Rotor Angle Transient

Samiha Mourad
Santa Clara University

Santa Clara University

- Private Jesuit University
- First University in California
- Total 7000 students
- School of Engineering
  - 600 undergraduates
  - 600 graduates Mostly master degree by professional working in Silicon Valley and 1 to 2 PhD per year
- Difficult to introduce Electric Energy on undergraduate
- However, won the 3rd place in the 2007 Solar Decathlon
- Concentrating on the graduate level only

Program a la U. of Minnesota

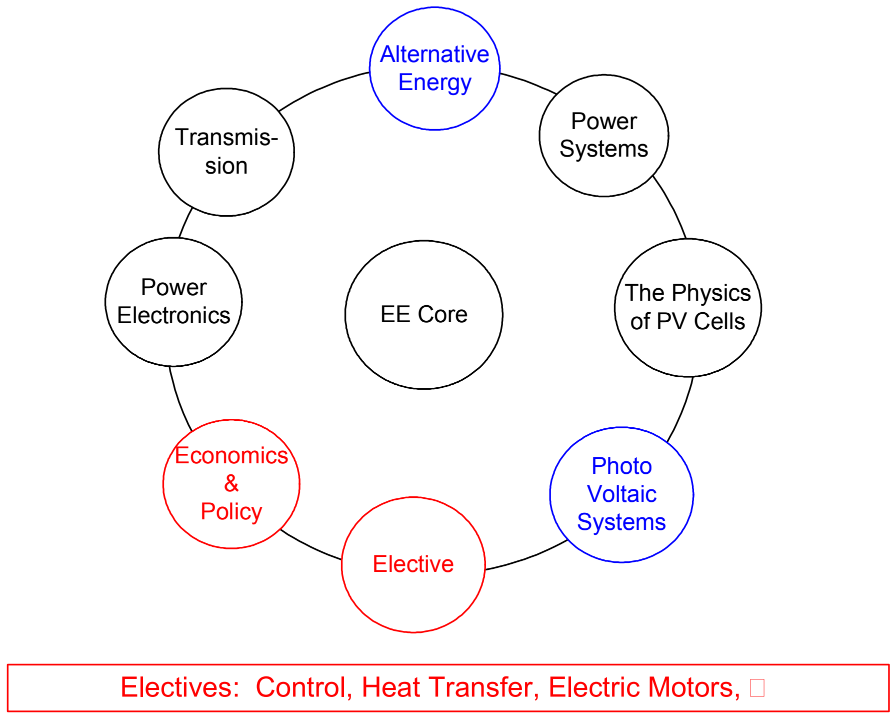


Figure 2. Electric Energy Concentration

Application of Synchronous Generators

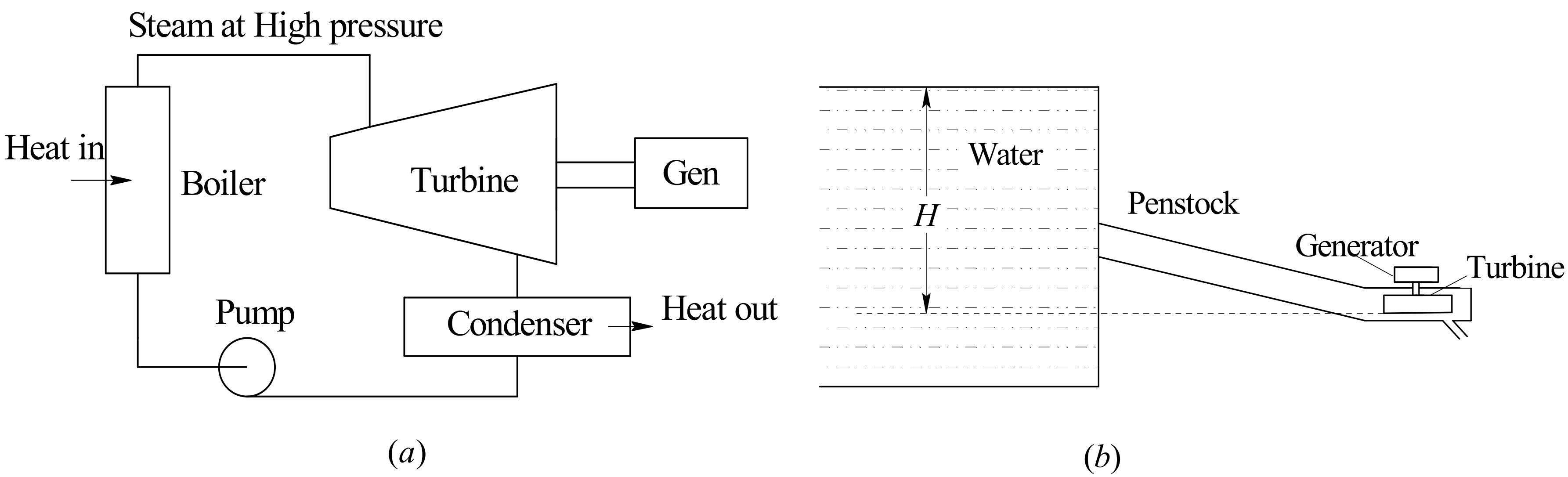


Fig. 9-1 Synchronous generators driven by (a) steam turbines, and (b) hydraulic turbines.

a) 1800 rpm at 60Hz b) slower few rpm and many poles

The motor consists of rotor and stator separated by a small air gap. The stator is made of high SiFe material laminated to reduce eddies

Synchronous Generator Rotor Field

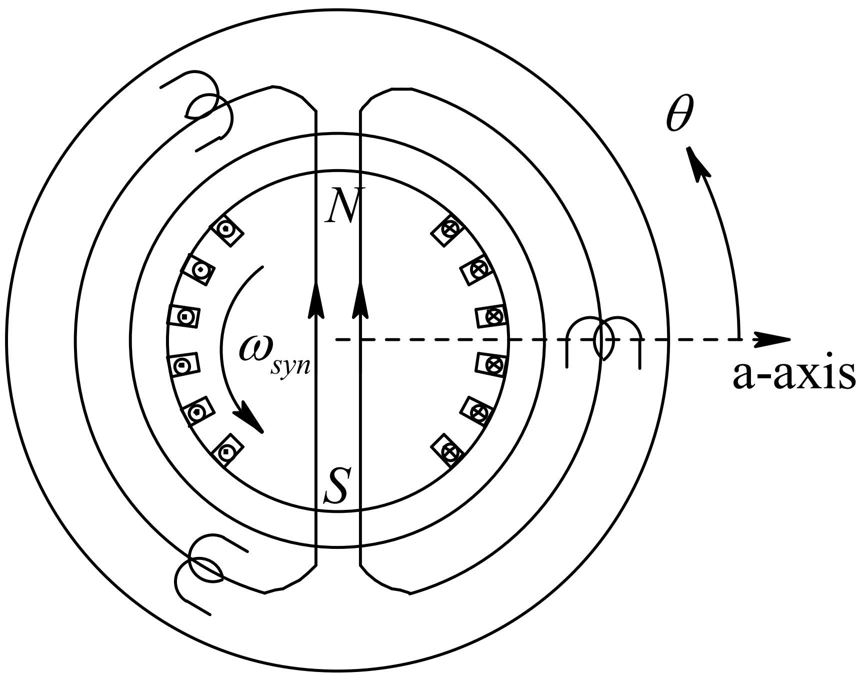


Fig. 9-6 Field winding on the rotor that is supplied by a dc current I_f .

A synchronous machine is a rotating body, the laws of mechanics of rotating bodies are applicable to it. Two or more poles

Voltage Induced

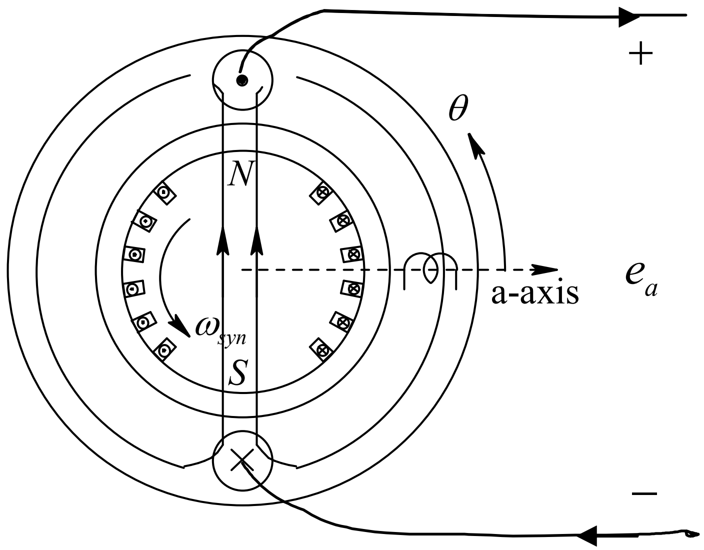


Fig. 9-7 Current direction and voltage polarities; the rotor position shown induces maximum e_a .

The induced emfs superimposed to yield the resultant field

Induced Stator Voltage due to Rotor Field

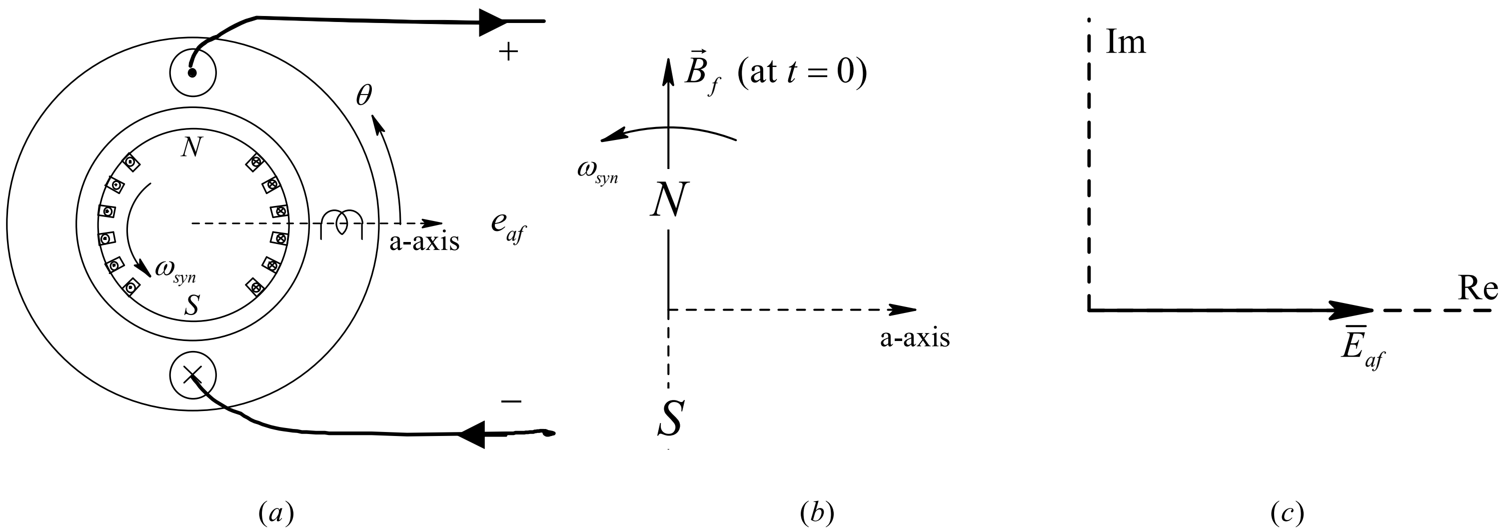


Fig. 9-8 Induced emf e_{af} due to rotating rotor field with the rotor.

Voltage induced in the stator circuit E_{af} =-jkwB$_f$

Armature Reaction Due to Three Stator Currents

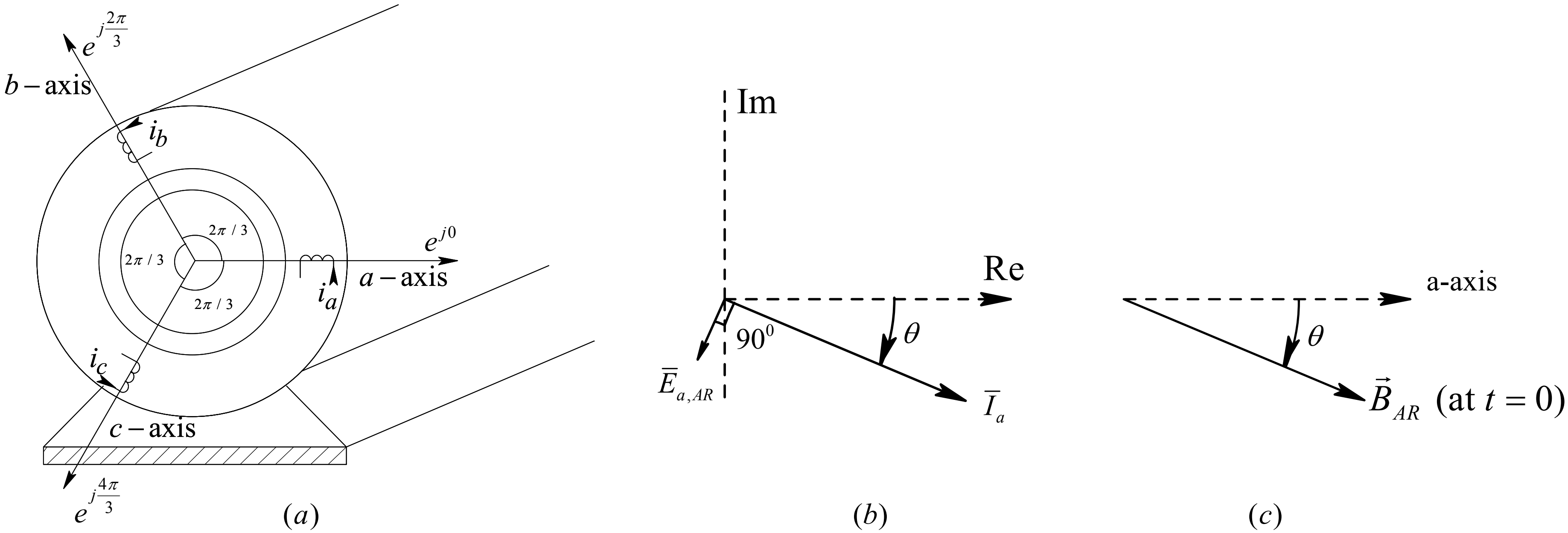


Fig. 9-9 Armature reaction due to phase currents.

A current produces a magnetic field $B_{ar} = 3/2KI_a$

Superposition of the two Induced Voltages and Per-Phase Representation

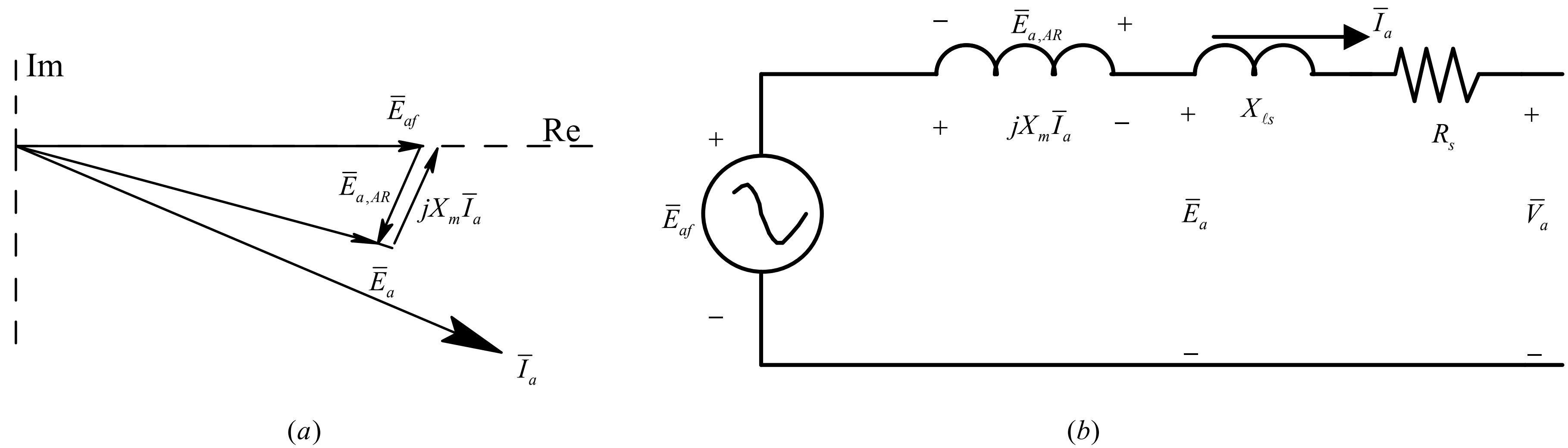


Fig. 9-10 Phasor diagram and per-phase equivalent circuit.

Also, B_f => E_{af}=>B_{AR} => $E_{a,AR}$ =-kwB_{AR}

Power Out as a function of rotor Angle

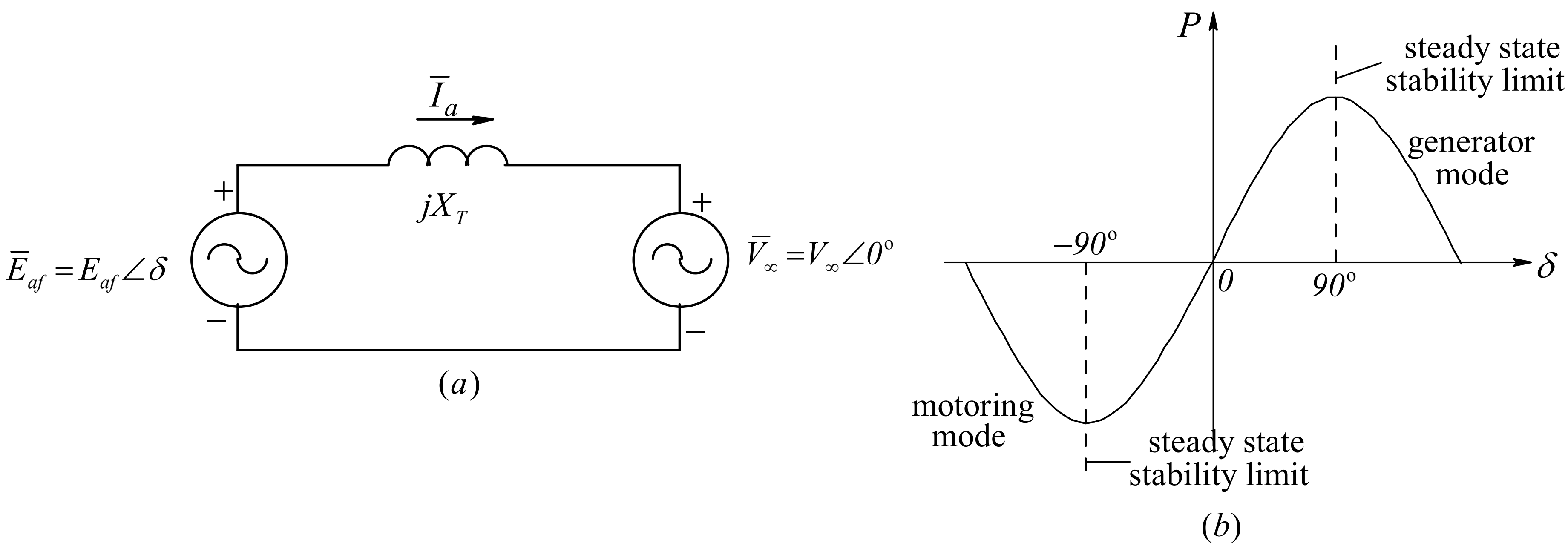
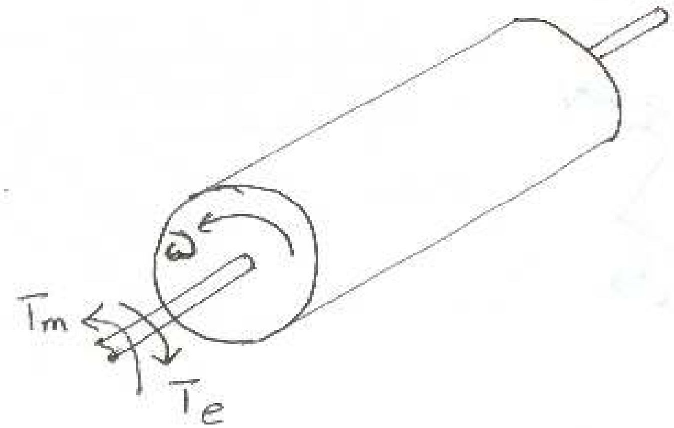
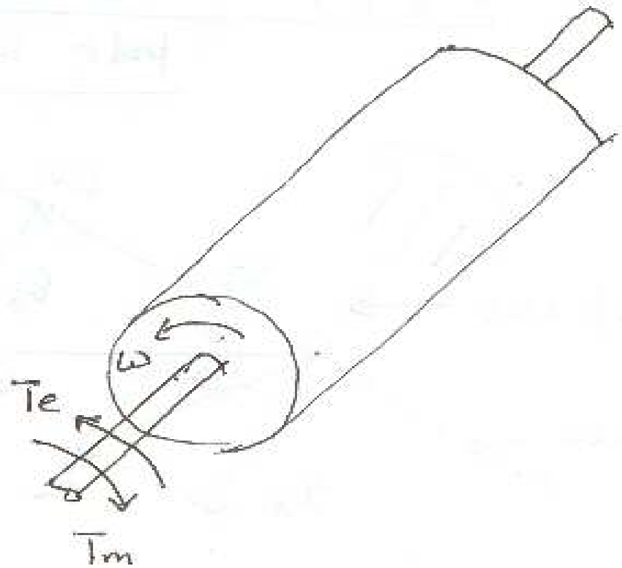


Fig. 9-11 Power output and synchronism.

The emf in the stator creates a toque to oppose the torque of the Turbine



(a) Generator



(b) Motor

Steady State Stability Limit

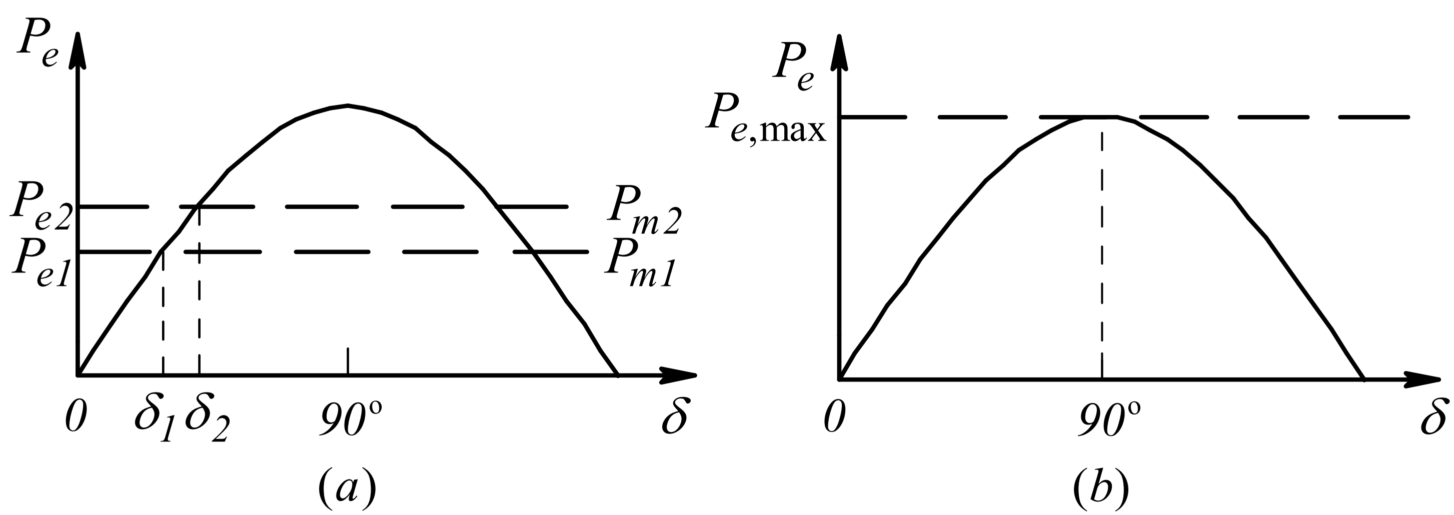


Fig. 9-12 Steady state stability limit.

Assume no losses at δ_1 for $P_{m1} = P_{e1}$ To supply more power, more steam is added, the rotor speeds up at δ causing $P_{m2} > P_{m1}$ results in P_{e2} at δ_2

Reactive Power Control by Field Excitation

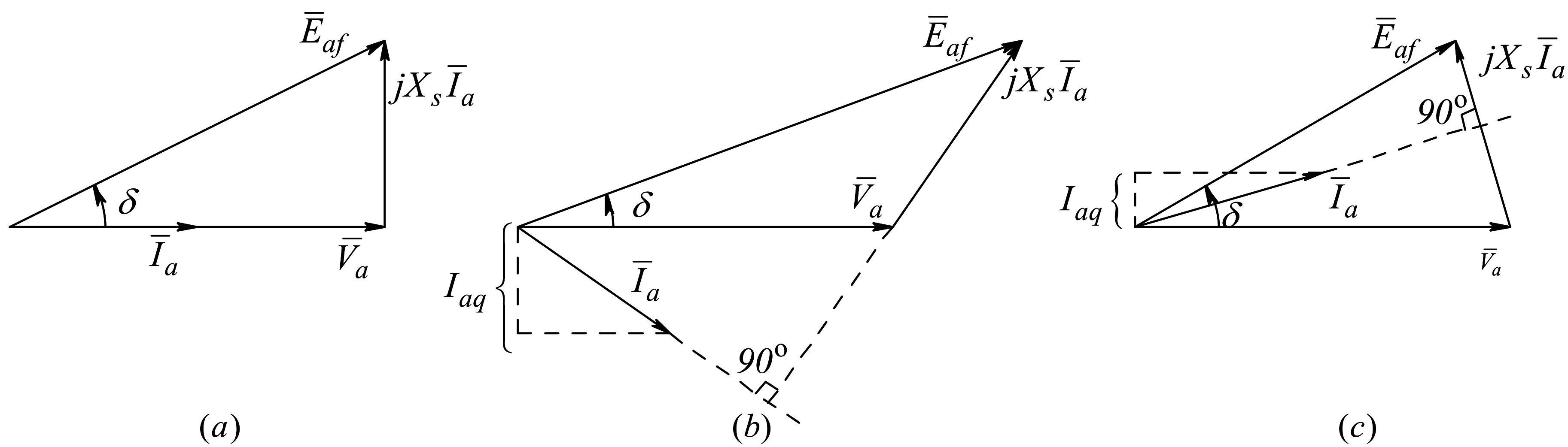


Fig. 9-13 Excitation control to supply reactive power.

Automatic Voltage Regulation (AVR)

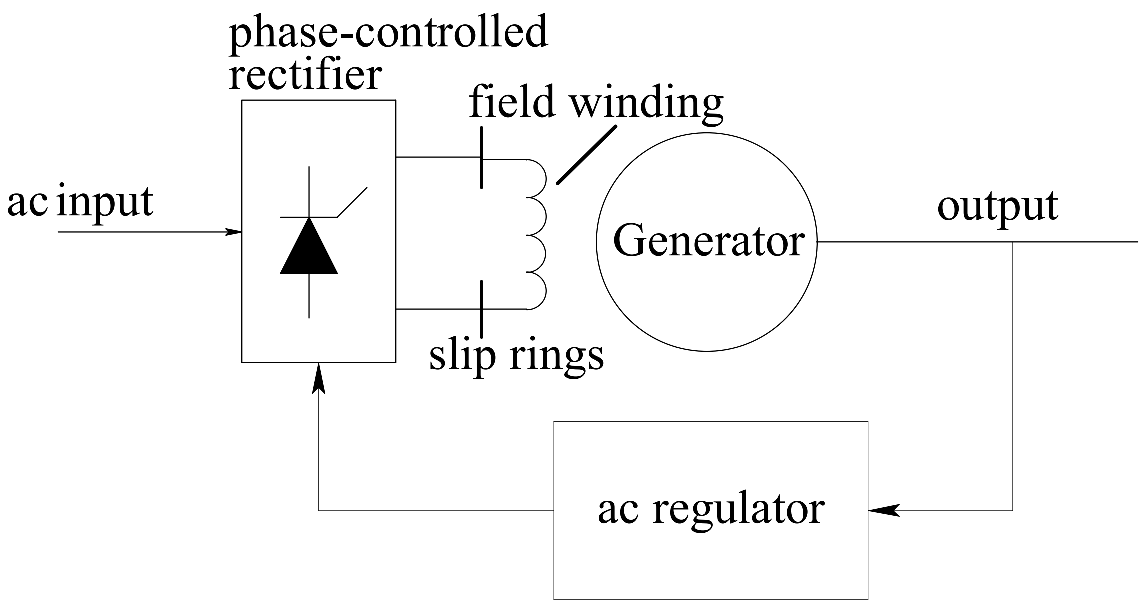


Fig. 9-15 Field exciter for automatic voltage regulation (AVR).

Representation for Steady State, Transient Stability and Fault Analysis

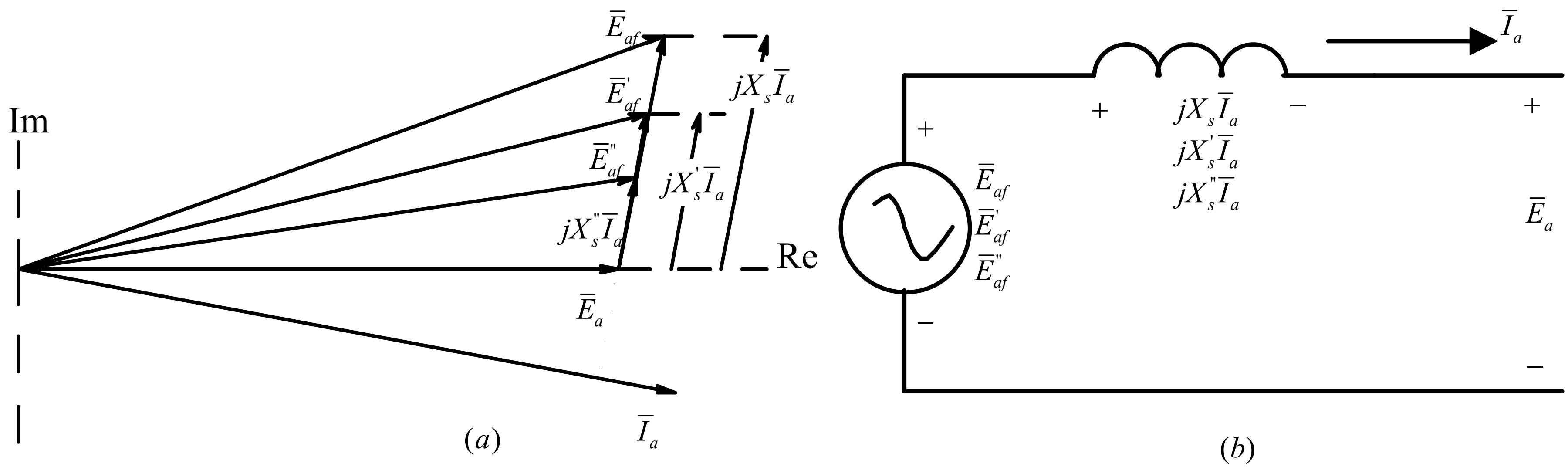


Fig. 9-18 Synchronous generator modeling for transient and sub-transient conditions.

One-Machine Infinite-Bus System

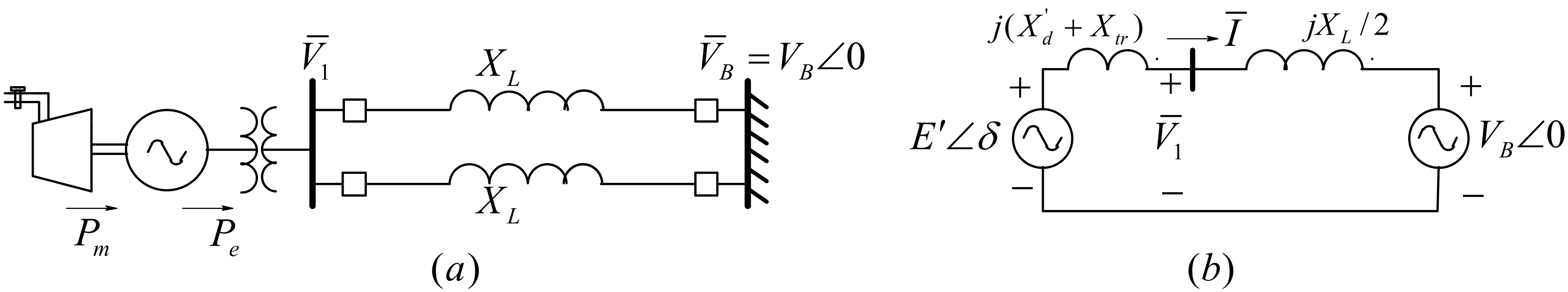


Fig. 11-1 Simple one-generator system connected to an infinite bus.

Representation of the system by a voltage source of constant amplitude at the back of the transient reactance $X'_d + X_{tr}$ is the leakage of the transformer. Ignoring all losses, $P_e = (E'V_b/X_{T1})\sin\delta$,

Power-Angle Characteristic in One-Machine Infinite-Bus System

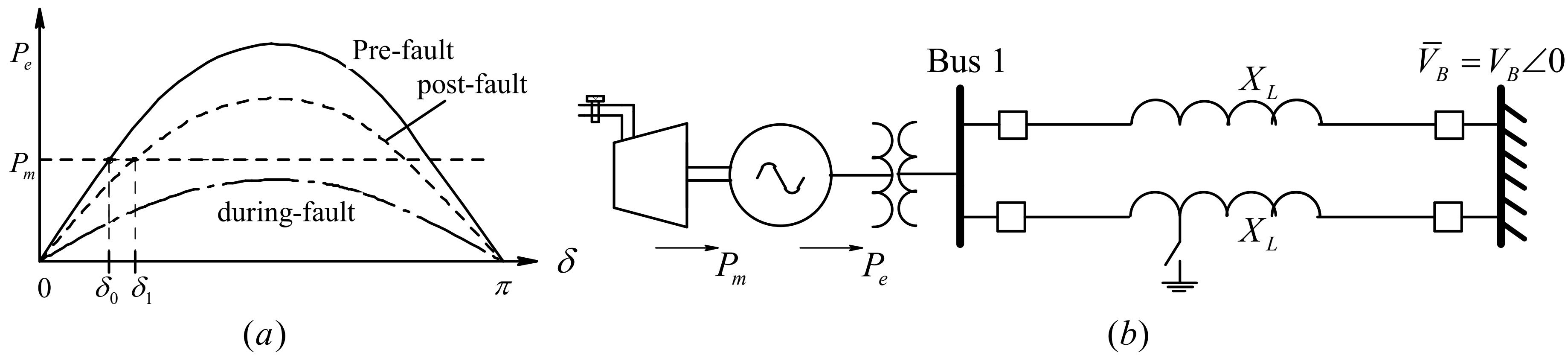


Fig. 11-2 Power-angle characteristics.

In steady state $P_e = P_m$ at δ_0 and after clearing the fault, the new steady state is at δ_1

Power-Angle Characteristic in One-Machine Infinite-Bus System

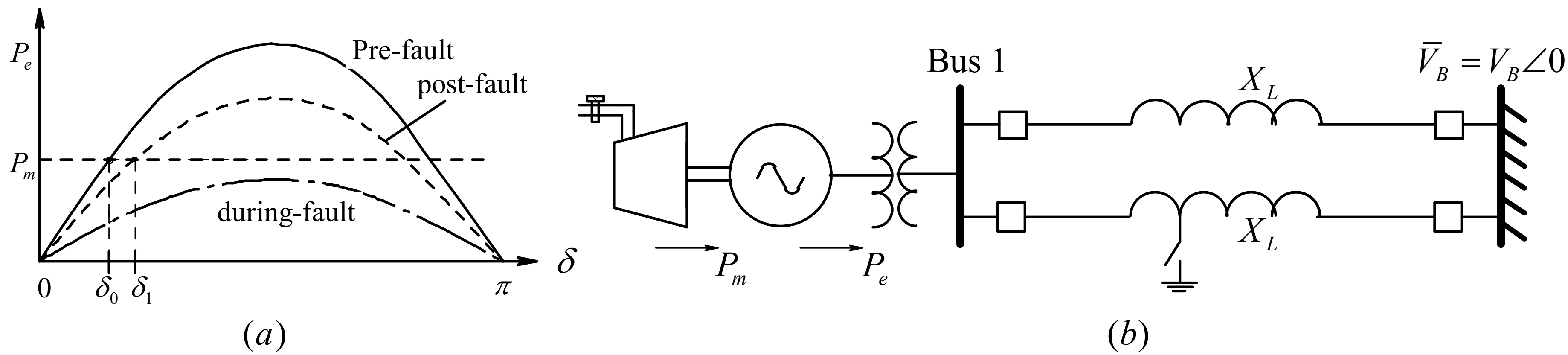


Fig. 11-2 Power-angle characteristics.

During and immediately after the fault, state P_e (T_e) is not equal P_m (T_m)
The rotor speed w will deviate and the corresponding angle is δ_m given by:
J_m ($d^2 \delta_m/d_t^2$) = $T_m - T_e$ and multiplying by w, we get $w_m J_m$ ($d^2 \delta_m/d_t^2$) = $P_m - P_e$

Power-Angle Characteristics

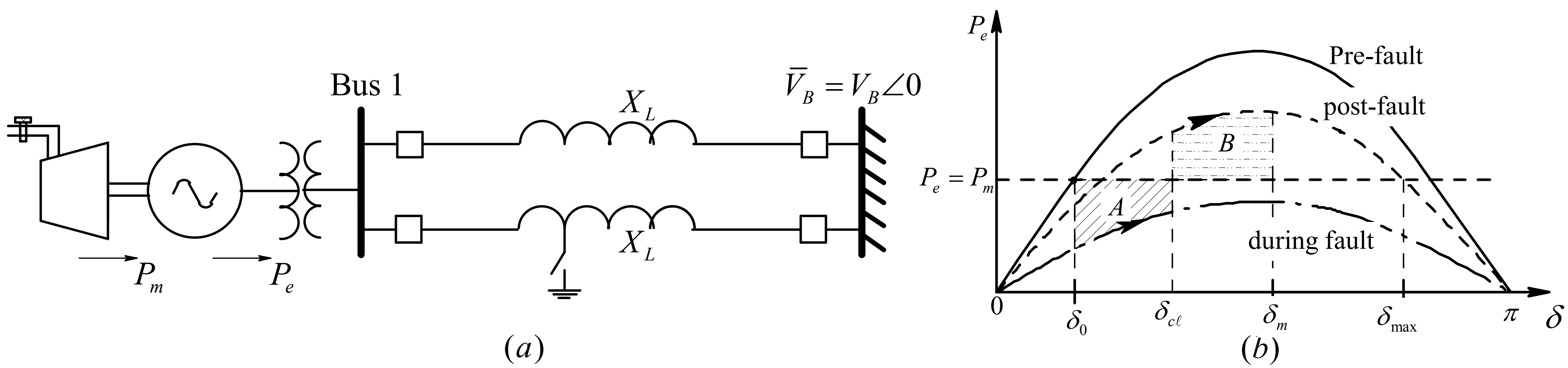


Fig. 11-4 Fault on one of the transmission lines.

$$S_{rated,gen}$$

$$H_{gen} = \frac{0.5 J_m \omega_{syn,m}^2}{S_{rated,gen}}$$

H=3-11 for turbo alternator
H = 1-2 for hydro gen

$$S_{rated-gen}$$

Rotor Angle

Expressing Jm in term of H we get:

$$\frac{2Hd^2\delta_m}{\omega_{sys,m}dt^2} = P_{m,pu} - P_{e,pu} \qquad 11\text{-}9$$

This the swing equation that describes how the angle d oscillates due
To unbalance between mech and elect powers of the generator.

Integrate this equation assuming small time increment delta t, during which
The difference in powers is constant, we get:

$$\delta(t) = \delta(t-\Delta t) + \omega(t-\Delta t)\Delta t$$

Rotor-Angle Swing Following a Fault and a Line Taken Out

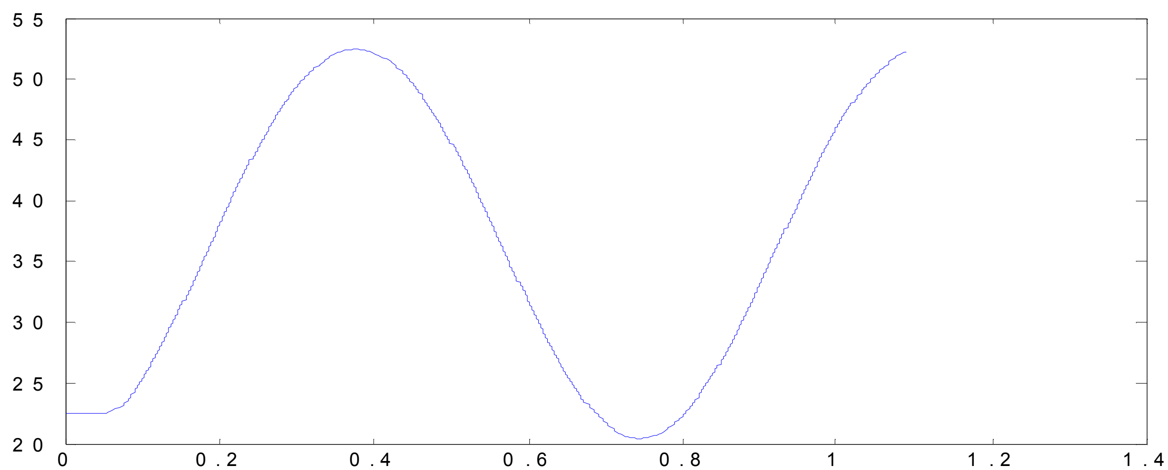


Fig. 11-3 Rotor-angle swing in Example 11-1.

Rotor Oscillations After the Fault is Cleared

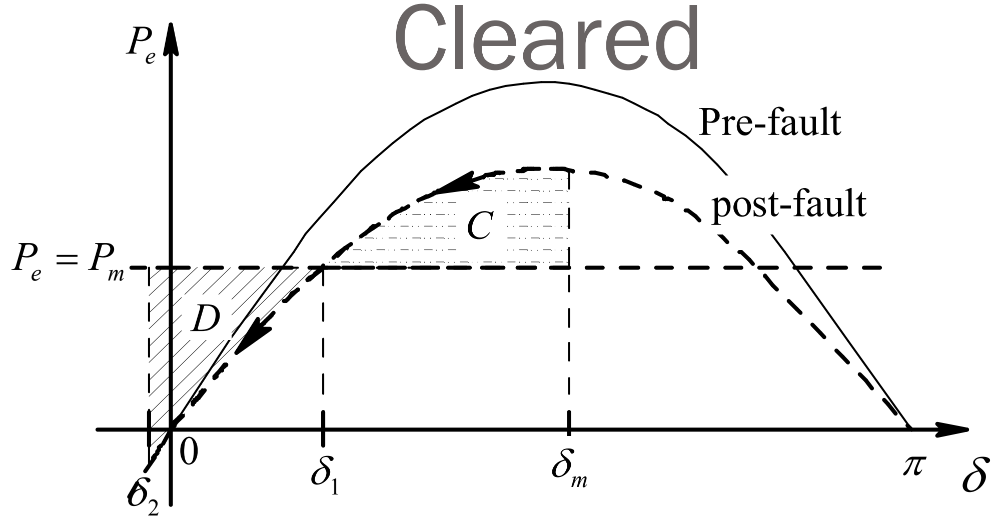


Fig. 11-5 Rotor oscillations after the fault is cleared.

Stating from eq. 11-9 we can after double integration obtain:

$$\int\int_{\partial 0}^{\partial cl}(P_{m,pu}-P_{e,fault,pu})d\partial-\int_{\partial cl}^{\partial m}(P_{e,postfault}-P_{m,pu})d\partial$$

Critical Clearing Angle using Equal-Area Criterion

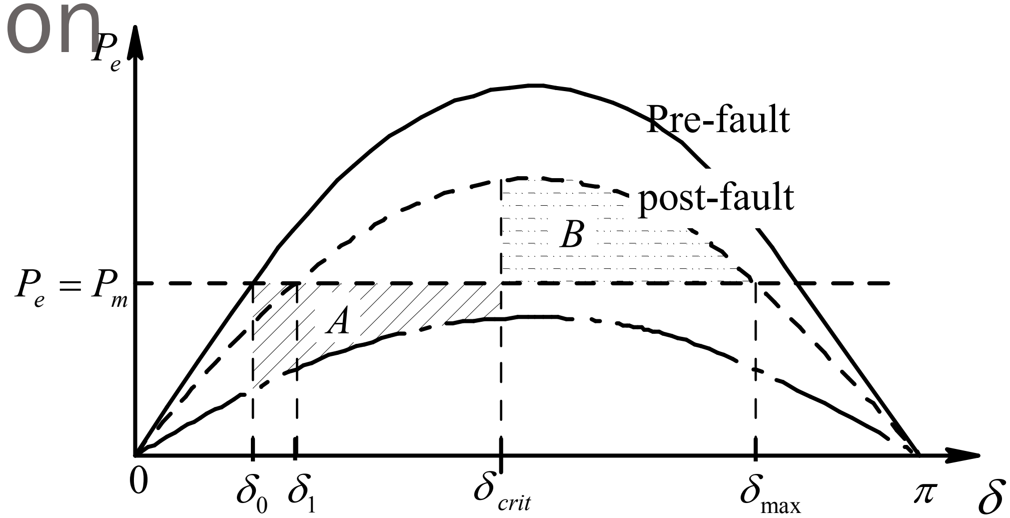


Fig. 11-6 Critical clearing angle.

$$\int\int_{\partial 0}^{\partial cl}(P_{m,pu}-P_{e,fault,pu})d\partial-\int_{\partial cl}^{\partial m}(P_{e,postfault}-P_{m,pu})d\partial$$

Example using Equal-Area Criterion

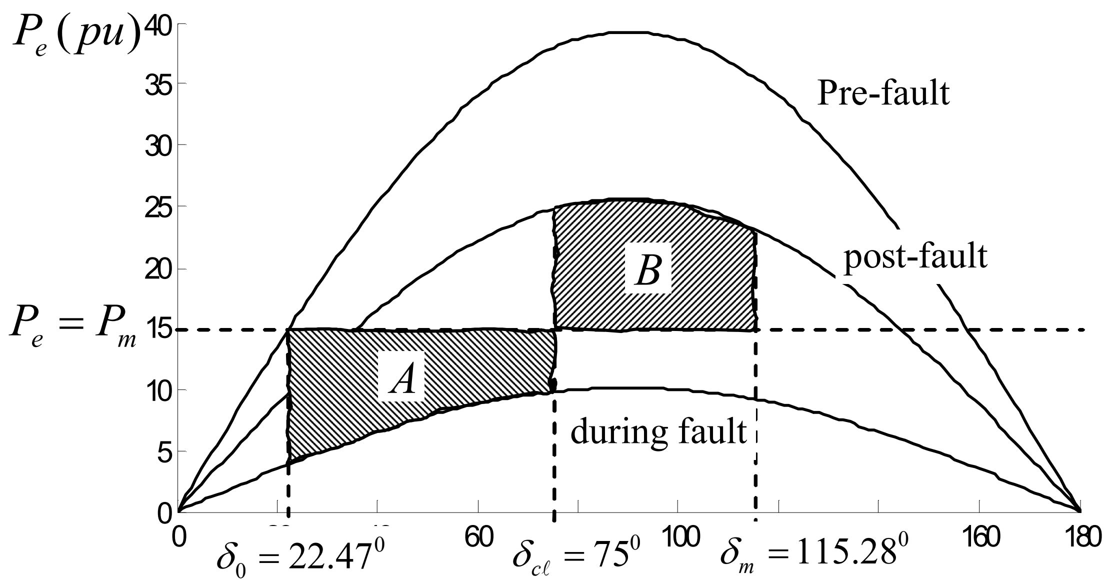


Fig. 11-7 Power angle curves and equal-area criterion in Example 11-2.

$$\int \int_{\partial 0}^{\partial cl} (P_{m,pu} - P_{e,fault,pu})\, d\partial - \int_{\partial cl}^{\partial m} (P_{e,postfault} - P_{m,pu})\, d\partial$$

Rotor Angle Swings in the Example Power System Following a Fault

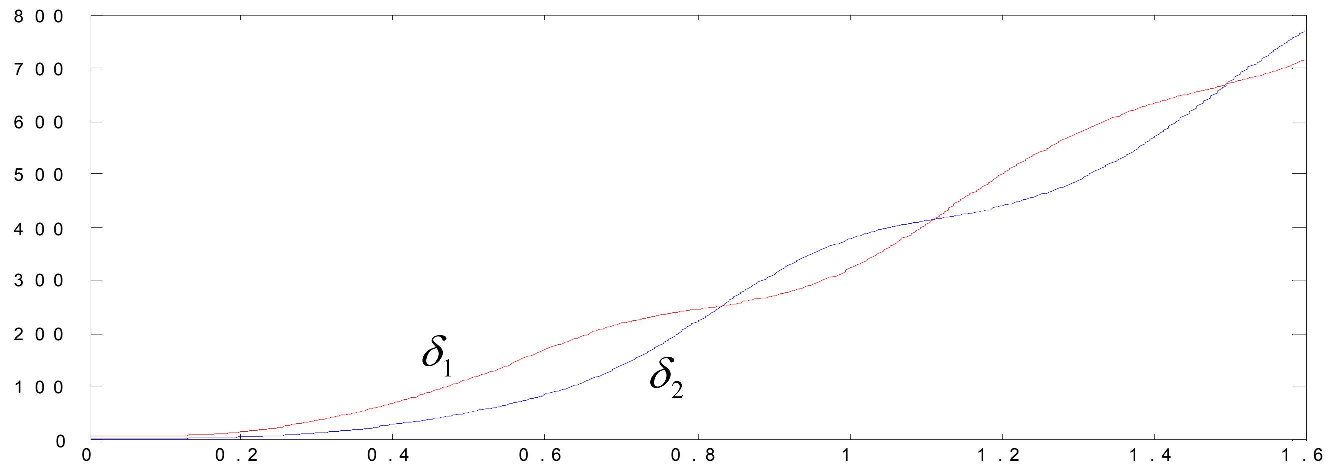


Fig. 11-10 Rotor-angle swings of δ_1 and δ_2 in Example 11-3.