COLORADO SCHOOL OF MINES
ELECTRICAL ENGINEERING DEPARTMENT

EENG 577

ADVANCED ELECTRICAL MACHINE DYNAMICS FOR SMART-GRID SYSTEMS

M3-P2 Synchronous Generators

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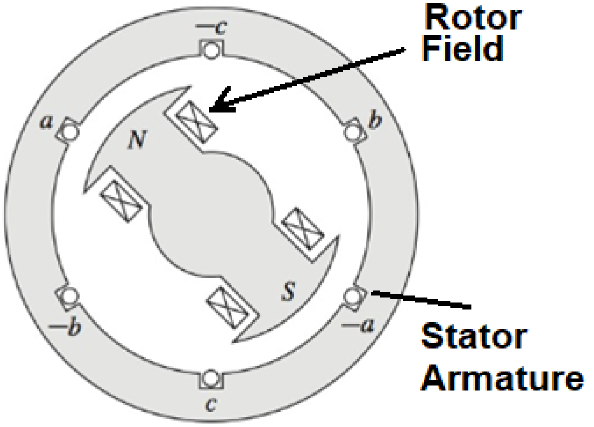
Learning Objectives

- Explain the equivalent circuit of a synchronous generator.
- Be able to sketch phasor diagrams for a synchronous generator.
- Write and explain the equations for power and torque in a synchronous generator.
- Extract the characteristics of a synchronous machine from measurements (OCC and SCC).
- Explain how terminal voltage varies with load in a synchronous generator operating alone.
- Be able to calculate the terminal voltage at various load conditions.
- Explain the conditions required to parallel two or more synchronous generators.
- Explain the operation of synchronous generators in parallel with a very large power system (or infinite bus).

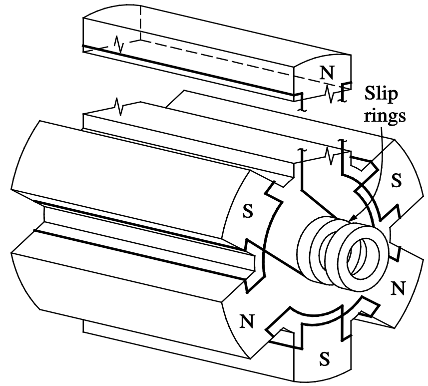
Basic Topology

- In the *stator*, we have a three-phase winding. Since the main voltage is induced in this winding, it is also called *armature winding*.

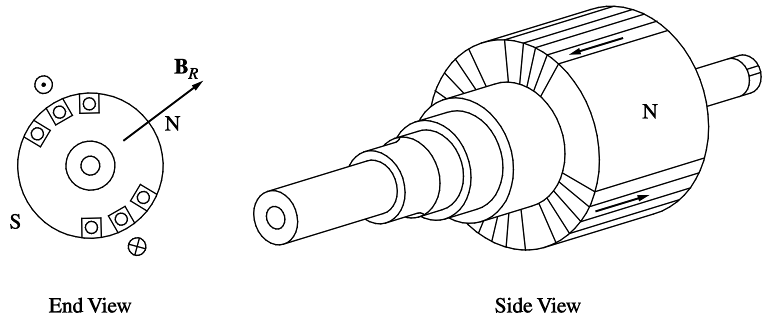
- In the *rotor*, the magnetic field is generated either by a permanent magnet or by applying dc current to rotor winding. Since rotor is producing the main field, it is also called *field winding*. Two rotor designs are common:



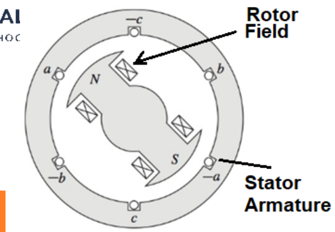
- Salient-pole rotor with “protruding” poles



- Round or Cylindrical rotor with a uniform air gap

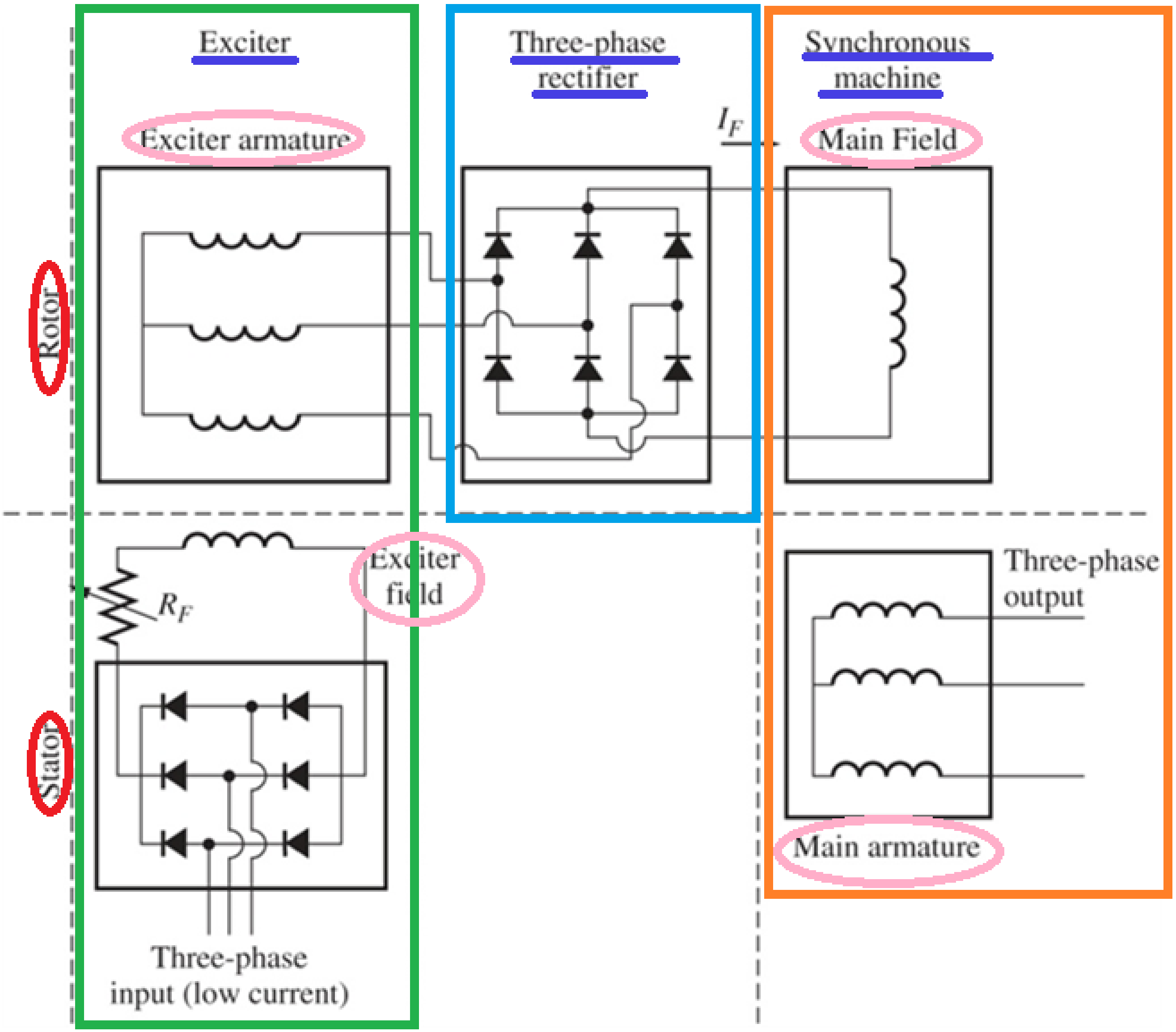


Brushless Exciter System
for Large Generators

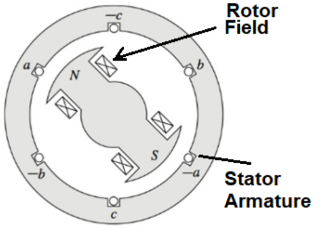


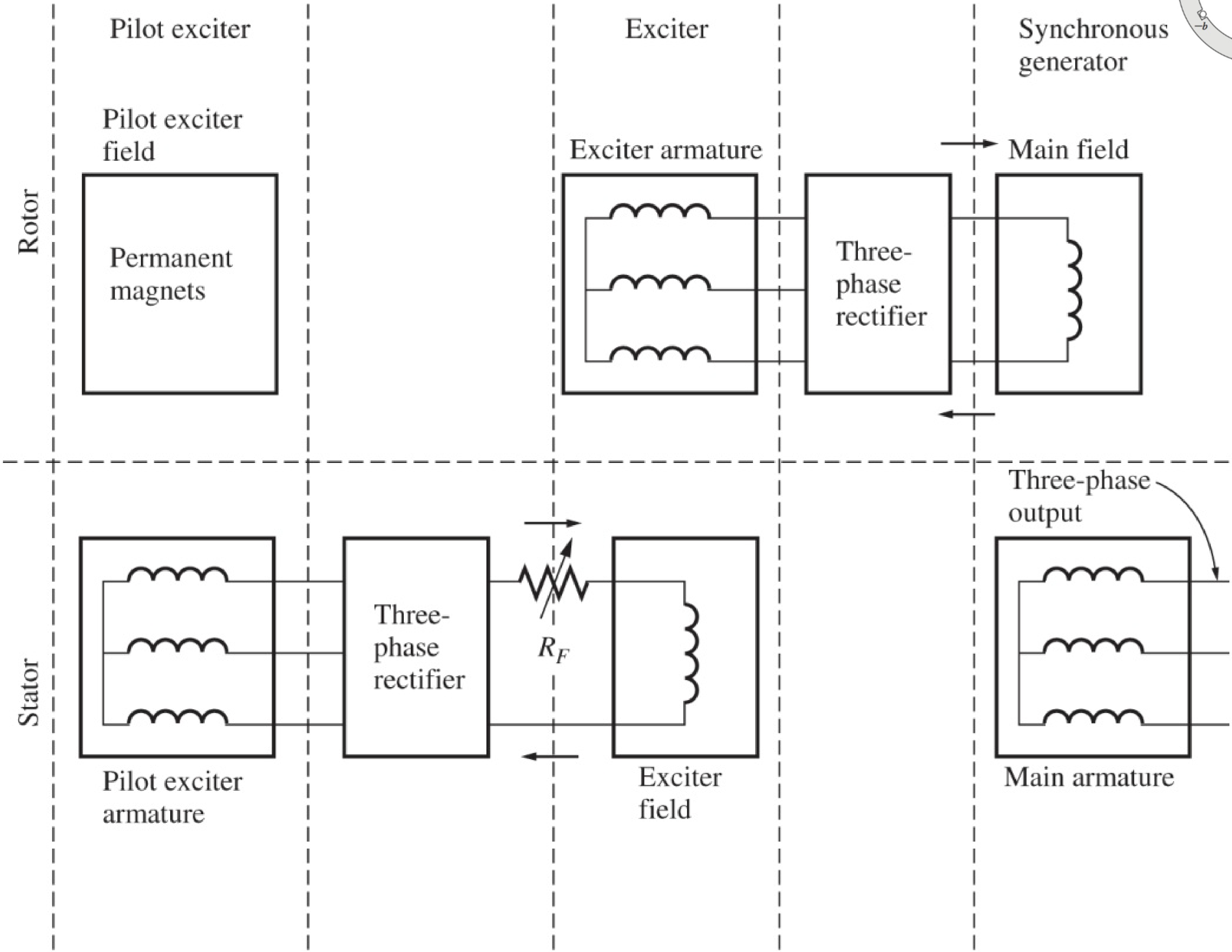
Rotating

Stationary



Brushless Excitation System with Pilot Exciter
for Large Generators





The Speed of Rotation of a Synchronous Generator

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

Where

f_e = electrical frequency, in Hz

n_m = mechanical speed of magnetic field, in rpm
= rotor speed, in rpm

P = number of poles

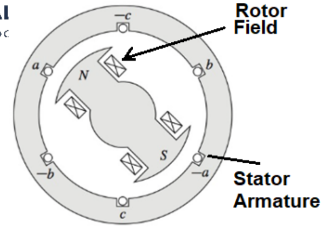
The Internal Generated Voltage of a Synchronous Generator

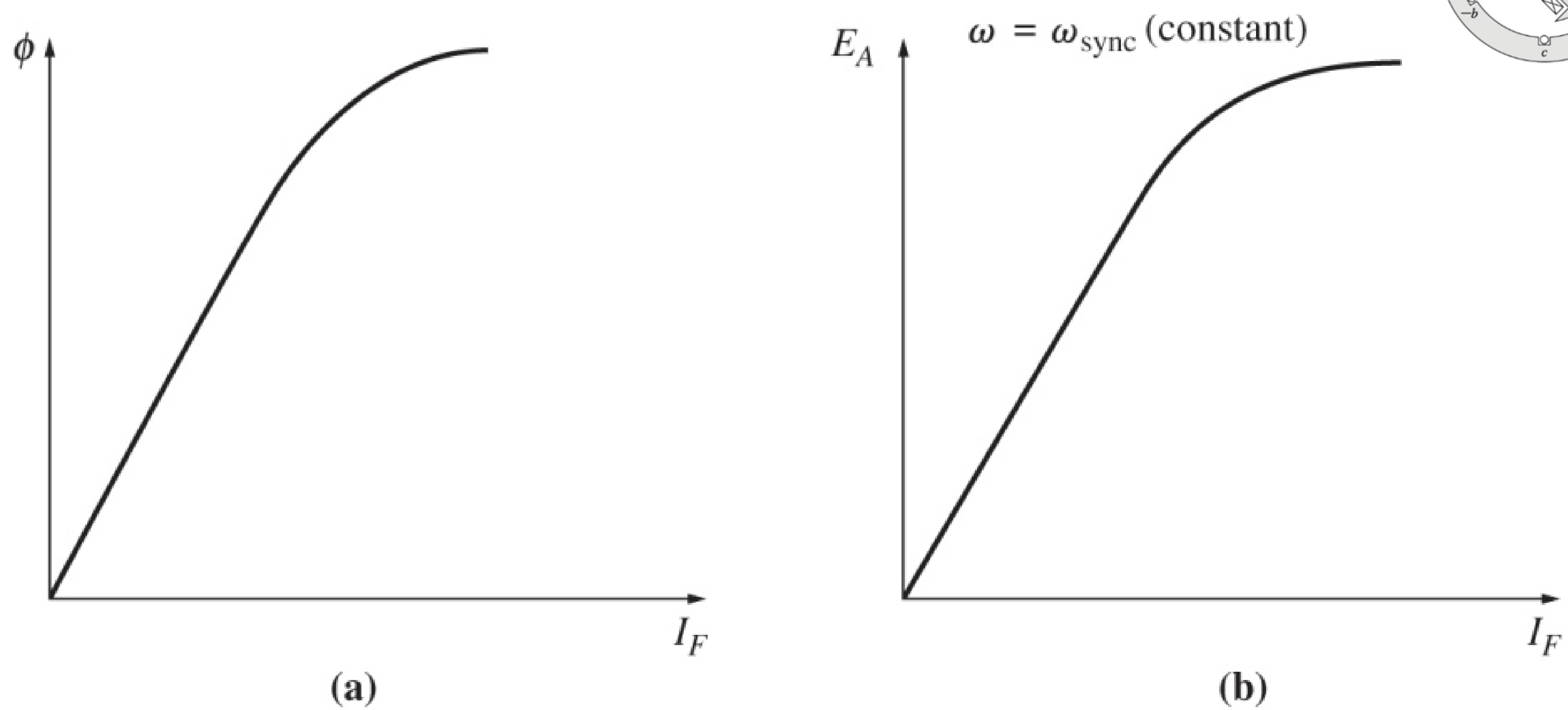
- It was shown previously, the ***magnitude of the rms*** voltage induced in each stator phase was found to be

$$E_A = \sqrt{2}\pi N_C \phi f = \frac{N_C \phi}{\sqrt{2}} \omega = K\phi\omega$$

- The induced voltage is proportional to the rotor flux for a given rotor angular frequency in electrical Radians per second.

- Since the rotor flux depends on the field current I_F, the induced voltage E_A is related to the field current as shown below. This is generator *magnetization curve* or the *open-circuit characteristics* of the machine**.**



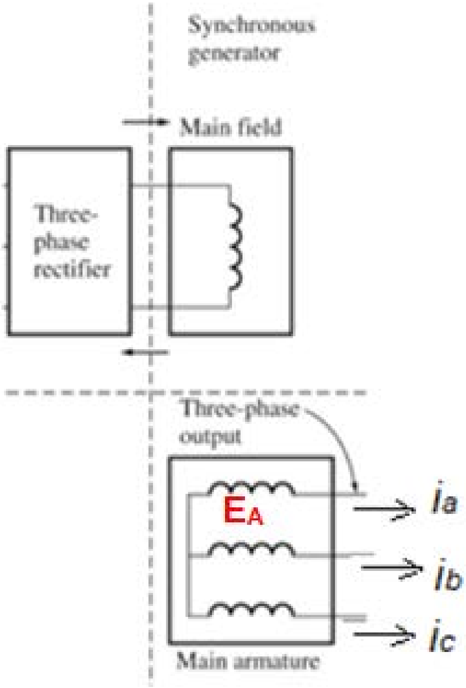


(a) Plot of flux versus field current for a synchronous generator. (b) The magnetization curve for the synchronous generator.

$$E_A = \sqrt{2}\pi N_C \phi f = \frac{N_C \phi}{\sqrt{2}} \omega = {\color{red} K\phi\omega}$$

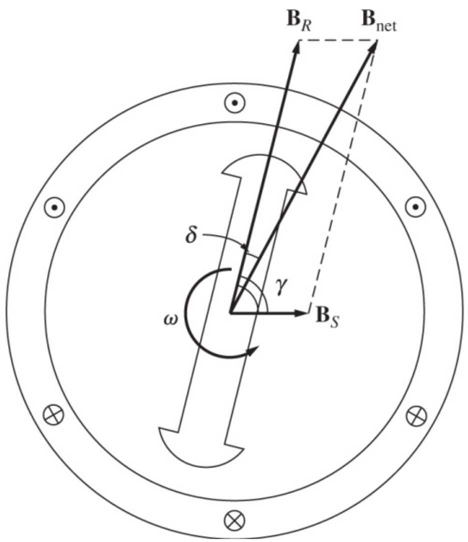
The Equivalent Circuit of a Synchronous Generator

- When generator is not loaded, the internal generated voltage E_A is the same as the voltage appearing at the terminals of the generator, V_ϕ.



- When generator is loaded, a balanced 3-phase current will flow which results in the stator rotating magnetic field B_S. The net air gap flux density is the sum of the rotor and stator magnetic fields:

$$\boldsymbol{B}_{net} = \boldsymbol{B}_R + \boldsymbol{B}_S$$



Note: Torque angle δ is the angle between B_R and B_{net}

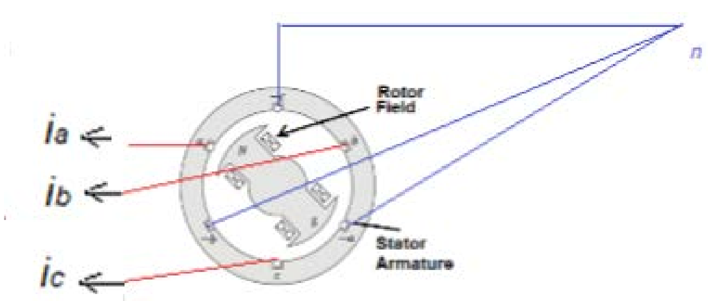
- The voltage induced in the armature would be the sum of the voltages induced by rotor field (E_A) and the voltage induced by the stator field (E_{AR}, or armature-reaction voltage due to the load current).

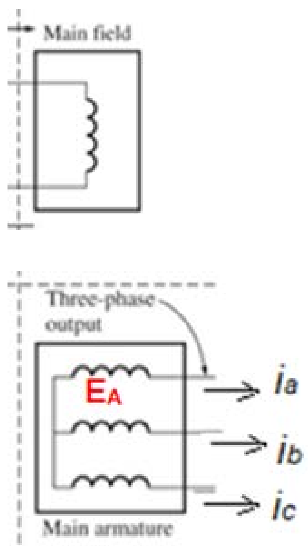
$$E_{net} = E_A + E_{AR}$$

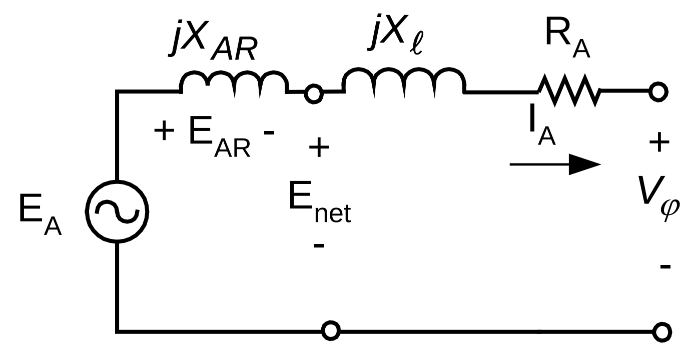
Two other voltage drops must be considered:

  - o Stator leakage inductance or reactance, X_ℓ, of the armature coils.
  - o Resistance of the armature coils, R_A.

- The armature-reaction voltage may be represented by an inductive voltage drop across an armature–reaction reactance X_{AR}, as shown here.

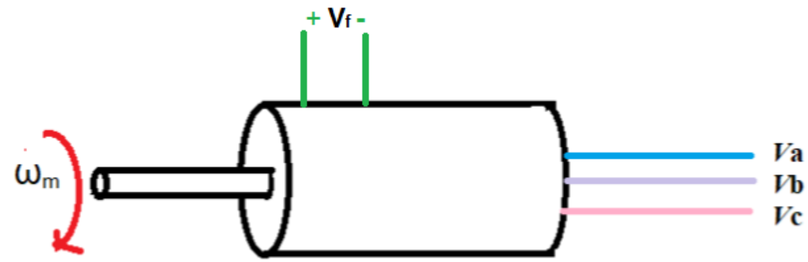


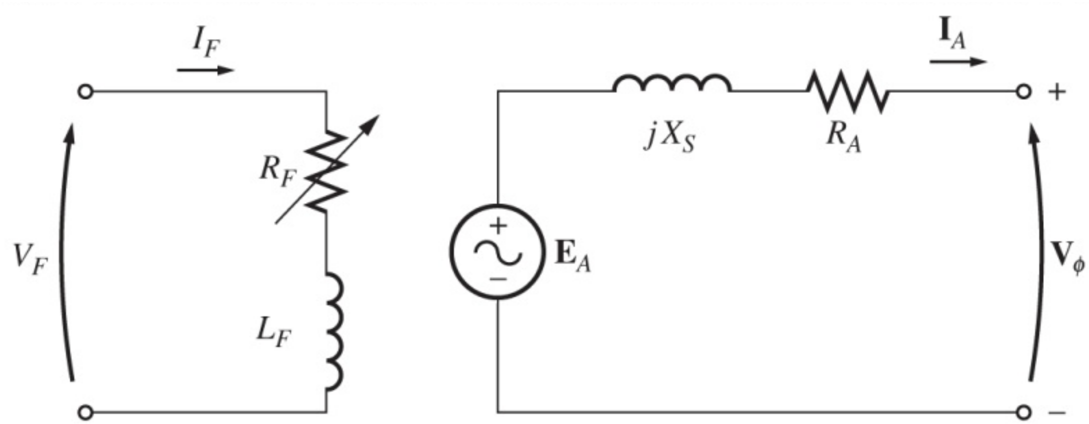




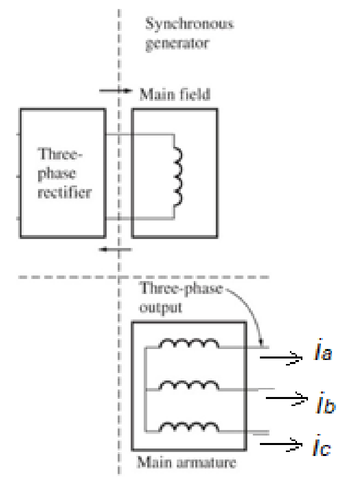
- The two reactances may be combined into a single reactance called the synchronous reactance of the machine:

$$X_S = X_{AR} + X_\ell$$



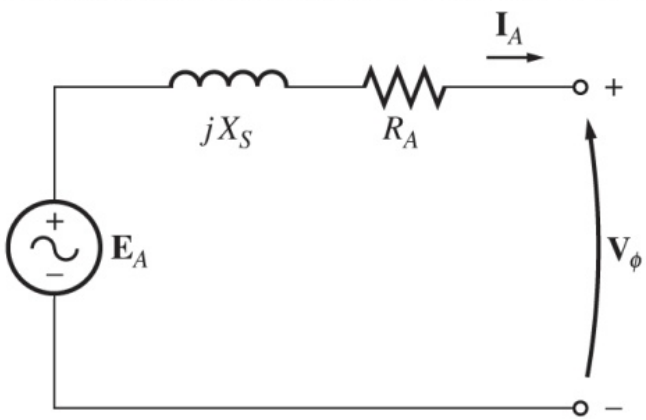


The per phase equivalent circuit of a synchronous generator.

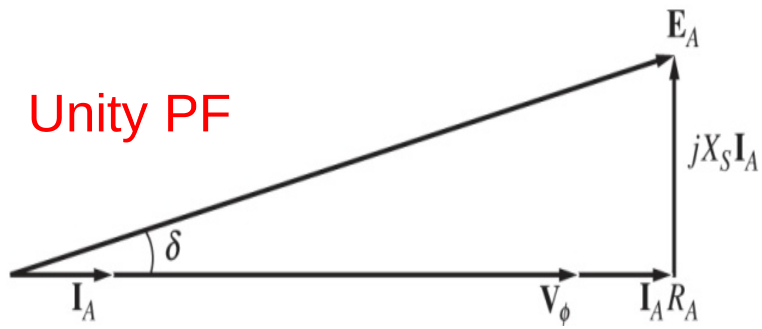


The Phasor Diagram of a Synchronous Generator

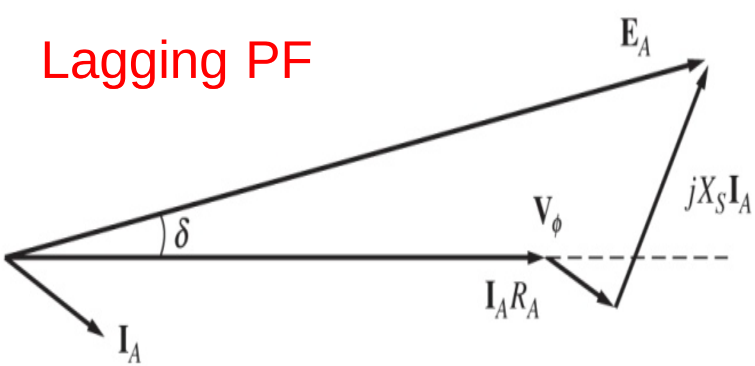
- The Kirchhoff's voltage law equation for the armature circuit is $\boldsymbol{E}_A = \boldsymbol{V}_\varphi + \boldsymbol{I}_A(R_A + jX_S)$
- The phasor diagrams for unity, lagging, and leading power factors load are shown here:



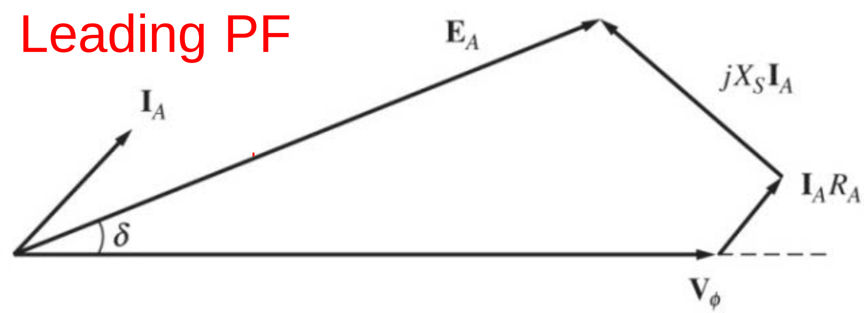
Unity PF



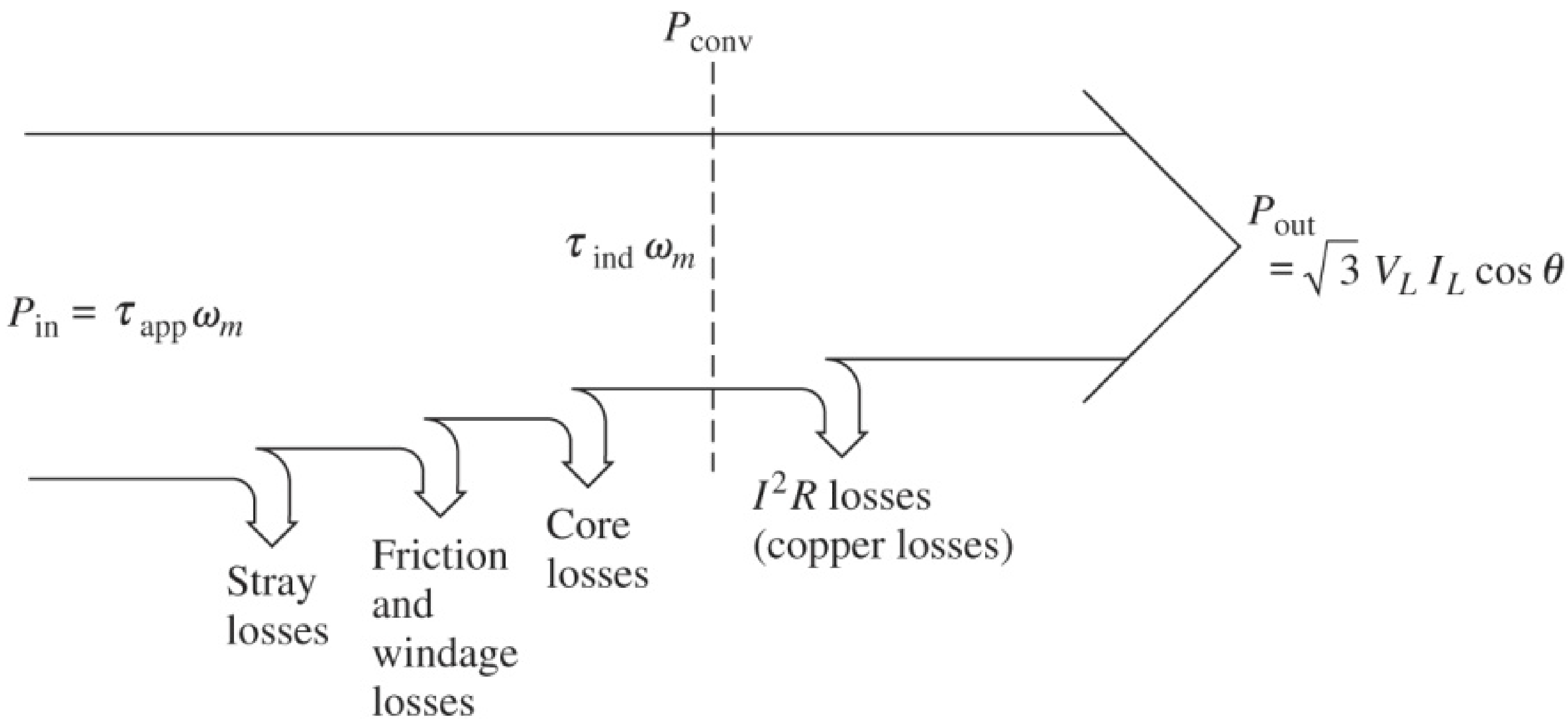
Lagging PF



Leading PF



Power and Torque in Synchronous Generators



The power-flow diagram of a synchronous generator

- The input mechanical power is given by

$$P_{in} = \tau_{app}\omega_m$$

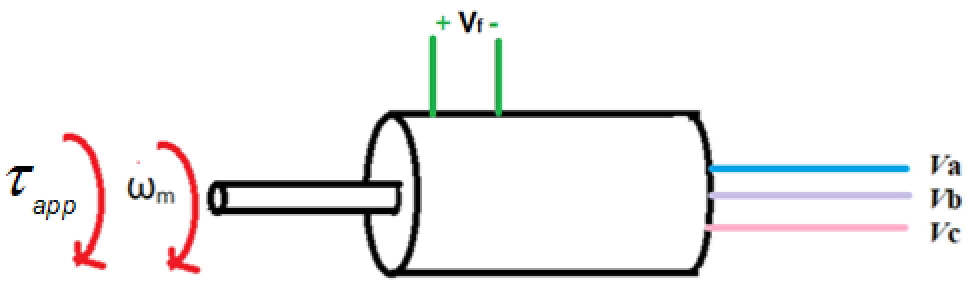
- The power converted from mechanical to electrical power is given by

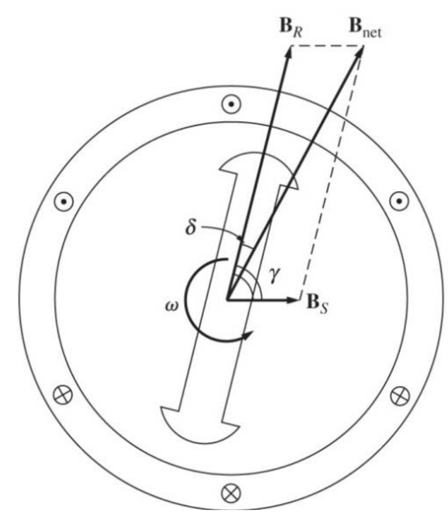
$$P_{conv} = \tau_{ind}\omega_m = 3E_A I_A Cos(\gamma)$$

- The real and reactive electrical output power is given by

$$P_{OUT} = 3V_\phi I_A Cos(\theta)$$

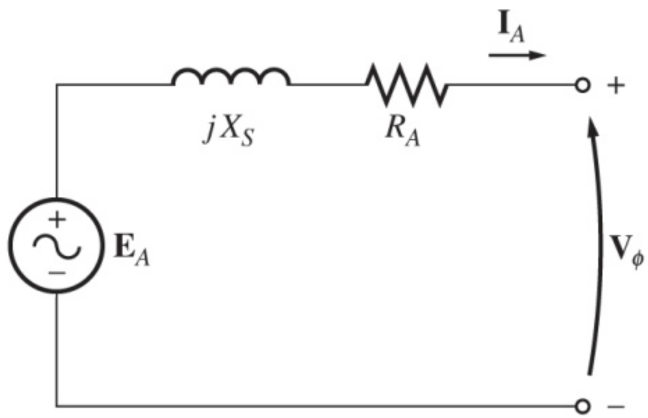
$$Q_{OUT} = 3V_\phi I_A Sin(\theta)$$

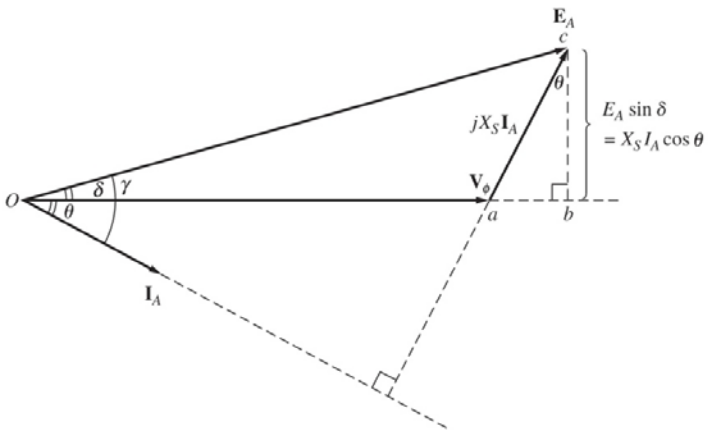




Maximum Power Delivered by a Synchronous Machine

- If the armature resistance is ignored (Since $R_A << X_S$),





$$I_A Cos(\theta) = \frac{E_A Sin(\delta)}{X_S}$$

Simplified phasor diagram with armature resistance ignored

$$P_{CONV} = P_{OUT} = \frac{3V\phi E_A Sin(\delta)}{X_S}$$

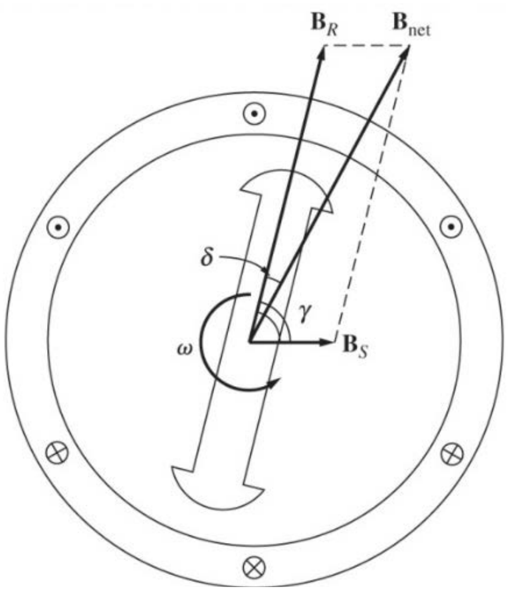
- Induced torque of the generator is given by

$$\tau_{ind} = \frac{3V\phi E_A Sin(\delta)}{\omega_m X_s}$$

<u>Also Note:</u>

Torque angle δ is the angle between B_R and B_{net}

$$\delta = \widehat{V_\varphi, E_A} \; ; \; \widehat{B_{net}, B_R}$$



Measuring Synchronous Generator Parameters

- Open-circuit and short-circuit tests to obtain magnetization characteristics and synchronous reactance of the generator.

  - Open-circuit test: With **loads disconnected**, generator is **driven at rated speed**. The **terminal voltage is measured as field current varied**.

  - Short-circuit test: **Armature terminals shorted**, generator is **driven at rated speed** and the **armature current is measured as field current varied**.

- DC voltage test to obtain the armature resistance.

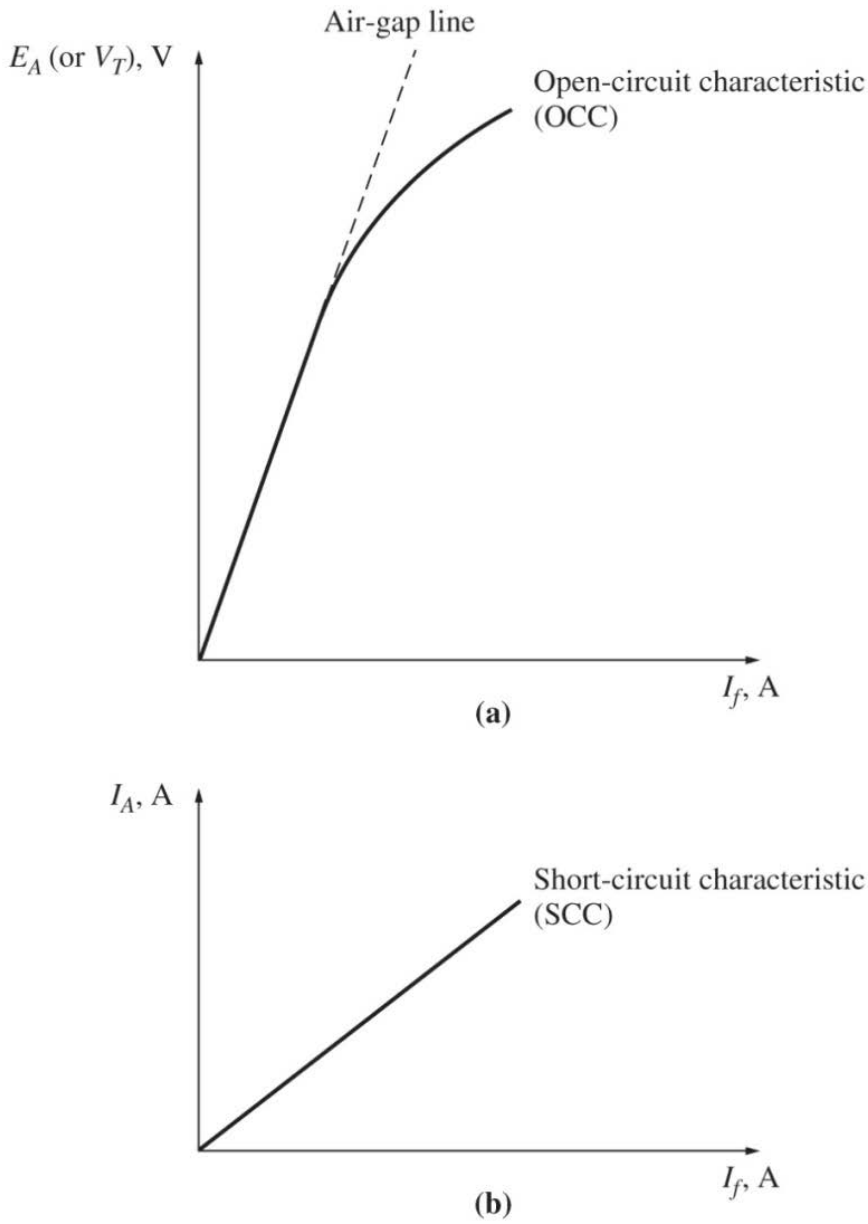
IEEE Std. 115-1995 (R2002)
IEEE Guide: Test Procedures for Synchronous Machines

Part I: Acceptance and Performance Testing

Part II: Test Procedures and Parameter Determination for Dynamic Analysis

Sponsor

- Electric Machinery Committee of the IEEE Power Engineering Society
- Reaffirmed 11 September 2002
- Approved 12 December1995, IEEE Standards Board
- Approved 16 July 1996, American National Standards Institute

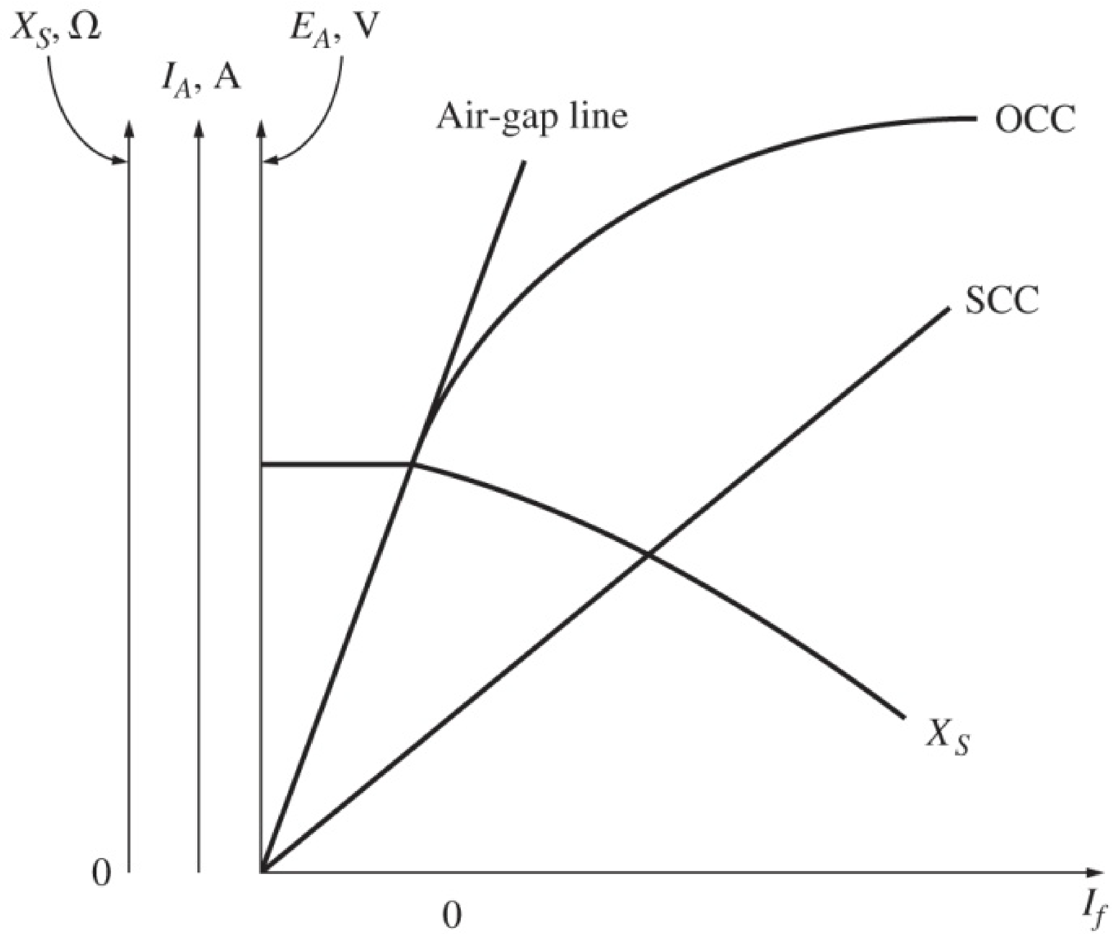


(a) The open-circuit characteristics (OCC) of a synchronous generator. (b) The short-circuit characteristics (SCC) of a synchronous generator.

Steps to obtain **unsaturated synchronous reactance X_{su}** at a given field current:

1. Get E_A from air-gap line on OCC for a selected I_f
2. Get the **armature current** at the same I_f from SCC

$$X_{Su} = \frac{E_A \big|_{OCC,Agline}}{I_A \big|_{SCC}}$$

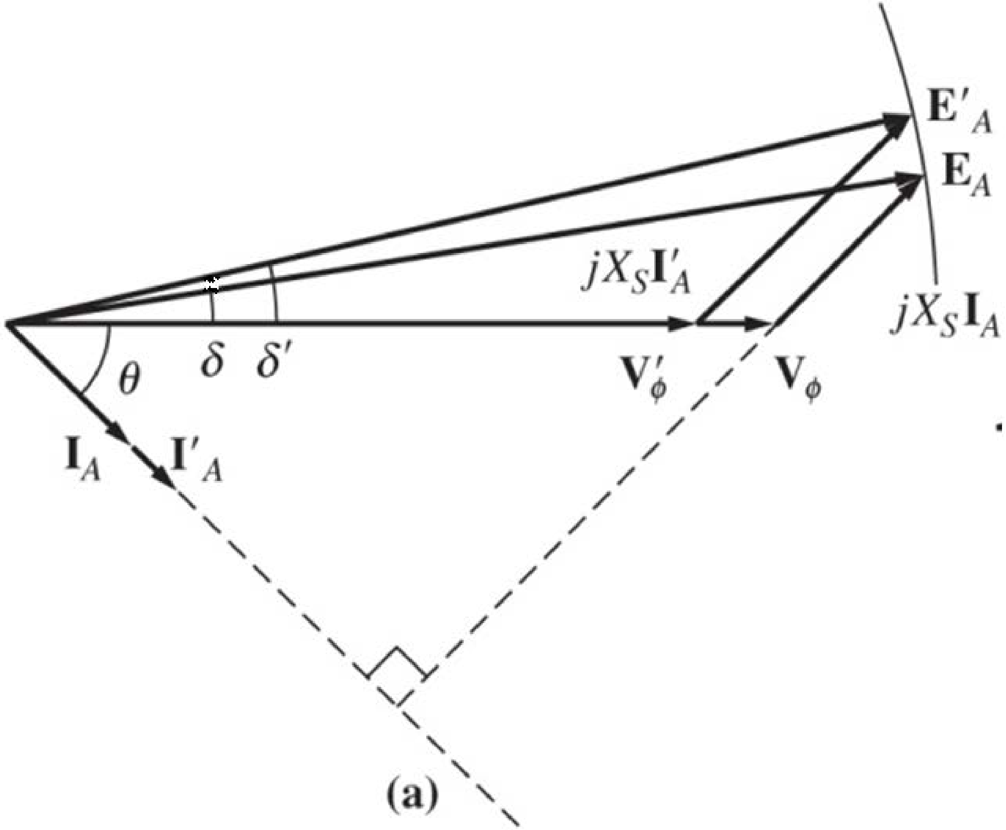


A sketch of the approximate synchronous reactance of a synchronous generator as a function of the field current.

Stand-Alone Operation

The Effect of Load Changes on a Synchronous Generator Operating Alone

- At **constant** ***field current & rotor speed***

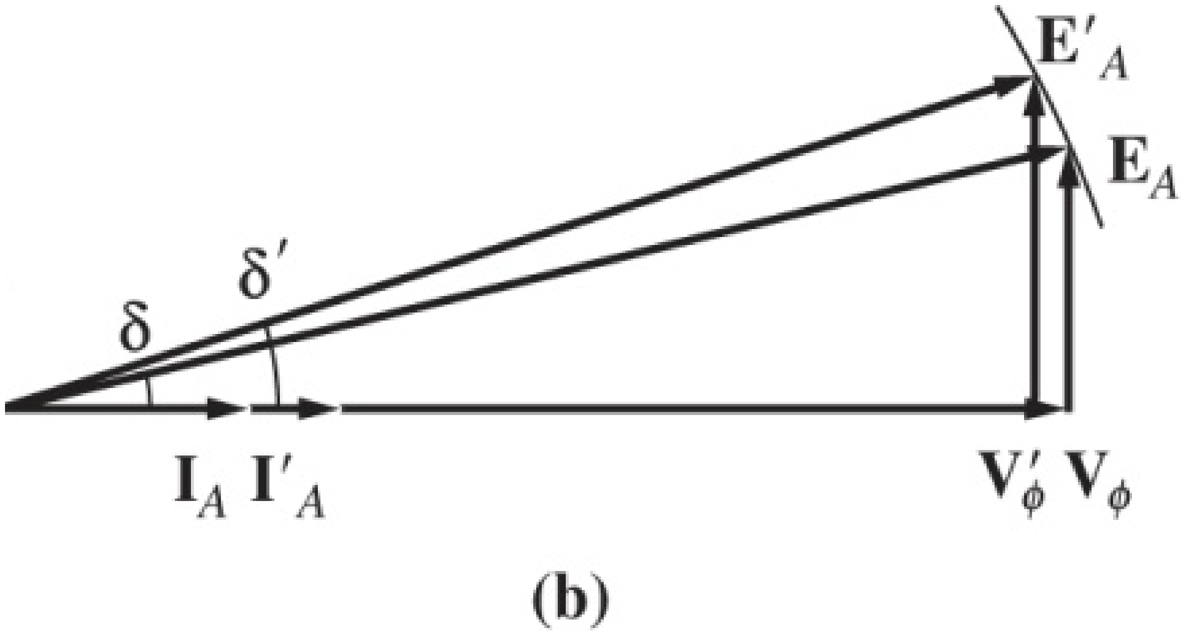


$$E_A = K\phi\omega$$

The effect of an increase in generator load upon its terminal voltage. At a fixed power factor (a) **Lagging**

The Effect of Load Changes on a Synchronous Generator Operating Alone

- At constant field current & rotor speed



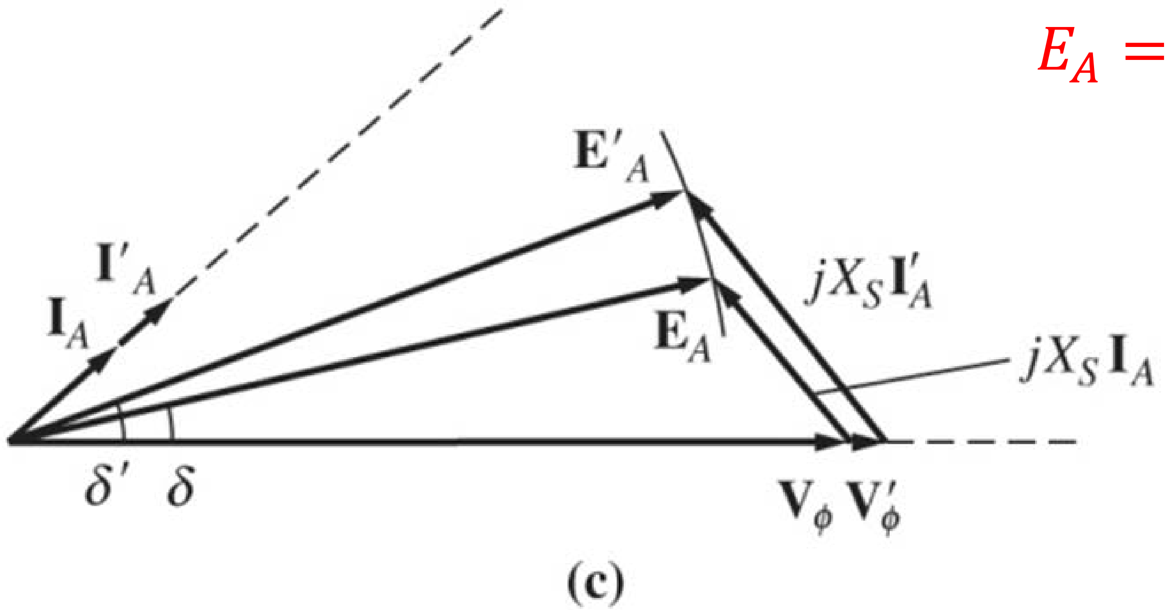
$$E_A = K\phi\omega$$

The effect of an increase in generator load upon its terminal voltage. At a fixed power factor (b) **unity**

The Effect of Load Changes on a Synchronous Generator Operating Alone

- At constant field current & rotor speed

$$E_A = K\phi\omega$$



The effect of an increase in generator load upon its terminal voltage. At a fixed power factor (c) **leading.**

Voltage Regulation of Generator Operating Alone

Voltage Regulation, VR, compares the output voltage of the generator at no load with the output voltage at full load while the input field current is kept constant:

$$VR=[(V_{nl}-V_{fl})/V_{fl}]\times 100\%$$

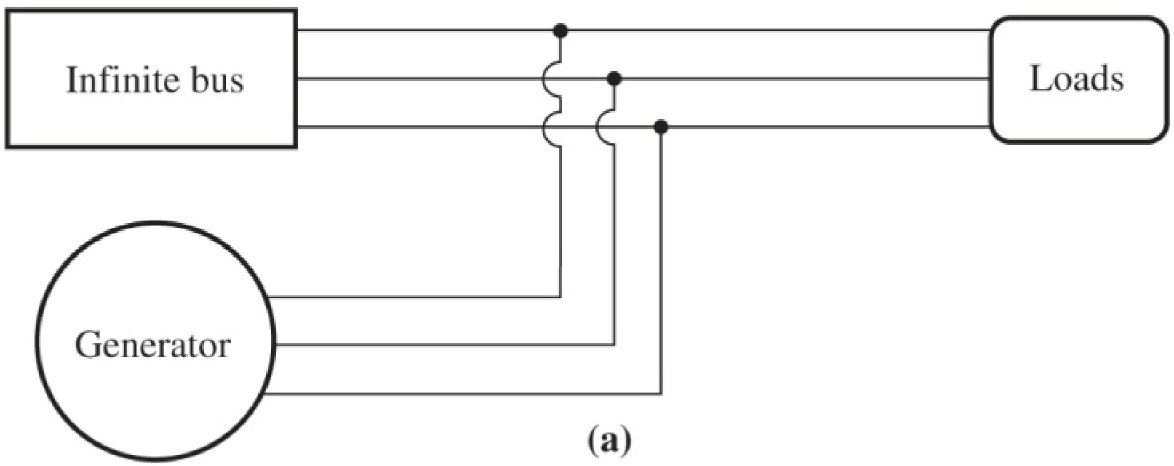
Typically, a synchronous generator operating at:

- lagging power factor has a large positive voltage regulation,
- unity power factor has a small positive voltage regulation, and
- leading power factor often has a negative voltage regulation.

How to control terminal voltage:

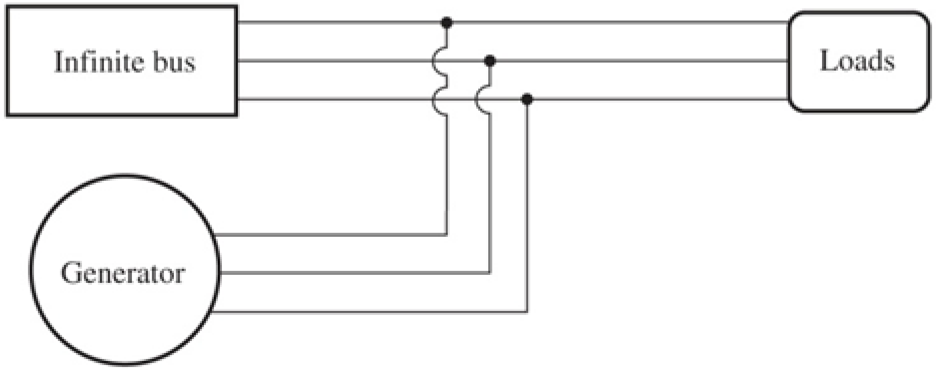
1. Decreasing the field resistance in the generator increases its field current.
2. An increase in the field current increases the flux in the machine.
3. An increase in the flux increases the internal generated voltage $E_A = K\phi\omega$
4. An increase in E_A increases V_ϕ and the terminal voltage of the generator.

Infinite Bus Operation



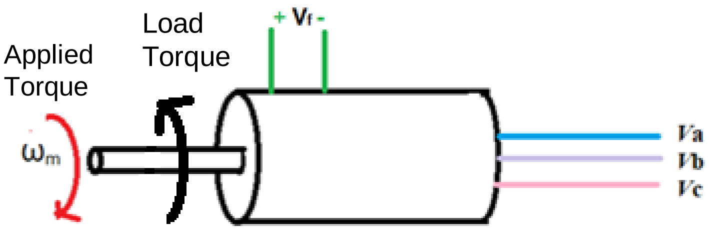
(a)

Operation of Synchronous Generators in Parallel with Large Power Systems



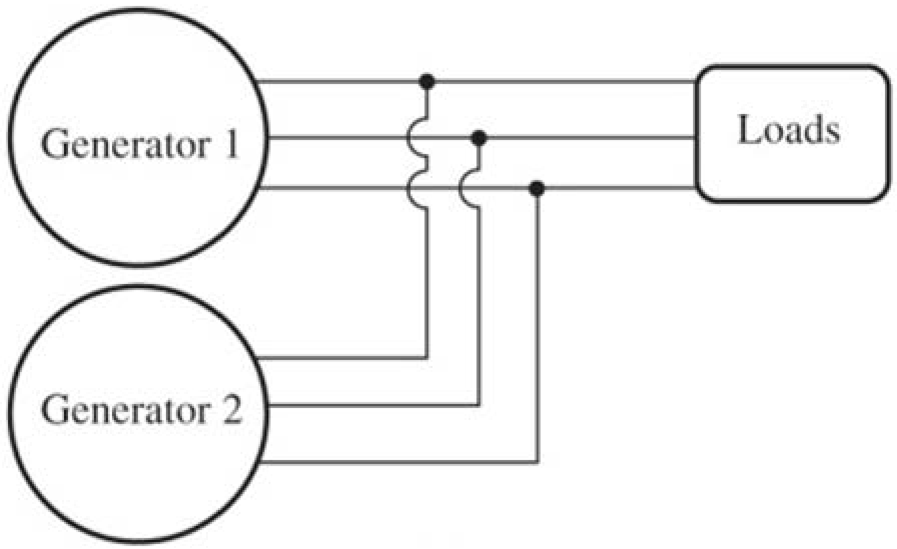
A synchronous generator operating in parallel with an infinite bus

- Generator and infinite bus have **same frequency and terminal voltage** since their output conductors are tied together.



$$P = \tau \omega_m$$

Parallel Operation of Two Generators



Two generators operating together:

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.

Note: *the **governor** or speed controller, is a device used to measure and regulate the speed of a machine.*

Learning Outcomes

At the completion of this module, the student should be able to:

1) Draw and explain the equivalent circuit of a synchronous generator.
2) Sketch phasor diagrams for a synchronous generator.
3) Write and explain the equations for power and torque in a synchronous generator.
4) Extract the characteristics of a synchronous machine from laboratory measurements (OCC and SCC).
5) Describe the operation of a synchronous generator ***operating alone*** and calculate a load current, voltage, power, torque and efficiency values.
6) Describe the operation of synchronous generators ***in parallel*** with a very large power system (or infinite bus) and calculate current, voltage, power, torque and efficiency values.
7) Describe the conditions required to ***parallel two or more synchronous*** generators and calculate current, voltage, power, torque and efficiency values.