Synchronous Machines

Pinjia Zhang

Chapter 5 Synchronous Generators

- Synchronous Generator Construction
- The Speed of Rotation
- The Internal Generated Voltage
- The Equivalent Circuit
- The Phasor Diagram
- Measuring the Model Parameters
- The Synchronous Generator Operating Alone
- Power and Torque

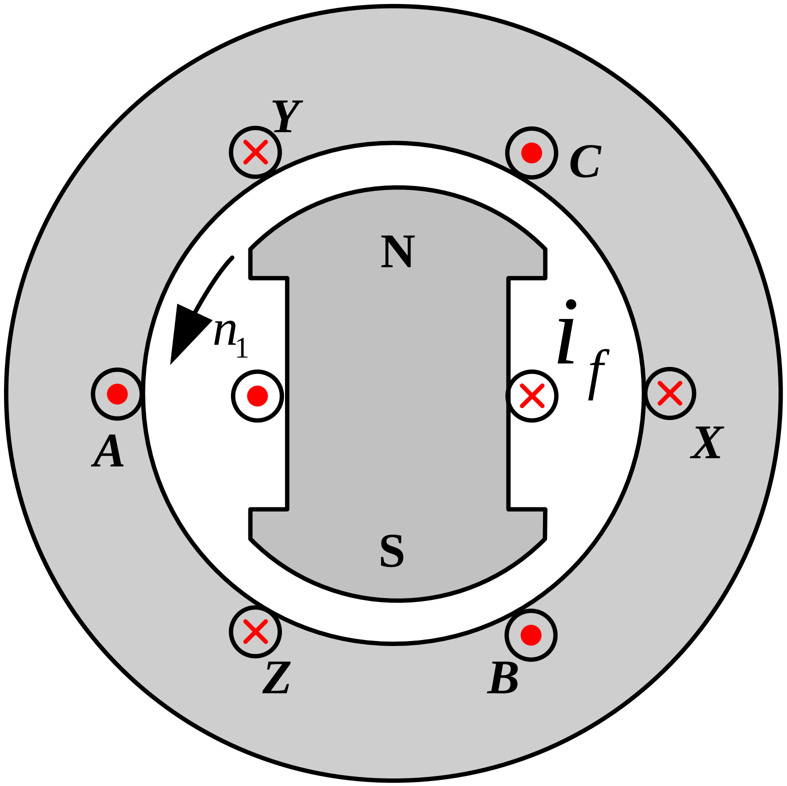
Chapter 5 Synchronous Generators

- Parallel Operation of the Synchronous Generator
- Synchronous motor operation

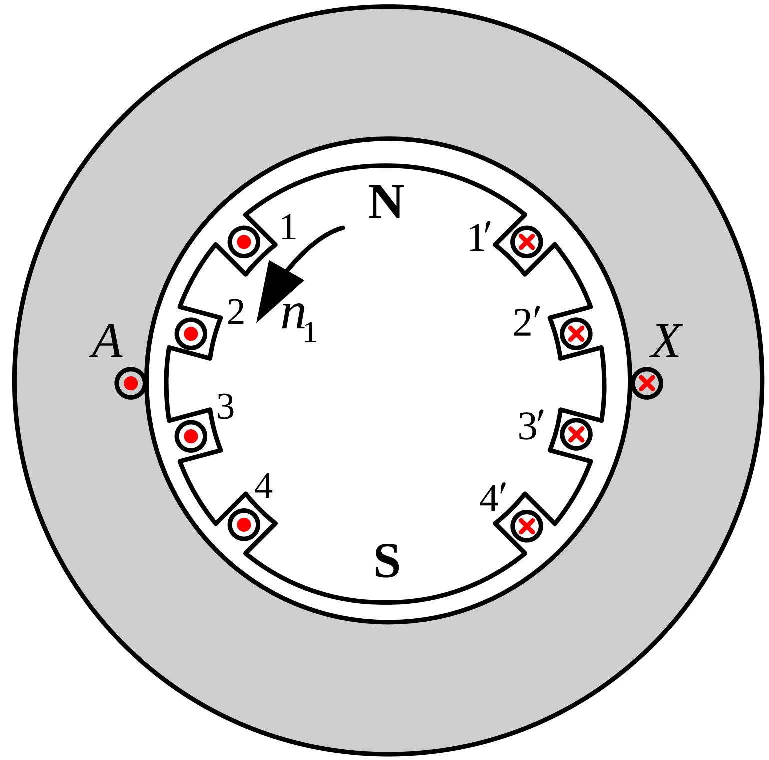
The Synchronous Generator Construction

- ***Field windings – at rotor***
  - A dc current is applied to the rotor winding to generate the magnetic field.
- ***Armature windings – at stator***
  - Three phase currents are generated out of these windings

Synchronous generator types



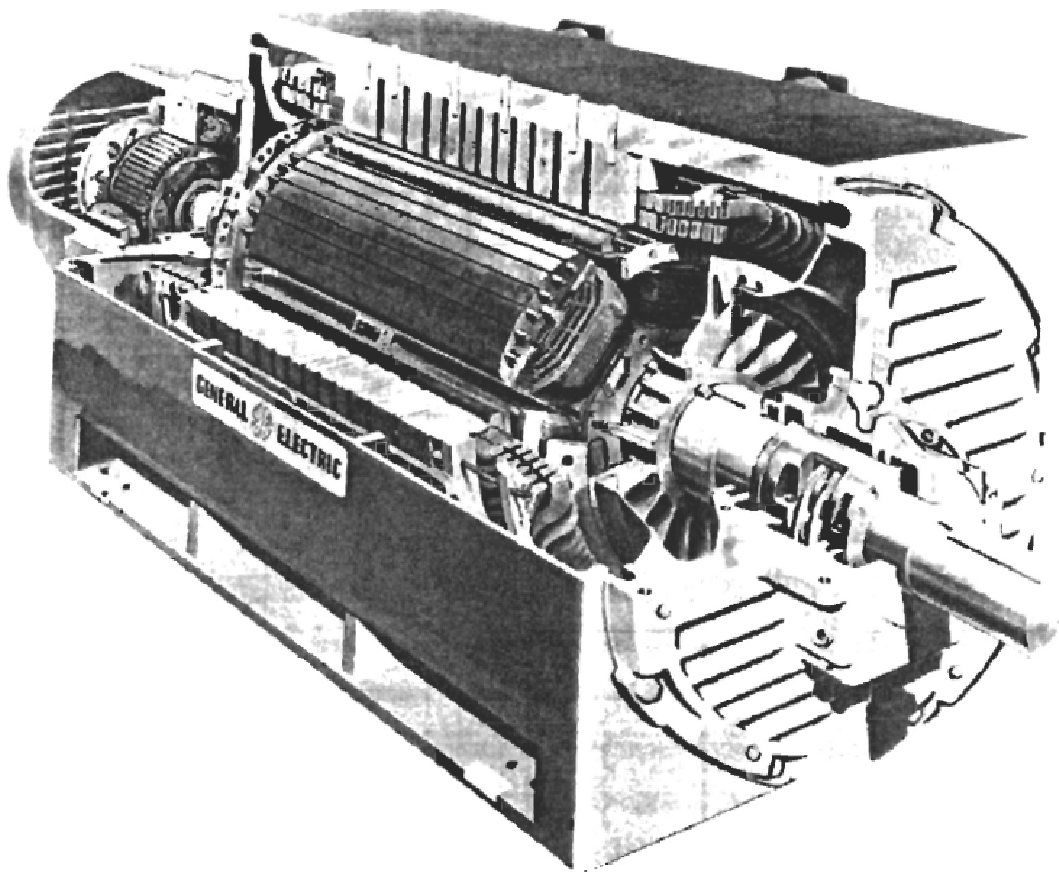
salient-pole generator



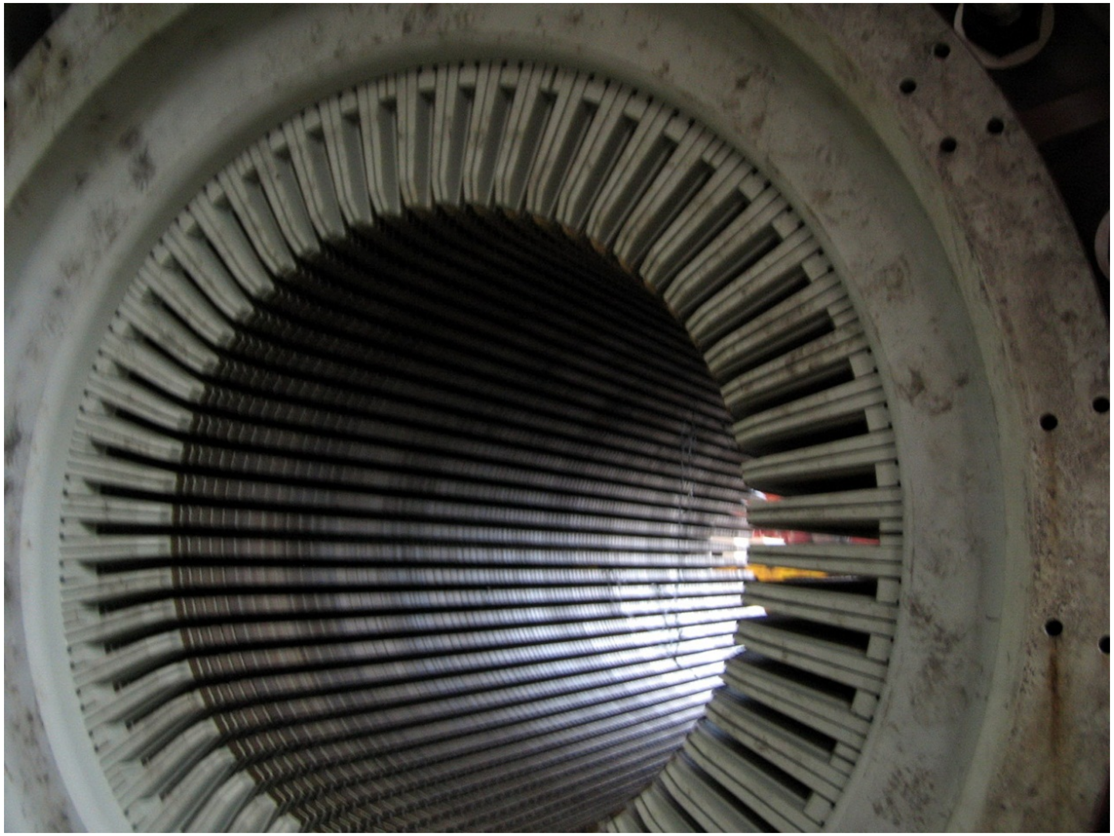
non-salient generator

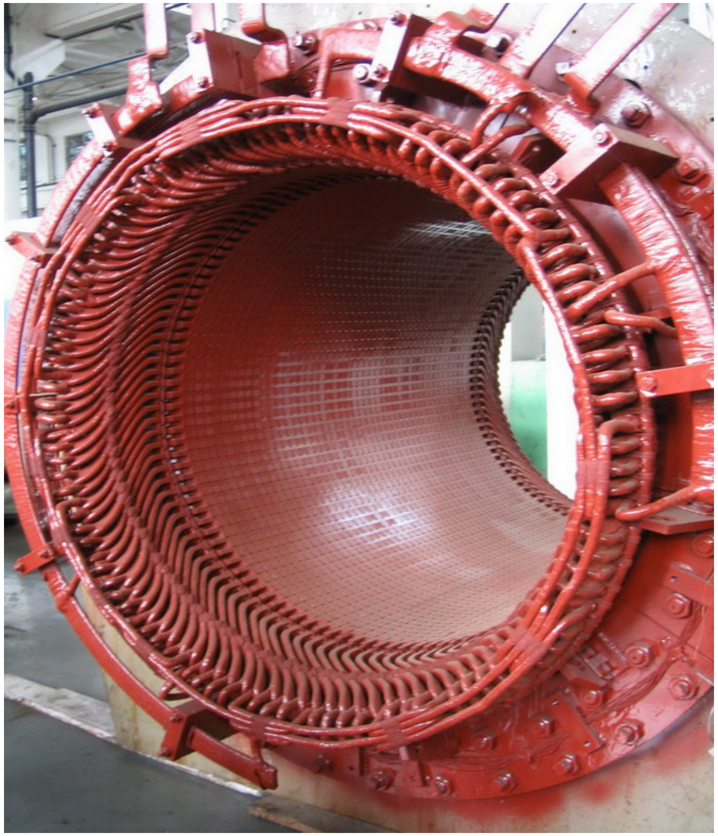
清華大学

synchronous machine cutaway diagram

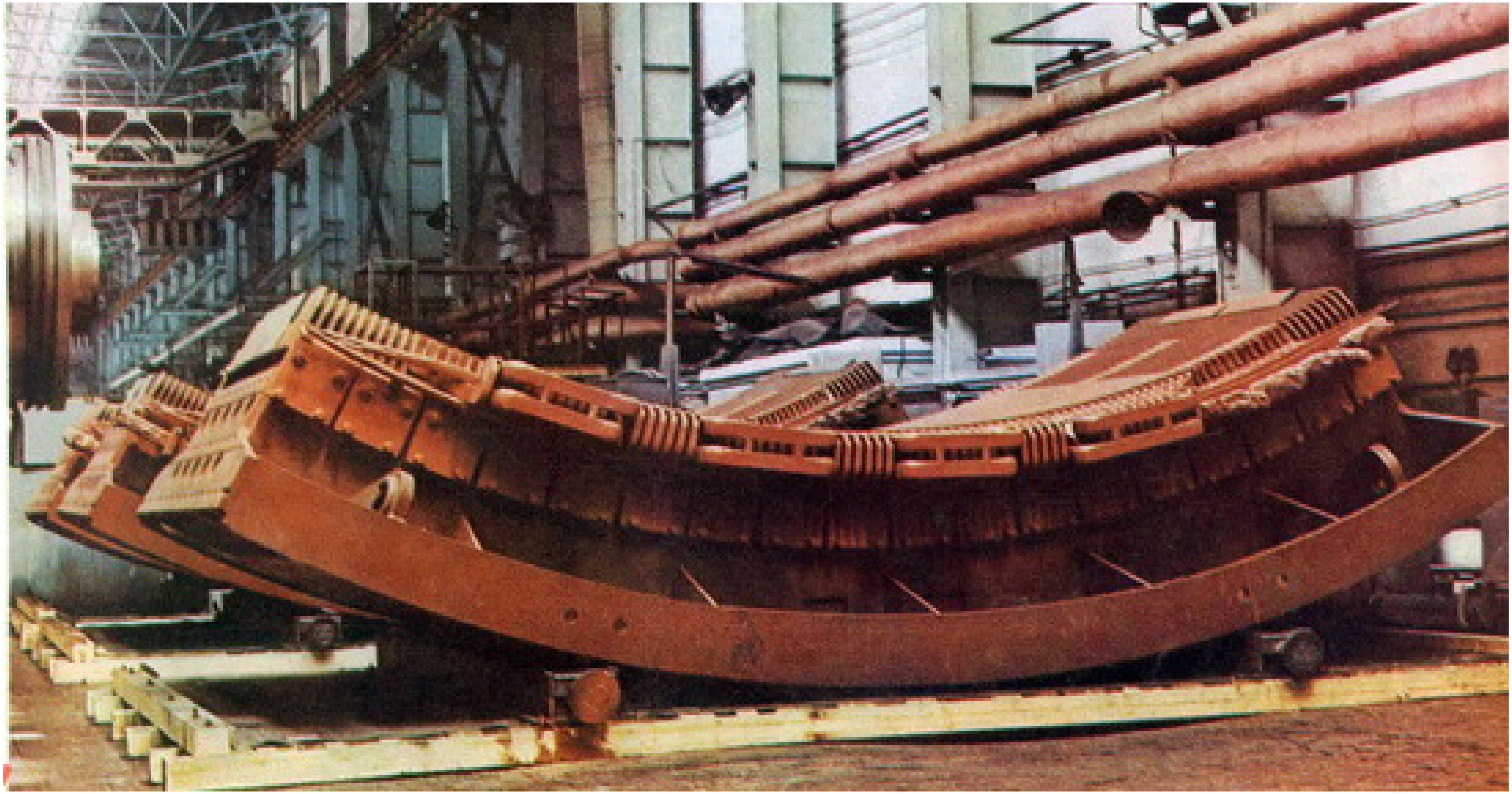


Stator structure





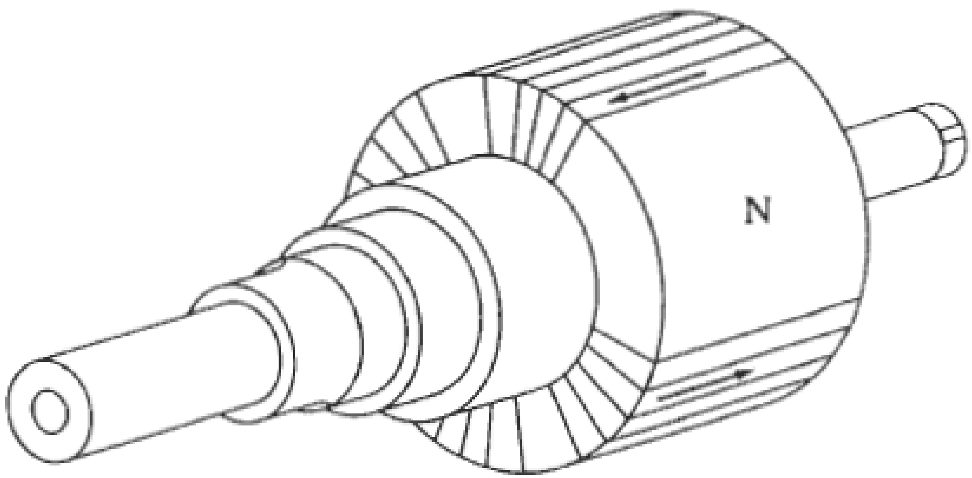
Stator structure



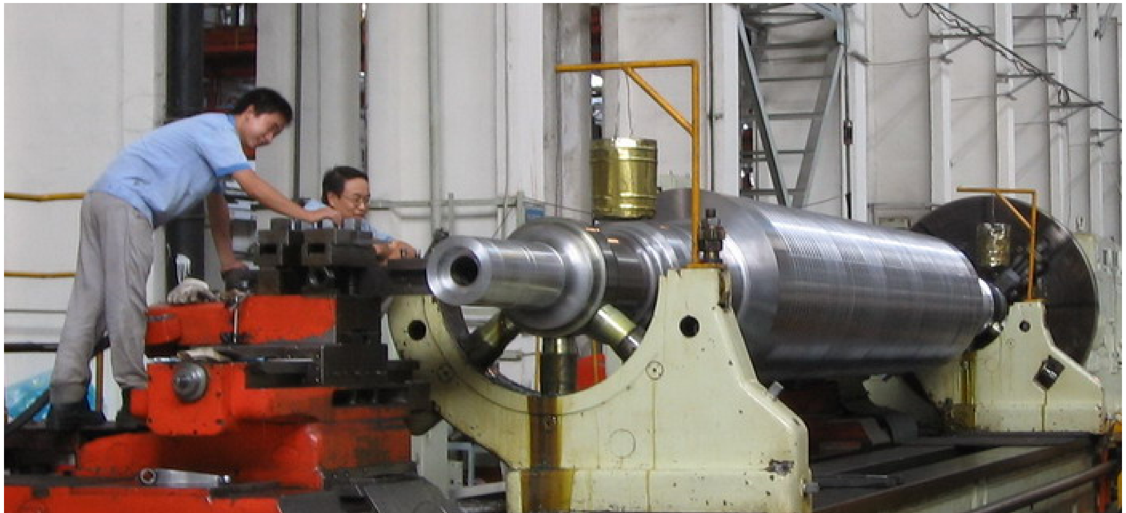
清華大學

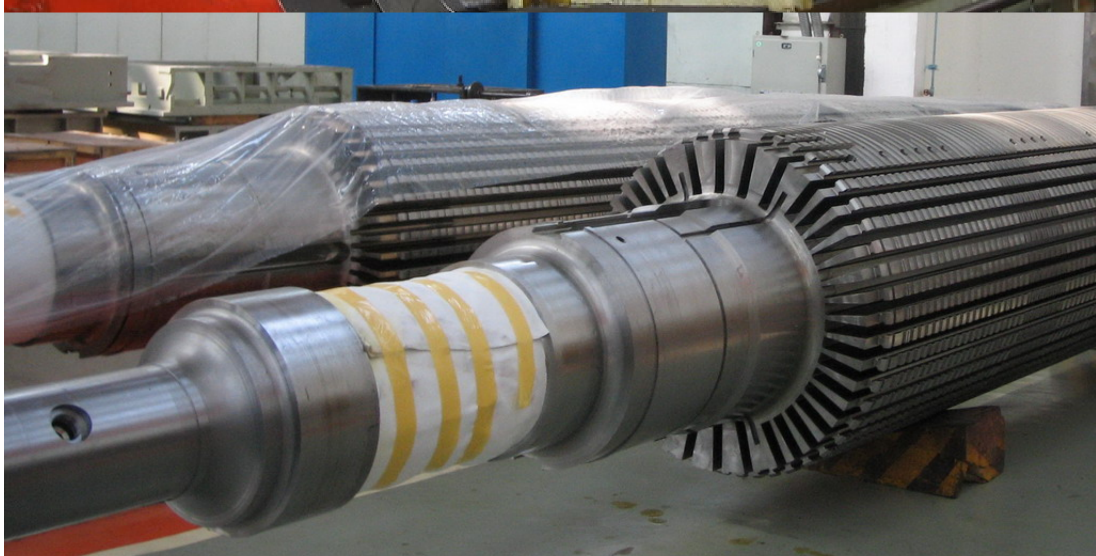
Rotor construction

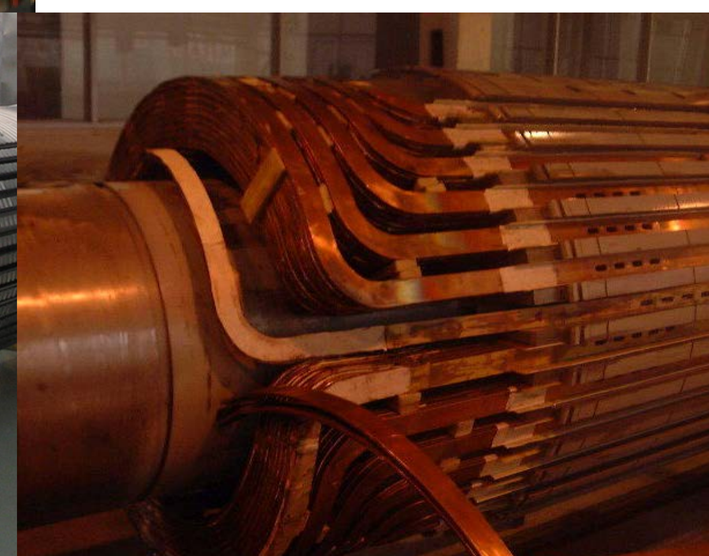
- ***Non-salient (cylindrical) construction***



Rotor structure

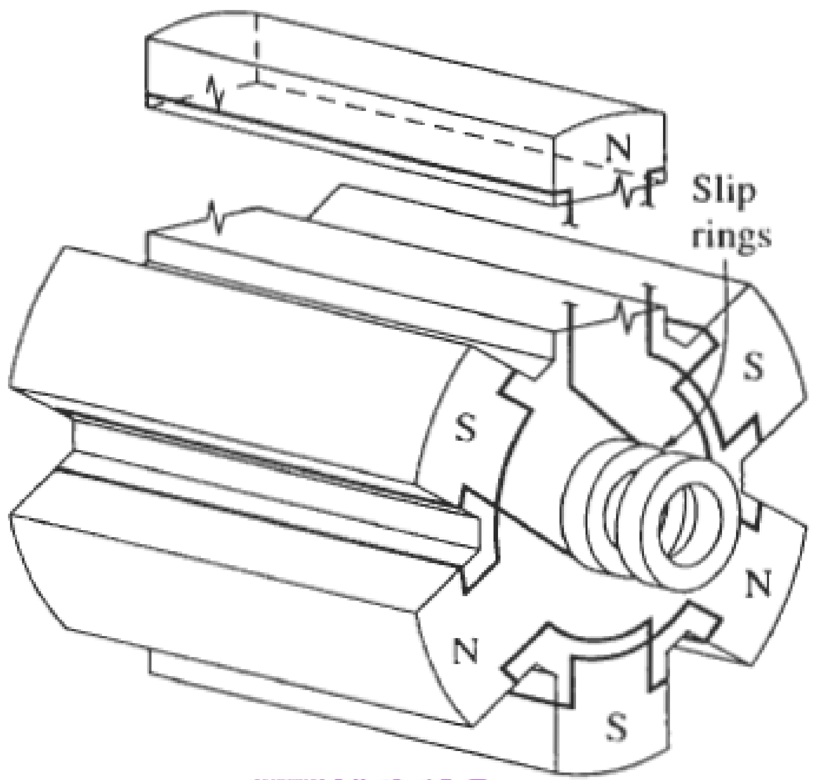




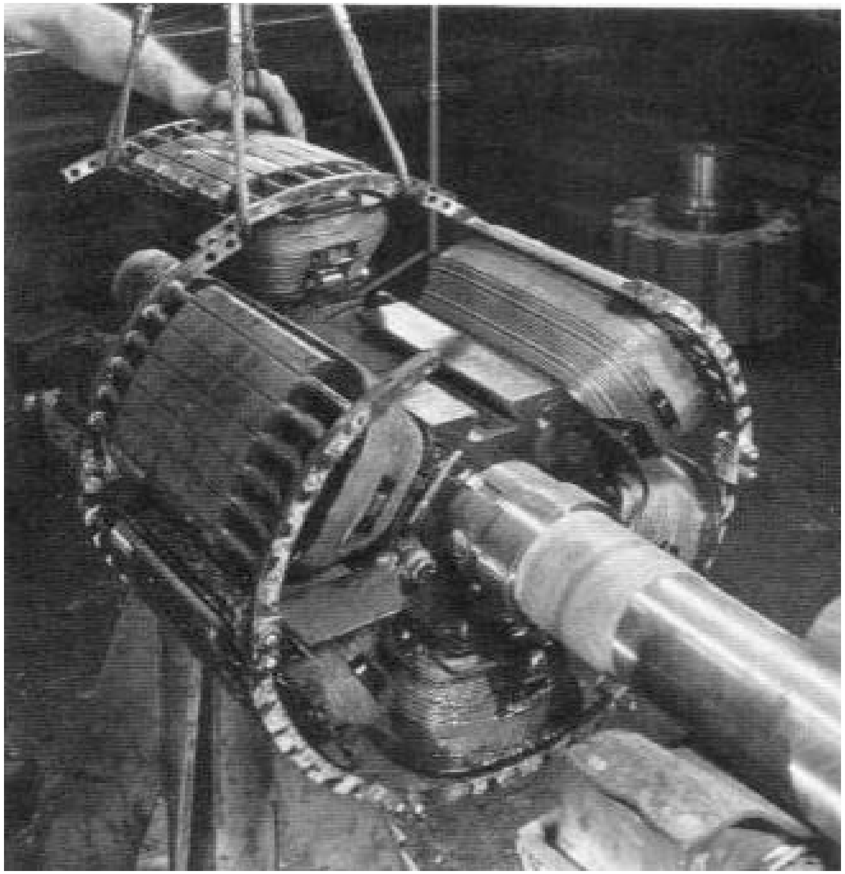


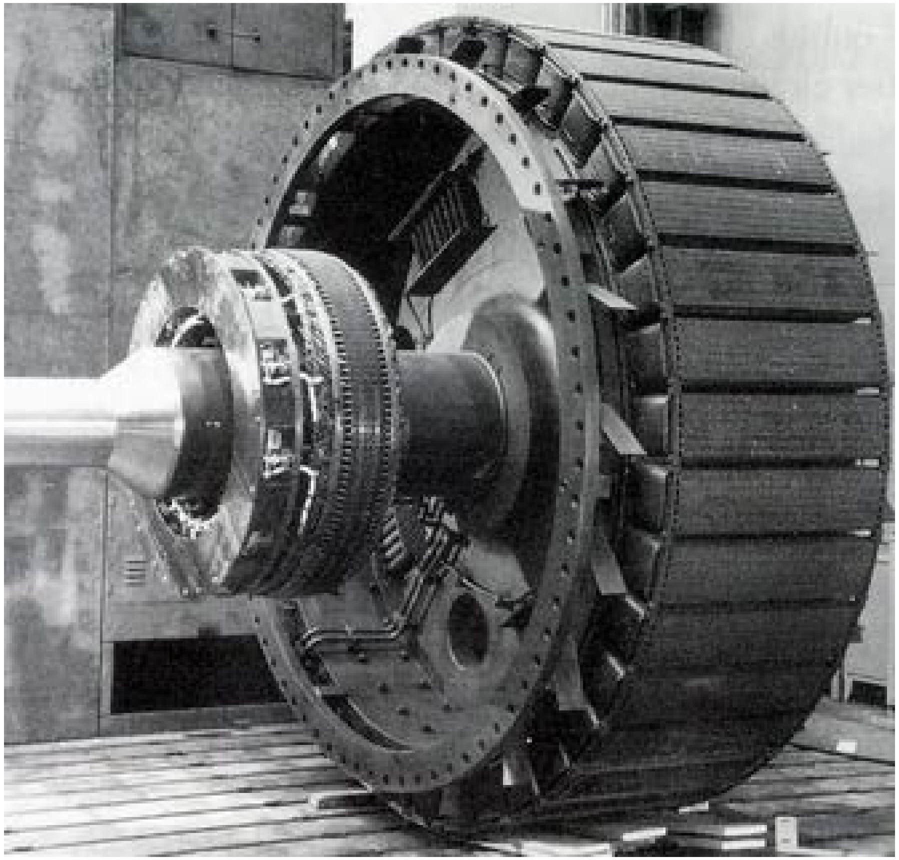
Rotor construction

- ***Salient construction***
  - The pole number is more

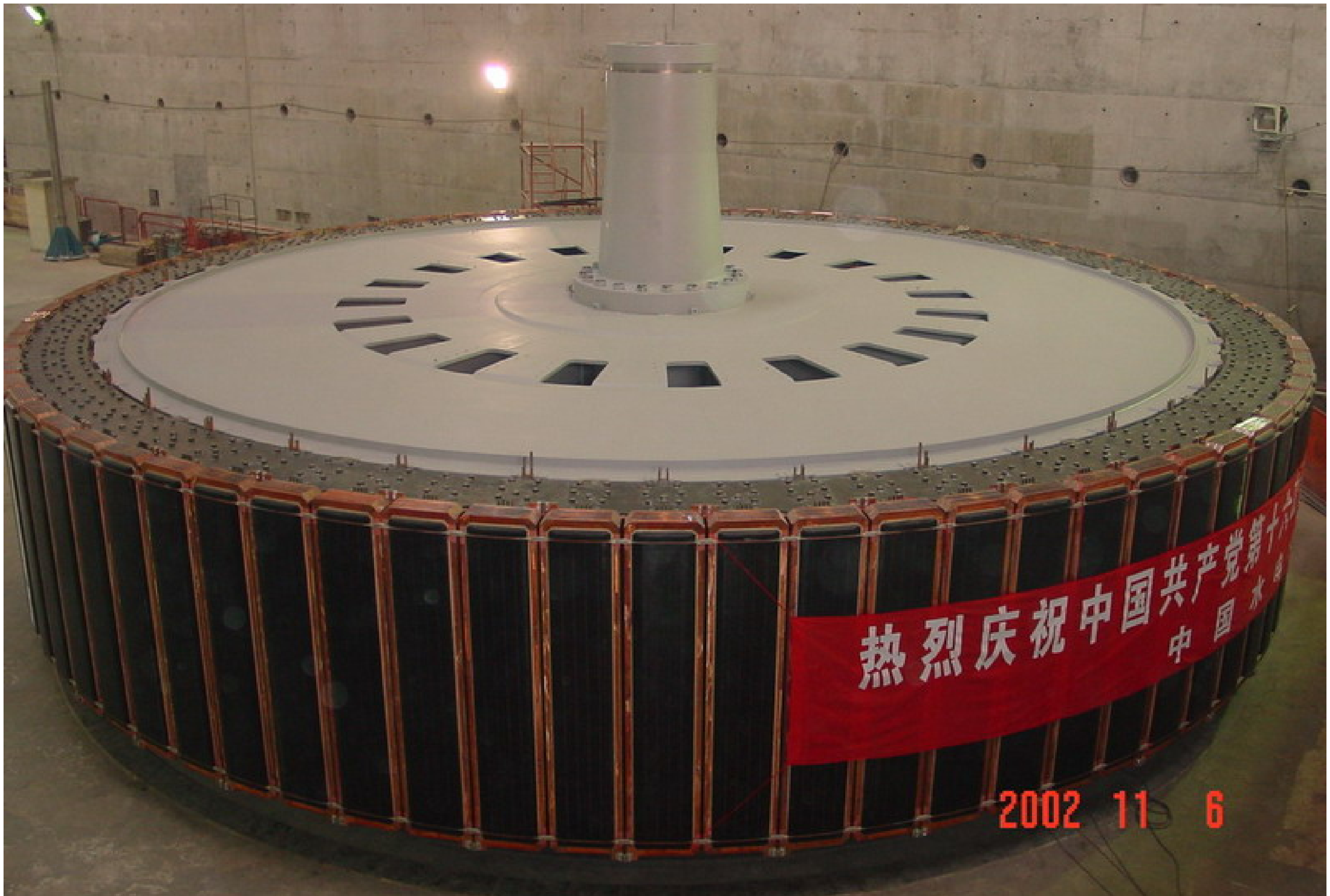


Rotor structure

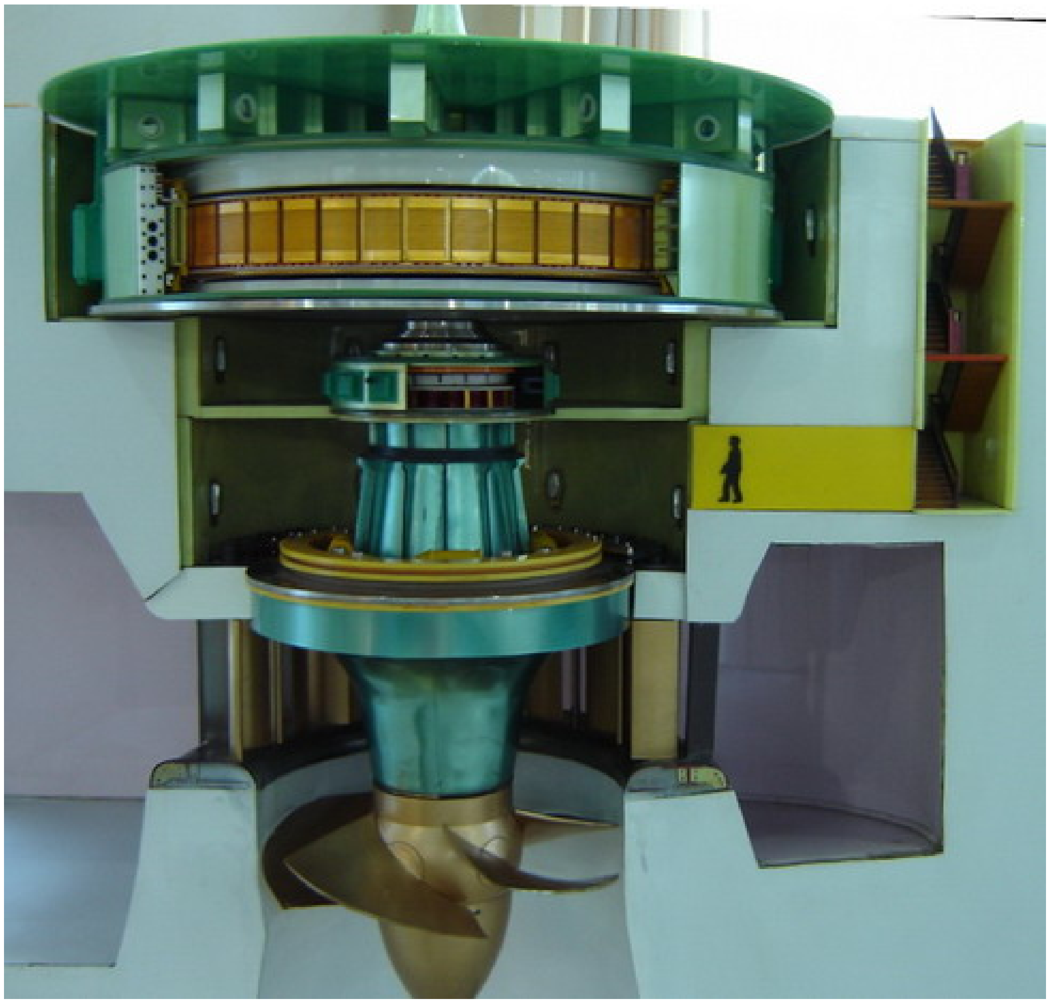


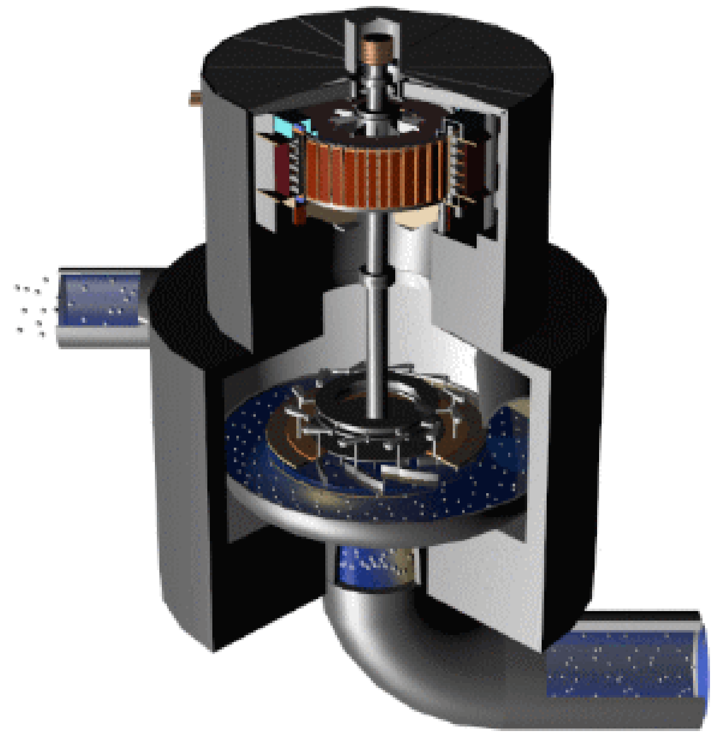


Rotor structure



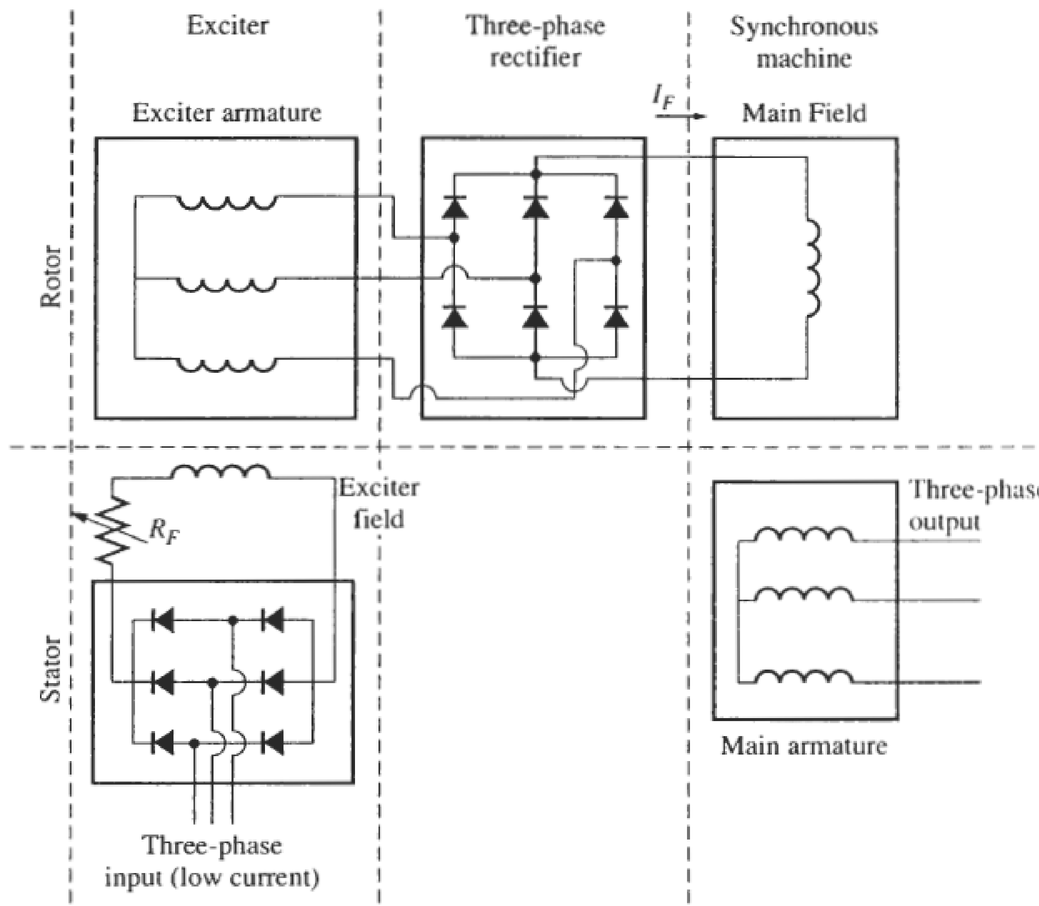
Hydro generation





How to translate the dc current to the rotor

- Brush or brushless type



The speed of rotation of a synchronous generator

- The electrical frequency produced is locked in or synchronized with the mechanical rate of rotation of the generator.

$$\boxed{f_e = \frac{n_m P}{120}}$$

f_e = electrical frequency, in Hz

n_m = mechanical speed of magnetic field, in r/min (equals speed of rotor for synchronous machines)

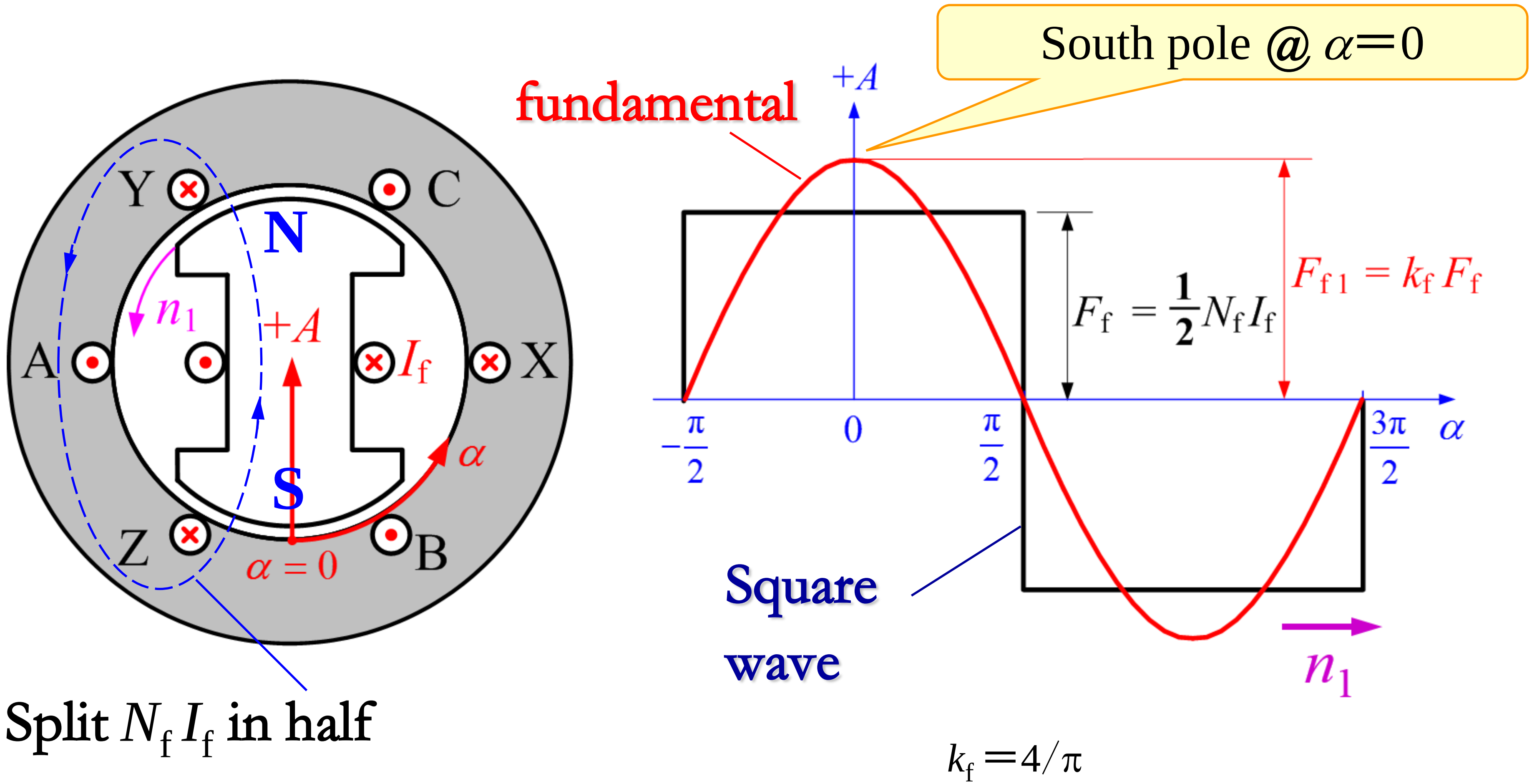
P = number of poles

Armature Reaction

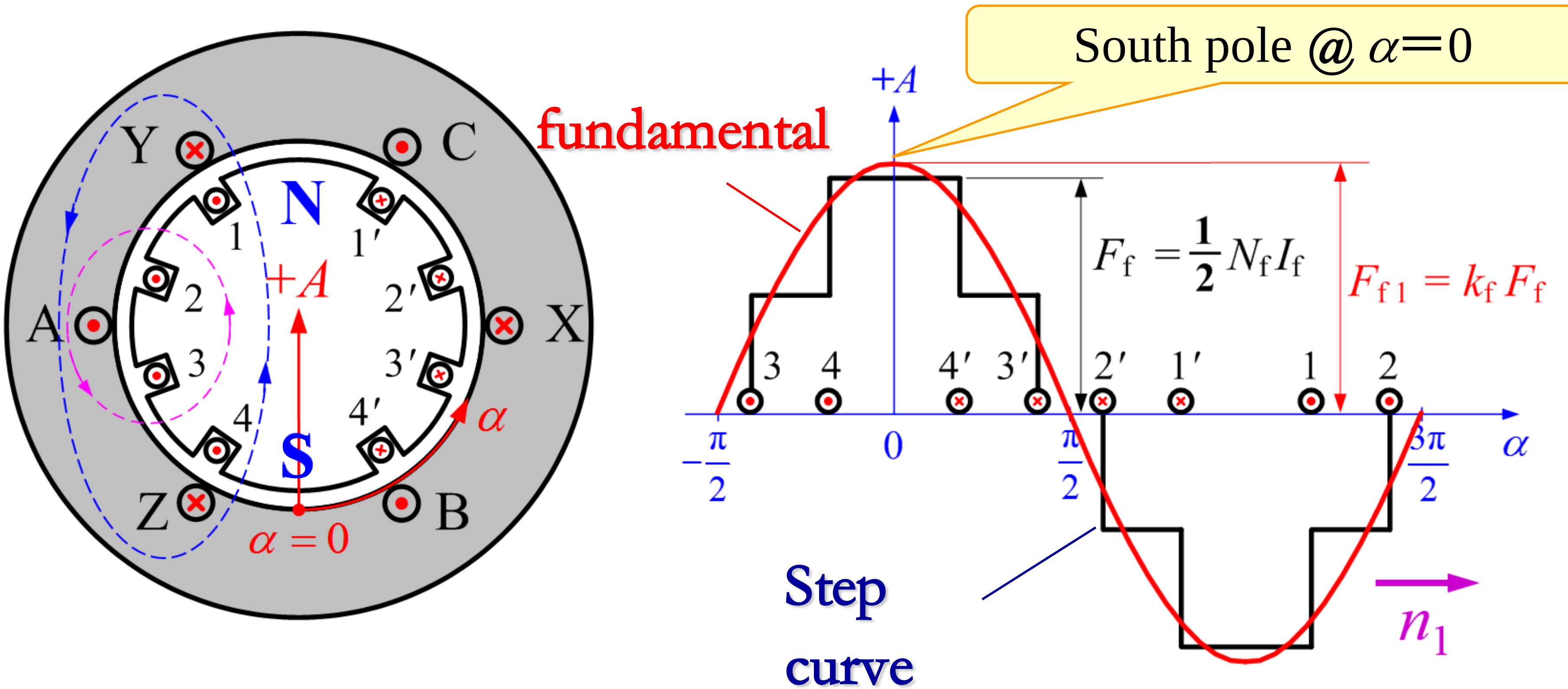
No Load Operation

$$\begin{tikzcd} I_f \arrow[r] & F_f & \text{(mmf)} & \\ & \boldsymbol{F_{f1}} \arrow[u, dash] \arrow[r] & \boldsymbol{B_0} \arrow[r, "\text{rotating}"] & \dot{E}_0 \\ & \text{(mmf)} & \text{(flux)} & \text{(emf)} \end{tikzcd}$$

Salient pole machine

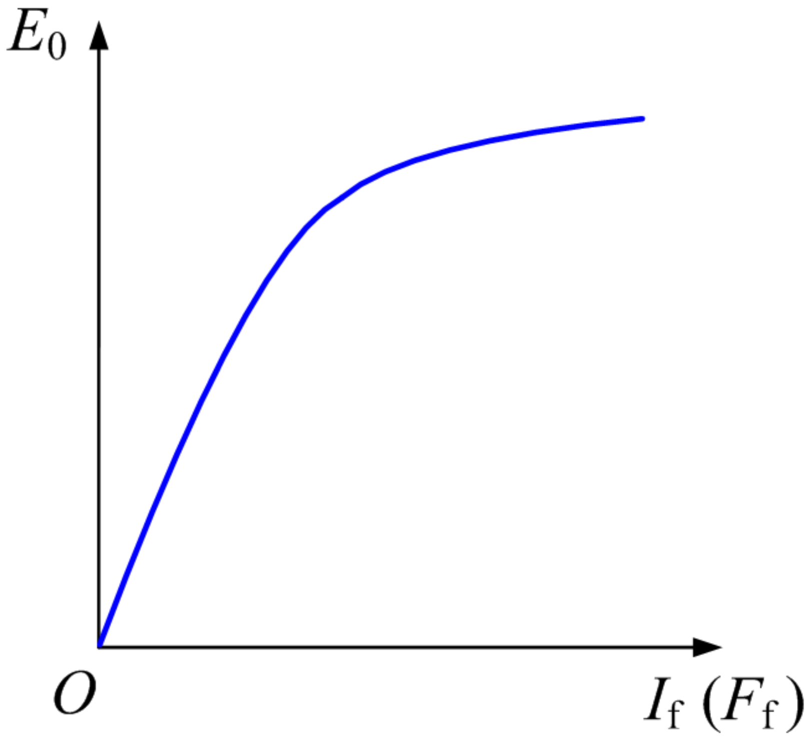


Non-salient pole machine



$k_f \approx 1$

No load characteristics



$$
\begin{aligned}
E_{\phi 1} &= \sqrt{2}\pi f N_c k_{b1} k_{p1} \Phi_1 \\
&= 4.44 f N_c k_{w1} \Phi_1
\end{aligned}
$$

Also referred as internal voltage

Armature Reaction

- Under no load condition

$$I_{\mathrm{f}} \rightarrow \boldsymbol{F}_{\mathrm{f1}} \rightarrow \boldsymbol{B}_0 \rightarrow \dot{\Psi}_0 \rightarrow \dot{E}_0$$

- Under loaded condition

$$\left.\begin{array}{l} I_{\mathrm{f}} \rightarrow \boldsymbol{F}_{\mathrm{f1}} \\ \dot{I} \rightarrow \boldsymbol{F}_{\mathrm{a}} \end{array}\right\} \boldsymbol{F}_{\delta} \rightarrow \boldsymbol{B}_{\delta} \rightarrow \dot{E}_{\delta}$$

Armature Reaction

Rotor mmf

$$F_{\mathrm{f}1} = k_{\mathrm{f}} \frac{1}{2} N_{\mathrm{f}} I_{\mathrm{f}}$$

Rotate at n_1

Stator mmf

$$F_{\mathrm{a}} = F_1 = 1.35 \frac{N_1 I}{p} k_{\mathrm{dp}1}$$

Rotate at n_1

$$\boxed{\begin{aligned} &\boldsymbol{F}_{\mathrm{f}1} \rightarrow \dot{E}_0 \\ &\dot{I} \rightarrow \boldsymbol{F}_{\mathrm{a}} \end{aligned}}$$

Need to solve the electrical circuit to confirm F_a

Armature reaction

- **No load** $I_\mathrm{f} \longrightarrow \boldsymbol{F}_{\mathrm{f1}} \longrightarrow \boldsymbol{B}_0 \rightarrow \dot{E}_0 \ (E_0 = U)$

nonlinear

- **loaded**

$$\left.\begin{array}{l} I_\mathrm{f} \rightarrow \boldsymbol{F}_{\mathrm{f1}} \\ \dot{I} \rightarrow \boldsymbol{F}_\mathrm{a} \end{array}\right\} \boldsymbol{F}_\delta \rightarrow \boldsymbol{B}_\delta \rightarrow \dot{E}_\delta$$

$$\dot{I} \longrightarrow \dot{\Phi}_\sigma \longrightarrow \dot{E}_\sigma$$

$$\left.\begin{array}{l} \dot{E}_\delta \\ \dot{E}_\sigma \\ \dot{U} \end{array}\right\} \rightarrow \dot{I}$$

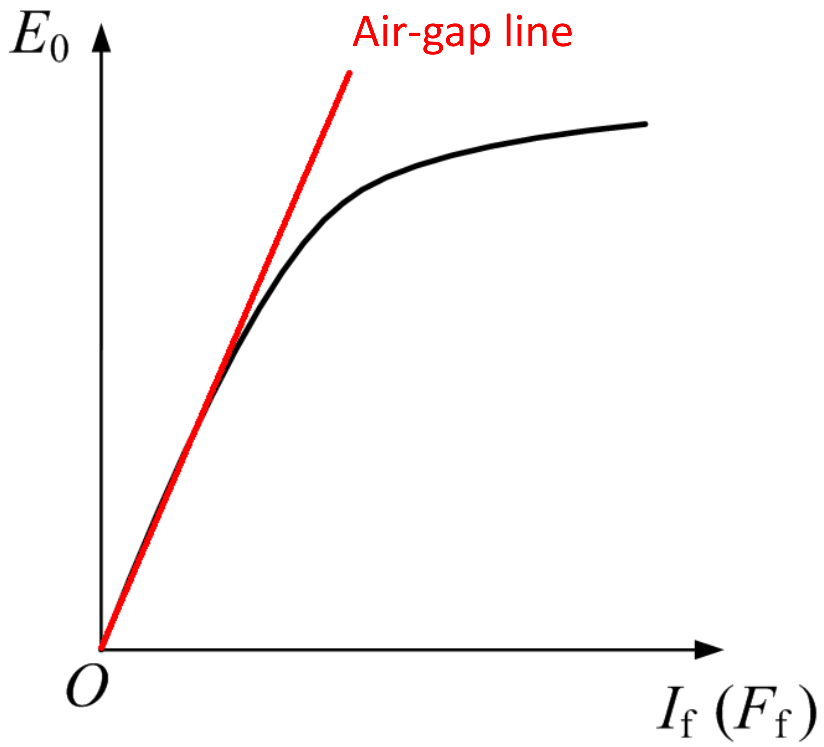
Magnetization curve (B-H)

Electrical circuit

The equivalent circuit of a synchronous generator

The equivalent circuit of a synchronous generator

- Neglect magnetic saturation



The equivalent circuit of a synchronous generator

$$\left.\begin{array}{l} I_f \rightarrow \boldsymbol{F}_{f1} \\ \dot{I} \rightarrow \boldsymbol{F}_a \end{array}\right\} \boldsymbol{F}_\delta \rightarrow \boldsymbol{B}_\delta \rightarrow \dot{E}_\delta$$

nonlinear

Neglect saturation

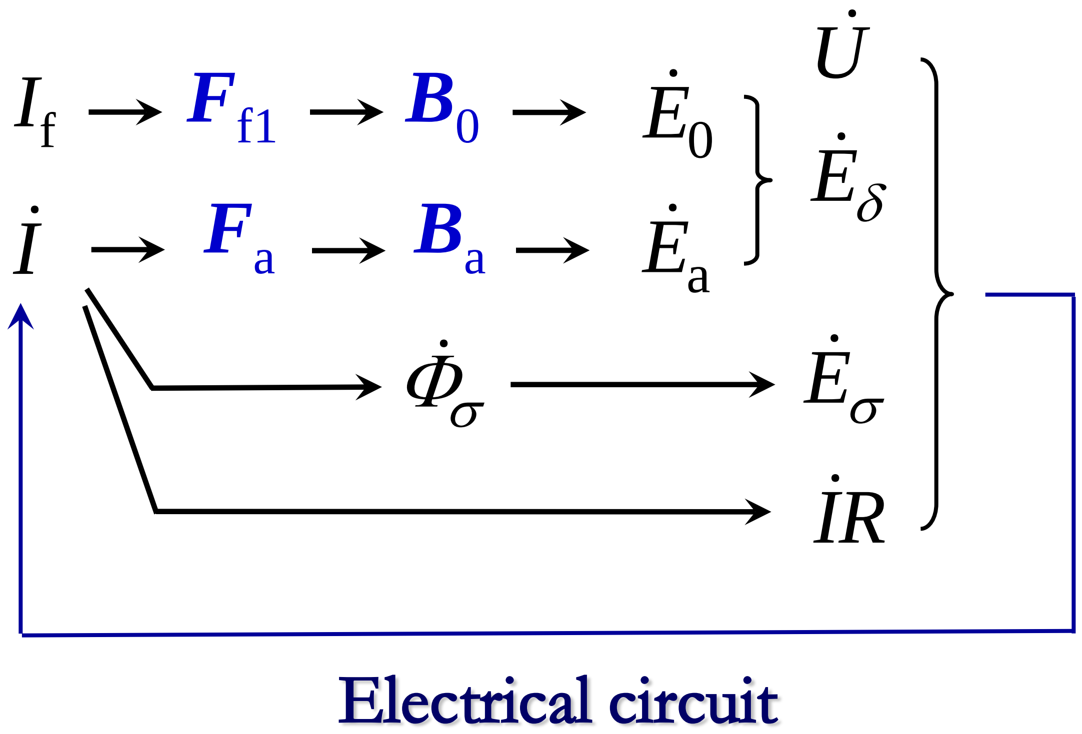
$$\begin{array}{l} I_f \rightarrow \boldsymbol{F}_{f1} \rightarrow \boldsymbol{B}_0 \rightarrow \\ \dot{I} \rightarrow \boldsymbol{F}_a \rightarrow \boldsymbol{B}_a \rightarrow \end{array} \left.\begin{array}{l} \dot{E}_0 \\ \dot{E}_a \end{array}\right\} \dot{E}_\delta$$

$$\boldsymbol{B}_0 + \boldsymbol{B}_a = \boldsymbol{B}_\delta$$

linear

$\dot{E}_a$: **emf of armature reaction**

The equivalent circuit of a synchronous generator



The equivalent circuit of a synchronous generator

$$\dot{E}_0 + \dot{E}_\mathrm{a} + \dot{E}_\sigma = \dot{U} + \dot{I}R$$

$$\dot{I} \xrightarrow{F_\mathrm{a} \propto I} \boldsymbol{F}_\mathrm{a} \xrightarrow{B_\mathrm{a} \propto F_\mathrm{a}} \boldsymbol{B}_\mathrm{a} \xrightarrow{E_\mathrm{a} \propto \Phi_\mathrm{a} \propto B_\mathrm{a}} \dot{E}_\mathrm{a}$$

$$\dot{E}_\mathrm{a} = -\mathrm{j}\dot{I}X_\mathrm{a}$$

$$X_\mathrm{a} = \frac{E_\mathrm{a}}{I} = \frac{4.44\, fN_1 k_{\mathrm{dp1}}\Phi_\mathrm{a}}{I} \Rightarrow X_\mathrm{a} \propto \frac{f(N_1 k_{\mathrm{dp1}})^2}{\delta}$$

The equivalent circuit of a synchronous generator

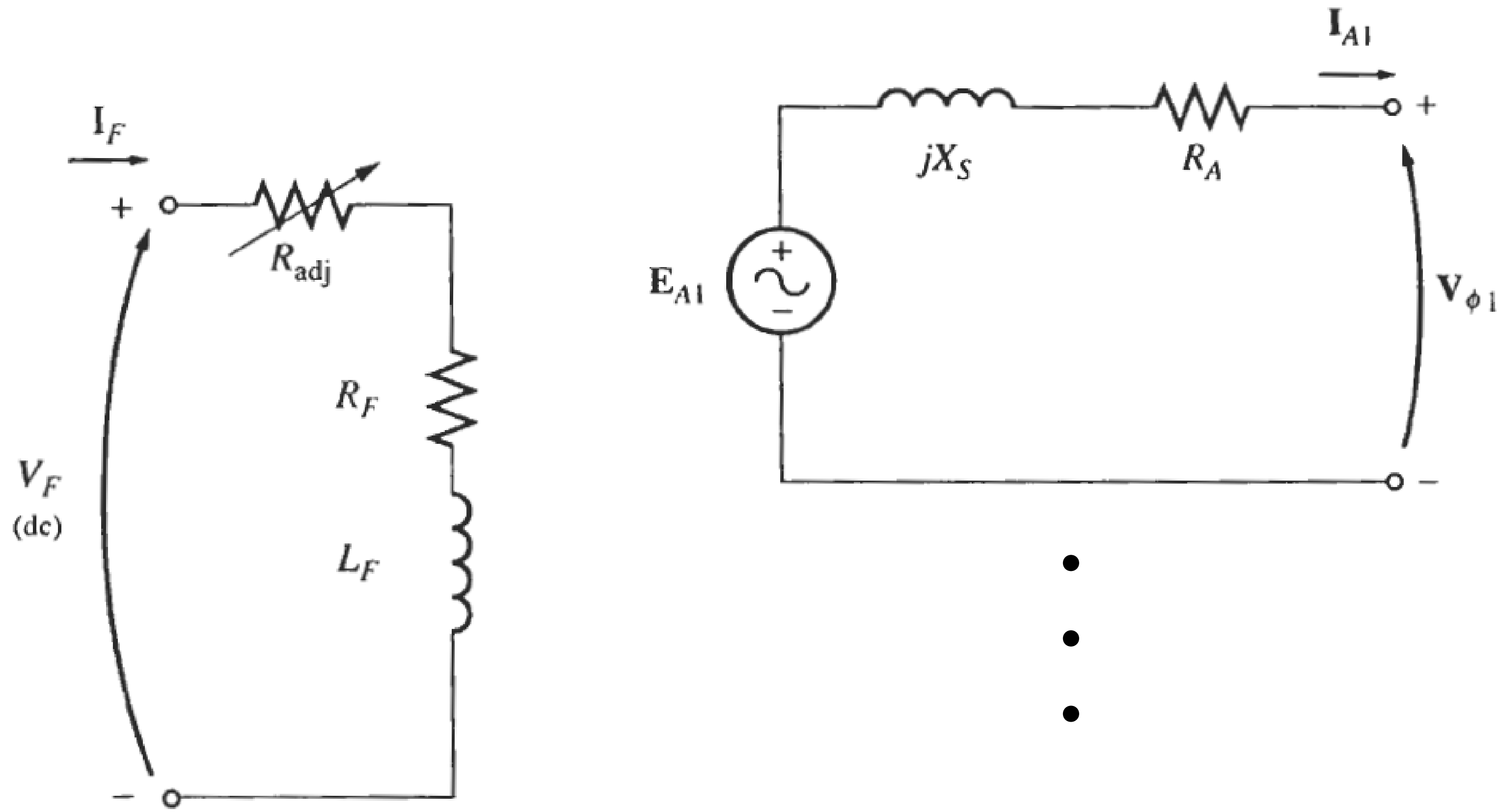
$$\dot{E}_0 + \underline{\dot{E}_{\mathrm{a}} + \dot{E}_{\sigma}} = \dot{U} + \dot{I}R$$

$$\dot{E}_{\mathrm{a}} = -\mathrm{j}\dot{I}X_{\mathrm{a}} \qquad \dot{E}_{\sigma} = -\mathrm{j}\dot{I}X_{\sigma}$$

$$\dot{E}_0 = \dot{U} + \dot{I}R + \mathrm{j}\dot{I}(X_{\sigma} + X_{\mathrm{a}}) = \dot{U} + \dot{I}R + \mathrm{j}\dot{I}X_{\mathrm{s}}$$

Synchronous reactance $X_{\mathrm{s}} = X_{\sigma} + X_{\mathrm{a}}$

The equivalent circuit of a three-phase synchronous generator



Effect of saturation

Armature reaction

- **No load** $I_f \longrightarrow \boldsymbol{F}_{f1} \longrightarrow \boldsymbol{B}_0 \rightarrow \dot{E}_0 \ (E_0 = U)$

nonlinear

Magnetization curve (B-H)

- **loaded** $\left.\begin{array}{l} I_f \rightarrow \boldsymbol{F}_{f1} \\ \dot{I} \rightarrow \boldsymbol{F}_a \end{array}\right\} \boldsymbol{F}_\delta \rightarrow \boldsymbol{B}_\delta \rightarrow \dot{E}_\delta$

$\dot{I} \longrightarrow \dot{\Phi}_\sigma \longrightarrow \dot{E}_\sigma$

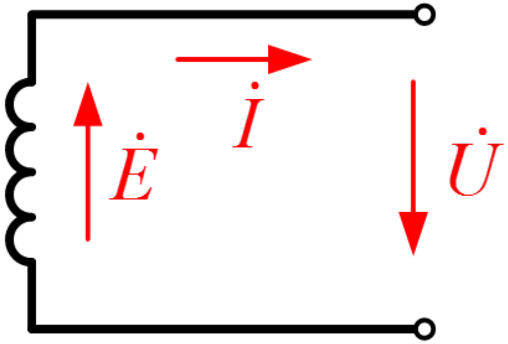
$\left.\begin{array}{l} \dot{E}_\delta \\ \dot{E}_\sigma \\ \dot{U} \end{array}\right\} \rightarrow \dot{I}$

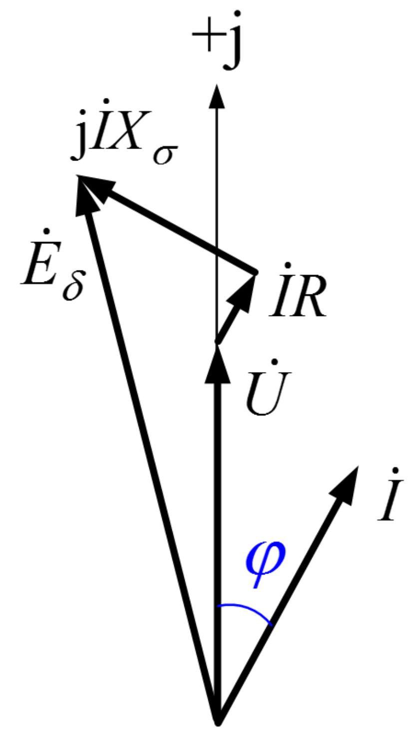
Electrical circuit

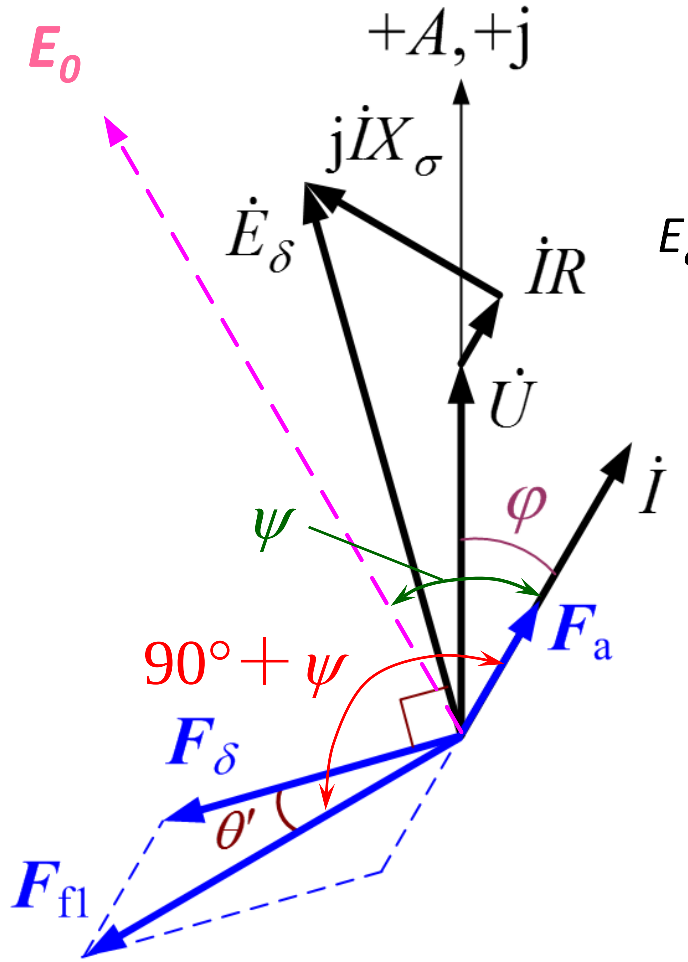
Equivalent circuit

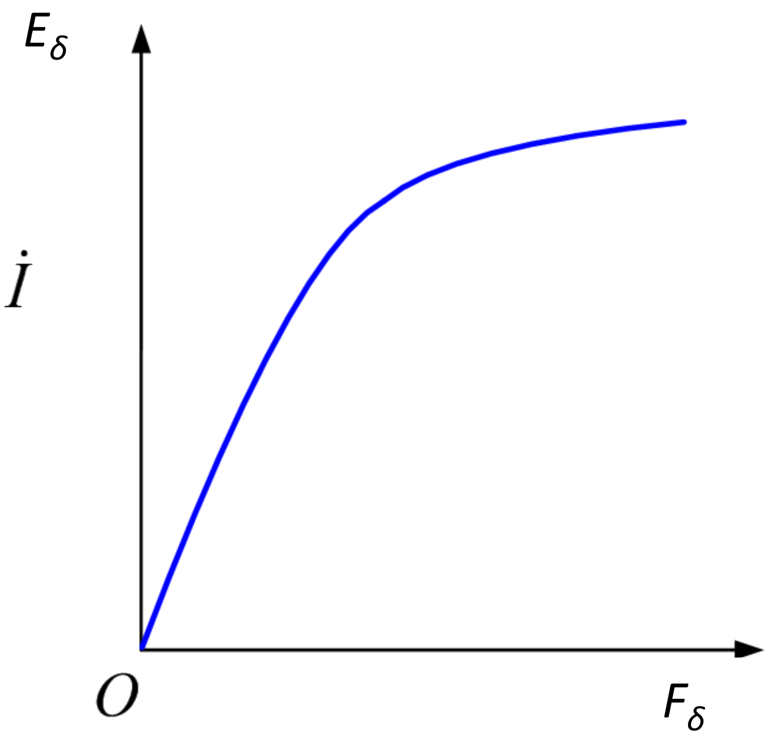
$$\dot{E}_\delta = \dot{U} + \dot{I}(R + \mathrm{j}X_\sigma) = \dot{U} + \dot{I}Z_\sigma$$

$$Z_\sigma = R + \mathrm{j}X_\sigma$$







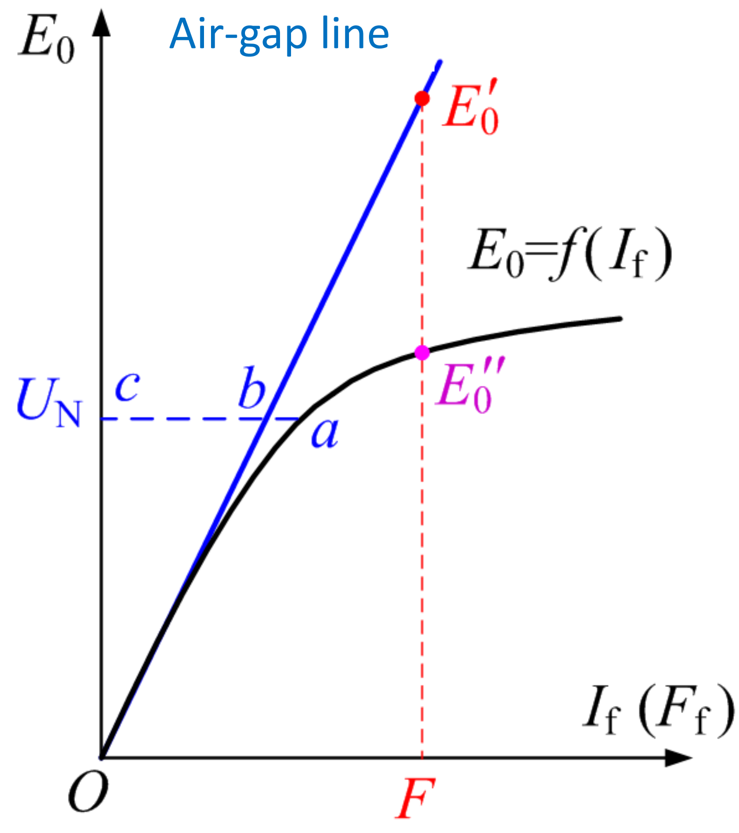


How do we solve it in practice?

Linearization of magnetization curve

- **Use E_0' for linearized equivalent circuit calculation**

- **Actual no load emf is E_0''**



清華大學

Armature Reaction Phasor Diagram

清華大學

Armature Reaction

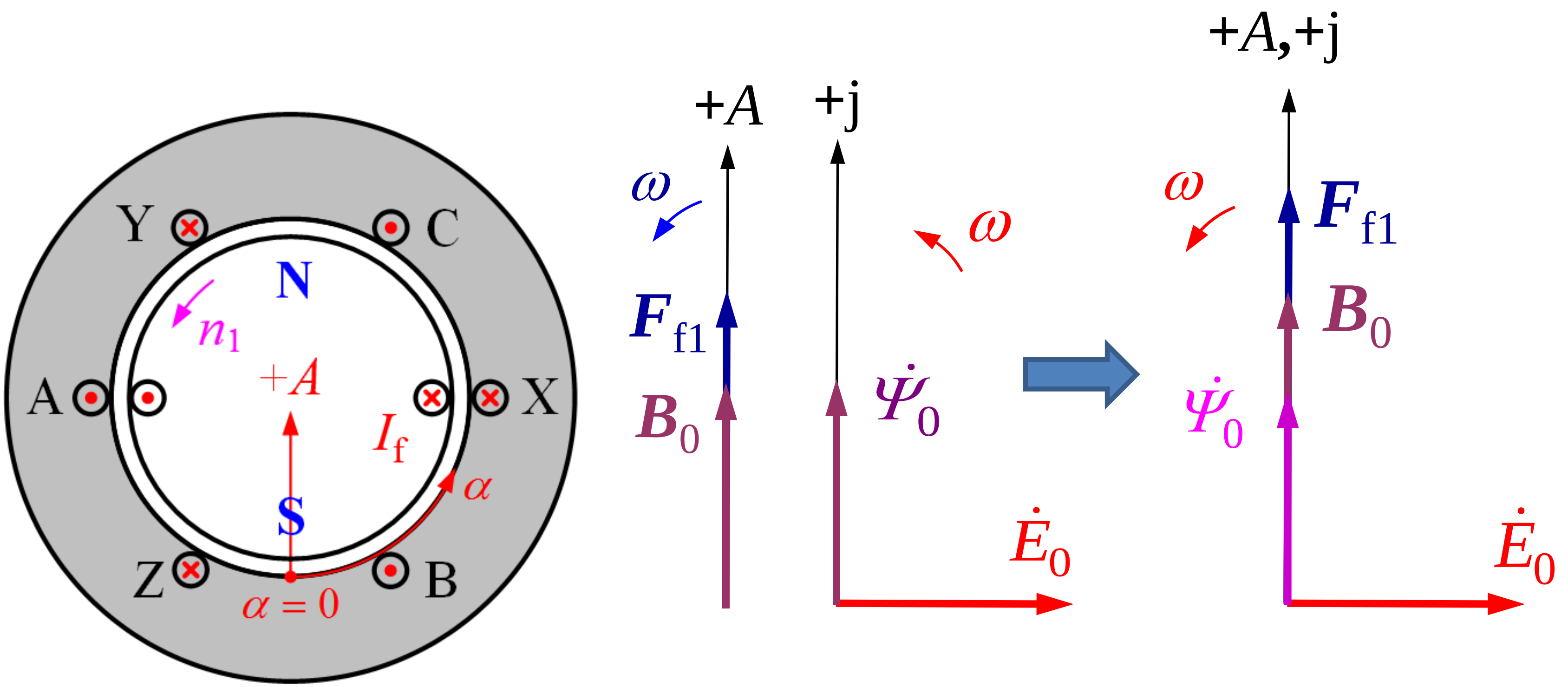
- Under no load condition

$$I_{\mathrm{f}} \rightarrow \boldsymbol{F}_{\mathrm{f1}} \rightarrow \boldsymbol{B}_0 \rightarrow \dot{\Psi}_0 \rightarrow \dot{E}_0$$

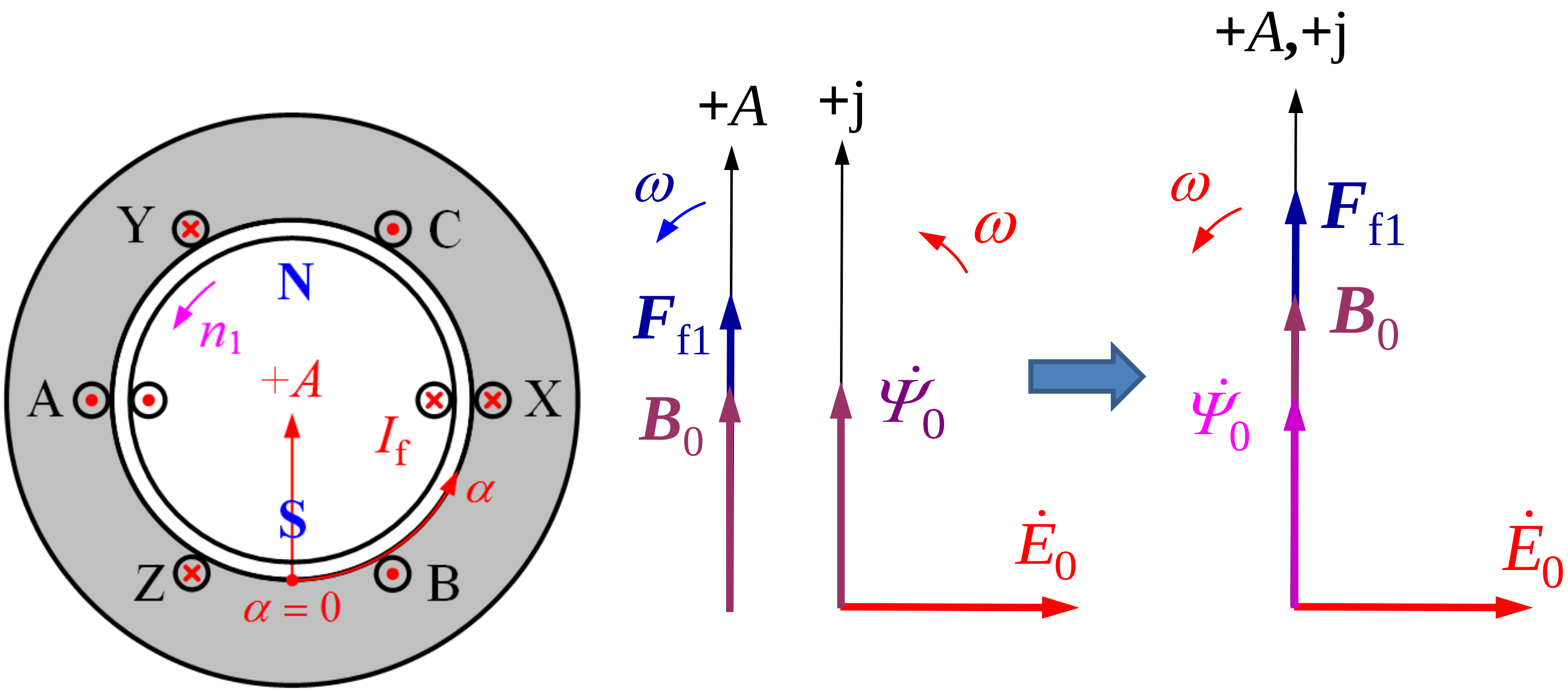
- Under loaded condition

$$\left.\begin{array}{l} I_{\mathrm{f}} \rightarrow \boldsymbol{F}_{\mathrm{f1}} \\ \dot{I} \rightarrow \boldsymbol{F}_{\mathrm{a}} \end{array}\right\} \boldsymbol{F}_{\delta} \rightarrow \boldsymbol{B}_{\delta} \rightarrow \dot{E}_{\delta}$$

Phasor diagram

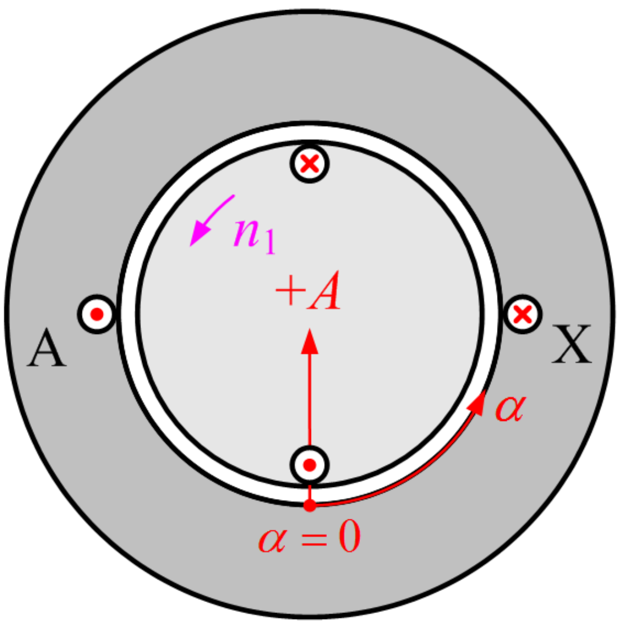


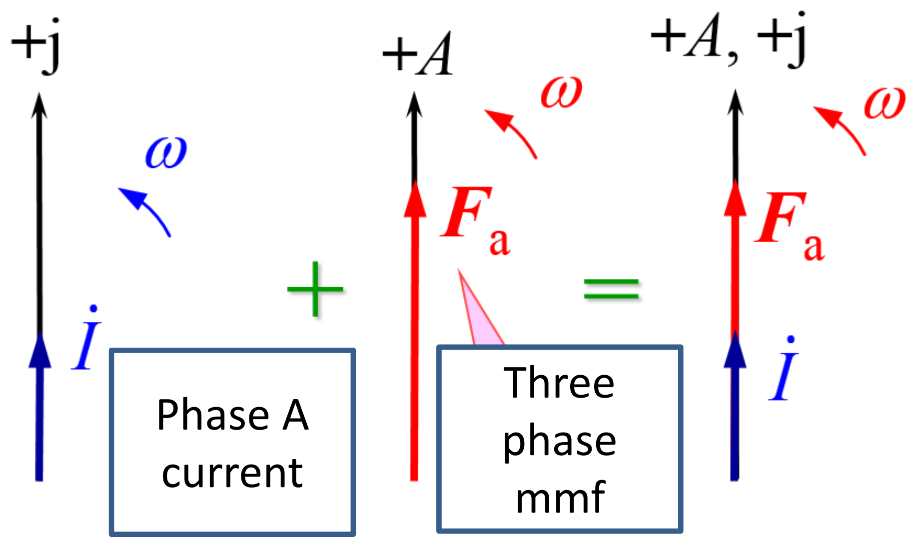
Phasor diagram



清華大學

Phasor Diagram

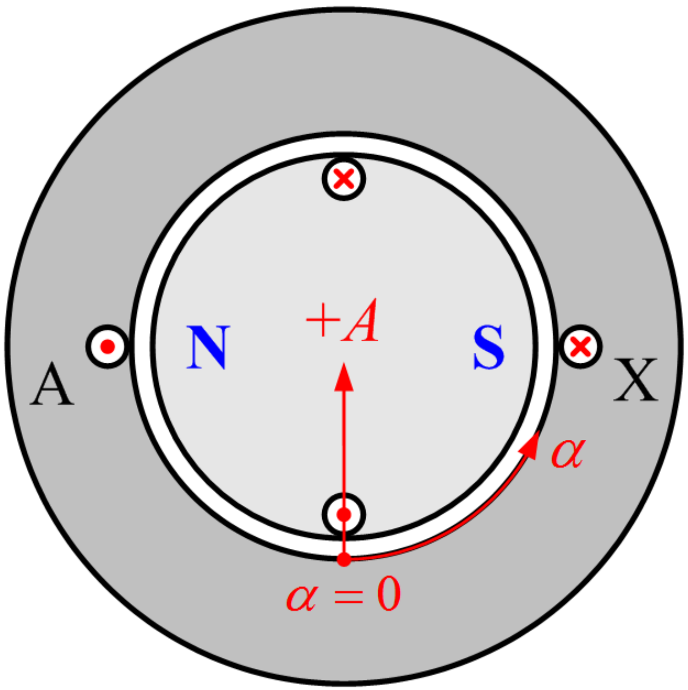


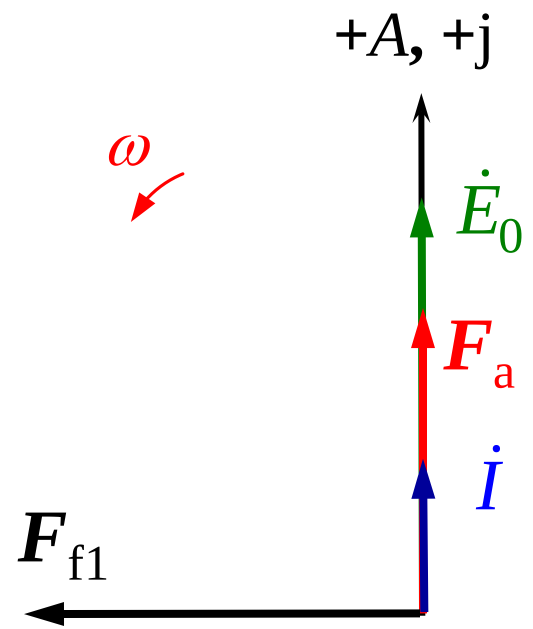


Phasor diagram

Define ψ as the angle between I and E_o

$\psi = 0$

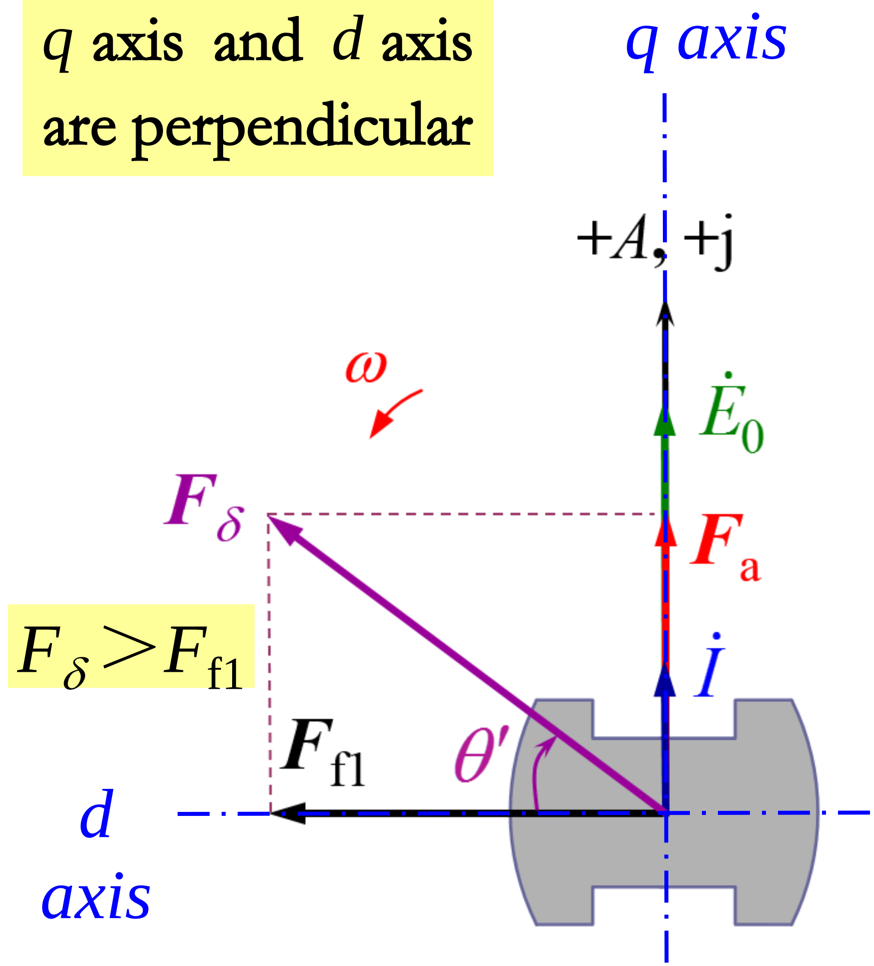




Phasor diagram

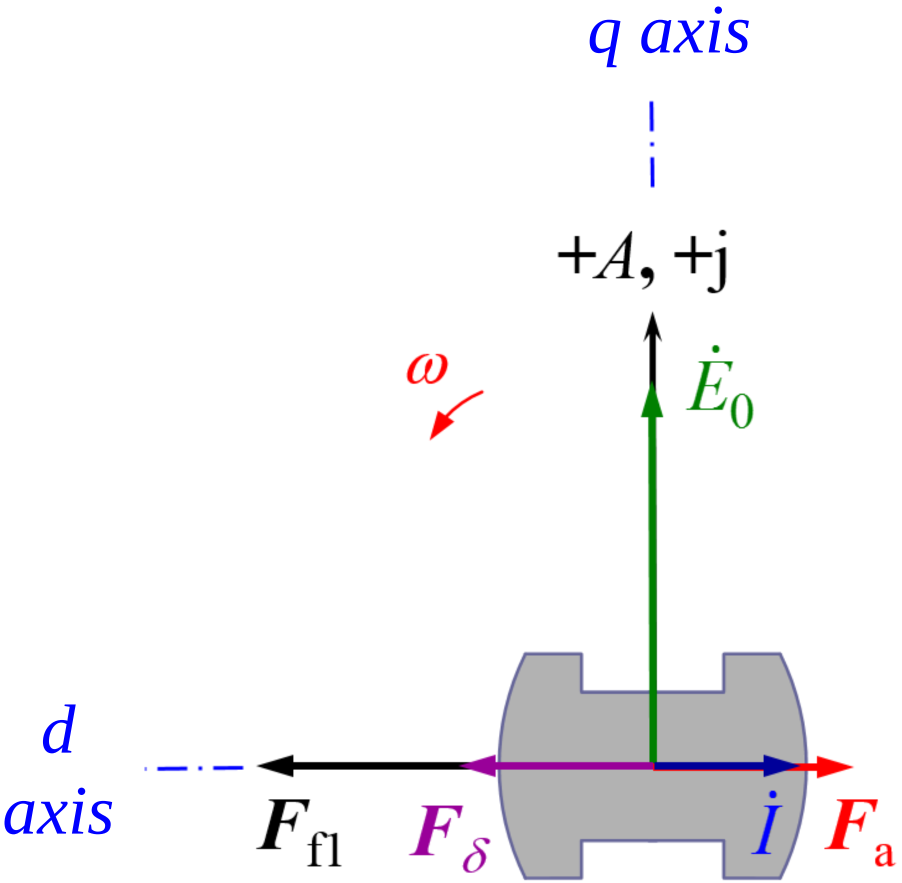
$\psi = 0$

q axis and d axis are perpendicular



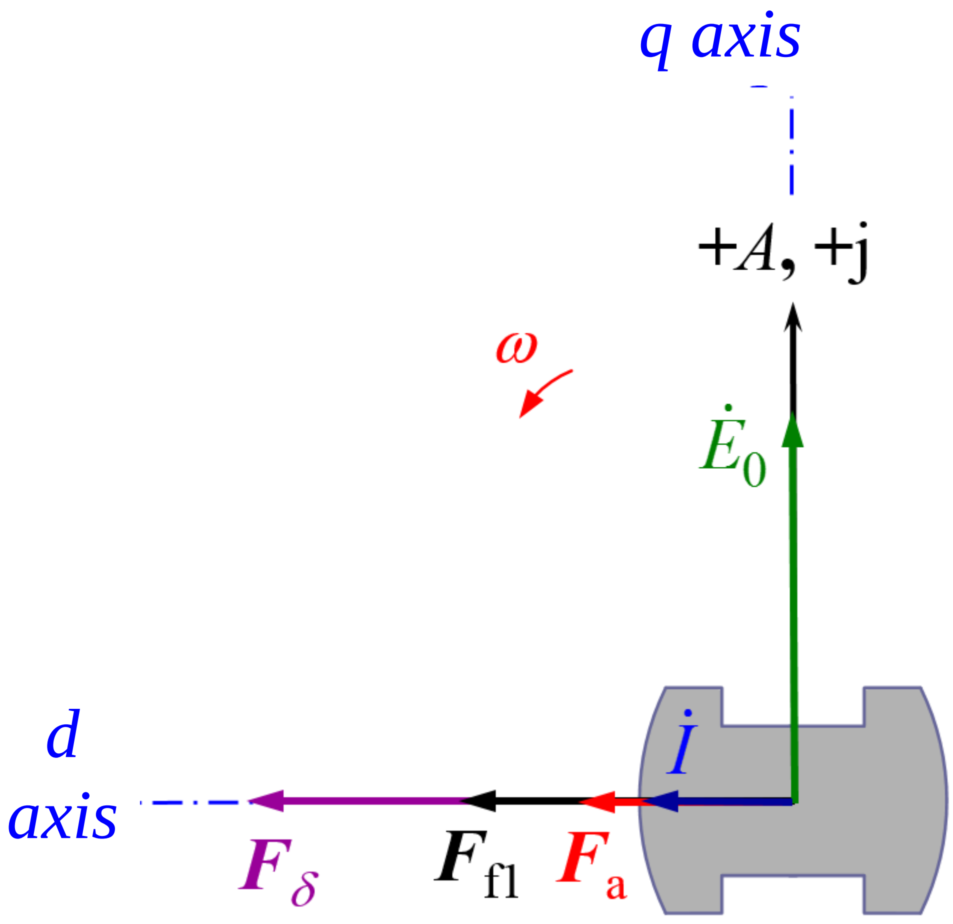
Phasor diagram

$\psi = 90°$



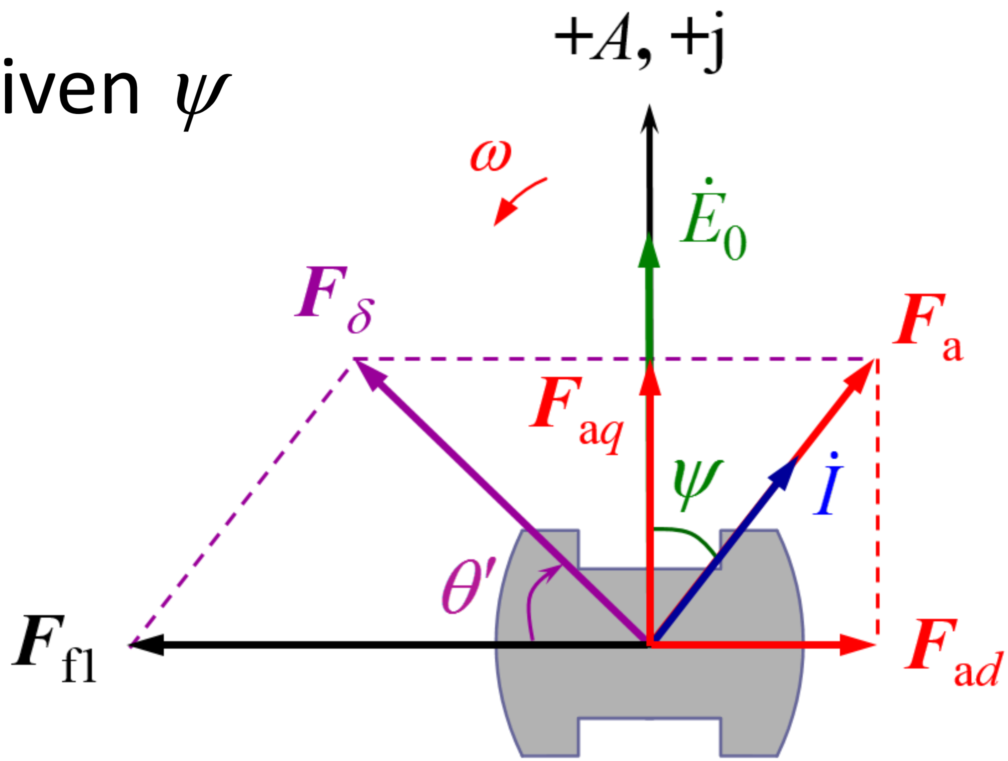
Phasor diagram

$\psi = \text{-}90°$



Phasor diagram

For any given ψ



Armature reaction may increase or decrease magnetization

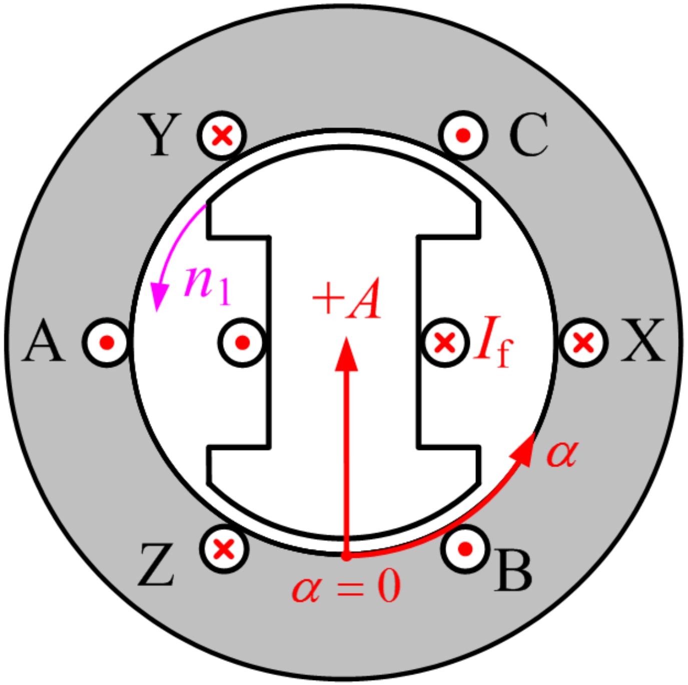
Question

- What happens to the equivalent circuit parameters if we consider saturation?

Salient pole machines

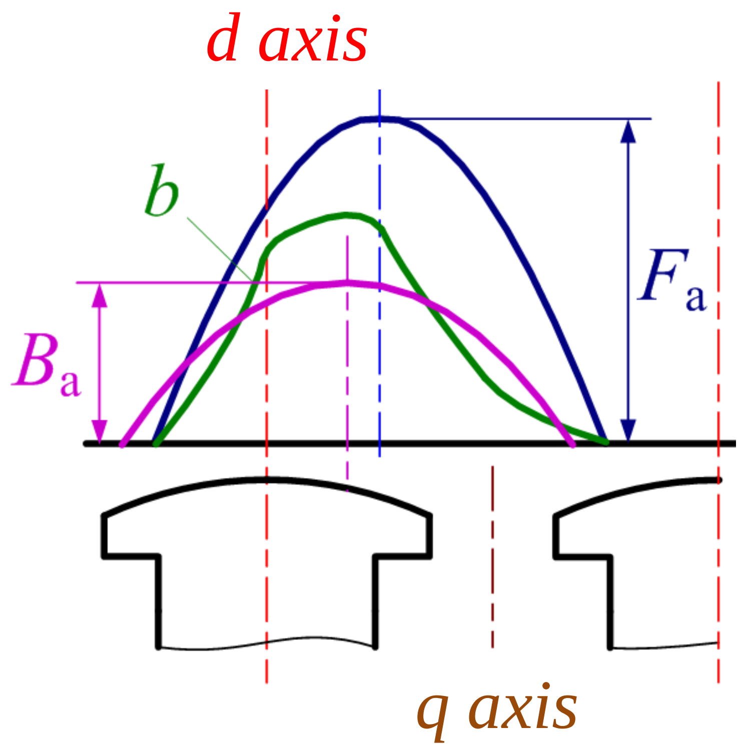
Salient-pole rotor

- Unevenly distributed air gap

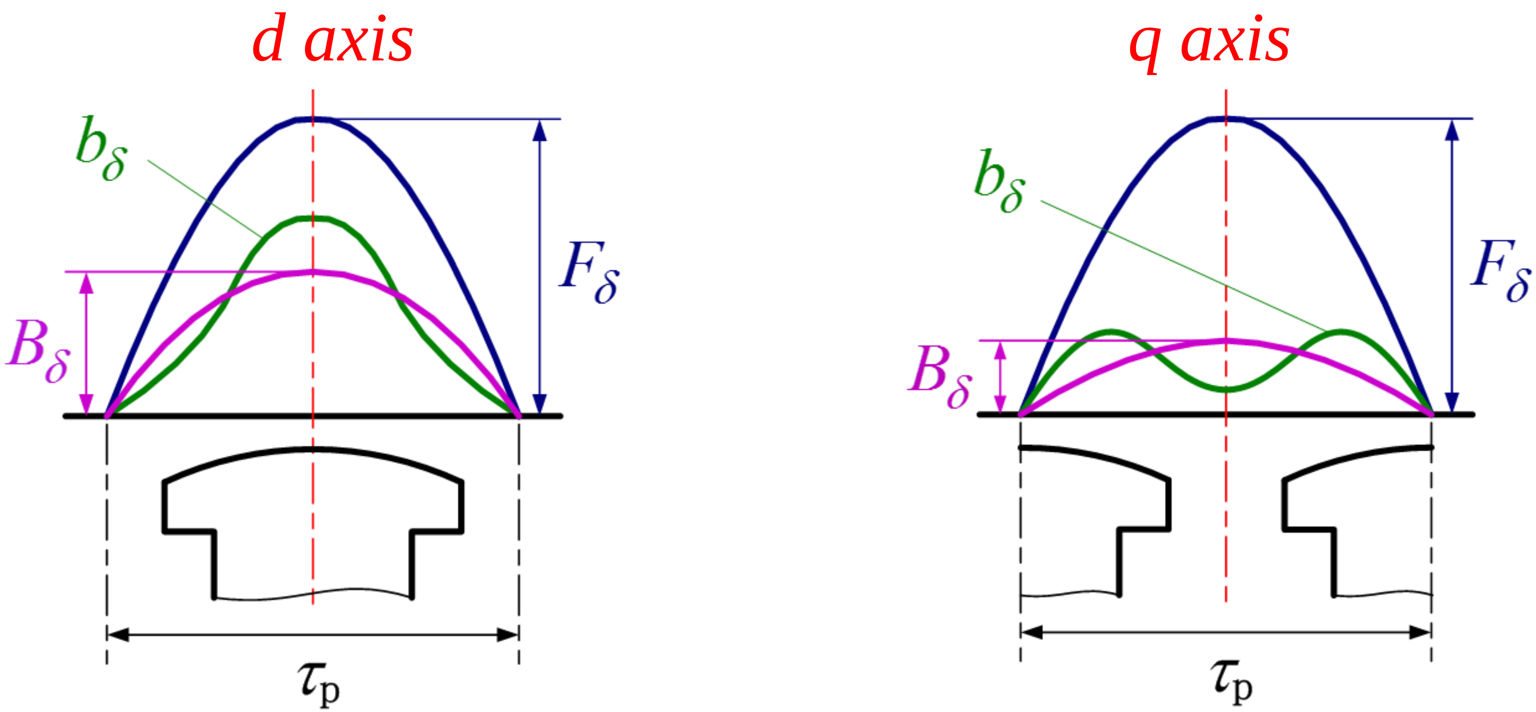


Effect of salient pole rotor

- $\boldsymbol{B_\delta}$ ($\boldsymbol{B_a}$) **and** $\boldsymbol{F_\delta}$ ($\boldsymbol{F_a}$) **may not be in phase anymore**



d-axis and q-axis

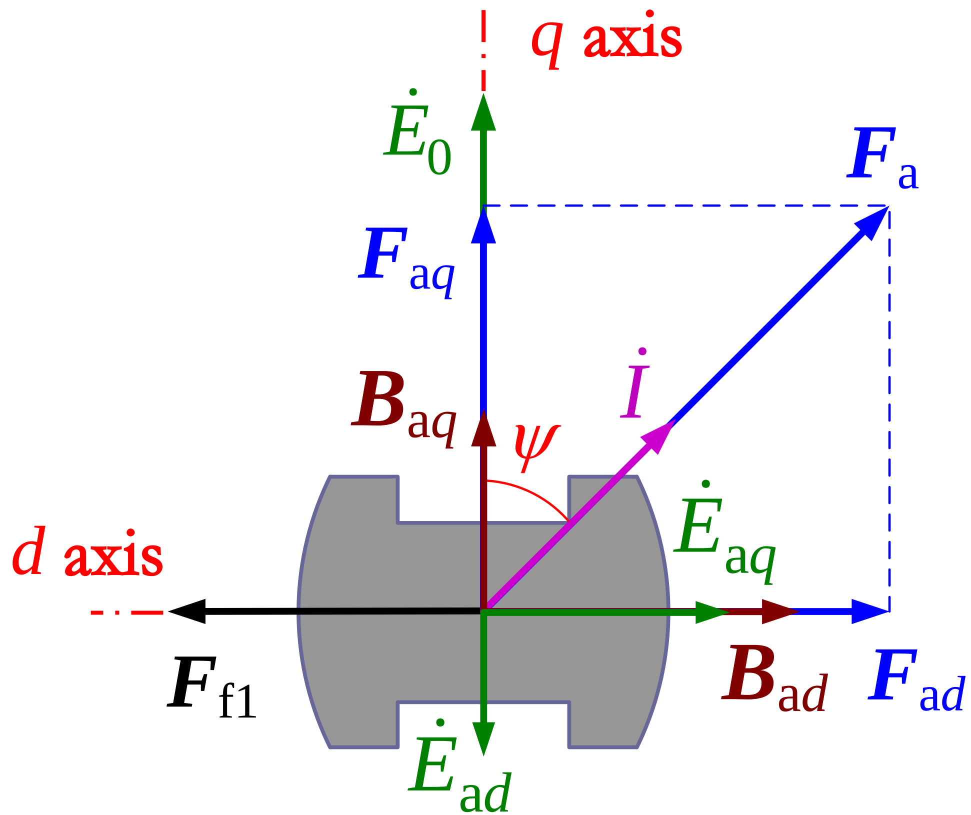


清華大學

d-axis and q-axis

- We decouple F_{a} into $F_{\mathrm{a}d}$ and $F_{\mathrm{a}q}$

$$\boldsymbol{F}_{\mathrm{a}} = \boldsymbol{F}_{\mathrm{a}d} + \boldsymbol{F}_{\mathrm{a}q}$$



清華大學

Electro-magnetic interaction

- Neglect saturation

$$\dot{I} = \dot{I}_d + \dot{I}_q$$

$$I_f \longrightarrow \boldsymbol{F}_{f1} \longrightarrow \boldsymbol{B}_0 \longrightarrow \dot{E}_0$$

$$\dot{I} \to \dot{I}_d \longrightarrow \boldsymbol{F}_{ad} \longrightarrow \boldsymbol{B}_{ad} \longrightarrow \dot{E}_{ad}$$

$$\dot{I} \to \dot{I}_q \longrightarrow \boldsymbol{F}_{aq} \longrightarrow \boldsymbol{B}_{aq} \longrightarrow \dot{E}_{aq}$$

$$\left.\begin{array}{l}\dot{E}_0\\ \dot{E}_{ad}\\ \dot{E}_{aq}\end{array}\right\} \dot{E}_\delta, \quad \left.\begin{array}{l}\dot{E}_\delta\\ \dot{U}\end{array}\right\} \longrightarrow \boxed{\dot{E}_\delta = \dot{U} + \dot{I}Z_\sigma}$$

Electrical Circuit

Non-salient pole $\quad \dot{I} \longrightarrow \boldsymbol{F}_a \longrightarrow \boldsymbol{B}_a \longrightarrow \dot{E}_a$

Equivalent circuit

$$\dot{E}_0 + \dot{E}_{\mathrm{ad}} + \dot{E}_{\mathrm{aq}} = \dot{U} + \dot{I}(R + \mathrm{j}X_\sigma)$$

$$\dot{E}_{\mathrm{ad}} = -\mathrm{j}\dot{I}_d X_{\mathrm{ad}} \quad , \quad \dot{E}_{\mathrm{aq}} = -\mathrm{j}\dot{I}_q X_{\mathrm{aq}}$$

$$\mathrm{j}\dot{I}X_\sigma = \mathrm{j}(\dot{I}_d + \dot{I}_q)X_\sigma = \mathrm{j}\dot{I}_d X_\sigma + \mathrm{j}\dot{I}_q X_\sigma$$

Equivalent circuit

$$\dot{E}_0 = \dot{U} + \dot{I}R + \mathrm{j}\dot{I}_d X_d + \mathrm{j}\dot{I}_q X_q$$

$$X_d = X_\sigma + X_{\mathrm{a}d}, \quad X_q = X_\sigma + X_{\mathrm{a}q}$$

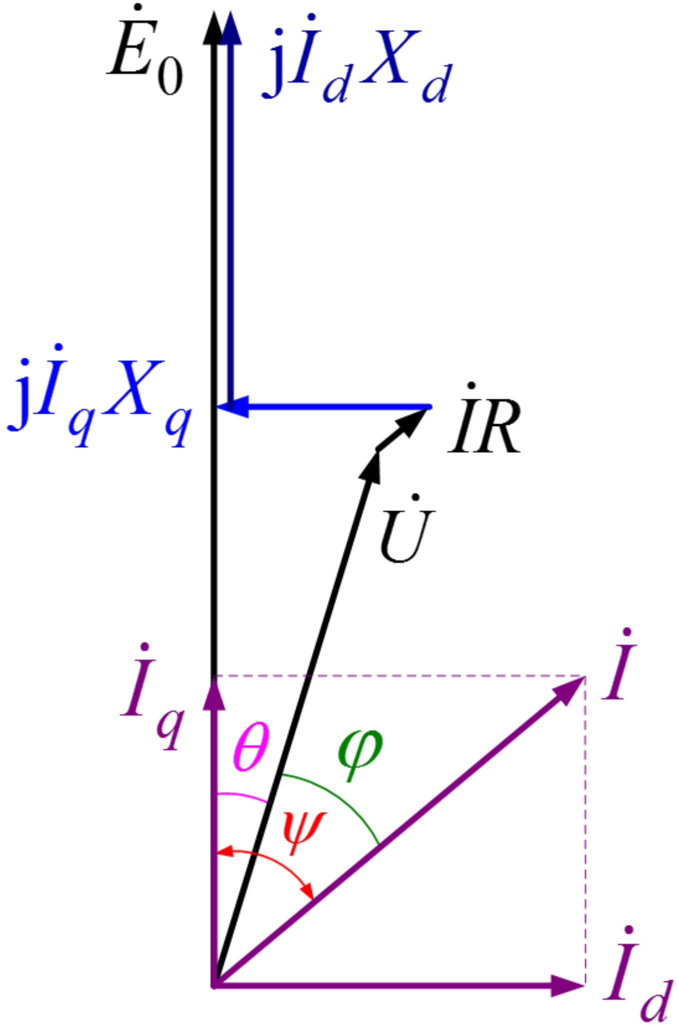
清华大学

Phasor diagram

$$\dot{E}_0 = \dot{U} + \dot{I}R + \mathrm{j}\dot{I}_d X_d + \mathrm{j}\dot{I}_q X_q$$

$$I_d = I \sin \psi$$

$$I_q = I \cos \psi$$

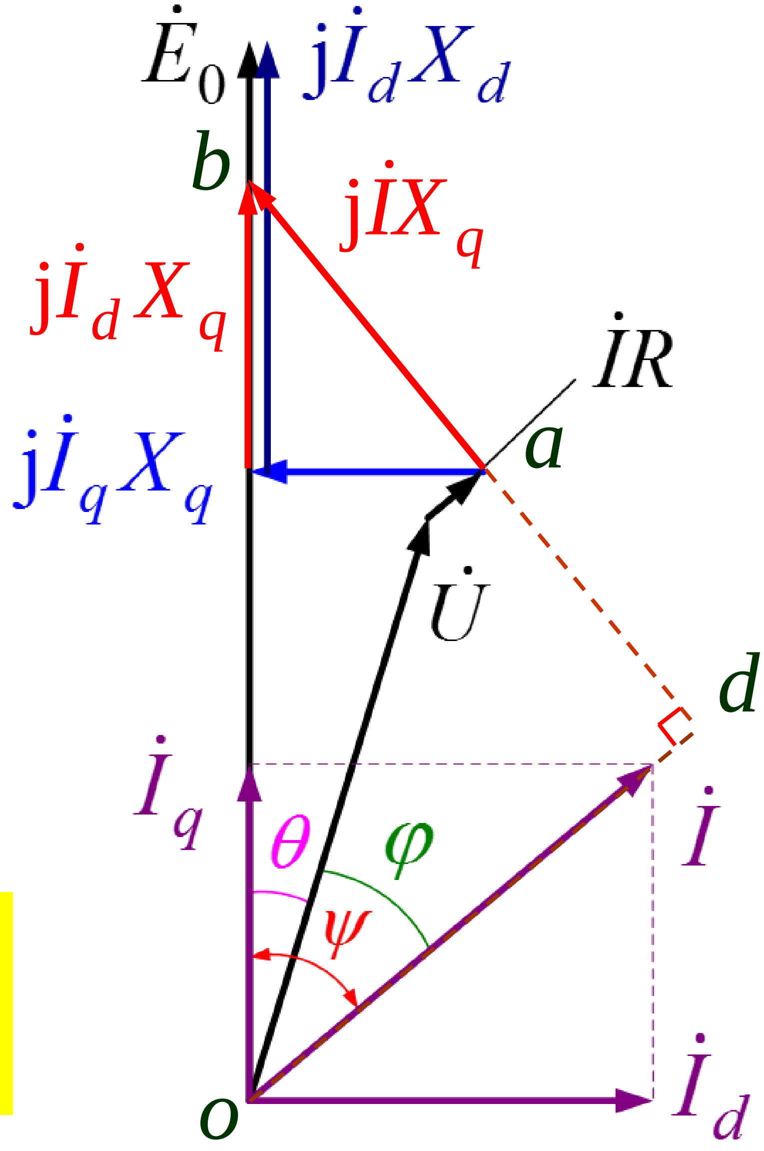


$$\tan\psi = \frac{bd}{od} = \frac{ab+ad}{od}$$

$$\Downarrow$$

$$\tan\psi = \frac{IX_q + U\sin\varphi}{IR + U\cos\varphi}$$

$$\psi = \varphi + \theta = \arctan\frac{IX_q + U\sin\varphi}{IR + U\cos\varphi}$$



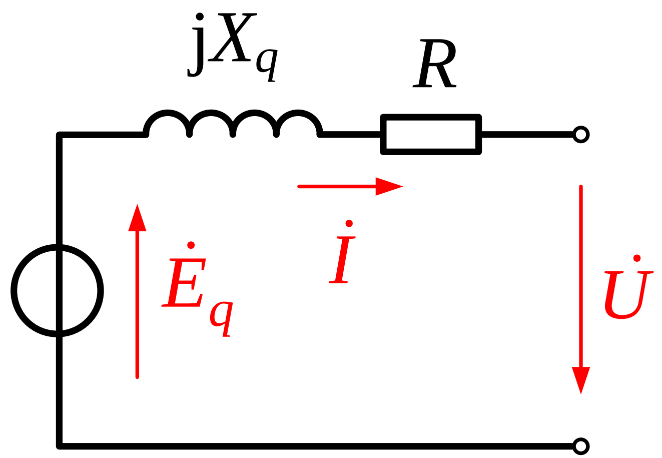
Approximate equivalent circuit

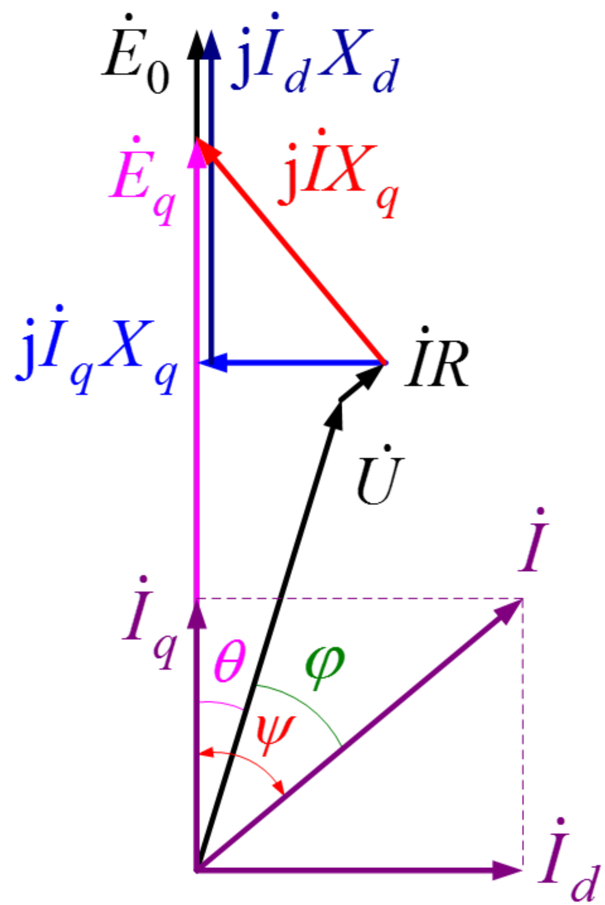
$$\dot{E}_q = \dot{U} + \dot{I}R + \mathrm{j}\dot{I}_d X_q + \mathrm{j}\dot{I}_q X_q = \dot{U} + \dot{I}R + \mathrm{j}\dot{I}X_q$$

$$\dot{E}_0 = \dot{E}_q + \mathrm{j}\dot{I}_d (X_d - X_q)$$

$\dot{E}_q$ is in phase with $\dot{E}_0$

If we substitute $\dot{E}_0$ with $\dot{E}_q$





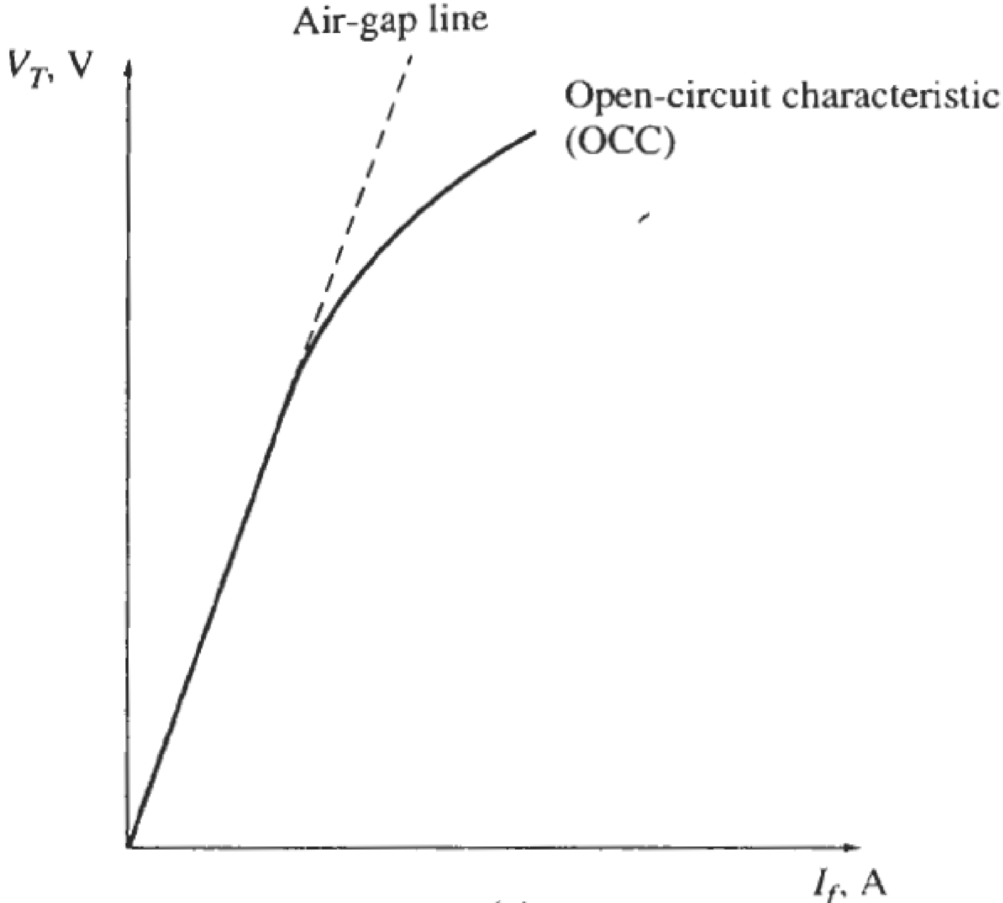
Measuring synchronous generator model parameters

- The armature resistance
- The relationship between field current and flux
- The synchronous reactance
- Leakage reactance

The open circuit test

- The generator is turned at the rated speed, the terminals are disconnected from all loads, and the field current is set to zero.
- We gradually increase the field current and measure the terminal voltage.
- The linear portion of OCC is the air-gap line

OCC (open circuit characteristic)

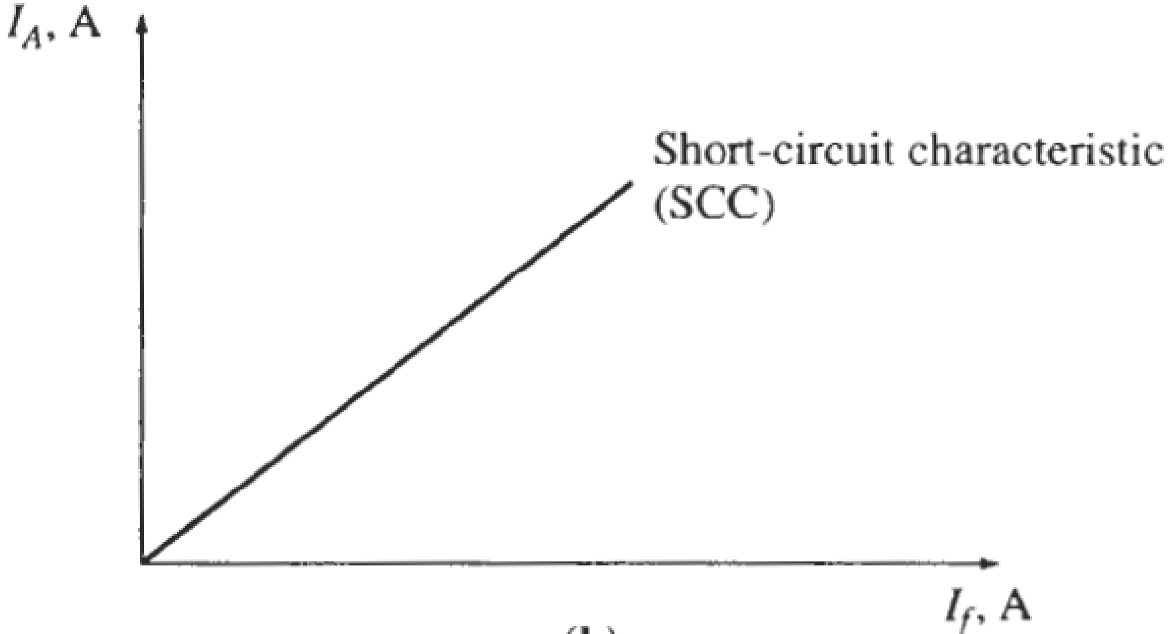


(a)

Short circuit test

- We adjust the field current to zero and short circuit the terminals of the generator
- Then, the armature current or the line current is measured as the field current is increased.

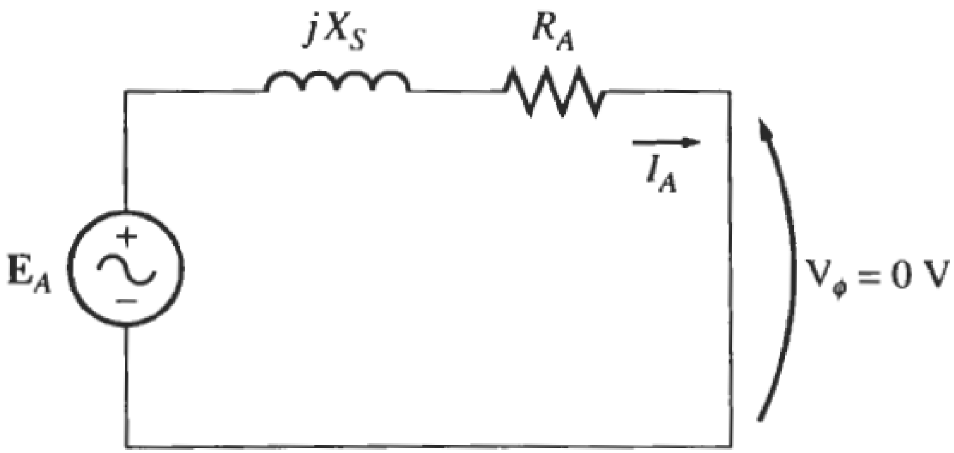
SCC (short circuit characteristic)

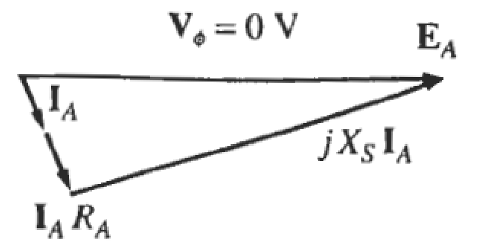


(b)

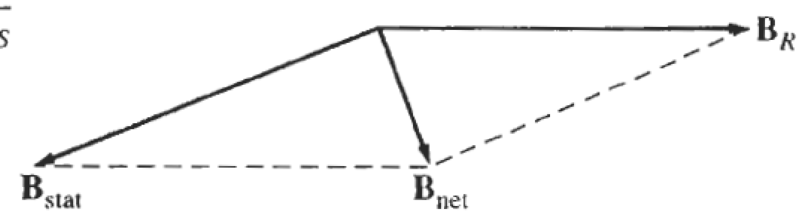
Why the SCC is a straight line ?

- Since the B_{net} is very small, the machine is unsaturated





$$\mathbf{I}_A = \frac{E_A}{R_A + jX_S}$$



The X_s obtained from OCC and SCC

- The internal impedance can be obtained

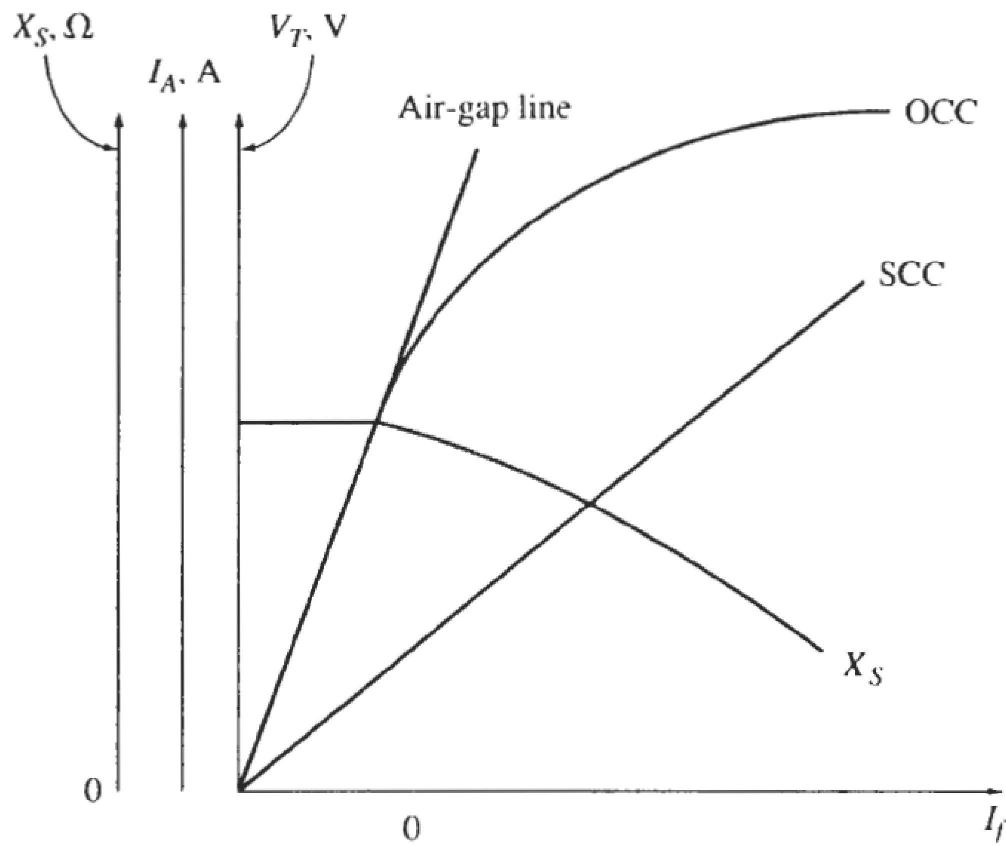
$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A} \qquad X_S \approx \frac{E_A}{I_A} = \frac{V_{\phi,oc}}{I_A}$$

- The computation procedures

1. Get the internal generated voltage E_A from the OCC at that field current.
2. Get the short-circuit current flow $I_{A,SC}$ at that field current from the SCC.
3. Find X_S by applying Equation (5–26).

- The resistance R_A can be obtained by dc voltage applied (the obtained value is slightly small)

The approximation of synchronous reactance



Short circuit ratio

- The ratio of the field current required for the rated voltage at open circuit to the field current required for the rated armature current at short circuit.

Example 5-1

Example 5–1. A 200-kVA, 480-V, 50-Hz, Y-connected synchronous generator with a rated field current of 5 A was tested, and the following data were taken:

1. $V_{T,OC}$ at the rated I_F was measured to be 540 V.
2. $I_{L,SC}$ at the rated I_F was found to be 300 A.
3. When a dc voltage of 10 V was applied to two of the terminals, a current of 25 A was measured.

Find the values of the armature resistance and the approximate synchronous reactance in ohms that would be used in the generator model at the rated conditions.

Example 5-1

Solution

The generator described above is Y-connected, so the direct current in the resistance test flows through two windings. Therefore, the resistance is given by

$$2R_A = \frac{V_{DC}}{I_{DC}}$$

$$R_A = \frac{V_{DC}}{2I_{DC}} = \frac{10\text{ V}}{(2)(25\text{ A})} = 0.2\ \Omega$$

The internal generated voltage at the rated field current is equal to

$$E_A = V_{\phi,OC} = \frac{V_T}{\sqrt{3}}$$

$$= \frac{540\text{ V}}{\sqrt{3}} = 311.8\text{ V}$$

The short-circuit current I_A is just equal to the line current, since the generator is Y-connected:

$$I_{A,SC} = I_{L,SC} = 300\text{ A}$$

Therefore, the synchronous reactance at the rated field current can be calculated from Equation (5–25):

$$\sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A} \tag{5–25}$$

$$\sqrt{(0.2\ \Omega)^2 + X_S^2} = \frac{311.8\ \text{V}}{300\ \text{A}}$$

$$\sqrt{(0.2\ \Omega)^2 + X_S^2} = 1.039\ \Omega$$

$$0.04 + X_S^2 = 1.08$$

$$X_S^2 = 1.04$$

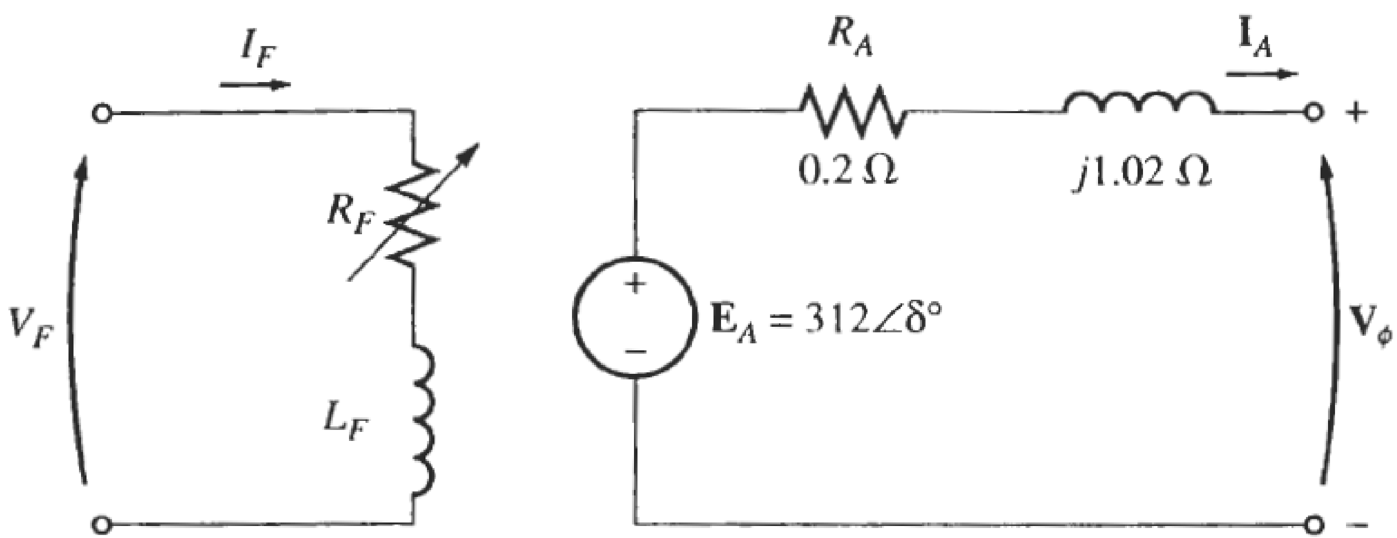
$$X_S = 1.02\ \Omega$$

How much effect did the inclusion of R_A have on the estimate of X_S? Not much. If X_S is evaluated by Equation (5–26), the result is

$$X_S = \frac{E_A}{I_A} = \frac{311.8\ \text{V}}{300\ \text{A}} = 1.04\ \Omega$$

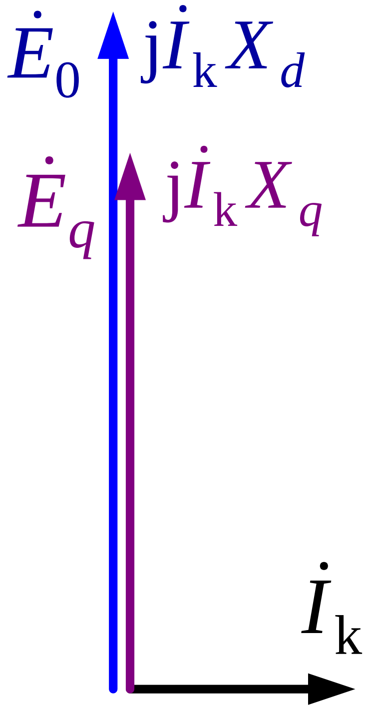
Since the error in X_S due to ignoring R_A is much less than the error due to saturation effects, approximate calculations are normally done with Equation (5–26).

Example 5-1

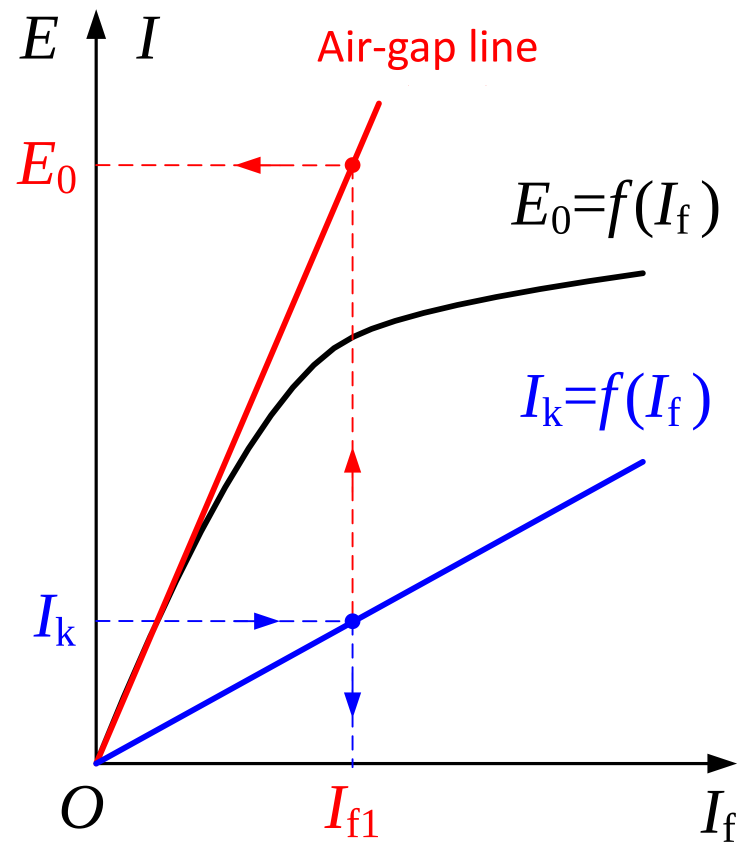


I_F
V_F
R_F
L_F
R_A
$0.2\ \Omega$
$j1.02\ \Omega$
$\mathbf{I}_A$
+
−
$\mathbf{E}_A = 312\angle\delta°$
$\mathbf{V}_\phi$
+
−

Salient pole machine



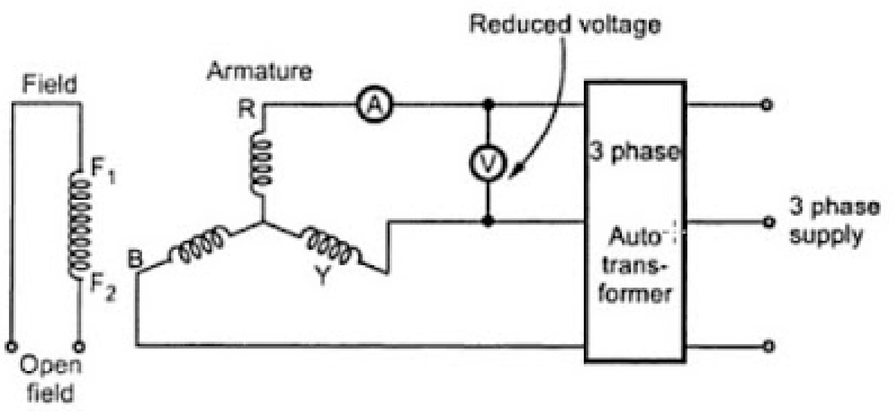
$$X_d = \frac{E_0}{I_k}$$



How to determine X_q

Slip test

- In the slip test, a three phase supply is applied to the armature, having voltage must less than the rated voltage while the field winding circuit is kept open
- The generator is run at a speed close to synchronous but little less than synchronous value.



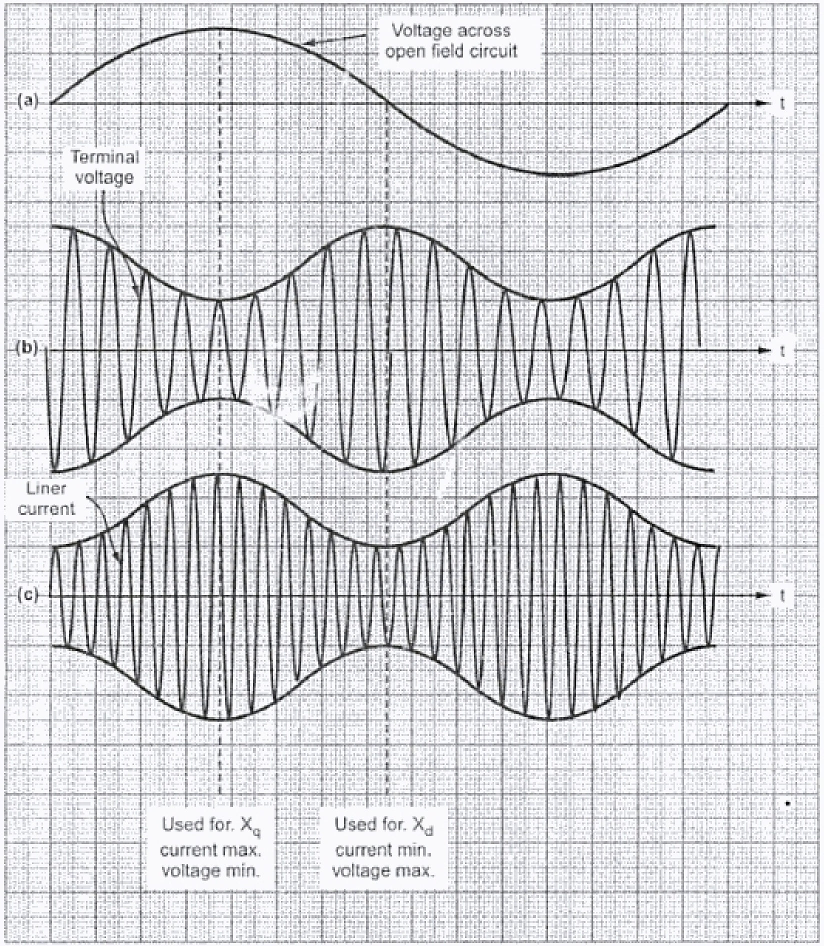
Slip test

- The rotor is made to rotate at a speed little less than the synchronous speed. Thus armature m.m.f. having synchronous speed, moves slowly past the filed poles at a slip speed (n_s -n) where n is actual speed of rotor. This causes an e.m.f. to be induced in the field circuit.
- When the stator m.m.f. is aligned with the d-axis of field poles then flux Φ_d per poles is set up and the effective reactance offered by the alternator is X_d.
- When the stator m.m.f. is aligned with the q-axis of field poles then flux Φ_q per pole is set up and the effective reactance offered by the alternator is X_q.

Slip test

$$X_d = \frac{\text{Maximum voltage}}{\text{Minimum current}} = \frac{(V_t)\text{ line (at minimum } I_a)}{\sqrt{3}\, I_a\,(\text{min})}$$

$$X_q = \frac{\text{Minimum voltage}}{\text{Maximum current}} = \frac{(V_t)\text{ line (at maximum } I_a)}{\sqrt{3}\, I_a\,(\text{max})}$$

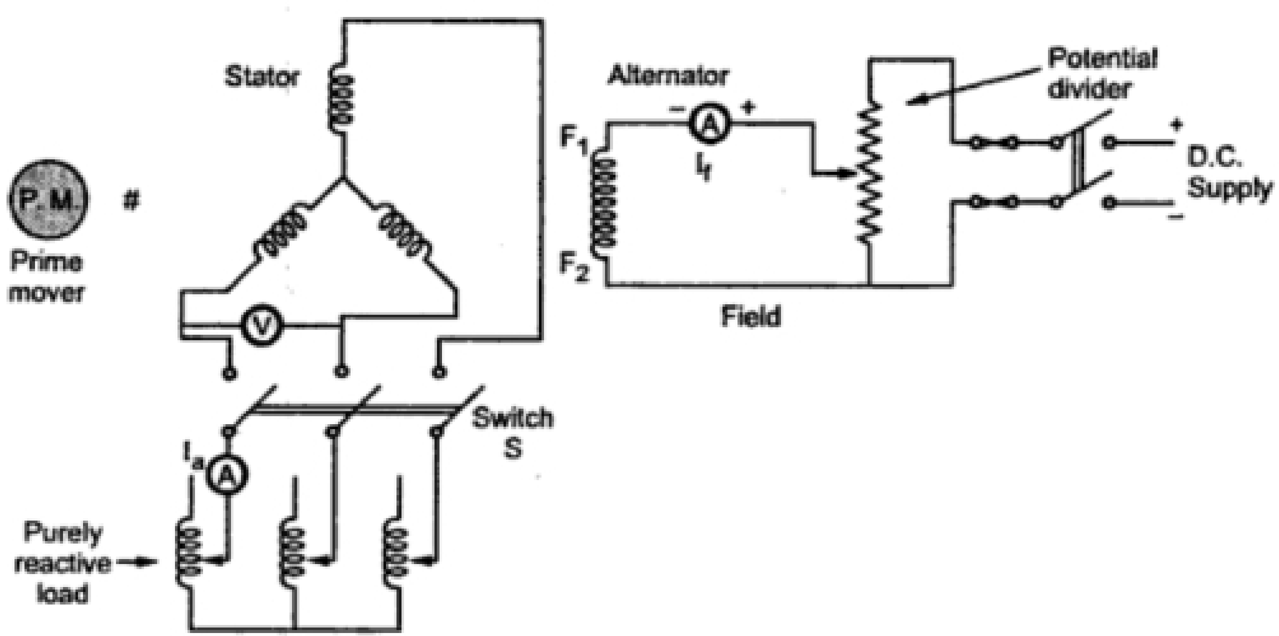


Zero-power-factor characteristics and Potier triangle

清華大學

Zero-power-factor test

- Zero-power-factor test is conducted to determine leakage reactance.
- The generator is connected an adjustable inductive load
- Vary I_f and load the same time, maintain I=constant, measure terminal voltage

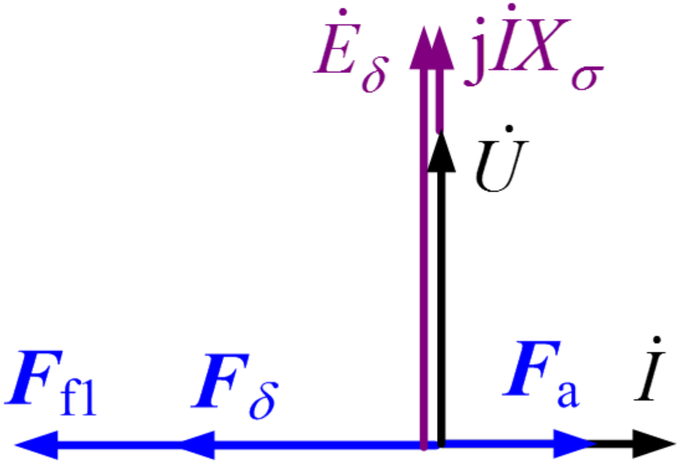


Zero-power-factor characteristics

- $\boldsymbol{F}_{\mathrm{a}d}=\boldsymbol{F}_{\mathrm{a}}$， $\boldsymbol{F}_{\mathrm{a}q}=0$

$$E_\delta=U+IX_\sigma$$

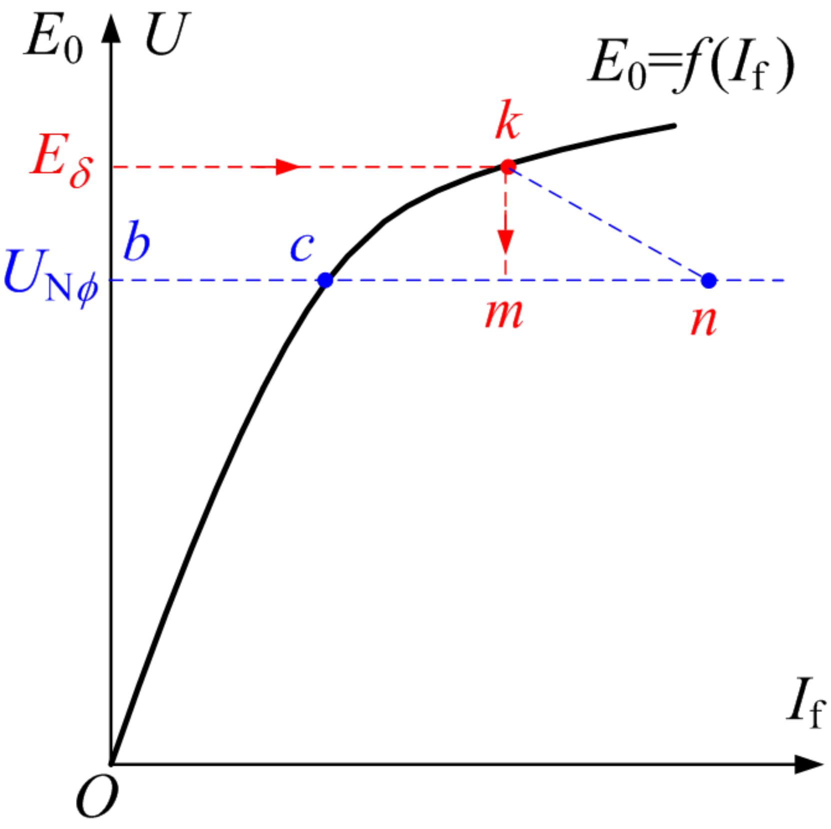
$$F_\delta=F_{\mathrm{f1}}-F_{\mathrm{a}}$$



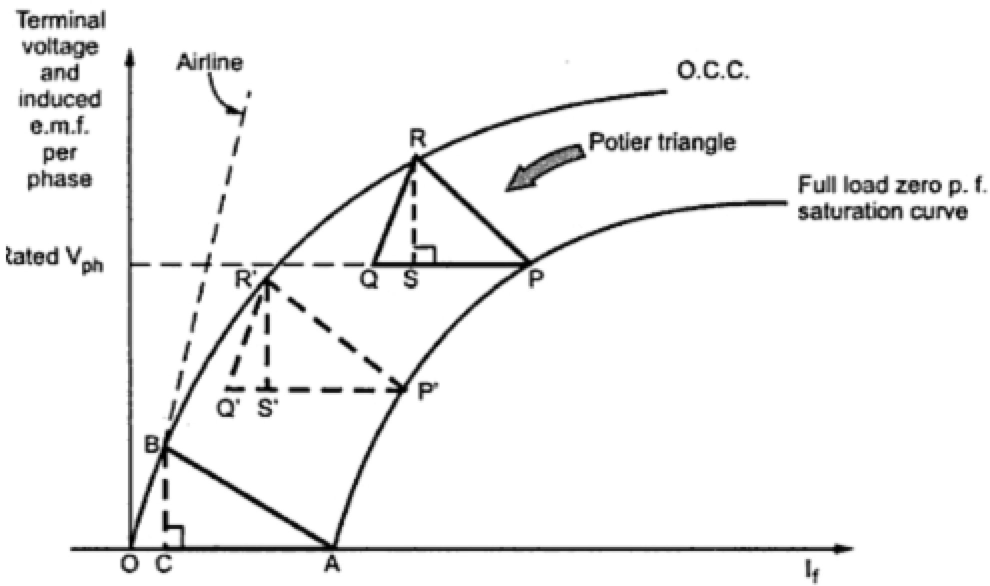
Zero-power-factor characteristics

- $km = I X_\sigma$
- $bm = I_f$ required to generate E_δ
- $mn = I_f$ required to compensate for $\boldsymbol{F}_a$

$$E_\delta = U + I X_\sigma$$
$$F_\delta = F_{f1} - F_a$$



Potier Triangle



$$l\,(RS) = l\,(BC) = (I_{aph})_{F.L.} \times X_{L\,ph}$$

$$X_{L\,ph} = \frac{l\,(RS)\ \text{or}\ l(BC)}{(I_{aph})\ F.L.}\quad \Omega$$

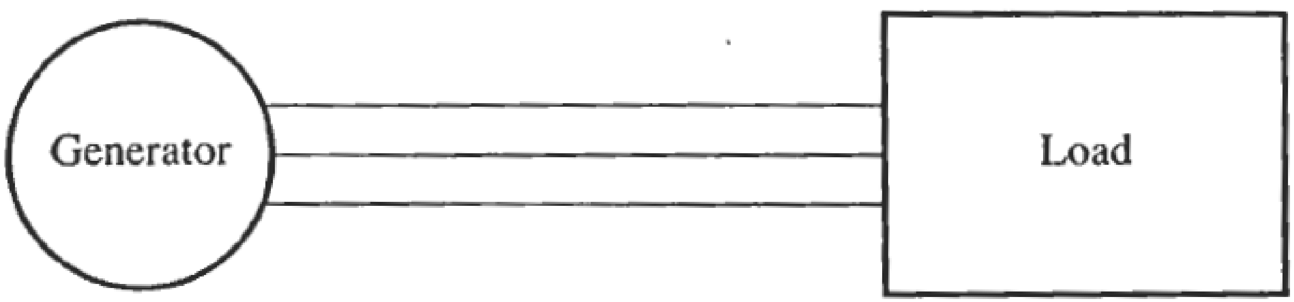
Potier Triangle

- Draw the tangent to O.C.C. through origin which is line OB as shown dotted in the Fig. 1. This is called air line.
- Draw the horizontal line PQ parallel and equal to OA.
- From point Q draw the line parallel to the air line which intersects O.C.C. at point R. Join RQ and join PR. The triangle PQR is called potier triangle.
- From point R, drop a perpendicular on PQ to meet at point S.
- The length PS gives field current necessary to overcome demagnetizing effect of armature reaction at full load.

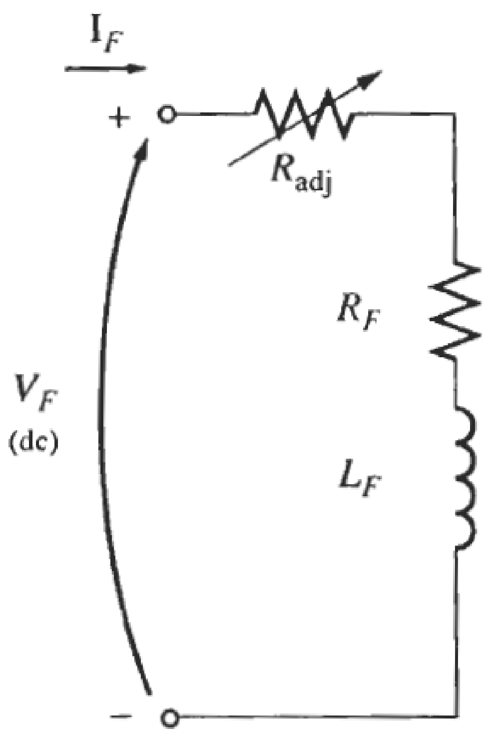
Voltage regulation (VR)

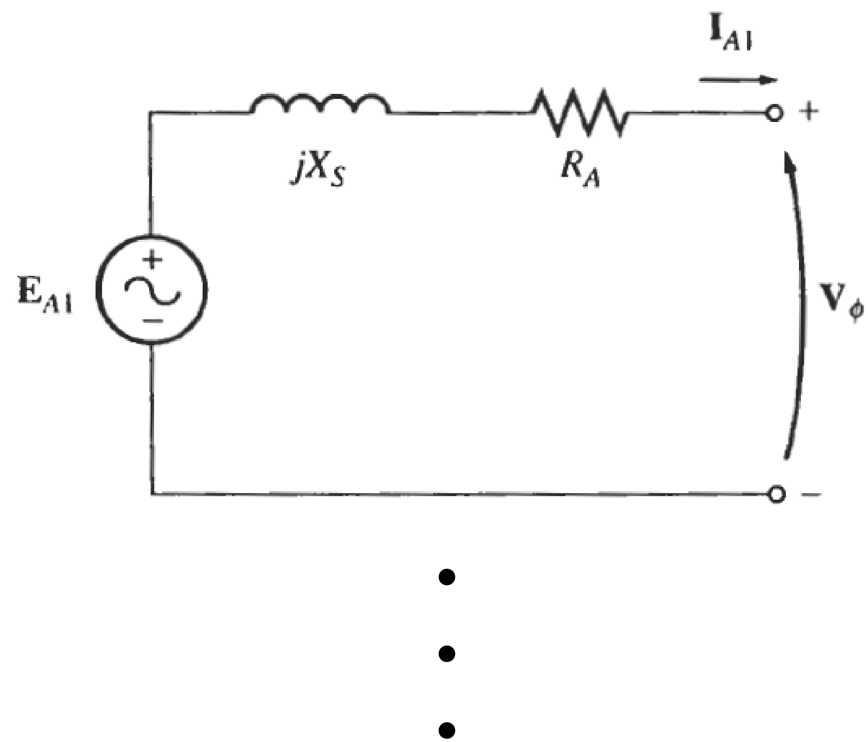
The synchronous generator operating alone

- The terminal voltage is not constant
- The machine speed is assumed as a constant
- The internal voltage is assumed as a constant
- The terminal voltage change due to the load change

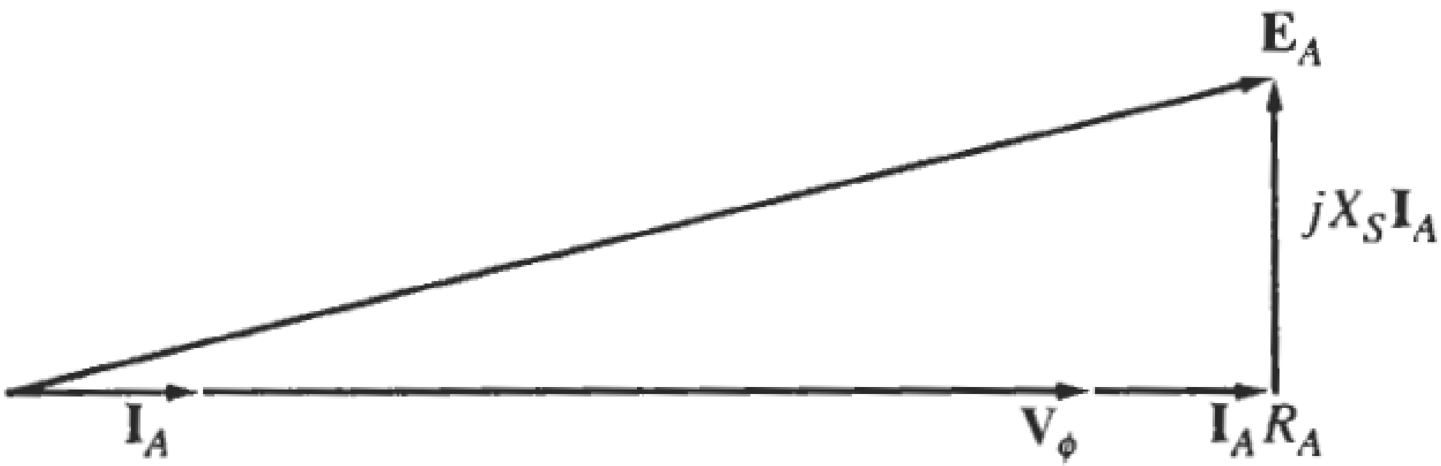


The equivalent circuit of a three-phase synchronous generator

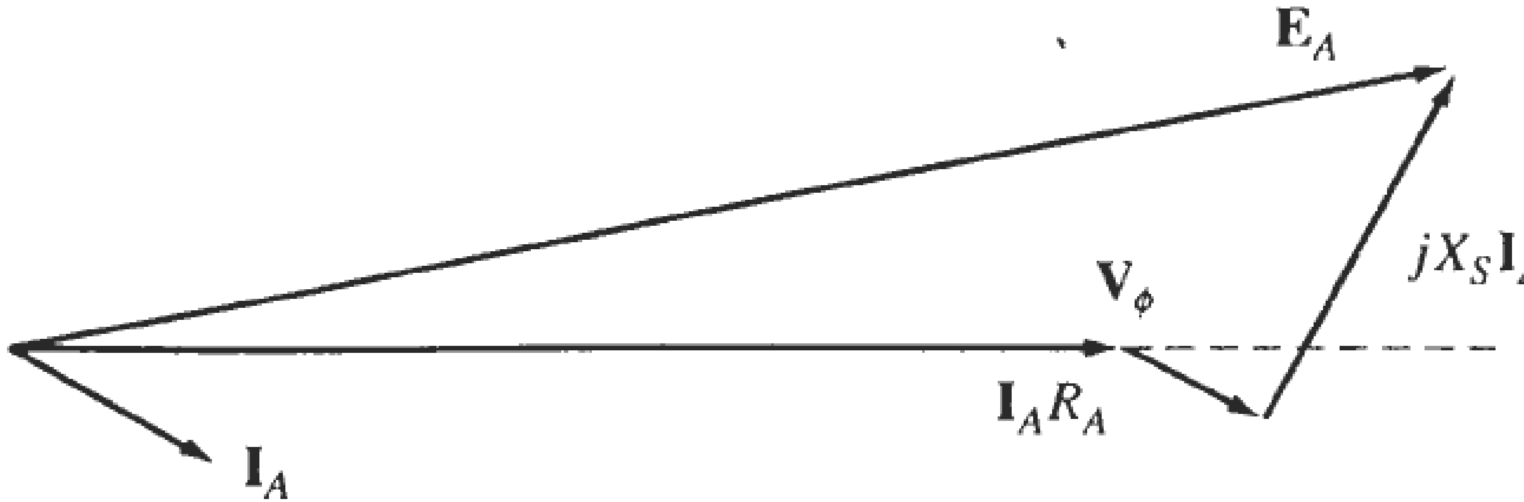




The phasor diagram of a synchronous generator – unity power factor

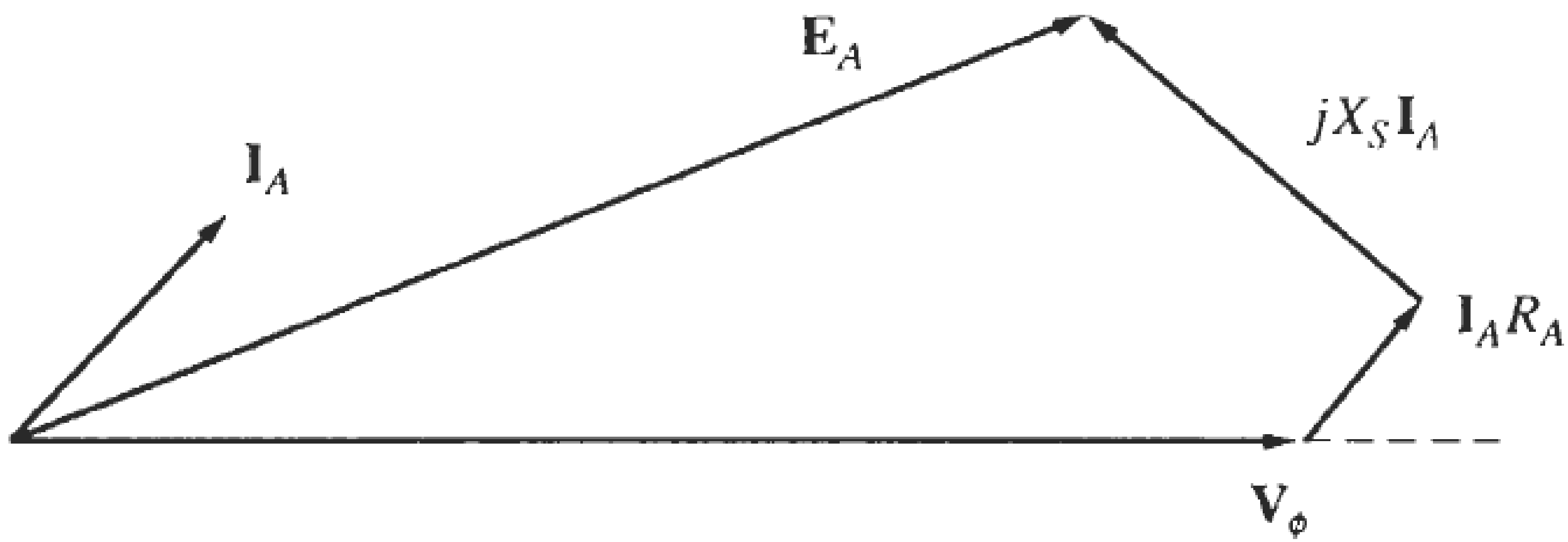


The phasor diagram of a synchronous generator – lagging power factor

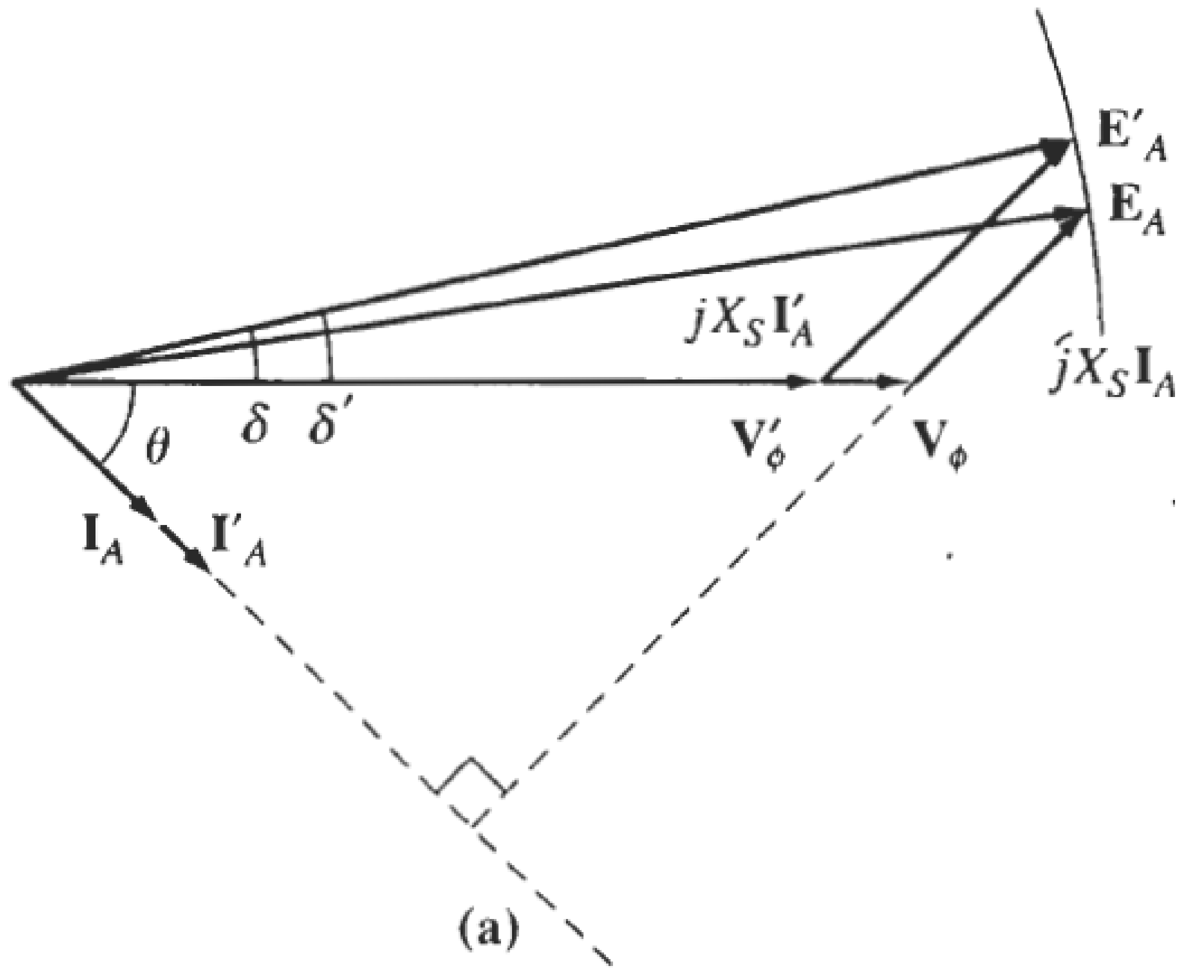


清華大學

The phasor diagram of a synchronous generator – leading power factor



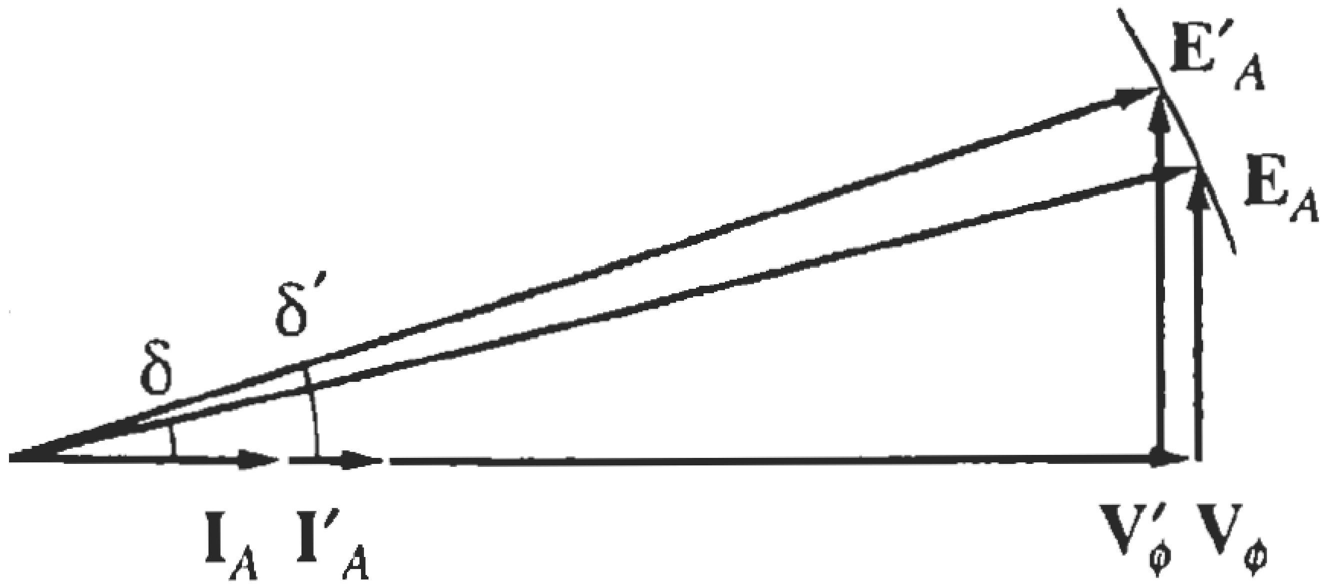
Lagging power factor load change



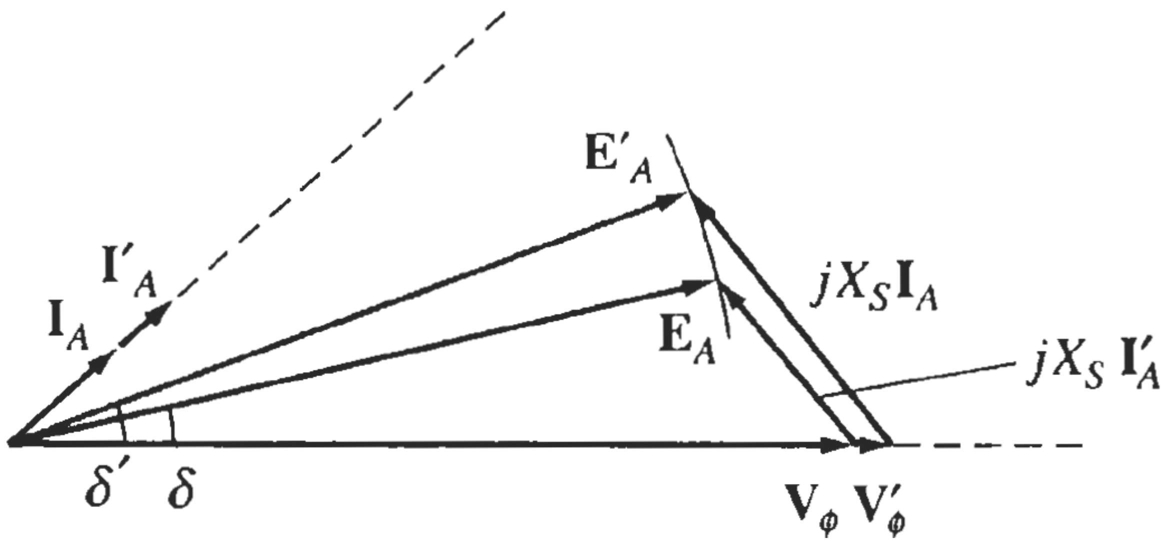
(a)

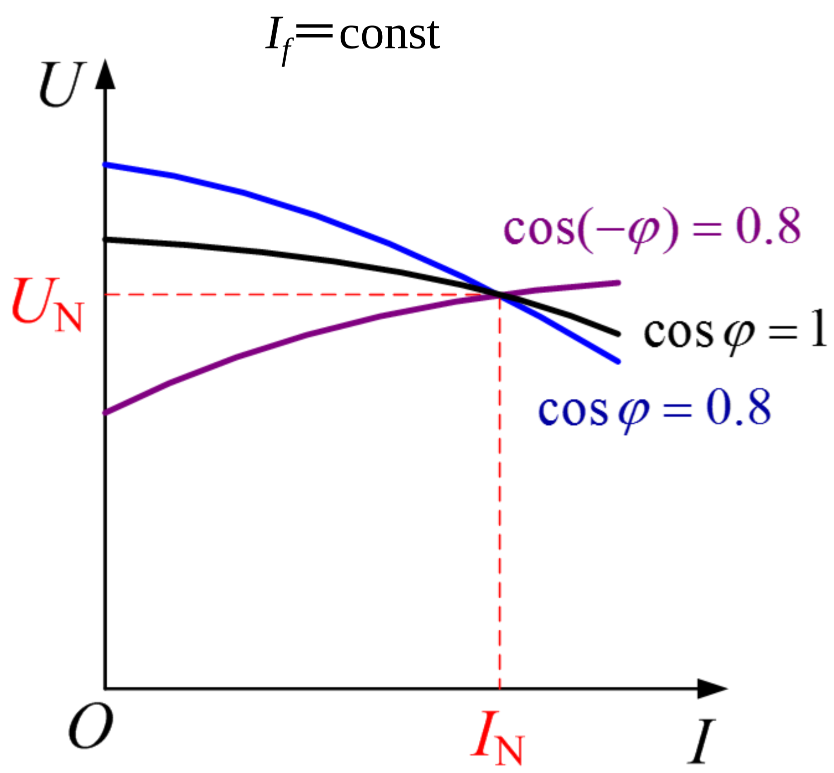
清華大學

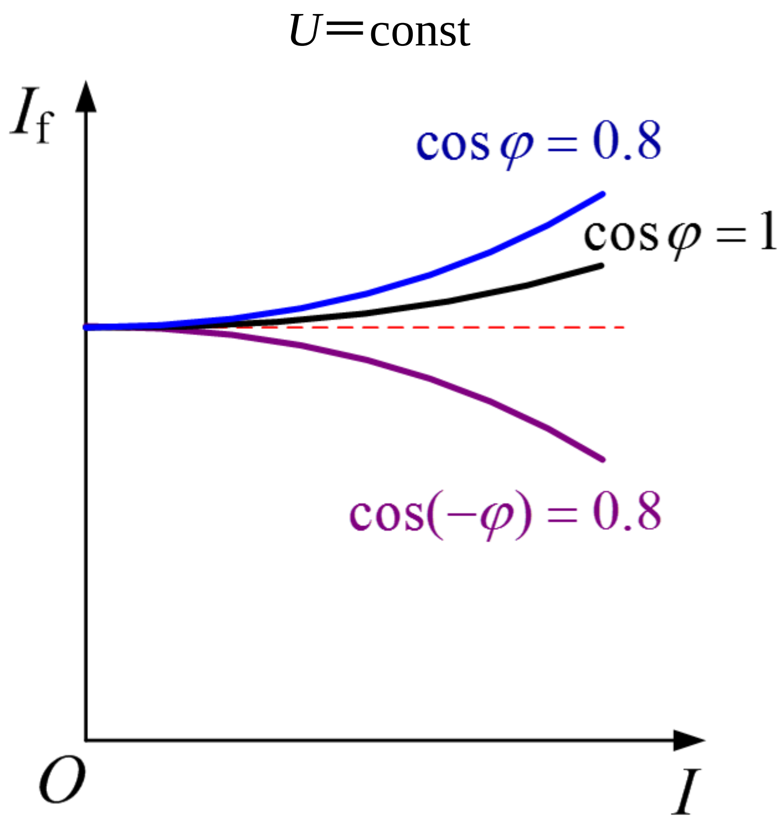
Unity power factor load change



Leading power factor load change




I_f=const
U
U_N
$\cos(-\varphi)=0.8$
$\cos\varphi=1$
$\cos\varphi=0.8$
O
I_N
I


U=const
I_f
$\cos\varphi=0.8$
$\cos\varphi=1$
$\cos(-\varphi)=0.8$
O
I

General conclusions from this discussions

1. If lagging loads ($+Q$ or inductive reactive power loads) are added to a generator, $\mathbf{V}_\phi$ and the terminal voltage V_T decrease significantly.
2. If unity-power-factor loads (no reactive power) are added to a generator, there is a slight decrease in $\mathbf{V}_\phi$ and the terminal voltage.
3. If leading loads ($-Q$ or capacitive reactive power loads) are added to a generator, $\mathbf{V}_\phi$ and the terminal voltage will rise.

Voltage regulation (VR)

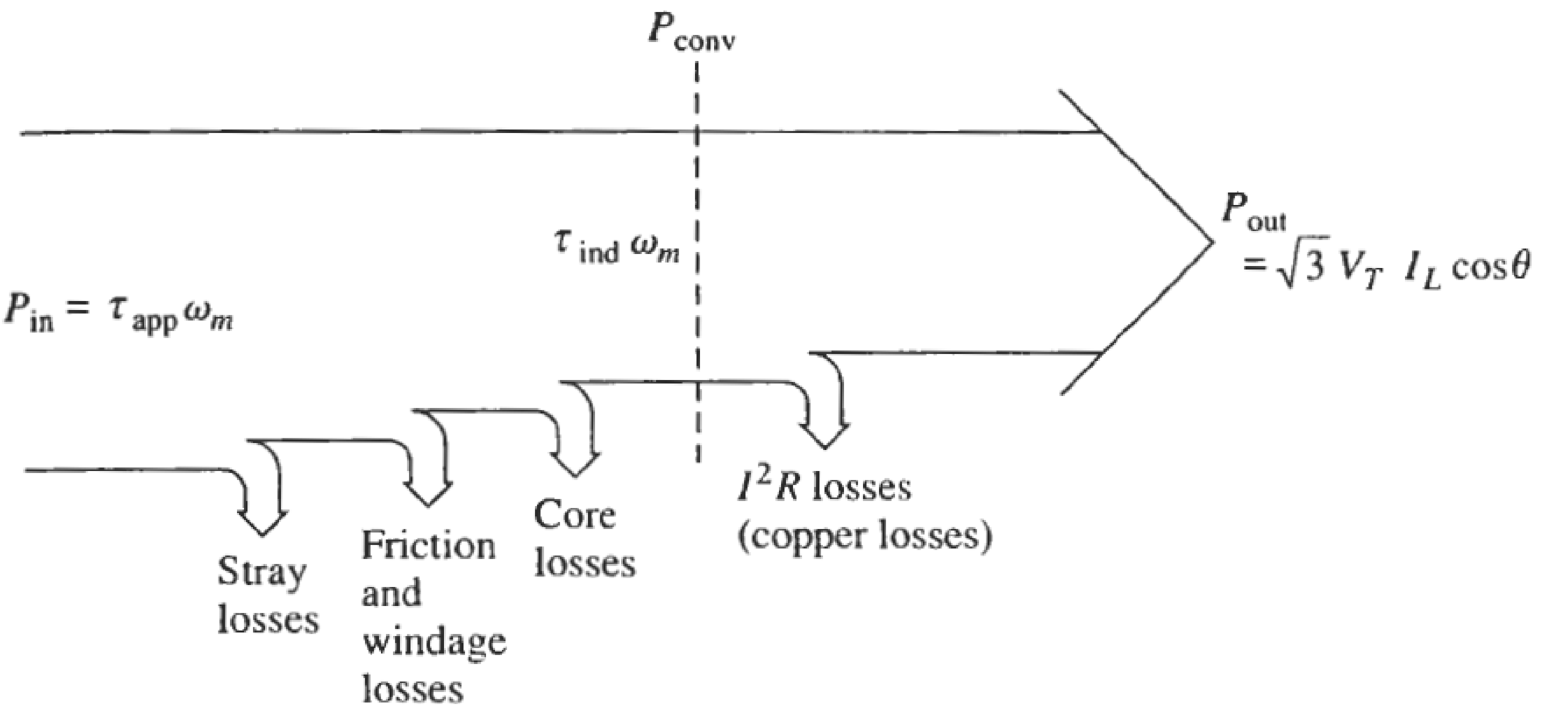
- The voltage of a generator is defined as

$$\mathrm{VR} = \frac{V_{\mathrm{nl}} - V_{\mathrm{fl}}}{V_{\mathrm{fl}}} \times 100\%$$

- How to keep the terminal voltage constant when load change ?
  - Since the frequency cannot be changed, the way to keep voltage constant is to tune the flux in the machine

Power and torque in synchronous generators

Power flow diagram of a synchronous generator



Power and torque in synchronous generators

- The power converted from mechanical to electrical is

$$P_{\text{conv}} = \tau_{\text{ind}}\omega_m = 3E_A I_A \cos\gamma$$

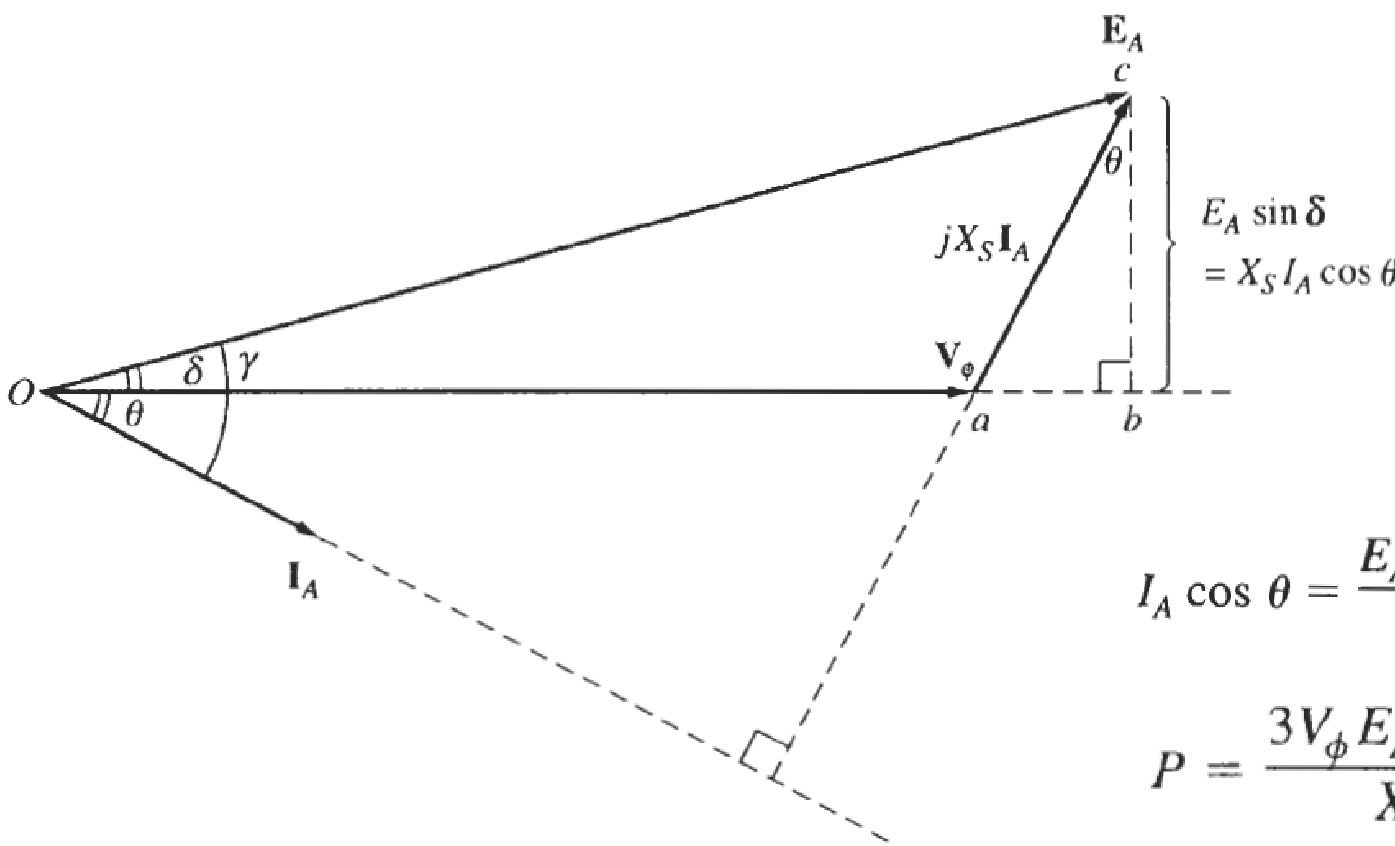
- The real electrical output power

$$P_{\text{out}} = \sqrt{3}V_T I_L \cos\theta \qquad P_{\text{out}} = 3V_\phi I_A \cos\theta$$

- The reactive output power

$$Q_{\text{out}} = \sqrt{3}V_T I_L \sin\theta \qquad Q_{\text{out}} = 3V_\phi I_A \sin\theta$$

Output power equation



$$I_A \cos \theta = \frac{E_A \sin \delta}{X_S}$$

$$P = \frac{3V_\phi E_A \sin \delta}{X_S}$$

The angle δ and torque τ_{ind}

- The angle δ is known as the torque angle (power angle) of the machine.
  - The angle difference between E_A (B_R) and V_ϕ (B_{net})
- The maximum output power can be supplied when δ = 90 degrees
- The induced torque in this generator is

$$\tau_{ind} = k\mathbf{B}_R \times \mathbf{B}_{net}$$

$$\tau_{ind} = \frac{3V_\phi E_A \sin \delta}{\omega_m X_S}$$

清華大学

Example 5-2

Example 5–2. A 480-V, 60-Hz, Δ-connected, four-pole synchronous generator has the OCC shown in Figure 5–23a. This generator has a synchronous reactance of 0.1 Ω and an armature resistance of 0.015 Ω. At full load, the machine supplies 1200 A at 0.8 PF lagging. Under full-load conditions, the friction and windage losses are 40 kW, and the core losses are 30 kW. Ignore any field circuit losses.

(a) What is the speed of rotation of this generator?

(b) How much field current must be supplied to the generator to make the terminal voltage 480 V at no load?

(c) If the generator is now connected to a load and the load draws 1200 A at 0.8 PF lagging, how much field current will be required to keep the terminal voltage equal to 480 V?

(d) How much power is the generator now supplying? How much power is supplied to the generator by the prime mover? What is this machine's overall efficiency?

(e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?

(f) Finally, suppose that the generator is connected to a load drawing 1200 A at 0.8 PF *leading*. How much field current would be required to keep V_T at 480 V?

Solution

This synchronous generator is Δ-connected, so its phase voltage is equal to its line voltage $V_\phi = V_T$, while its phase current is related to its line current by the equation $I_L = \sqrt{3} I_\phi$.

(a) The relationship between the electrical frequency produced by a synchronous generator and the mechanical rate of shaft rotation is given by Equation (4–34):

$$f_e = \frac{n_m P}{120} \tag{4–34}$$

Therefore,

$$n_m = \frac{120 f_e}{P}$$

$$= \frac{120(60\text{ Hz})}{4\text{ poles}} = 1800\text{ r/min}$$

(b) In this machine, $V_T = V_\phi$. Since the generator is at no load, $\mathbf{I}_A = 0$ and $\mathbf{E}_A = \mathbf{V}_\phi$. Therefore, $V_T = V_\phi = E_A = 480$ V, and from the open-circuit characteristic, $I_F = 4.5$ A.

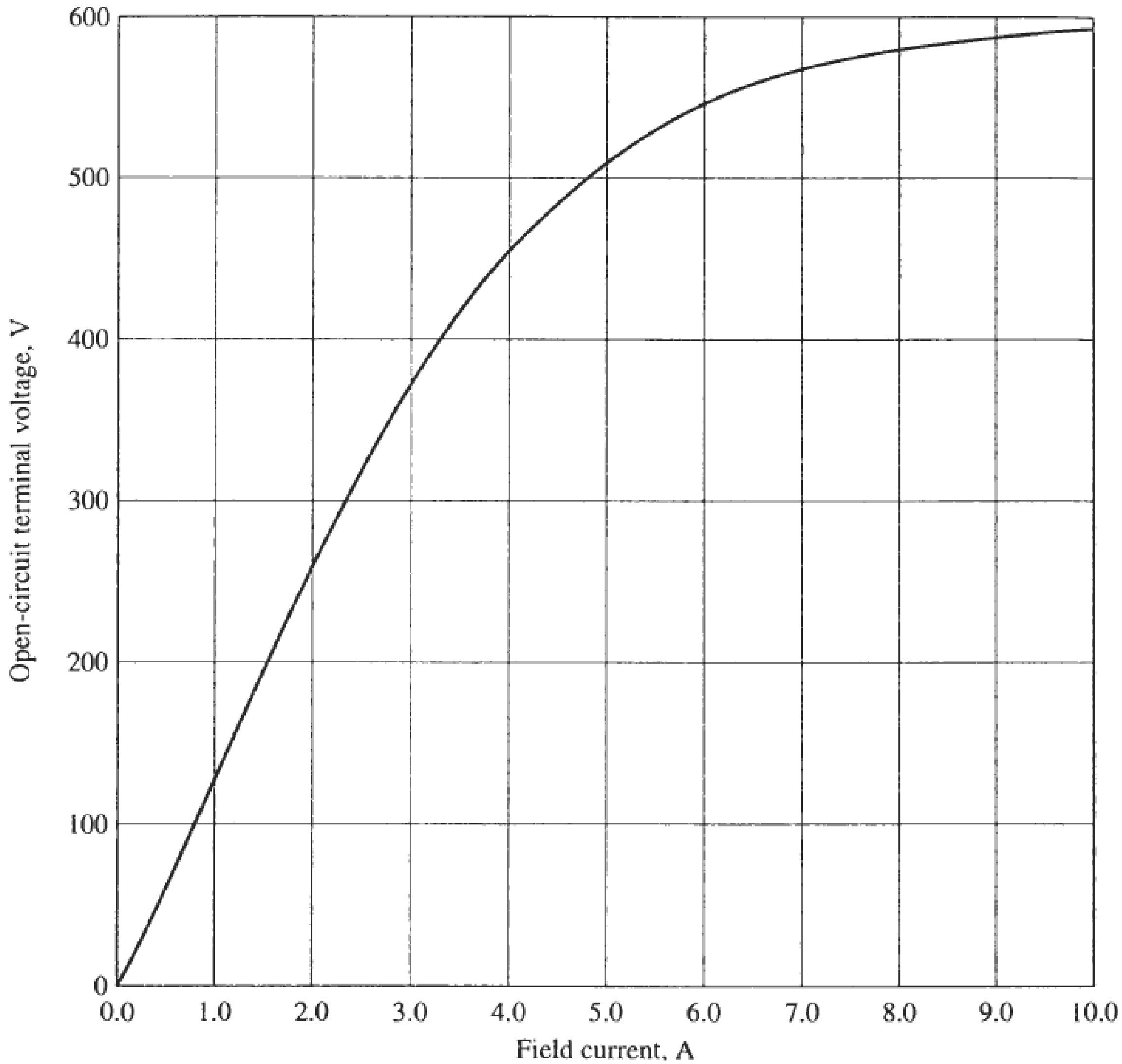
(c) If the generator is supplying 1200 A, then the armature current in the machine is

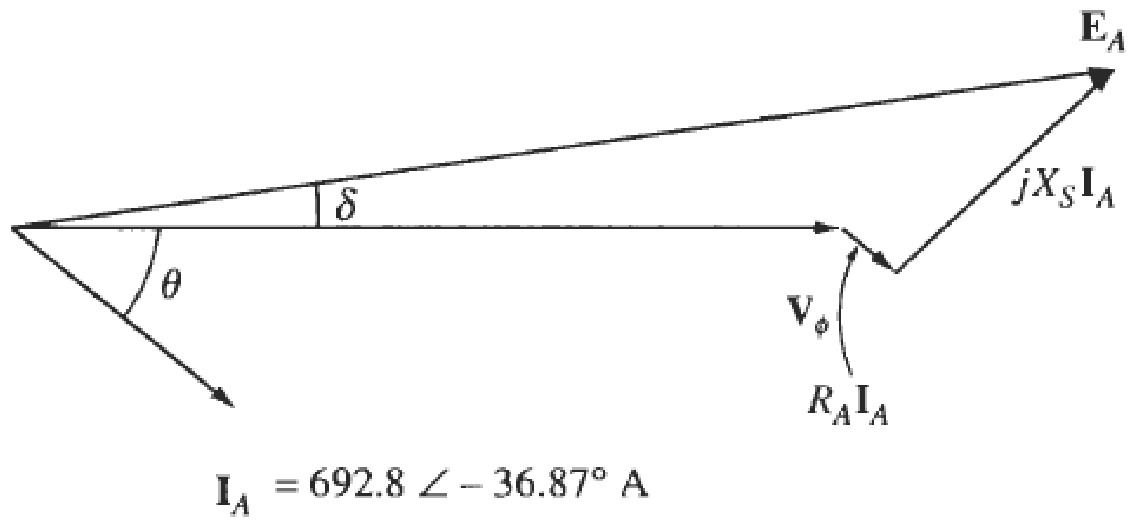
$$I_A = \frac{1200\ \text{A}}{\sqrt{3}} = 692.8\ \text{A}$$

The phasor diagram for this generator is shown in Figure 5–23b. If the terminal voltage is adjusted to be 480 V, the size of the internal generated voltage $\mathbf{E}_A$ is given by

$$\begin{aligned}
\mathbf{E}_A &= \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A \\
&= 480\angle 0°\ \text{V} + (0.015\ \Omega)(692.8\angle -36.87°\ \text{A}) + (j0.1\ \Omega)(692.8\angle -36.87°\ \text{A}) \\
&= 480\angle 0°\ \text{V} + 10.39\angle -36.87°\ \text{V} + 69.28\angle 53.13°\ \text{V} \\
&= 529.9 + j49.2\ \text{V} = 532\angle 5.3°\ \text{V}
\end{aligned}$$

To keep the terminal voltage at 480 V, $\mathbf{E}_A$ must be adjusted to 532 V. From Figure 5–23, the required field current is 5.7 A.


600
500
400
300
200
100
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Open-circuit terminal voltage, V
Field current, A


$\mathbf{E}_A$
δ
$jX_S\mathbf{I}_A$
θ
$\mathbf{V}_\phi$
$R_A\mathbf{I}_A$
$\mathbf{I}_A = 692.8\angle -36.87°$ A

(d) The power that the generator is now supplying can be found from Equation (5–16):

$$
\begin{aligned}
P_{out} &= \sqrt{3} V_T I_L \cos \theta \qquad (5\text{–}16) \\
&= \sqrt{3}(480 \text{ V})(1200 \text{ A}) \cos 36.87° \\
&= 798 \text{ kW}
\end{aligned}
$$

To determine the power input to the generator, use the power-flow diagram (Figure 5–15). From the power-flow diagram, the mechanical input power is given by

$$P_{in} = P_{out} + P_{elec\ loss} + P_{core\ loss} + P_{mech\ loss} + P_{stray\ loss}$$

The stray losses were not specified here, so they will be ignored. In this generator, the electrical losses are

$$
\begin{aligned}
P_{elec\ loss} &= 3 I_A^2 R_A \\
&= 3(692.8 \text{ A})^2(0.015\ \Omega) = 21.6 \text{ kW}
\end{aligned}
$$

The core losses are 30 kW, and the friction and windage losses are 40 kW, so the total input power to the generator is

$$P_{in} = 798 \text{ kW} + 21.6 \text{ kW} + 30 \text{ kW} + 40 \text{ kW} = 889.6 \text{ kW}$$

Therefore, the machine's overall efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{798 \text{ kW}}{889.6 \text{ kW}} \times 100\% = 89.75\%$$

(*e*) If the generator's load were suddenly disconnected from the line, the current $\mathbf{I}_A$ would drop to zero, making $\mathbf{E}_A = \mathbf{V}_\phi$. Since the field current has not changed, $|\mathbf{E}_A|$ has not changed and $\mathbf{V}_\phi$ and V_T must rise to equal $\mathbf{E}_A$. Therefore, if the load were suddenly dropped, the terminal voltage of the generator would rise to 532 V.

(*f*) If the generator were loaded down with 1200 A at 0.8 PF leading while the terminal voltage was 480 V, then the internal generated voltage would have to be

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$

$$= 480\angle 0^\circ \text{ V} + (0.015\ \Omega)(692.8\angle 36.87^\circ \text{ A}) + (j0.1\ \Omega)(692.8\angle 36.87^\circ \text{ A})$$
$$= 480\angle 0^\circ \text{ V} + 10.39\angle 36.87^\circ \text{ V} + 69.28\angle 126.87^\circ \text{ V}$$
$$= 446.7 + j61.7 \text{ V} = 451\angle 7.1^\circ \text{ V}$$

Therefore, the internal generated voltage E_A must be adjusted to provide 451 V if V_T is to remain 480 V. Using the open-circuit characteristic, the field current would have to be adjusted to 4.1 A.

清華大学

Example 5-3

Example 5–3. A 480-V, 50-Hz, Y-connected, six-pole synchronous generator has a per-phase synchronous reactance of 1.0 Ω. Its full-load armature current is 60 A at 0.8 PF lagging. This generator has friction and windage losses of 1.5 kW and core losses of 1.0 kW at 60 Hz at full load. Since the armature resistance is being ignored, assume that the I^2R losses are negligible. The field current has been adjusted so that the terminal voltage is 480 V at no load.

(a) What is the speed of rotation of this generator?

(b) What is the terminal voltage of this generator if the following are true?

1. It is loaded with the rated current at 0.8 PF lagging.
2. It is loaded with the rated current at 1.0 PF.
3. It is loaded with the rated current at 0.8 PF leading.

(c) What is the efficiency of this generator (ignoring the unknown electrical losses) when it is operating at the rated current and 0.8 PF lagging?

(d) How much shaft torque must be applied by the prime mover at full load? How large is the induced countertorque?

(e) What is the voltage regulation of this generator at 0.8 PF lagging? At 1.0 PF? At 0.8 PF leading?

Solution

This generator is Y-connected, so its phase voltage is given by $V_\phi = V_T / \sqrt{3}$. That means that when V_T is adjusted to 480 V, $V_\phi = 277$ V. The field current has been adjusted so that $V_{T,\text{nl}} = 480$ V, so $V_\phi = 277$ V. At *no load*, the armature current is zero, so the armature reaction voltage and the $I_A R_A$ drops are zero. Since $\mathbf{I}_A = 0$, the internal generated voltage $E_A = V_\phi = 277$ V. The internal generated voltage $E_A (= K\phi\omega)$ varies only when the field current changes. Since the problem states that the field current is adjusted initially and then left alone, the magnitude of the internal generated voltage is $E_A = 277$ V and will not change in this example.

(a) The speed of rotation of a synchronous generator in revolutions per minute is given by Equation (4–34):

$$f_e = \frac{n_m P}{120} \tag{4–34}$$

Therefore,

$$n_m = \frac{120 f_e}{P}$$

$$= \frac{120(50\text{ Hz})}{6\text{ poles}} = 1000\text{ r/min}$$

(*b*) 1. If the generator is loaded down with rated current at 0.8 PF lagging, the resulting phasor diagram looks like the one shown in Figure 5–24a. In this phasor diagram, we know that $\mathbf{V}_\phi$ is at an angle of 0°, that the magnitude of $\mathbf{E}_A$ is 277 V, and that the quantity $jX_S\mathbf{I}_A$ is

$$jX_S\mathrm{I}_A = \mathrm{j}(1.0\ \Omega)(60\angle -36.87°\ \mathrm{A}) = 60\angle 53.13°\ \mathrm{V}$$

The two quantities not known on the voltage diagram are the magnitude of $\mathbf{V}_\phi$ and the angle δ of $\mathbf{E}_A$. To find these values, the easiest approach is to construct a right triangle on the phasor diagram, as shown in the figure. From Figure 5–24a, the right triangle gives

$$E_A^2 = (V_\phi + X_S I_A \sin\theta)^2 + (X_S I_A \cos\theta)^2$$

Therefore, the phase voltage at the rated load and 0.8 PF lagging is

$$(277\ \mathrm{V})^2 = [V_\phi + (1.0\ \Omega)(60\ \mathrm{A})\sin 36.87°]^2 + [(1.0\ \Omega)(60\ \mathrm{A})\cos 36.87°]^2$$
$$76{,}729 = (V_\phi + 36)^2 + 2304$$
$$74{,}425 = (V_\phi + 36)^2$$
$$272.8 = V_\phi + 36$$
$$V_\phi = 236.8\ \mathrm{V}$$

Since the generator is Y-connected, $V_T = \sqrt{3}V_\phi = 410$ V.

2. If the generator is loaded with the rated current at unity power factor, then the phasor diagram will look like Figure 5–24b. To find $\mathbf{V}_\phi$ here the right triangle is

$$E_A^2 = V_\phi^2 + (X_S I_A)^2$$

$$(277 \text{ V})^2 = V_\phi^2 + [(1.0 \ \Omega)(60 \text{ A})]^2$$

$$76{,}729 = V_\phi^2 + 3600$$

$$V_\phi^2 = 73{,}129$$

$$V_\phi = 270.4 \text{ V}$$

Therefore, $V_T = \sqrt{3} V_\phi = 468.4$ V.

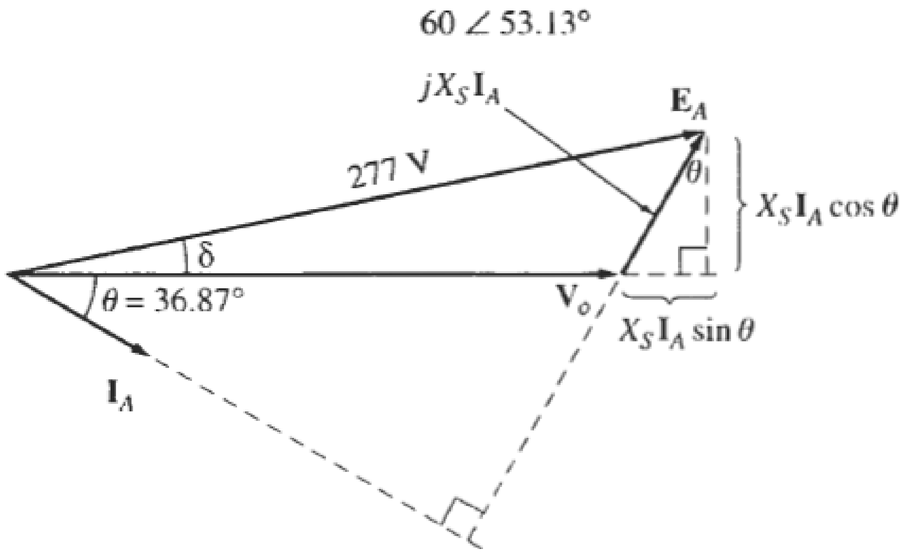
3. When the generator is loaded with the rated current at 0.8 PF leading, the resulting phasor diagram is the one shown in Figure 5–24c. To find $\mathbf{V}_\phi$ in this situation, we construct the triangle *OAB* shown in the figure. The resulting equation is

$$E_A^2 = (V_\phi - X_S I_A)^2 + (X_S I_A \cos\theta)^2$$

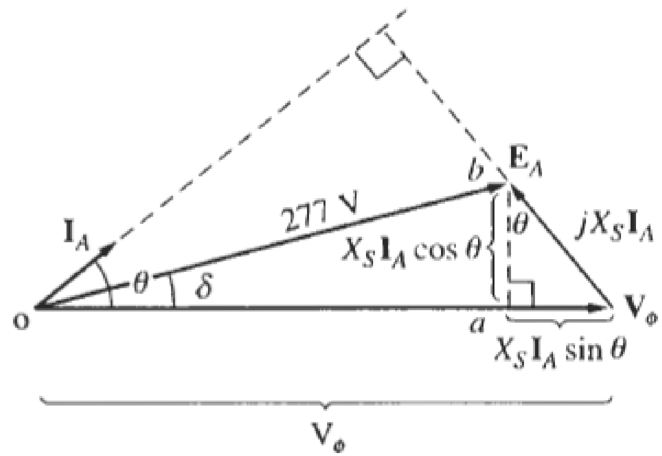
Therefore, the phase voltage at the rated load and 0.8 PF leading is

$$\begin{aligned}
(277\text{ V})^2 &= [V_\phi - (1.0\ \Omega)(60\text{ A})\sin 36.87°]^2 + [(1.0\ \Omega)(60\text{ A})\cos 36.87°]^2 \\
76{,}729 &= (V_\phi - 36)^2 + 2304 \\
74{,}425 &= (V_\phi - 36)^2 \\
272.8 &= V_\phi - 36 \\
V_\phi &= 308.8\text{ V}
\end{aligned}$$

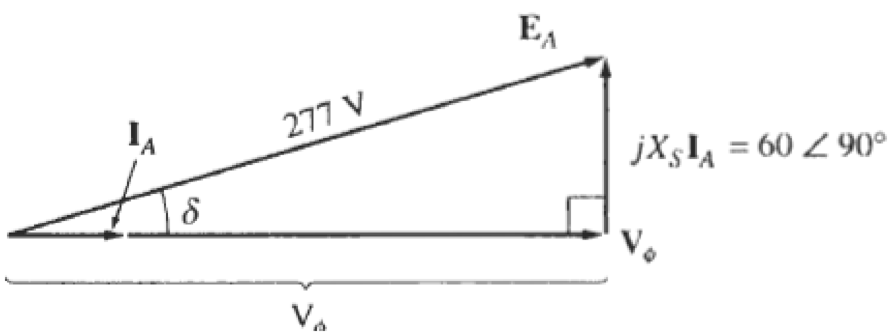
Since the generator is Y-connected, $V_T = \sqrt{3}V_\phi = 535$ V.



60 ∠ 53.13°
$jX_S\mathbf{I}_A$
$\mathbf{E}_A$
277 V
θ
$X_S\mathbf{I}_A\cos\theta$
δ
$\theta = 36.87°$
$\mathbf{V}_\phi$
$X_S\mathbf{I}_A\sin\theta$
$\mathbf{I}_A$



b
$\mathbf{E}_A$
277 V
$\mathbf{I}_A$
θ
$jX_S\mathbf{I}_A$
$X_S\mathbf{I}_A\cos\theta$
θ
δ
o
a
$\mathbf{V}_\phi$
$X_S\mathbf{I}_A\sin\theta$
V_ϕ



$\mathbf{E}_A$
277 V
$\mathbf{I}_A$
$jX_S\mathbf{I}_A = 60 \angle 90°$
δ
$\mathbf{V}_\phi$
V_ϕ

(*c*) The output power of this generator at 60 A and 0.8 PF lagging is

$$P_{\text{out}} = 3V_\phi I_A \cos\theta$$
$$= 3(236.8\ \text{V})(60\ \text{A})(0.8) = 34.1\ \text{kW}$$

The mechanical input power is given by

$$P_{\text{in}} = P_{\text{out}} + P_{\text{elec loss}} + P_{\text{core loss}} + P_{\text{mech loss}}$$
$$= 34.1\ \text{kW} + 0 + 1.0\ \text{kW} + 1.5\ \text{kW} = 36.6\ \text{kV}$$

The efficiency of the generator is thus

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = \frac{34.1\ \text{kW}}{36.6\ \text{kW}} \times 100\% = 93.2\%$$

(d) The input torque to this generator is given by the equation

$$P_{\text{in}} = \tau_{\text{app}}\omega_{\text{m}}$$

so
$$\tau_{\text{app}} = \frac{P_{\text{in}}}{\omega_m} = \frac{36.6\ \text{kW}}{125.7\ \text{rad/s}} = 291.2\ \text{N}\cdot\text{m}$$

The induced countertorque is given by

$$P_{\text{conv}} = \tau_{\text{app}}\omega_{\text{m}}$$

so
$$\tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_V} = \frac{34.1\ \text{kW}}{125.7\ \text{rad/s}} = 271.3\ \text{N}\cdot\text{m}$$

(*e*) The voltage regulation of a generator is defined as

$$\mathrm{VR} = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\% \tag{4-67}$$

By this definition, the voltage regulation for the lagging, unity, and leading power-factor cases are

1. Lagging case: $\mathrm{VR} = \dfrac{480\text{ V} - 410\text{ V}}{410\text{ V}} \times 100\% = 17.1\%$

2. Unity case: $\mathrm{VR} = \dfrac{480\text{ V} - 468\text{ V}}{468\text{ V}} \times 100\% = 2.6\%$

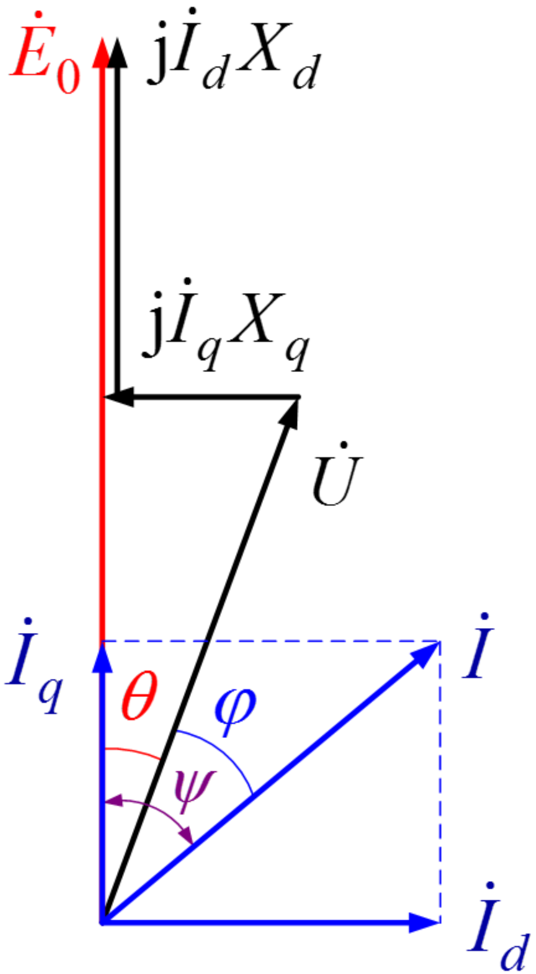
3. Leading case: $\mathrm{VR} = \dfrac{480\text{ V} - 535\text{ V}}{535\text{ V}} \times 100\% = -10.3\%$

Power Angle of Salient-pole Machine

$$P_{em} = mUI(\cos\psi\cos\theta + \sin\psi\sin\theta)$$
$$= mUI_q\cos\theta + mUI_d\sin\theta$$

$$I_d = \frac{E_0 - U\cos\theta}{X_d}, \quad I_q = \frac{U\sin\theta}{X_q}$$

$$P_{em} = m\frac{E_0U}{X_d}\sin\theta + mU^2\frac{X_d - X_q}{2X_dX_q}\sin 2\theta$$



Power Angle of Salient-pole Machine

- Torque of salient-pole machine is consisted of two parts:

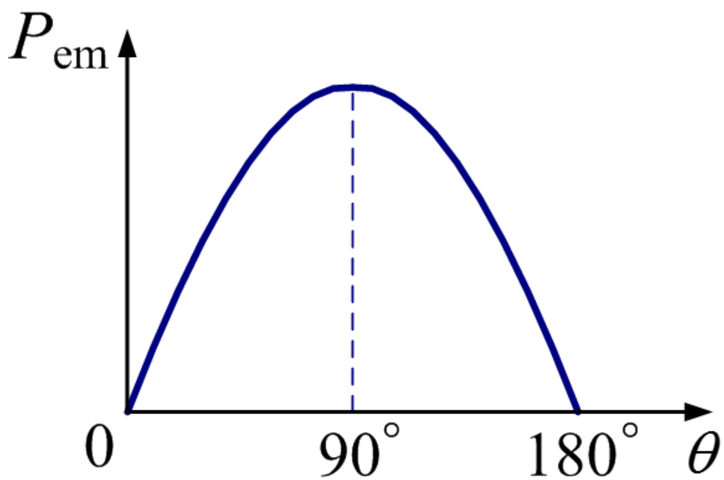
$$P'_{\mathrm{em}} = m\frac{E_0 U}{X_d}\sin\theta$$

$$P''_{\mathrm{em}} = mU^2\frac{X_d - X_q}{2X_d X_q}\sin 2\theta$$

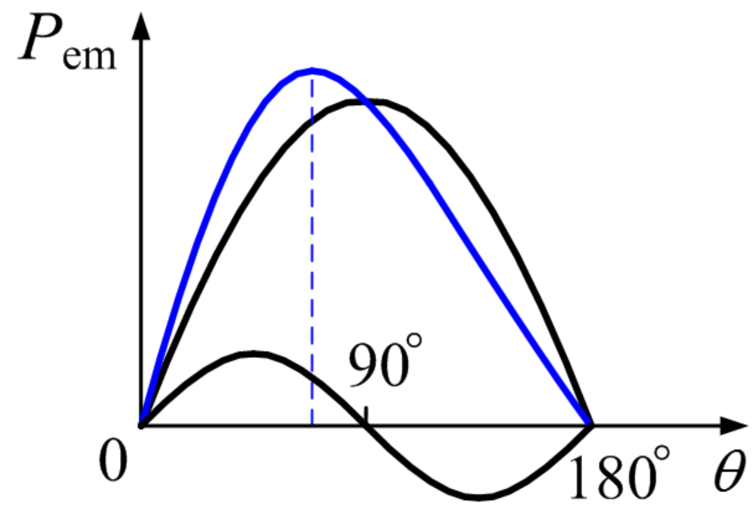
- What is the root cause of the second part?

Power angle summary

Non salient pole machine



salient pole machine



清華大學

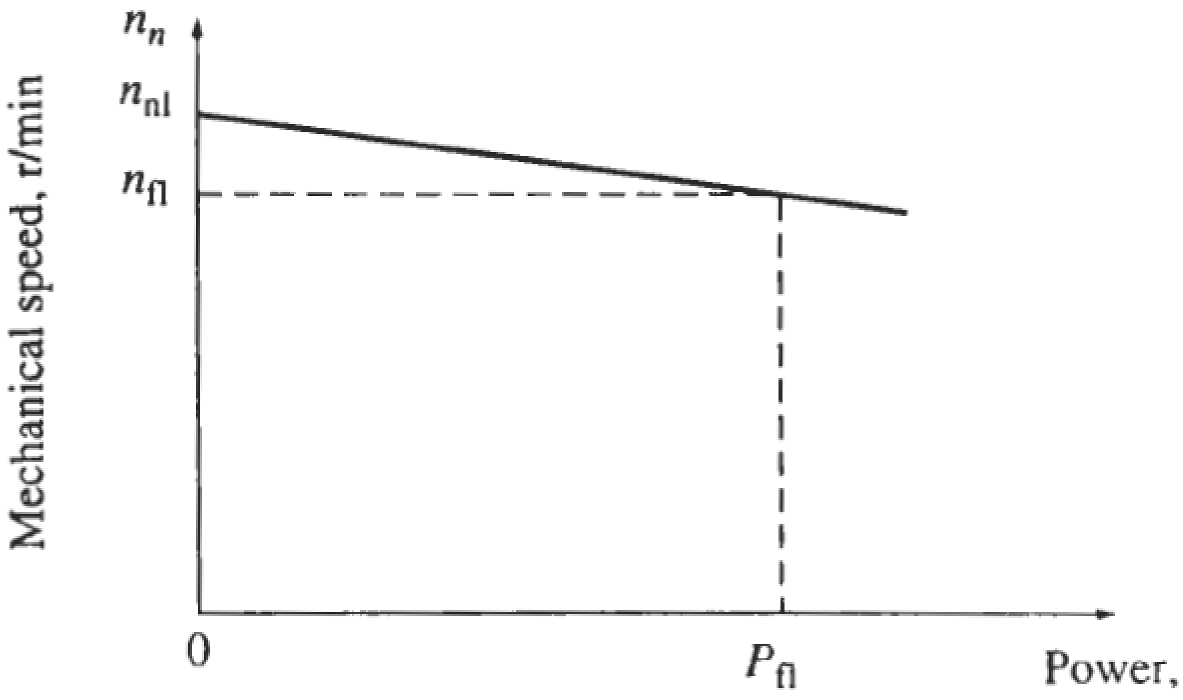
Frequency – power characteristics

Frequency – power characteristics

- Before discussion the parallel operation, we should know the characteristics of generator operate alone.
- From the previous discussions, what is the effect of generator while the real power output increases ?
- The speed of Prime mover (steam turbine) is inversely proportional to the real power load increase.
- The speed droop (SD) of a prime mover

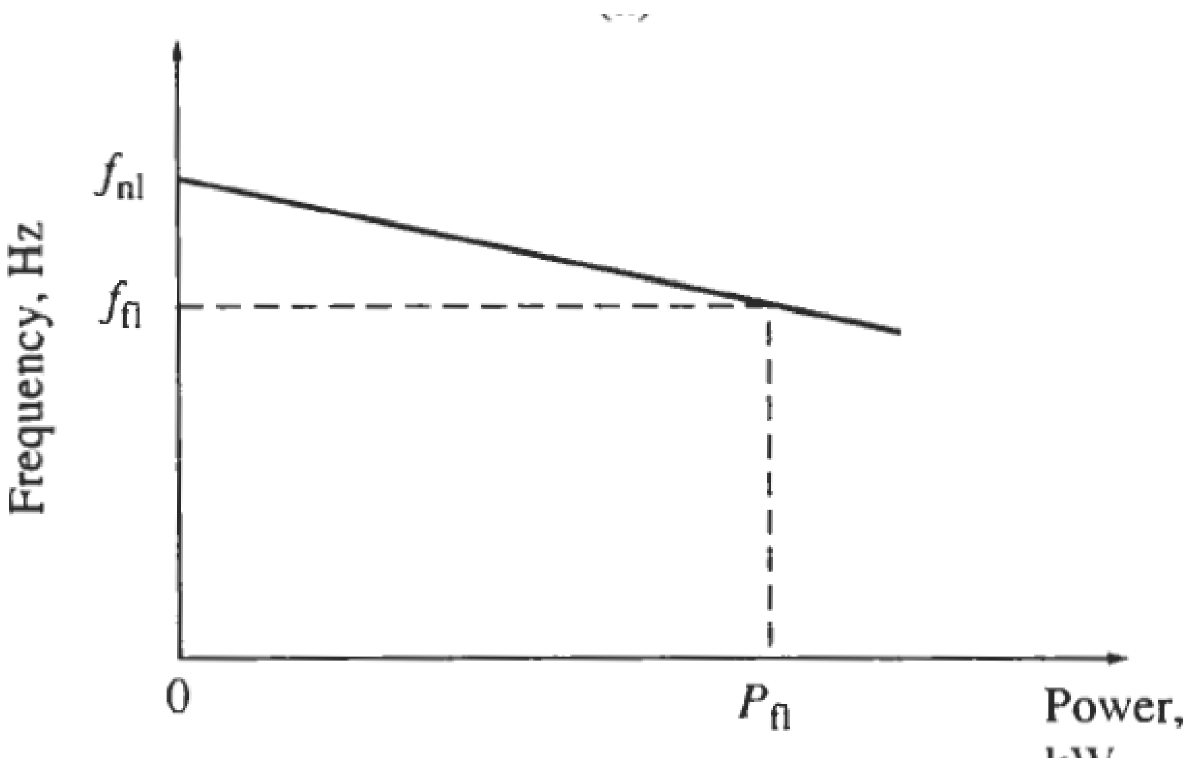
$$\boxed{\mathrm{SD} = \frac{n_{\mathrm{nl}} - n_{\mathrm{fl}}}{n_{\mathrm{fl}}} \times 100\%}$$

A typical speed-versus-power plot



(a)

A typical frequency-versus-power plot



(b)

$$f_e = \frac{n_m P}{120}$$

The relationship between frequency and output power

- The mathematical relation between output frequency and output power is

$$P = s_P(f_{nl} - f_{sys})$$

P = power output of the generator

f_{nl} = no-load frequency of the generator

f_{sys} = operating frequency of system

s_P = slope of curve, in kW/Hz or MW/Hz

The reactive power Q ?

- From the previous discussions, the reactive power Q is mainly relative to the terminal voltage.
- The terminal voltage is controlled by the exciter
  - Exciter voltage, current
  - Flux

Control of reactive power

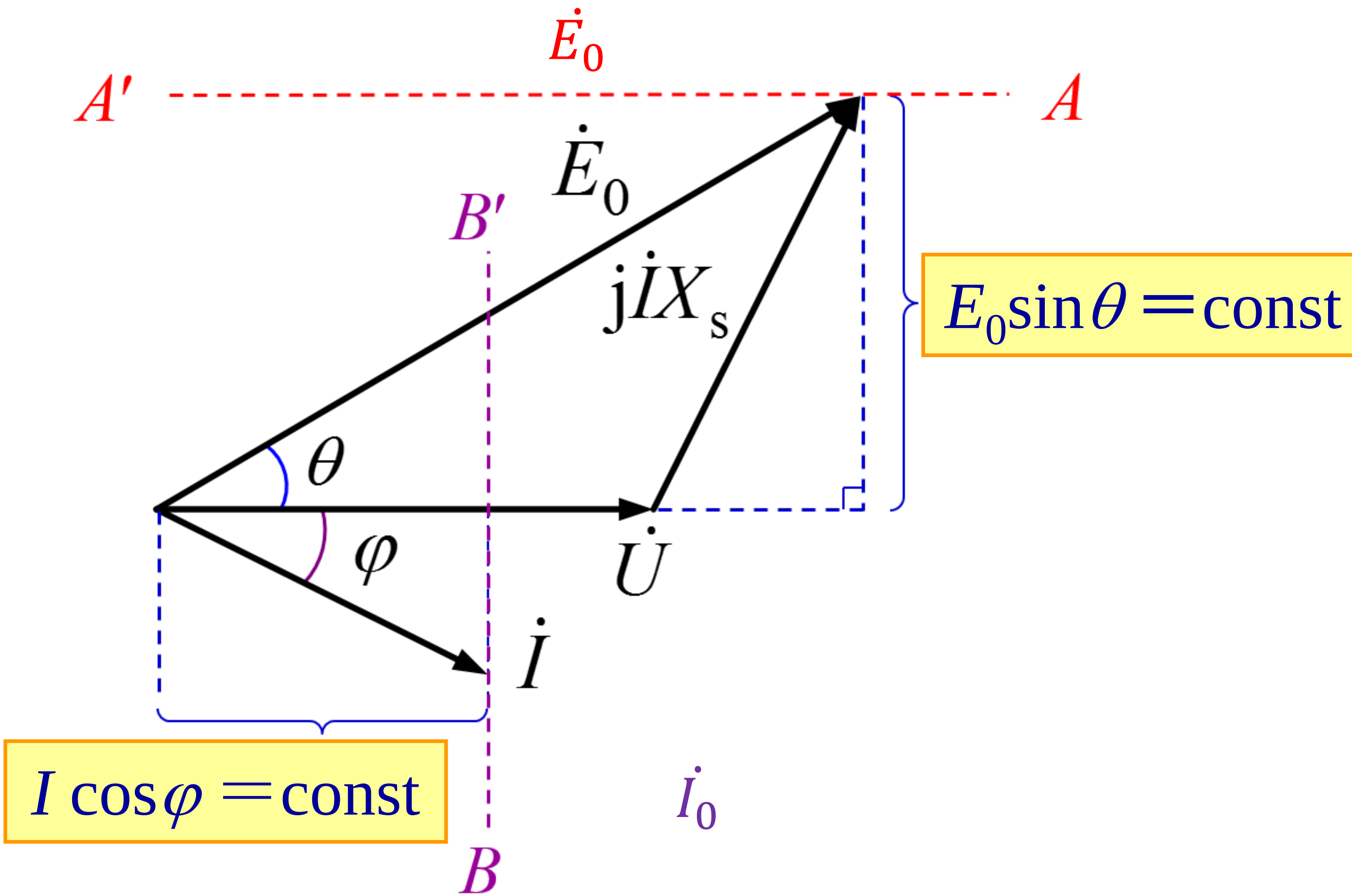
- Assume output power is constant

$$P_2 = mUI\cos\varphi = \text{const}$$

$$P_{\text{em}} = m\frac{E_0 U}{X_s}\sin\theta = P_2 = \text{const}$$

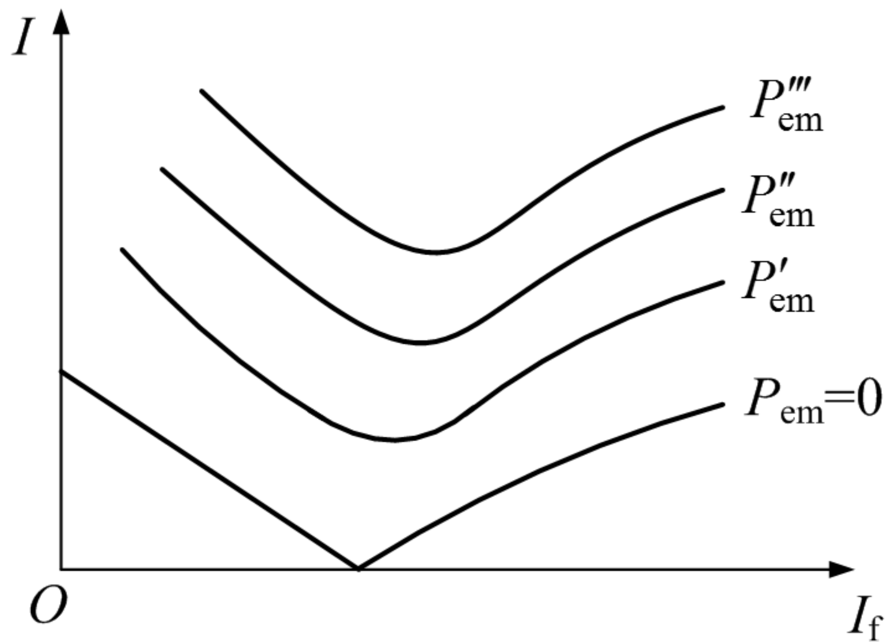
$$\boxed{I\cos\varphi = \text{const}\ ,\quad E_0\sin\theta = \text{const}}$$

Control of reactive power



V shape curve characteristics

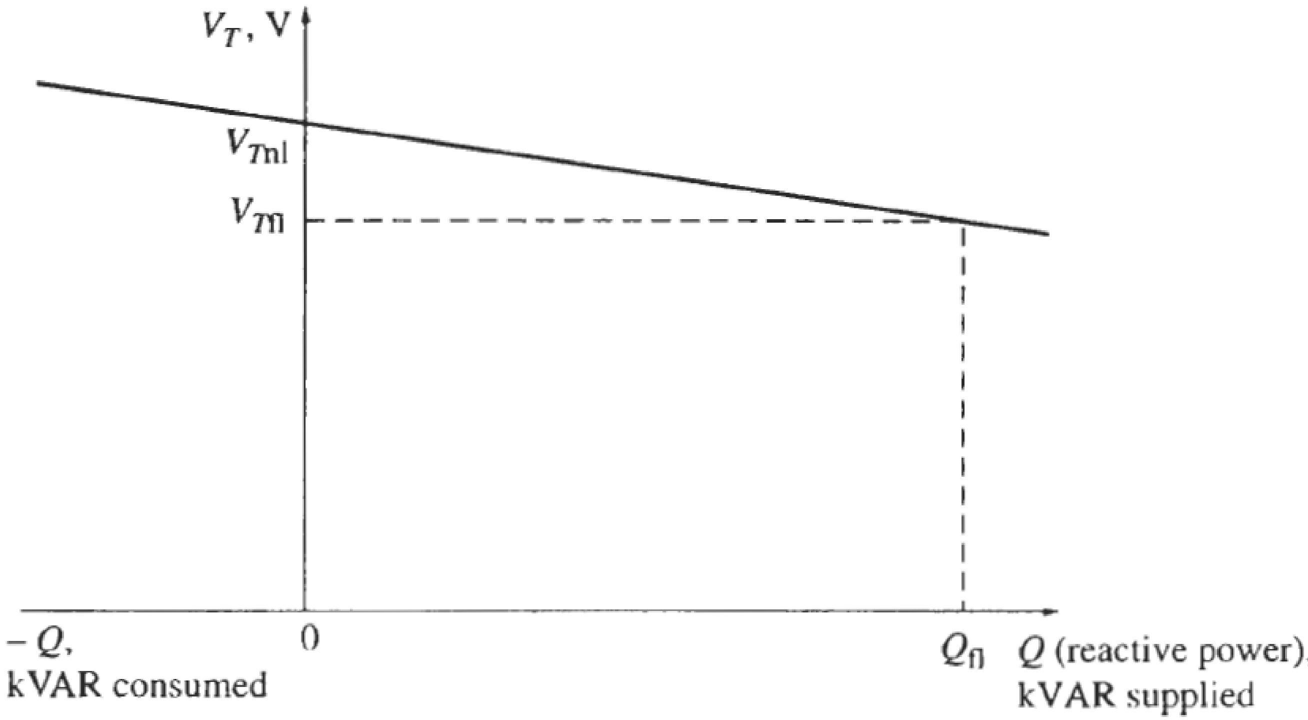
- I vs I_f at different power levels.



Draw this curve through matlab simulation

Typical curve of terminal voltage versus reactive power output

- The terminal voltage is relative to the load power factor



The frequency and terminal voltage of a generator operation

- The frequency only depends on the P demand
- The terminal voltage only depends on the Q demand
- Only the load characteristics will affect the generator characteristics (f_e and V_T)

The summarize of a generator operating alone

1. The real and reactive power supplied by the generator will be the amount demanded by the attached load.
2. The governor set points of the generator will control the operating frequency of the power system.
3. The field current (or the field regulator set points) control the terminal voltage of the power system.

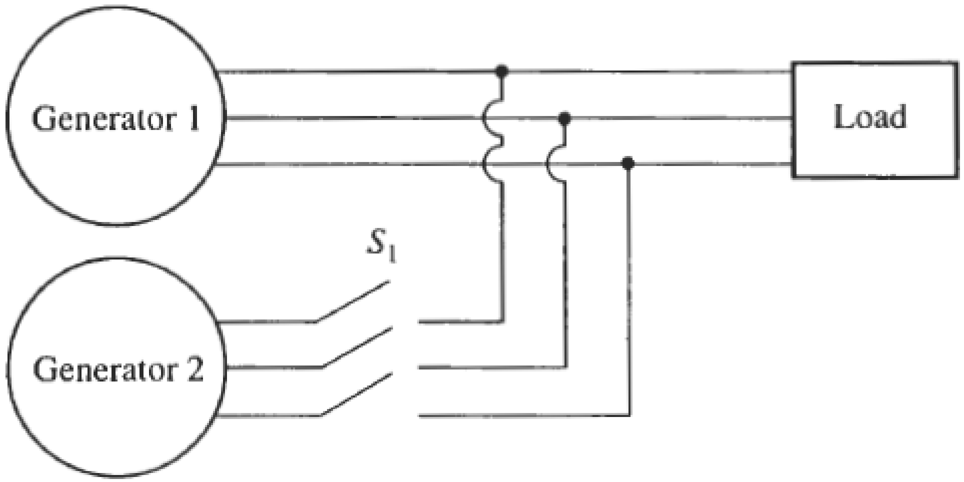
Parallel operation of AC generators

Parallel operation of AC generators

Why are synchronous generators operated in parallel? There are several major advantages to such operation:

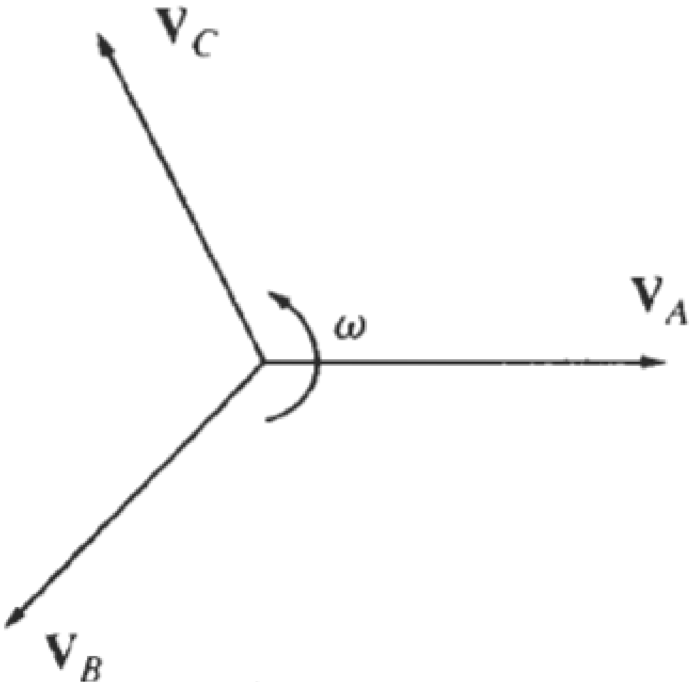
1. Several generators can supply a bigger load than one machine by itself.
2. Having many generators increases the reliability of the power system, since the failure of any one of them does not cause a total power loss to the load.
3. Having many generators operating in parallel allows one or more of them to be removed for shutdown and preventive maintenance.
4. If only one generator is used and it is not operating at near full load, then it will be relatively inefficient. With several smaller machines in parallel, it is possible to operate only a fraction of them. The ones that do operate are operating near full load and thus more efficiently.

The conditions required for parallel operation

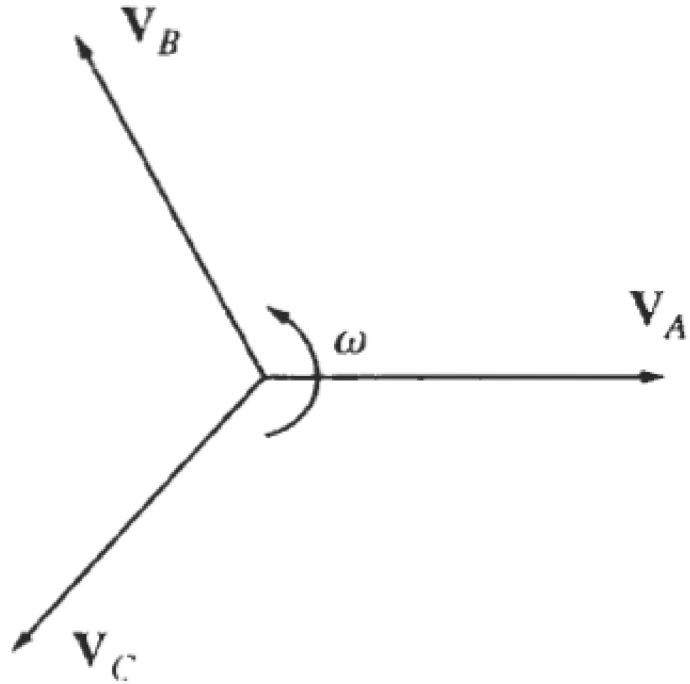


1. The rms *line voltages* of the two generators must be equal.
2. The two generators must have the same *phase sequence*.
3. The phase angles of the two *a* phases must be equal.
4. The frequency of the new generator, called the *oncoming generator*, must be slightly higher than the frequency of the running system.

Two possible phase sequences (*abc* and *acb* sequences)



abc phase sequence



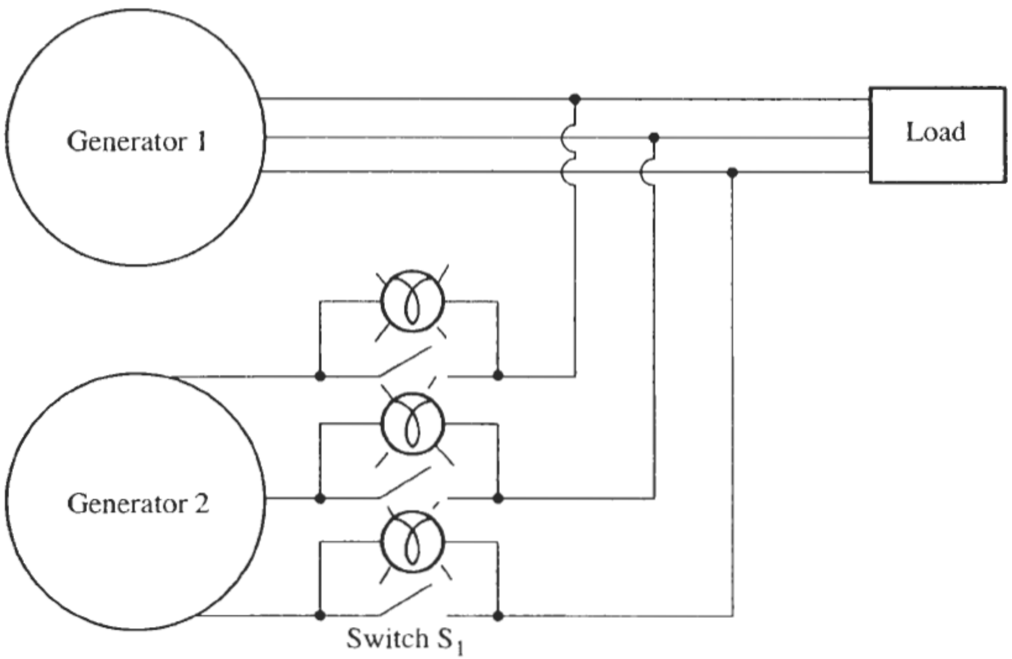
acb phase sequence

What problems will occur ?

- If the rms voltages are not equal ?
  - We may use the voltage meter to check the rms voltage.
- If the phase sequences are not equal ?
  - How to check the phase sequence ?
- If the frequencies are not equal ?
  - We may use the frequency meter to check the frequency.
  - What is the frequency relation between running the machines and the oncoming machine ?
    - The frequency of the oncoming machine must be slightly higher than that of the running machines.

Methods to check phase sequence

- Alternatively connect the Induction machine to two generator and check the rotation direction
- Three light-bulb method

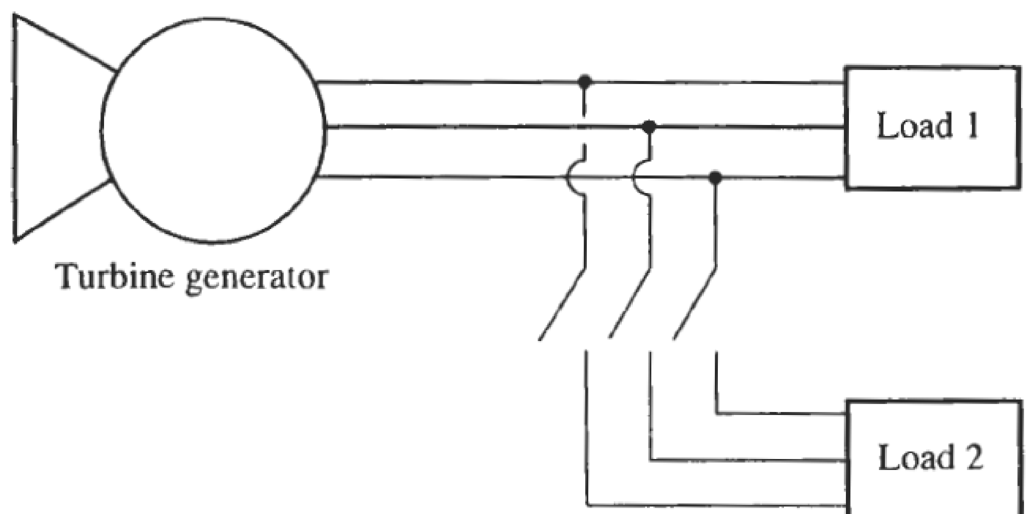


清華大學

Example 5-5

Example **5–5.** Figure 5–31 shows a generator supplying a load. A second load is to be connected in parallel with the first one. The generator has a no-load frequency of 61.0 Hz and a slope s_P of 1 MW/Hz. Load 1 consumes a real power of 1000 kW at 0.8 PF lagging, while load 2 consumes a real power of 800 kW at 0.707 PF lagging.

(a) Before the switch is closed, what is the operating frequency of the system?
(b) After load 2 is connected, what is the operating frequency of the system?
(c) After load 2 is connected, what action could an operator take to restore the system frequency to 60 Hz?



This problem states that the slope of the generator's characteristic is 1 MW/Hz and that its no-load frequency is 61 Hz. Therefore, the power produced by the generator is given by

$$P = s_P(f_{\text{nl}} - f_{\text{sys}}) \tag{5–28}$$

so

$$f_{\text{sys}} = f_{\text{nl}} - \frac{P}{s_P}$$

(a) The initial system frequency is given by

$$\begin{aligned} f_{\text{sys}} &= f_{\text{nl}} - \frac{P}{s_P} \\ &= 61\text{ Hz} - \frac{1000\text{ kW}}{1\text{ MW/Hz}} = 61\text{ Hz} - 1\text{ Hz} = 60\text{ Hz} \end{aligned}$$

(b) After load 2 is connected,

$$\begin{aligned} f_{\text{sys}} &= f_{\text{nl}} - \frac{P}{s_P} \\ &= 61\text{ Hz} - \frac{1800\text{ kW}}{1\text{ MW/Hz}} = 61\text{ Hz} - 1.8\text{ Hz} = 59.2\text{ Hz} \end{aligned}$$

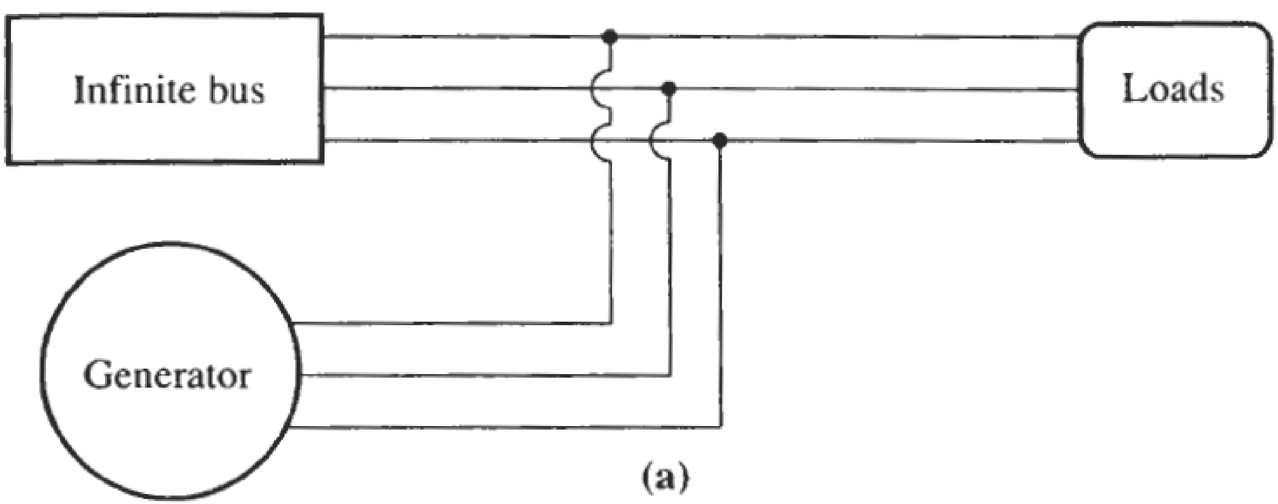
(c) After the load is connected, the system frequency falls to 59.2 Hz. To restore the system to its proper operating frequency, the operator should increase the governor no-load set points by 0.8 Hz, to 61.8 Hz. This action will restore the system frequency to 60 Hz.

Parallel operation

- What are the effects of f_e and V_T when the generator parallel operates with other power system?
- The rating of the power system
  – Large
  – The same size.

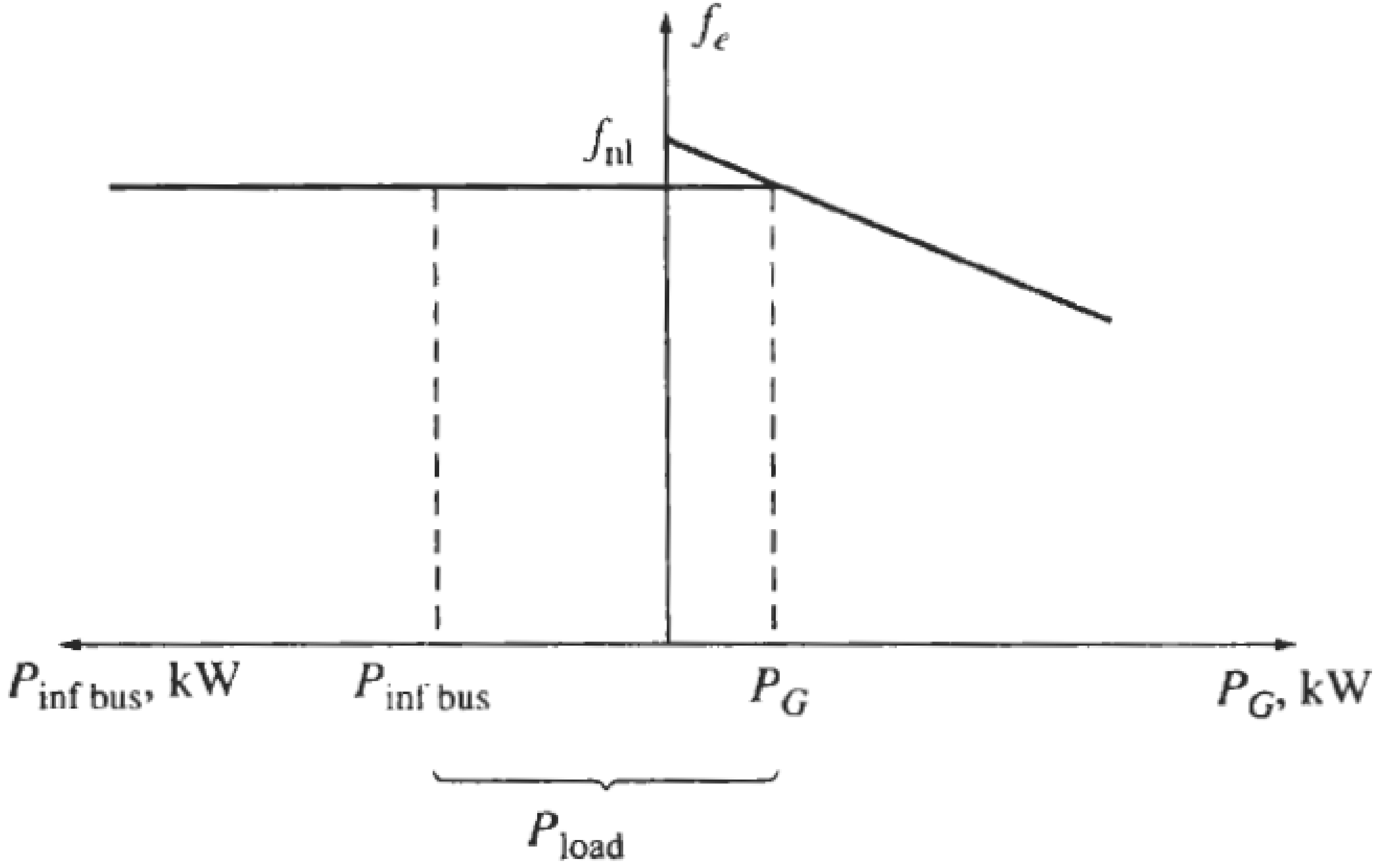
Parallel operate with power grid (infinite bus)

- All the generators in the system have the same frequency and voltage
- The frequency and voltage will not change by adding the load and the generator

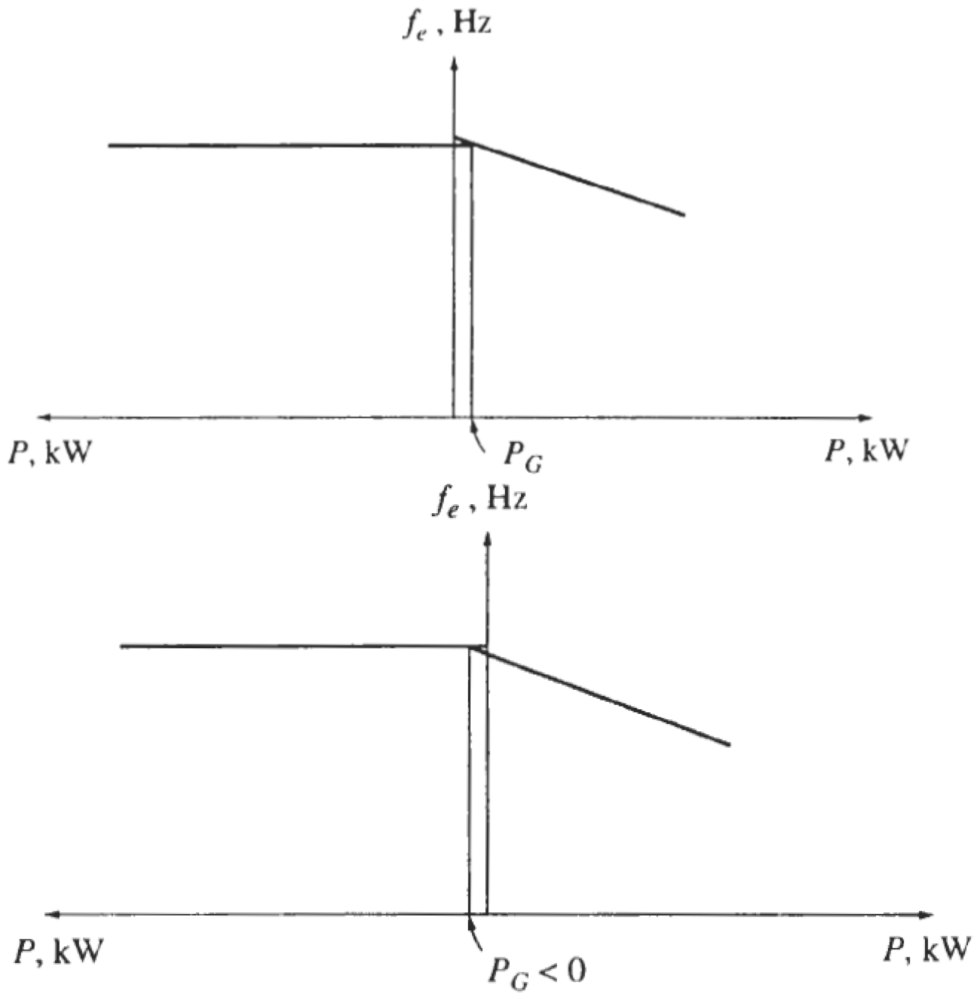


(a)

The frequency-power relation



The generator and motor mode in parallel operation



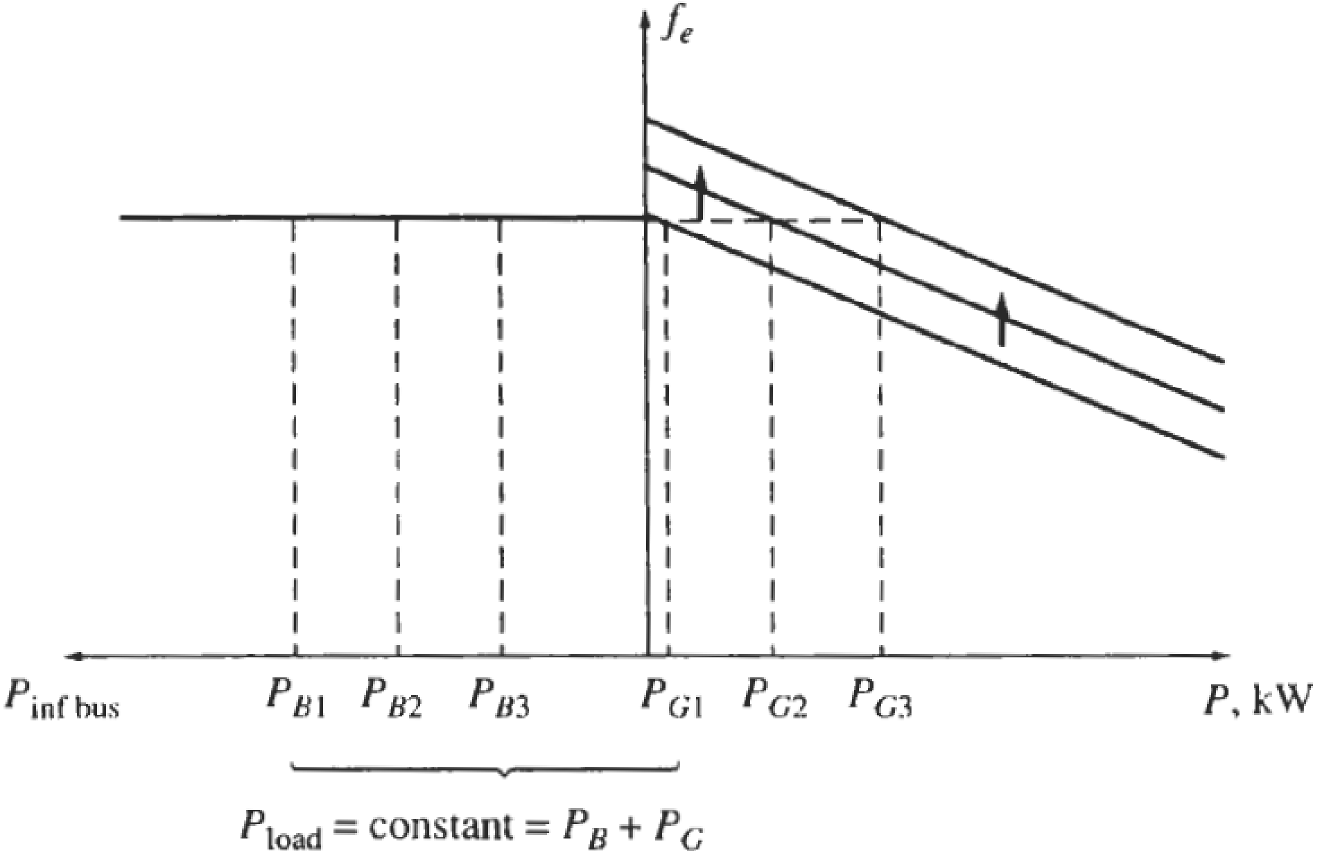
- The no load frequency must be higher than the power grid frequency
- We need the reverse power trip to prevent the motor mode

Changing the governor setting power

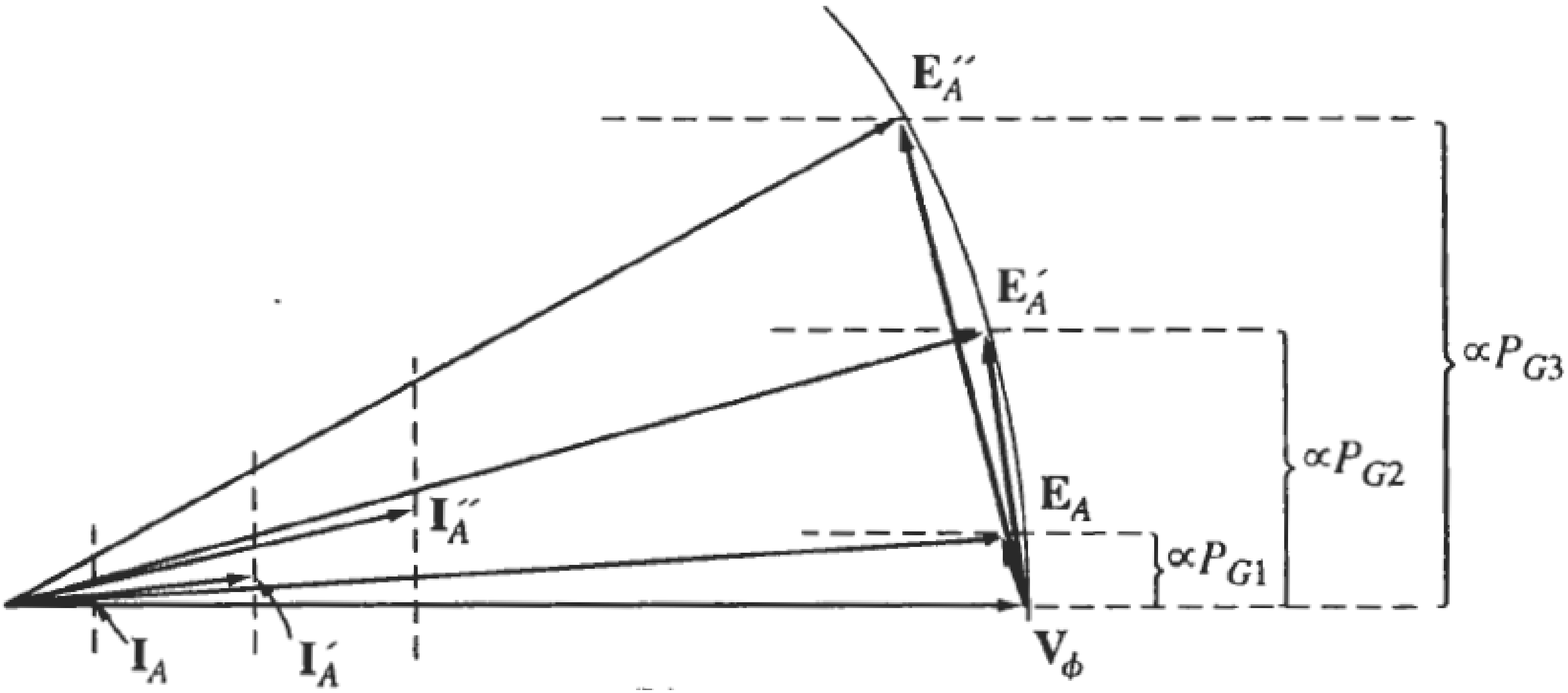
- Once the generator is parallel connected, what is the effect of changing the governor setting point (f_{nl})
- We can change the generating power of each generator by changing their governor setting point

清華大學

Changing the governor setting power



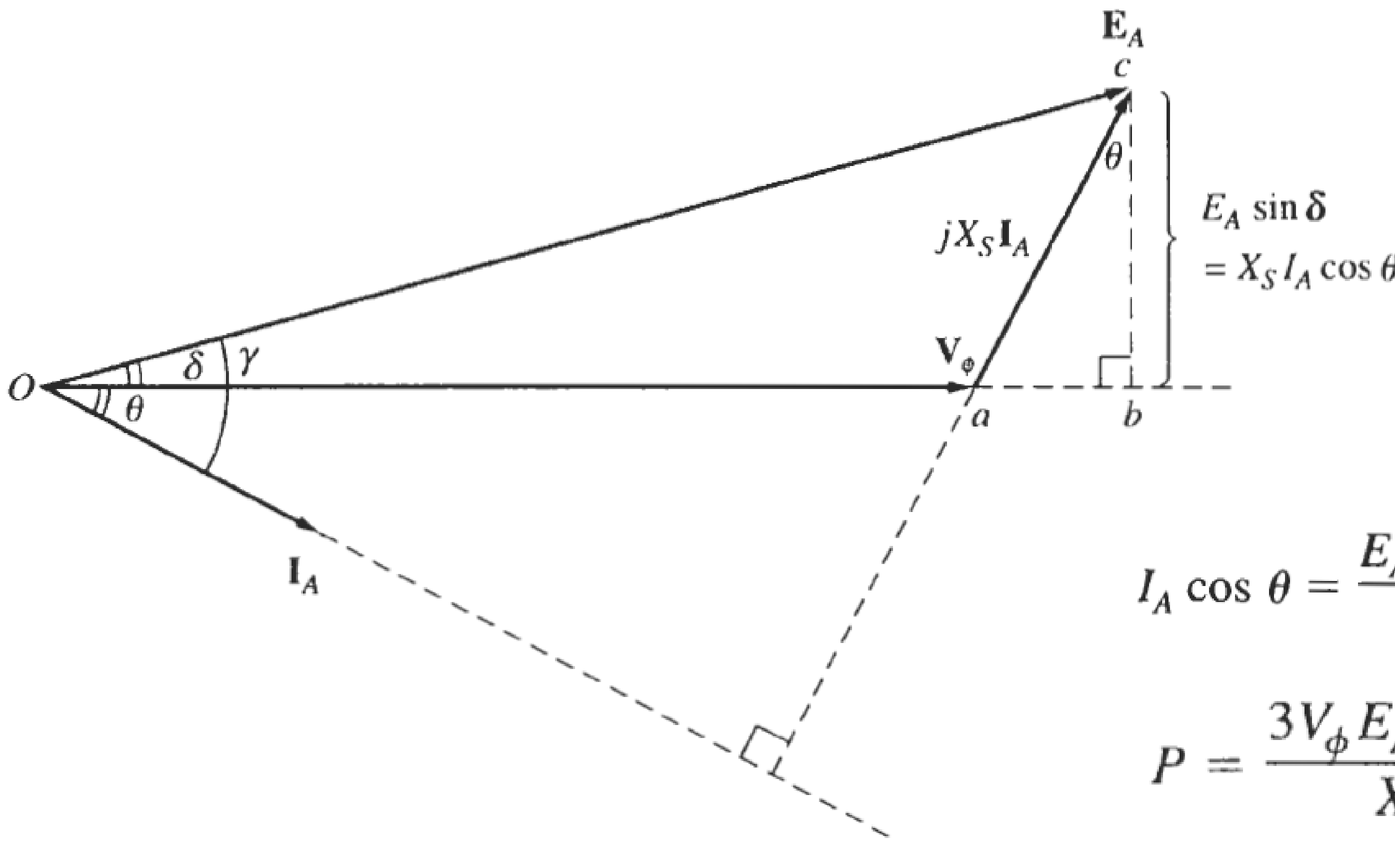
The phasor diagram of generators



Adjusting the reactive power Q ?

- The reactive power Q can be adjusted by changing the field current of each generator.
- While tuning the field current, the real power P must remain constant.

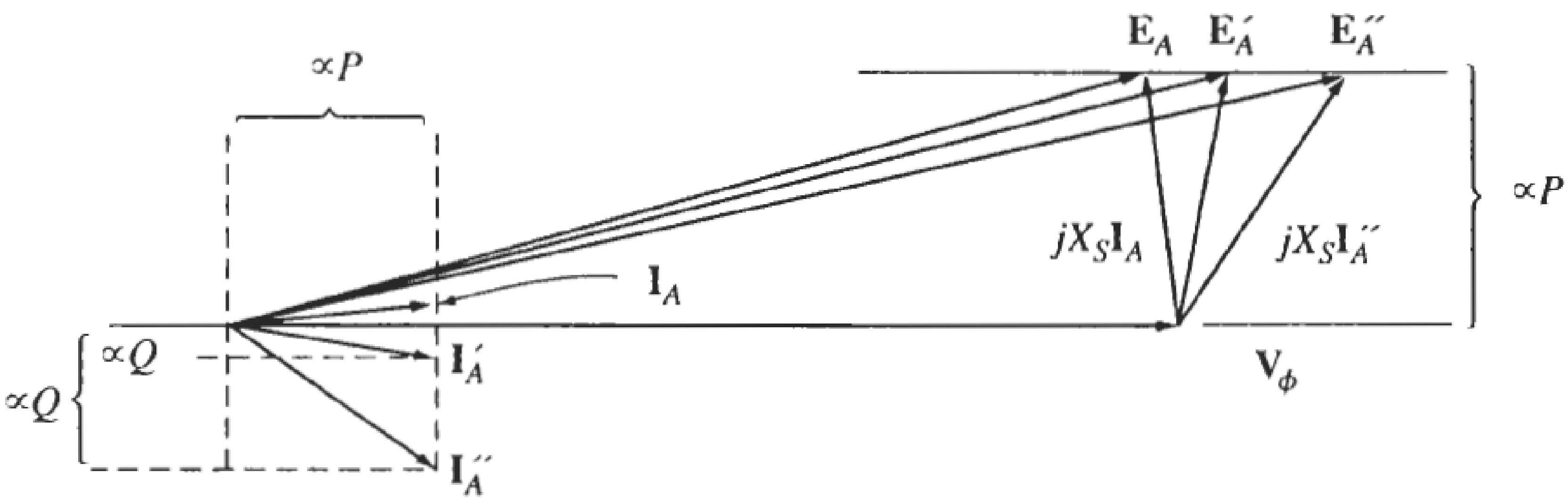
Output power equation



$$I_A \cos \theta = \frac{E_A \sin \delta}{X_S}$$

$$P = \frac{3V_\phi E_A \sin \delta}{X_S}$$

Adjusting the reactive power Q ?

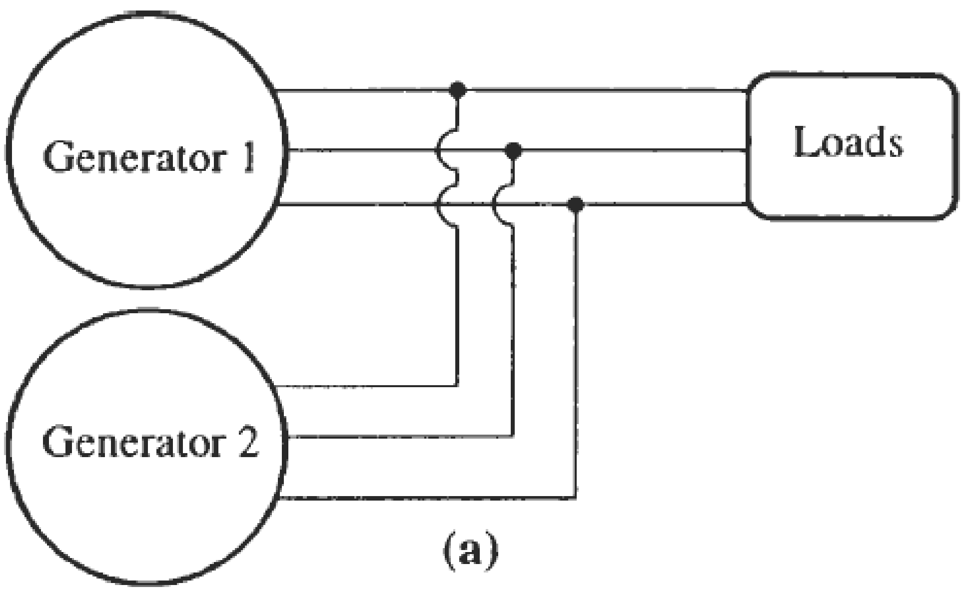


Summarized the situation that a generator connects to an infinite bus

1. The frequency and terminal voltage of the generator are controlled by the system to which it is connected.
2. The governor set points of the generator control the real power supplied by the generator to the system.
3. The field current in the generator controls the reactive power supplied by the generator to the system.

Operation of generators in parallel with other generators of the same size

- If a generator is connected in parallel with another one of the same size.
- The frequency and voltage are no more constants.



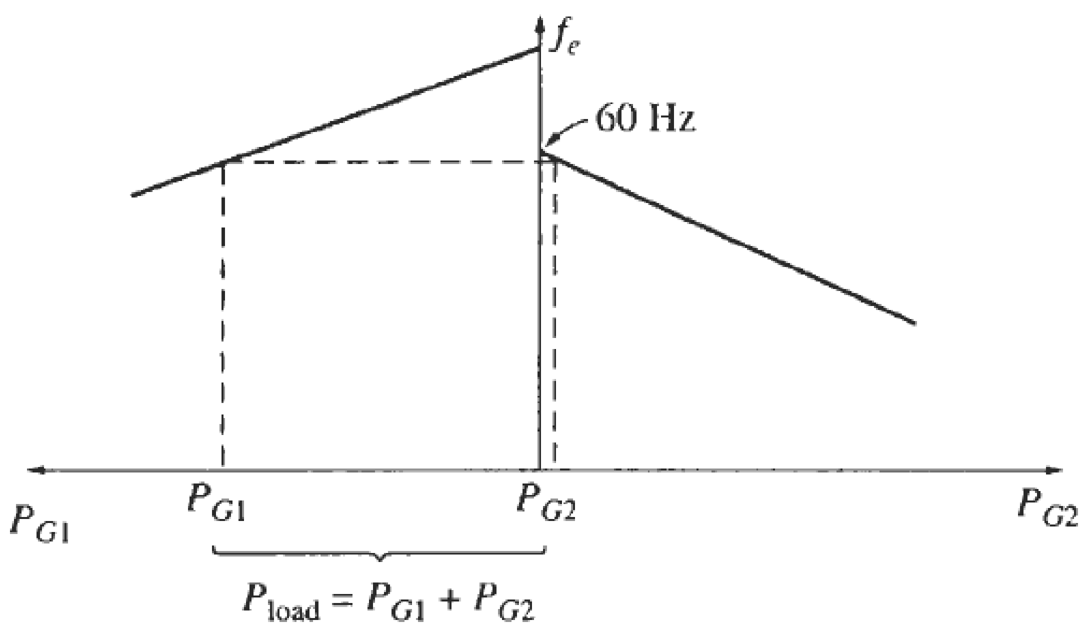
(a)

What are the constraints in parallel connection

- The final situation of the parallel connection system

$$P_{tot} = P_{load} = P_{G1} + P_{G2}$$

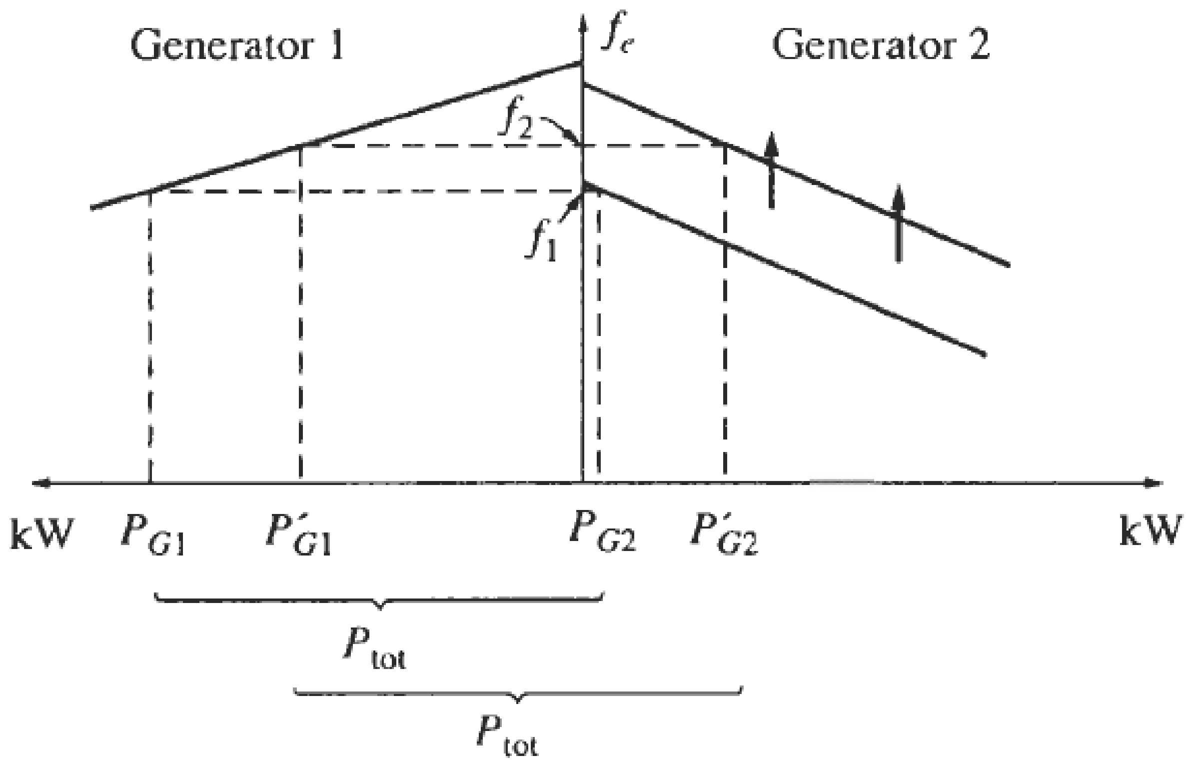
$$Q_{tot} = Q_{load} = Q_{G1} + Q_{G2}$$



清华大学

Change the governor set point

- If we change the governor set points of one generator

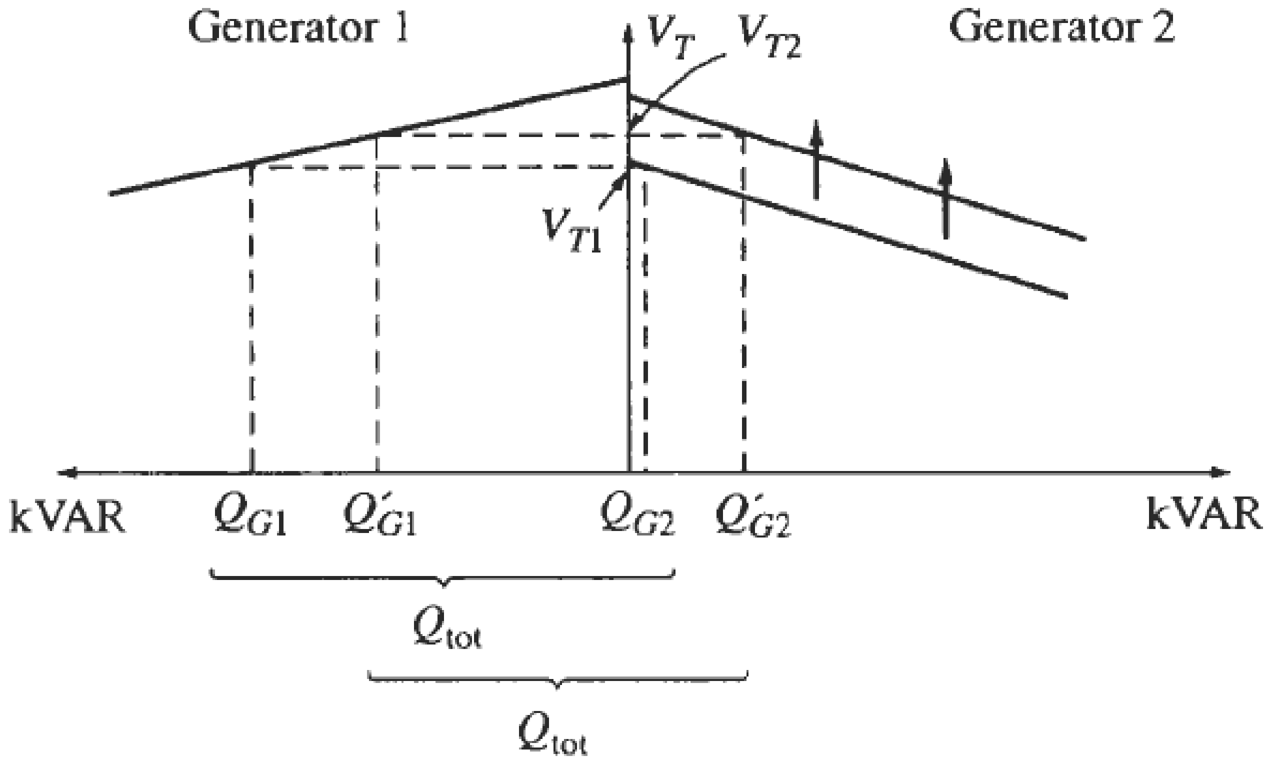


Power dispatch between different generator

1. *Increases the system frequency.*
2. *Increases the power supplied by that generator, while reducing the power supplied by the other one.*

Change the field current

- If we change the field current of one generator



清華大學

Power system voltage control and reactive power (Q) dispatch

1. *The system terminal voltage is increased.*
2. *The reactive power Q supplied by that generator is increased, while the reactive power supplied by the other generator is decreased.*

Example 5-6

Example 5–6. Figure 5–38a shows two generators supplying a load. Generator 1 has a no-load frequency of 61.5 Hz and a slope s_{P1} of 1 MW/Hz. Generator 2 has a no-load frequency of 61.0 Hz and a slope s_{P2} of 1 MW/Hz. The two generators are supplying a real load totaling 2.5 MW at 0.8 PF lagging. The resulting system power-frequency or house diagram is shown in Figure 5–39.

(a) At what frequency is this system operating, and how much power is supplied by each of the two generators?

(b) Suppose an additional 1-MW load were attached to this power system. What would the new system frequency be, and how much power would G_1 and G_2 supply now?

(c) With the system in the configuration described in part *b*, what will the system frequency and generator powers be if the governor set points on G_2 are increased by 0.5 Hz?

The power produced by a synchronous generator with a given slope and no-load frequency is given by Equation (5–28):

$$P_1 = s_{P1}(f_{\text{nl},1} - f_{\text{sys}})$$
$$P_2 = s_{P2}(f_{\text{nl},2} - f_{\text{sys}})$$

Since the total power supplied by the generators must equal the power consumed by the loads,

$$P_{\text{load}} = P_1 + P_2$$

These equations can be used to answer all the questions asked.

(a) In the first case, both generators have a slope of 1 MW/Hz, and G_1 has a no-load frequency of 61.5 Hz, while G_2 has a no-load frequency of 61.0 Hz. The total load is 2.5 MW. Therefore, the system frequency can be found as follows:

$$
\begin{aligned}
P_{\text{load}} &= P_1 + P_2 \\
&= s_{P1}(f_{\text{nl},1} - f_{\text{sys}}) + s_{P2}(f_{\text{nl},2} - f_{\text{sys}}) \\
2.5 \text{ MW} &= (1 \text{ MW/Hz})(61.5 \text{ Hz} - f_{\text{sys}}) + (1 \text{ MW/Hz})(61 \text{ Hz} - f_{\text{sys}}) \\
&= 61.5 \text{ MW} - (1 \text{ MW/Hz})f_{\text{sys}} + 61 \text{ MW} - (1 \text{ MW/Hz})f_{\text{sys}} \\
&= 122.5 \text{ MW} - (2 \text{ MW/Hz})f_{\text{sys}}
\end{aligned}
$$

therefore $$f_{\text{sys}} = \frac{122.5 \text{ MW} - 2.5 \text{ MW}}{(2\text{MW/Hz})} = 60.0 \text{ Hz}$$

The resulting powers supplied by the two generators are

$$
\begin{aligned}
P_1 &= s_{P1}(f_{\text{nl},1} - f_{\text{sys}}) \\
&= (1 \text{ MW/Hz})(61.5 \text{ Hz} - 60.0 \text{ Hz}) = 1.5 \text{ MW} \\
P_2 &= s_{P2}(f_{\text{nl},2} - f_{\text{sys}}) \\
&= (1 \text{ MW/Hz})(61.0 \text{ Hz} - 60.0 \text{ Hz}) = 1 \text{ MW}
\end{aligned}
$$

(*b*) When the load is increased by 1 MW, the total load becomes 3.5 MW. The new system frequency is now given by

$$\begin{aligned}
P_{\text{load}} &= s_{P1}(f_{\text{nl},1} - f_{\text{sys}}) + s_{P2}(f_{\text{nl},2} - f_{\text{sys}}) \\
3.5\text{ MW} &= (1\text{ MW/Hz})(61.5\text{ Hz} - f_{\text{sys}}) + (1\text{ MW/Hz})(61\text{ Hz} - f_{\text{sys}}) \\
&= 61.5\text{ MW} - (1\text{ MW/Hz})f_{\text{sys}} + 61\text{ MW} - (1\text{ MW/Hz})f_{\text{sys}} \\
&= 122.5\text{ MW} - (2\text{ MW/Hz})f_{\text{sys}}
\end{aligned}$$

therefore $$f_{\text{sys}} = \frac{122.5\text{ MW} - 3.5\text{ MW}}{(2\text{MW/Hz})} = 59.5\text{ Hz}$$

The resulting powers are

$$\begin{aligned}
P_1 &= s_{P1}(f_{\text{nl},1} - f_{\text{sys}}) \\
&= (1\text{ MW/Hz})(61.5\text{ Hz} - 59.5\text{ Hz}) = 2.0\text{ MW} \\
P_2 &= s_{P2}(f_{\text{nl},2} - f_{\text{sys}}) \\
&= (1\text{ MW/Hz})(61.0\text{ Hz} - 59.5\text{ Hz}) = 1.5\text{ MW}
\end{aligned}$$

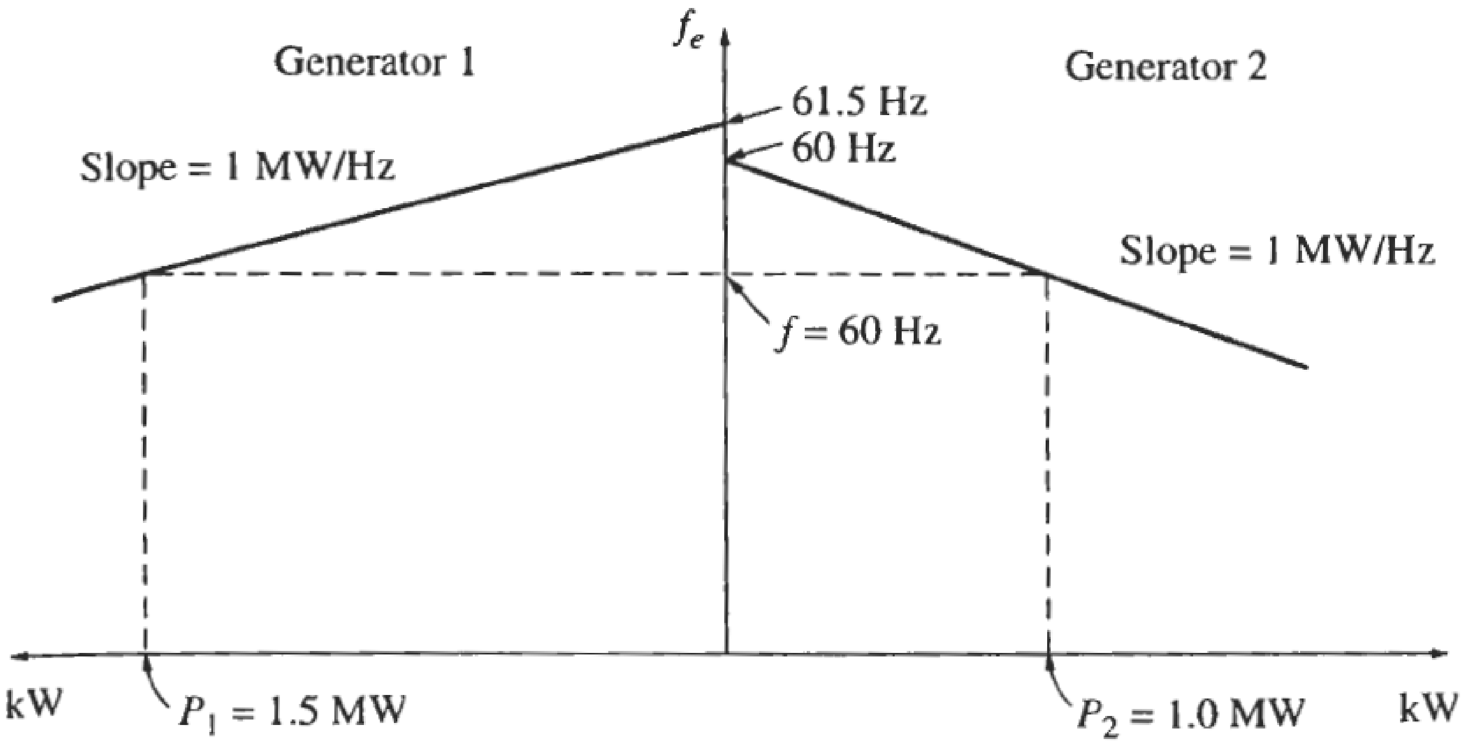
(c) If the no-load governor set points of G_2 are increased by 0.5 Hz, the new syst[cut off]
frequency becomes

$$
\begin{aligned}
P_{\text{load}} &= s_{P1}(f_{\text{nl},1} - f_{\text{sys}}) + s_{P2}(f_{\text{nl},2} - f_{\text{sys}}) \\
3.5\text{ MW} &= (1\text{ MW/Hz})(61.5\text{ Hz} - f_{\text{sys}}) + (1\text{ MW/Hz})(61.5\text{ Hz} - f_{\text{sys}}) \\
&= 123\text{ MW} - (2\text{ MW/Hz})f_{\text{sys}} \\
f_{\text{sys}} &= \frac{123\text{ MW} - 3.5\text{ MW}}{(2\text{MW/Hz})} = 59.75\text{ Hz}
\end{aligned}
$$

The resulting powers are

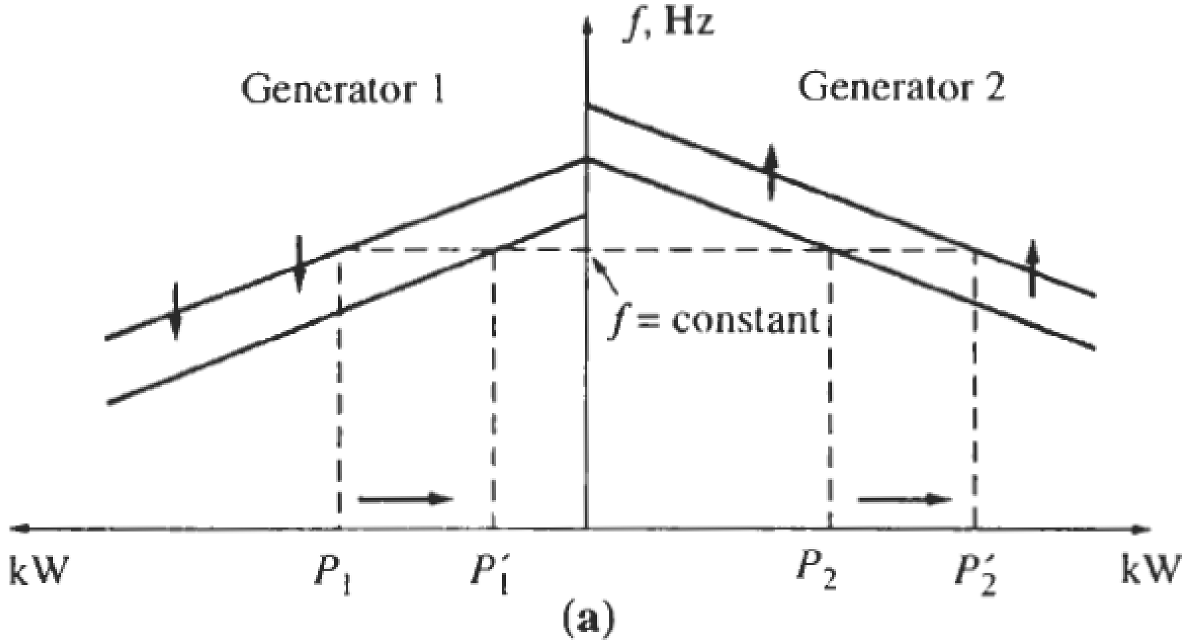
$$
\begin{aligned}
P_1 = P_2 &= s_{P1}(f_{\text{nl},1} - f_{\text{sys}}) \\
&= (1\text{ MW/Hz})(61.5\text{ Hz} - 59.75\text{ Hz}) = 1.75\text{ MW}
\end{aligned}
$$

House diagram for the parallel system



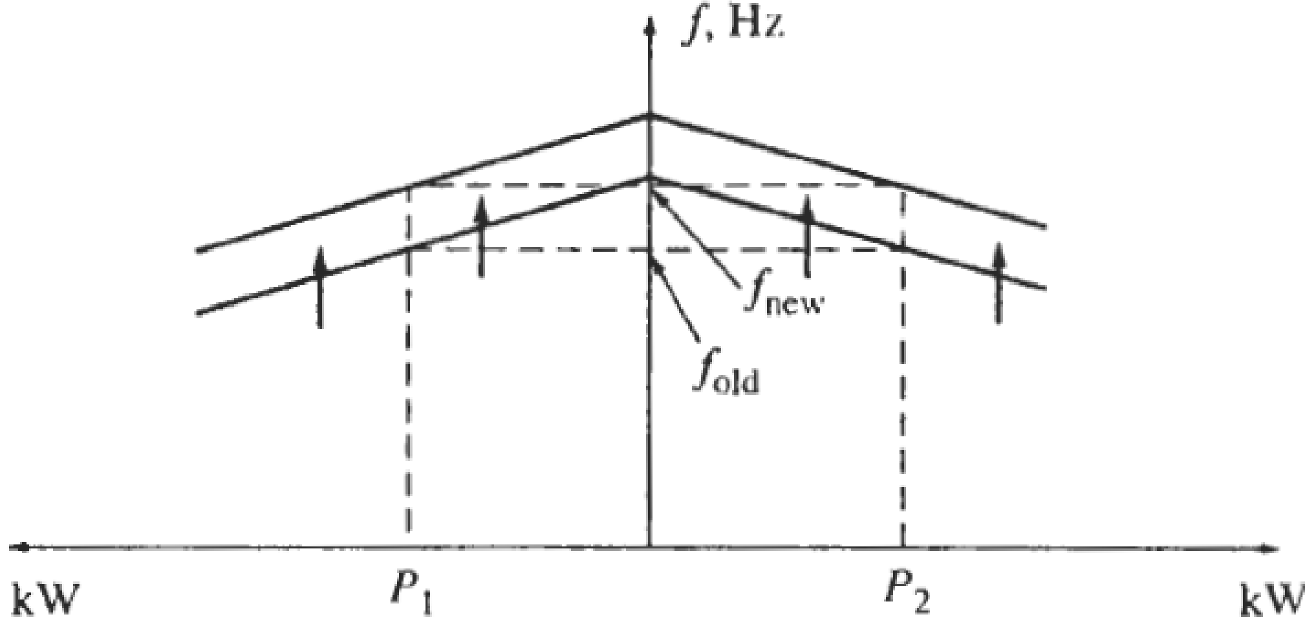
Power sharing problem – how to keep the frequency constant

- How can we keep the frequency constant when the power sharing is adjusted ?



Power sharing problem – keep the power sharing constant

- How can we keep the power sharing constant when the system frequency is adjusted ?

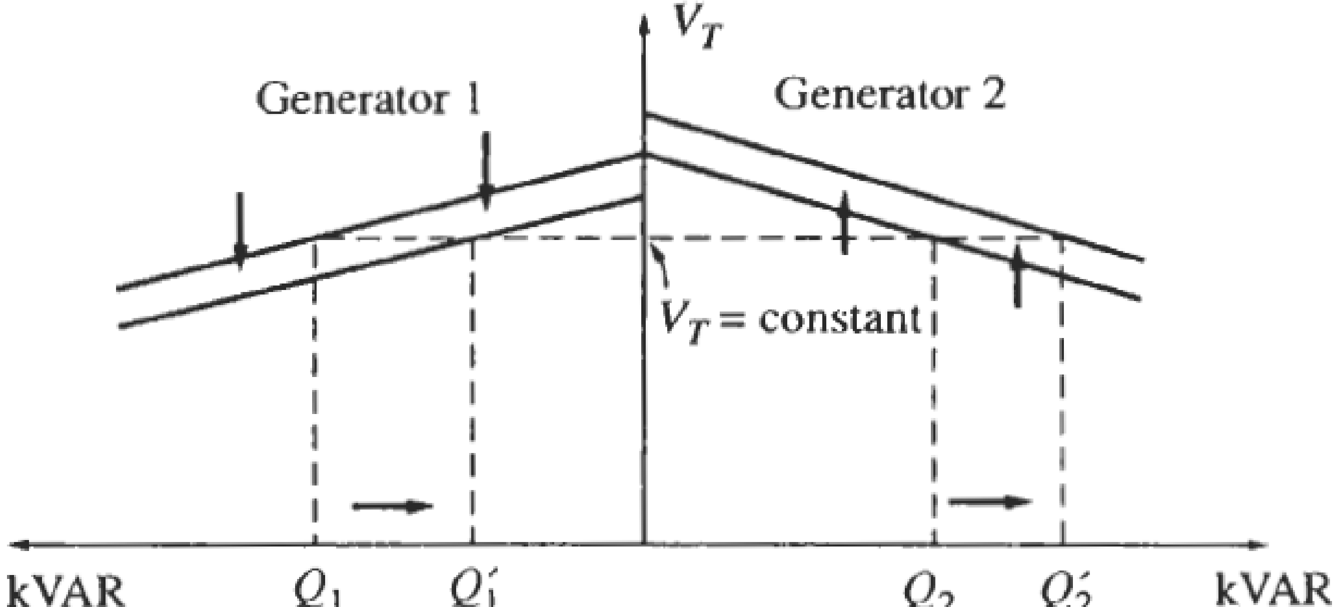


(b)

清華大學

Reactive Power sharing problem – how to keep the terminal voltage constant

- How can we keep the terminal voltage constant when the reactive power sharing is adjusted ?

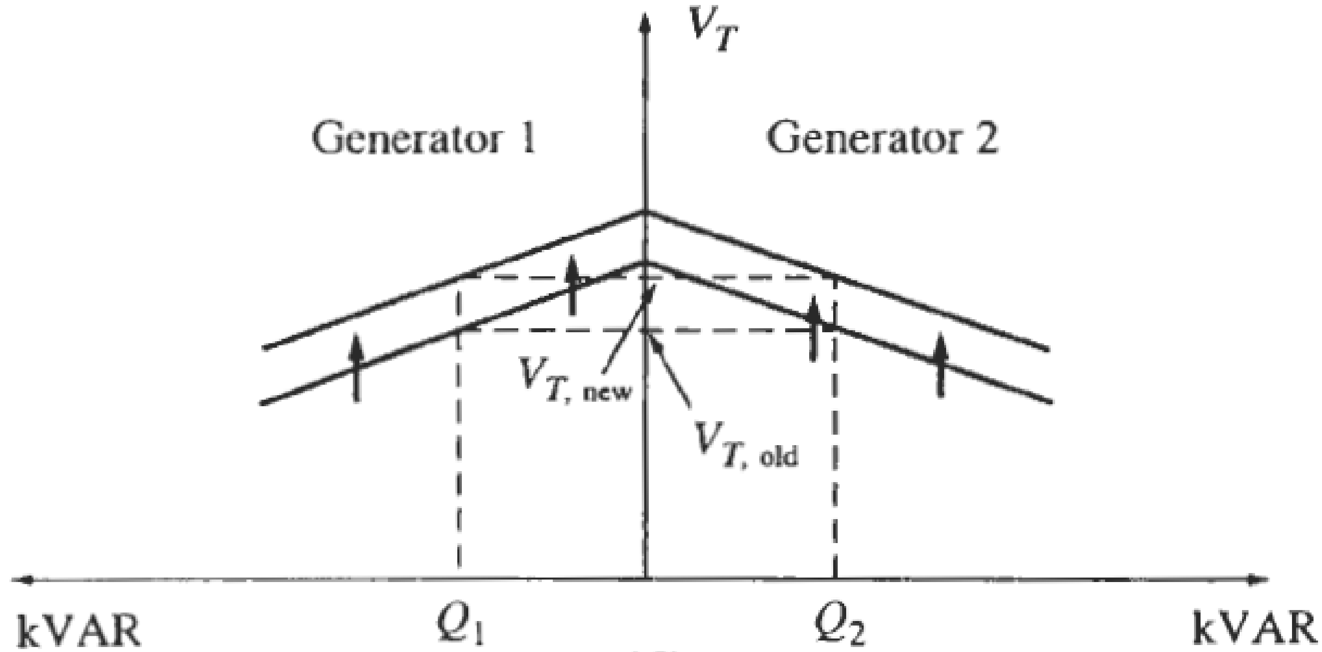


(c)

清華大學

Reactive power sharing problem – keep the reactive power sharing constant

- How can we keep the reactive power sharing constant when the terminal voltage is adjusted ?



(d)

Summarized the situation that a generator connects to another generator

1. The system is constrained in that the total power supplied by the two generators together must equal the amount consumed by the load. Neither f_{sys} nor V_T is constrained to be constant.
2. To adjust the real power sharing between generators without changing f_{sys}, simultaneously increase the governor set points on one generator while decreasing the governor set points on the other. The machine whose governor set point was increased will assume more of the load.
3. To adjust f_{sys} without changing the real power sharing, simultaneously increase or decrease both generators' governor set points.
4. To adjust the reactive power sharing between generators without changing V_T, simultaneously increase the field current on one generator while decreasing the field current on the other. The machine whose field current was increased will assume more of the reactive load.
5. To adjust V_T without changing the reactive power sharing, simultaneously increase or decrease both generators' field currents.

Synchronous generator transients

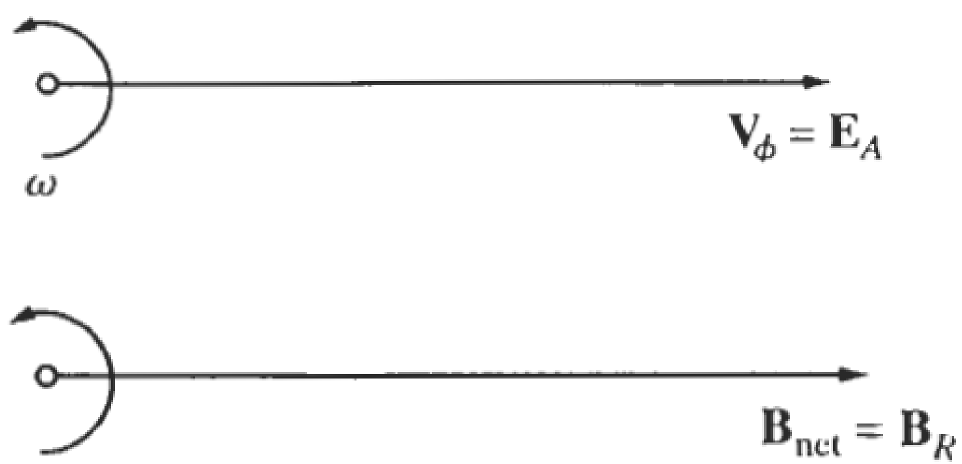
Synchronous generator transients

- When a shaft torque applied to a generator or the output load on a generator changes suddenly.
  - When a generator is paralleled with a running power system. (infinite bus)
  - It is initially turning ***faster*** and has a ***higher frequency*** than the power system does.
  - There is a transient period before the generator steadies down on the line and runs at line frequency.

Use phasor diagram to illustrate the synchronous generator transients

- Before connection, the oncoming generator is supplying no load and its stator current is zero

$\mathbf{E}_A = \mathbf{V}_\phi \qquad \mathbf{B}_R = \mathbf{B}_{net}$



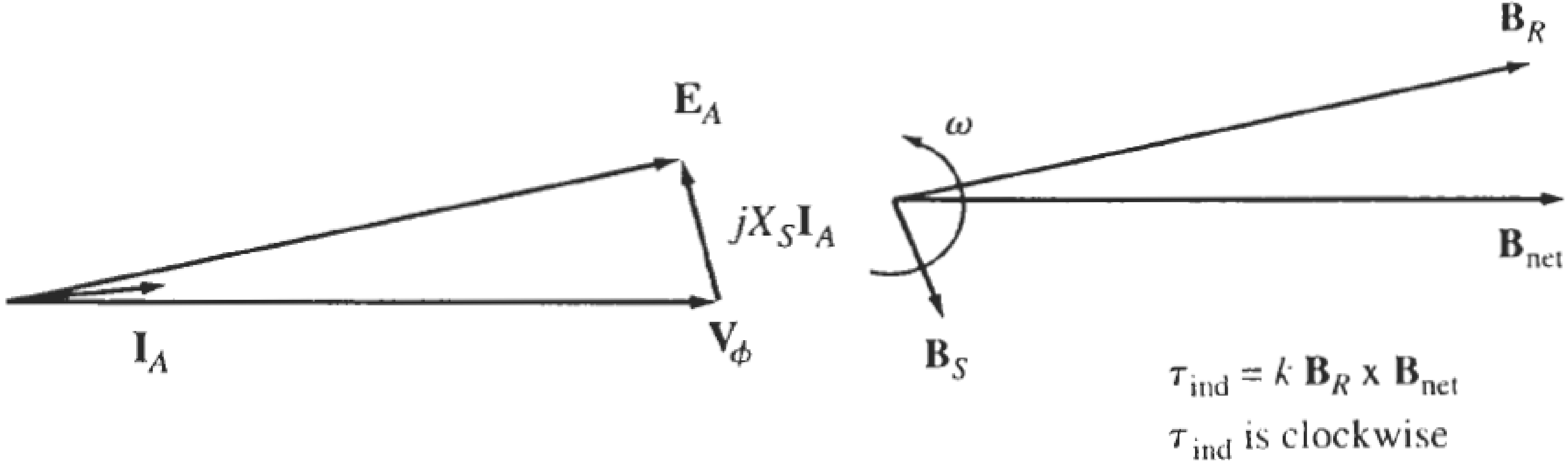
At the instant of connection

- At the instant of parallel connection, a stator current flows out between the generator and power system
- Since the generator's rotor is still turning faster than the system speed, the voltage E_A leads the terminal voltage V_ϕ.
- The induced torque is

$$\tau_{\text{ind}} = k\mathbf{B}_R \times \mathbf{B}_{\text{net}}$$

The phasor diagrams

- The direction of the induced torque is opposite to the direction of motion
- Thus, the generator's speed slows down to equal to the speed of power system



Another case

- How about the situation that the generator speed is ***lower*** than the speed of power system ?

ratings

The synchronous generator ratings

- The limit to the speed and power that may be obtained from a synchronous generator – ***rating***
- What is the purpose of rating
  - To protect the generator from damage due to improper operation
- Typical rating
  - ***Voltage, frequency, speed,***
  - ***apparent power, power factor, field current,***
  - ***service factor***

Voltage, Speed, and Frequency Ratings

- ***Frequency*** – the rating frequency depends on the power system to which it is connected. (50Hz or 60Hz)
- ***Rotation speed*** – the relation between frequency and speed is

$$f_e = \frac{n_m P}{120}$$

- ***Voltage*** – the voltage rating depends on
  - The flux, (speed and structure)
  - The breakdown value of the winding insulation

Voltage, Speed, and Frequency Ratings

- Can we operate the 60Hz generator in the 50Hz environment ?

$$E_A = K\phi\omega$$

- The operating voltage must be derated to 50/60 (or 83.3%)

Apparent power and Power factor ratings

- Two possible factor to limit the output power
  - The shaft torque limitation – the factor is not important
  - The heating of the windings – the factor is important
- Heating of the windings
  - Armature winding
  - Field winding

Power Capability Curve

The maximum acceptable armature current

- The maximum acceptable armature current sets the apparent power rating for a generator

$$S = 3V_\phi I_A$$

- If the ratted voltage is known, the maximum acceptable armature current can determine the rated KVA of the generator

$$S_{\text{rated}} = 3V_{\phi,\text{rated}} I_{A,\max}$$

$$S_{\text{rated}} = \sqrt{3}V_{L,\text{rated}} I_{L,\max}$$

清華大學

The power factor rating

- The power factor of the armature current is irrelevant

- The stator copper losses are independent of the angle of current with respect to V_ϕ.

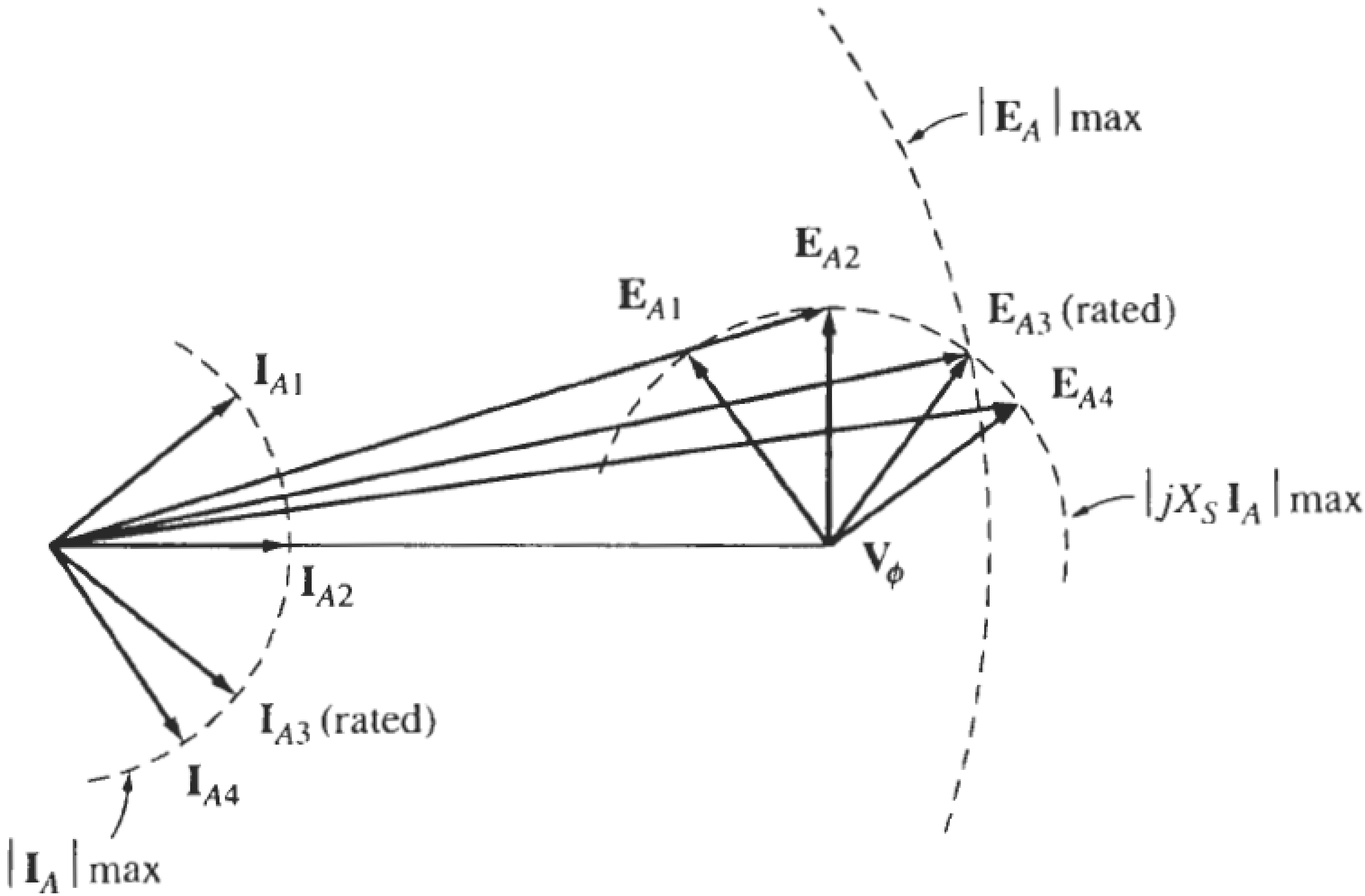
$$P_{\mathrm{SCL}} = 3I_A^2 R_A$$

- The field winding copper losses will limit the E_A and the lowest power factor

$$P_{\mathrm{RCL}} = I_F^2 R_F \qquad E_A = K\phi\omega$$

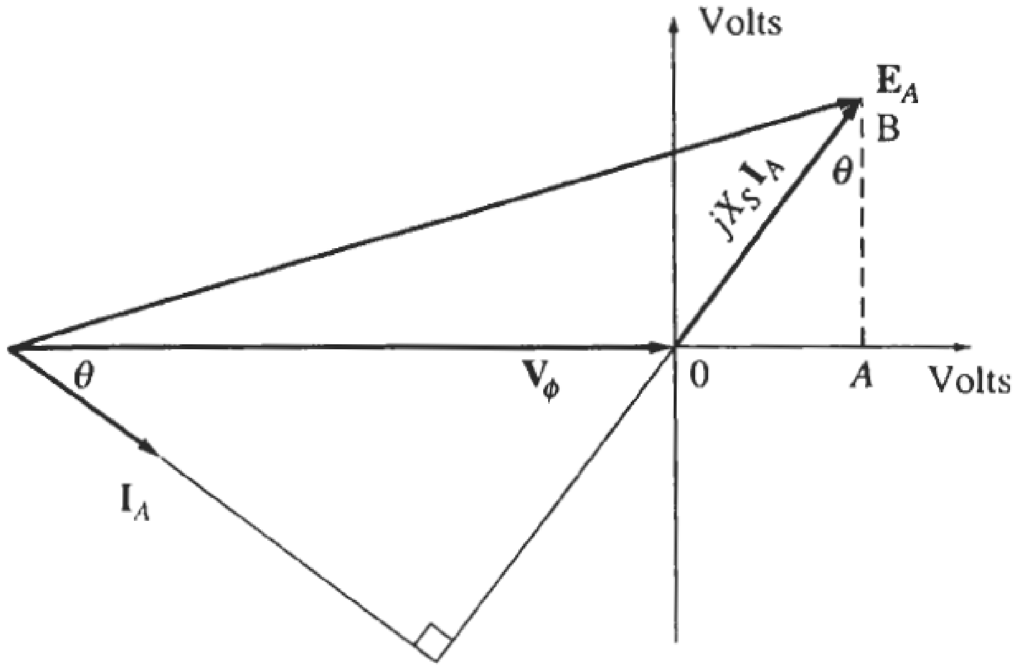
清華大学

The effect of maximum field current I_F



Power diagram - Synchronous generator capability curves

- The stator and rotor heat limits can be expressed in ***graphical form*** by a generator ***capability diagram***
- First we observe the phasor diagram



Obtain the power diagram from the phasor diagram

- The real and reactive power

$$P = 3V_\phi I_A \cos\theta = \frac{3V_\phi}{X_S}(X_S I_A \cos\theta)$$

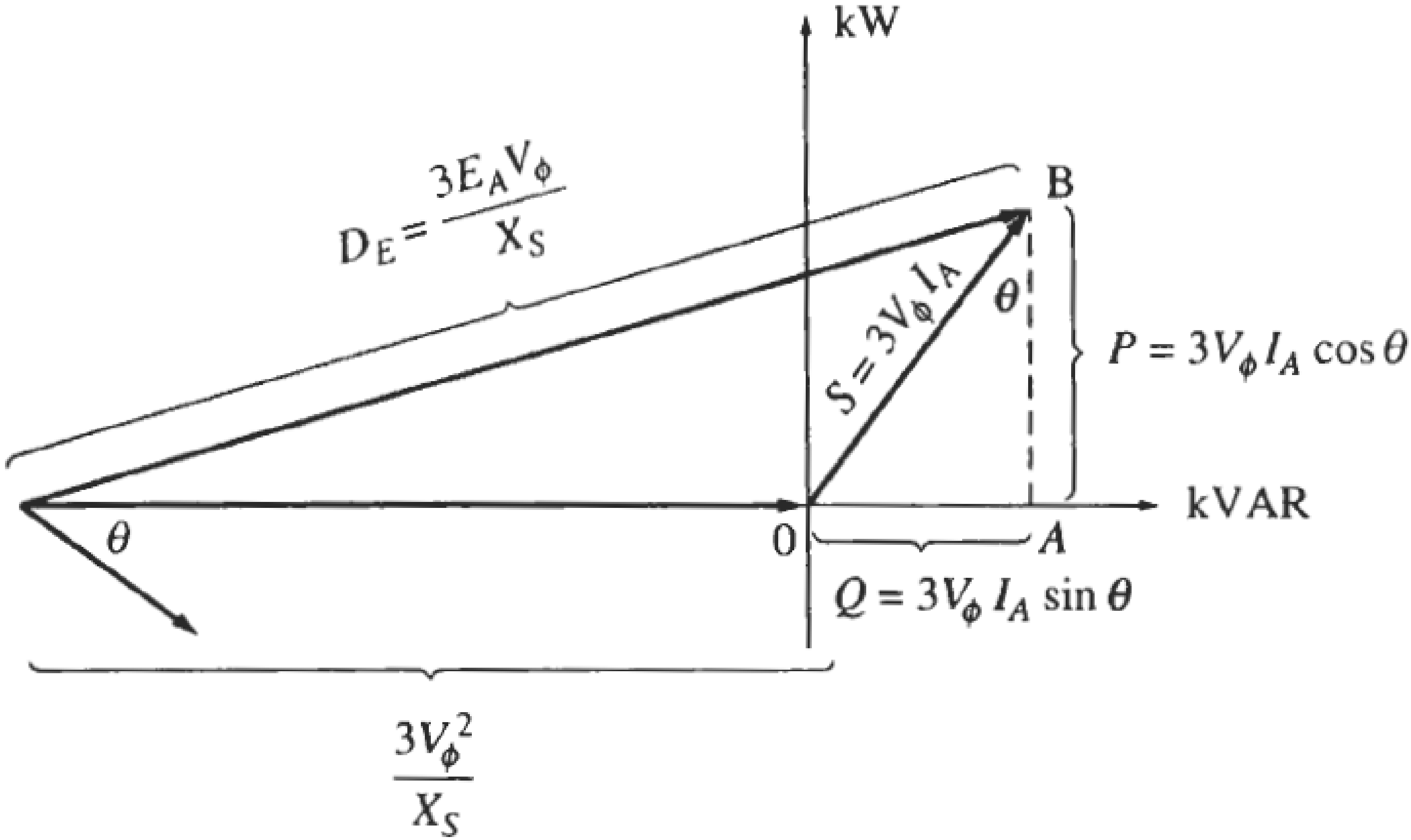
$$Q = 3V_\phi I_A \sin\theta = \frac{3V_\phi}{X_S}(X_S I_A \sin\theta)$$

- So, the relation between the phasor diagram and power diagram is $3V_\phi/X_S$
- Thus, the origin on the power diagram is O' = $\frac{3V_\phi}{X_S}(-V_\phi)$
- The length of E_A on the power diagram is

$$D_E = -\frac{3E_A V_\phi}{X_S}$$

清華大學

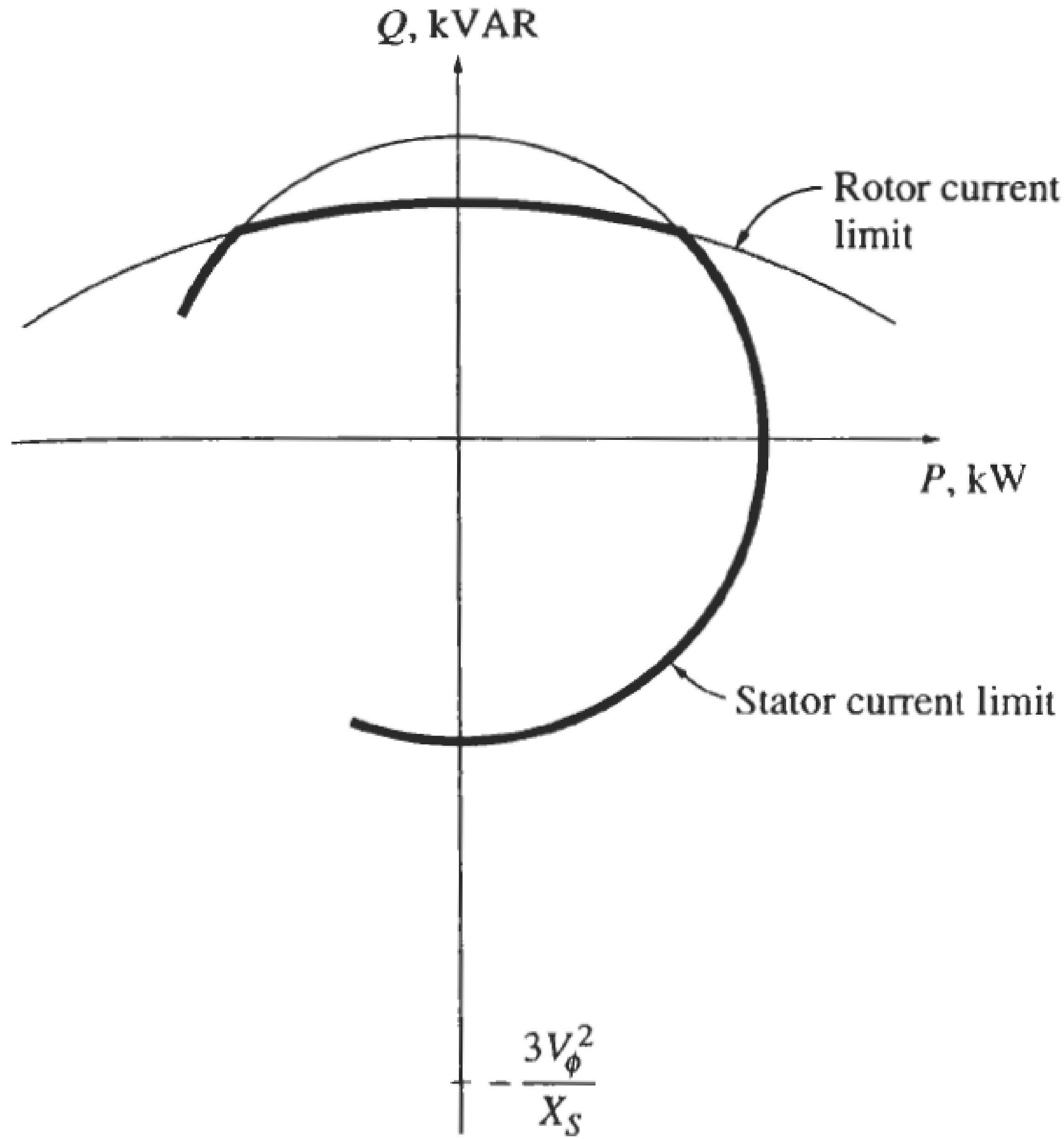
The corresponding power units



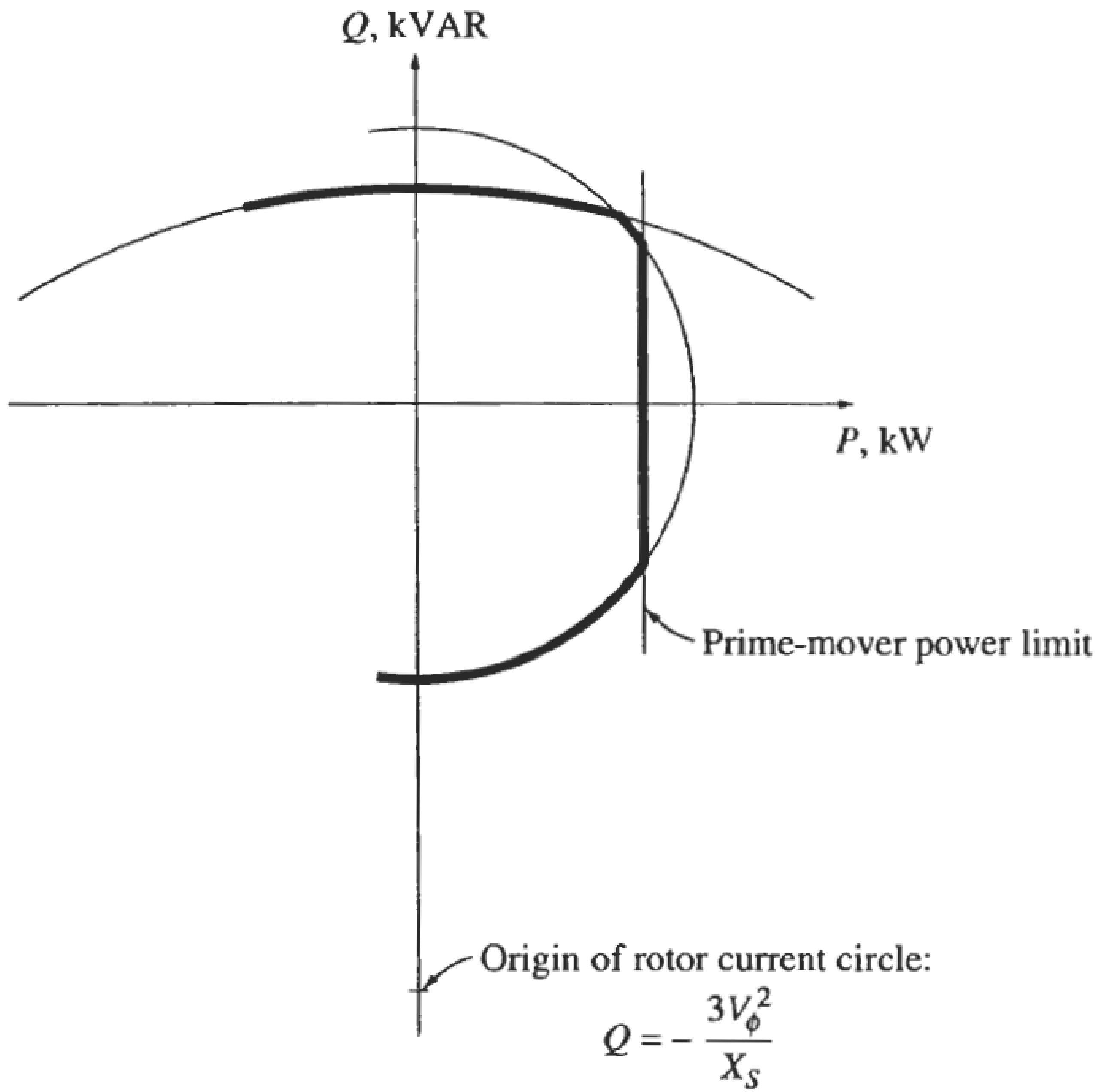
The power capability

- If we consider the terminal voltage V_ϕ is constant
- We can illustrate the winding limitation by the power limitation
- The armature winding limitation (I_A) can be represented by apparent power $S = 3V_\phi I_A$
- The field (rotor) winding limitation (IF) can be represented by E_A or the circle with origin O’ and radius D_E

The generator capability curve



Adding the maximum prime mover constraint



Example 5-8

Example 5–8. A 480-V, 50-Hz, Y-connected, six-pole synchronous generator is rated at 50 kVA at 0.8 PF lagging. It has a synchronous reactance of 1.0 Ω per phase. Assume that this generator is connected to a steam turbine capable of supplying up to 45 kW. The friction and windage losses are 1.5 kW, and the core losses are 1.0 kW.

(a) Sketch the capability curve for this generator, including the prime-mover power limit.

(b) Can this generator supply a line current of 56 A at 0.7 PF lagging? Why or why not?

(c) What is the maximum amount of reactive power this generator can produce?

(d) If the generator supplies 30 kW of real power, what is the maximum amount of reactive power that can be simultaneously supplied?

The maximum armature current

The maximum current in this generator can be found from Equation (5–36):

$$S_{\text{rated}} = 3V_{\phi,\text{rated}}\, I_{A,\max}$$

The voltage V_ϕ of this machine is

$$V_\phi = \frac{V_T}{\sqrt{3}} = \frac{480\ \text{V}}{\sqrt{3}} = 277\ \text{V}$$

so the maximum armature current is

$$I_{A,\max} = \frac{S_{\text{rated}}}{3V_\phi} = \frac{50\ \text{kVA}}{3(277\ \text{V})} = 60\ \text{A}$$

With this information, it is now possible to answer the questions.

(*a*) The maximum permissible apparent power is 50 kVA, which specifies the maximum safe armature current. The center of the E_A circles is at

$$Q = -\frac{3V_\phi^2}{X_S} \tag{5–42}$$

$$= -\frac{3(277\text{ V})^2}{1.0\ \Omega} = -230\text{ kVAR}$$

The maximum size of E_A is given by

$$\mathbf{E}_A = \mathbf{V}_\phi + jX_S\mathbf{I}_A$$

$$= 277\angle 0°\text{ V} + (j1.0\ \Omega)(60\angle -36.87°\text{ A})$$

$$= 313 + j48\text{ V} = 317\angle 8.7°\text{ V}$$

Therefore, the magnitude of the distance proportional to E_A is

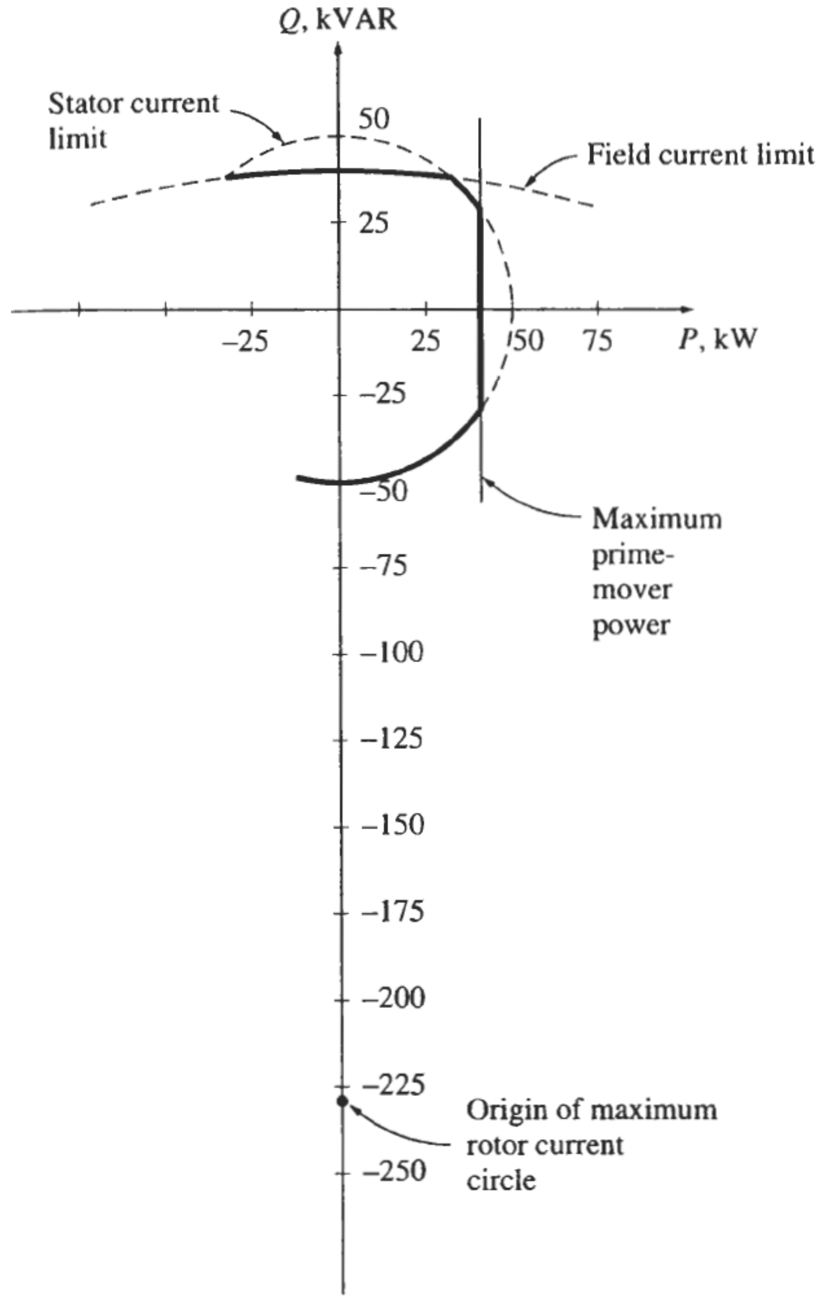
$$D_E = \frac{3E_AV_\phi}{X_S} \tag{5–43}$$

$$= \frac{3(317\text{ V})(277\text{ V})}{1.0\ \Omega} = 263\text{ kVAR}$$

The maximum output power available with a prime-mover power of 45 kW is approximately

$$P_{\text{max,out}} = P_{\text{max,in}} - P_{\text{mech loss}} - P_{\text{core loss}}$$
$$= 45 \text{ kW} - 1.5 \text{ kW} - 1.0 \text{ kW} = 42.5 \text{ kW}$$

(This value is approximate because the I^2R loss and the stray load loss were not considered.) The resulting capability diagram is shown in Figure 5–51.


Q, kVAR
Stator current limit
Field current limit
50
25
–25
25
50
75
P, kW
–25
–50
–75
–100
–125
–150
–175
–200
–225
–250
Maximum prime-mover power
Origin of maximum rotor current circle

(*b*) A current of 56 A at 0.7 PF lagging produces a real power of

$$P = 3V_\phi I_A \cos\theta$$
$$= 3(277 \text{ V})(56 \text{ A})(0.7) = 32.6 \text{ kW}$$

and a reactive power of

$$Q = 3V_\phi I_A \sin\theta$$
$$= 3(277 \text{ V})(56 \text{ A})(0.714) = 33.2 \text{ kVAR}$$

Plotting this point on the capability diagram shows that it is safely within the maximum I_A curve but outside the maximum I_F curve. Therefore, this point is *not* a safe operating condition.

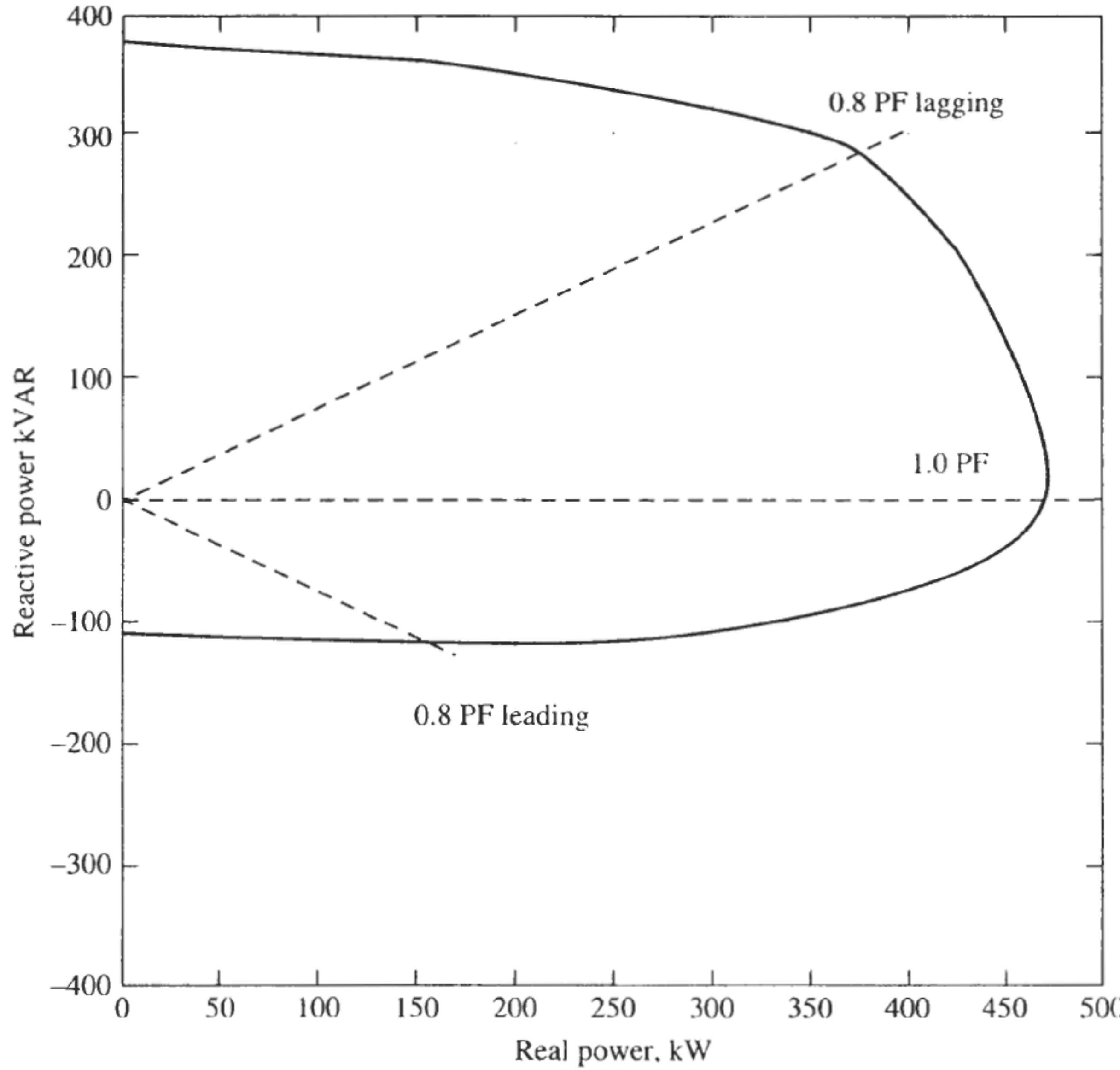
(*c*) When the real power supplied by the generator is zero, the reactive power that the generator can supply will be maximum. This point is right at the peak of the capability curve. The Q that the generator can supply there is

$$Q = 263 \text{ kVAR} - 230 \text{ kVAR} = 33 \text{ kVAR}$$

(*d*) If the generator is supplying 30 kW of real power, the maximum reactive power that the generator can supply is 31.5 kVAR. This value can be found by entering the capability diagram at 30 kW and going up the constant-kilowatt line until a limit is reached. The limiting factor in this case is the field current—the armature will be safe up to 39.8 kVAR.

清華大学

Typical capability cure of a real generator



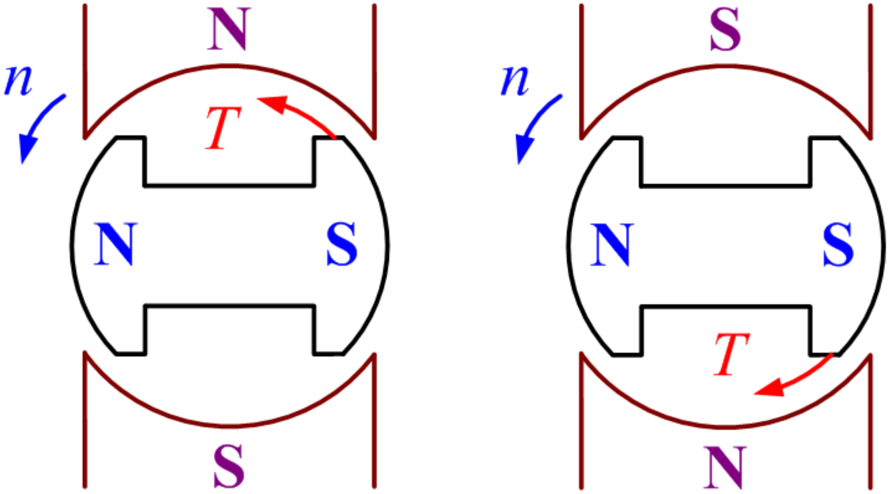
Short time operation and service factor

- Usually, a typical generator is often able to supply up to 300 percent of its rated power for a while (until its windings burn up)
- There are four standard insulation classes: A, B, F, H. for 60, 80, 105, and 125 Celsius degrees.
- The higher the insulation class of a machine, the greater the power that can be drawn out of its without overheating its windings.

Synchronous motor

Starting of synchronous motor

- Synchronous motors cannot start by itself due to fast alternating torque



Ways to start synchronous motor

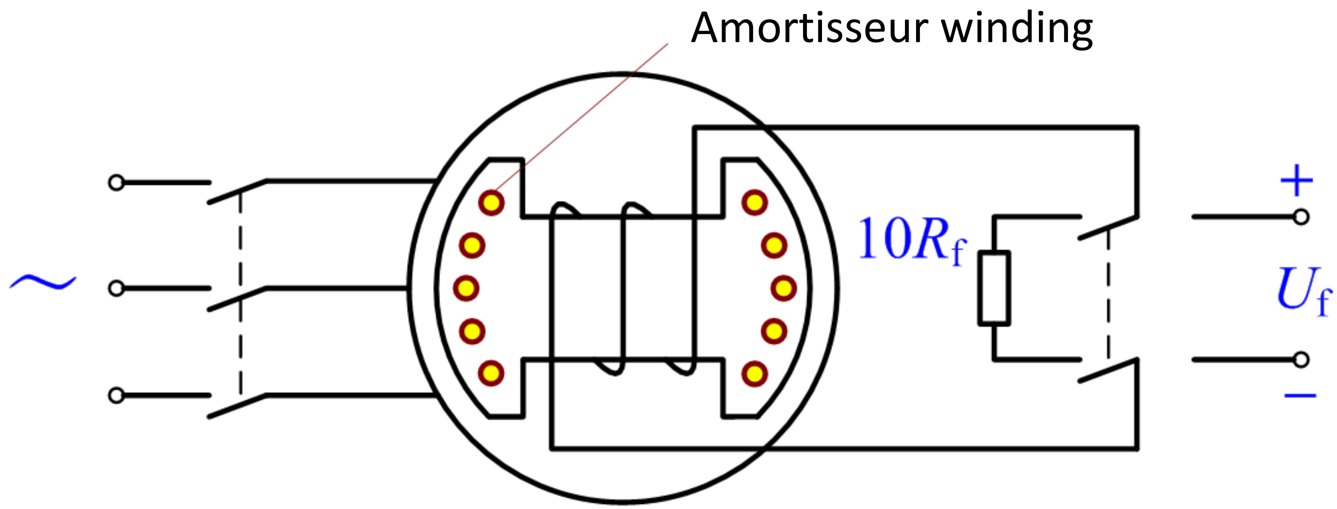
- Assisted motor start
  - Use another induction motor to start the synchronous motor close to rated speed, then connect to the grid

- Variable frequency start
  - Use variable frequency power supply

- Use Amortisseur windings

Introduction of Amortisseur winding

- Amortisseur (damper) winding is copper conductors shorted on the rotor
- Never leave the field winding in open circuit



Recap

- Armature Reaction
- Equivalent circuit of a synchronous generator
- Power and torque
- Measure the generator model parameters
- Operating alone.
- Parallel operation
- Transient
- Capability Curve
- Synchronous Motor