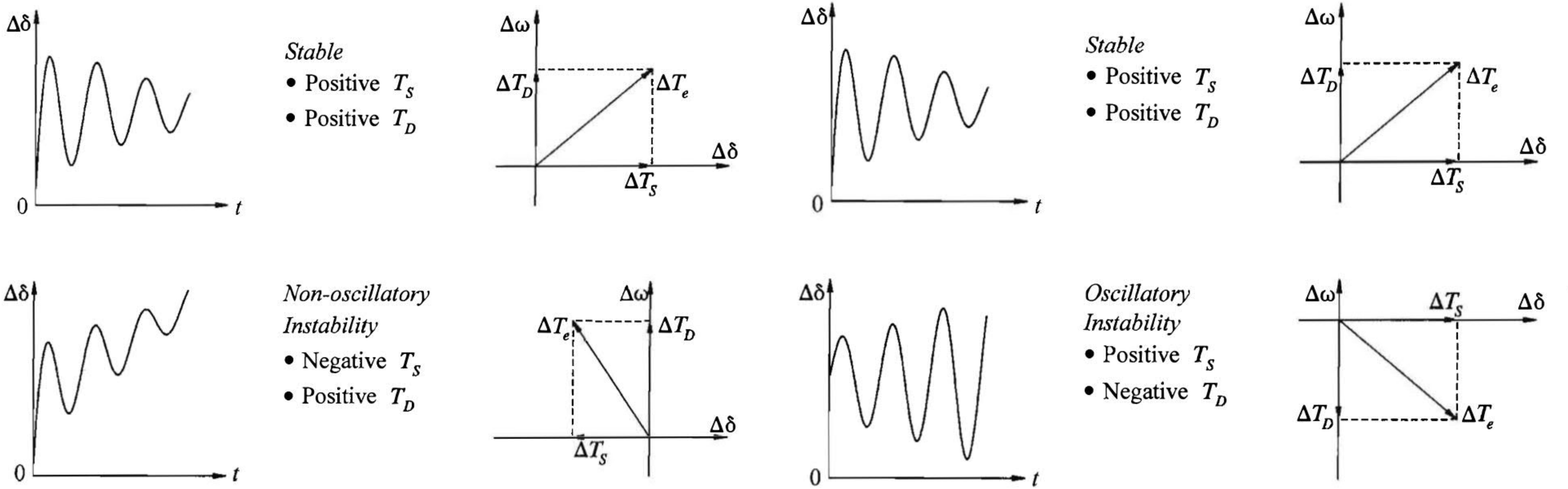
Rotor Angle Stability
The Stability Phenomena



(a) With constant field voltage

(b) With excitation control

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Rotor Angle Stability
The Stability Phenomena

- Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance.
  - The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship.
  - Stability depends on both the initial operating state of the system and the severity of the disturbance.
  - The system is designed and operated so as to be stable for a selected set of contingencies.
    - short-circuits of different types
    - the fault is assumed to be cleared by the opening of appropriate breakers to isolate the faulted element
    - unexpected shut-downs of large generating units

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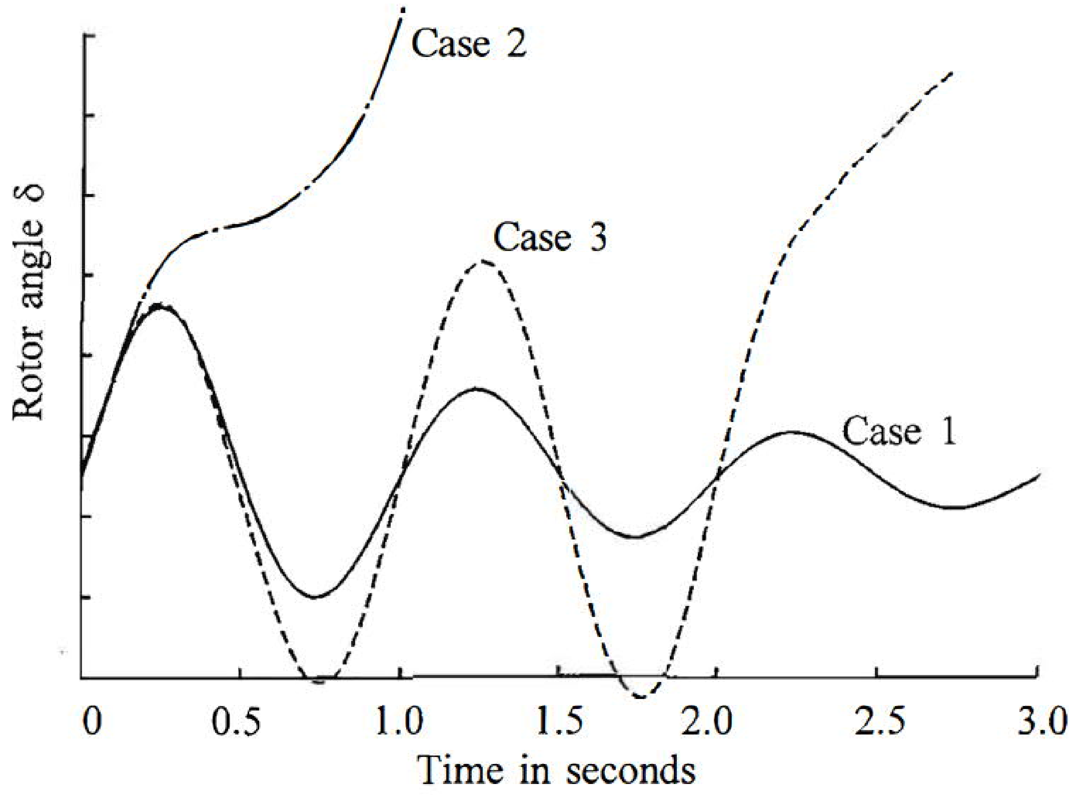
Rotor Angle Stability
The Stability Phenomena

- The behaviour of a synchronous machine for stable and unstable situations.
  - Case 1: stable with damped oscillations
  - Case 2: the rotor angle continues to increase steadily until synchronism is lost.
    - first-swing instability caused by insufficient synchronizing torque.
  - Case 3: the system is stable in the first swing but becomes unstable as a result of growing oscillations as the end state is approached.
    - This form of instability generally occurs when the post fault steady-state condition itself is "small-signal" unstable



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Voltage Stability

- A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage.
- The main factor causing instability is the inability of the power system to meet the demand for reactive power.
- The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through inductive reactances associated with the transmission network.
- A criterion for voltage stability is that, at a given operating condition for every bus in the system, the bus voltage magnitude increases as the reactive power injection at the same bus is increased.

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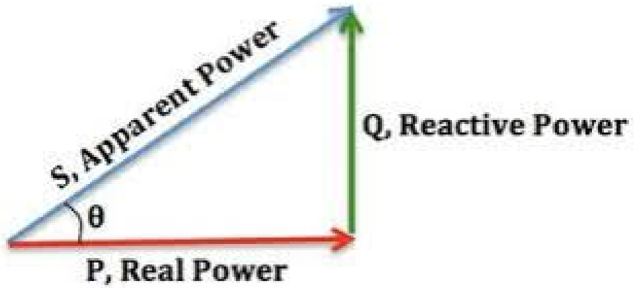
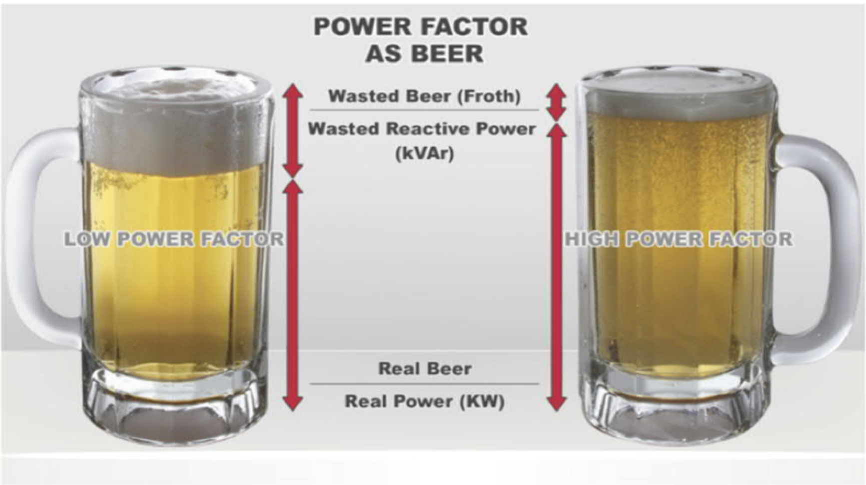
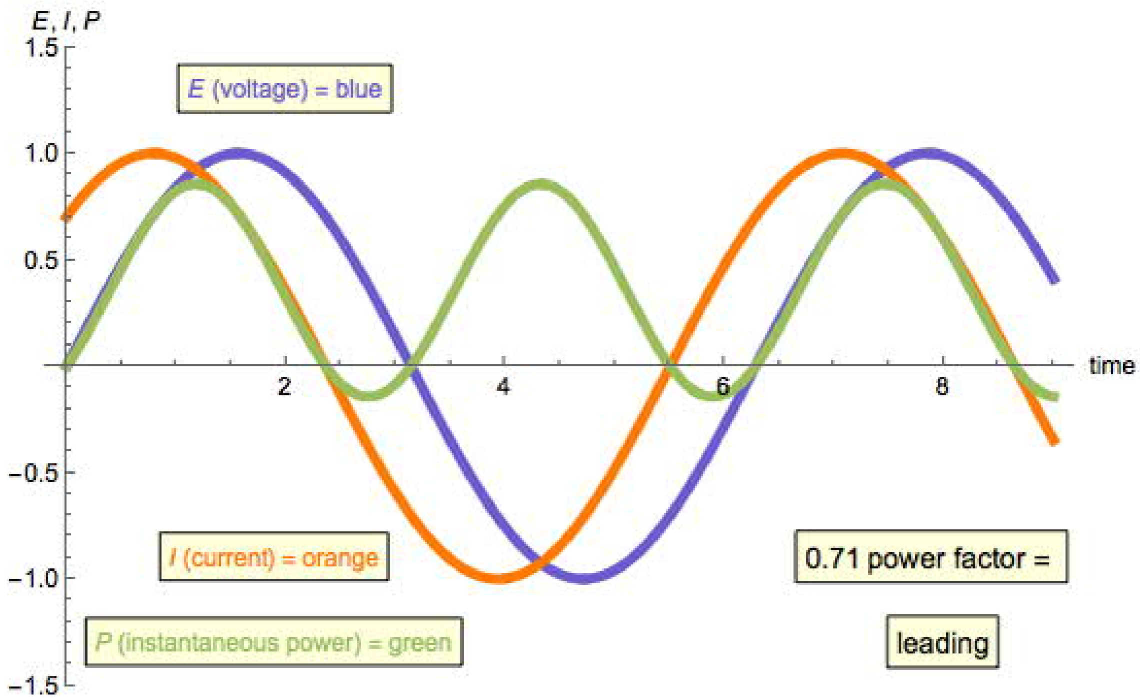
Short Recap





Power factor



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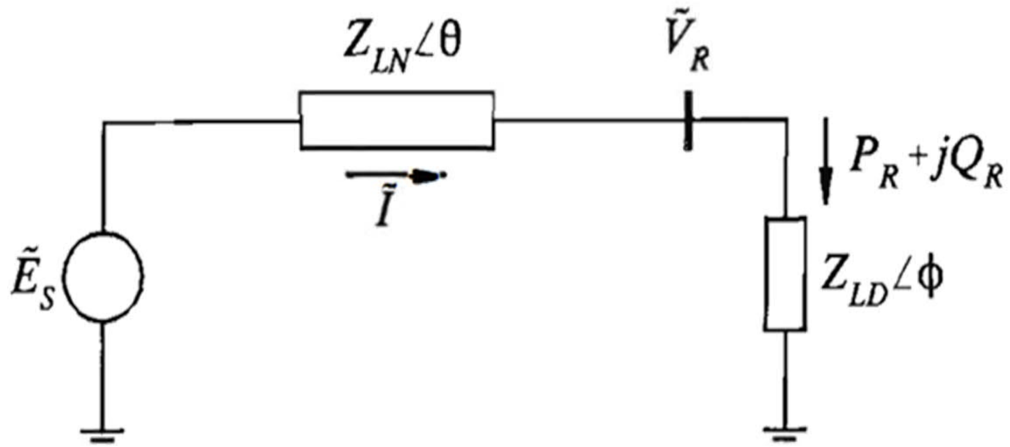
Voltage Stability

- Voltage instability may occur in several different ways. In its simple form it can be illustrated by considering the two terminal network.
- It consists of a constant voltage source (E_s) supplying a load (Z_{LD}) through a series impedance (Z_{LN})



$$\tilde{I} = \frac{\tilde{E}_S}{\tilde{Z}_{LN} + \tilde{Z}_{LD}}$$

$$\tilde{Z}_{LN} = Z_{LN}\angle\theta, \quad \tilde{Z}_{LD} = Z_{LD}\angle\phi$$

$$I = \frac{E_S}{\sqrt{\left(Z_{LN}\cos(\theta) + Z_{LD}\cos(\phi)\right)^2 + \left(Z_{LN}\sin(\theta) + Z_{LD}\sin(\phi)\right)^2}}$$

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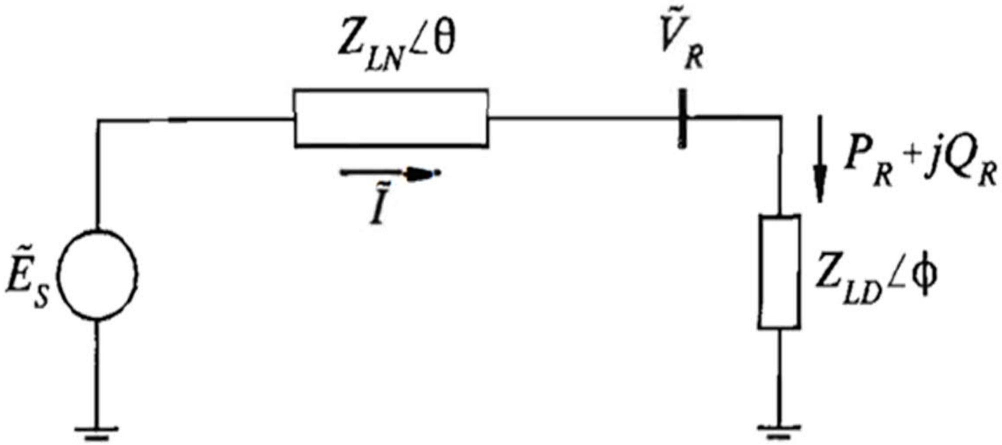
Voltage Stability

$$I = \frac{1}{\sqrt{F}} \frac{E_S}{Z_{LN}}$$



where

$$F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z_{LD}}{Z_{LN}}\right)\cos(\theta - \phi)$$

The magnitude of the receiving end voltage $\widetilde{V_R}$ is given by

$$V_R = Z_{LD} I = \frac{1}{\sqrt{F}} \frac{Z_{LD}}{Z_{LN}} E_S$$

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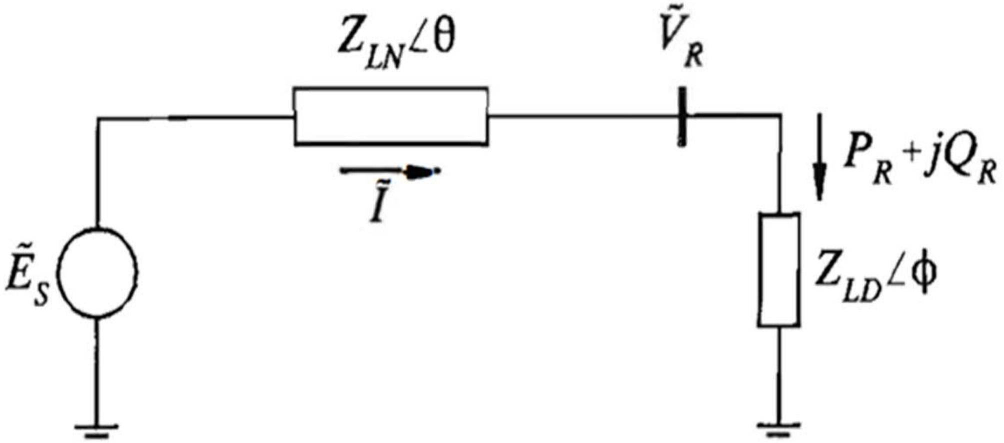
Voltage Stability

- The power supplied to the load is

$$P_R = V_R I \cos(\phi) = \frac{Z_{LD}}{F}\left(\frac{E_S}{Z_{LN}}\right)^2 \cos(\phi)$$



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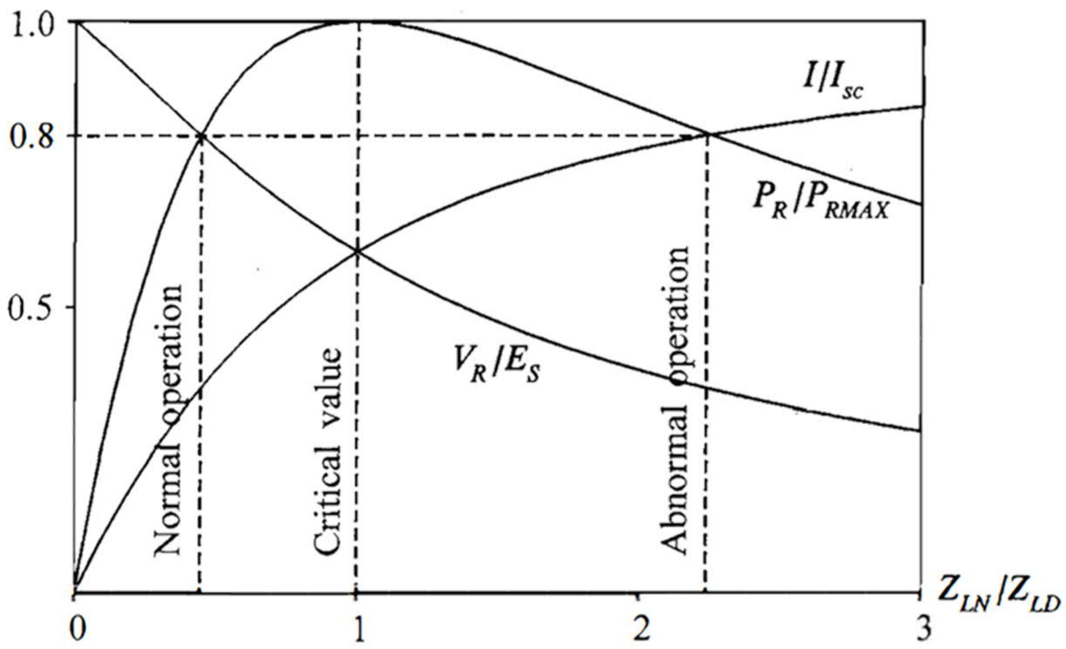
Voltage Stability

- Plots of I, V_R, and P_R are shown as a function of Z_{LN}/Z_{LD}, for the case with tan(θ) =10.0 and cos(ϕ) =0.95 .
- To make the results applicable to any value of Z_{LN}, the values of I, V_R, and P_R are appropriately normalized.
- As the load demand is increased by decreasing Z_{LD} , P_R increases rapidly at first and then slowly before reaching a maximum, after which it decreases.
- There is thus a maximum value of active power that can be transmitted through an impedance from a constant voltage source.



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Voltage Stability

- The power transmitted is maximum when the voltage drop in the line is equal in magnitude to V_R, that is when $Z_{LN}/Z_{LD} = 1$.
- As Z_{LD} is decreased gradually, I increases and V_R decreases.
- Initially, at high values of Z_{LD}, the increase in I dominates over the decrease in V_R, and hence P_R increases rapidly with decrease in Z_{LD}.
- As Z_{LD} approaches Z_{LN}, the effect of the decrease in I is only slightly greater than that of the decrease in V_R. When Z_{LD} is less than Z_{LN}, the decrease in V_R dominates over the increase in I, and the net effect is a decrease in P_R.

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Voltage Stability

- The critical operating condition corresponding to maximum power represents the limit of satisfactory operation.
- For higher load demand, control of power by varying load would be unstable; that is, a decrease in load impedance reduces power.
- Whether voltage will progressively decrease and the system will become unstable depends on the load characteristics.

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Voltage Stability

- With a constant-impedance static load characteristic, the system stabilizes at power and voltage levels lower than the desired values.
- On the other hand, with a constant-power load characteristic, the system becomes unstable through collapse of the load bus voltage.
- If the load is supplied by transformers with automatic underload tap-changing (ULTC), the tap-changer action will try to raise the load voltage. This has the effect of reducing the effective Z_{LD} as seen from the system. This in turn lowers V_R still further and leads to a progressive reduction of voltage. This is a simple and pure form of voltage instability.

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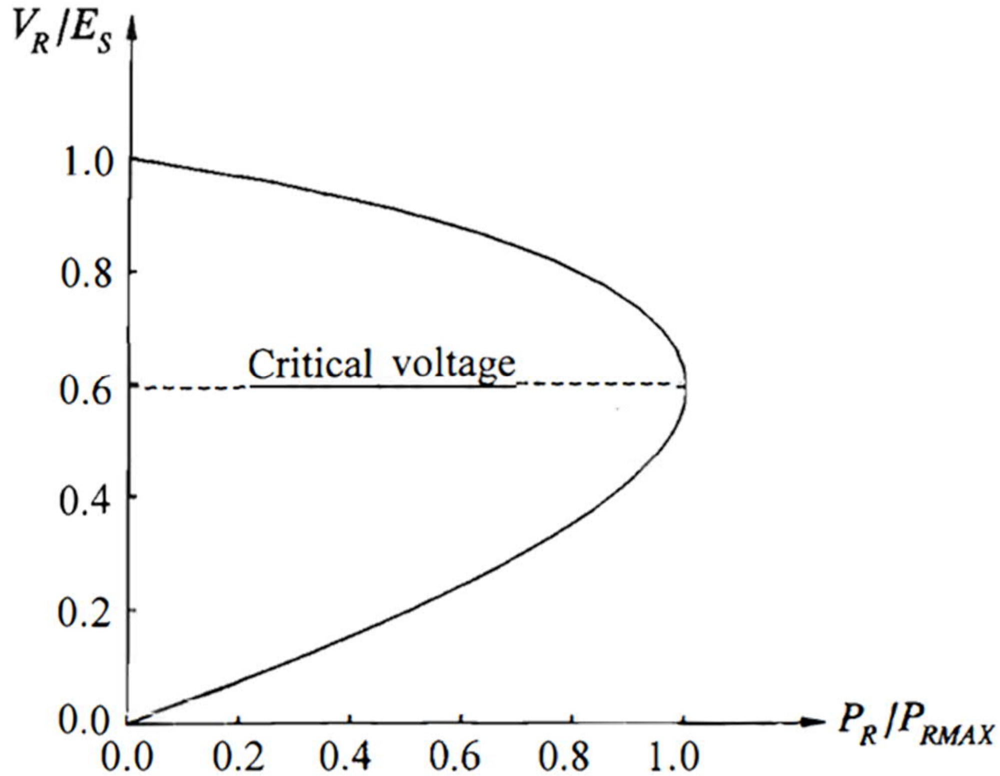
Voltage Stability

- From the viewpoint of voltage stability, the relationship between P_R and V_R is of interest.
- This is shown in the figure for the system under consideration when the load power factor is equal to 0.95 lag.



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Voltage Stability

- From equations

$$V_R = Z_{LD} I = \frac{1}{\sqrt{F}} \frac{Z_{LD}}{Z_{LN}} E_S$$

and

$$P_R = V_R I \cos(\phi) = \frac{Z_{LD}}{F} \left(\frac{E_S}{Z_{LN}} \right)^2 \cos(\phi)$$

- we see that the load-power factor has a significant effect on the power-voltage characteristics of the system.
- This is to be expected since the voltage drop in the transmission line is a function of active as well as reactive power transfer. Voltage stability, in fact, depends on the relationships between P, Q and V.

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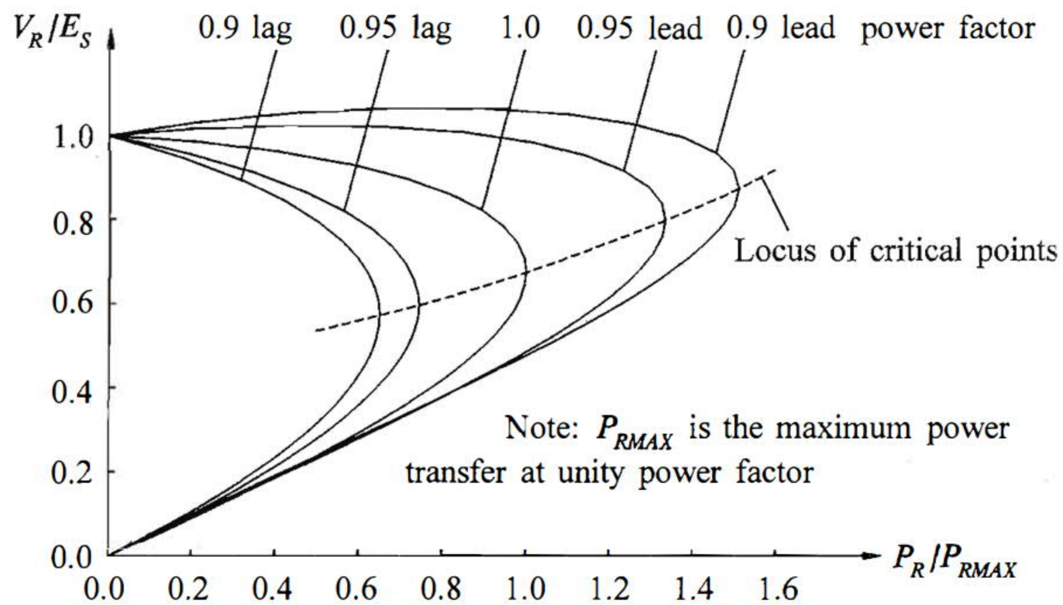
Voltage Stability

The locus of critical operating points

- Normally, only the operating points above the critical points represent satisfactory operating conditions.
- A sudden reduction in power factor (increase in Q_R) can thus cause the system to change from a stable operating condition to an unsatisfactory, and possibly unstable, operating condition represented by the lower part of a V-P curve.



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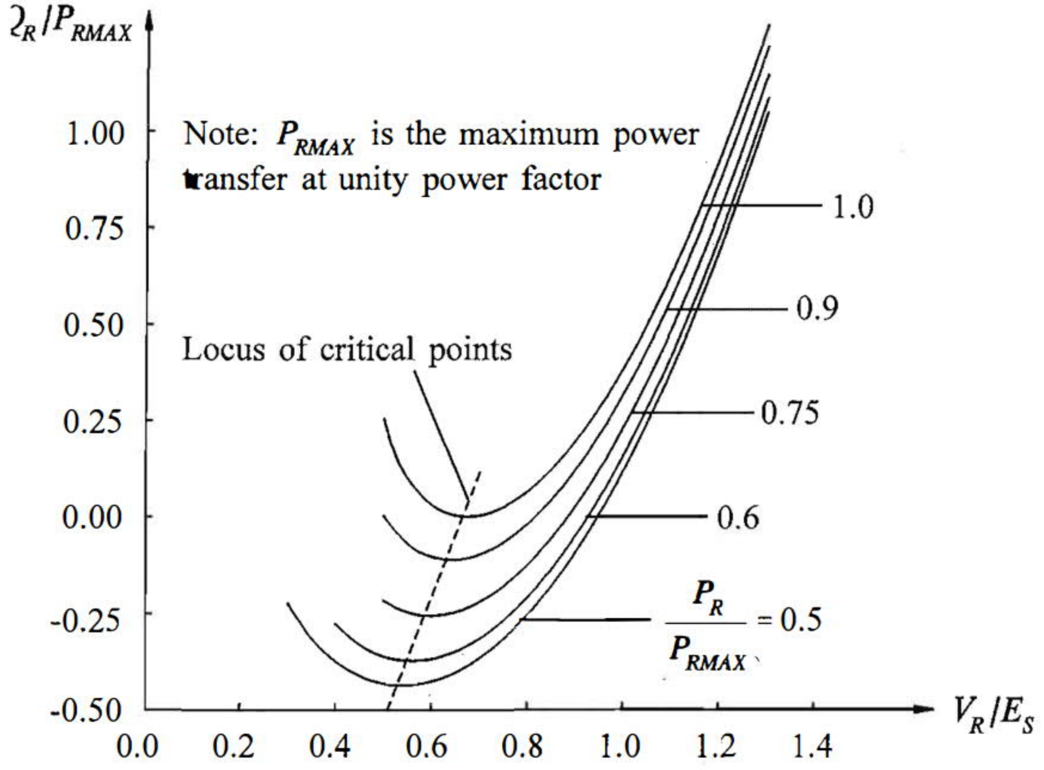
Voltage Stability

- The influence of the reactive power characteristics of the devices at the receiving end (loads and compensating devices) is more apparent.
- The system is stable in the region where the derivative dQ_R / dV_R is positive.
- The parts of the Q - V curves to the right of the minima represent stable operation, and the parts to the left represent unstable operation
- Stable operation in the region where dQ_R/dV_R is negative can be achieved only with a regulated reactive power compensation having sufficient control range and a high Q/V gain with a polarity opposite to that of the normal.

Relationship between V_R and Q_R for a fixed value of P_R



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Voltage Stability

Large-disturbance voltage stability

- Concerned with a system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.
  - determined by the systemload characteristics and the interactions of both continuous and discrete controls and protections
  - the study period of interest may extend from a few seconds to tens of minutes
  - dynamic analysis needed

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Voltage Stability

Small-disturbance voltage stability

- Concerned with a system's ability to control voltages following small perturbations such as incremental changes in system load.
  - The basic processes contributing to small-disturbance voltage instability are essentially of a steady-state nature => static analysis can be effectively used

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Mid-Tem and Long-Term Stability

- The characteristic times of the processes and devices activated by the large voltage and frequency shifts will range from a matter of seconds (the responses of devices such as generator controls and protections) to several minutes (the responses of devices such as prime mover energy supply systems and load-voltage regulators).
- Long-term stability: a few minutes to 10's of minutes
  - boiler dynamics of thermal units, penstock and conduit dynamics of hydro units, automatic generation control, power plant and transmission system protection/controls, transformer saturation, and off-nominal frequency effects on loads and the network.
- Mid-term stability: 10 seconds to a few minutes
  - the focus is on synchronizing power oscillations between machines, including the effects of some of the slower phenomena, and possibly large voltage or frequency excursions.

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Mid-Tem and Long-Term Stability

- Generally, the long-term and mid-term stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient active/reactive power reserves.
- Long-term stability is usually concerned with system response to major disturbances that involve contingencies beyond the normal system design criteria.

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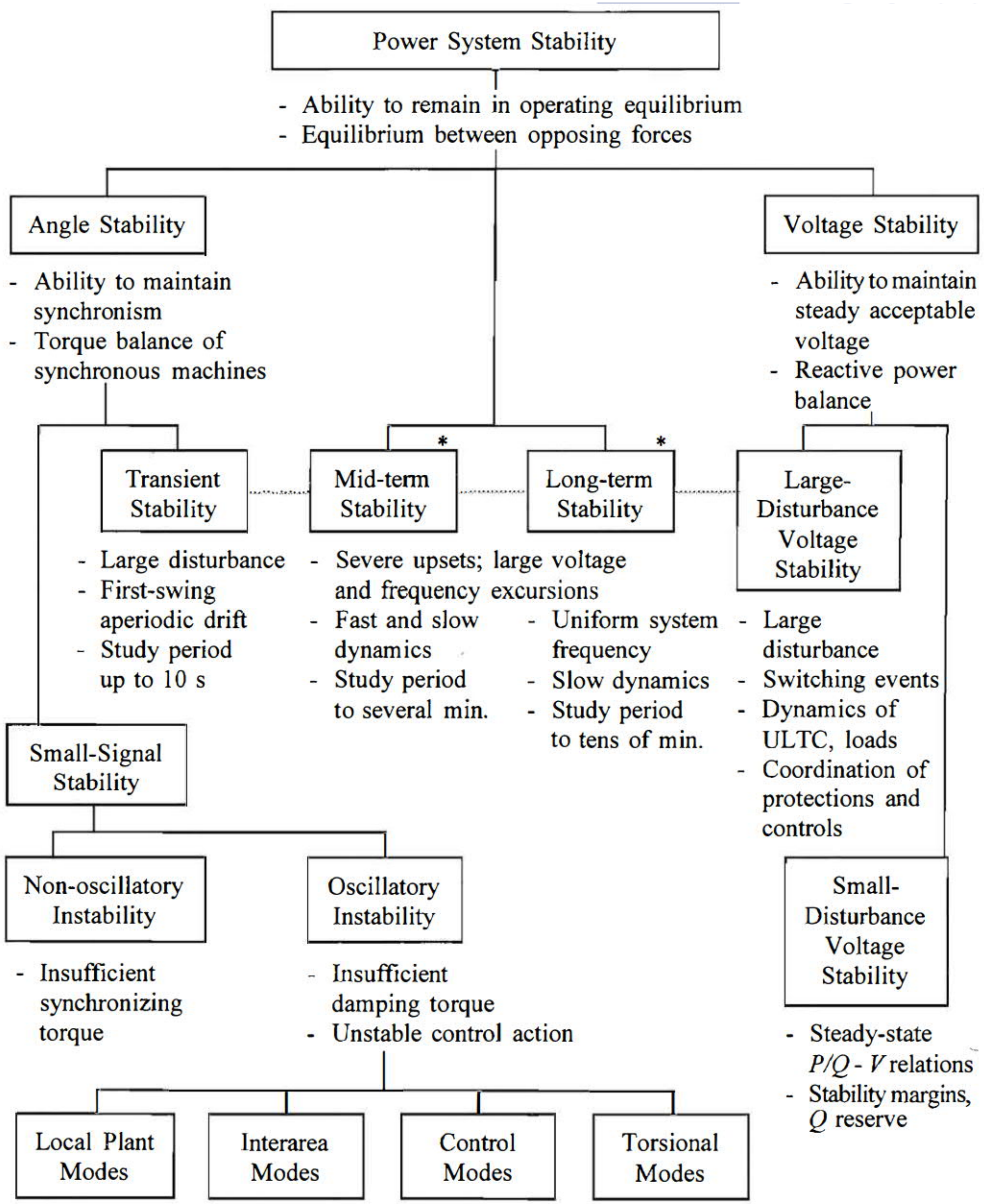
Classification of Stability

- Instability of a power system can take different forms and can be influenced by a wide range of factors.
  - The physical nature of the resulting instability;
  - The size of the disturbance considered;
  - The devices, processes, and time span that must be taken into consideration in order to determine stability; and
  - The most appropriate method of calculation and prediction of stability.
- Solutions to stability problems of one category should not be at the expense of another.
- It is essential to look at all aspects of the stability phenomena and at each aspect from more than one viewpoint.

Tampere University

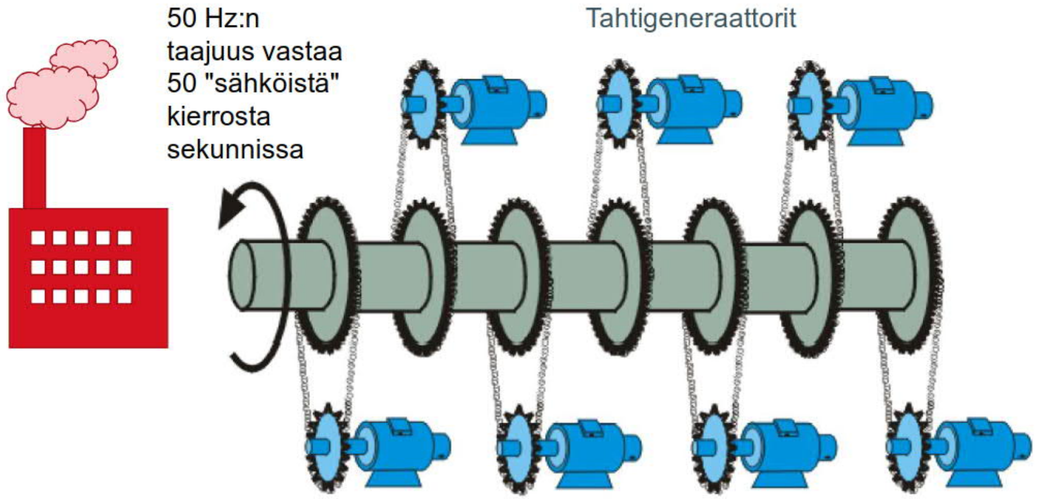
Classification of Stability

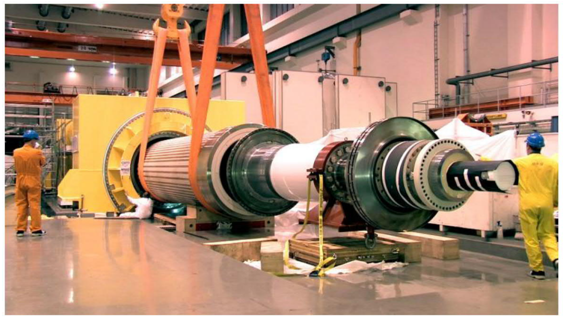


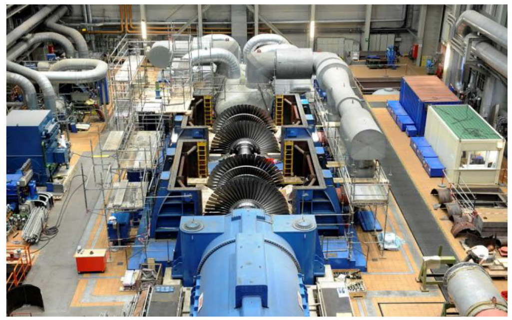
* With availability of improved analytical techniques providing unified approach for analysis of fast and slow dynamics, distinction between mid-term and long-term stability has become significant

Power System Inertia

- Power system inertia originates from rotating kinetic energy connected with the system
  - Synchronous generators together with steam turbines
  - Directly to network connected rotating loads (synchronous and induction motors)
- Kinetic energy stored in the system resists system frequency to change due to power imbalance in a system







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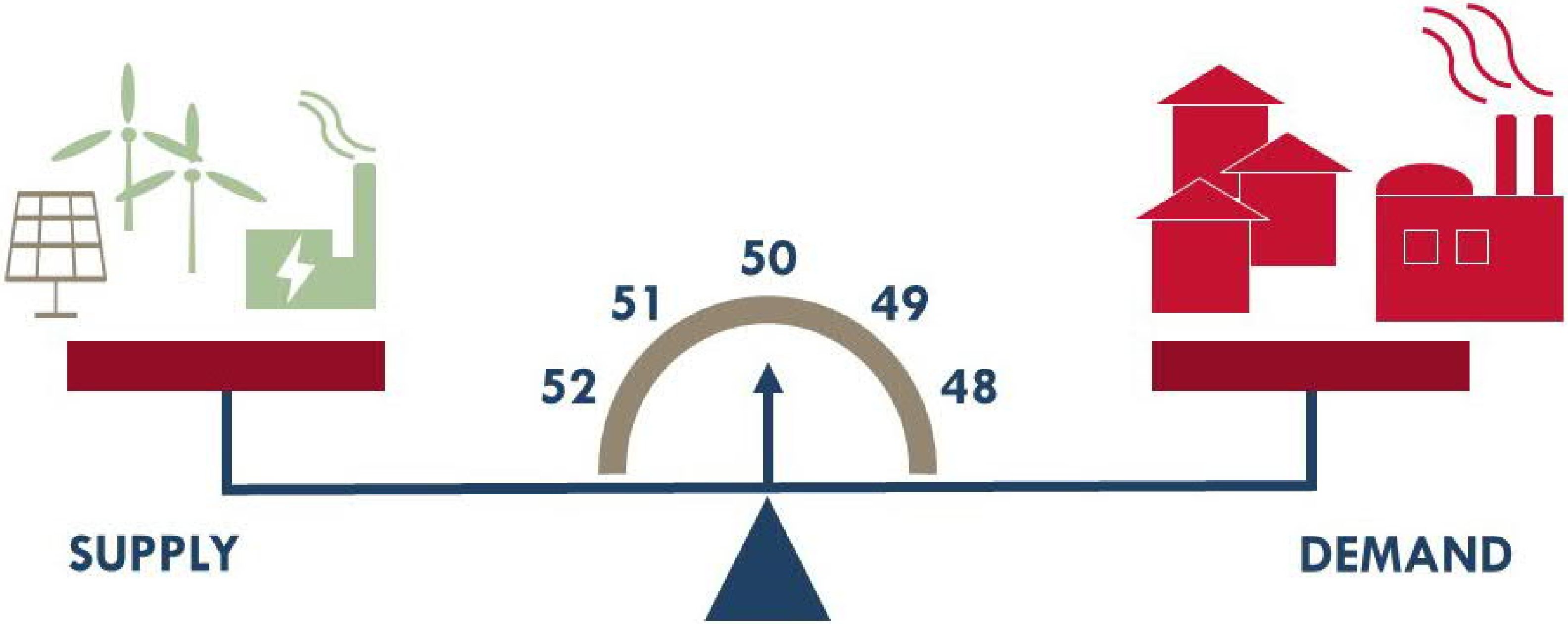
Power System Inertia



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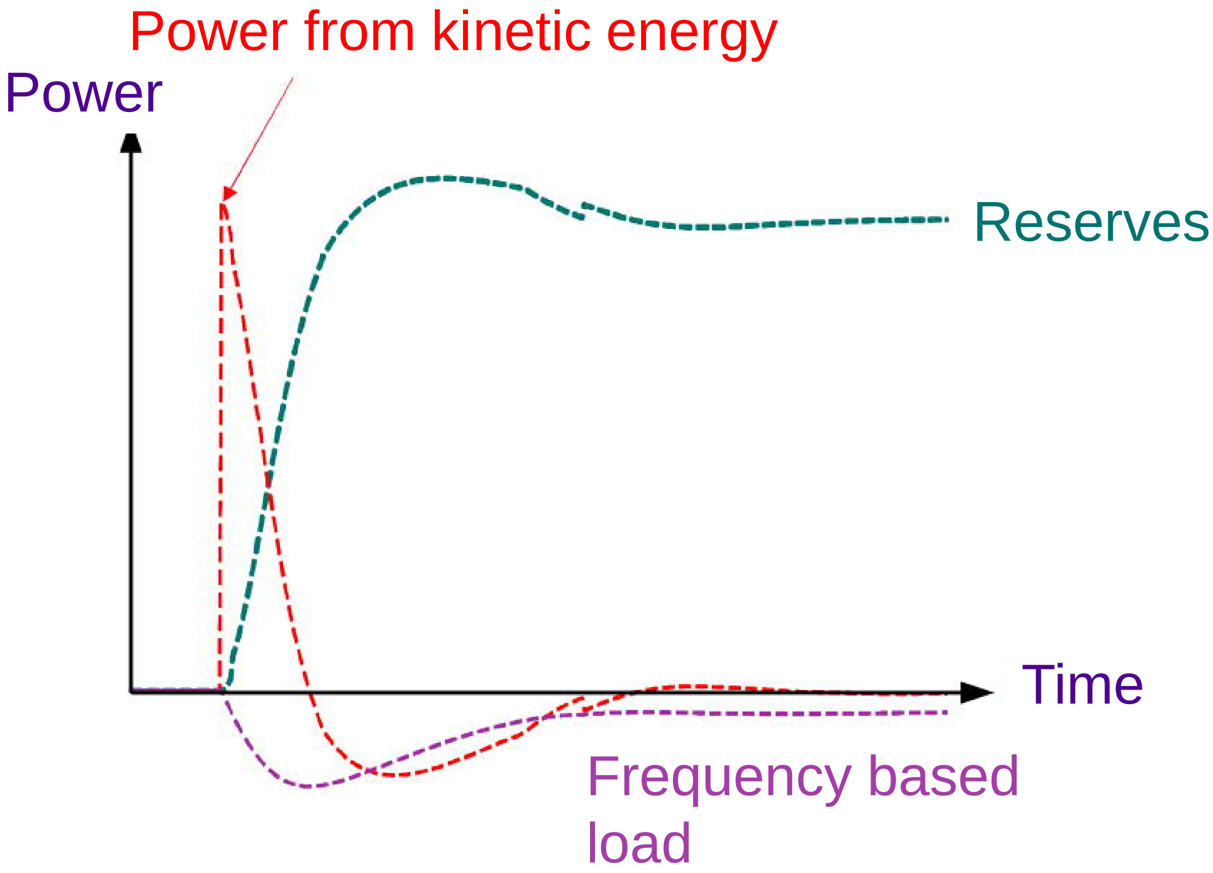
Power System Inertia

- System inertia plays a VERY important role in maintaining frequency stability
  - responses first, within 0.1 - 2 seconds, to frequency disturbances by injecting energy to a system in case of power deficit and vice versa in case of excessive power
- After 2-5 seconds fast controllable resources start to take the responsibility of balancing the system



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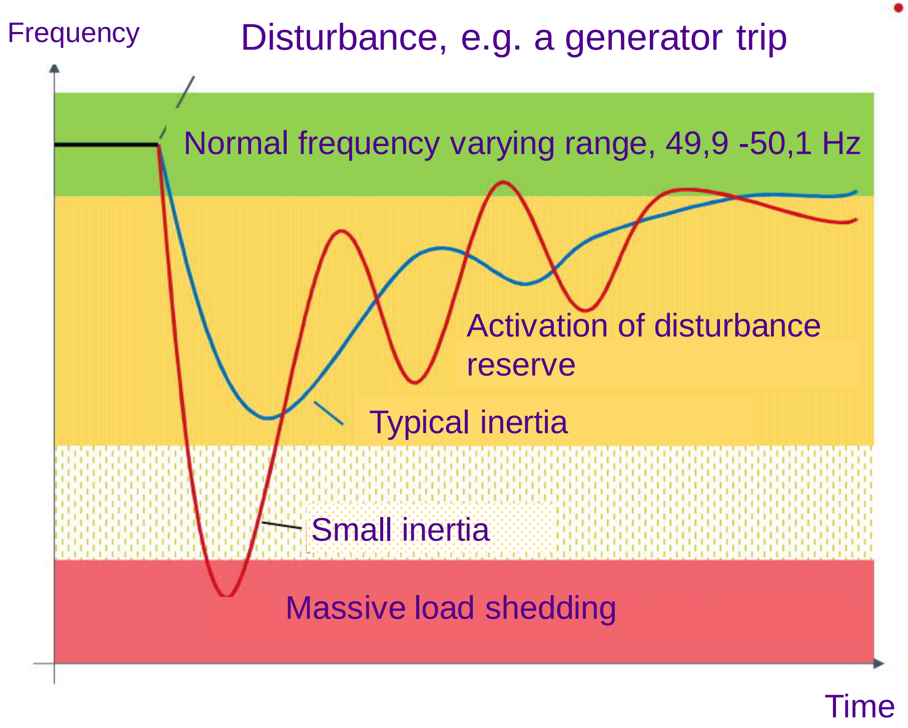
Power System Inertia

- Generators connected to electric grid by frequency converters do not supply inertia to the system
  - No direct electromagnetic coupling between rotating masses and system frequency
- Such generators are
  - Variable speed operated wind generators connected via AC-DC-AC converters
  - Solar PV generators connected via DC- AC converters
- Frequency converter controlled synchronous and induction motors do not either produce inertia to the system



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Power System Inertia

- Increasing share of variating renewable asynchronous generation will increase challenges in power system control
  - Increases disturbances in power balance
  - Reduces resources of controllable generation
  - Reduces mechanical inertia -> more sensitive system
- Needed a new concept: virtual inertia produced by power electronics to replace reduced mechanical inertia
- Good thing for us: Increases need and improves employment of control engineers to keep the system running

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Conclusions

- Present trends in the planning and operation of power systems have resulted in new kinds of stability problems.
- Financial and regulatory conditions have caused electric utilities to build power systems with less redundancy and operate them closer to transient stability limits.
- Interconnections are continuing to grow with more use of new technologies such as multiterminal HVDC transmission.

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Conclusions

- Composition and characteristics of loads are changing contributing to significant changes in the dynamic characteristics of modern power systems.
  - E.g. frequency converter connected generation and loads
- Modes of instability are becoming increasingly more complex and require a comprehensive consideration of the various aspects of system stability.
- In particular, voltage instability and low-frequency inter - area oscillations have become greater sources of concern than in the past.

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