

EE 742

# Chapter 6 – Transient Stability

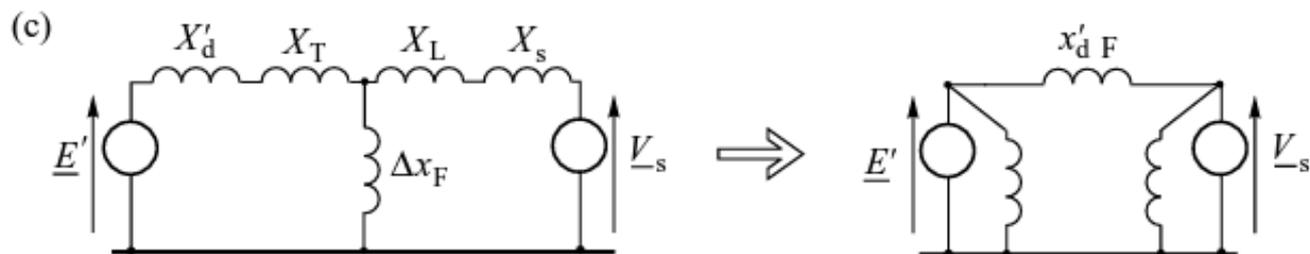
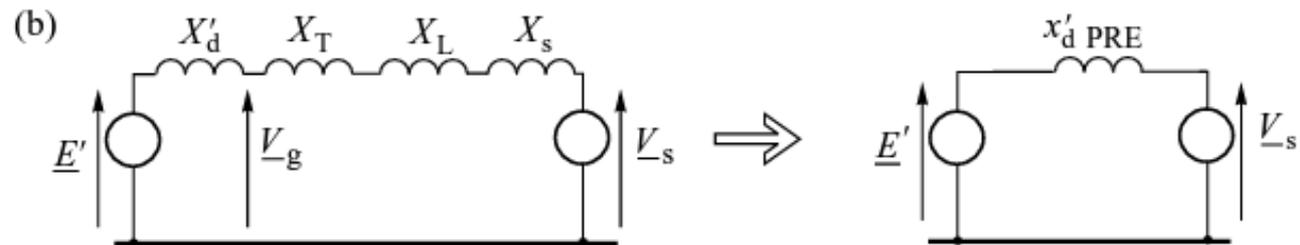
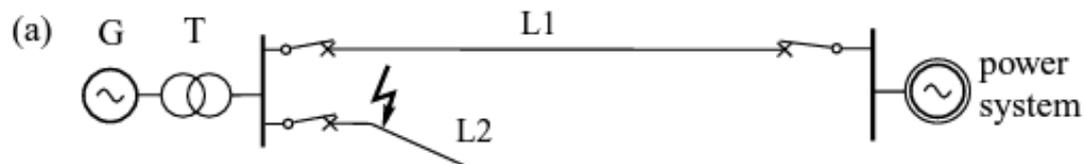
Y. Baghzouz

# Introduction

- In this chapter, we consider large disturbances such as short circuit or line tripping – action must be taken right away to maintain stability.
  - Effect of subtransient on electromechanical dynamics can be neglected.
  - Classical model is used to study the transient stability problem,
  - The air-gap reactance  $x_{d'}$  is subject to change
  - The mechanical power is assumed to be constant
- There are three steps associated with a disturbance:
  - Pre-fault state:  $x_{d'} = x_{d'PRE}$
  - Fault state:  $x_{d'} = x_{d'F}$
  - Post-fault state:  $x_{d'} = x_{d'POST}$

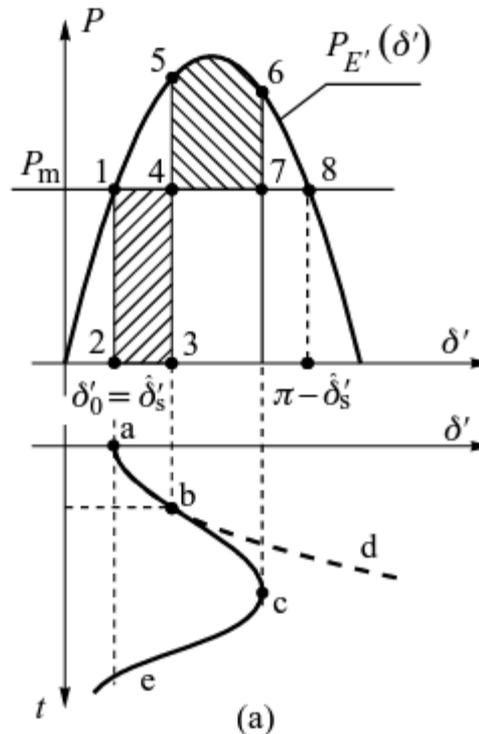
# 1. Fault cleared w/o change in equivalent network impedance ( $x_{d'PRE} = x_{d'POST}$ )

- Pre- and post-fault reactance:  $x'_{dPRE} = X'_d + X_T + X_L + X_s.$
  - Reactance during fault:  $x'_{dF} = X'_d + X_T + X_L + X_s + \frac{(X'_d + X_T)(X_L + X_s)}{\Delta x_F}.$
- where  $\Delta x_F$  is the fault impedance which depends on the fault type



# 3-phase fault ( $\Delta x_F = 0$ )

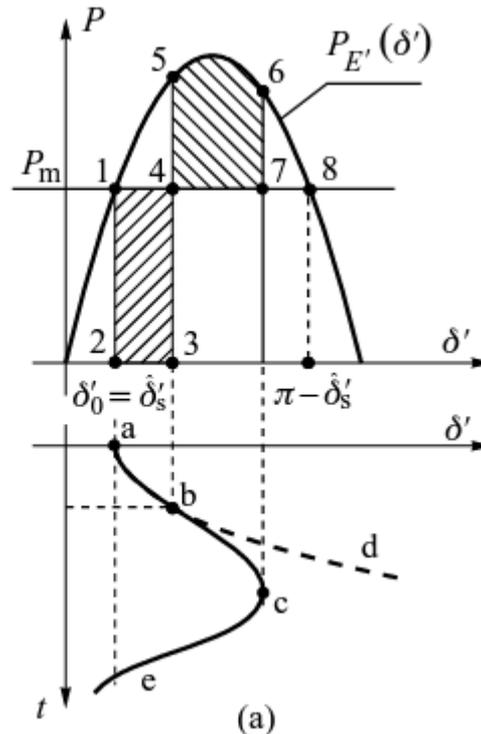
- If the damping power is neglected, the rotor will experience constant acceleration during the fault:  $\varepsilon = \frac{d^2\delta'}{dt^2} = \frac{P_m}{M} = \text{constant}.$
- Power angle trajectory:  $\delta' = \delta'_0 + \frac{\varepsilon t^2}{2}$  or  $\Delta\delta' = \delta' - \delta'_0 = \frac{\varepsilon t^2}{2}.$
- Rotor acquires kinetic energy proportional to area 1-2-3-4



# 3-phase fault ( $\Delta x_F = 0$ )

- After the fault is cleared at  $t = t_1$  by opening the circuit breaker, the rotor follows the transient power angle curve and experiences a decelerating torque.
- Angle continued to increase due to rotor momentum, till the work done during deceleration equals the kinetic energy gained:

$$(\text{area } 4-5-6-7) = \text{area } (1-2-3-4)$$



The generator does not lose synchronism – stable system

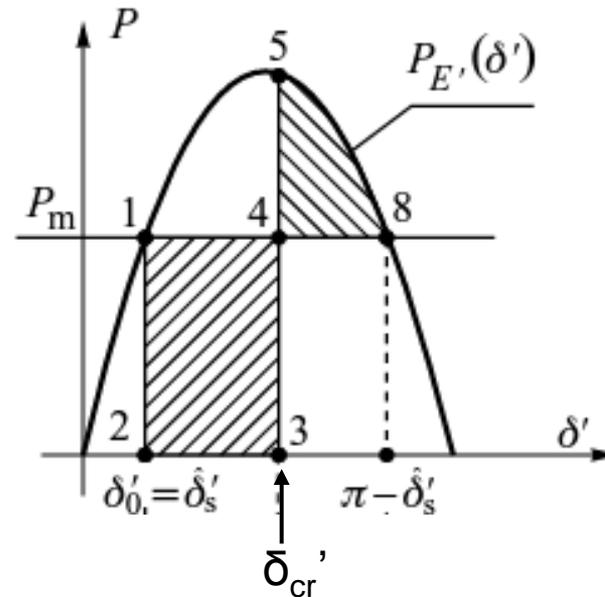
Measures of transient stability margin:

$$K_{\text{area}} = \frac{\text{area } 6-7-8}{\text{area } 4-5-8}$$

$$K_{\text{time}} = \frac{t_{\text{cr}} - t_f}{t_{\text{cr}}}$$

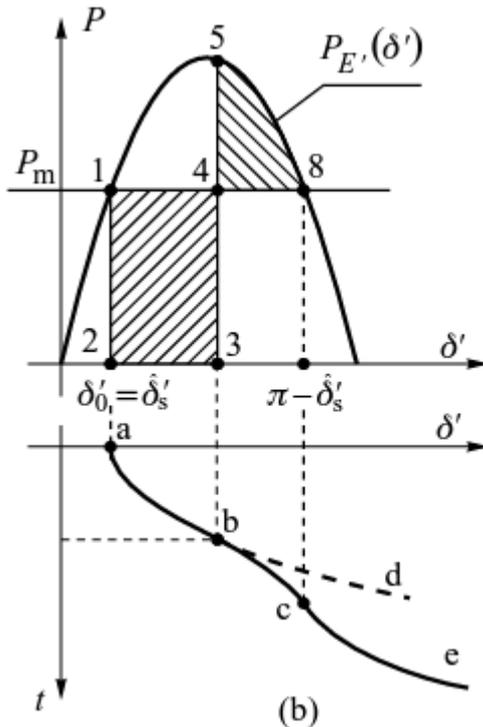
# Critical Clearing Time

- Let  $P_{E'}(\delta') = P_{E'_{\max}} \sin(\delta')$ , where  $P_{E'_{\max}} = E'V_s$
- Initial angle:  $\delta_o'$  where  $P_{E'}(\delta_o') = P_{E'_{\max}} \sin(\delta_o') = P_m$
- Critical clearing angle  $\delta_{cr}'$  occurs when area 1-2-3-4 = area 4-5-8.
- $\rightarrow (\delta_{cr}' - \delta_o') P_m = P_{E'_{\max}} [\cos(\delta_{cr}') - \cos(\pi - \delta_o')] - P_m [(\pi - \delta_o') - \delta_{cr}']$
- $\rightarrow \delta_{cr}' = \cos^{-1}[(\pi - 2\delta_o') \sin(\delta_o') - \cos(\delta_o')]$
- Also,  $\delta_{cr}' = \delta_o' + (P_m/2M)t_{cr}^2$
- $\rightarrow t_{cr} = [2M(\delta_{cr}' - \delta_o')/P_m]^{1/2}$



## 3-phase fault ( $\Delta x_F = 0$ )

- With a longer fault clearing time at  $t = t_2$ , the work performed during deceleration (proportional to area 4-5-8, cannot absorb the kinetic energy acquired during acceleration.
- After passing point 8, the machine starts to accelerate again further increasing its rotor angle
- The rotor will make an asynchronous rotation and loses synchronism



The generator loses synchronism – unstable system

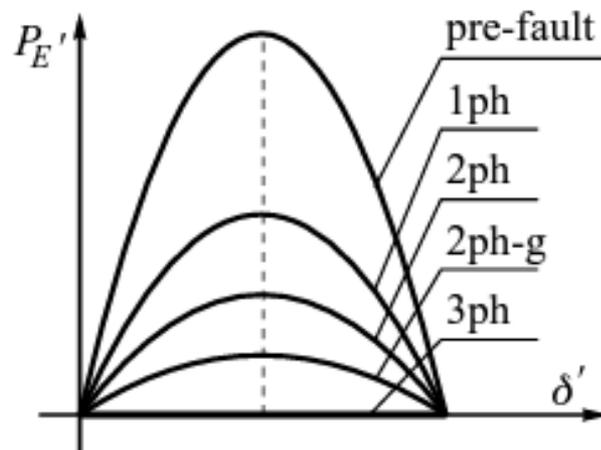
# Unbalanced faults ( $\Delta x_F \neq 0$ )

- In an unbalanced fault, some power will still be transmitted to the system through the unaffected phase.
- The shunt reactance  $\Delta x_F$  is non-zero and depends of the type of fault, thus resulting in a finite equivalent fault reactance  $x_{d'F}$

**Table 6.1** Shunt reactances representing different types of fault

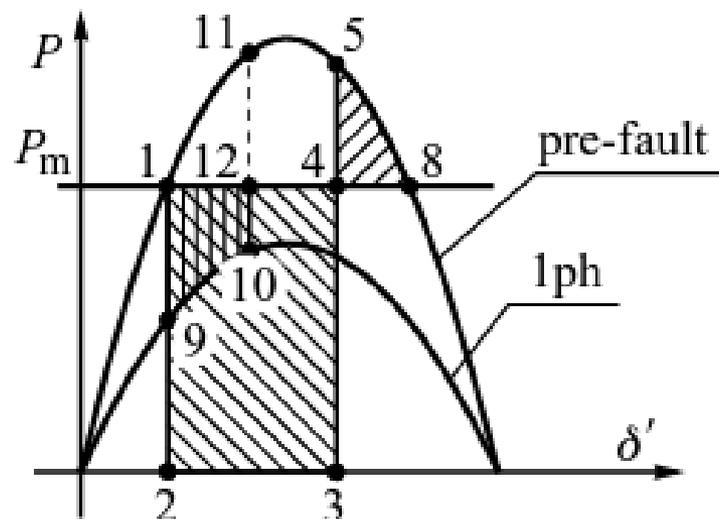
Fault type	Three phase (3ph)	Double phase to ground (2ph-g)	Phase to phase (2ph)	Single phase (1ph)
$\Delta x_F$	0	$\frac{X_2 X_0}{X_2 + X_0}$	$X_2$	$X_1 + X_2$

- The corresponding power angle curves during the fault are shown:



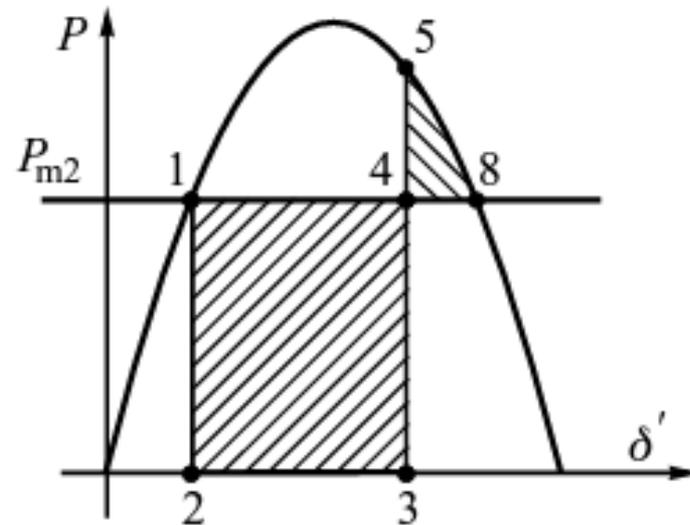
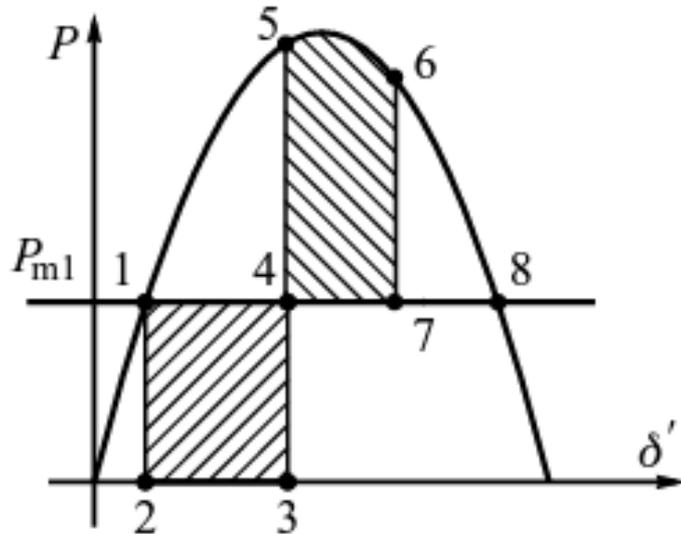
# Unbalanced faults

- Consider the least severe fault (single-phase fault):
  - The fault clearing time is assumed longer than the critical clearing time of the three-phase fault - unstable system in case of 3-phase fault (since area 1-2-3-4 > area 4-5-8).
  - For the 1-phase fault, the accelerating torque is smaller, thus the rotor will accelerate less rapidly. By the time the fault is cleared, the rotor reaches point 10.
  - The system is stable as area 1-9-10-12 is much smaller than area 12-11-8.
  - The  $t_{cr}$  of a single-phase fault is much longer than that of a 3-phase fault.



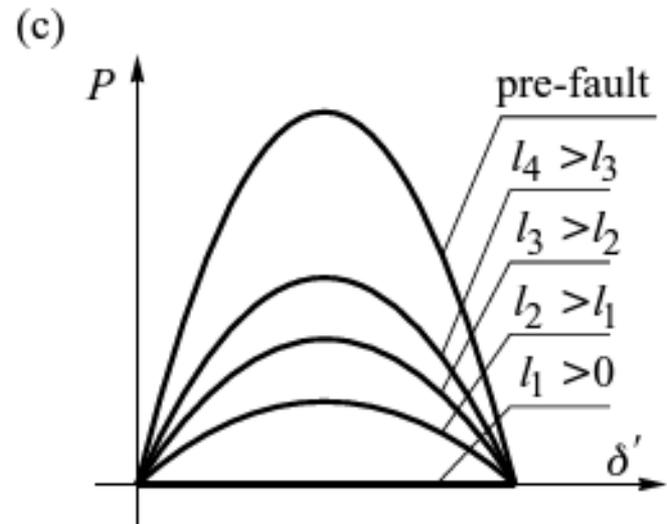
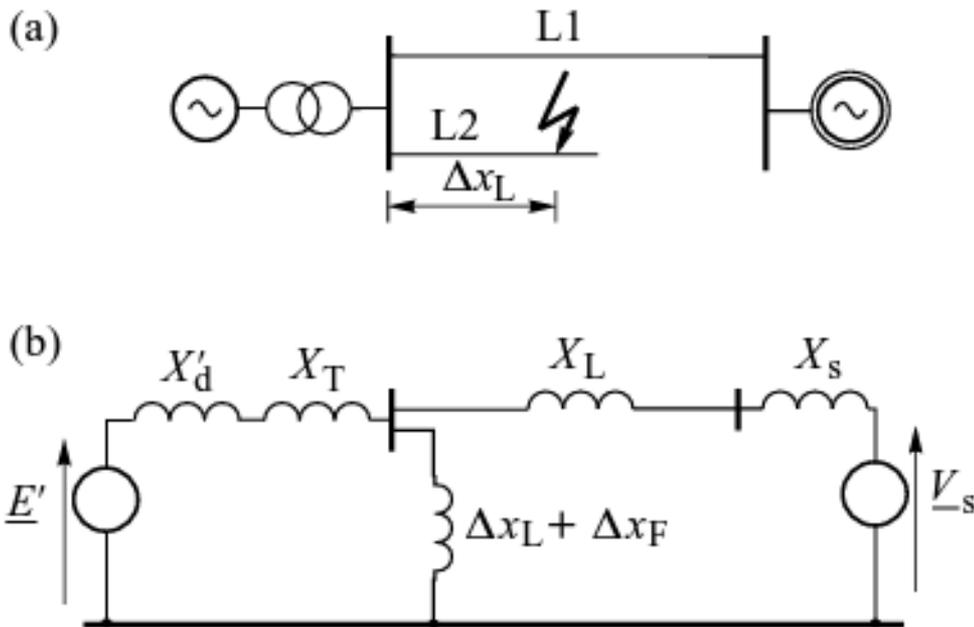
# Effect of pre-fault load

- Refer to the figure below
  - With  $P_{m1}$ , the system is stable.
- Now the pre-fault load is increased by 50%  $P_{m2} = 1.5 P_{m1}$ 
  - The rotor acceleration  $\epsilon$ , and the change in power angle  $\Delta\delta'$  also increases by the same factor.
  - $\rightarrow$  each side of area 1-2-3-4 is increased by 50%.
  - The result: unstable system.



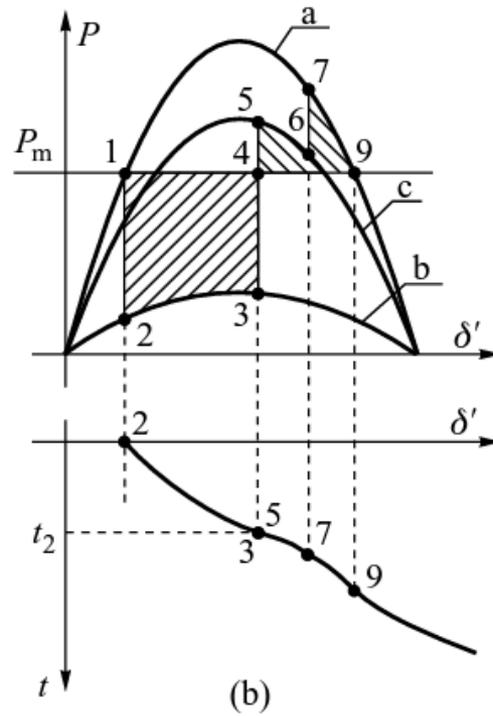
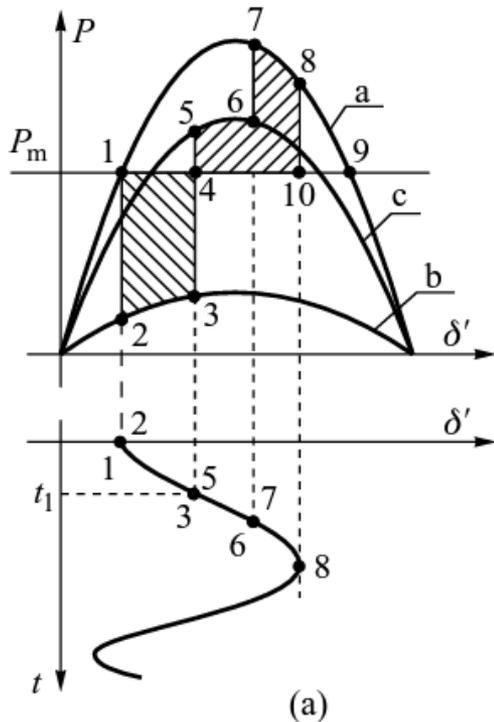
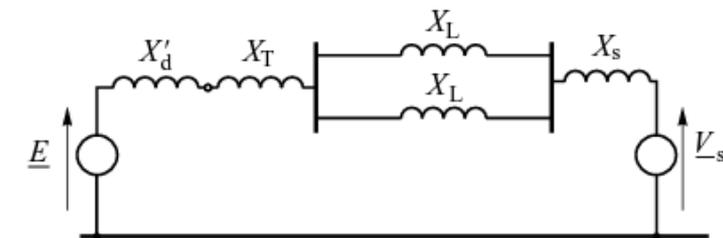
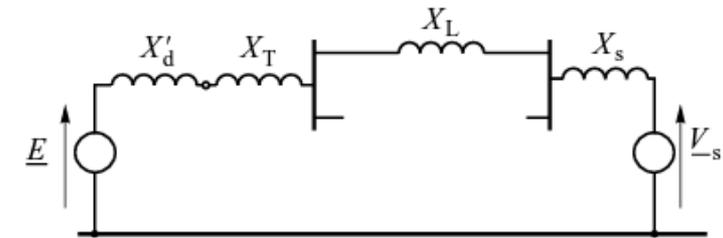
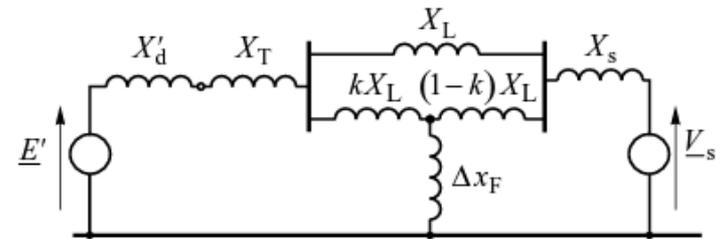
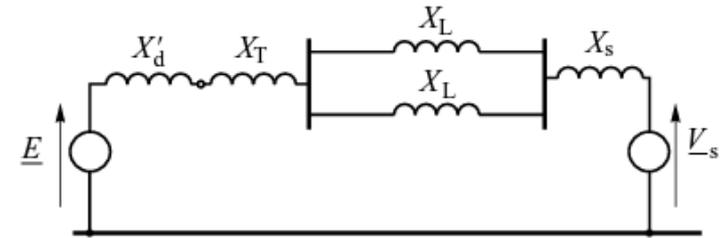
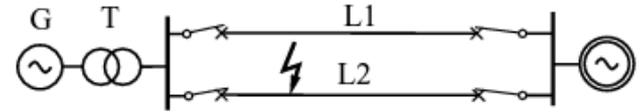
# Influence of fault distance

- With the fault further down the line from the bus bar, the equivalent fault reactance is increased:  $\Delta x_F + \Delta x_L$ .
- The figure below shows a family of power angle curves for different fault distances from the bus bar.
- The further is the fault, the less severe and the longer critical clearing time.



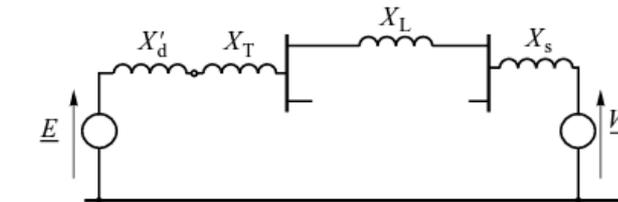
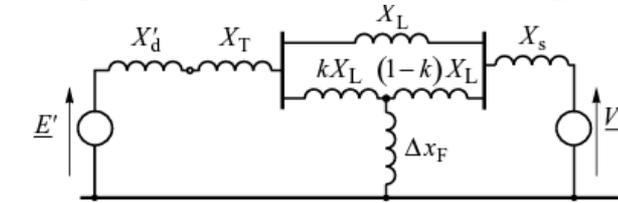
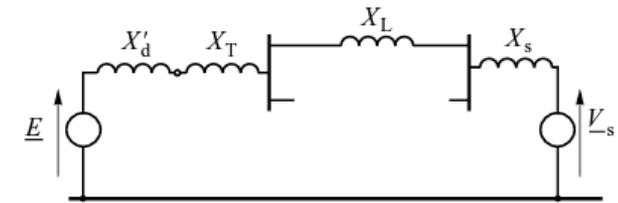
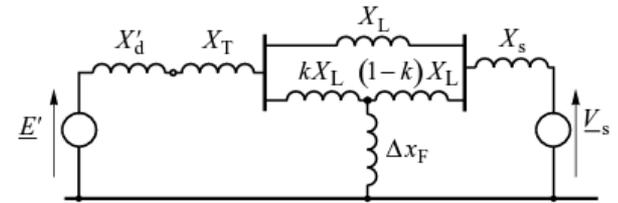
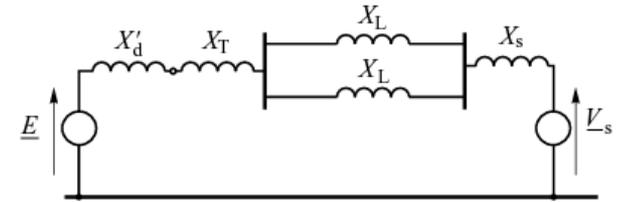
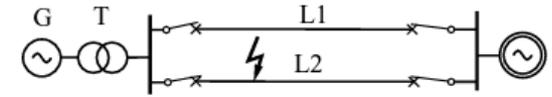
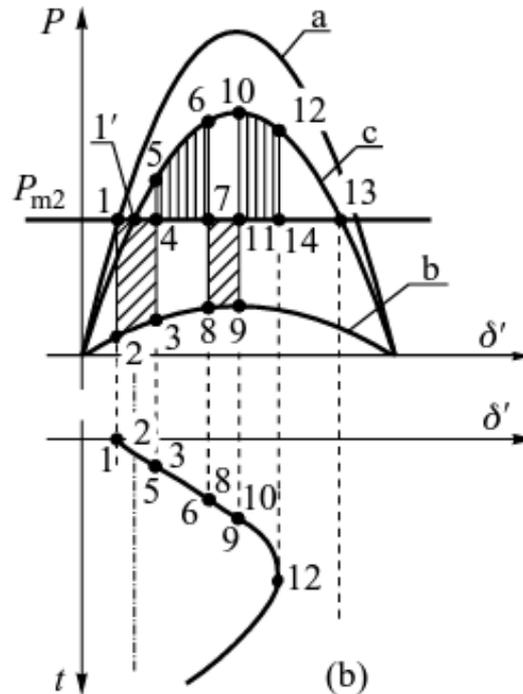
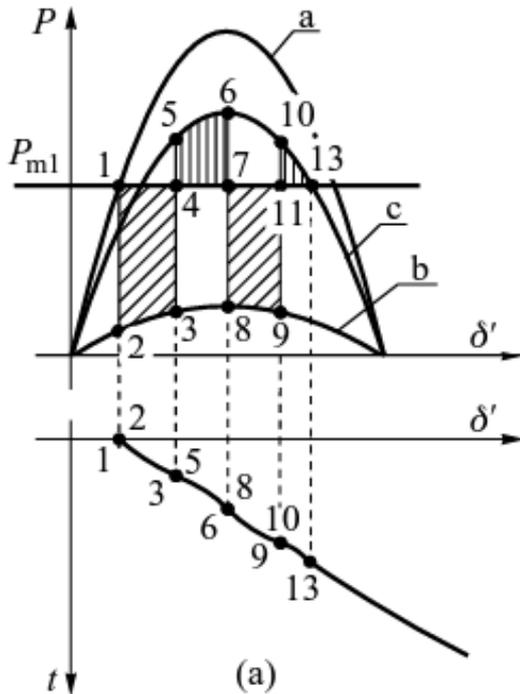
# Fault cleared with successful auto-reclosing

- In most situations, faults occur on loaded lines.
- Successful auto-reclosing if the fault is intermittent (temporary)
- See sequence of events to the right, and corresponding power-angle curves below.



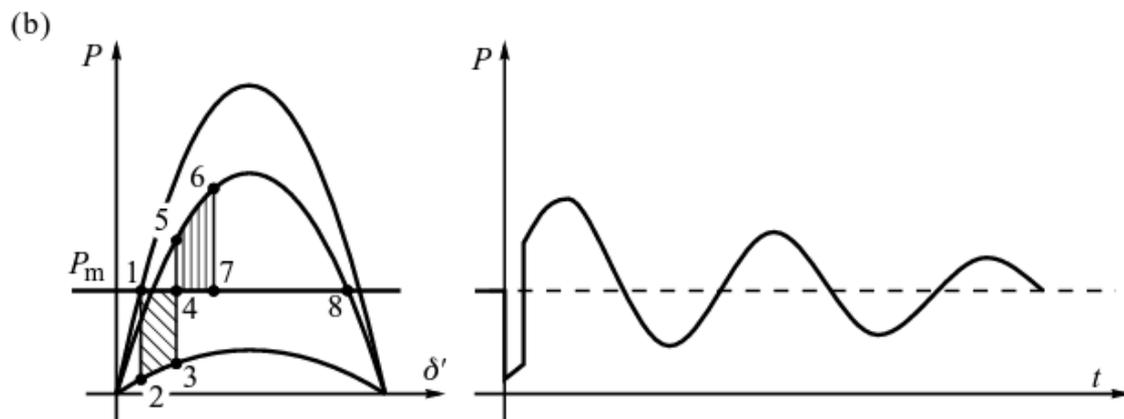
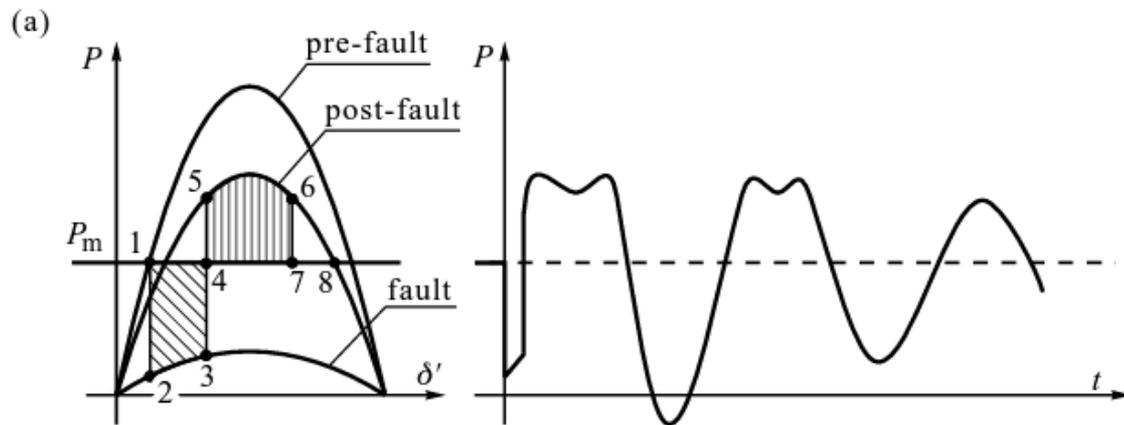
# Fault cleared with un-successful auto-reclosing

- Un-successful auto-reclosing if the fault is not cleared (permanent)
- See sequence of events to the right, and corresponding power-angle curves below for both stable and unstable operations.



# Power Swings - Refer to figures (a) and (b) below

- Figure (a): small stability margin,  $\delta'$  passes over  $\pi/2$ , the power exhibits “humps” during the first few cycles of oscillations.
- Figure (b): large stability margin,  $\delta'$  does not reach  $\pi/2$ , the power oscillations do not exhibit the “humps” above.



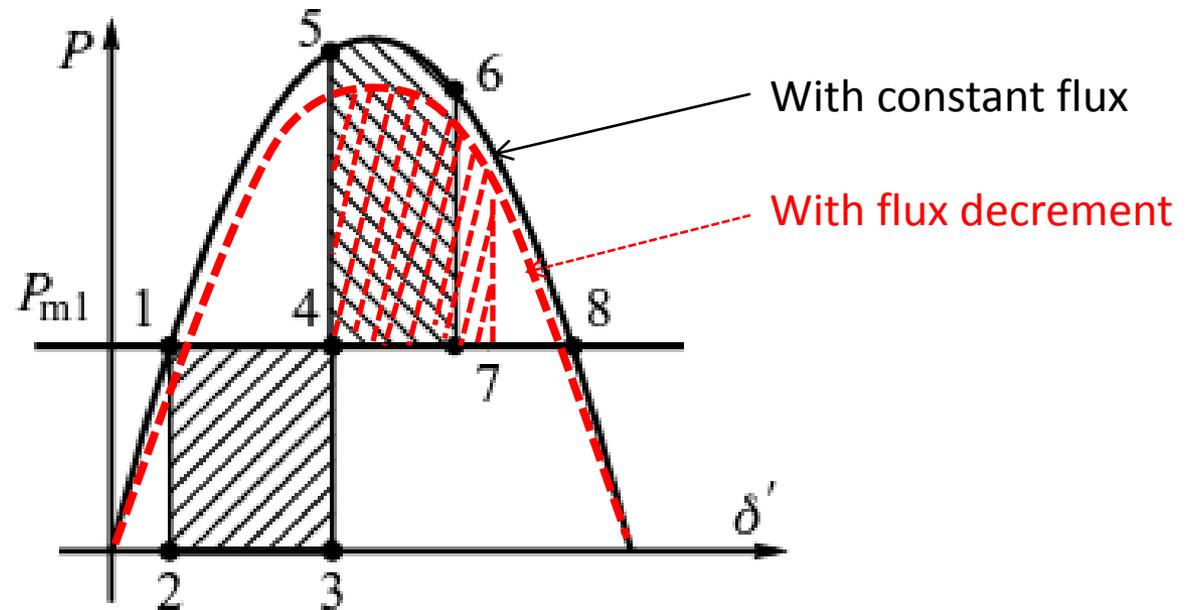
# Homework # 6

A 2-pole, 60 Hz, synchronous machine is connected to an infinite bus through a transformer and a double transmission line. The infinite bus voltage is 1 pu, the machine  $X_d' = 0.2$  pu, transformer reactance = 0.1 pu, reactance of each transmission line = 0.4 pu, inertia coefficient  $M = 0.0265$ . Initially, the machine is delivering 0.8 pu +j 0.0 pu. The inertia constant,  $H = 5$  MJ/MVA. Ignore all resistances and damping power.

- 1) Determine the internal voltage and power angle, then the equation of motion.
- 2) Assume a three-phase fault is about to occur in one of the lines near the bus connecting it to the transformer. determine the new equation of motion and initial rotor acceleration.
- 3) Now assume that after some time, the circuit breaker at the sending end of the faulted line clears the fault by opening that line. Determine the now equation of motion.
- 4) Calculate the rotor angle as a function of time - assuming that the fault is cleared in 0.15 sec.
- 5) Determine the critical clearing angle and corresponding critical clearing time.

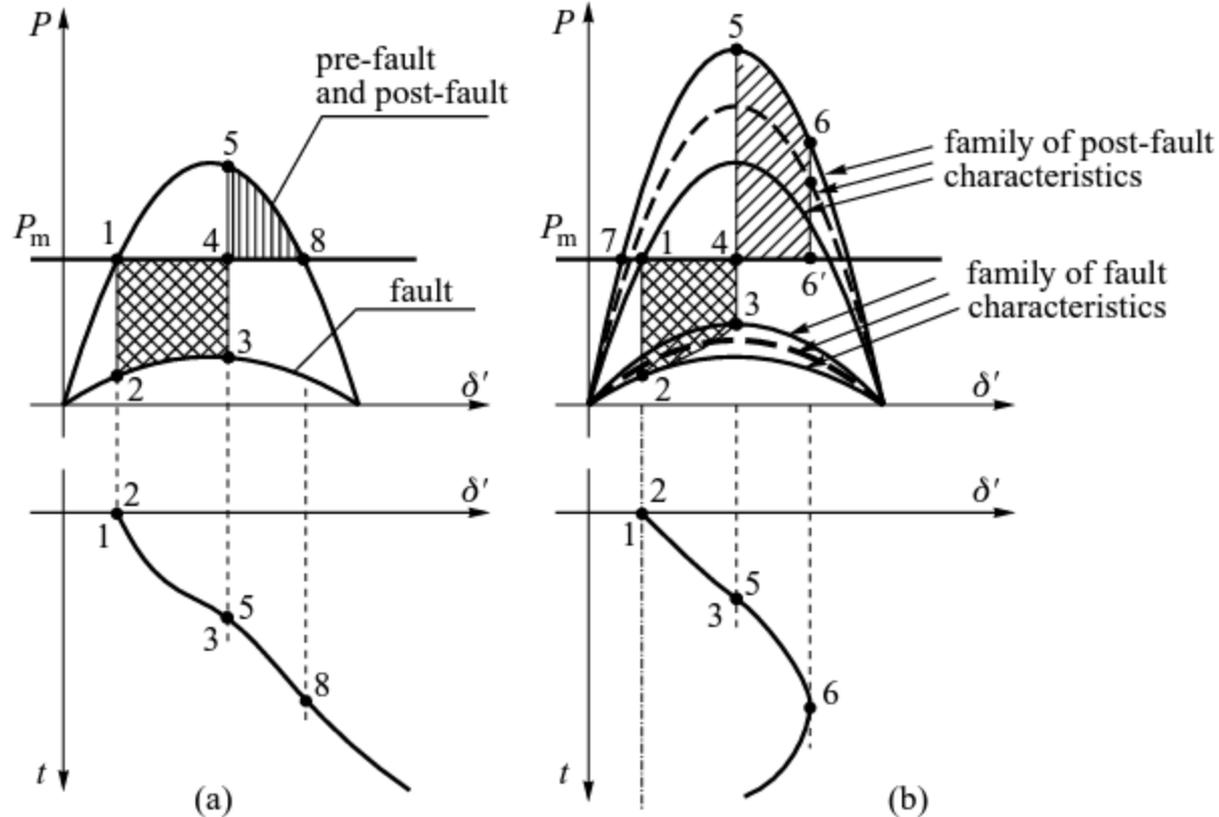
# Effect of flux decrement

- Flux decrement causes  $E'$  to decrease with time.
- If the fault clearing time is sufficiently long, then the decay in  $E'$  may have considerable impact as it reduces the amplitude of  $P_{E'}(\delta')$ .
- → This leads to a decrease in the available deceleration area and a lower stability margin.



# Effect of the AVR

- Fig. (a): Without an AVR, the system loses synchronism.
- Fig. (b): a fast-acting AVR may increase  $E'$  to its ceiling before the fault is cleared – this has two positive effects on the first swing:
  - The accelerating area is decreased.
  - The available decelerating area is increased.

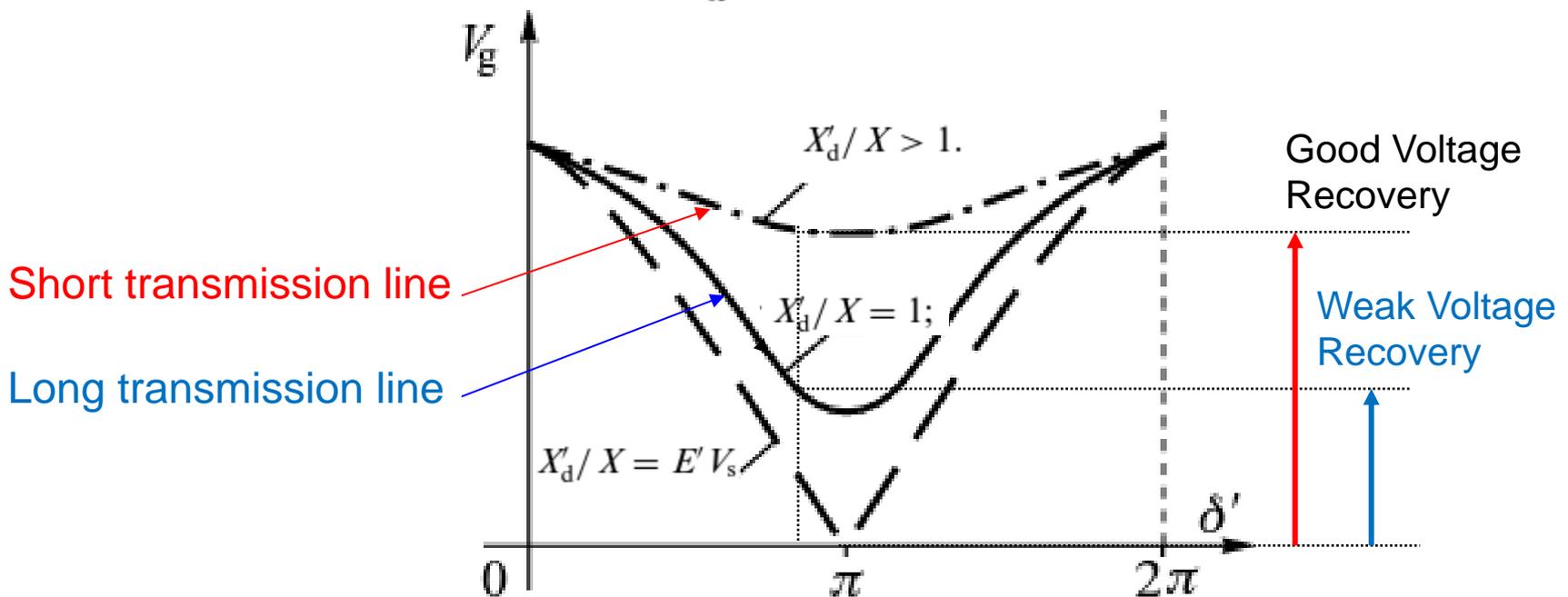


# Effect of the AVR

- However, the AVR can increase the swings that follow (depending on the AVR dynamic properties and system parameters)

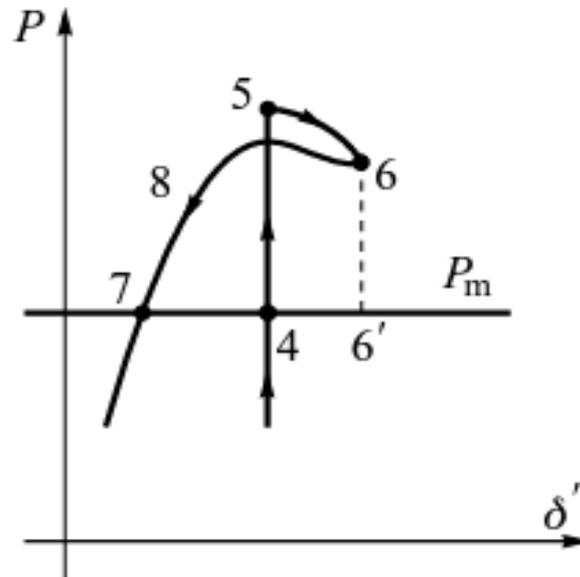
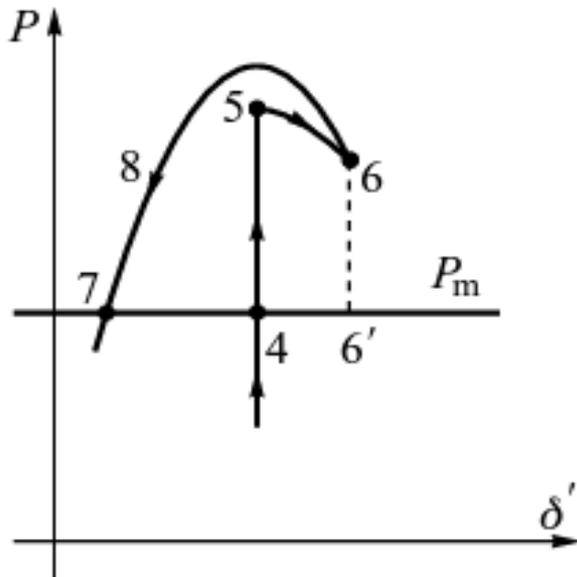
- Recall equation of regulated generator:  $\left(E'_a + \frac{X'_d}{X} V_s\right)^2 + E'_b{}^2 = \left[\frac{X'_d + X}{X} V_g\right]^2$ .

- Solve for  $V_g$ : 
$$V_g = \frac{\sqrt{E'^2 + 2 \frac{X'_d}{X} E' V_s \cos \delta' + \left(\frac{X'_d}{X} V_s\right)^2}}{\frac{X'_d}{X} + 1}$$
.



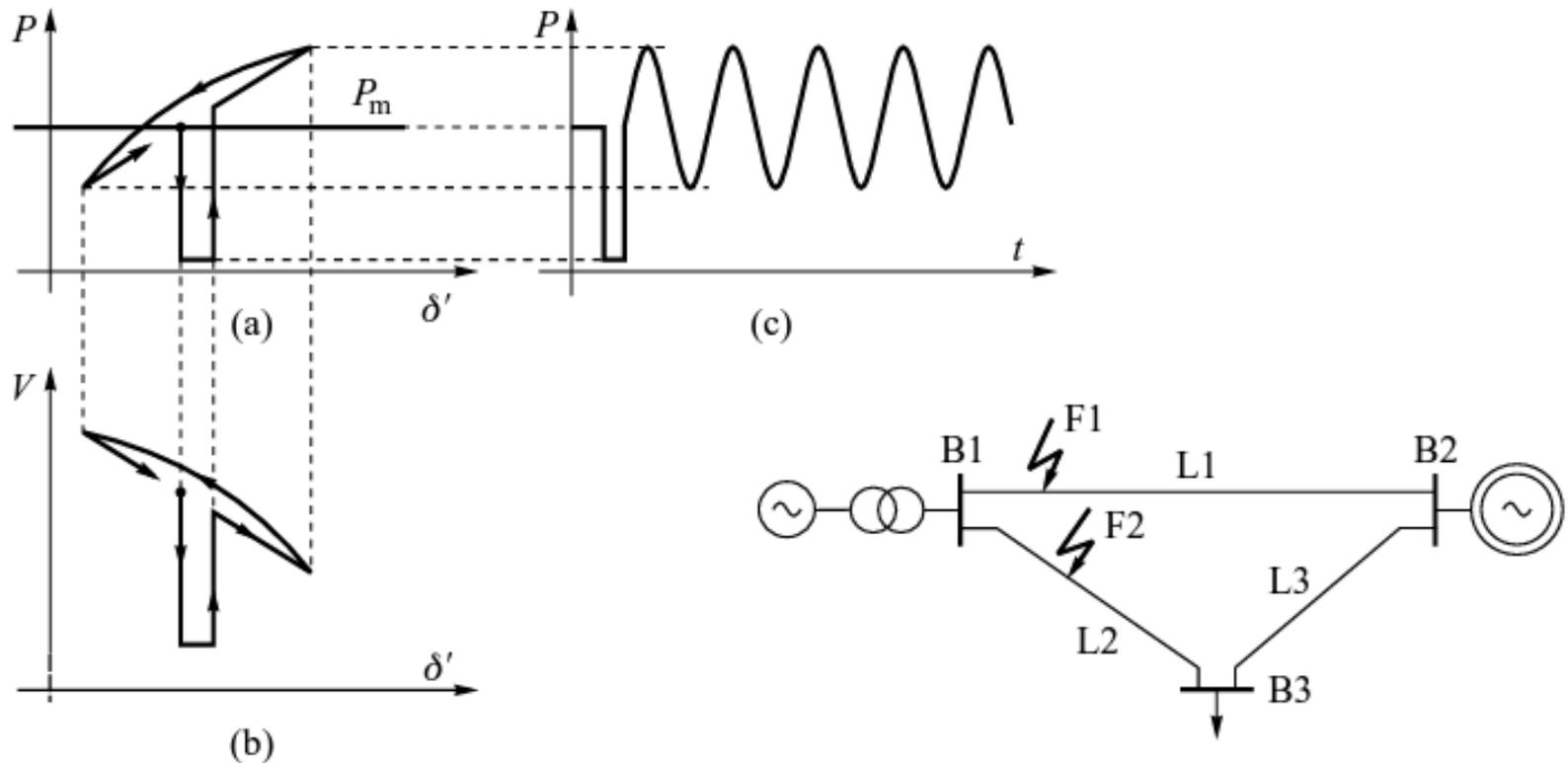
# Effect of the AVR

- For a long transmission line, the AVR will continue to increase the excitation current to recover the terminal voltage during the back swing – this will increase the rotor backswing.
- For a short transmission line, the increase in excitation current during the fault may result in a terminal voltage slightly higher than the reference value – this will lead the AVR to reduce the field current after the fault, thus reducing the rotor backswing.



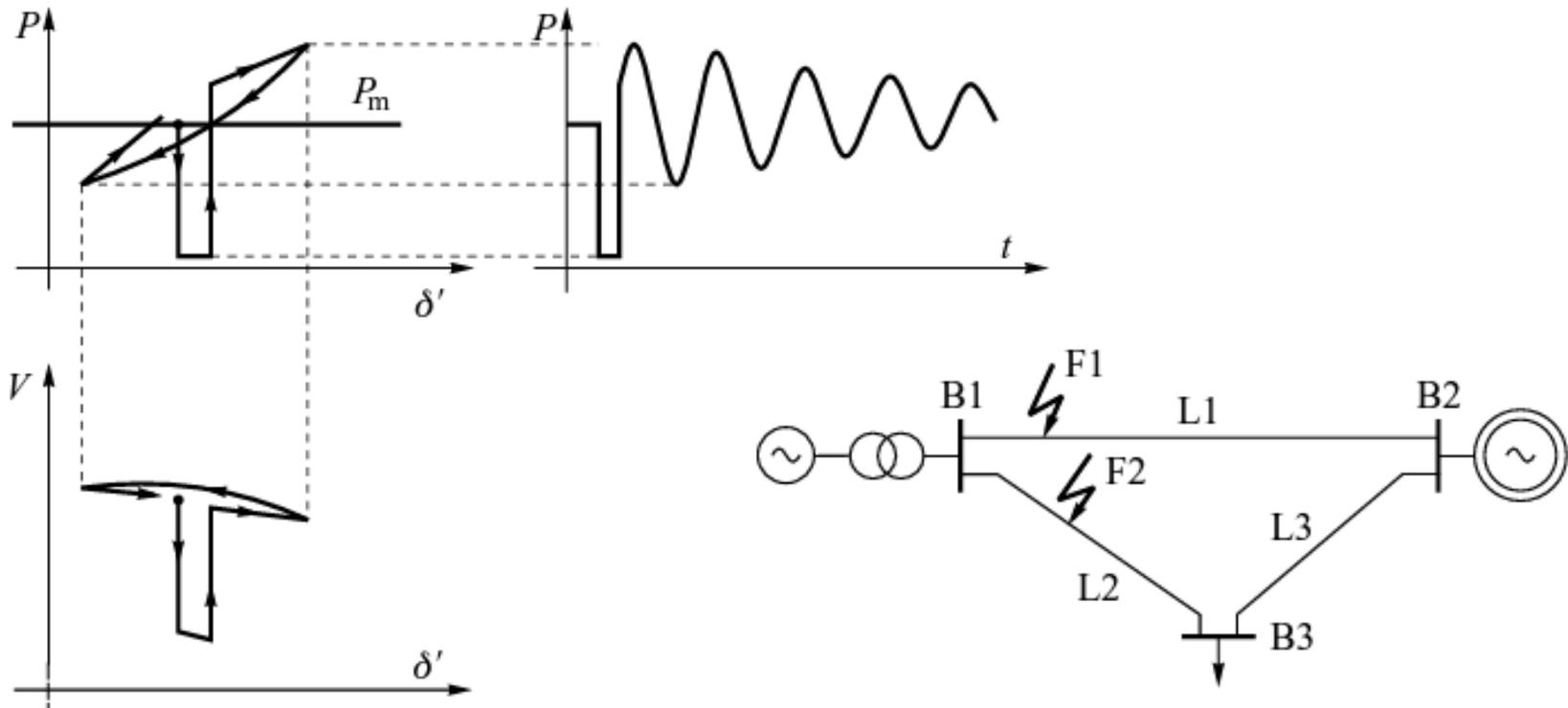
# Effect of AVR

- The dynamic response depends on the post-fault system reactance.
- consider fault F1 that is cleared by tripping the faulted line.
  - The post-fault system reactance is larger (“equivalent to longer line”)
  - This will result in poor voltage recovery
  - The AVR keeps increasing the excitation current, resulting in poor damping.



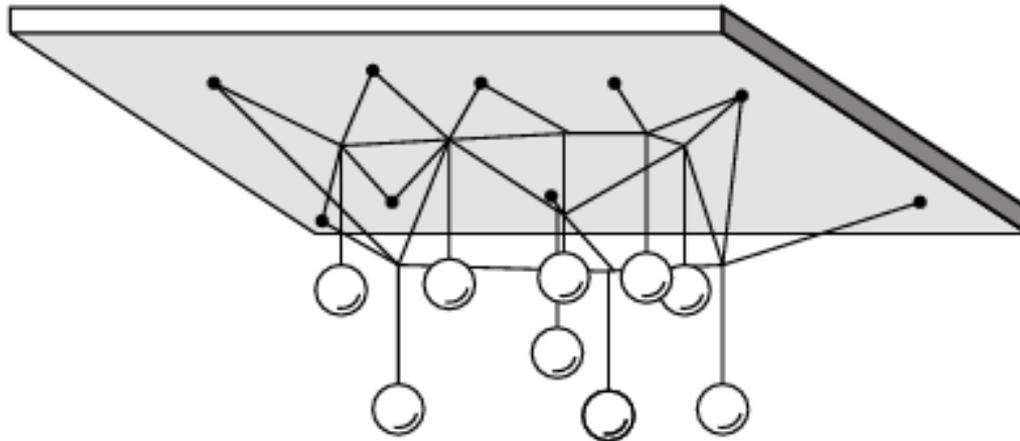
# Effect of AVR

- Now consider fault F2 that is cleared by tripping the faulted line.
  - The post-fault system reactance is smaller (“equivalent to shorter line”)
  - This will result in good voltage recovery
  - The AVR decreases the excitation current, resulting in better damping.
- In any case, AVR supplementary control loops will be added later.



# Swings in multi-machine systems

- Real life power systems consist of a number of generators interconnected through the transmission system.
- A fault near a power generator will also disturb the power balance of nearby generators.
- The electromechanical swing can be compared to movement of masses in the mechanical system below. Cutting one string results swing which can lead to either
  - a new equilibrium,
  - or system collapse (after a chain reaction)

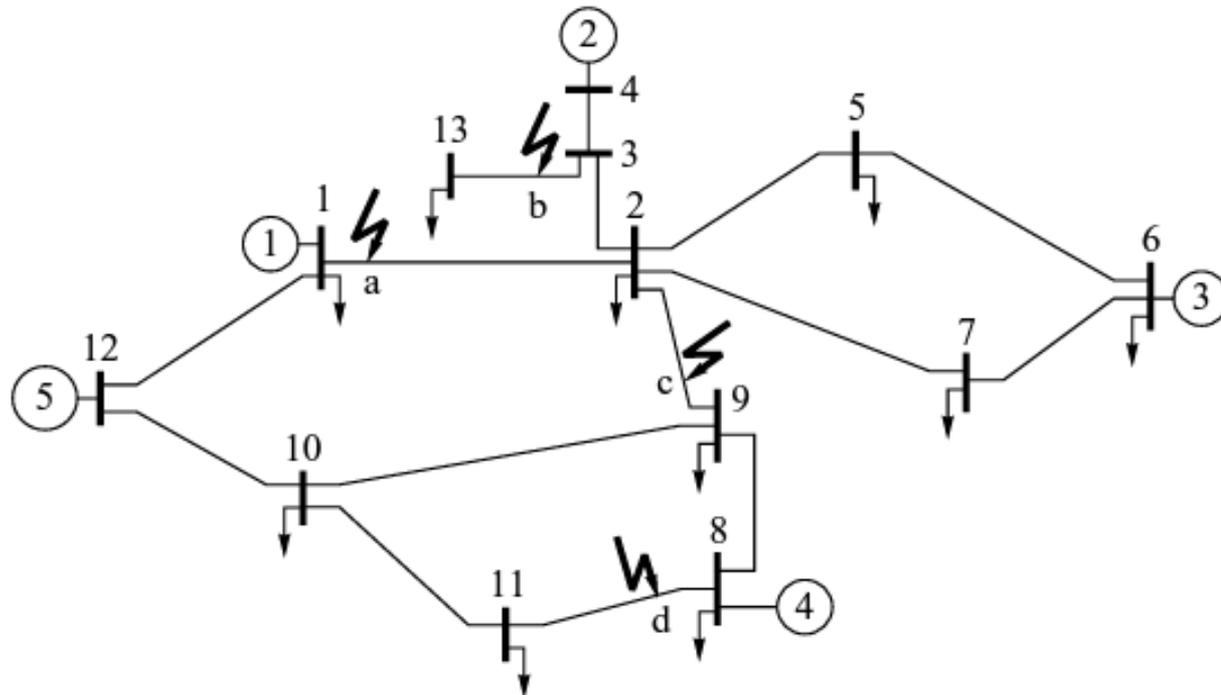


# Swings in multi-machine systems

- In practice, a disturbance may affect the power system stability in one of the following four cases:
  1. The generator (or generators) nearest to the fault may lose synchronism without exhibiting any synchronous swings; other generators affected by the fault undergo a period of synchronous oscillations until they eventually return to synchronous operation.
  2. The generator (or generators) nearest to the fault lose synchronism after exhibiting synchronous oscillations.
  3. The generator (or generators) nearest to the fault are the first to lose synchronism and are then followed by other generators in the system.
  4. The generator (or generators) nearest to the fault exhibit synchronous swings without losing stability but one, or more, of the other generators remote from the fault lose synchronism with the system.

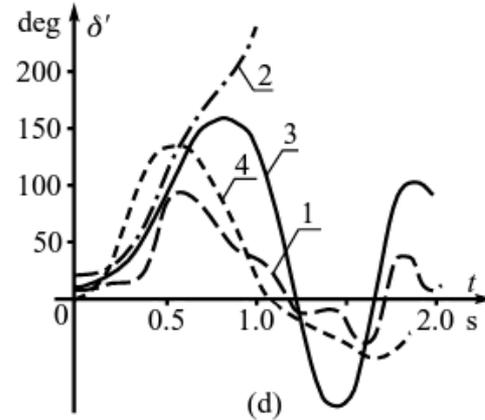
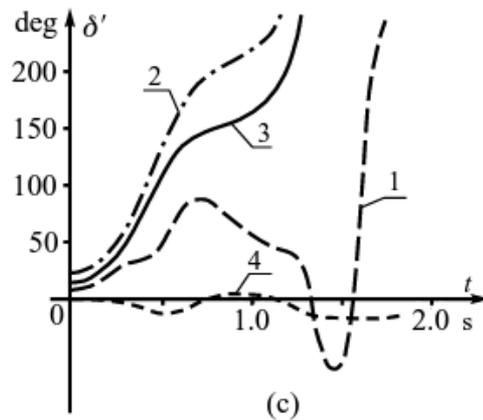
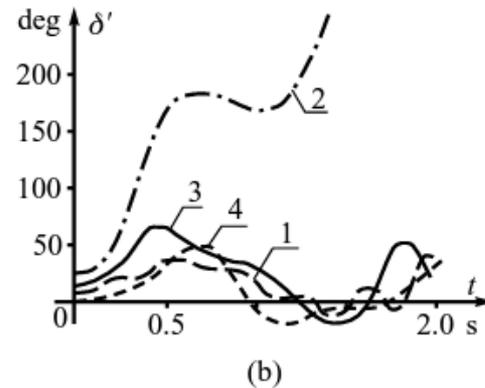
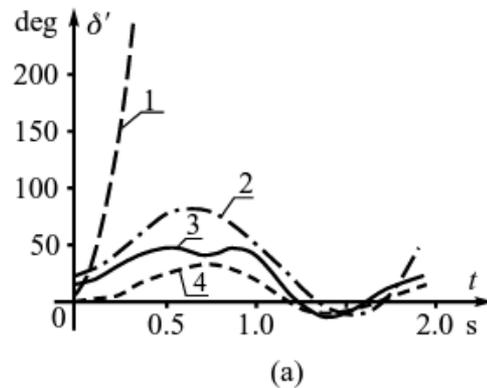
# Swings in multi-machine systems - Example

- Three subsystems connected at node 2.
- The capacity of generator 5 is large – can be considered as an infinite bus bar. Hence the power angles of other generators are measured with respect to this generator.
- Faults located at *a*, *b*, *c*, and *d* are considered without auto-reclosing. Simulation results are shown next.



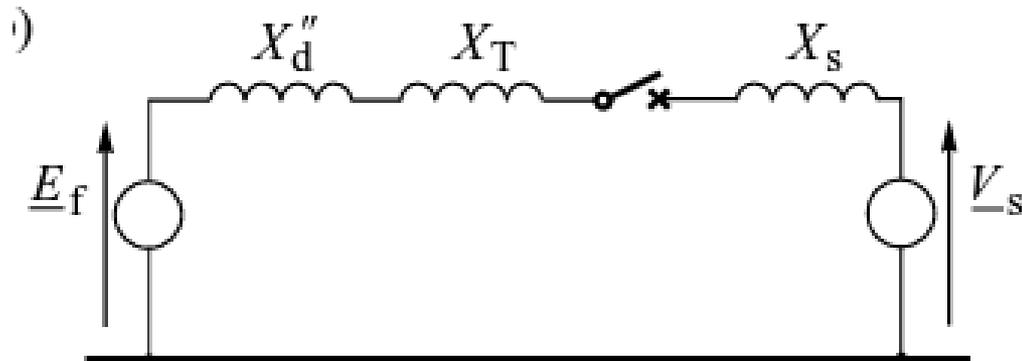
# Swings in multi-machine systems - Example

- Fault a – fig. (a): generator 1 loses synchronism without exhibiting synch. swinging
- Fault b – fig. (b): generator 2 loses synchronism after exhibiting synch. swinging
- Fault c – fig. (c): generators 2 and 3 lose synchronism, followed by generator 1
- Fault d – fig. (d): generator 2 (far from fault) loses synchronism



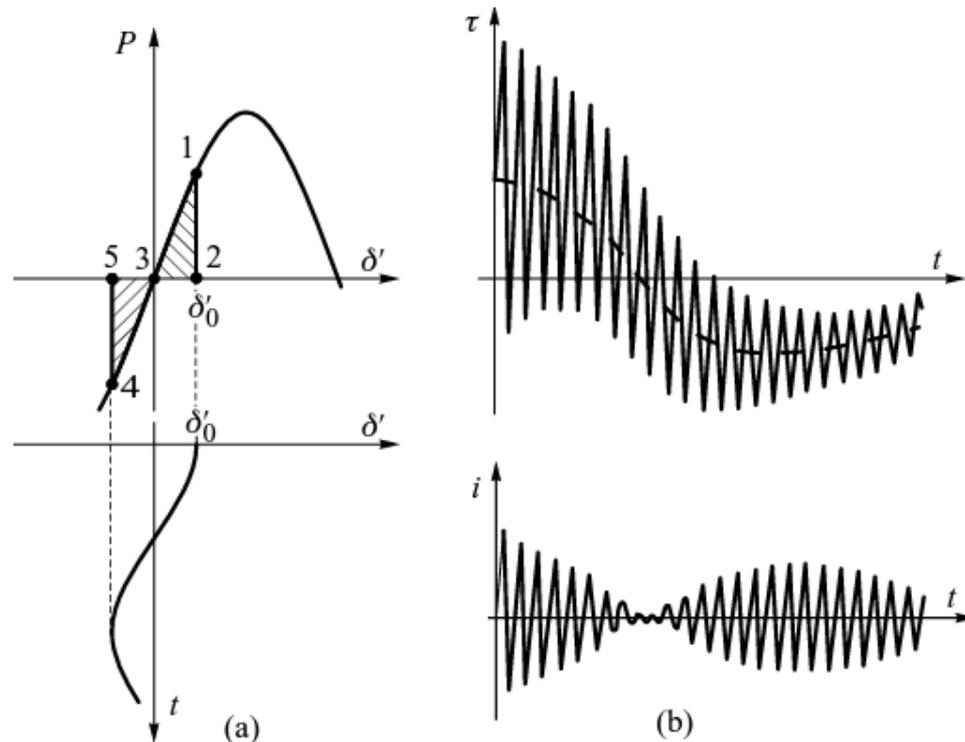
# Synchronization

- This section considers the effects of the electromechanical dynamics following synchronization and conditions for re-synchronization.
- Ideal synchronization occurs when  $\omega = \omega_s$ ,  $\underline{E}_f = \underline{V}_s$  and  $\delta = 0$
- Assume the generator is under no load prior to synchronization, i.e.,  
$$E' = E_f \text{ and } \delta = \delta'$$
- Now consider the case where all conditions are satisfied except that  $E_f$  and  $V_s$  are slightly out of phase:  $\delta'_0 > 0$ ,



# Synchronization

- Initial operating point: 1 - Equilibrium point: 3
- Changes in the  $\delta'$  due to rotor swings produce oscillations in torque and current.
- As energy is dissipated in the windings, the generator shifts from the sub-transient state, to the transient state, and finally to the steady-state where the oscillations vanish.



# Synchronization

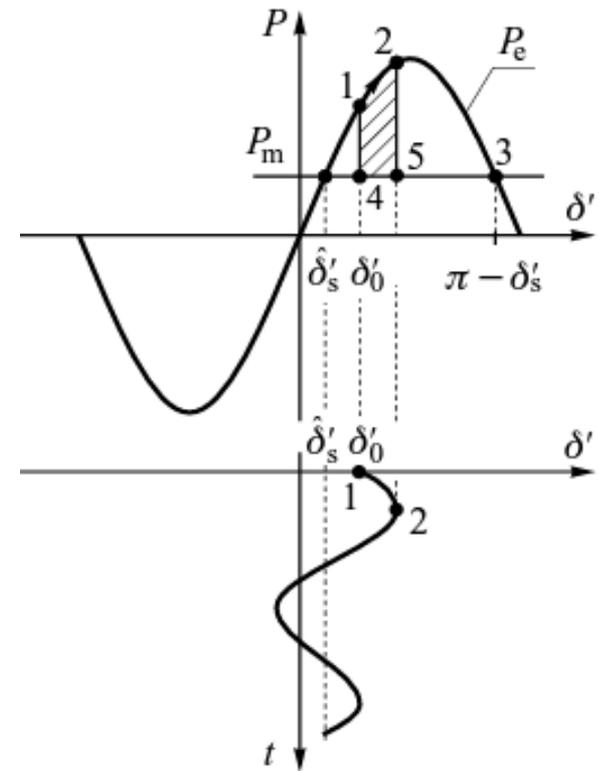
- If  $\delta'_0 \neq 0$  and  $\omega_0 \neq \omega_s$ , then changes in  $\delta'$  can be quite large.
- The angle  $\delta'$  increases until the shaded area 1-2-5-4 equals the excess kinetic energy of the rotor:

$$E_k = \frac{1}{2} M \Delta \omega_0^2,$$

- The maximum deceleration work that can be done is proportional to area 1-2-3-4. hence, the necessary condition for synchronization is  $E_k < W_{\max}$  where

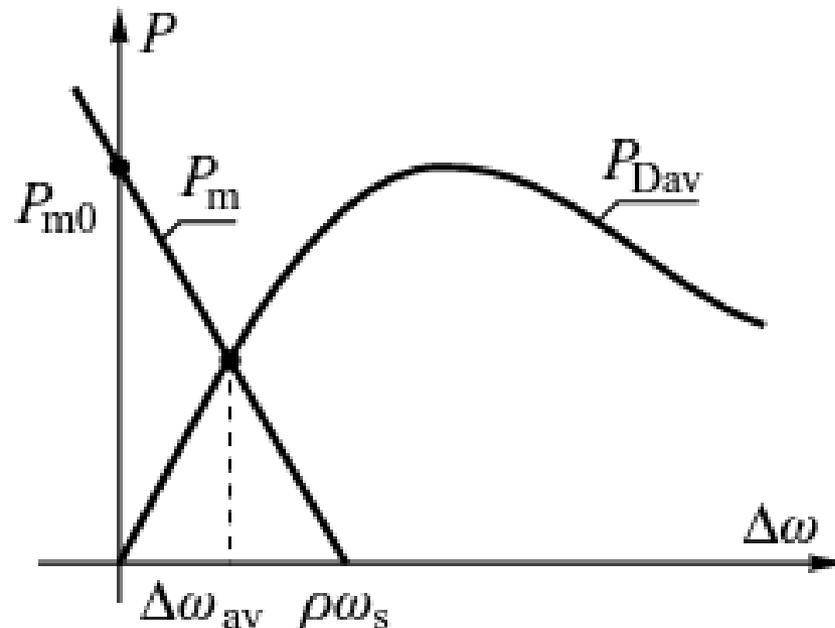
$$W_{\max} = \int_{\delta'_0}^{\pi - \hat{\delta}'_s} \left[ \frac{E' V_s}{x'_d} \sin \delta' - P_m \right] d\delta' = \frac{E' V_s}{x'_d} (\cos \hat{\delta}'_s + \cos \delta'_0) - P_m [(\pi - \hat{\delta}'_s) - \delta'_0].$$

$$\text{i.e., } \Delta \omega_0^2 < \frac{2}{M} \left[ \frac{E' V_s}{x'_d} (\cos \hat{\delta}'_s + \cos \delta'_0) - P_m (\pi - \hat{\delta}'_s - \delta'_0) \right]$$



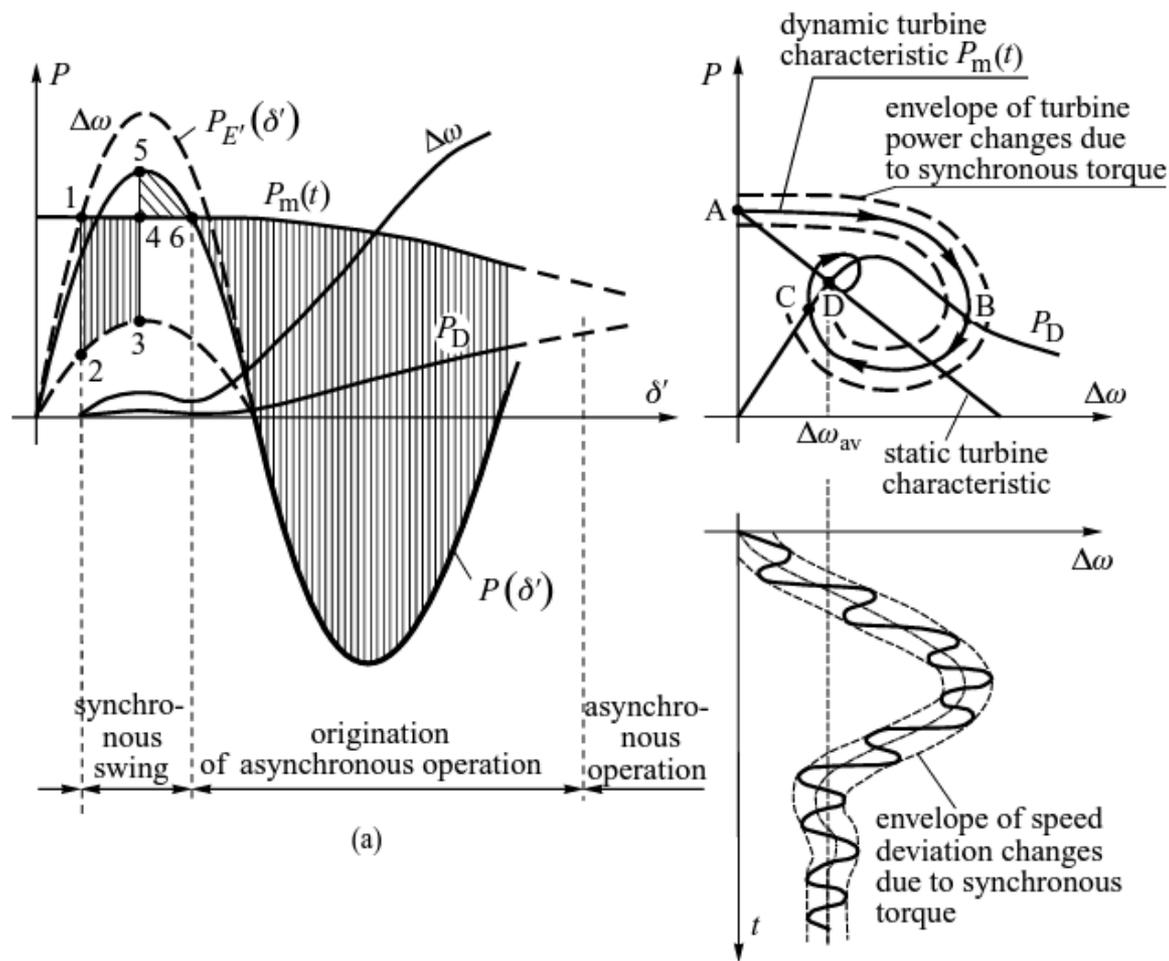
# Asynchronous operation and re-synchronization

- The avg. synch. power over each asynchronous rotation equal zero.
- Hence, under asynchronous operation, the turbine-governor characteristics and the asynchronous damping power determine the generator operating point.
- Refer to the asynchronous damping power (Chap. 5), and to the static turbine power characteristic (Chap. 2). But the dynamic turbine power is different from the static one to the long time constant of the turbine-governor system.



# What happens when a generator loses synchronism?

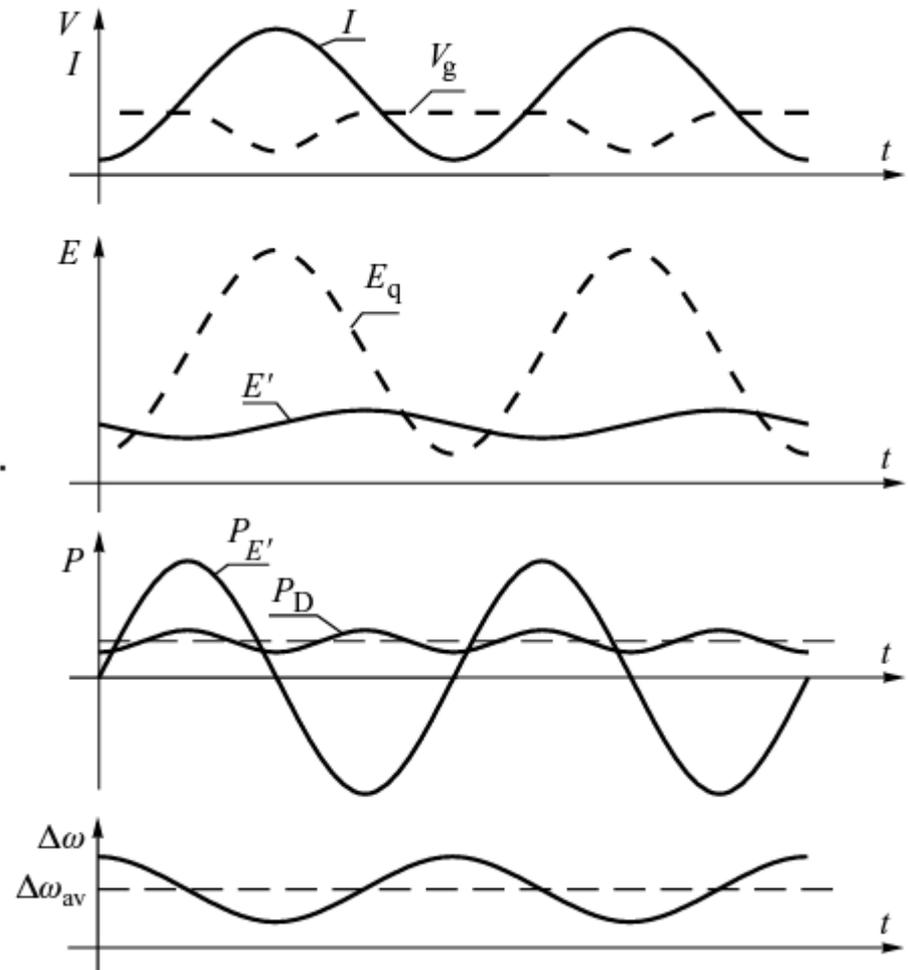
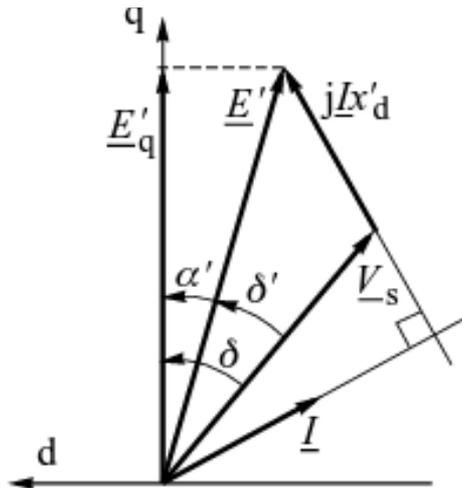
- Synchronism is lost when the rotor passes point 6.
- The system will settle at point D (intersection of static turbine power curve and generator asynchronous power curve), not at points B or C due to turbine time delay.



# Asynchronous Operation

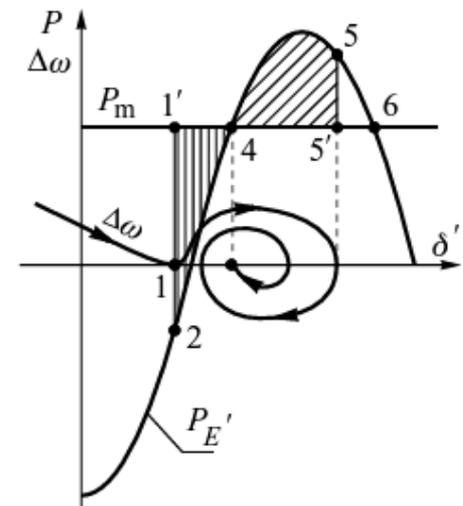
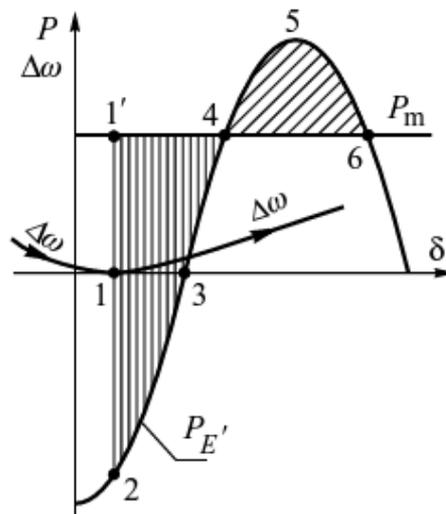
- The generator current peaks when  $\delta' = (2n+1)\pi$ .
- The generator terminal voltage will vary with  $\delta'$  as seen before.
- Armature reaction will induce large variations in field current and hence in  $E_q$ , but small deviations in  $E'$ .

$$\Delta V^2 = (Ix'_d)^2 = (E')^2 + (V_s)^2 - 2E'V_s \cos \delta'.$$



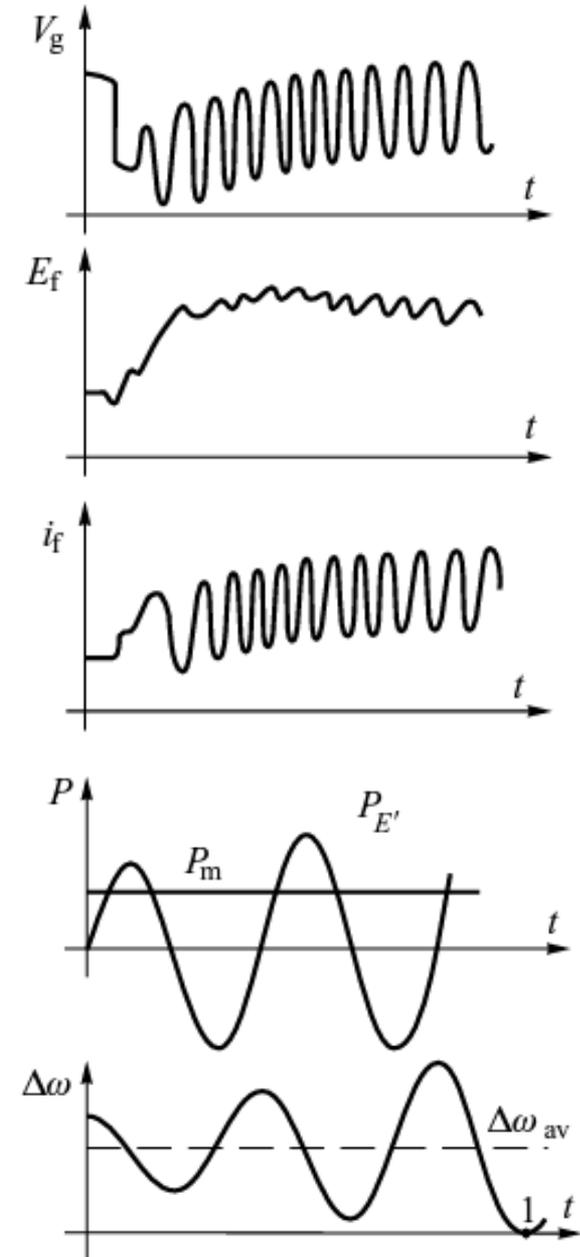
# Possibility of re-synchronization

- Re-synchronization is possible under
  - Small value of speed deviation  $\Delta\omega_{\text{avg}}$
  - Large variations in  $\Delta\omega$  (i.e.,  $\Delta\omega$  approaches zero at some points)
  - The speed deviation approaches zero when the synchronous power is sufficiently small.



# Effect of AVR

- Changes in the generator terminal voltage  $V_g$  are too fast for a typical AVR to follow.
  - The AVR increases  $E_f$  to the ceiling
  - this increases the amplitude of the electrical power  $P_{E'}$
  - this will in turn increase the speed deviations, thus more chance for re-synchronization.
- Re-synchronization can also be achieved by adding supplementary control loops (i.e., fast valving) to be discussed in Chap. 10.



# Sections skipped in Chap. 6

- 6.3 Liapunov's direct method of stability
- 6.6 Out-of-step protection
- 6.7 Torsional oscillations in the drive shaft