Steady-state analysis for synchronous machines

Dr. Luo Ciyong

Synchronous motors can be represented as an impedance in series with a voltage source.

The basic structure and operations of synchronous machines

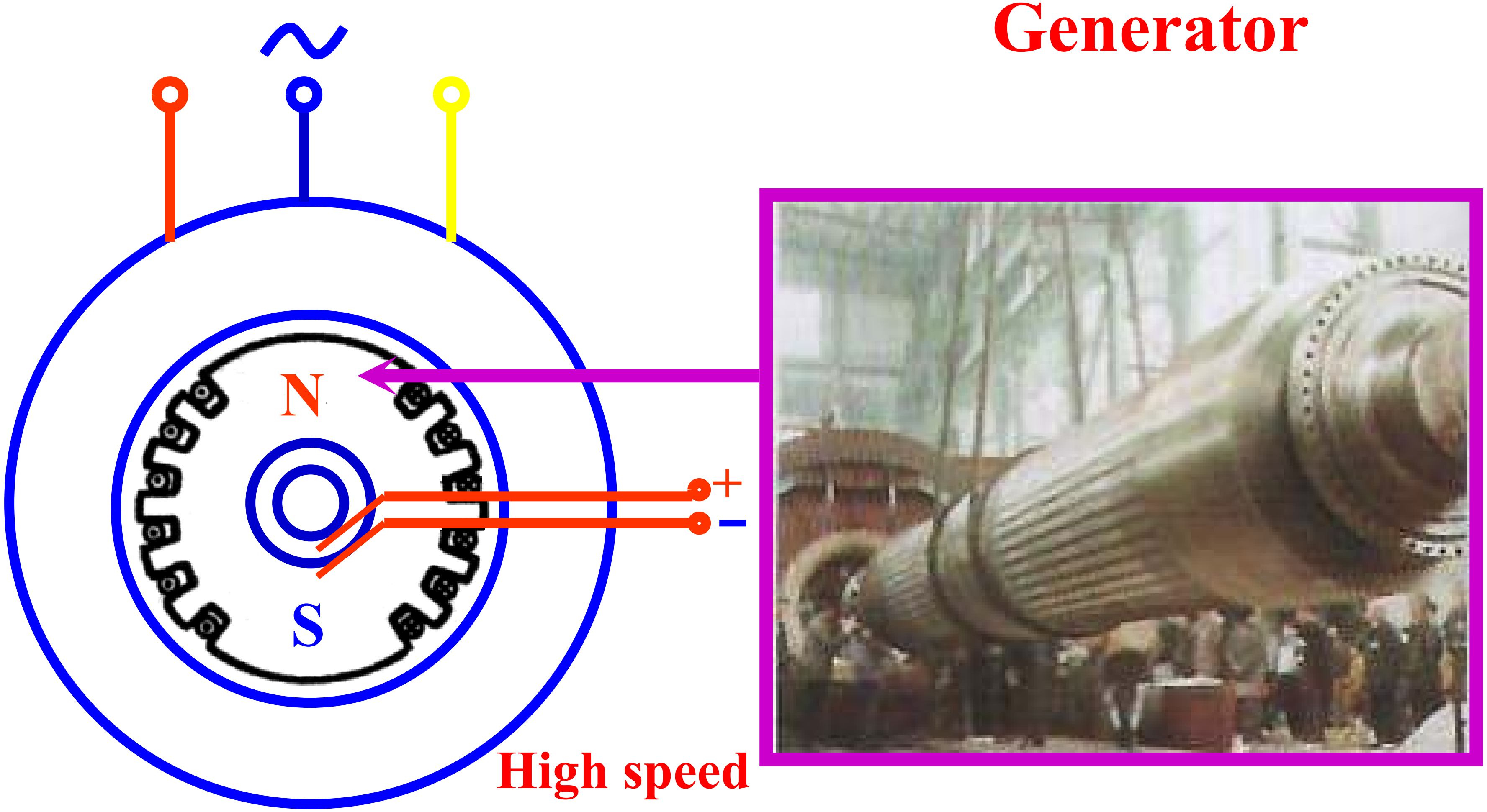
1) Basic Structure

- synchronous machines
  - Rotary armature
  - Rotary magnetic poles
    - Salient-pole
    - Cylindrical-Rotor

Basic structure

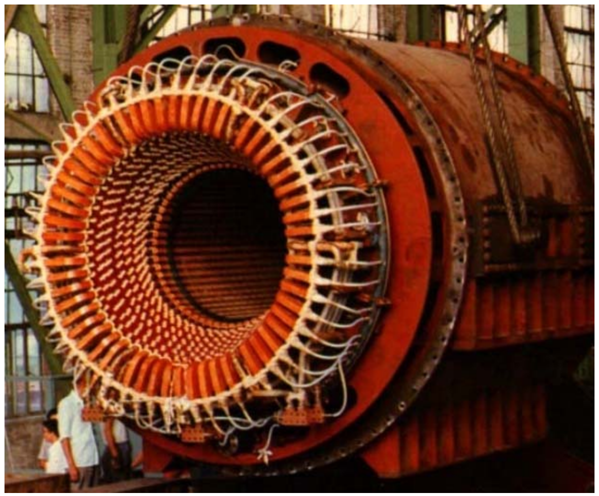
Cylindrical-Rotor

Steam Turbine Generator

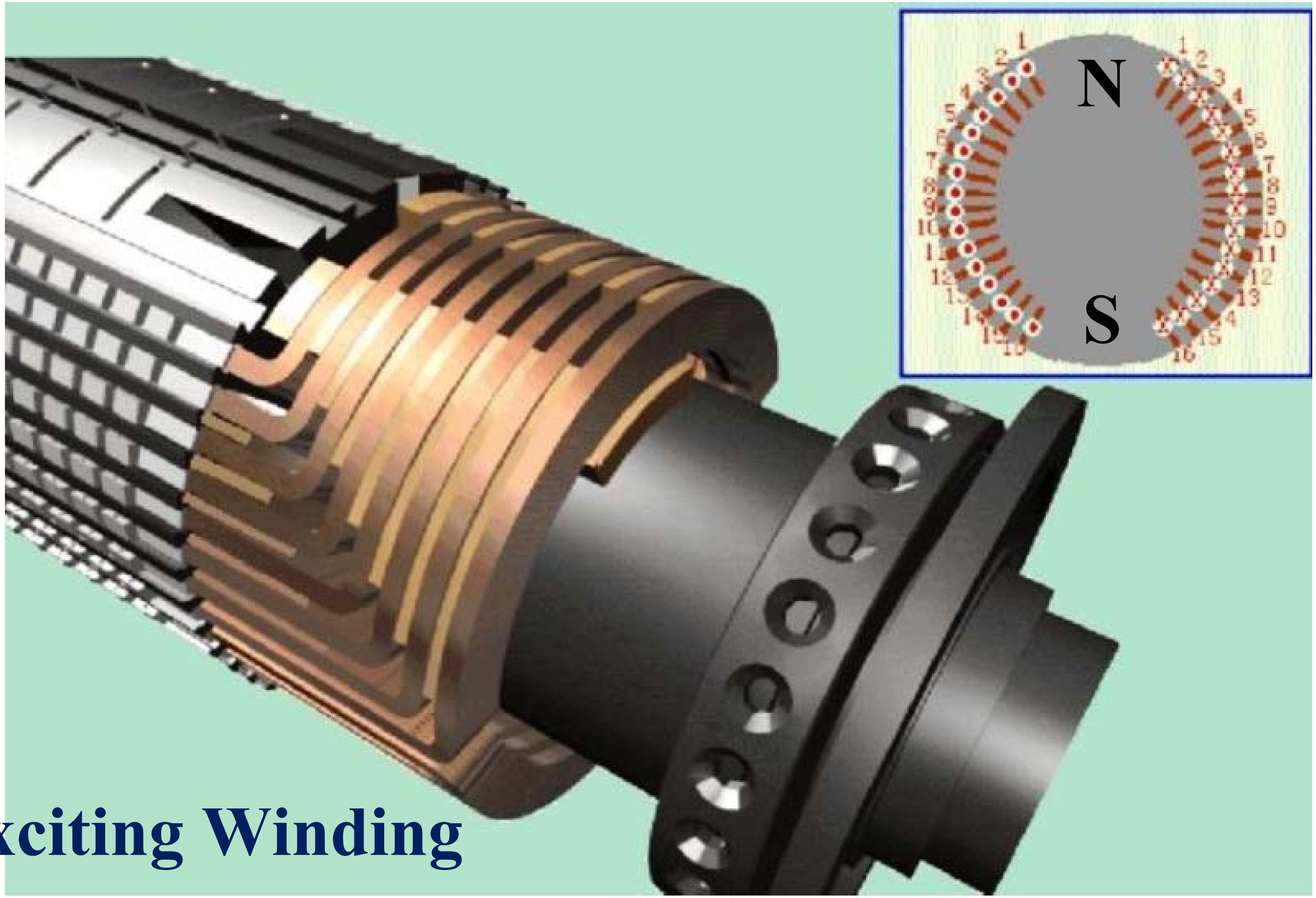


Structure features: a long cylindrical rotor, a relatively uniform air gap, big and small tooth on the rotor surface, two poles, driving by steam turbines, named as a turbine generator.



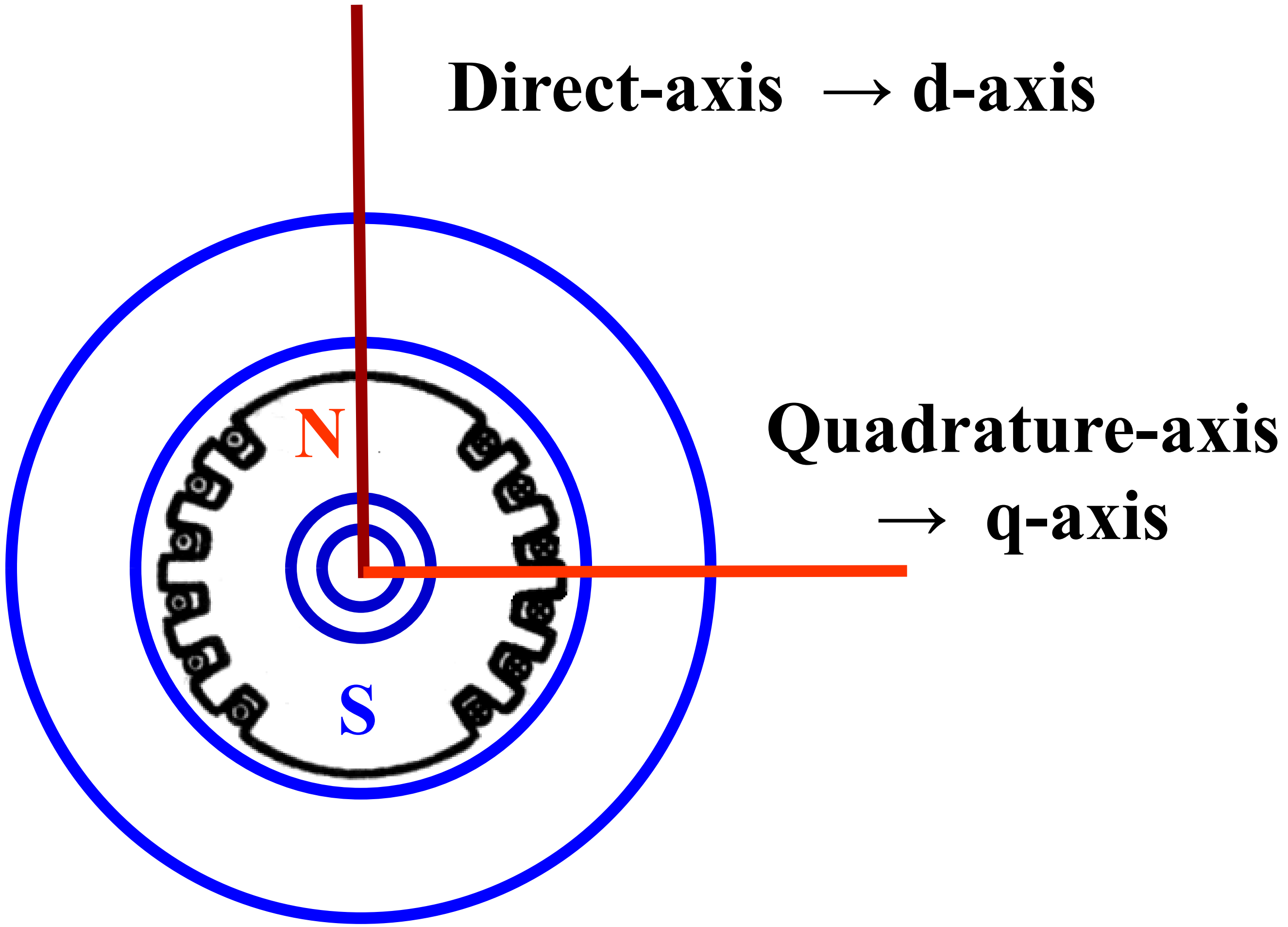



Steam Turbine Generator



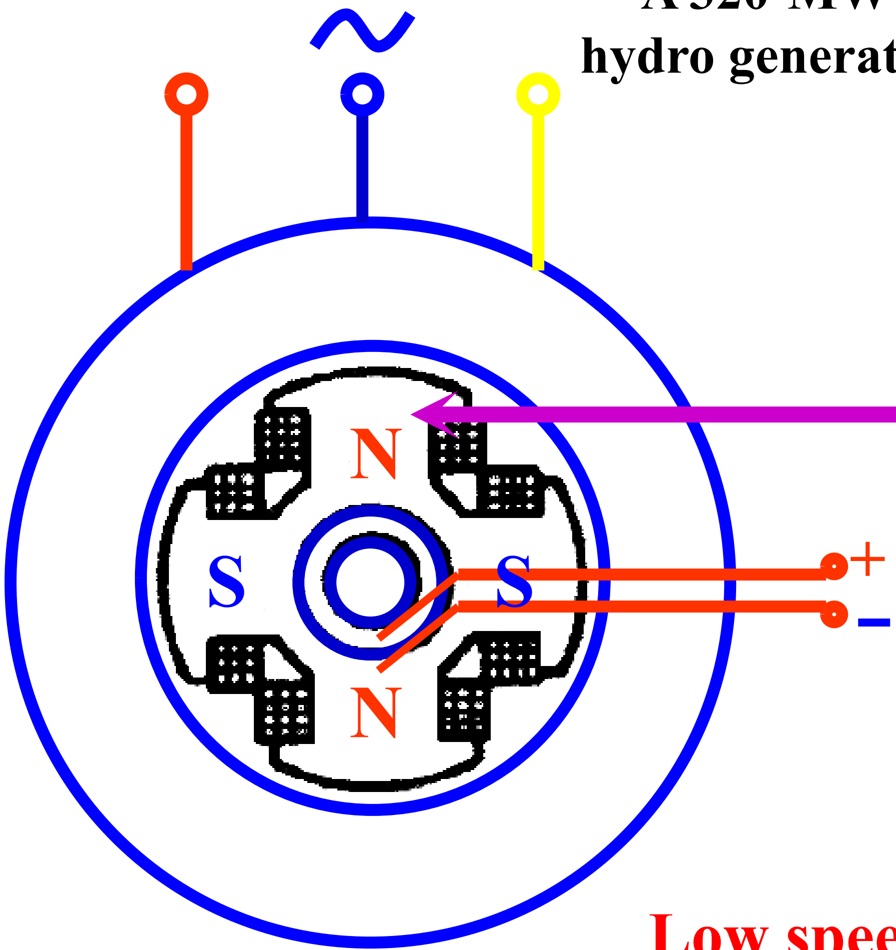
Exciting Winding

Cylindrical-Rotor

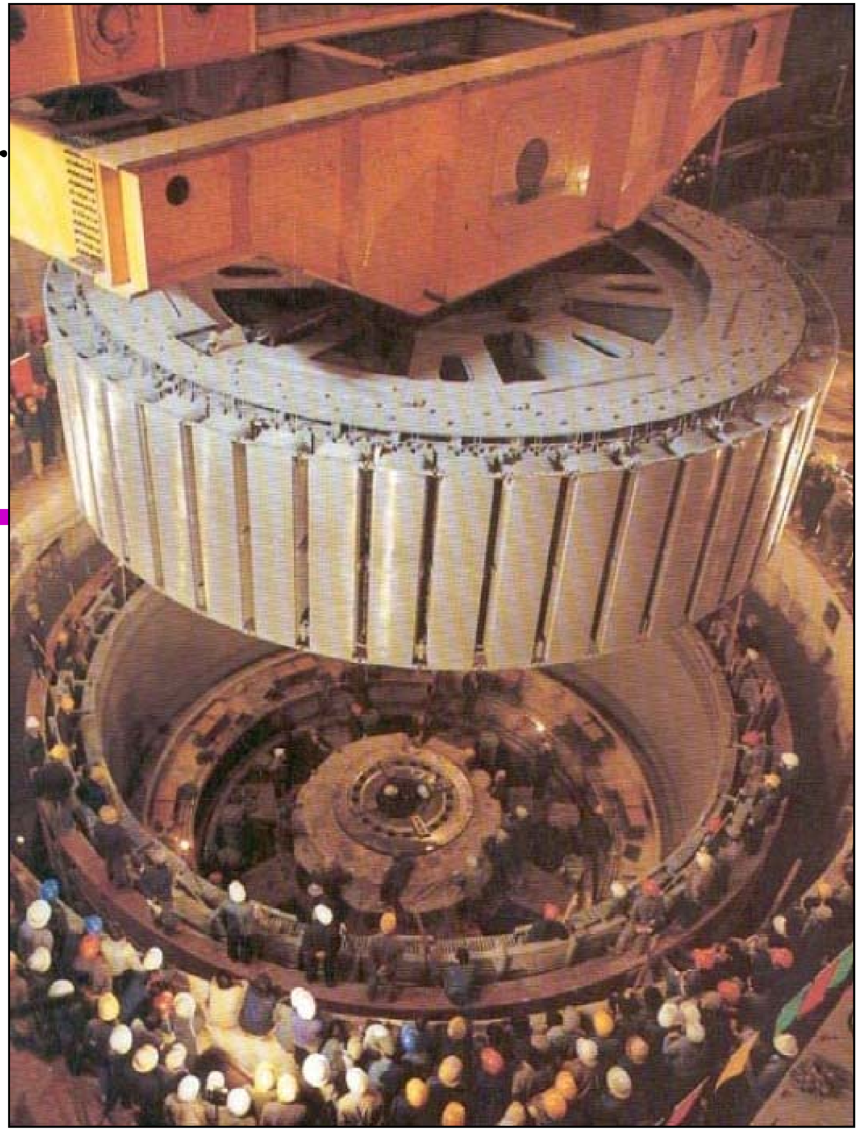


See direct- and quadrature-axis armature reaction of DC motors

Salient-pole

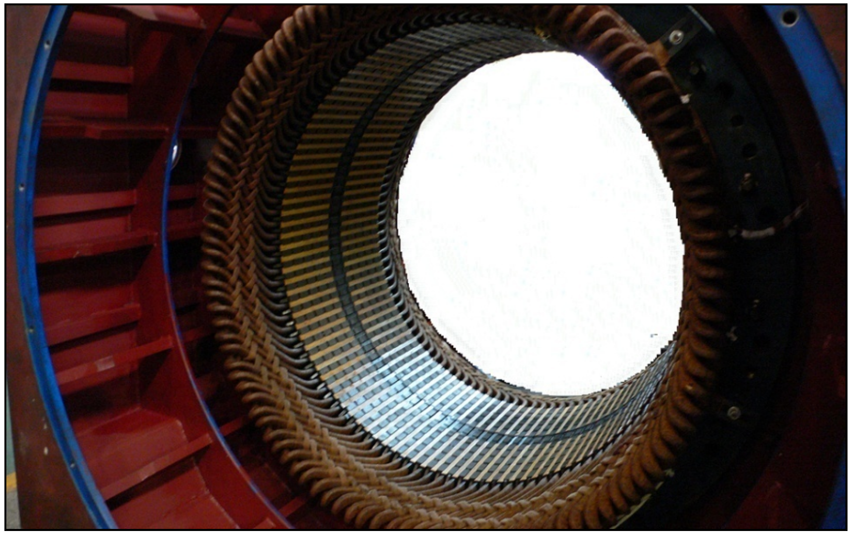


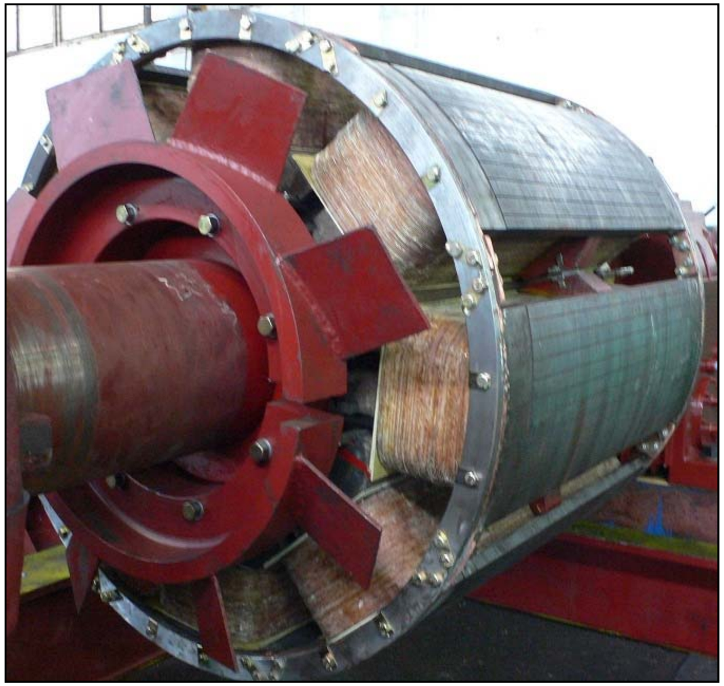
A 320-MW hydro generator

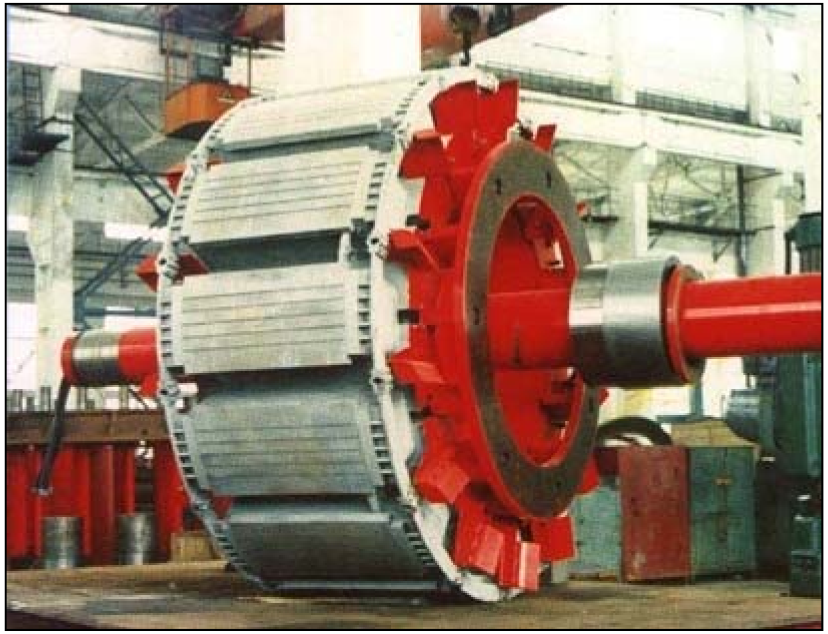


Low speed

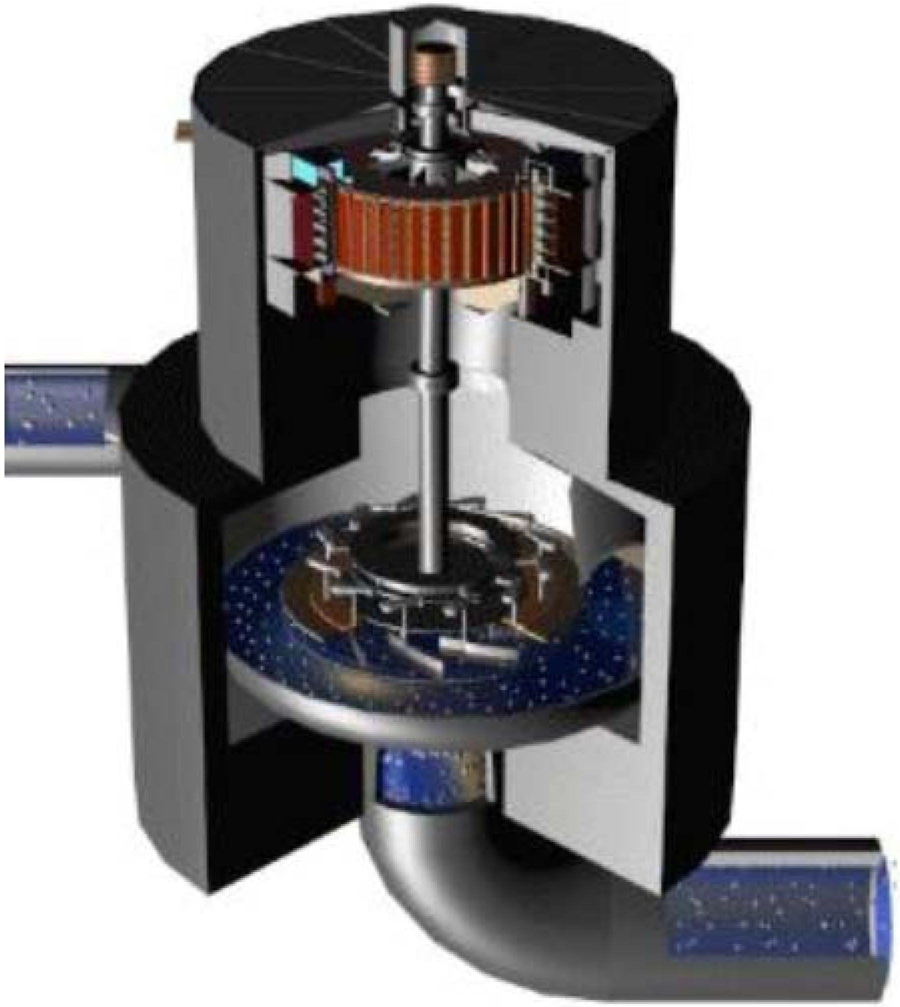
Structure features: a pancake-like rotor structure, salient poles on rotor surface, nonuniform air gap, several pairs of poles, driving by hydro turbine, named hydro generator



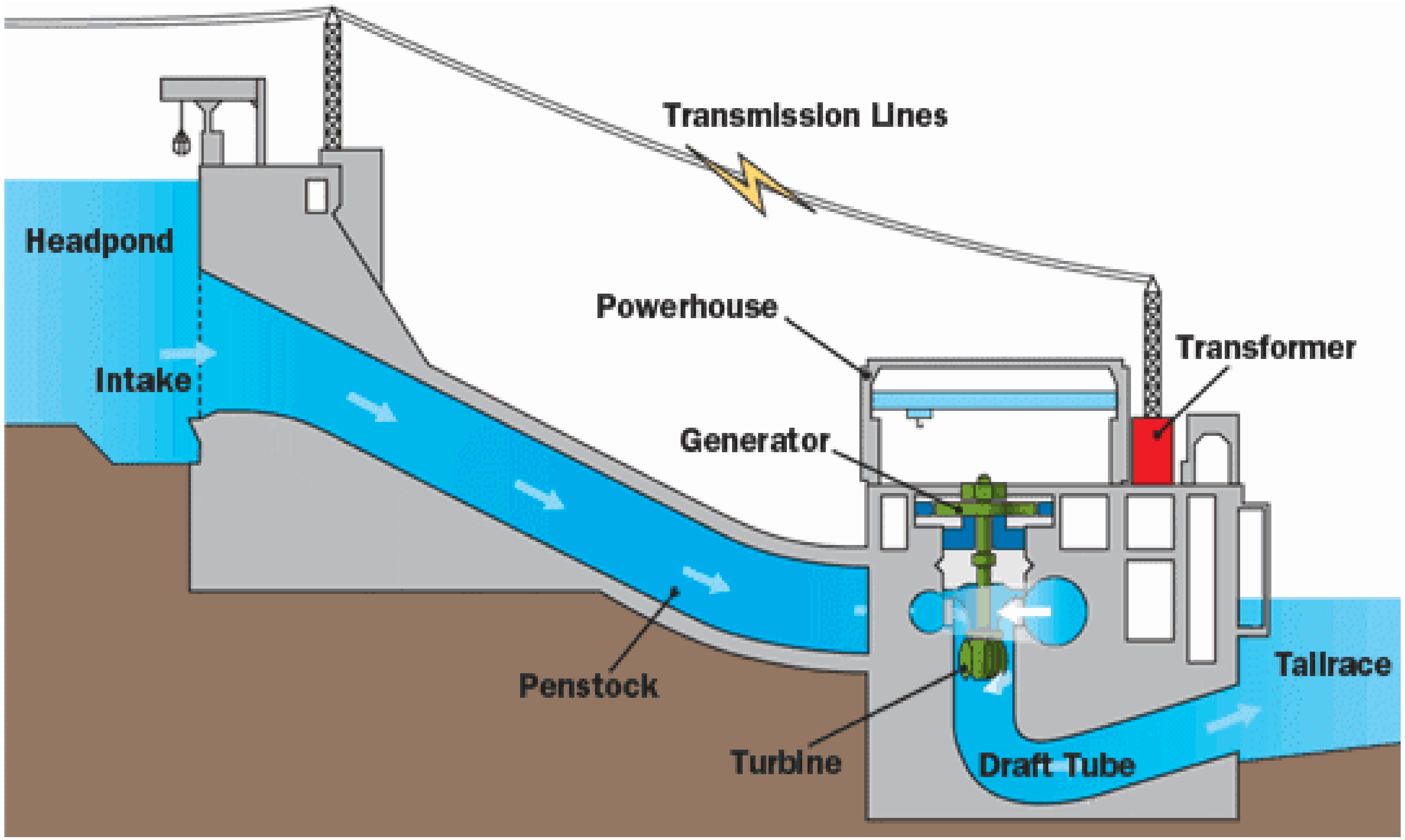




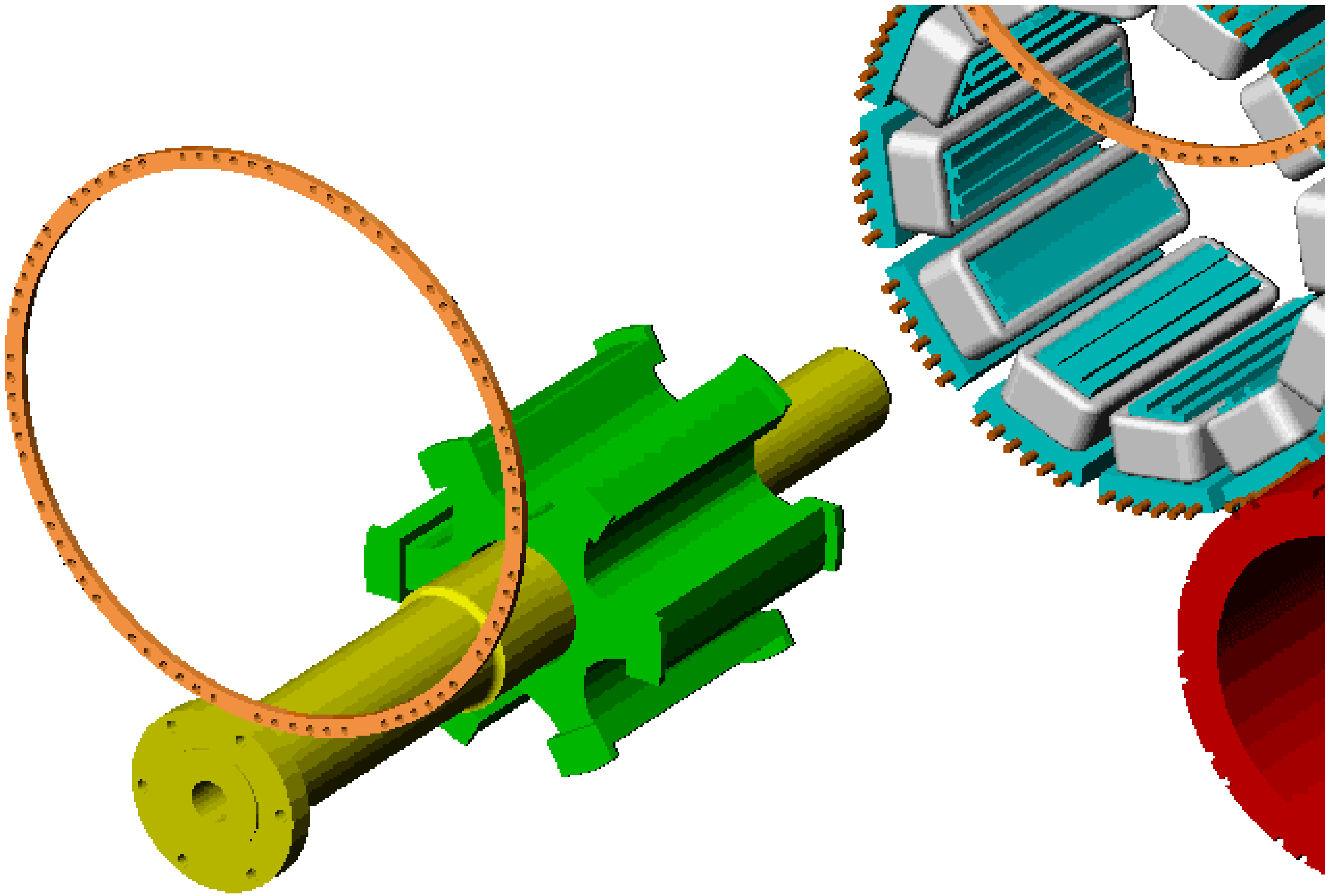
Models of Synchronous Machine



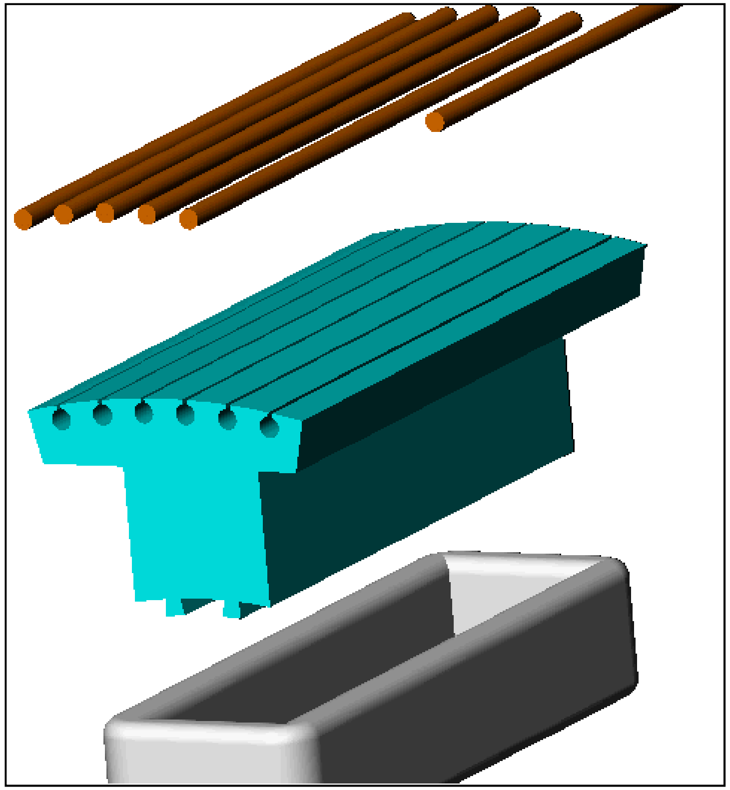
Models of Synchronous Machine

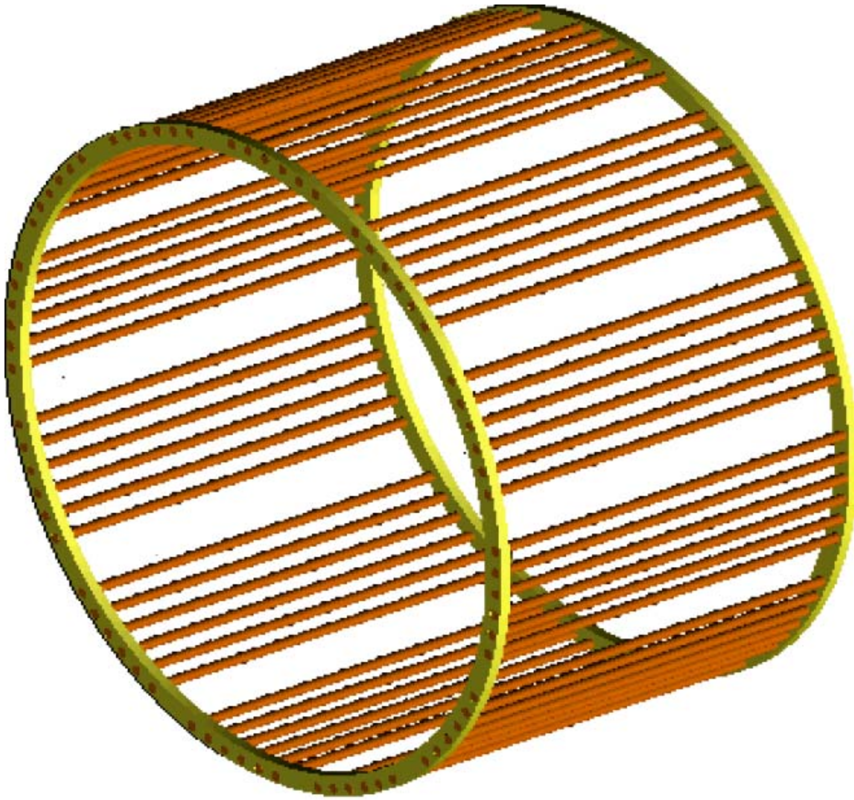


Models of Synchronous Machine

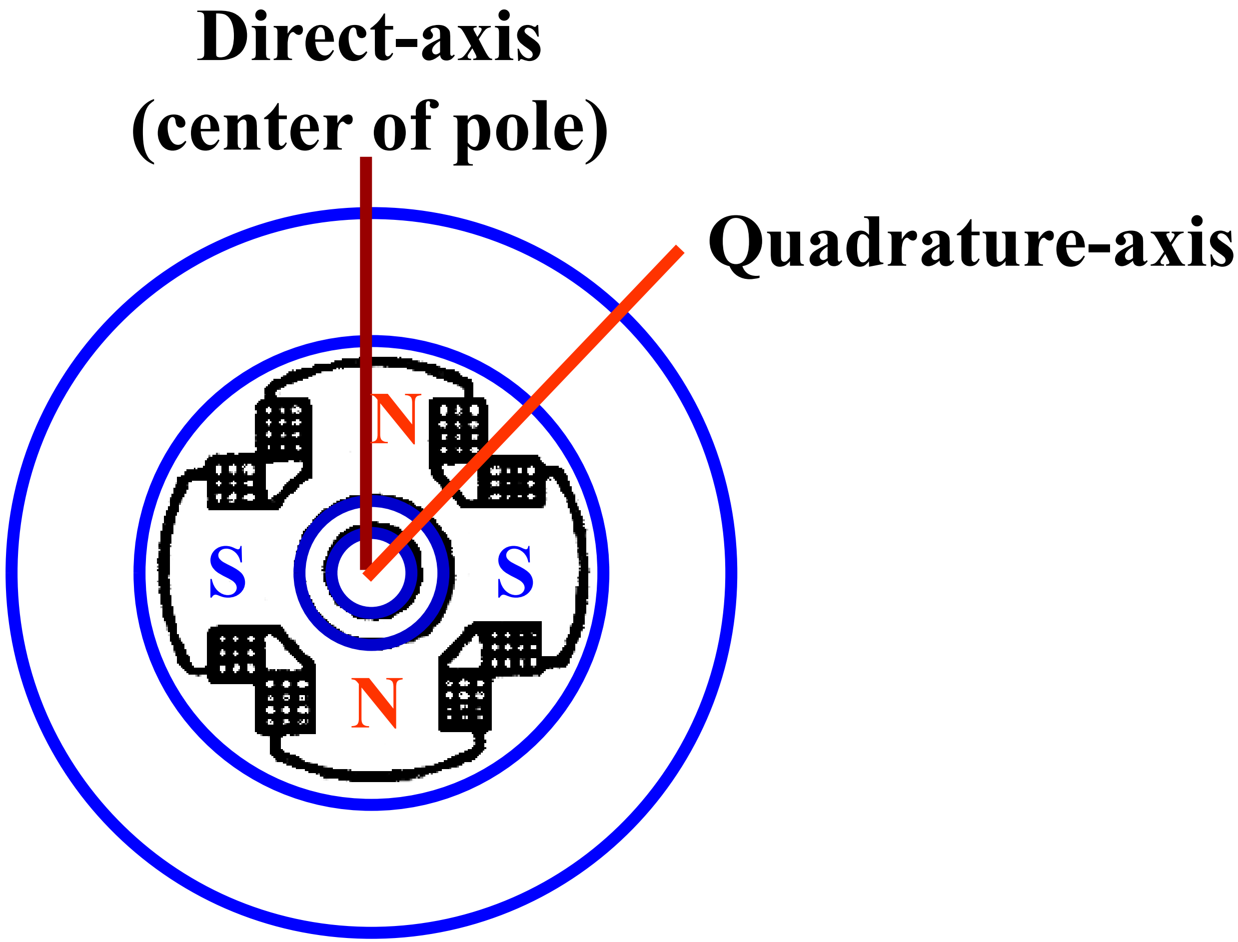


Models of Synchronous Machine



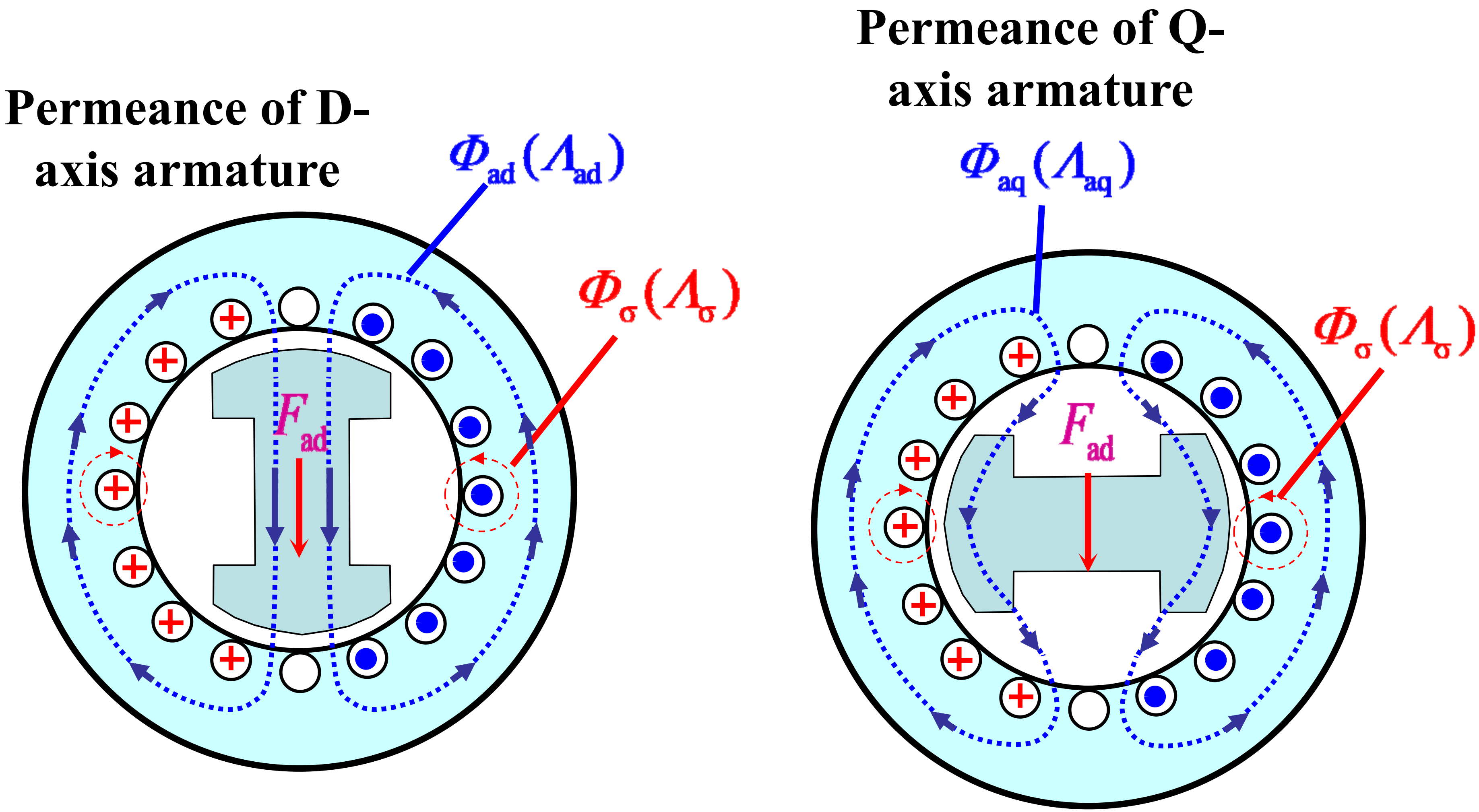


Salient-pole



See direct- and quadrature-axis armature reaction of dc motors

The air gap of direct- and quadrature-axis is nonuniform



Salient-pole synchronous machines: $\Lambda_{ad} > \Lambda_{ad}$, so $X_{ad}>X_{aq}$, then, $X_d>X_q$。

Cylindrical-rotor synchronous machines: $X_d \approx X_q \approx X_s$

2 Operations of synchronous machines

The voltage induced in a stator coil is generated by cutting of flux . And the frequency is given by:

$$f = \frac{pn_s}{60}$$

The stator winding with closed loop excited by balanced three-phase currents produces a magnetic flux wave in the air gap which rotates at synchronous speed. At steady state, rotor current also creates a magnetic flux wave which rotates at synchronous speed. So the magnetic fields created by rotor and stator current keep relative rest. The electromechanical torque is generated. For this reason, the synchronous generator converts mechanical to electric energy.

****The relationship between speed and frequency of synchronous generator keeps strictly unchanged, which is one of the major differences that distinguish from asynchronous machines.**

2 Operations of synchronous machines

motor——converts electric to mechanical energy

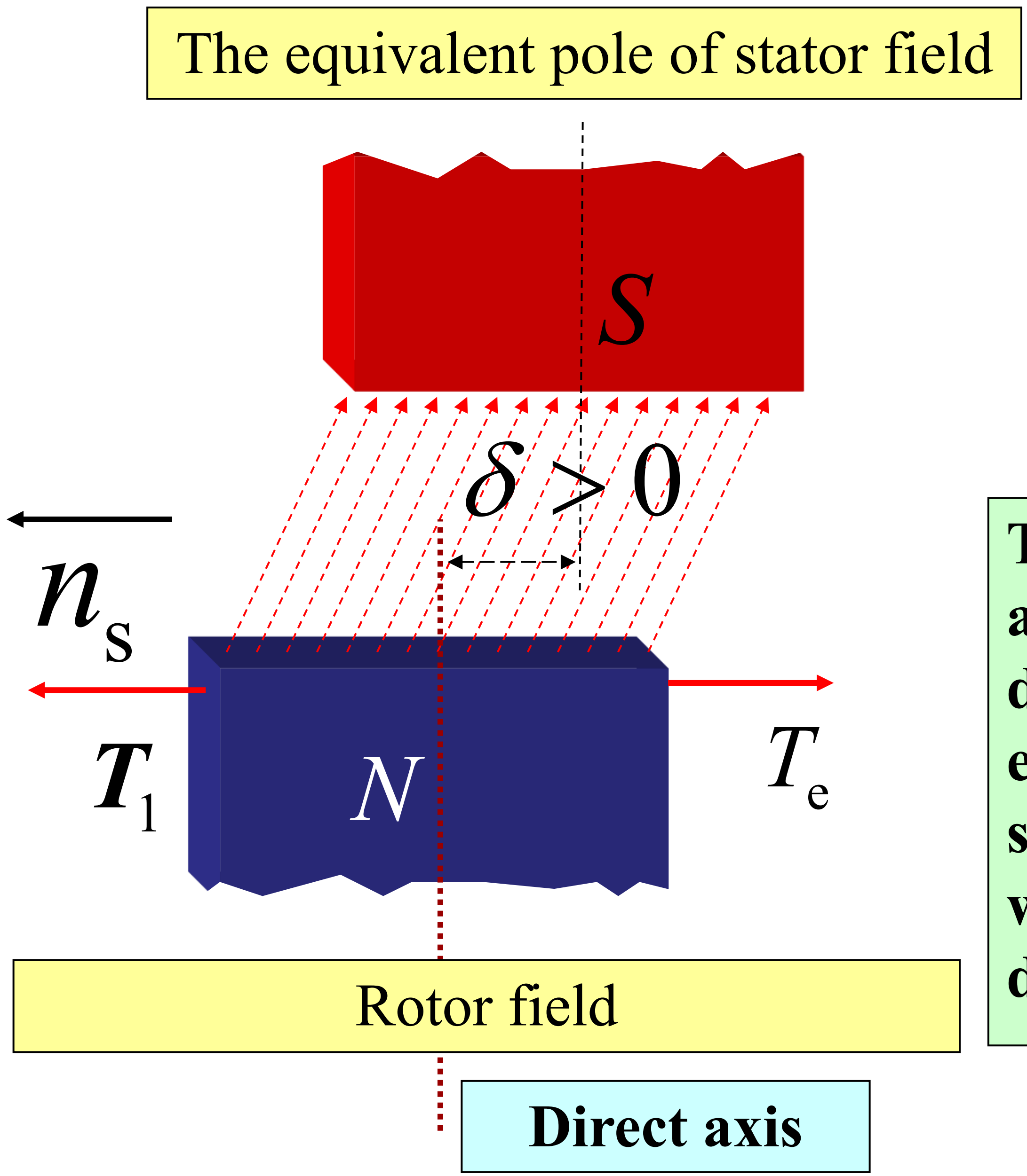
synchronous compensator——its purpose is not to convert electric power to mechanical power or vice versa, but generates or absorbs reactive power as needed to adjust the grid's voltage, or to improve power factor

generator——converts mechanical to electric energy

The operations of a synchronous machine are determined by the space electric angle δ of stator magnetic field with respect to rotor main field.

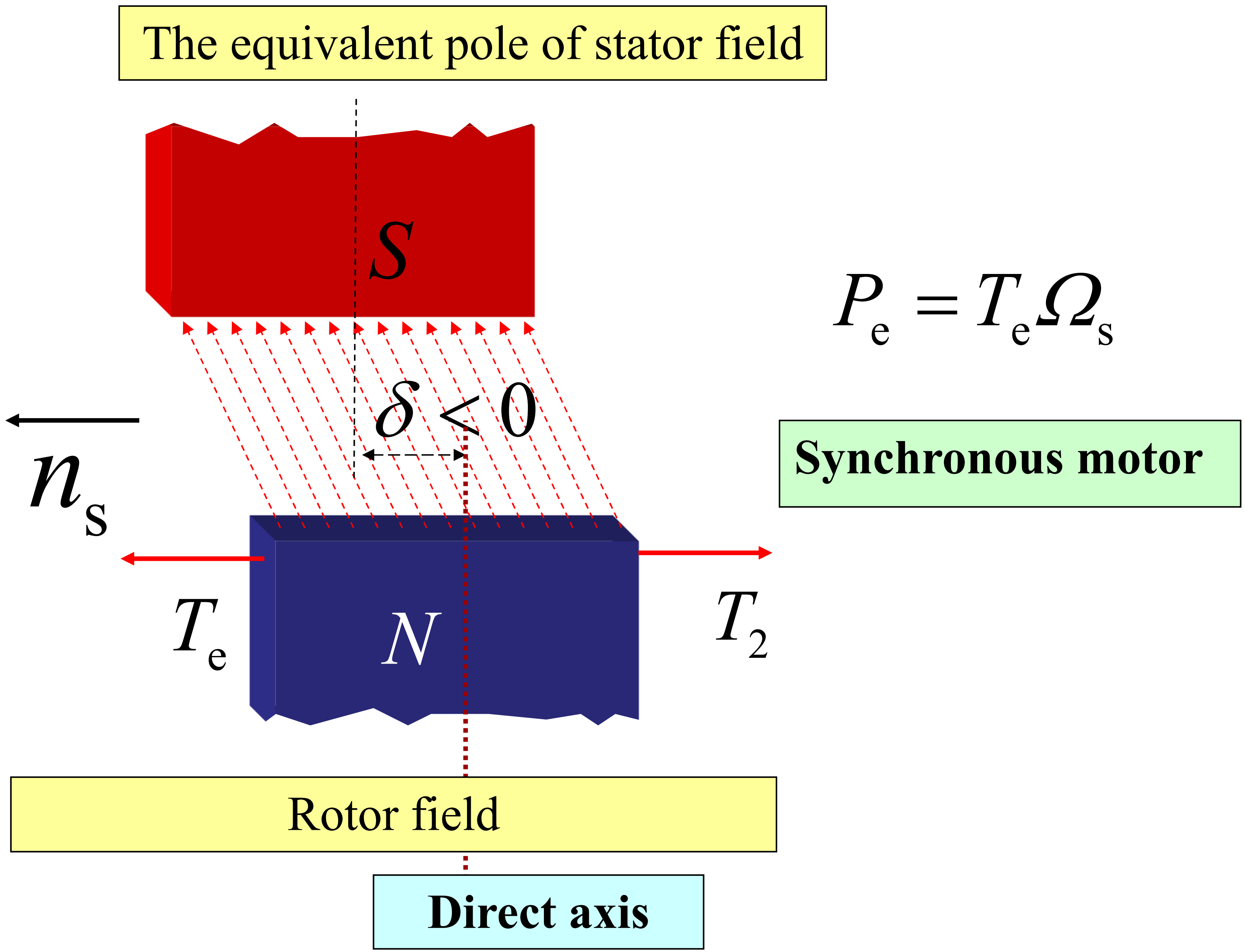
δ is called power angle

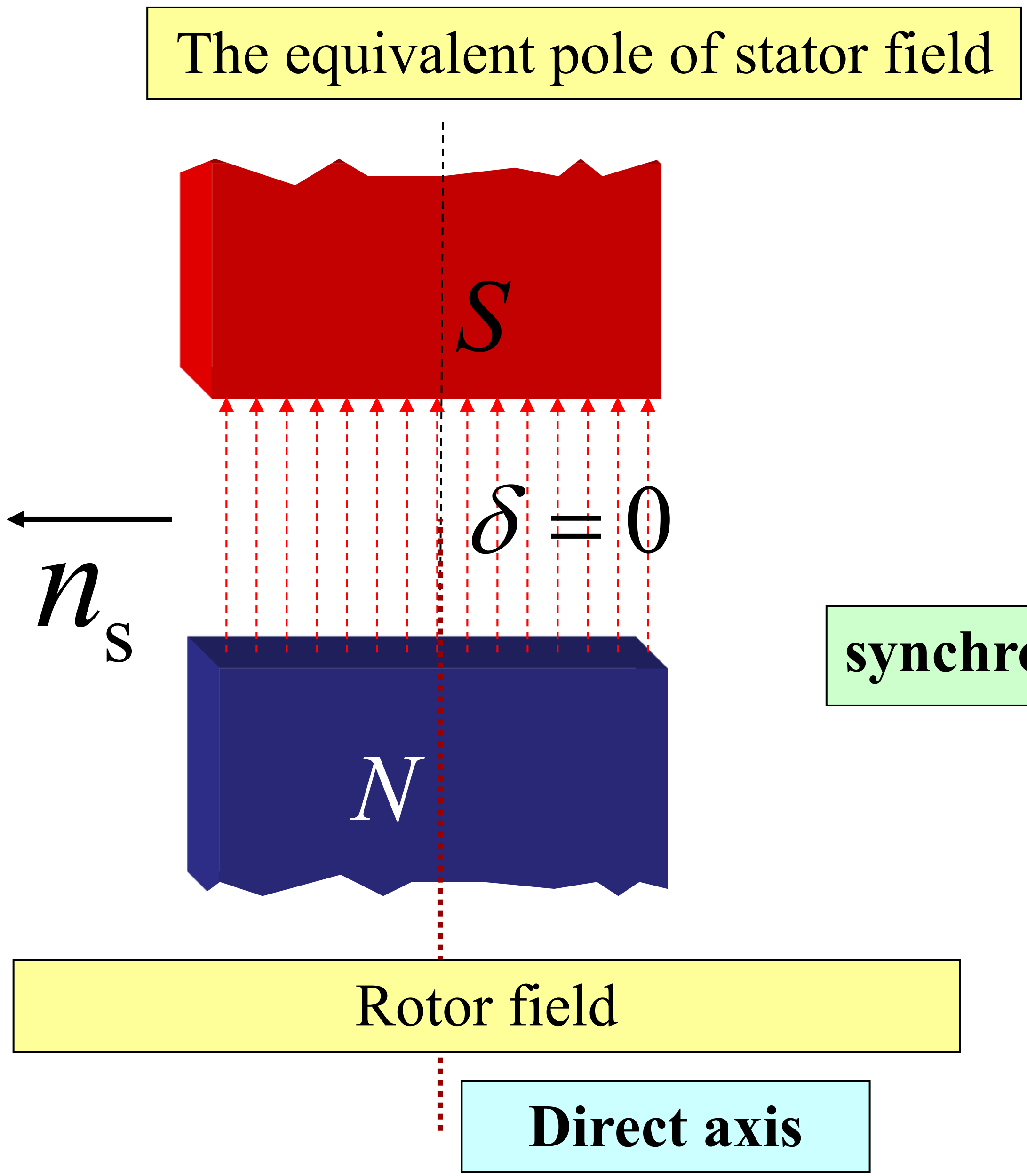
Note that if δ is positive, rotor field leads stator field



$$P_e = T_e \Omega_s$$

The work and armature reaction is determined by the electric angle of stator-field axis with respect to direct axis.

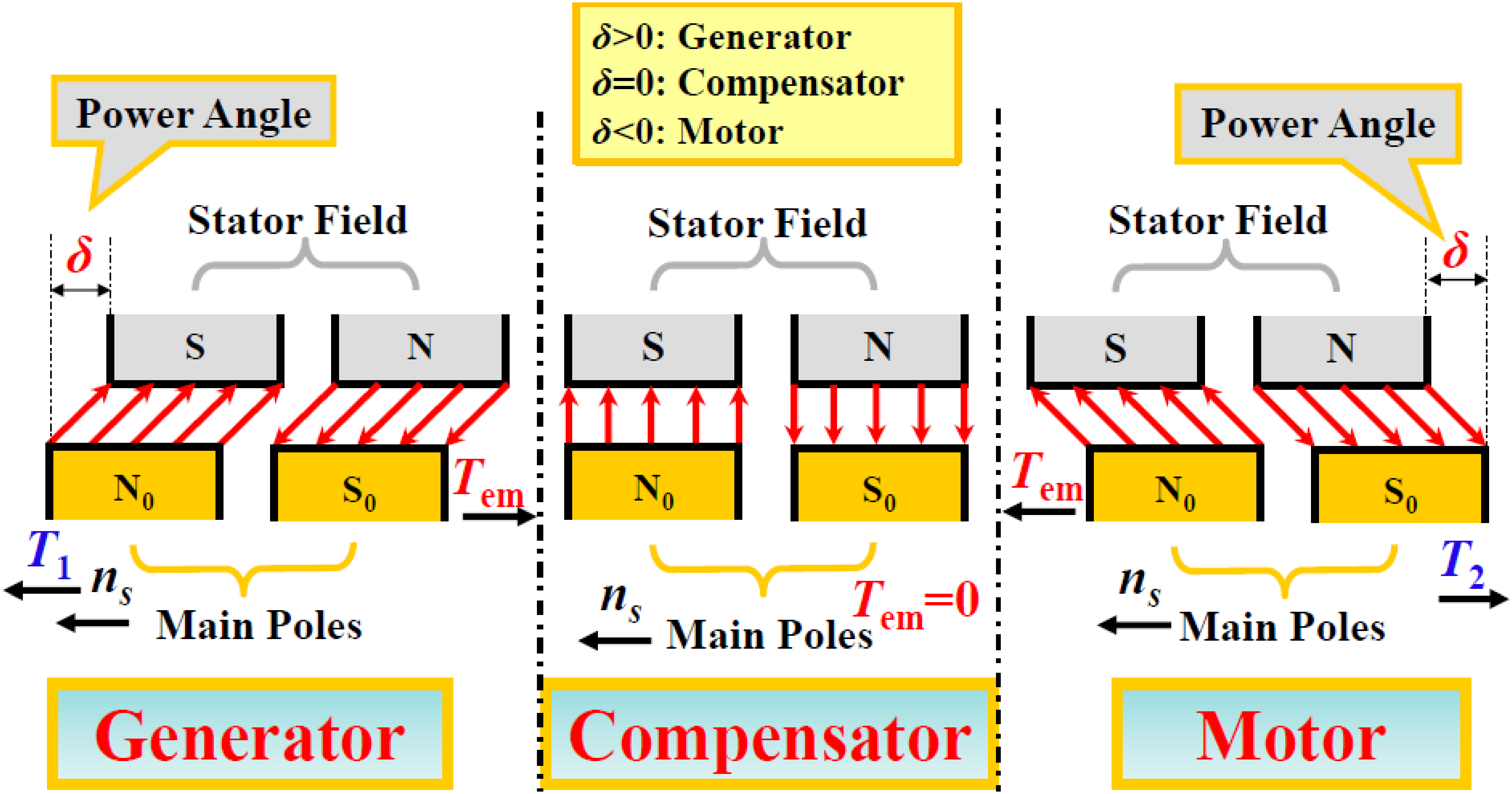

The equivalent pole of stator field
S
$P_e = T_e \Omega_s$
$\delta < 0$
n_s
Synchronous motor
N
T_e
T_2
Rotor field
Direct axis



$$P_e = 0$$

synchronous compensator

Operating States of synchronous machines



3 Field excitation of synchronous machines

In synchronous machines, field winding must to be excited by dc current, and creating excitation flux. The whole device that supplies field current is called **excitation system**.

Use dc generator to supply field current

Use dc shunt generator with independent power supply (which was often mounted on the same shaft as the synchronous machine). The rectifier excitation current is fed to the rotor via **carbon brush and slip rings.**

Use rectifier to convert ac to dc

- static
- Rotary (brushless excitation)

3 Field excitation of synchronous machines

Static ac rectifier excitation system

Replace dc exciter with ac exciter， the semiconductor rectifier systems convert ac to dc and supply for field winding of synchronous machines.

Advantage：**sparkless commutation;** disadvantage：**carbon brush and slip ring are still a contact control system**

Rotary ac rectifier excitation system

(Sometimes called a brushless excitation system)

The alternator of the ac exciter is on the rotor, as is the rectification system, and the current is supplied directly to the field-winding without the need for carbon brush and slip rings.

4 Rated value

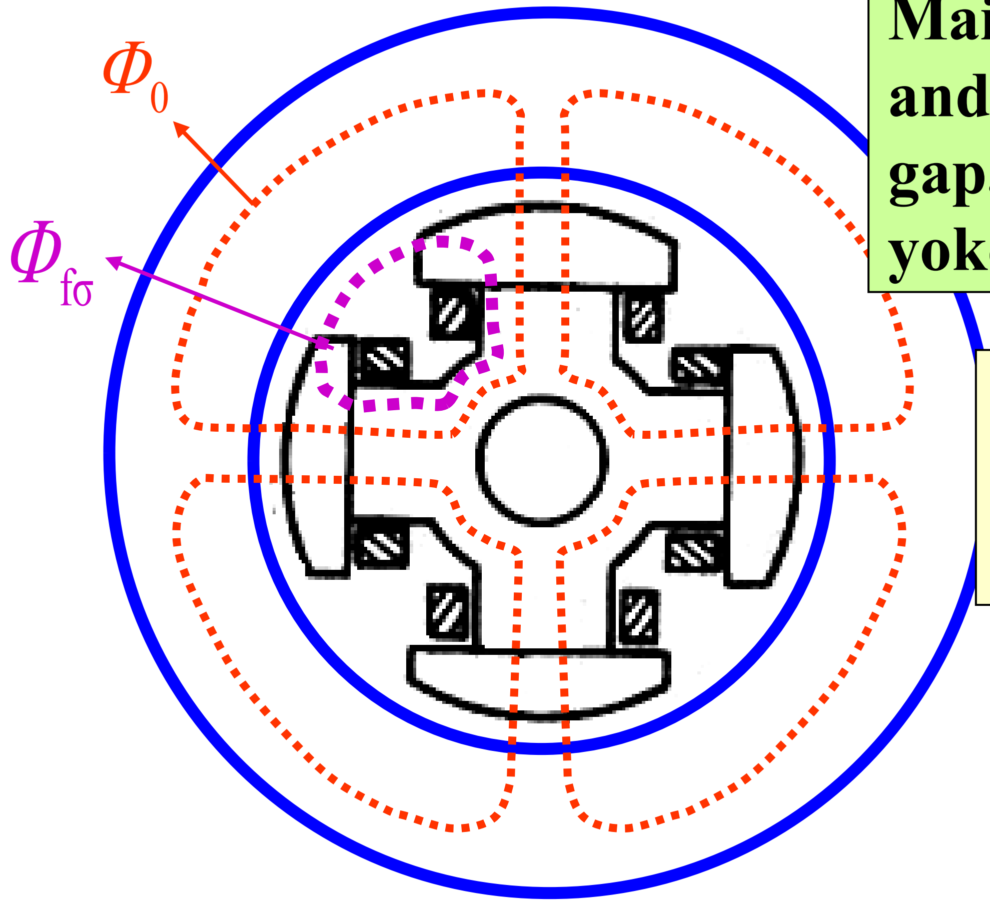
- **Rated capacity (or rated power P_N) —— the output power at rated operating condition.**

Unit: kVA for capacity, kW for active power

- **Rated voltage U_N——line voltage of stator at rated operating condition**
- **Rated current I_N——line current of stator at rated operating condition**
- **Rated power factor cos φ——power factor at rated operating condition**
- **Rated frequency f_N ——armature frequency at rated operating condition. Public frequency: 50Hz**
- **Rated speed n_N ——motor speed at rated operating condition, which is so-called synchronous speed.**

6.2 Synchronous generator field at no-load and loaded conditions

1. Only field current that creates main flux when synchronous machines is at no-load condition



Main flux Φ_0 links both stator and rotor winding (through air gap, armature tooth, armature yoke, poles and rotor yoke).

Leakage fulx $\Phi_{f\sigma}$ only links field winding without going through the air gap.

When rotor rotates at synchronous speed, the main magnetic field will create a rotating field in the air gap， cutting of balanced three-phase stator winding and induced balanced three-phase voltage of frequency *f* in stator winding, which is named as excitation emf.

Main field in the air gap rotates at synchronous speed

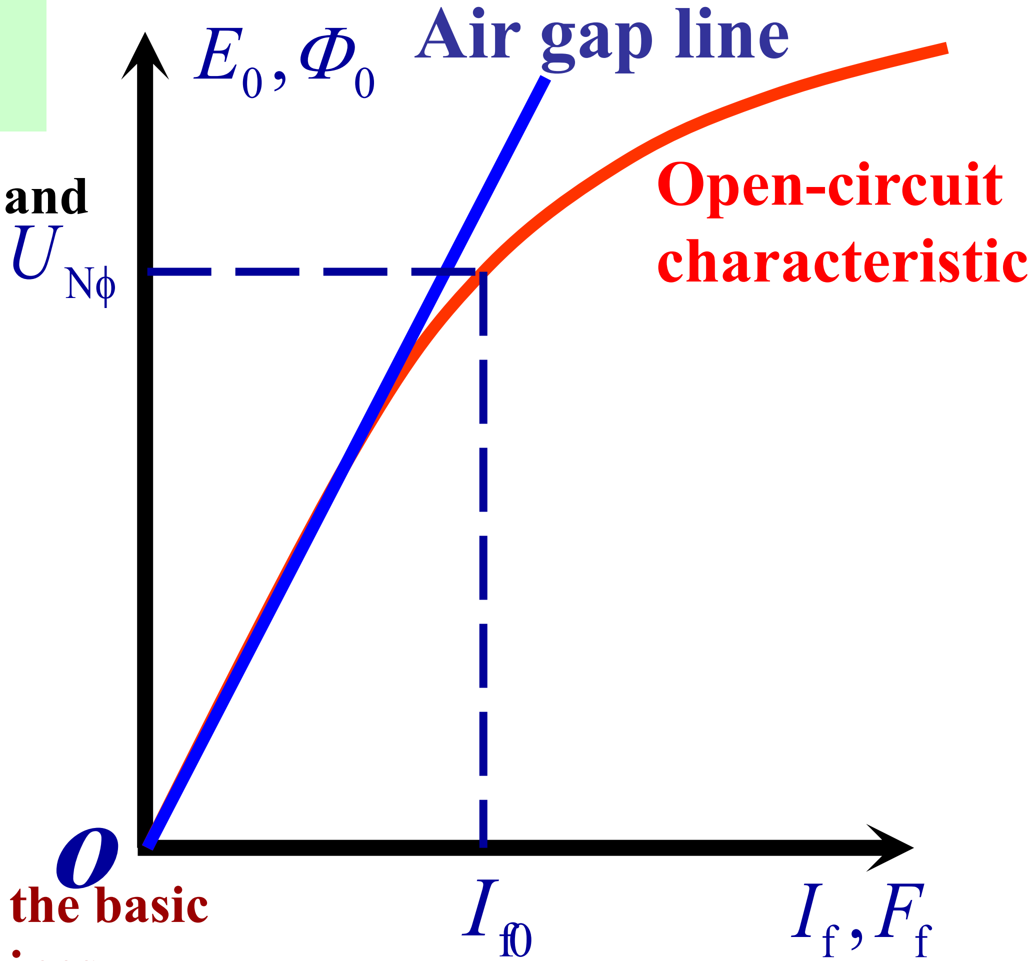
The flux that links both rotating field and full-pitch winding is called main flux

Time phasor $\dot{\Phi}_0$

$$\dot{E}_{0A} = E_0 \angle 0^0$$

$$\dot{E}_{0B} = E_0 \angle -120^0$$

$$\dot{E}_{0C} = E_0 \angle -240^0$$

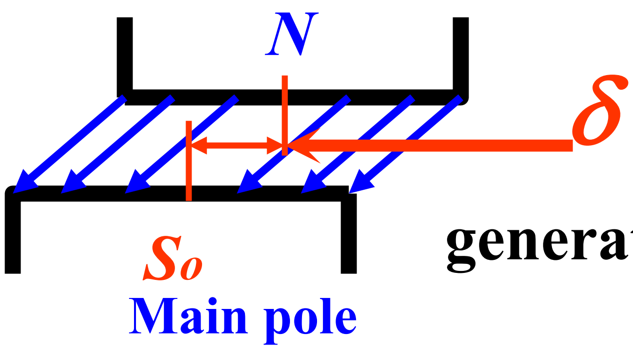


Open-circuit characteristic is one of the basic characteristics of synchronous machines

1.Excitation emf is the voltage induced by the rotating field on one phase.
2.Magnetic field is rotating, while armature is fixed, and the flux that links both of them is time-varying.

NOTE: the relationship between I_f and E_0

1.The magnitude of excitation emf shows the excitation level
2. The magnitude of excitation emf can be adjusted by changing the field current.
3. The magnitude of excitation emf is unchanged if field current unchanged.
4. Ignoring the saturation, field current is proportional to excitation emf .



generator

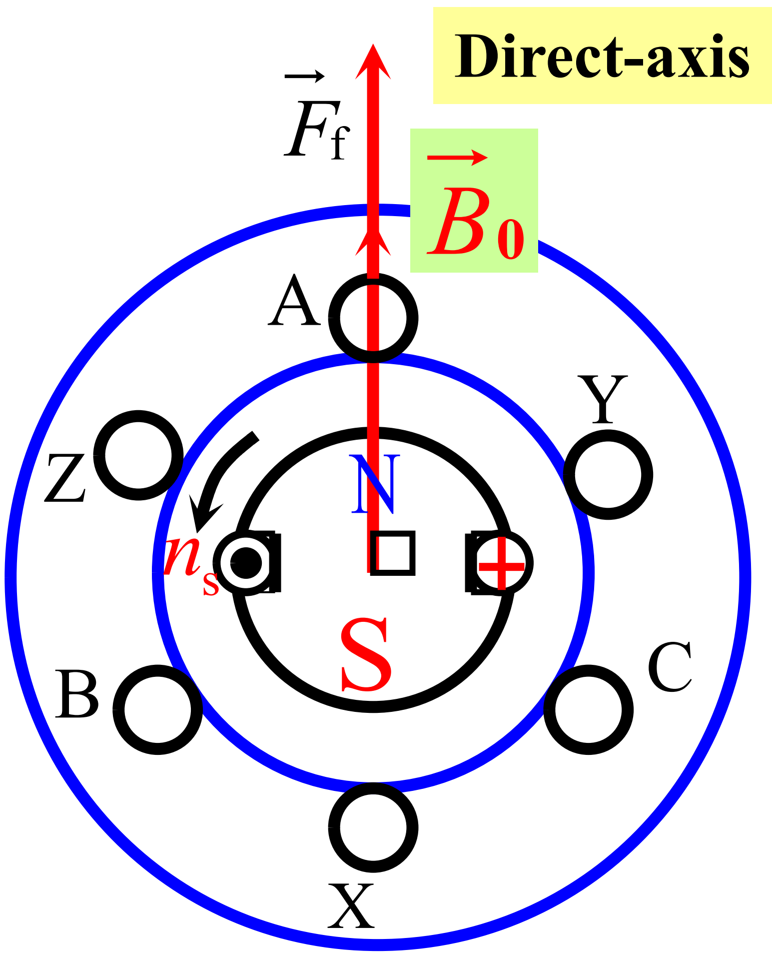
$$P_e = m\frac{E_0 U}{X_s}\sin\delta$$

The effect of field current on reactive power—see the phasor diagram of zero power angle

field current ↑, power angle ↓

field current ↓, power angle ↓

Using later formula



Excitation mmf $\vec{F}_f$ is fixed on the direct-axis rotor. Changing the magnitude of field current will change the magnitude of $\vec{F}_f$ only, but does not change the relative position of rotor.

2. Armature reaction at balanced load

•Balanced three-phase current is fed to armature winding when stator is at balanced load. The armature current creates armature mmf.

•Synthesis mmf is created by the interaction bteween armature mmf and excitation mmf. At this time, though field current is not changed, the air gap field is different from the original.

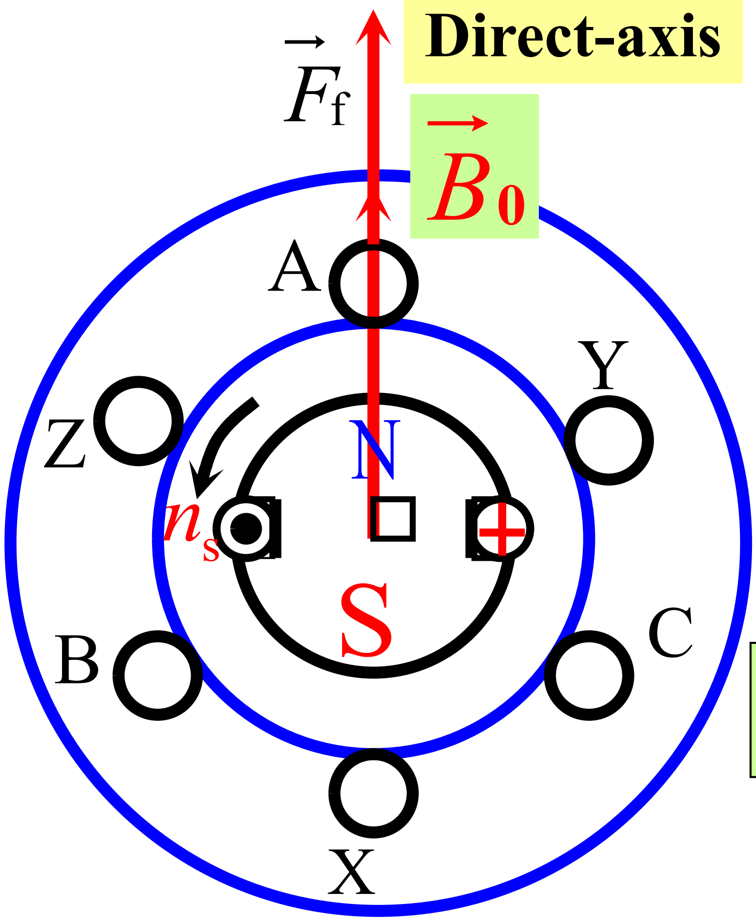
•The influence of fundamental armature mmf in the fundamental main mmf at balanced load is called armature reaction.

•The property of armature reaction is determined by the spatial relative position of armature mmf and excitation mmf

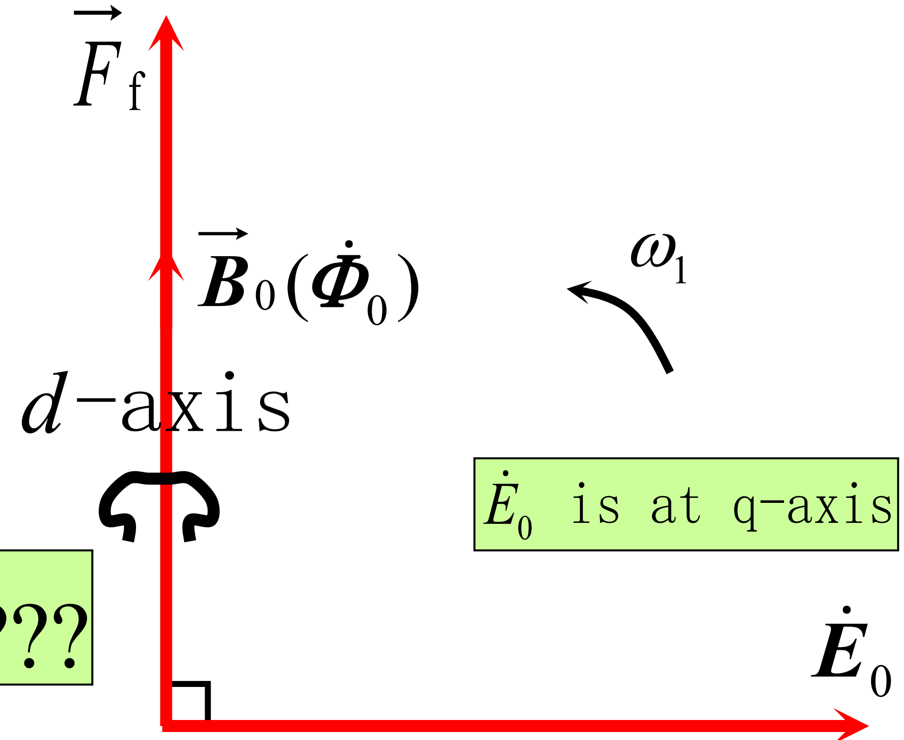
Time and space vector diagram—A phase for instance

ignore the htsteresis, flux density $\vec{B}_0$ (space) is alined with its mmf (space)

flux $\dot{\Phi}_0$(time) is alined with flux density $\vec{B}_0$(space)



$\dot{E}_0$(time) lags flux $\dot{\Phi}_0$(time) by 90°



$\vec{F}_a$???

$\dot{E}_0$ is at q-axis

$\vec{F}_a$ is alined with $\dot{I}$(time)

2. Armature reaction at balanced load

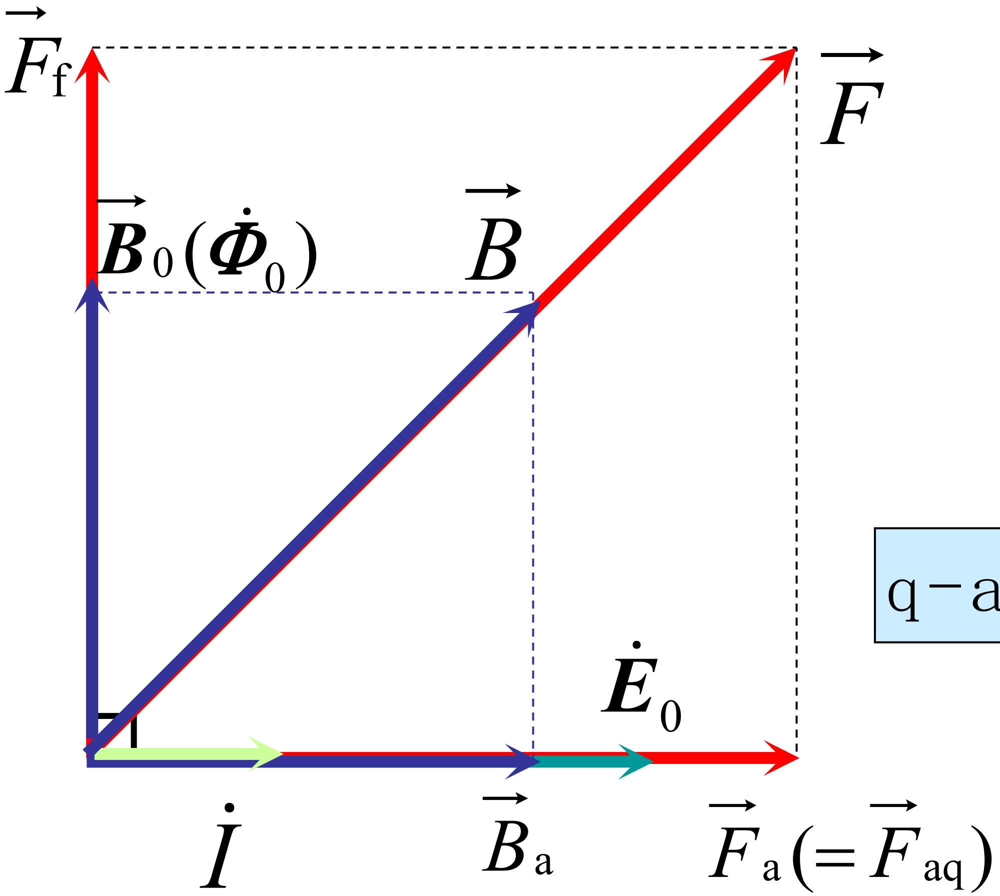
The field that creates in the air gap by the fundamental armature mmf is called armature reaction.

The property of armature reaction is determined by the spatial relative position of armature mmf and main field.

The relative position of armature mmf and excitation mmf in space is determined by the phaspor angle of excitation emf $\dot{E}_0$ with respect to load current ψ_0.

(1) $\dot{I}$ and $\dot{E}_0$ -- same phase

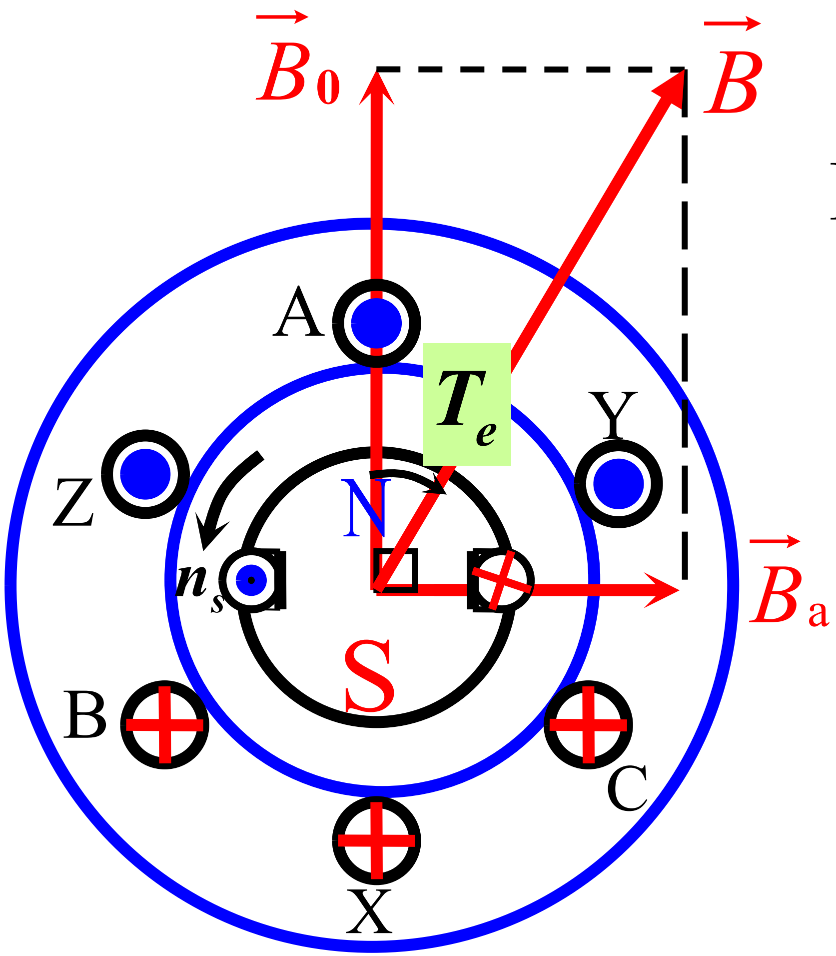
$\psi_0 = 0$



q-axis mmf $\vec{F}_{aq}$

flux density in air gap $\vec{B}$

(1) $\dot{I}$ and $\dot{E}_0$ (same phase)   conclusion



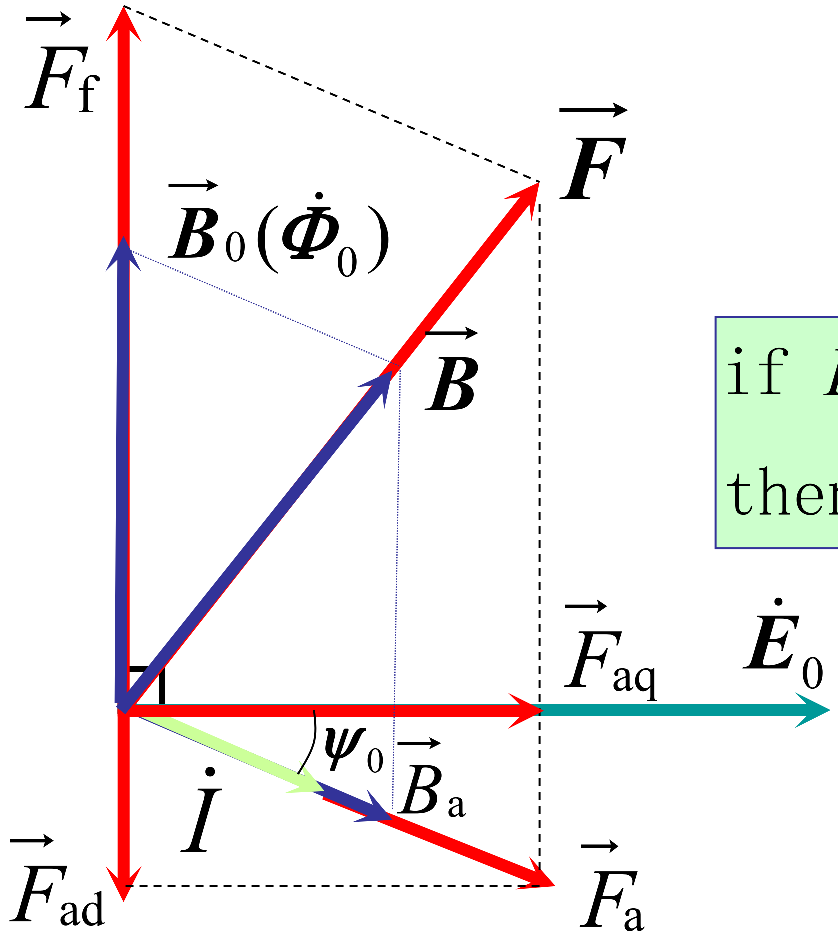
main field $\vec{B}_0$

Resultant field in air gap $\vec{B}$

armature field $\vec{B}_a$

(2) $\dot{I}$ and $\dot{E}_0$ (different phase)

a) $\dot{I}$ lags $\dot{E}_0$



$\vec{F}_{ad}$ is demagnetizing mmf

if $\dot{E}_0$ leads $\dot{I}$ by 30°

then $\vec{F}_f$ leads $\vec{F}_a$ by 120° !!!

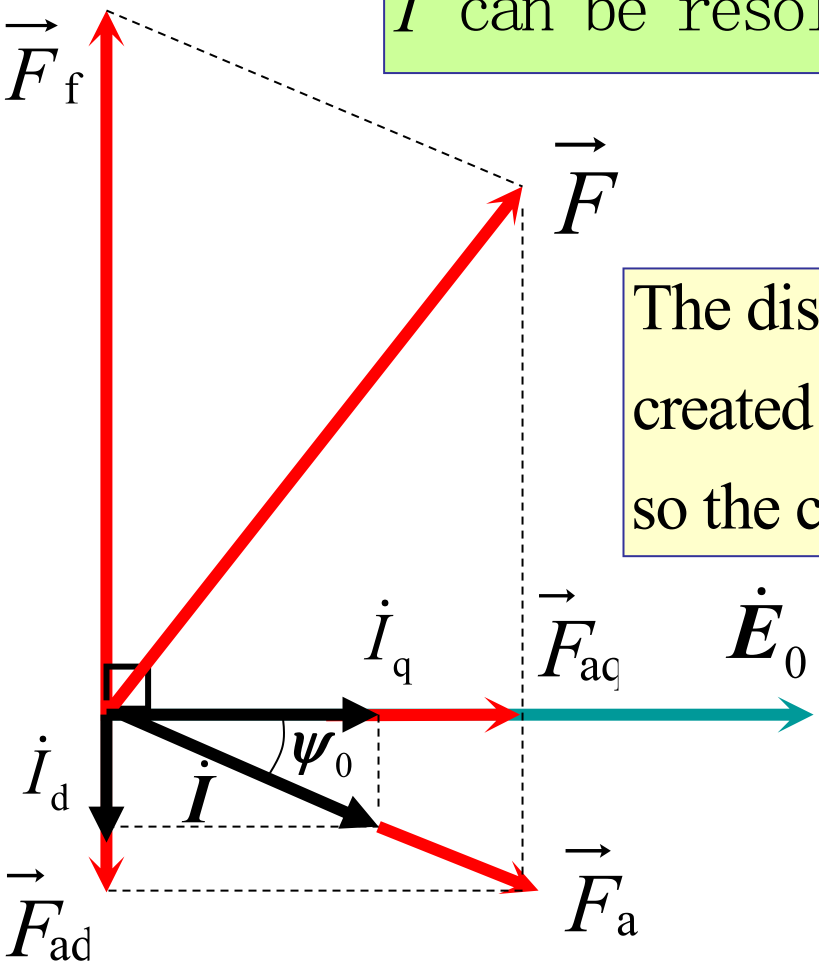
$\vec{F}_a$ lags $\vec{F}_f$ by $90° + \psi_0$

(2) $\dot{I}$ and $\dot{E}_0$ (different phase)

Analysis in terms of current

a) $\dot{I}$ lags $\dot{E}_0$

$\dot{I}$ can be resolved into two components $\dot{I}_d$ and $\dot{I}_q$

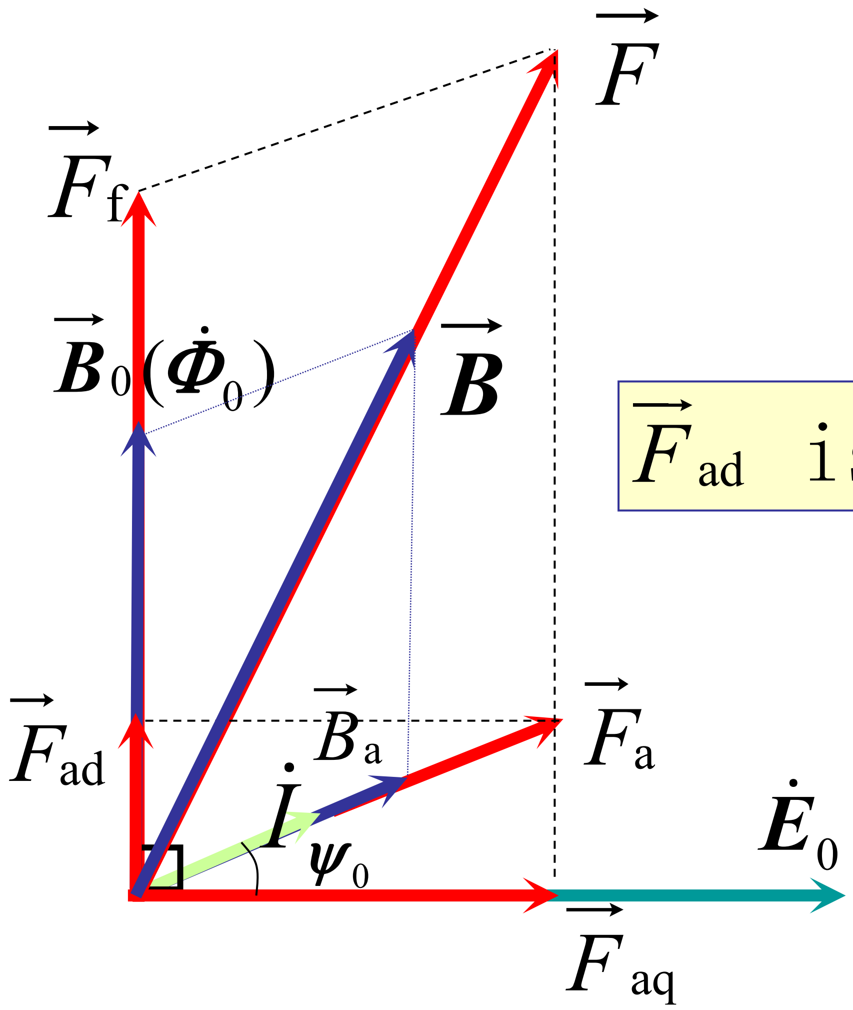


The distortion of the flux distribution is only created by cross-megnetizing armature reaction, so the current must have q-axis component.

Both $\dot{I}_q$ and $\dot{E}_0$ are at q axis

(2) $\dot{I}$ and $\dot{E}_0$ (different phase)

b) $\dot{I}$ leads $\dot{E}_0$



$\vec{F}_{ad}$ is megnetizing mmf

Armature mmf

$$\boxed{\vec{F}_{a} = \vec{F}_{ad} + \vec{F}_{aq}}$$

$$\boxed{\dot{I} = \dot{I}_{d} + \dot{I}_{q}}$$

$$\boxed{\begin{aligned} F_{ad} &= F_{a} \sin\psi_{0} \\ F_{aq} &= F_{a} \cos\psi_{0} \end{aligned}}$$

$$\boxed{\begin{aligned} I_{d} &= I \sin\psi_{0} \\ I_{q} &= I \cos\psi_{0} \end{aligned}}$$

Field of synchronous machines with armature reaction

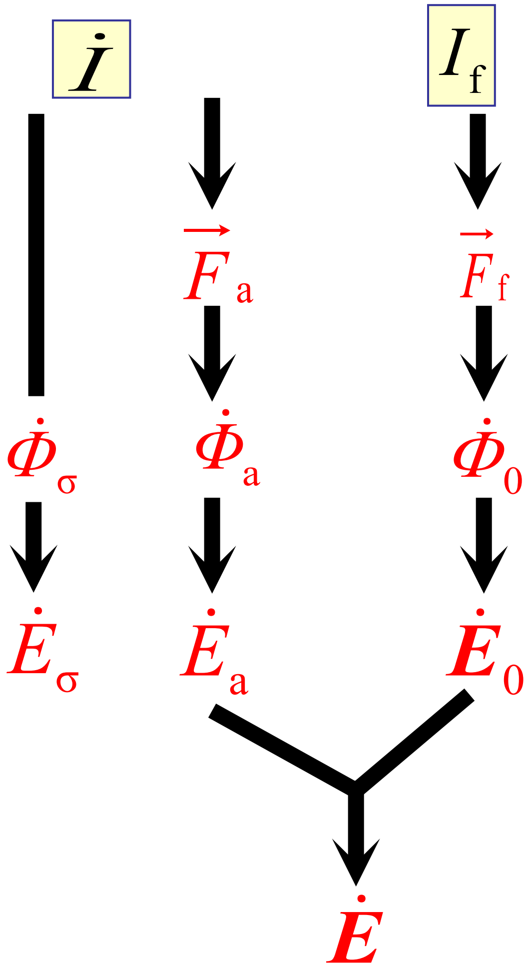
cross-megnetizing armature reaction

- **The resultant mmf can be resolved by two components, excitation mmf and armature mmf**
- **Cross-megnetizing armature reaction distorts the flux in air gap.**

- **The power angle is used to measure the distortion degree of the flux in the air gap.**

The voltage equation, phasor diagram and equivalent circuit of cylindrical-rotor synchronous machines

synchronous machines operates at load, when ignoring the saturation.



$$\boxed{\dot{E}_0 + \dot{E}_a + \dot{E}_\sigma = \dot{U} + \dot{I}R_a}$$

$$\boxed{\dot{E}_0 = \dot{U} + \dot{I}R_a - \dot{E}_a - \dot{E}_\sigma}$$

$$I \propto F_a \propto \Phi_a \propto E_a$$

$$\dot{E}_a = -\mathrm{j}\dot{I}X_a$$

$$I \propto \Phi_\sigma \propto E_\sigma$$

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

Synchronous reactance

$$\dot{E}_a = -j\dot{I}X_a \qquad \dot{E}_\sigma = -j\dot{I}X_\sigma$$

$$\dot{E}_0 = \dot{U} + \dot{I}R_a - \dot{E}_a - \dot{E}_\sigma$$

$$\dot{E}_0 = \dot{U} + \dot{I}R_a + j\dot{I}X_a + j\dot{I}X_\sigma = \dot{U} + \dot{I}R_a + j\dot{I}X_s$$

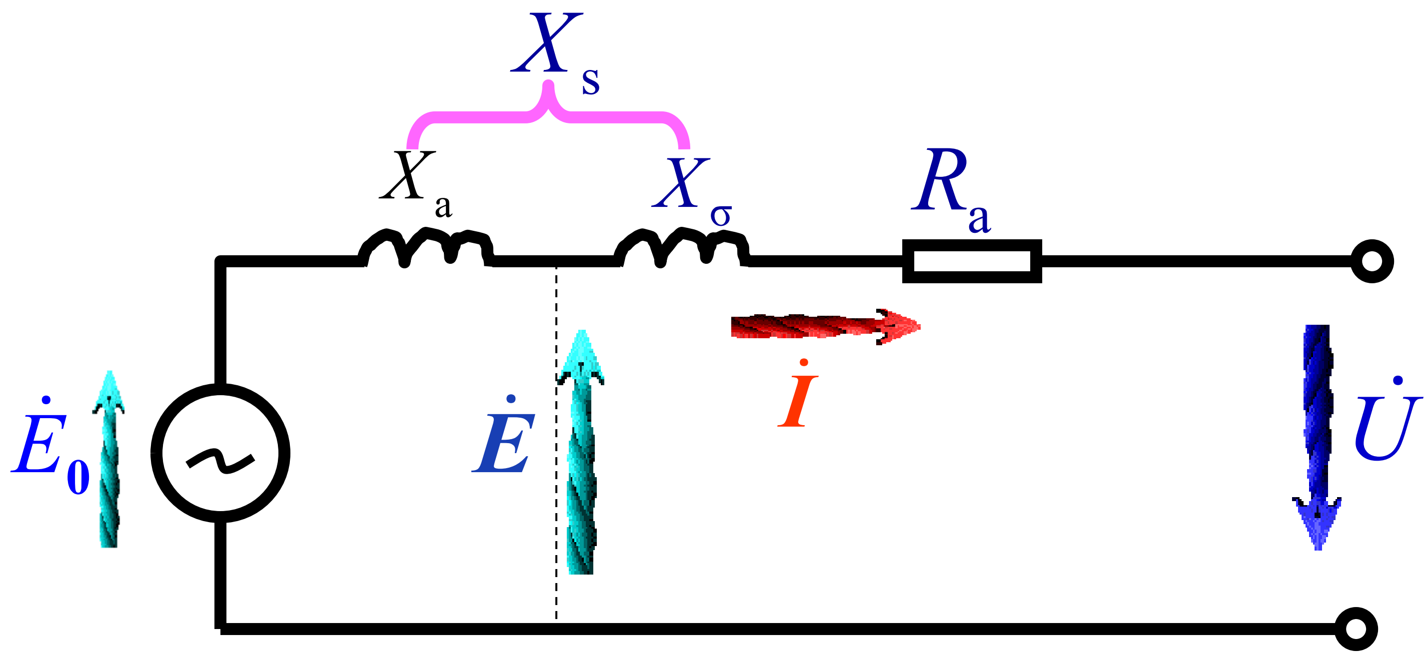
X_s – Synchronous reactance， $X_s = X_a + X_\sigma$

X_a – armature reaction reactance

X_σ – armature linkage reactance

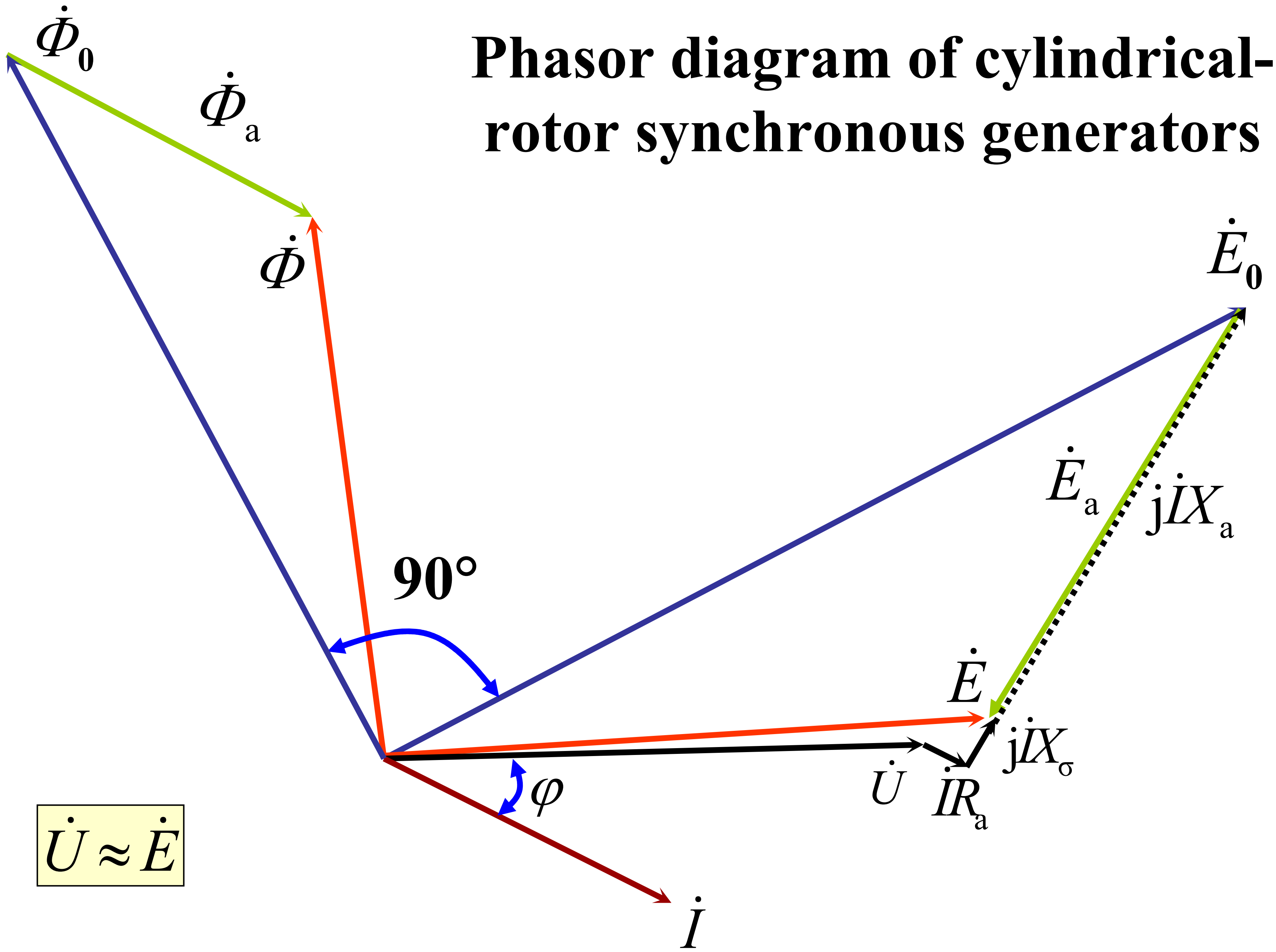
Equivalent circuit of cylindrical-rotor synchronous generators

$$\boxed{\dot{E}_0 = \dot{U} + \dot{I}R_a + j\dot{I}X_a + j\dot{I}X_\sigma = \dot{U} + \dot{I}R_a + j\dot{I}X_s}$$



an impedance in series with
a voltage source

Phasor diagram of cylindrical-rotor synchronous generators



$\dot{U} \approx \dot{E}$

Phasor diagram of cylindrical-rotor synchronous generators

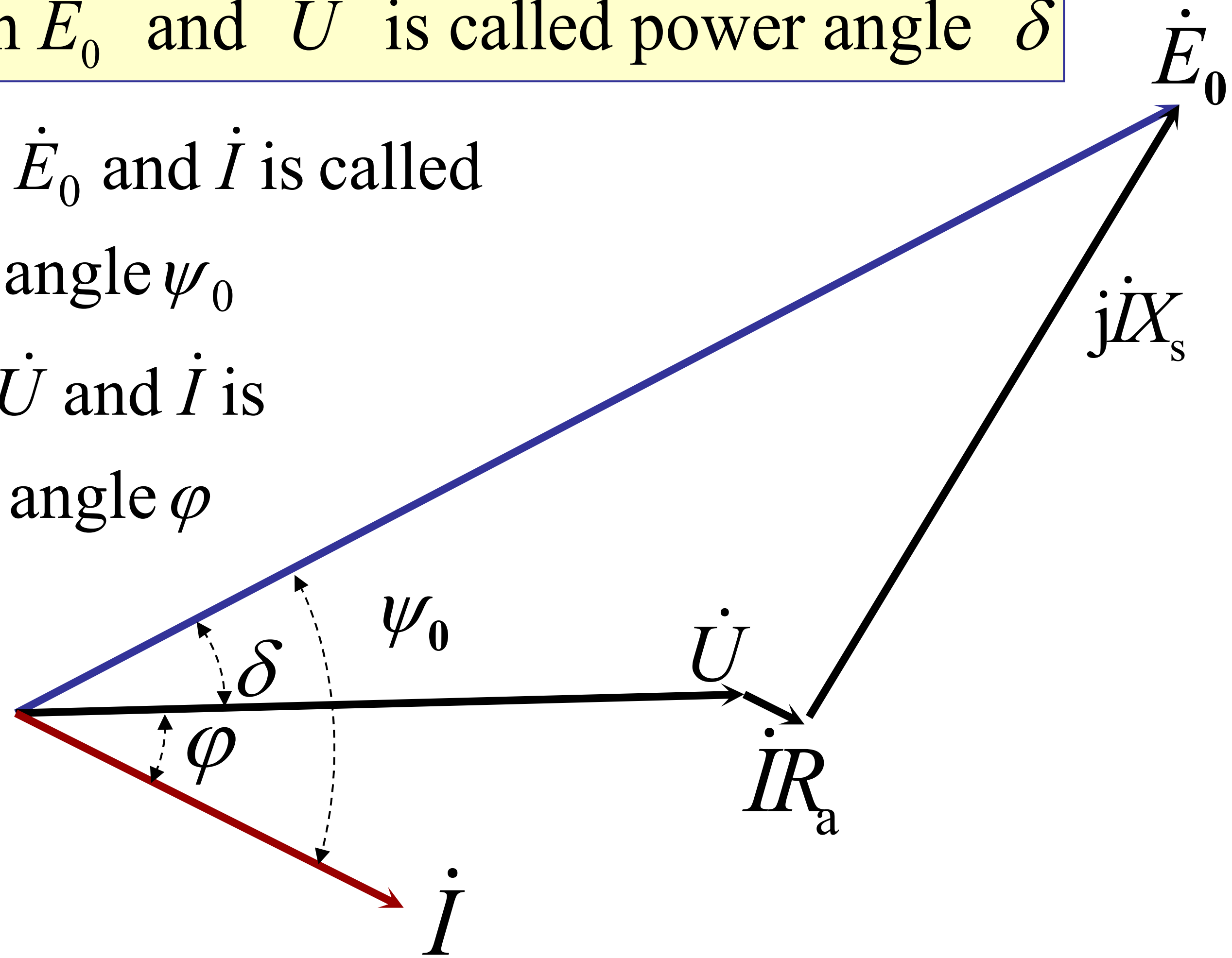
$\dot{E}_0$ is power source

$R_a + jX_s$ is an impedance

The angle between $\dot{E}_0$ and $\dot{U}$ is called power angle δ

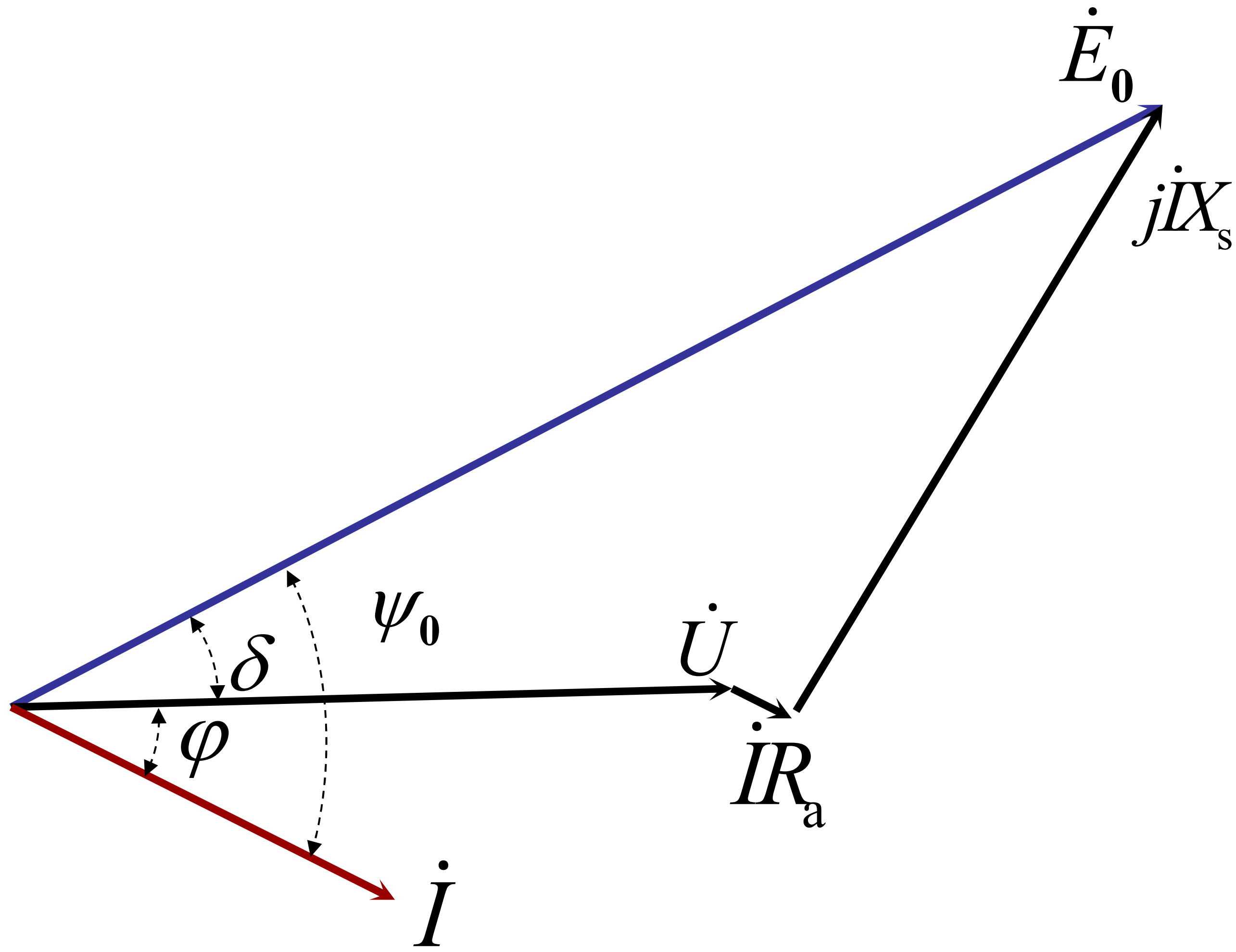
The angle between $\dot{E}_0$ and $\dot{I}$ is called inner power factor angle ψ_0

The angle between $\dot{U}$ and $\dot{I}$ is called power factor angle φ



$$\psi_0 = \delta + \varphi$$

Drawing steps of phasor diagram of cylindrical-rotor synchronous generators



Geometrical relationship of phasor diagram of cylindrical-rotor synchronous generators

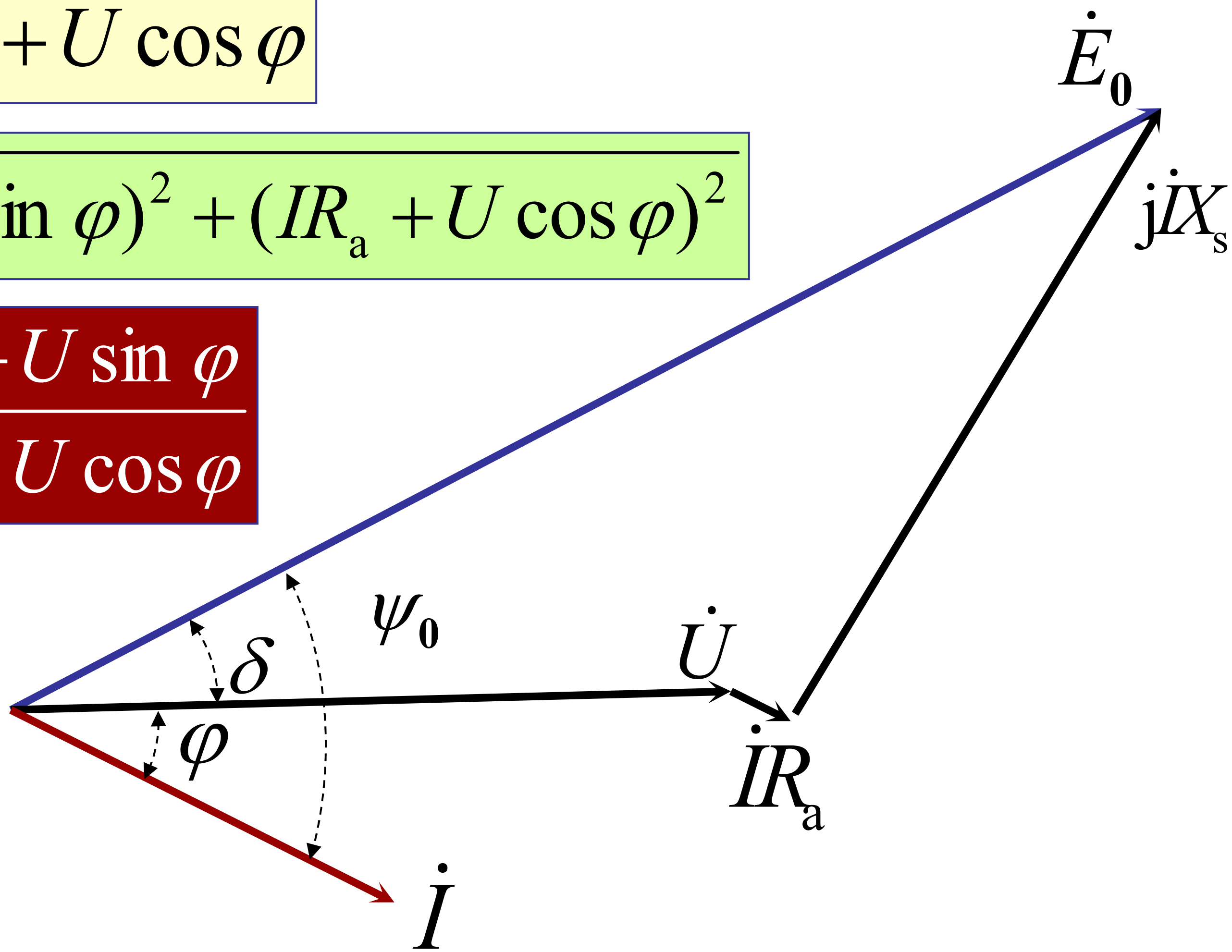
$$E_0 \sin \psi_0 = IX_s + U \sin \varphi$$

$$E_0 \cos \psi_0 = IR_a + U \cos \varphi$$

$$E_0 = \sqrt{(IX_s + U \sin \varphi)^2 + (IR_a + U \cos \varphi)^2}$$

$$\psi_0 = \arctan \frac{IX_s + U \sin \varphi}{IR_a + U \cos \varphi}$$

$$\delta = \psi_0 - \varphi$$



Geometrical relationship of phasor diagram of cylindrical-rotor synchronous generators

$$E_0 = \sqrt{(IX_s + U\sin\varphi)^2 + (U\cos\varphi)^2}$$

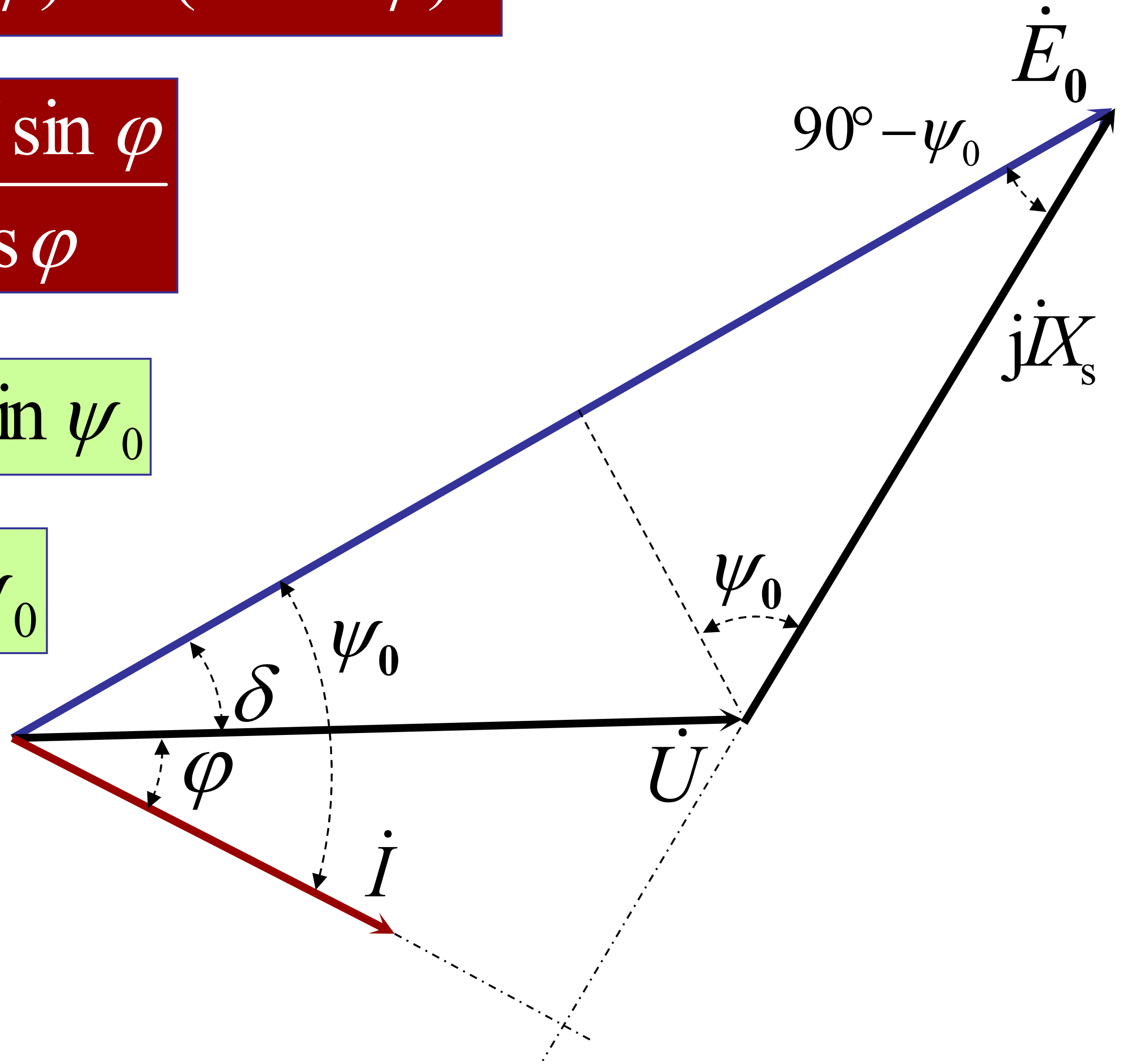
ignoring R_a

$$\psi_0 = \arctan\frac{IX_s + U\sin\varphi}{U\cos\varphi}$$

$$E_0 = U\cos\delta + IX_s\sin\psi_0$$

$$U\sin\delta = IX_s\cos\psi_0$$

$$\sin\delta = \frac{IX_s\cos\psi_0}{U}$$

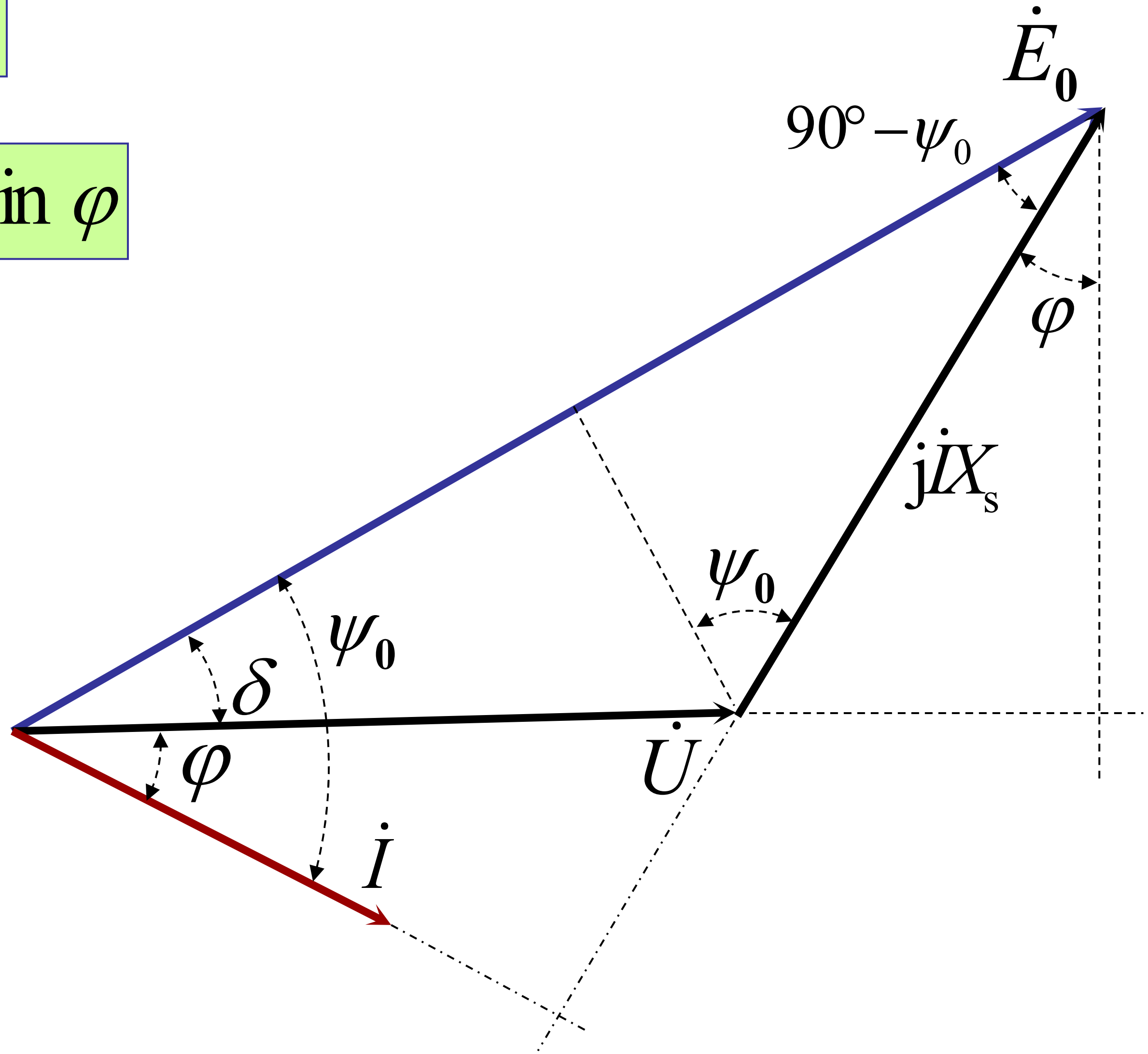


Geometrical relationship of phasor diagram of cylindrical-rotor synchronous generators

ignoring R_a

$$E_0 \sin\delta = IX_s \cos\varphi$$

$$E_0 \cos\delta = U + IX_s \sin\varphi$$



6.4 The voltage equation, phasor diagram and equivalent circuit of salient-pole synchronous machines

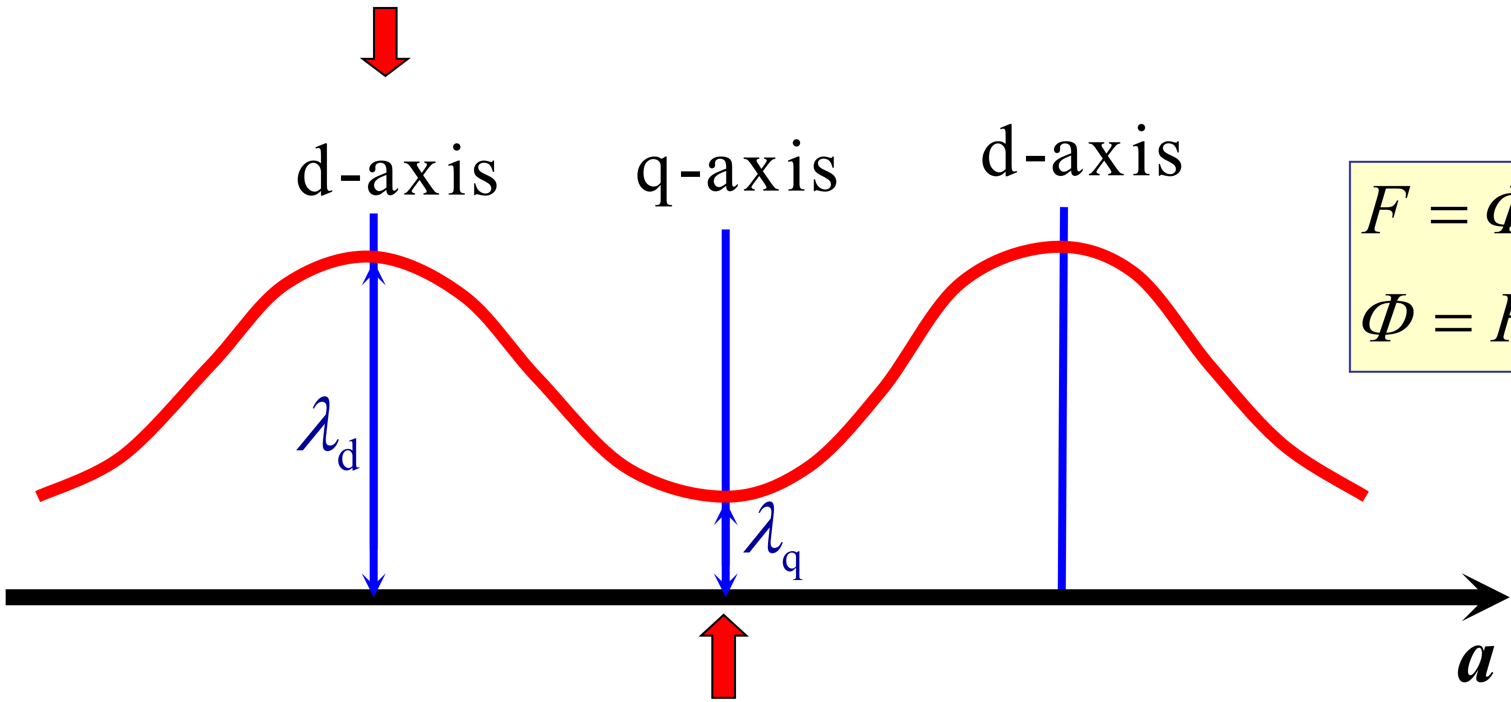
1 direct- and quadrature-axis theory

Because the air gap is non-uniform, the armature reaction can be resolved into d- and q-axis armature reaction

The air gap is non-uniform, but is axisymmetric with respect to d- and q-axis

The superposition principle will be used to analyze the field

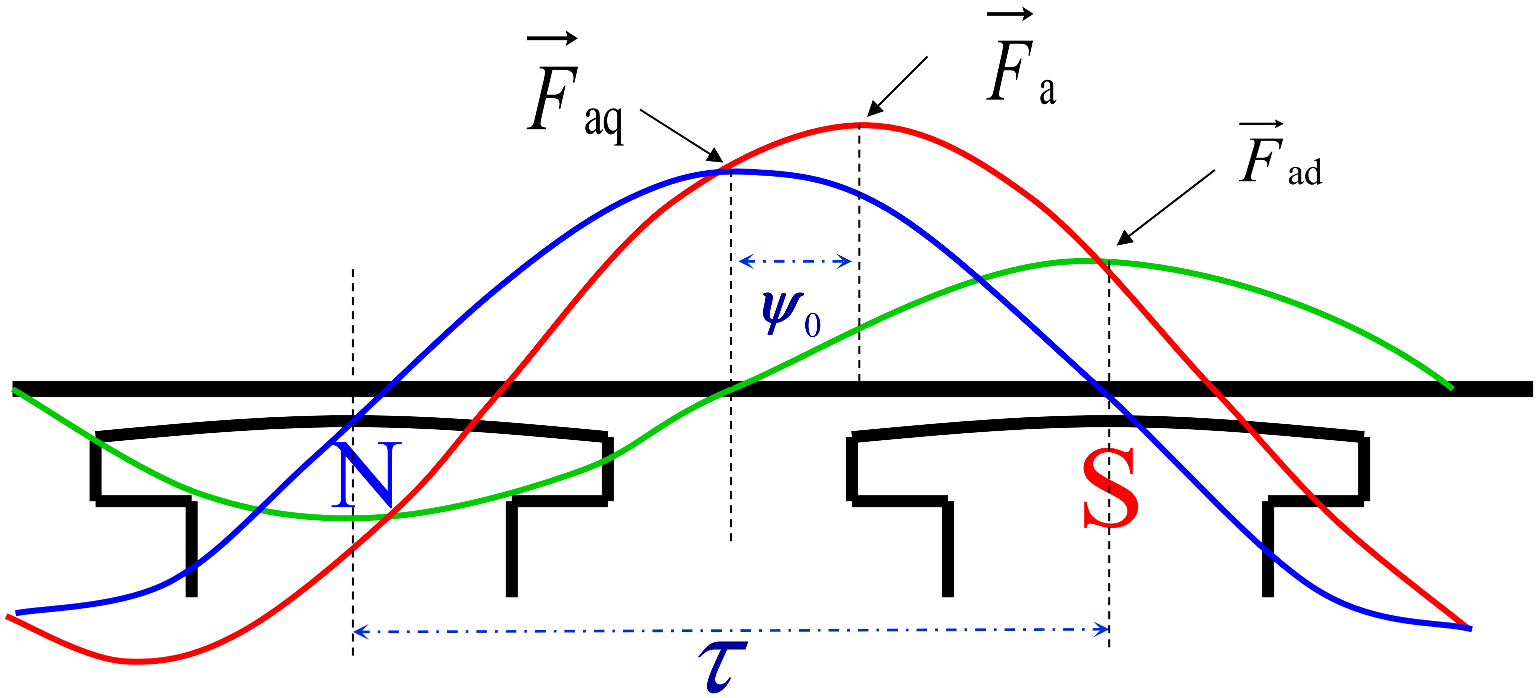
$\lambda_d \ (\lambda_d = \mu_0 / \delta_d)$ $>$ $\lambda_q \ (\lambda_q = \mu_0 / \delta_q)$



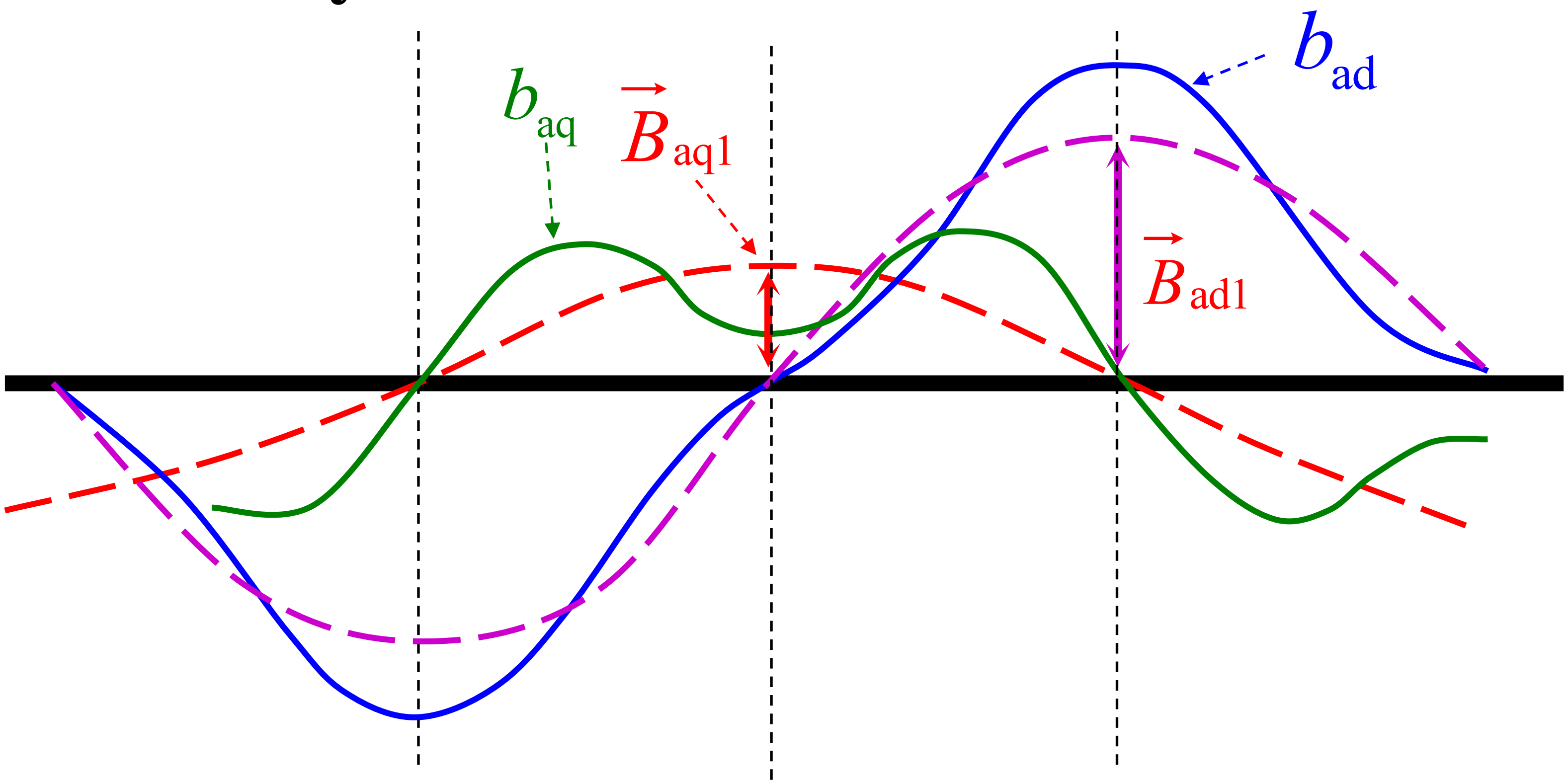
$$F = \Phi R_m$$

$$\Phi = F \Lambda_m$$

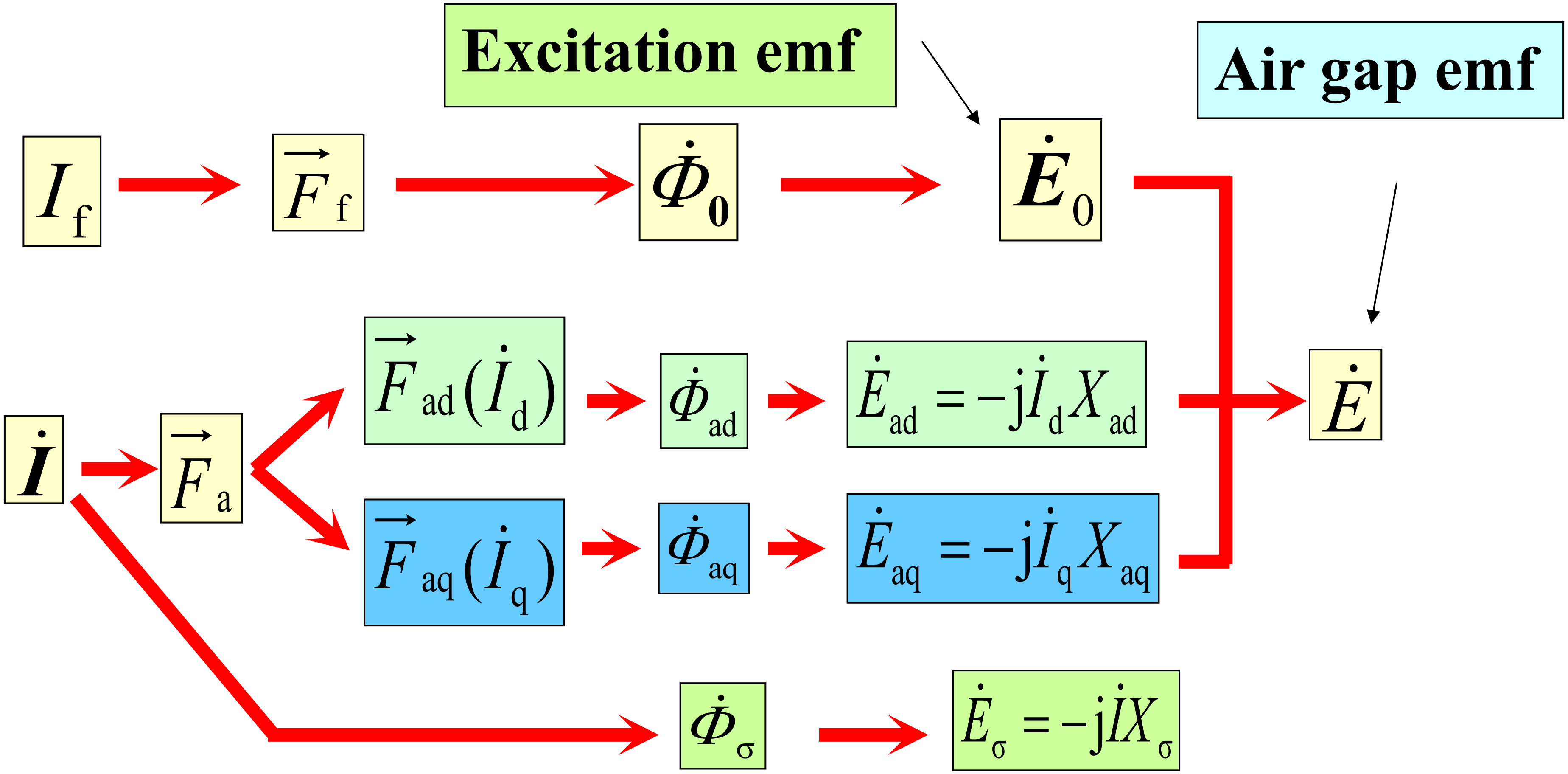
$$\boxed{\vec{F}_{a} = \vec{F}_{ad} + \vec{F}_{aq}}$$



direct- and quadrature-axis theory



2、 The voltage equation, phasor diagram and equivalent circuit of salient-pole synchronous machines



$$\dot{E}_0 + \dot{E}_{ad} + \dot{E}_{aq} + \dot{E}_\sigma = \dot{U} + \dot{I}R_a$$

$$\dot{I} = \dot{I}_{\mathrm{d}} + \dot{I}_{\mathrm{q}}$$

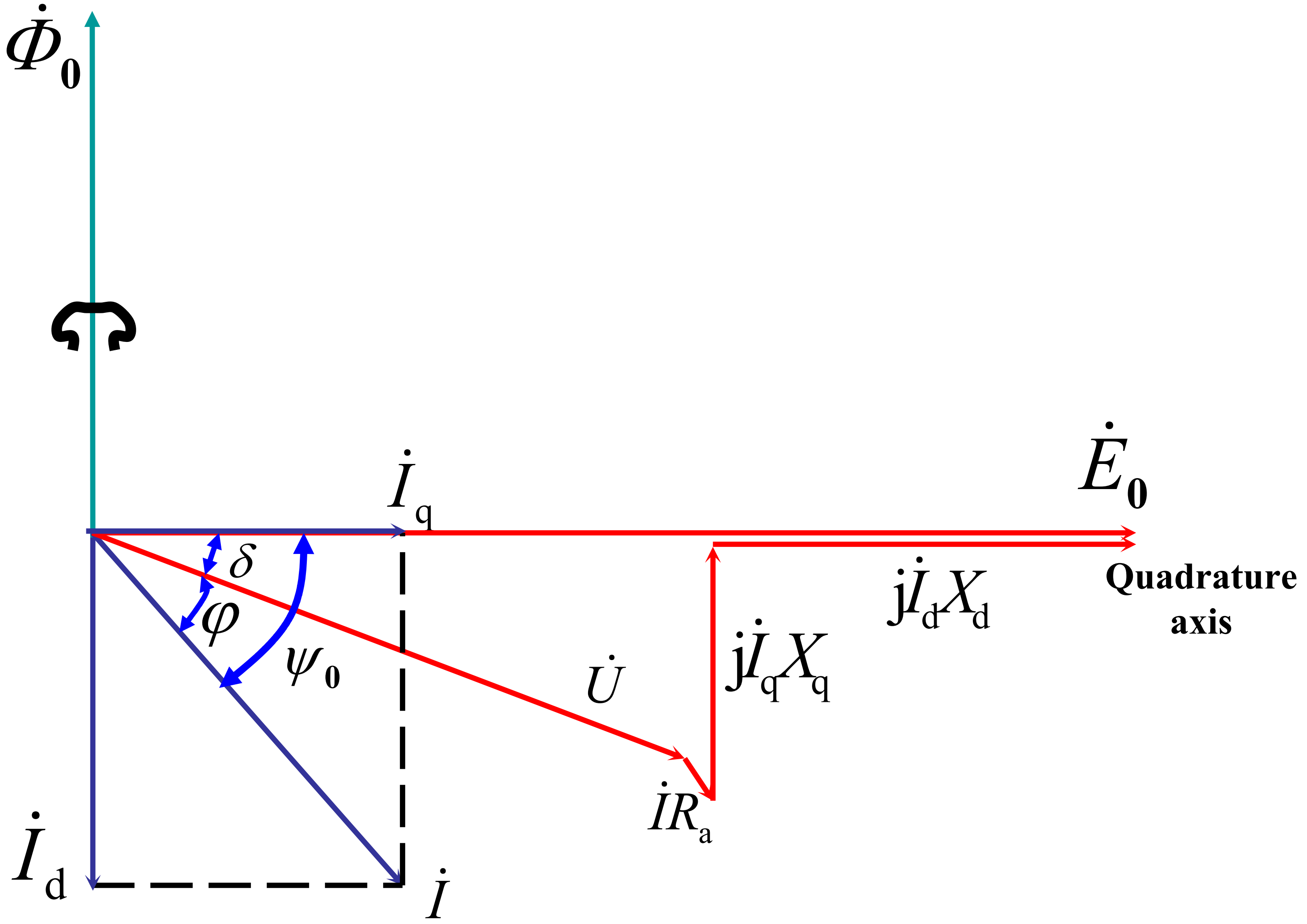
$$\dot{E}_{\mathrm{ad}} = -\mathrm{j}\dot{I}_{\mathrm{d}} X_{\mathrm{ad}}$$

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

$$\dot{E}_0 = \dot{U} + \dot{I}R_{\mathrm{a}} + \mathrm{j}\dot{I}X_{\sigma} - \dot{E}_{\mathrm{ad}} - \dot{E}_{\mathrm{aq}}$$

$$\begin{aligned}
\dot{E}_0 &= \dot{U} + \dot{I}R_{\mathrm{a}} + \mathrm{j}(\dot{I}_{\mathrm{d}} + \dot{I}_{\mathrm{q}})X_{\sigma} + \mathrm{j}\dot{I}_{\mathrm{d}} X_{\mathrm{ad}} + \mathrm{j}\dot{I}_{\mathrm{q}} X_{\mathrm{aq}} \\
&= \dot{U} + \dot{I}R_{\mathrm{a}} + \mathrm{j}\dot{I}_{\mathrm{d}}(X_{\sigma} + X_{\mathrm{ad}}) + \mathrm{j}\dot{I}_{\mathrm{q}}(X_{\sigma} + X_{\mathrm{aq}}) \\
&= \dot{U} + \dot{I}R_{\mathrm{a}} + \mathrm{j}\dot{I}_{\mathrm{d}} X_{\mathrm{d}} + \mathrm{j}\dot{I}_{\mathrm{q}} X_{\mathrm{q}}
\end{aligned}$$

The voltage equation, phasor diagram and equivalent circuit of salient-pole synchronous machines



The determination of ψ_0

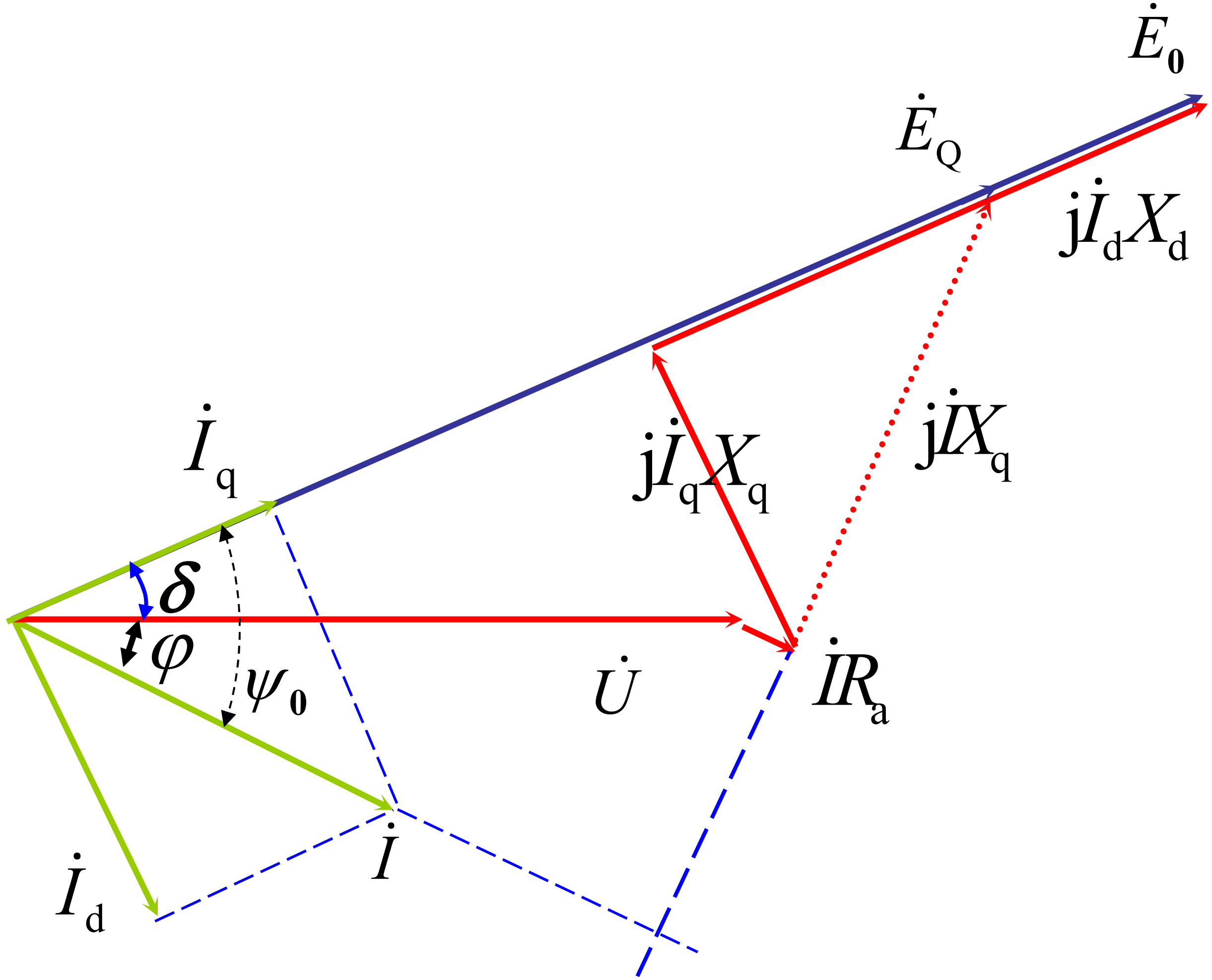
Q-axis **D-axis**

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

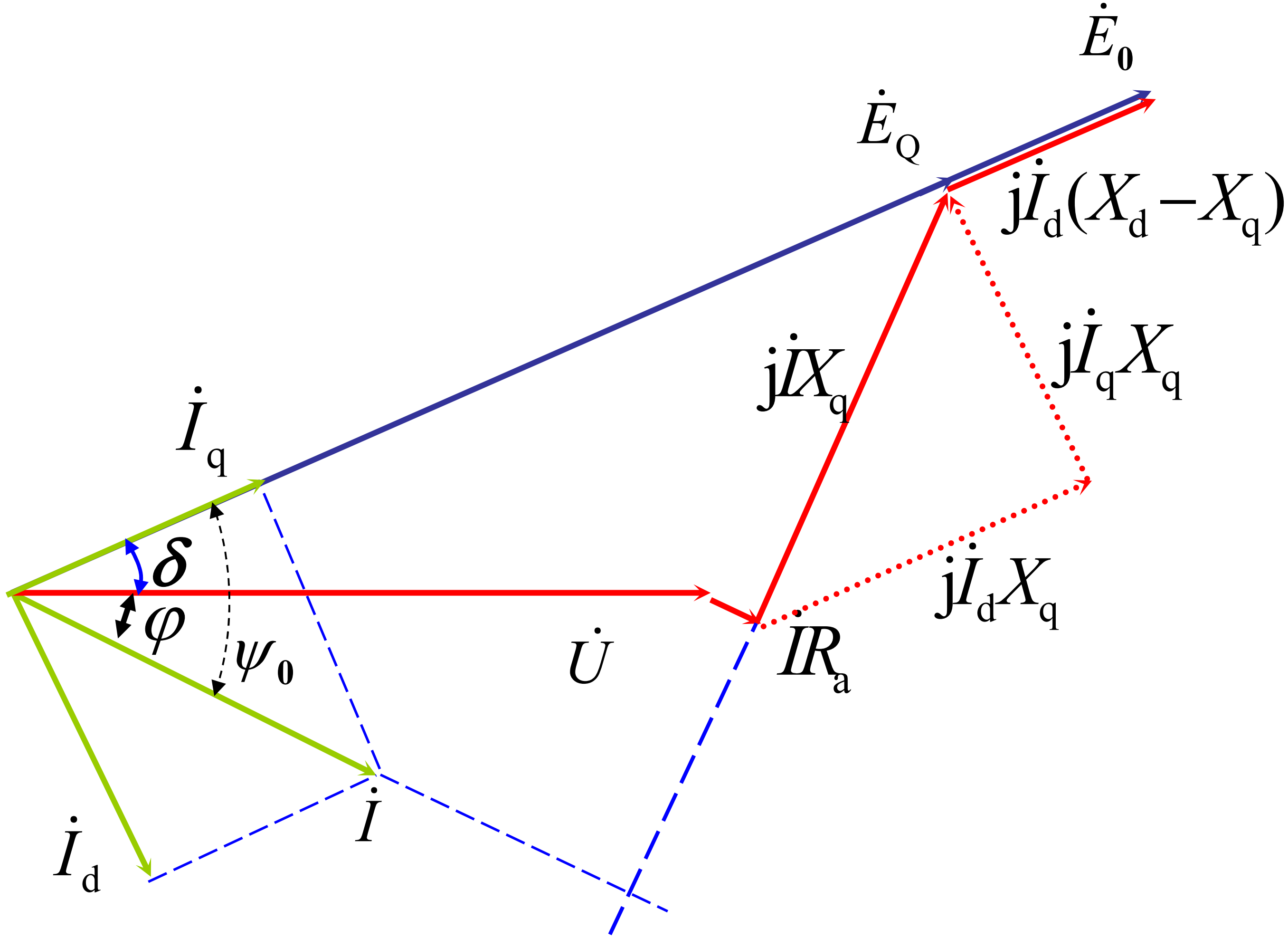
$$\dot{E}_Q = (\dot{U} + \dot{I}R_a + j\dot{I}_d X_d + j\dot{I}_q X_q) - j\dot{I}_d(X_d - X_q) = \dot{U} + \dot{I}R_a + j\dot{I}X_q$$

$\dot{E}_Q$ is called virtual emf without any physical meaning, but has the same phase direction with $\dot{E}_0$

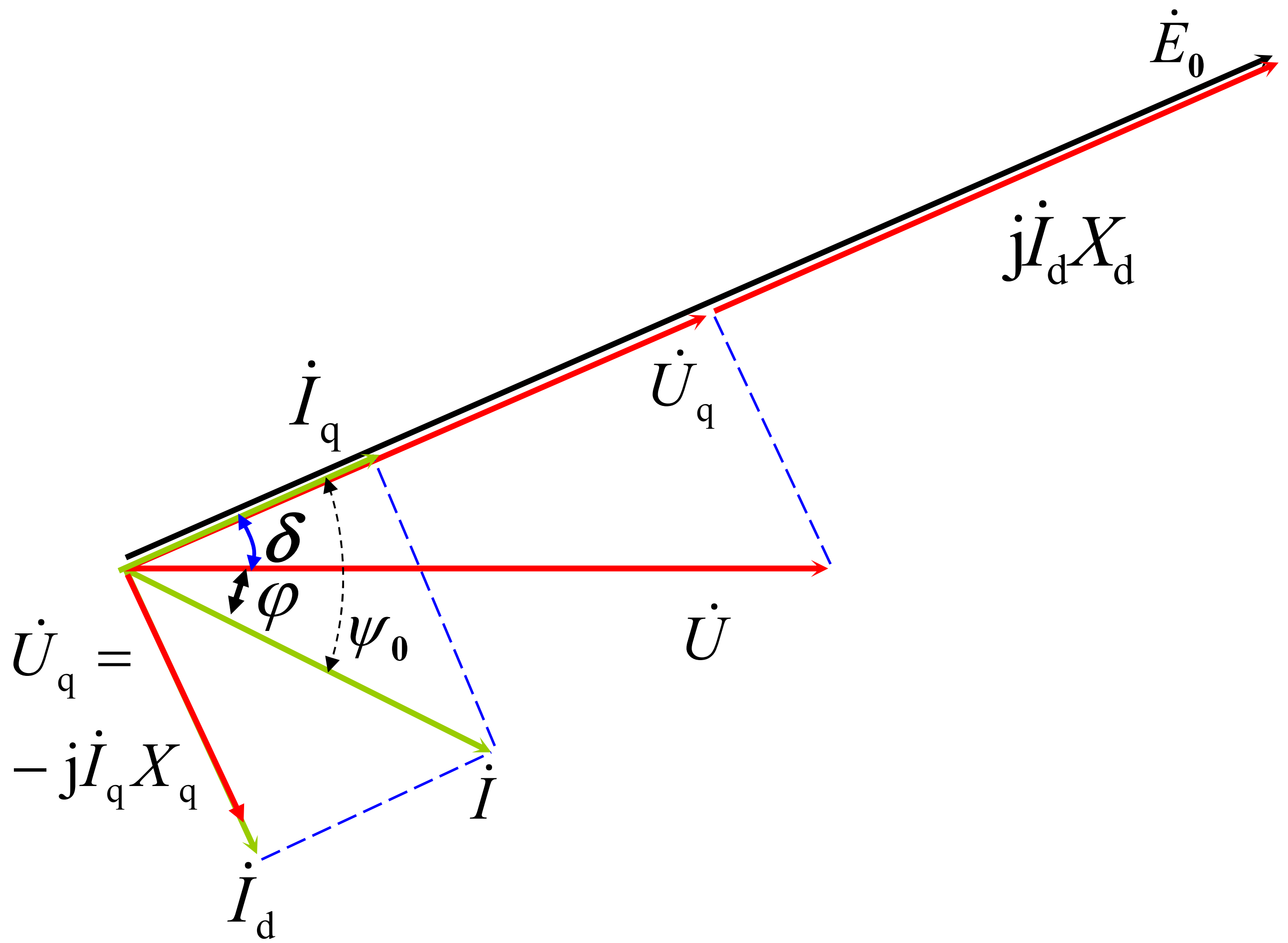
Drawing steps of phasor diagram



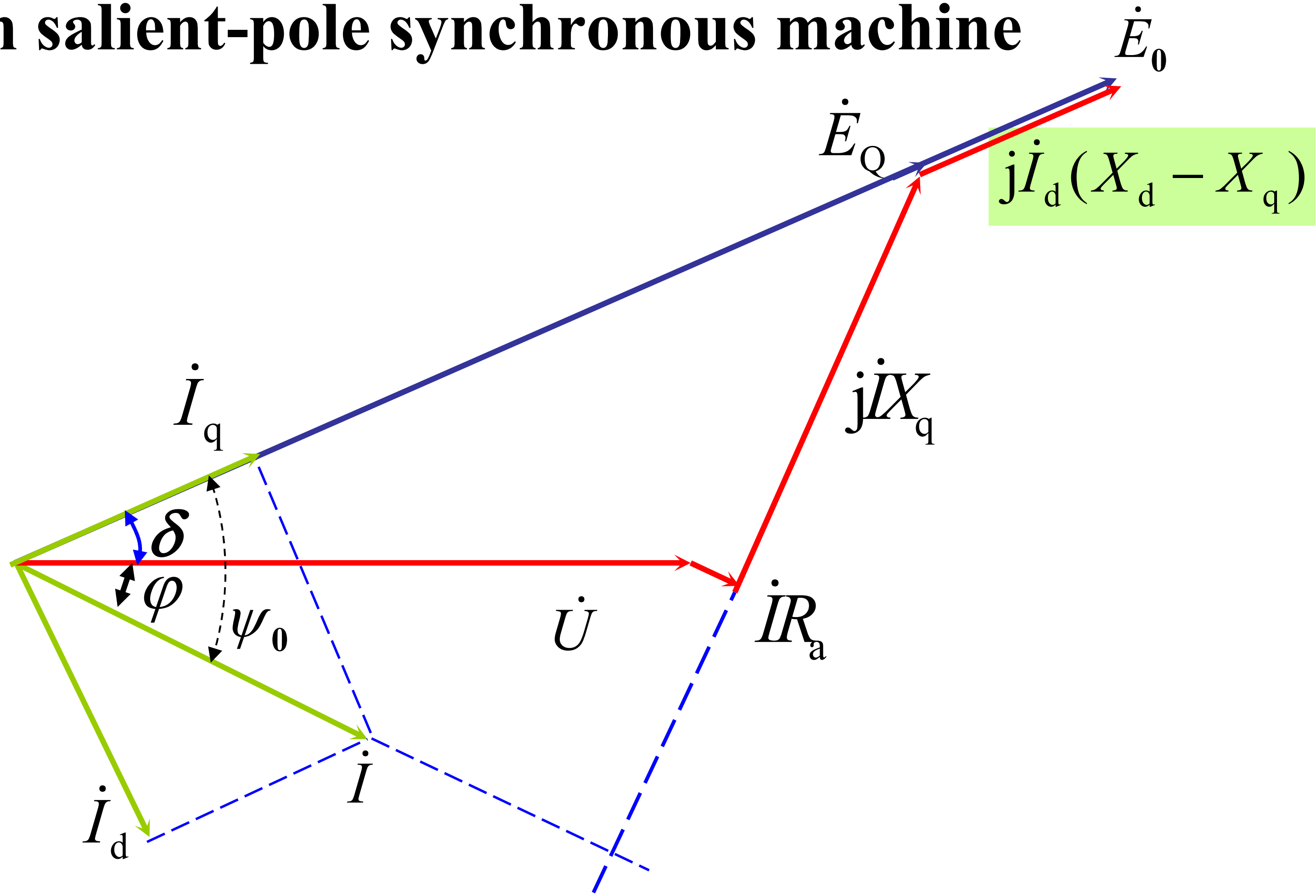
Drawing steps of phasor diagram



Drawing steps of phasor diagram



Compare Cylindrical-Rotor with salient-pole synchronous machine



$X_d = X_q = X_s$ in the cylindrical-rotor machines

$$\psi_0 = \arctan\frac{U\sin\phi + IX_q}{U\cos\phi + IR_a}$$

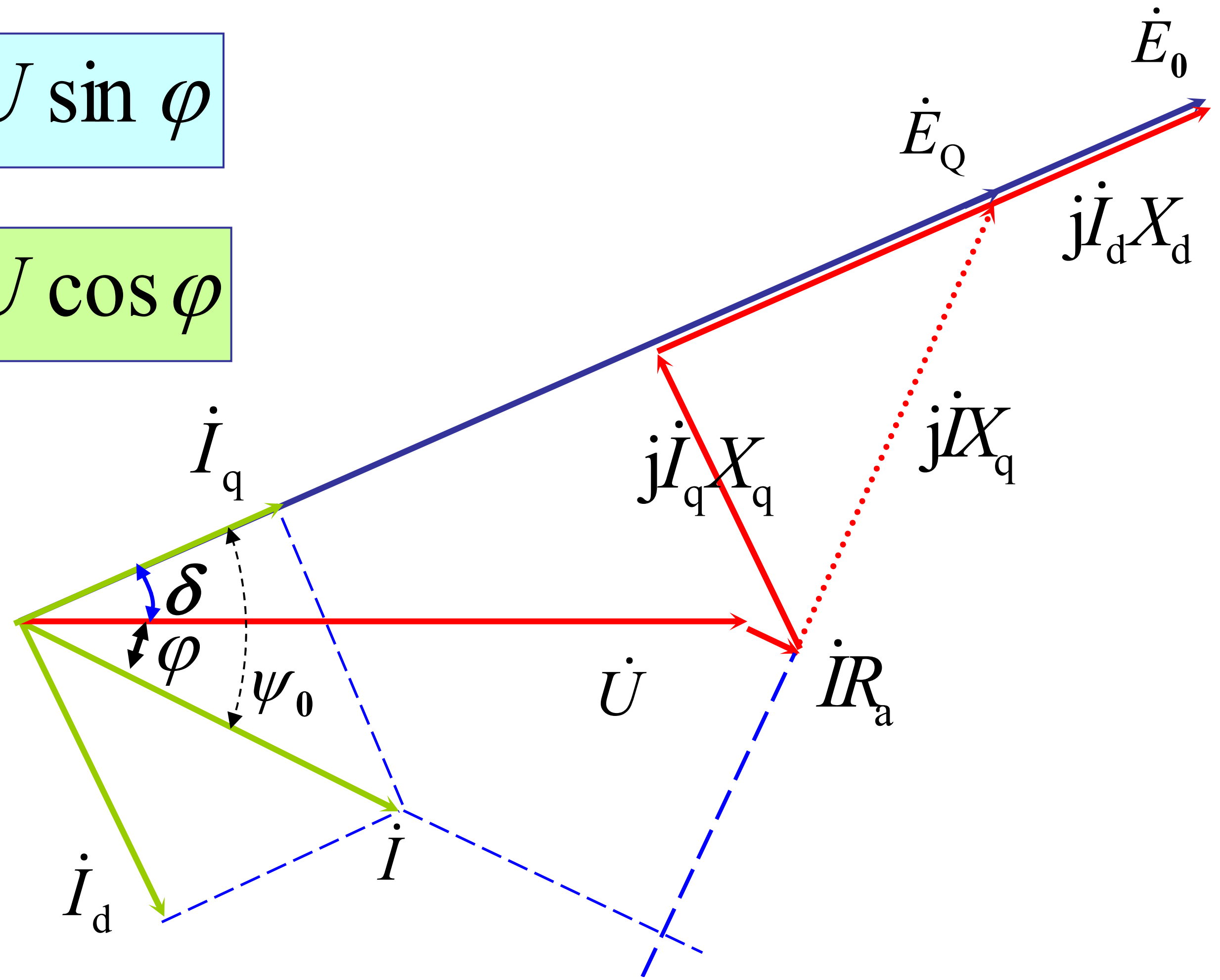
$$E_Q = \sqrt{(IX_q + U\sin\varphi)^2 + (IR_a + U\cos\varphi)^2}$$

$$E_Q \sin\psi_0 = IX_q + U\sin\varphi$$

$$E_Q \cos\psi_0 = IR_a + U\cos\varphi$$

$$\delta = \psi_0 - \varphi$$

$$E_0 = E_Q + I_d(X_d - X_q)$$



ignoring R_a:

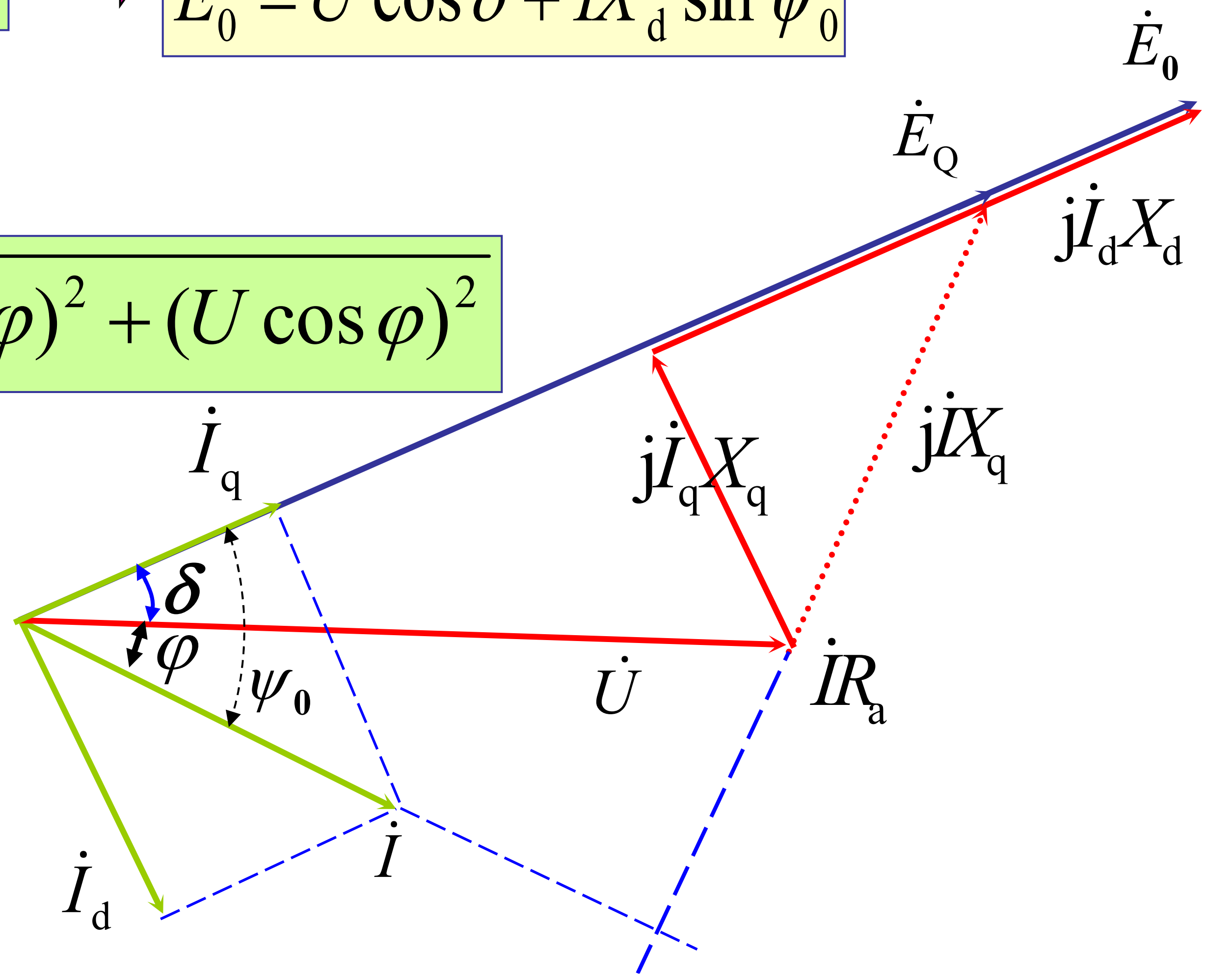
$$\psi_0 = \arctan\frac{U\sin\phi + IX_q}{U\cos\phi}$$

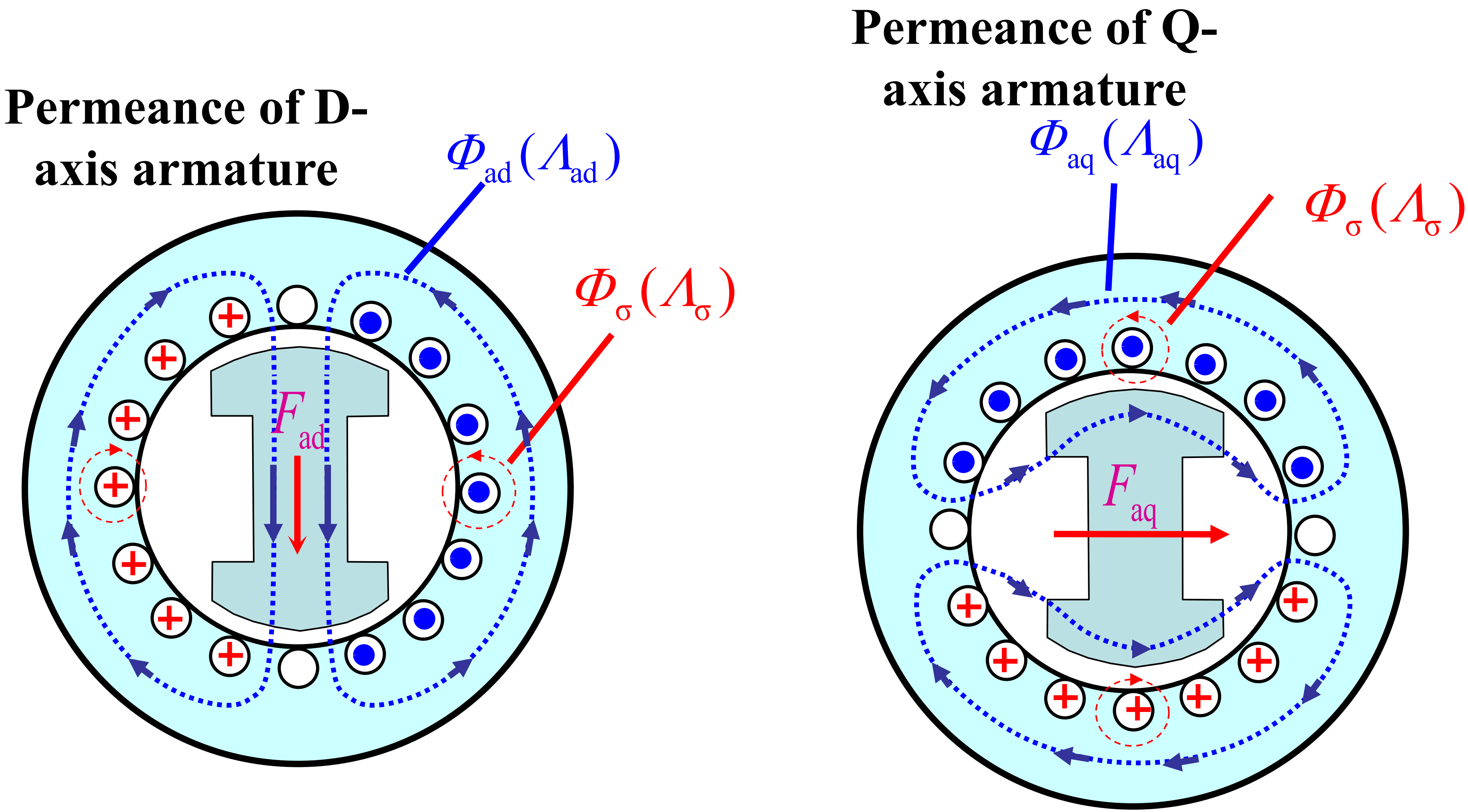
$$E_0 = U\cos\delta + I_d X_d$$ ➡ $$E_0 = U\cos\delta + IX_d\sin\psi_0$$

$$I_q X_q = U\sin\delta$$

$$E_Q = \sqrt{(IX_q + U\sin\varphi)^2 + (U\cos\varphi)^2}$$

$$\delta = \psi_0 - \varphi$$





Salient-pole synchronous machines: $\Lambda_{ad} > \Lambda_{ad}$， so $X_{ad} > X_{aq}$, then, $X_d > X_q$。

Cylindrical-rotor synchronous machines: $X_d \approx X_q \approx X_s$

Discussion: **Give the relational expression about the power angle δ, the power factor angle φ and the inner power factor angle Ψ_0. When δ=30° and φ=-30°, please draw the phase diagram and analyze the armature reaction property of a synchronous generator with cylindrical rotor.**

Analyze: $\Psi_0=\delta+\varphi$

At this time, Ψ_0=0, the armature reaction of this type is called cross-magnetizing armature reaction.

Power equation and torque equation of SM

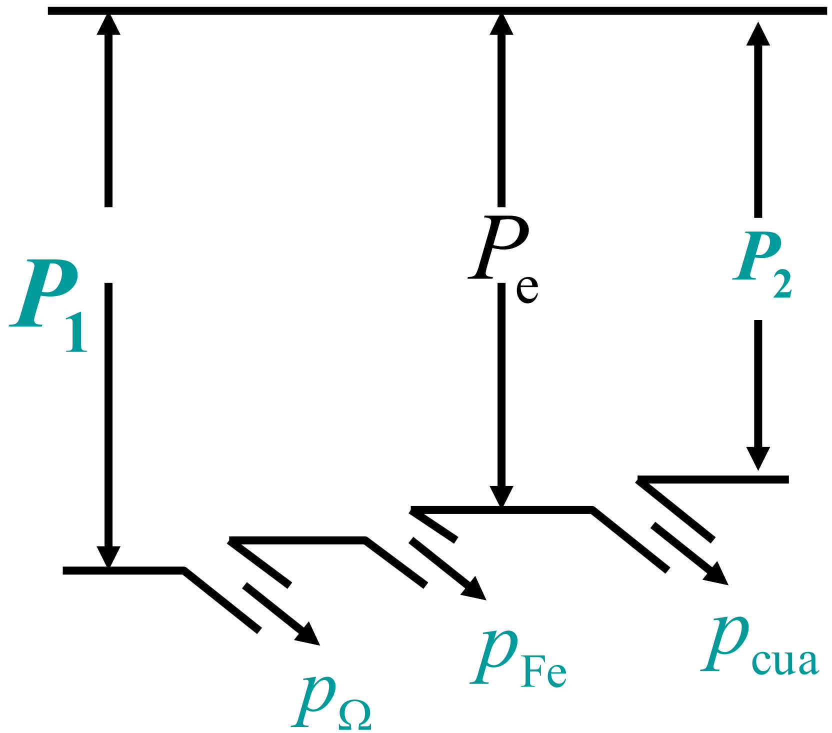
1、 Power equation and electromagnetic power

$$P_1 = p_\Omega + p_{\mathrm{Fe}} + P_{\mathrm{e}}$$

$$P_{\mathrm{e}} = p_{\mathrm{Cua}} + P_2$$

$$p_{\mathrm{Cua}} = mI^2 R_{\mathrm{a}}$$

$$P_2 = mUI\cos\varphi$$



P_1
P_e
P_2
p_Ω
p_{Fe}
p_{cua}

$$P_{\mathrm{e}} = mUI\cos\varphi + mI^2R_a = mI(U\cos\varphi + IR_{\mathrm{a}})$$

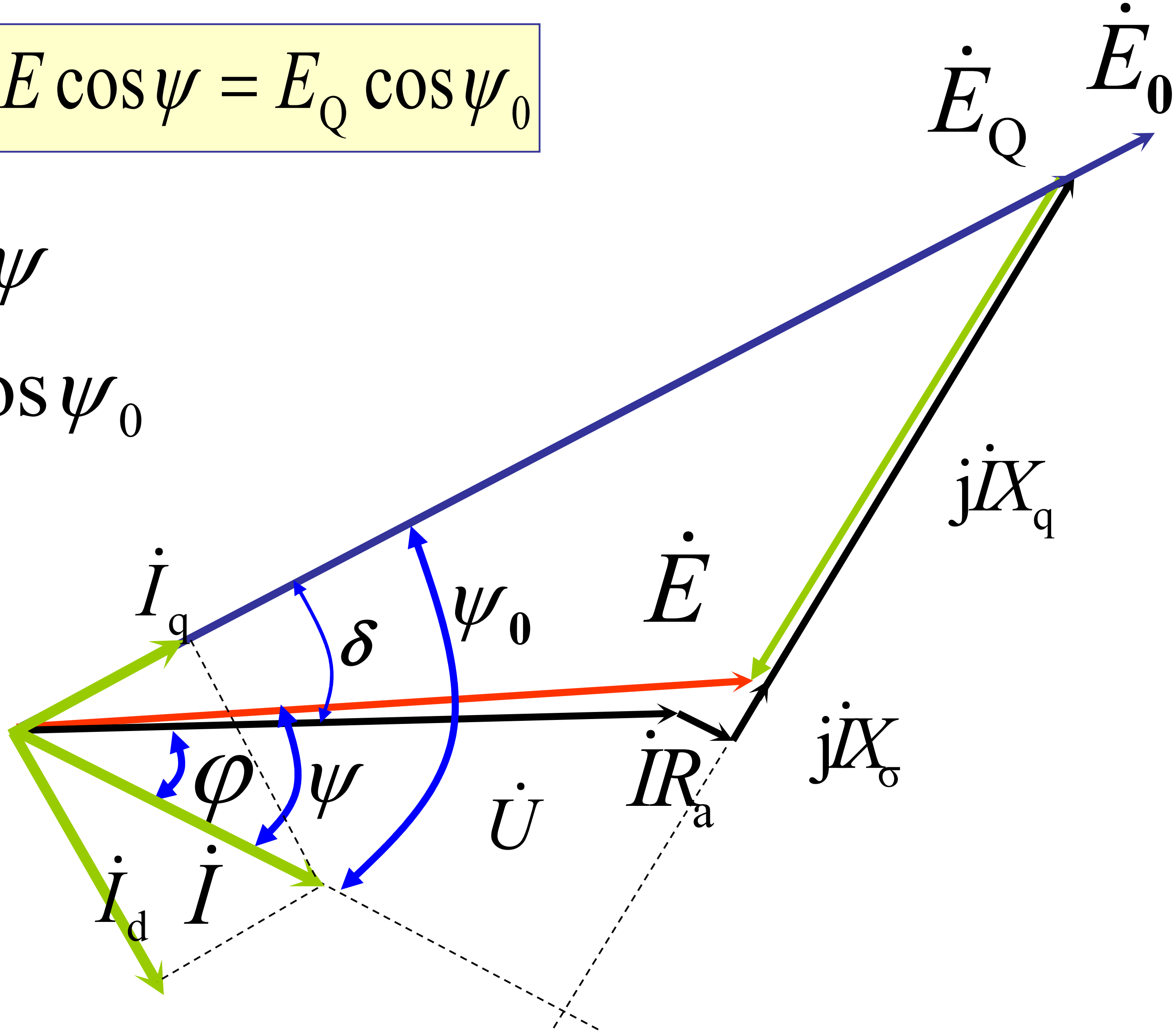
$$\boxed{U\cos\varphi + IR_{\mathrm{a}} = E\cos\psi = E_{\mathrm{Q}}\cos\psi_0}$$

$$P_{\mathrm{e}} = mEI\cos\psi$$

$$= mE_{\mathrm{Q}}I\cos\psi_0$$

$$= mE_{\mathrm{Q}}I_{\mathrm{q}}$$

$\boxed{\boldsymbol{I_{\mathrm{q}}=0\quad P_{\mathrm{e}}=0}}$

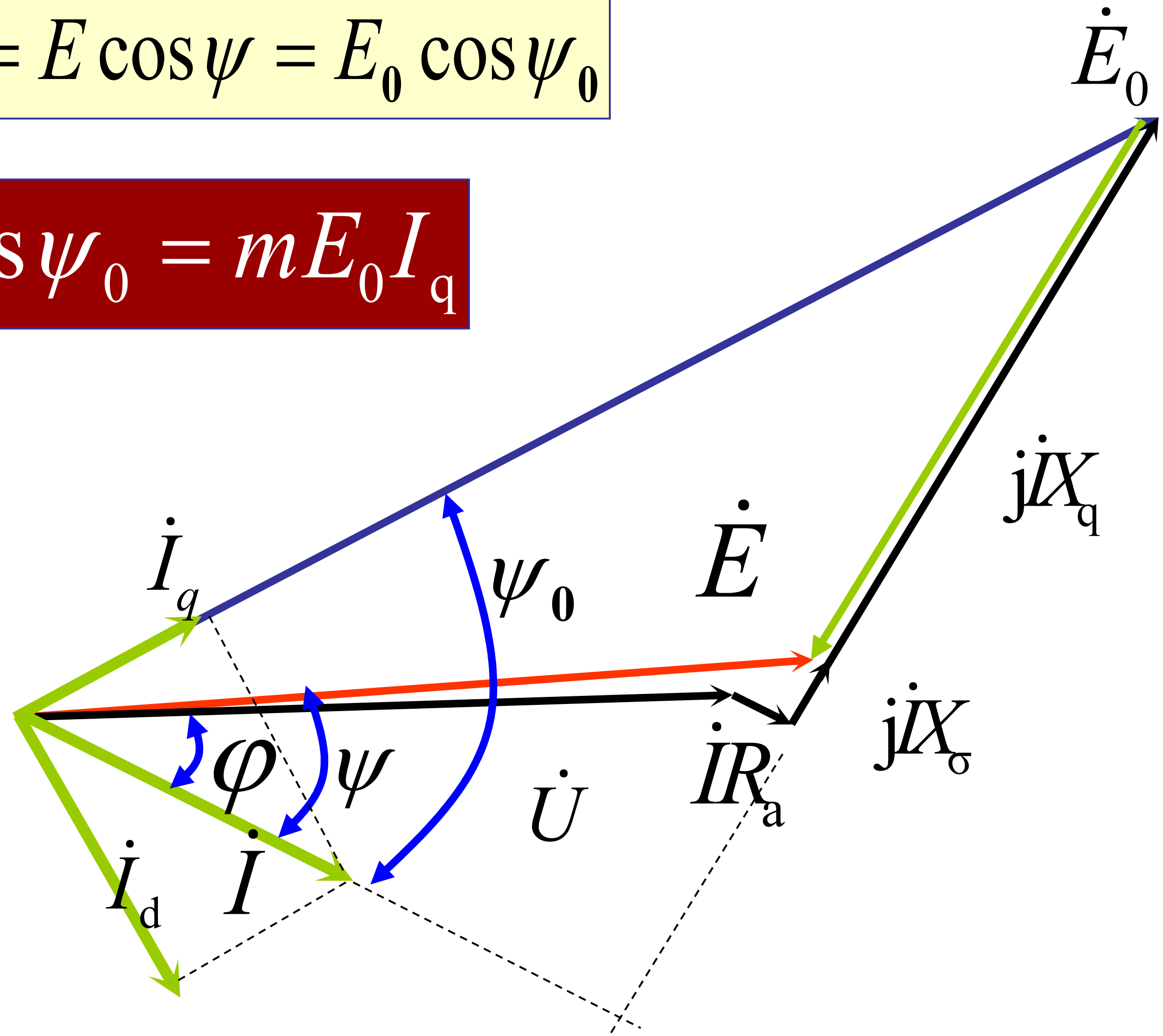


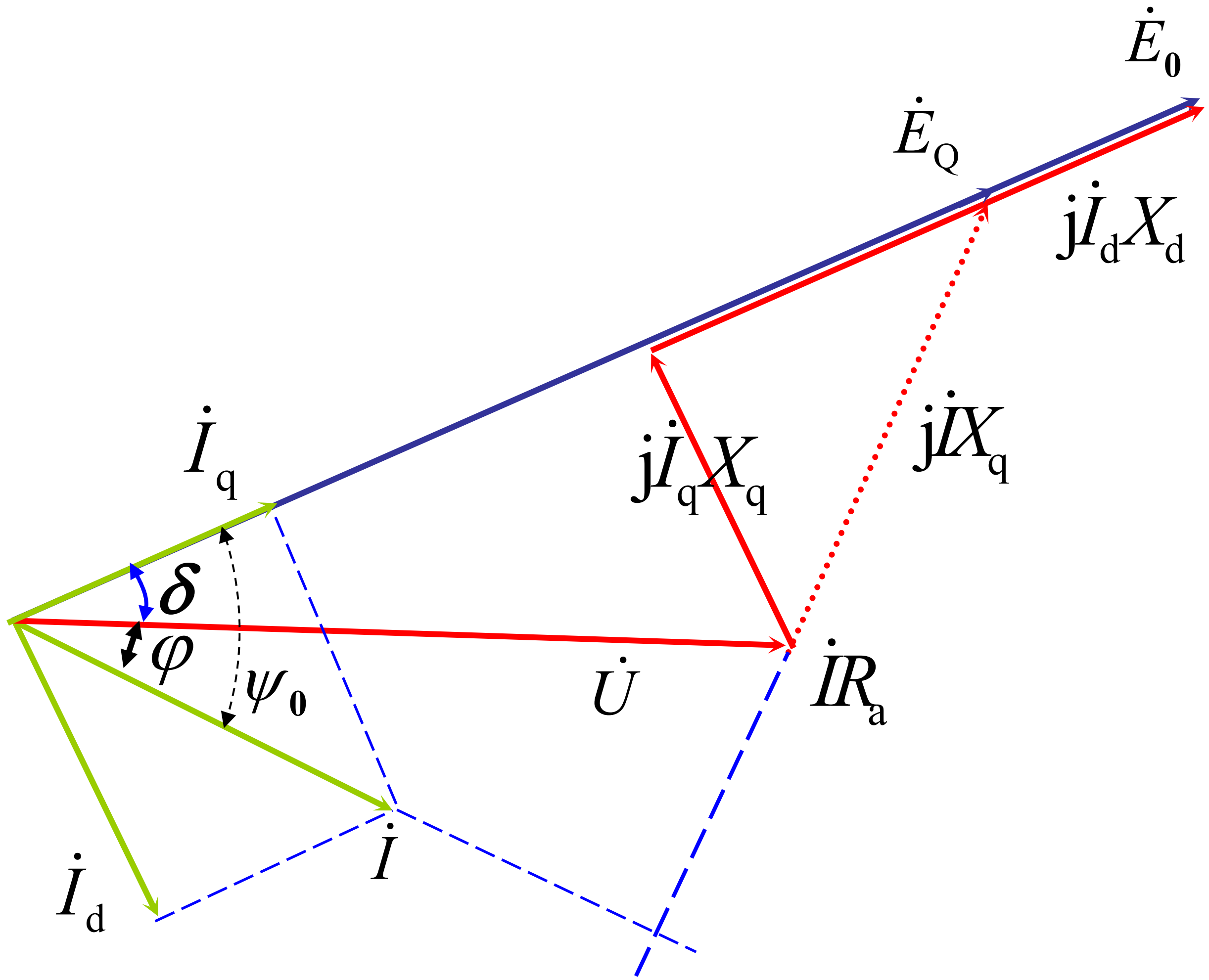
$$P_e = mUI\cos\varphi + mI^2R_a = mI(U\cos\varphi + IR_a)$$

$$U\cos\varphi + IR_a = E\cos\psi = E_0\cos\psi_0$$

$$P_e = mE_0I\cos\psi_0 = mE_0I_q$$

I_q=0 P_e=0





Q-axis armature current I_q is the necessary condition to produce electromagnetic power and to convert electromechanical energy.

2、torque equation

$$T_1 = T_0 + T_e$$

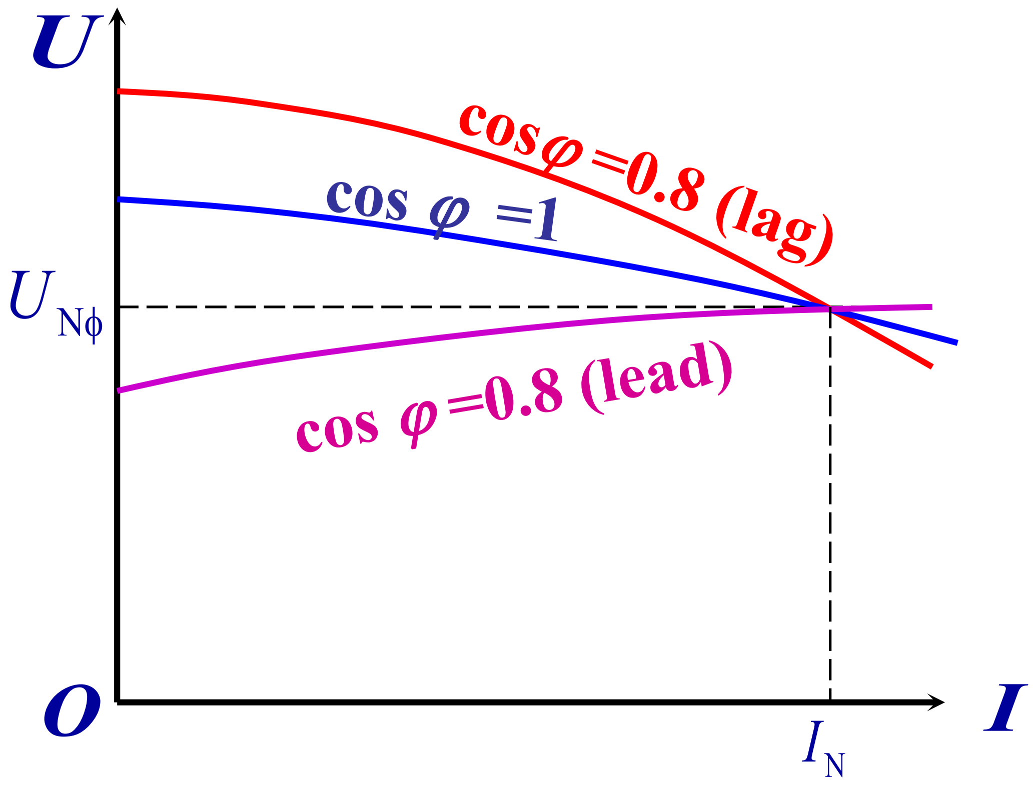
$$T_1 = \frac{P_1}{\Omega_s}$$ → **Driving torque of prime motor**

$$T_e = \frac{P_e}{\Omega_s}$$ → **electromagnetic torque**

$$T_0 = \frac{p_\Omega + p_{Fe}}{\Omega_s}$$ → **No-load torque of generator**

***T*e is breaking torque for generator.**

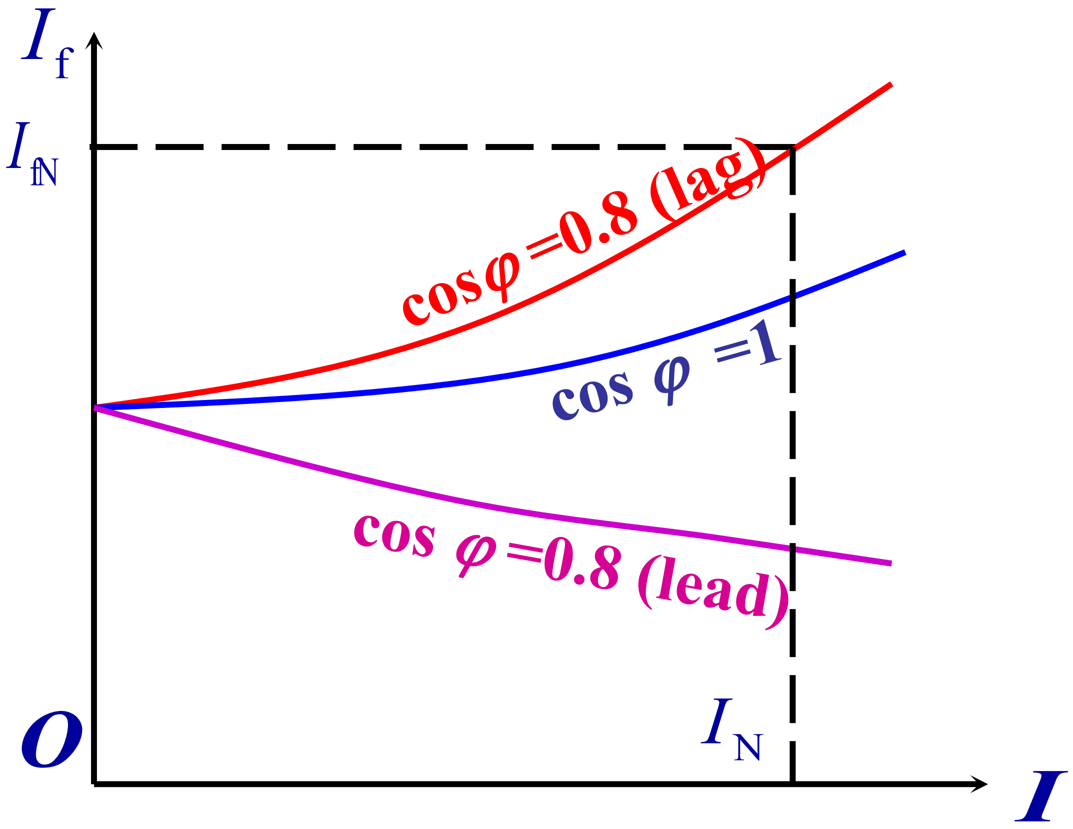
Operating Performance of Synchronous Generators



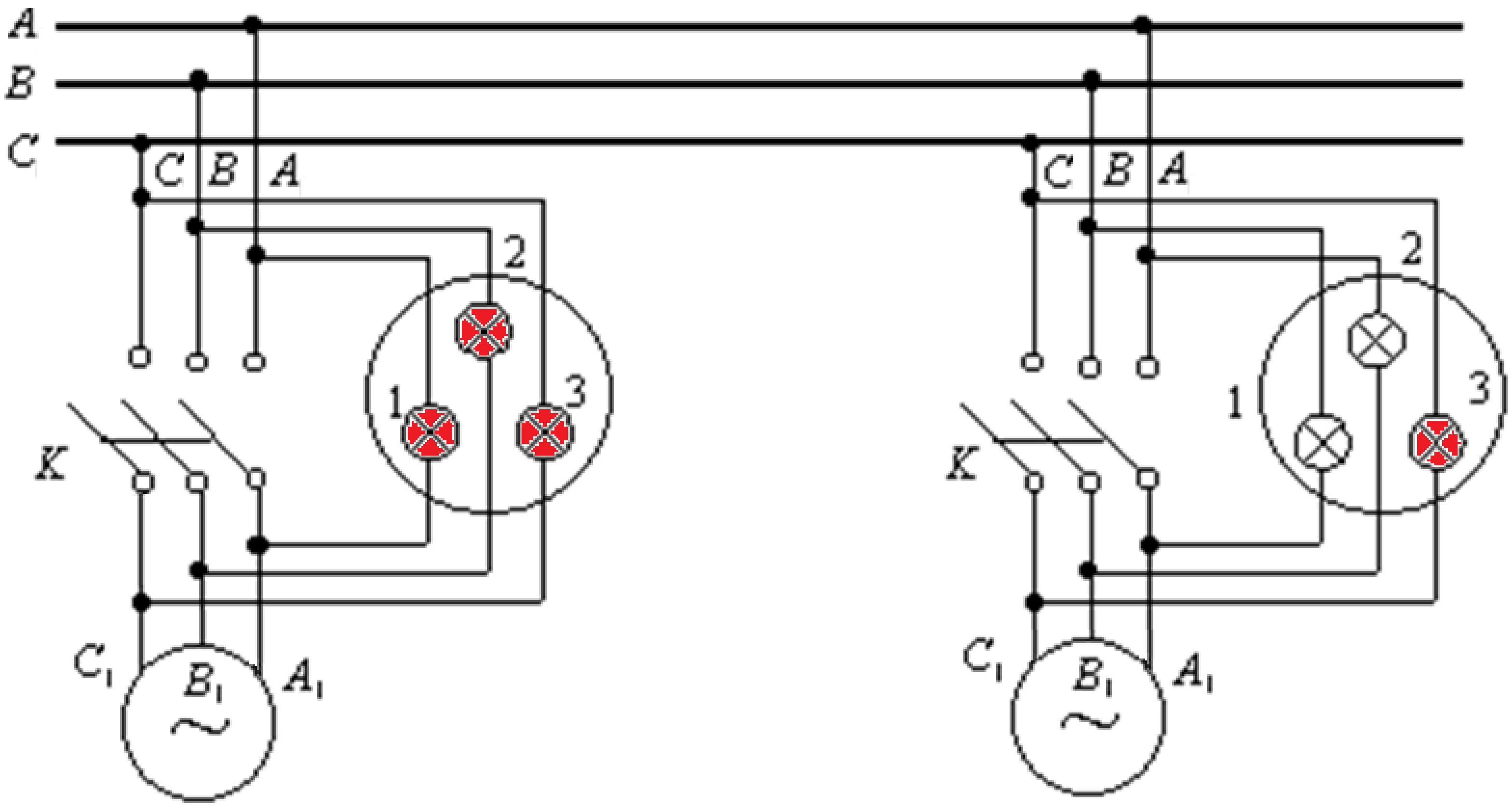
Note: the power factor of generators is determined by load without parallel operation.

Regulation characteristic

n=n_s， U=$U_{N\phi}$， $\cos\varphi$ **=constant**， I_f= f (I)。



Parallel Operation with Infinite Bus



Require: phase sequences, waveforms, frequencies, amplitudes and phase angles between the generator and bus are same.

Parallel Operation with Infinite Bus

Power-Angle Characteristic

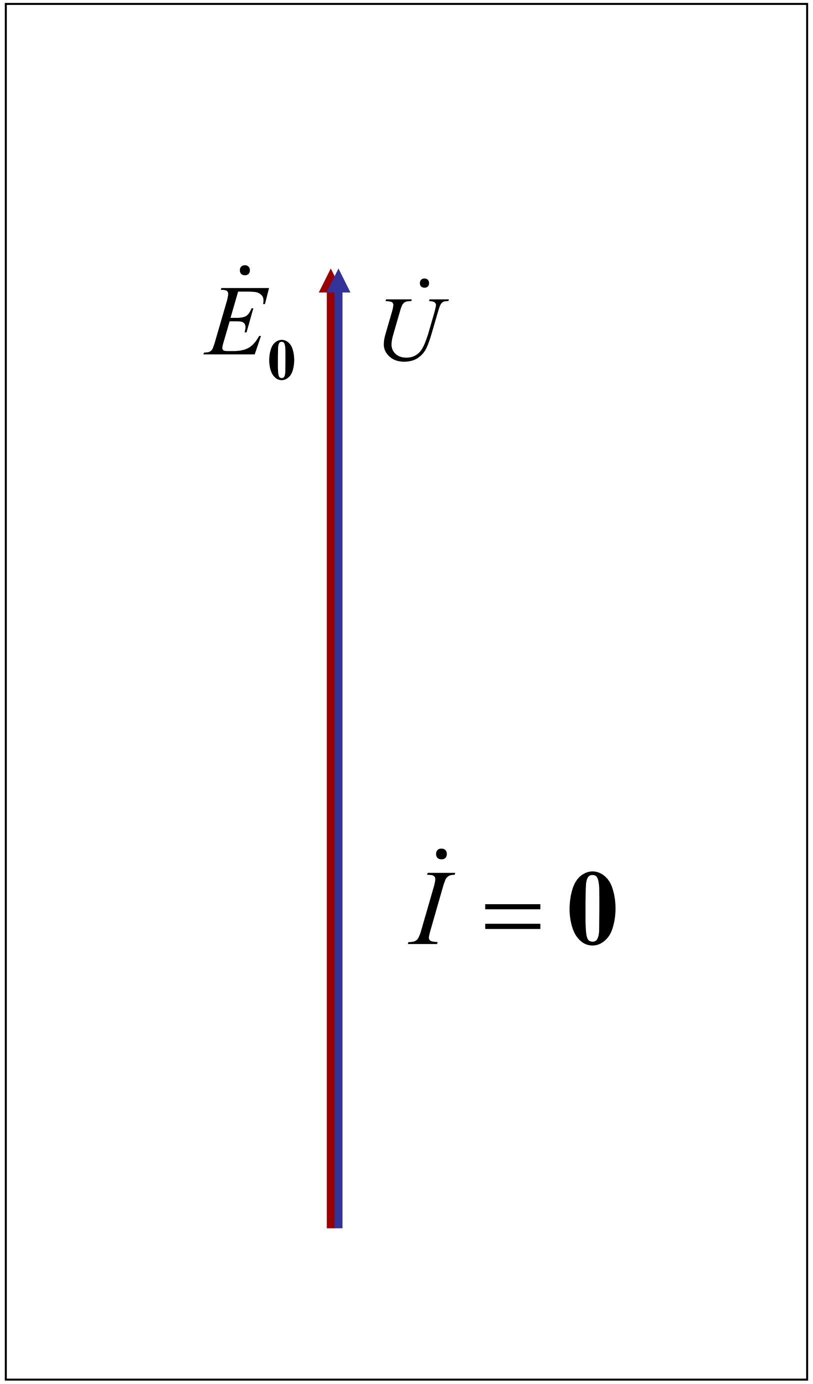
Preconditions:

E_0, U and f keep constant.

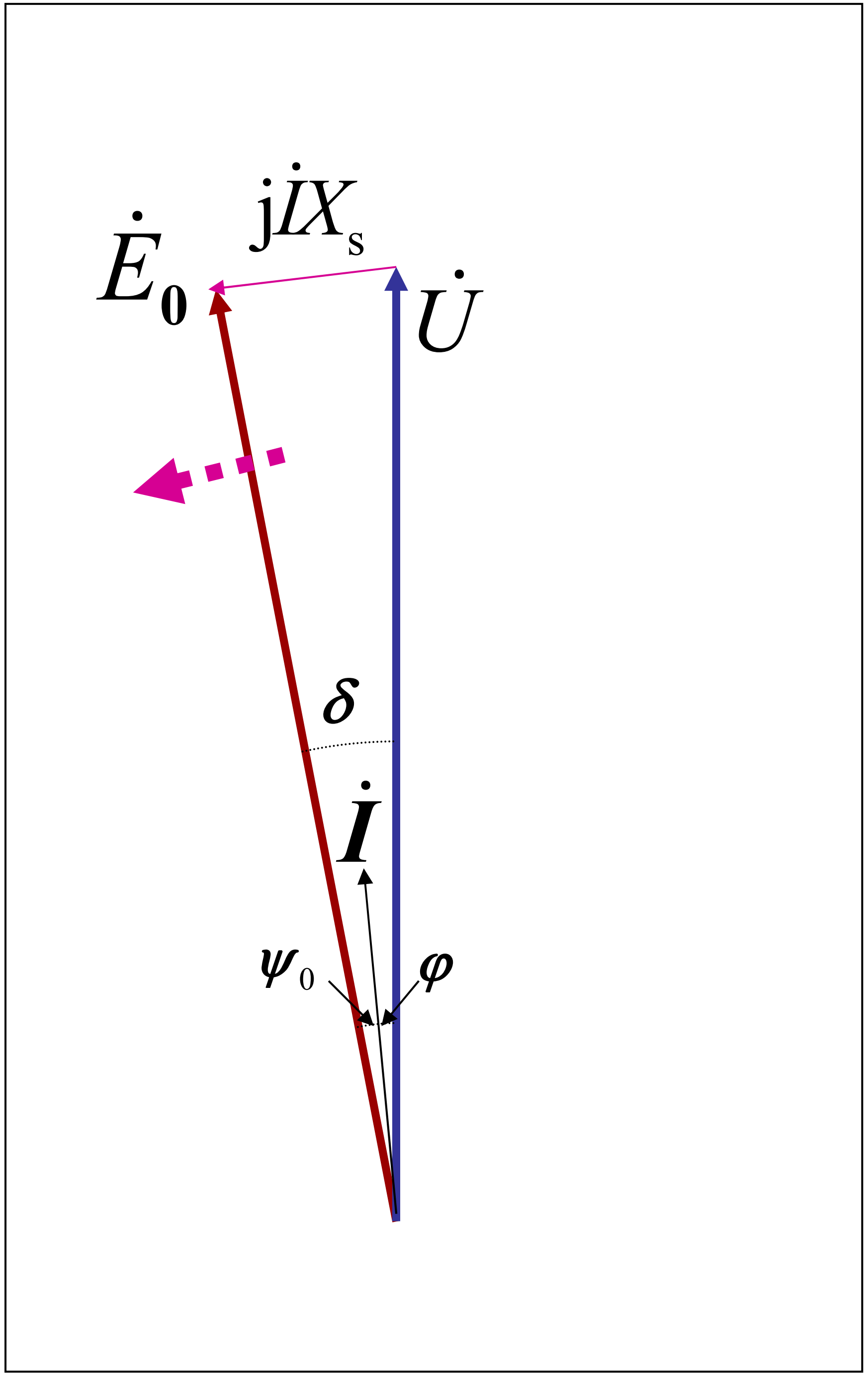
R_a=0.

Saturation is ignored.

Find: $P_e = f(\delta)$



$\dot{E}_0$
$\dot{U}$
$\dot{I} = 0$



$\mathrm{j}\dot{I}X_s$
$\dot{E}_0$
$\dot{U}$
δ
$\dot{I}$
ψ_0
φ

$$P_e \approx mUI\cos(\psi_0 - \delta) = mUI(\cos\psi_0 \cos\delta + \sin\psi_0 \sin\delta)$$
$$= mU(I_q \cos\delta + I_d \sin\delta)$$

Power-Angle Characteristic

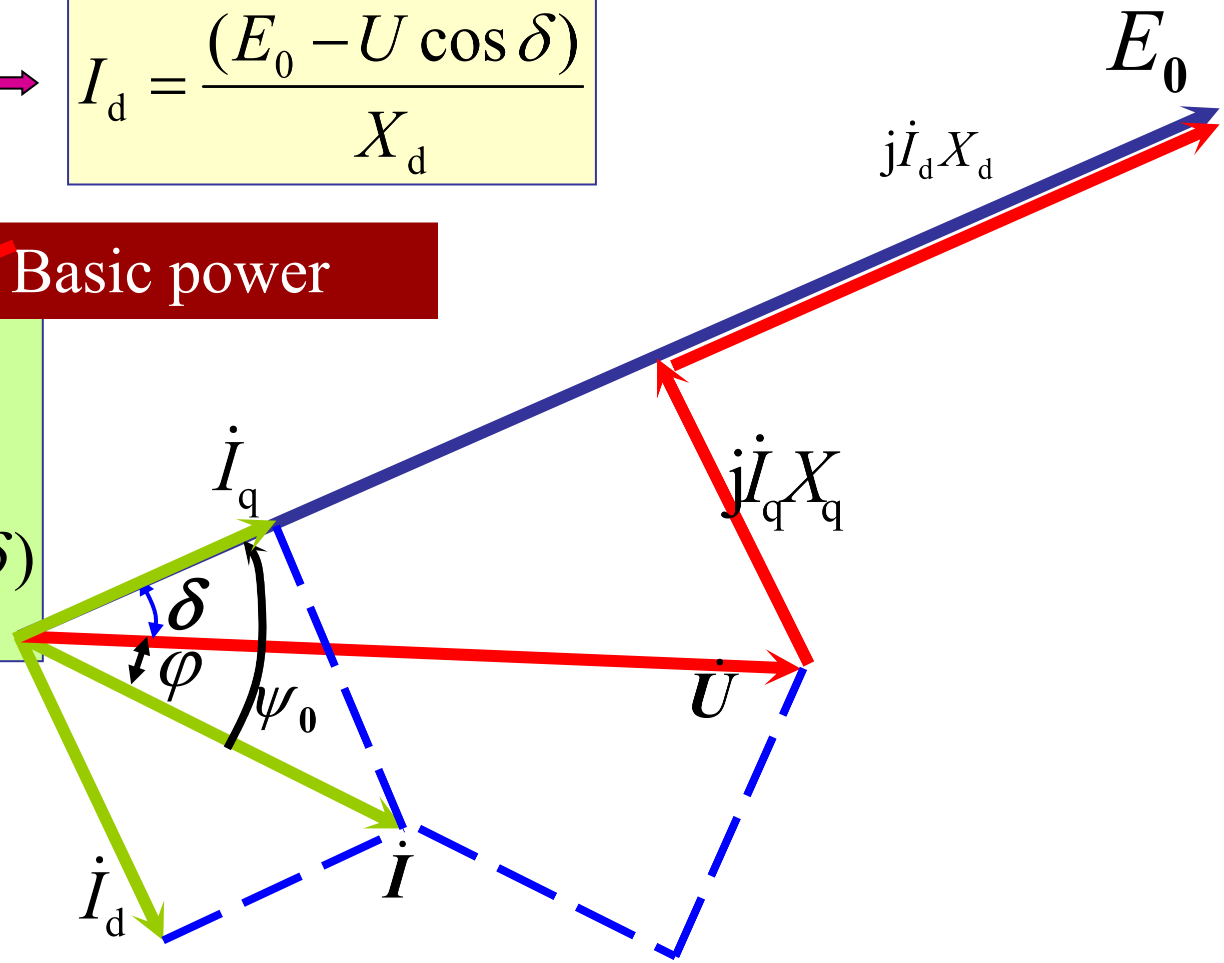
$$I_q X_q = U\sin\delta \Rightarrow I_q = U\sin\delta / X_q$$

$$I_d X_d = E_0 - U\cos\delta \Rightarrow I_d = \frac{(E_0 - U\cos\delta)}{X_d}$$

$$P_e = m\frac{E_0 U}{X_d}\sin\delta$$
$$+ m\frac{U^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin(2\delta)$$

Basic power

Additional power
or Reluctance power



Parallel Operation with Infinite Bus

Power-Angle Characteristic

$$P_e = m\frac{E_0 U}{X_d}\sin\delta + m\frac{U^2}{2}\left(\frac{1}{X_q}-\frac{1}{X_d}\right)\sin(2\delta)$$

Salient-pole Rotor Synchronous Generator

$$P_e = m\frac{E_0 U}{X_s}\sin\delta$$

Cylindrical Rotor Synchronous Generator

Discussion: Please write the voltage equations and power-angle equations of and a cylindrical rotor synchronous generator and a salient-pole rotor synchronous generator respectively. And then, analyze their similarities and differences.

Parallel Operation with Infinite Bus

Generator of Power Plant

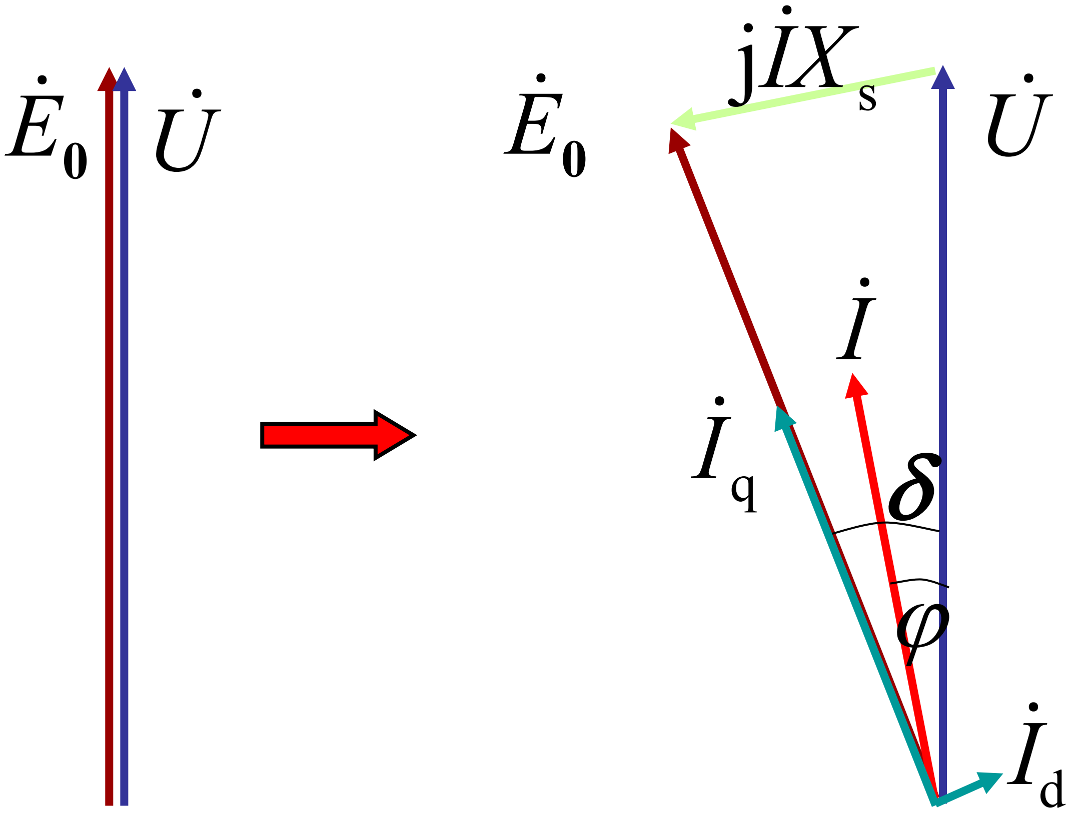
Infinite Bus

Constant-frequency and constant-voltage AC Source

Apparent power of the grid $S \approx \infty$
Voltage of the grid U=C
Frequency of the grid f

Parallel Operation with Infinite Bus

Regulation of Active Power



Changing P_1 can regulate active power

Parallel Operation with Infinite Bus

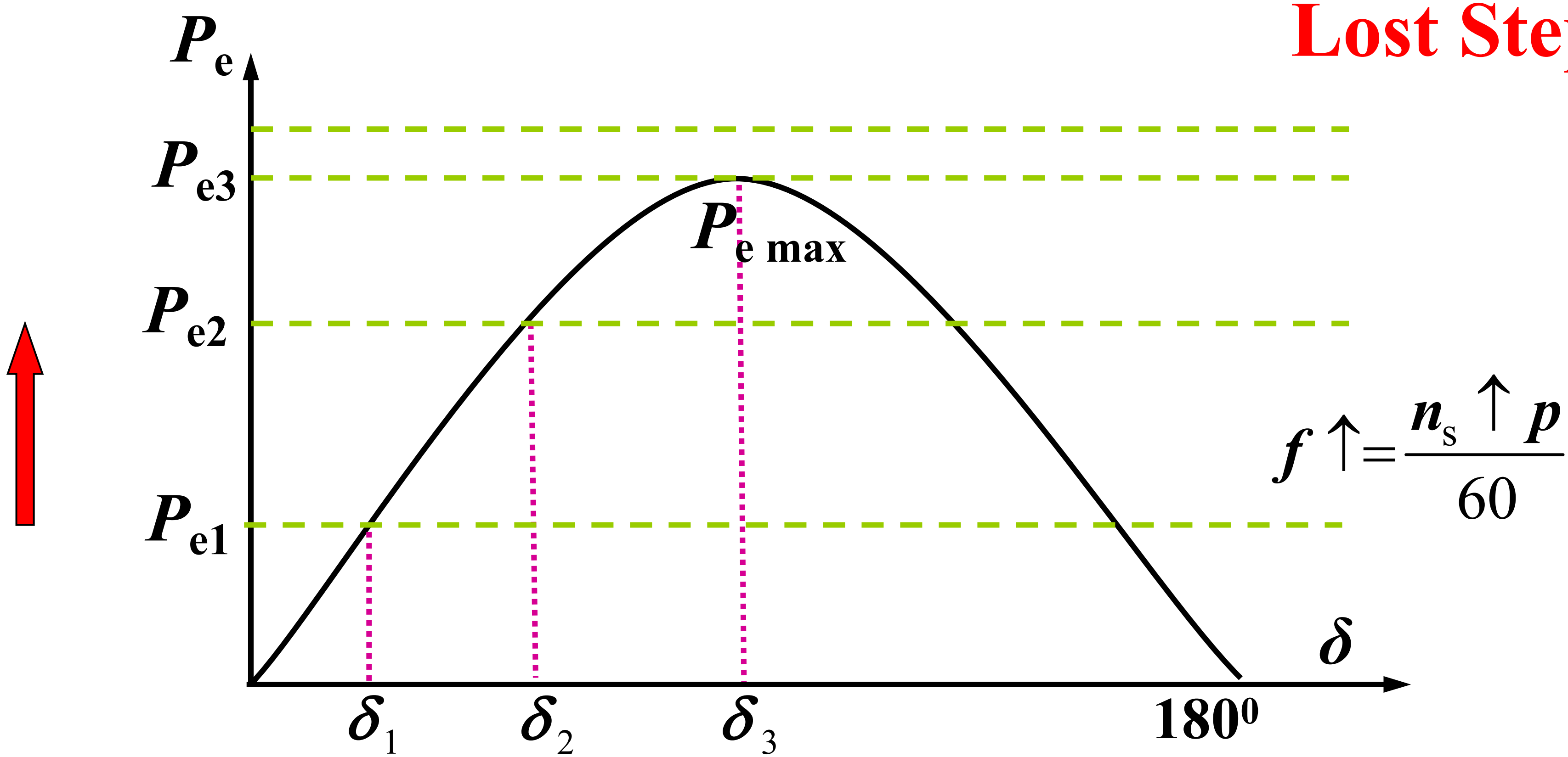
Regulation of Active Power

To increase the output active power of generator P_2, the input mechanical power(torque) P_1(T_1) must be increased. This leads to the increase of power angle δ.

For a constant-frequency and constant-voltage AC source (infinite bus), active power P_2 can be regulated by changing the power angle δ when the field current of generator I_f keeps constant.

For a cylindrical rotor synchronous generator, electromagnetic power P_e and active power P_2 reaches maximum when the power angle δ=90° .

Lost Step



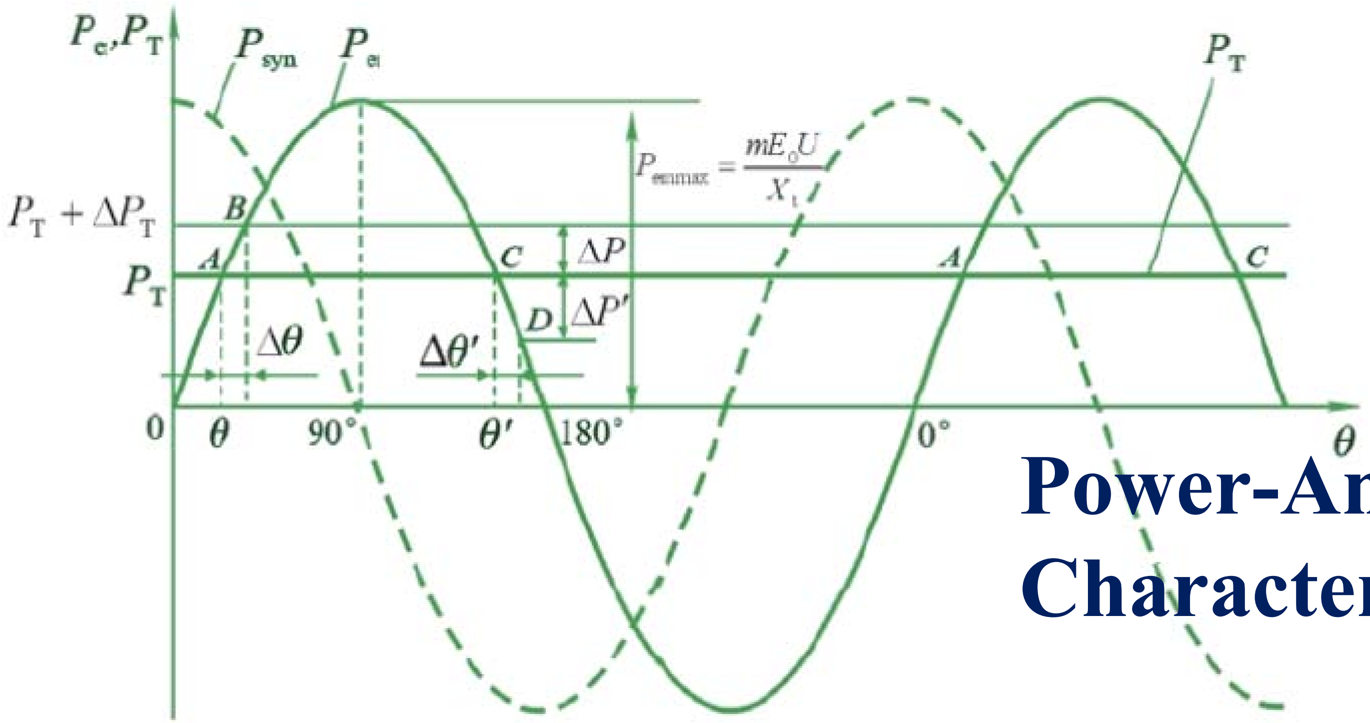
Static Stabilization

A.The synchronous generator can keep steady operation when the infinite bus or prime mover are disturbed slightly.

B.The synchronous generator can return to the original steady operating state when the disturbances of infinite bus or prime mover disappear.

Parallel Operation with Infinite Bus

Static Stabilization



Power-Angle Characteristic

Condition of static stabilization: $$P_{syn} = \frac{dP_e}{d\delta} = m\frac{E_0U}{X_s}\cos\delta$$

Parallel Operation with Infinite Bus

Static Stabilization

Static stabilization: $\frac{\mathrm{d}P_\mathrm{e}}{\mathrm{d}\delta} > 0$

Static unstabilization: $\frac{\mathrm{d}P_\mathrm{e}}{\mathrm{d}\delta} < 0$

Limit of static stabilization: $\frac{\mathrm{d}P_\mathrm{e}}{\mathrm{d}\delta} = 0$

Methods of improving static stabilization:
A. Decrease P_1
B. Increase I_f
C. Decrease X_s

For a cylindrical rotor synchronous generator,
Ability of Overload:

$$k_\mathrm{p} = \frac{P_\mathrm{emax}}{P_\mathrm{N}} = \frac{1}{\sin\delta_\mathrm{N}}$$

The smaller the power angle δ, the better the static stabilization.

Regulation of Reactive Power

$$P_e = m\frac{E_0 U}{X_s}\sin\delta = \text{const} \quad \Rightarrow \quad E_0 \sin\delta = \text{const}$$

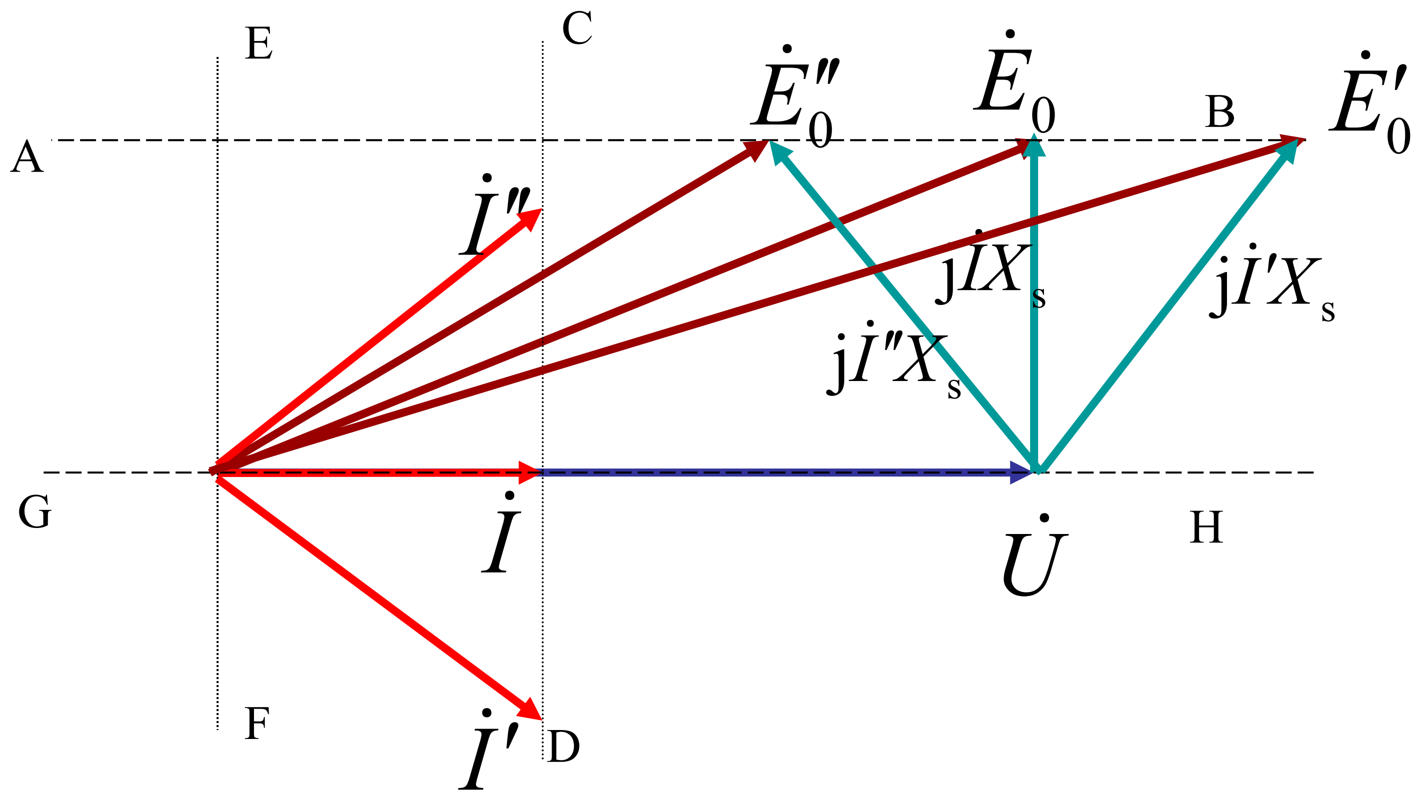
$$P_2 = mUI\cos\varphi = \text{const} \quad \Rightarrow \quad I\cos\varphi = \text{const}$$

Normal excitation: φ=0, cosφ=1, Q=0 (resistive).

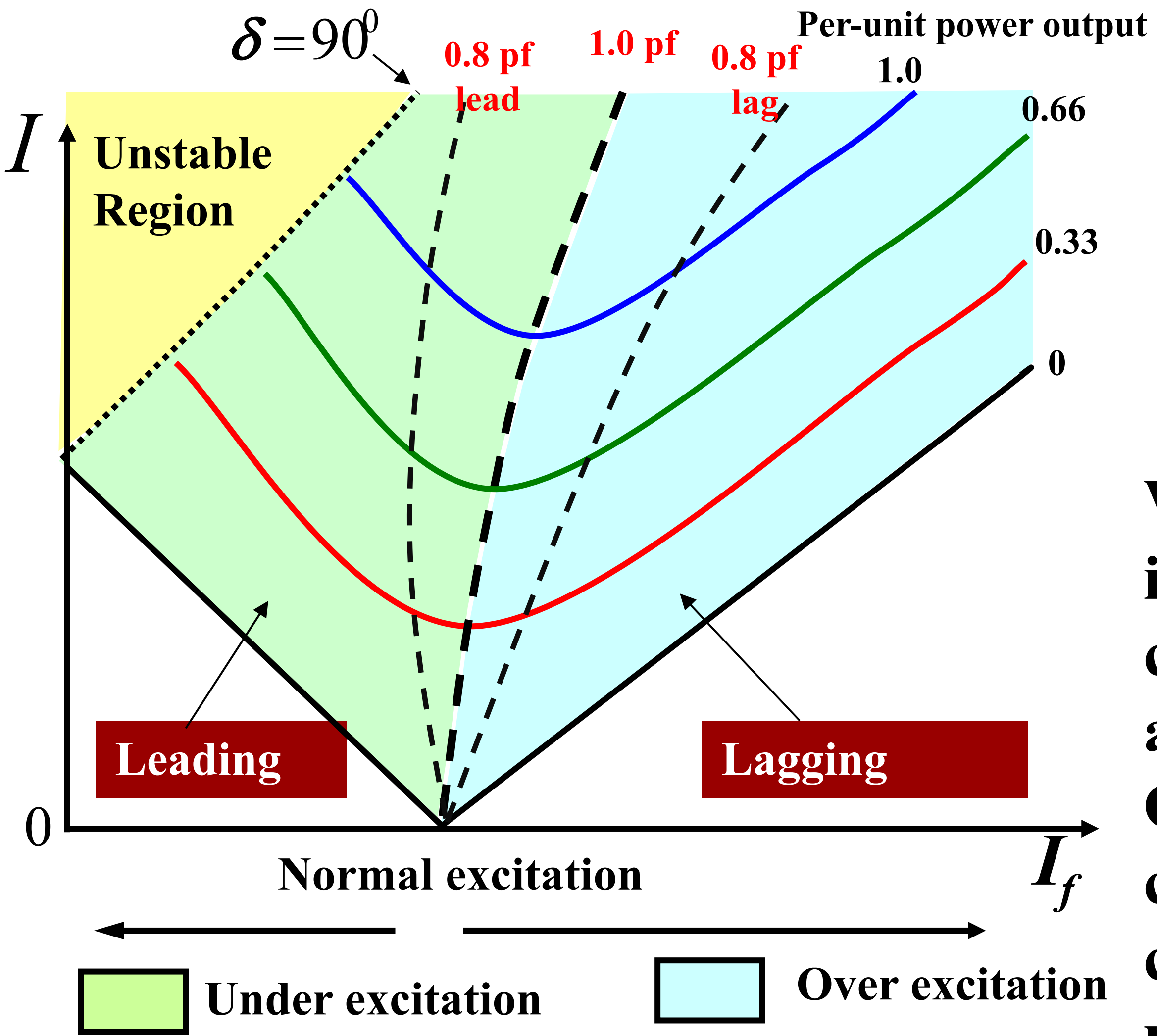
Over excitation: φ>0, cosφ is lagging, Q>0 (inductive).

Under excitation: φ<0, cosφ is leading, Q<0 (capacitive).

Regulation of Reactive Power



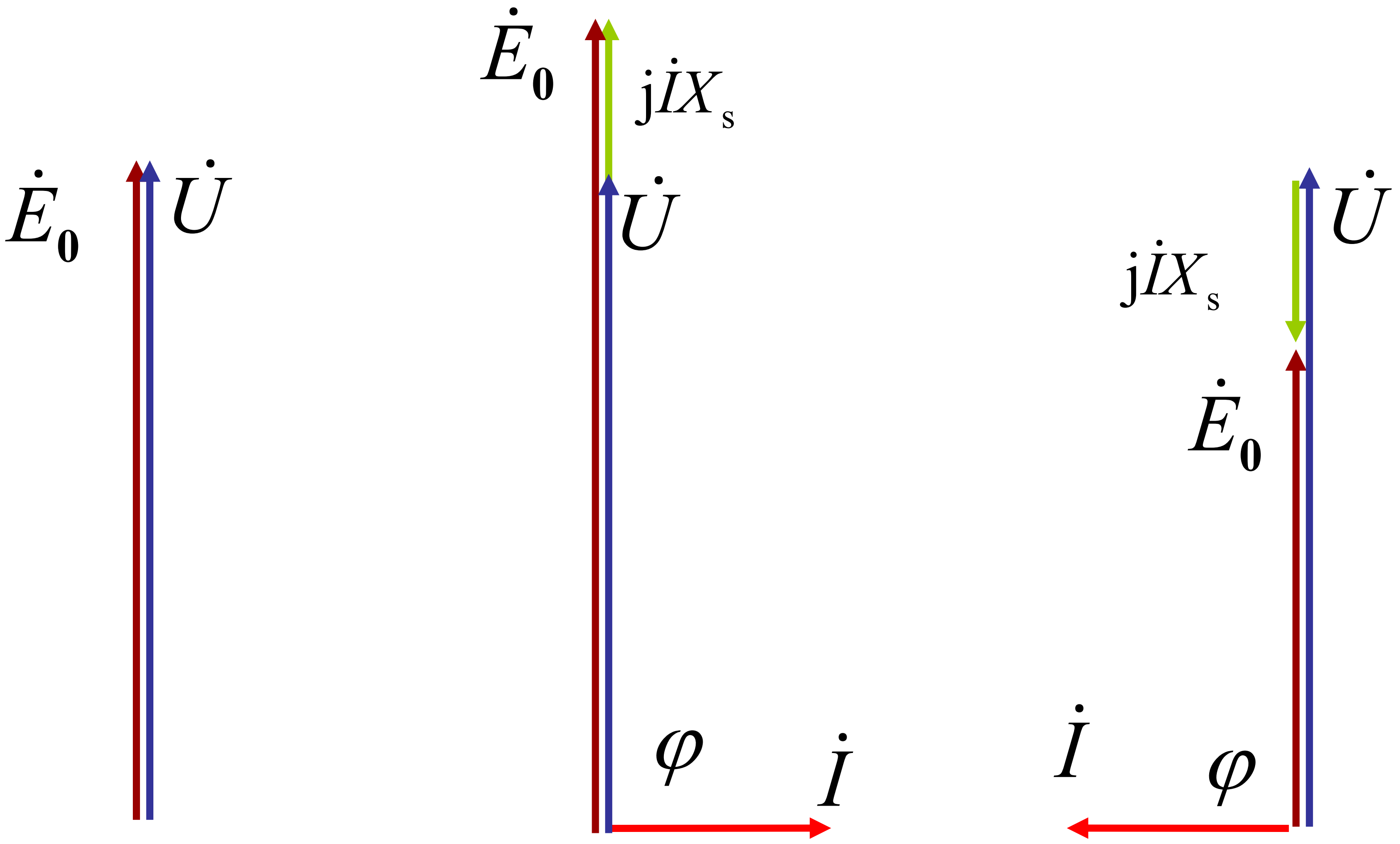
V Curves of Synchronous Generator



When P_e=C, find: $I=f(I_f)$

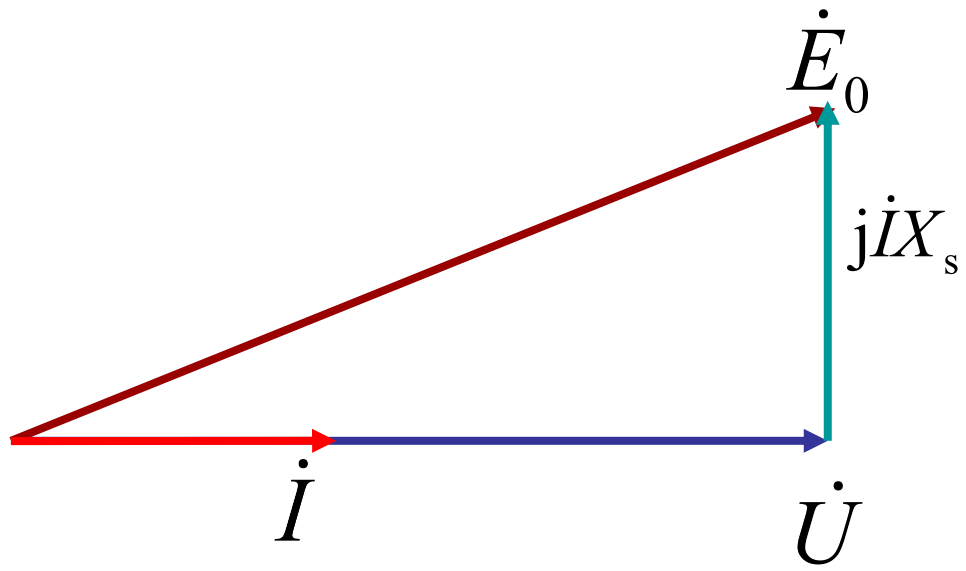
When the field current I_f increases, the armature current I decreases first, and then increases.

On each V curve, the changing armature current is only reactive part.

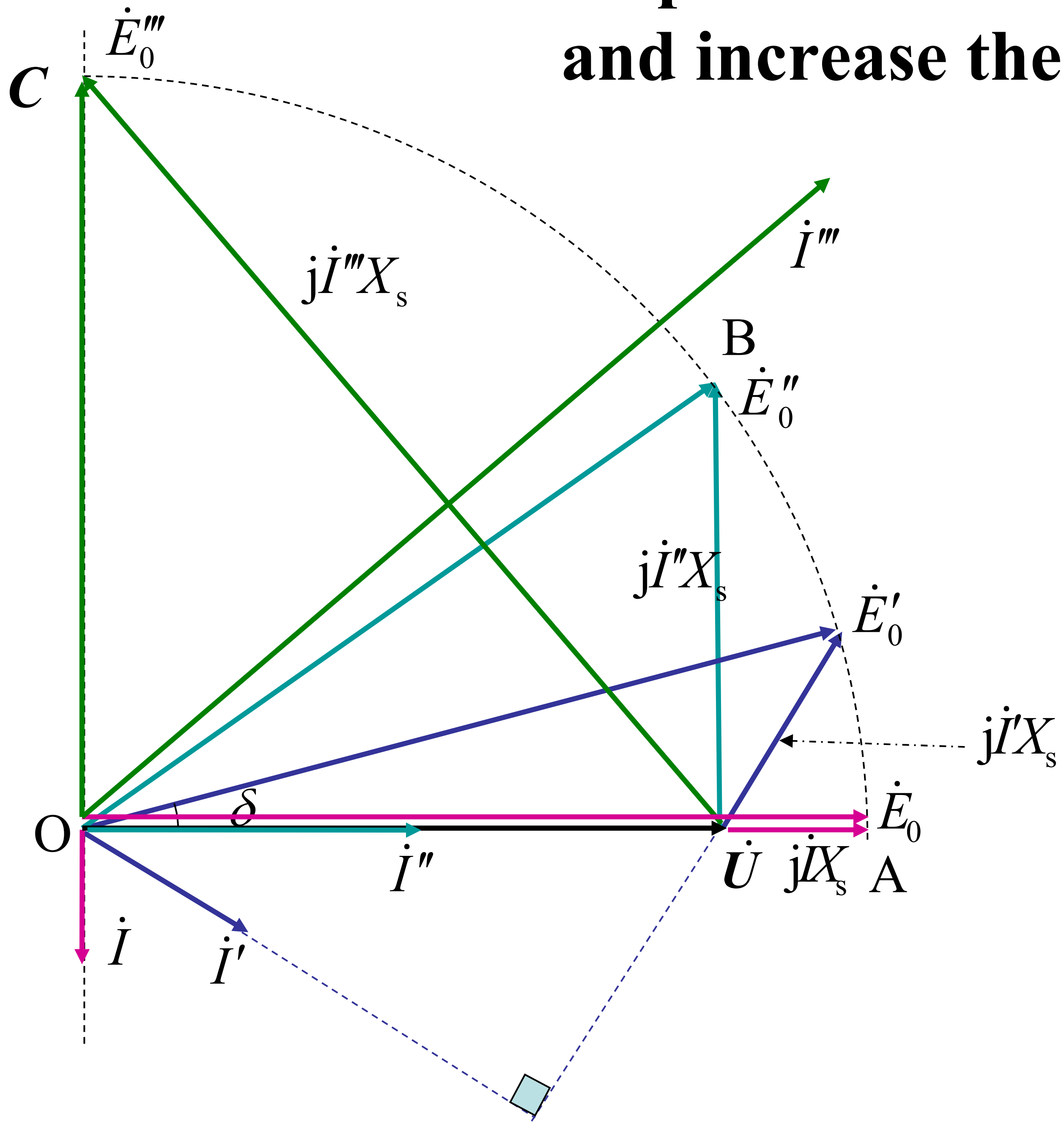


$\dot{E}_0$
$\dot{U}$
$\dot{E}_0$
$j\dot{I}X_s$
$\dot{U}$
φ
$\dot{I}$
$\dot{U}$
$j\dot{I}X_s$
$\dot{E}_0$
$\dot{I}$
φ

Discussion: A steam turbine generator is connected with the infinite bus and R_a=0. The phase diagram is shown as follows. Keep the field current constant and increase the active power, please draw the changes of the phase diagram.

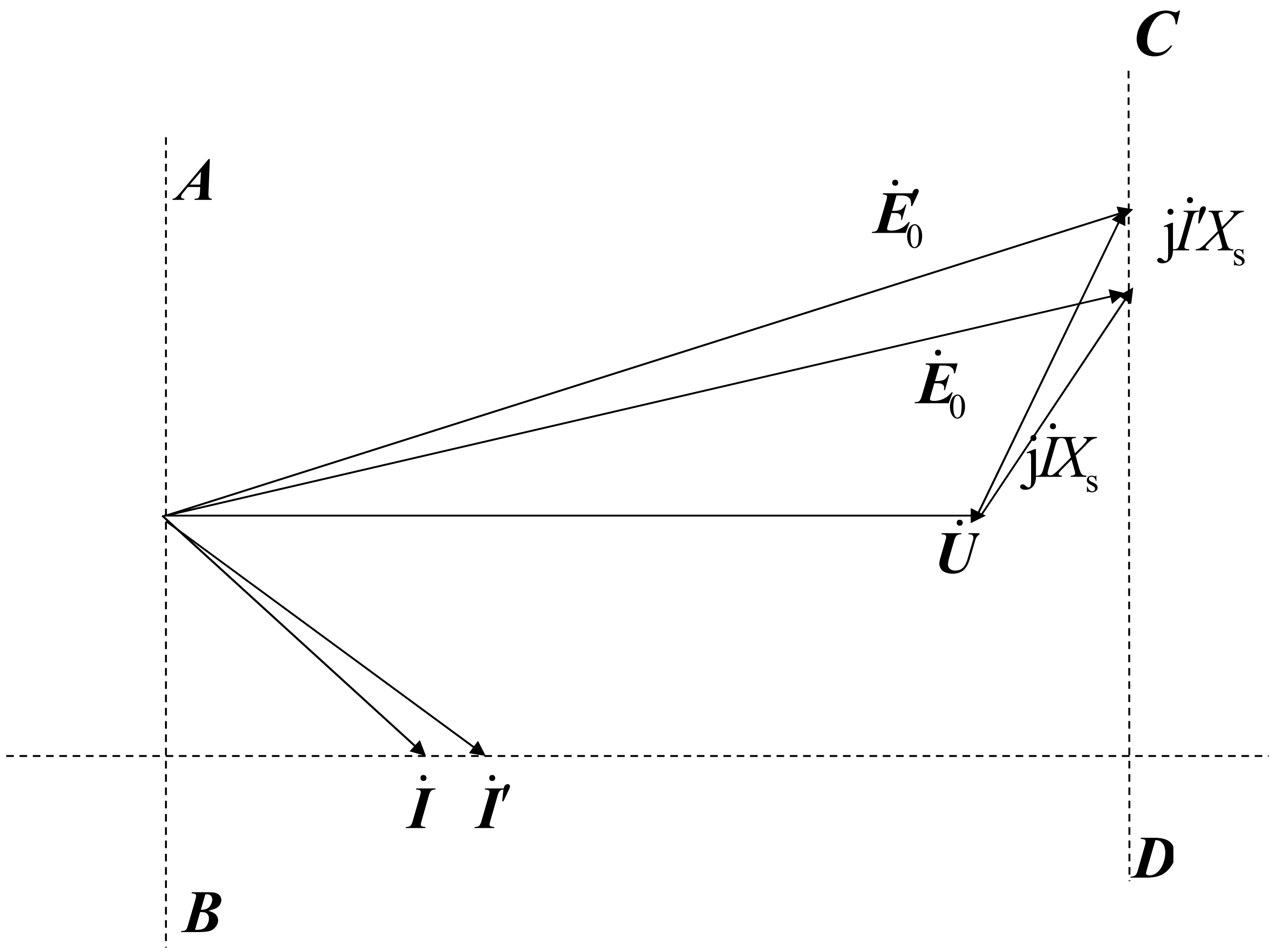


Keep the field current constant and increase the active power

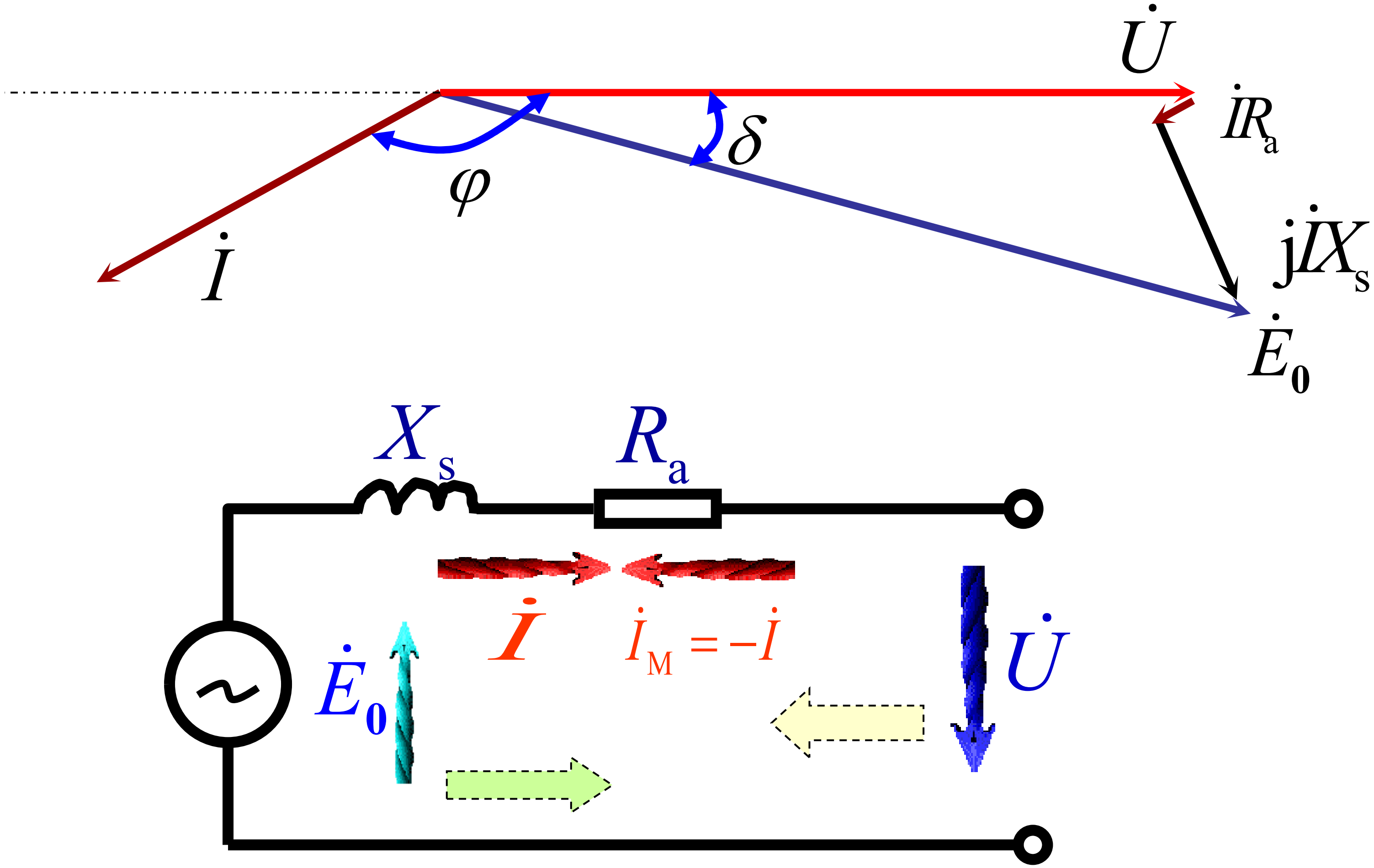


$0 \le \delta < 90^0$

Keep the reactive power increase the active power with over excitation

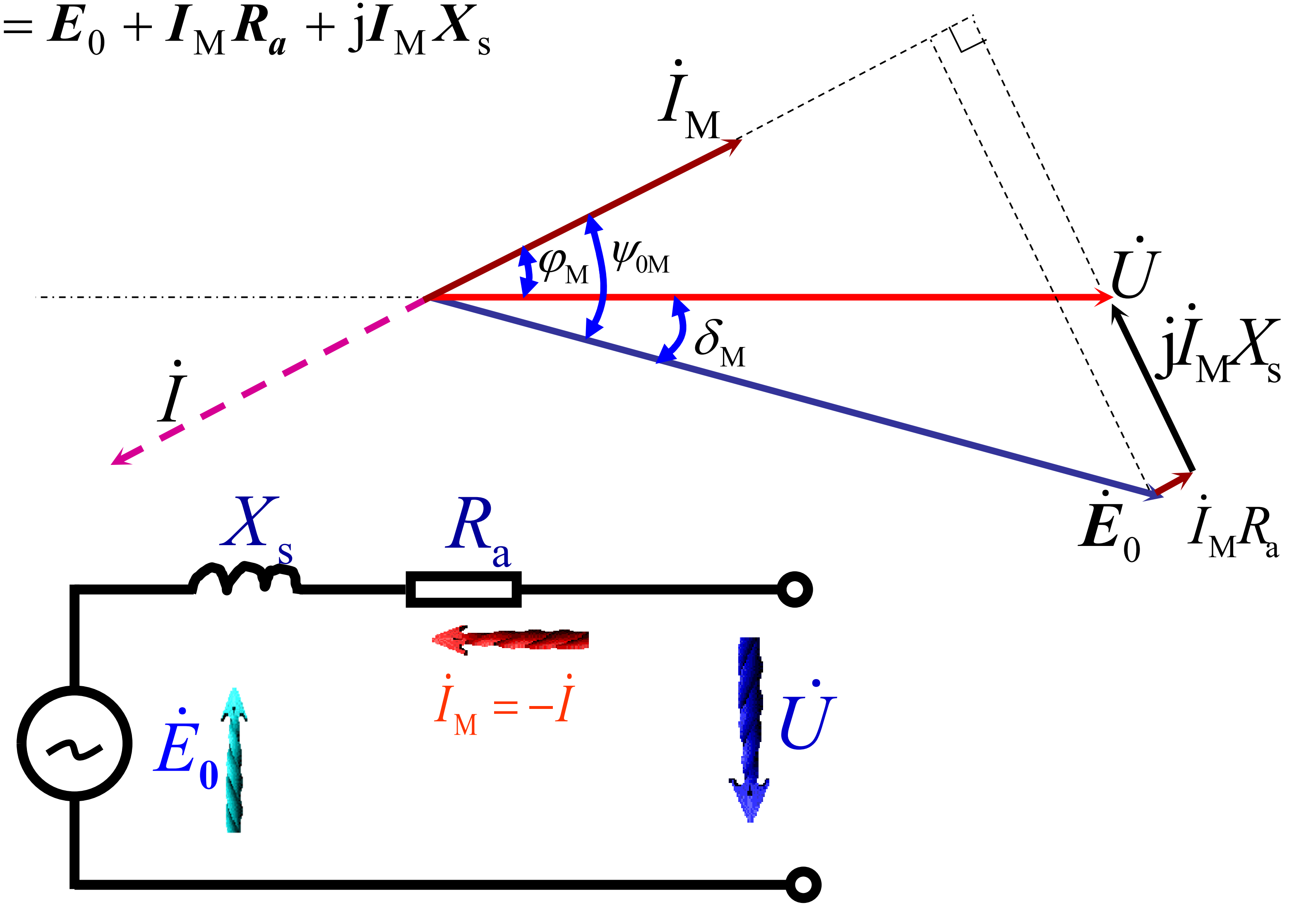


Synchronous Motors



Synchronous Motors

$$\dot{U} = \dot{E}_0 + \dot{I}_M R_a + \mathrm{j}\dot{I}_M X_s$$



Synchronous Motors

$$\dot{\boldsymbol{U}} = \dot{\boldsymbol{E}}_0 + \mathrm{j}\dot{\boldsymbol{I}}_{\mathrm{M}}\boldsymbol{X}_{\mathrm{s}}$$