# Synchronous Machines



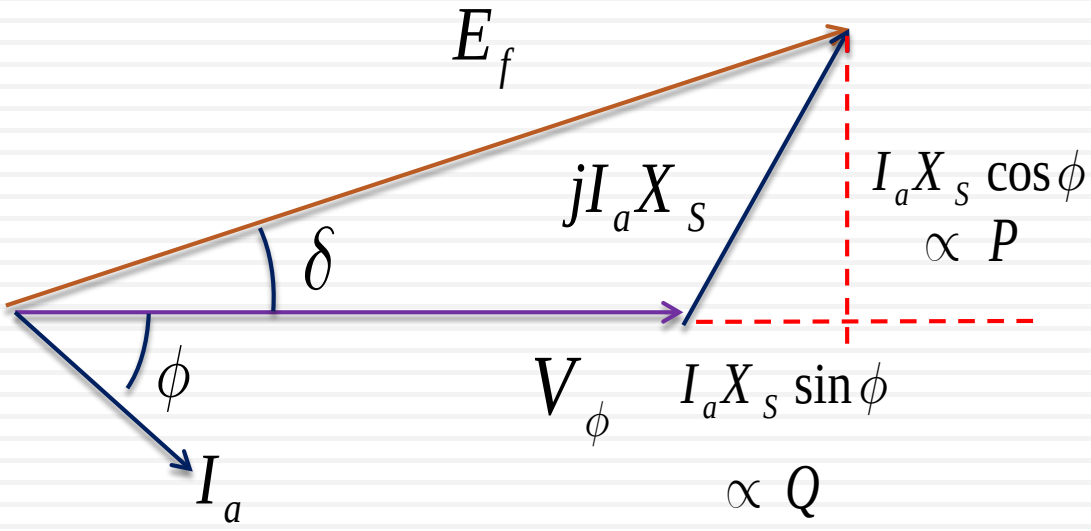
***1. Synchronous Generators***

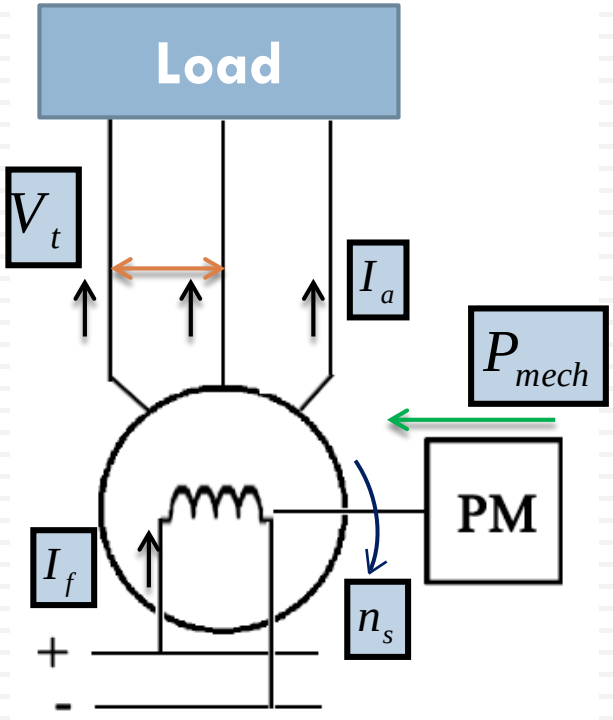
- Principle of Operation
- Phasor Diagram and Equivalent Circuit
- Power and Torque
- Synchronous Generator Characteristics & Tests
- Generator Modes of Operation
- Generator Stability
- Generator Rating
- Practical Generator

# Synchronous Generator: Modes of Operation



## 1. Stand-alone (isolated) Generators




$$V_\phi = E_f - jI_aX_S$$

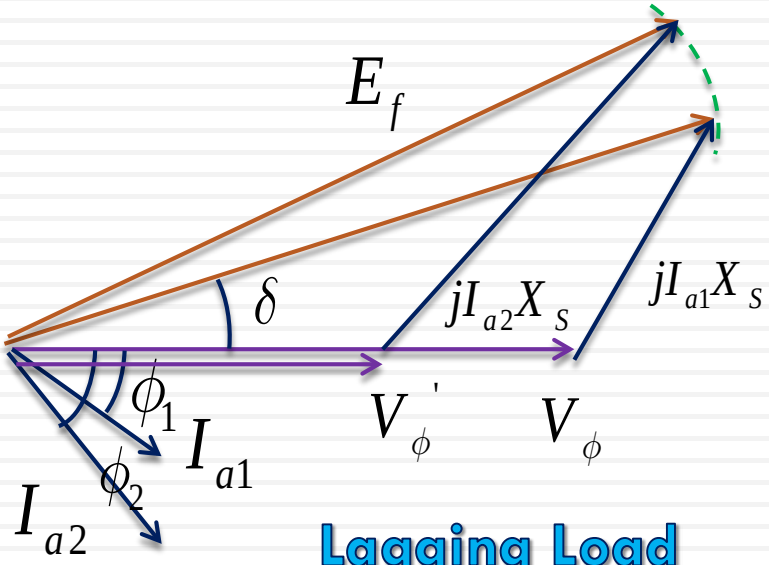
# Synchronous Generator: Modes of Operation



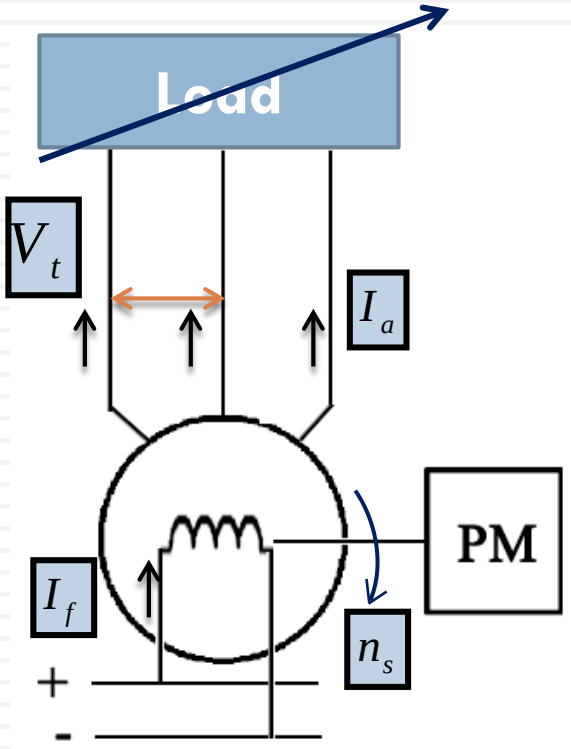
## 1. Stand-alone (isolated) Generators

For $I_f$ = const. ( $E_f$ = const.)

$$V_\phi = E_f - jI_a X_S$$




Lagging Load




As the load power (S) increases, terminal voltage decreases

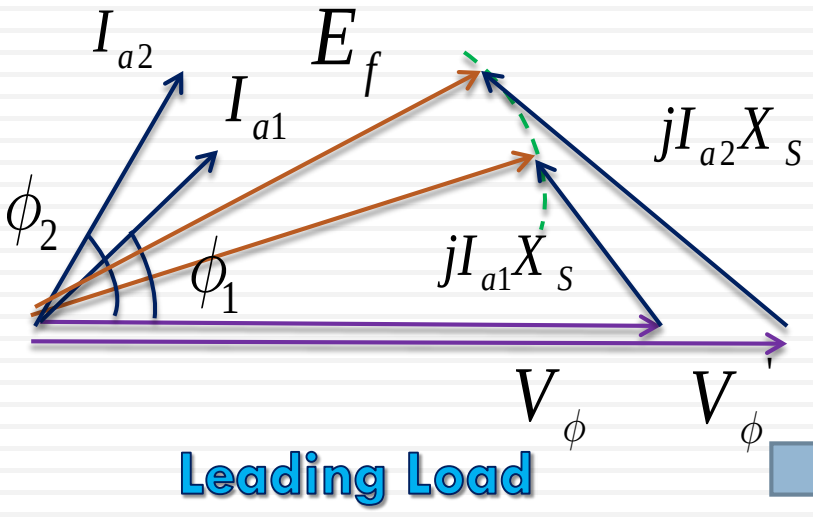
# Synchronous Generator: Modes of Operation



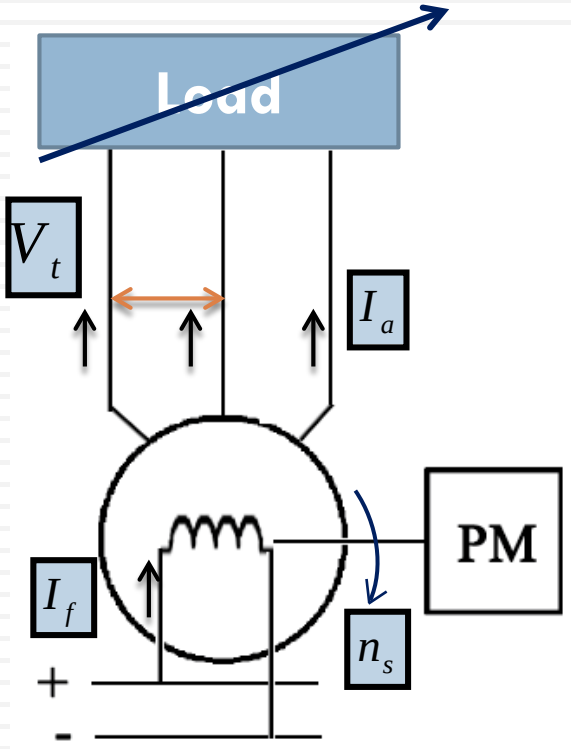
## 1. Stand-alone (isolated) Generators

For $I_f$ = const. ( $E_f$ = const.)

$$V_\phi = E_f - jI_aX_S$$




Leading Load



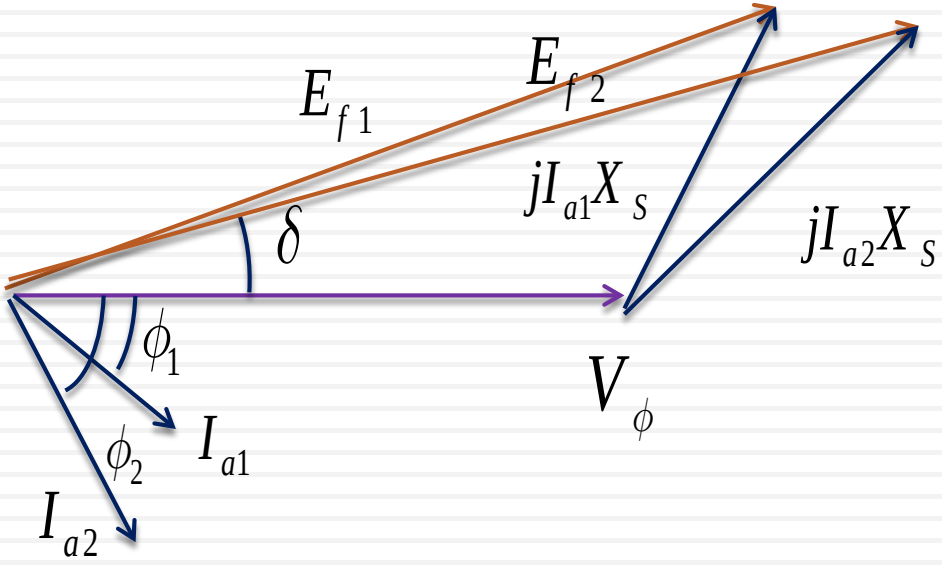

As the load power (S) increases, terminal voltage increases

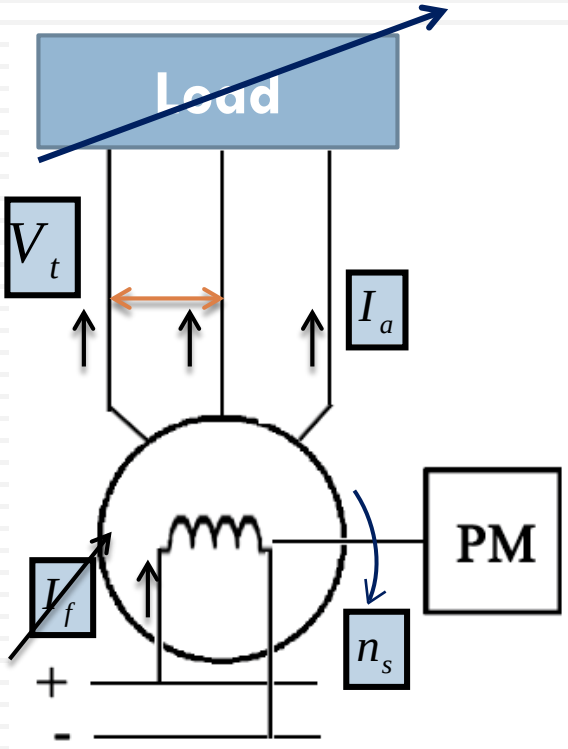
# Synchronous Generator: Modes of Operation



## 1. Stand-alone (isolated) Generators

*To keep $V_t$ constant, $I_f$ should be adjusted at each condition*



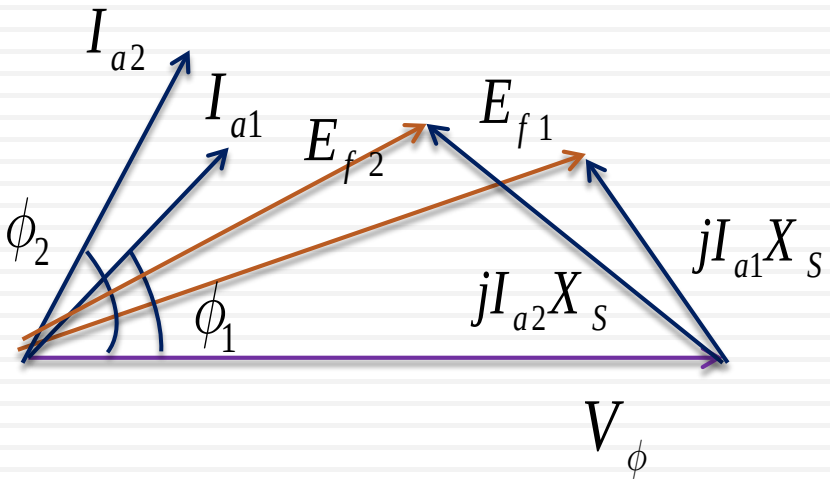

**Lagging Load** → **As the load power (S) increases, $I_f$ should increase (over-excited)**

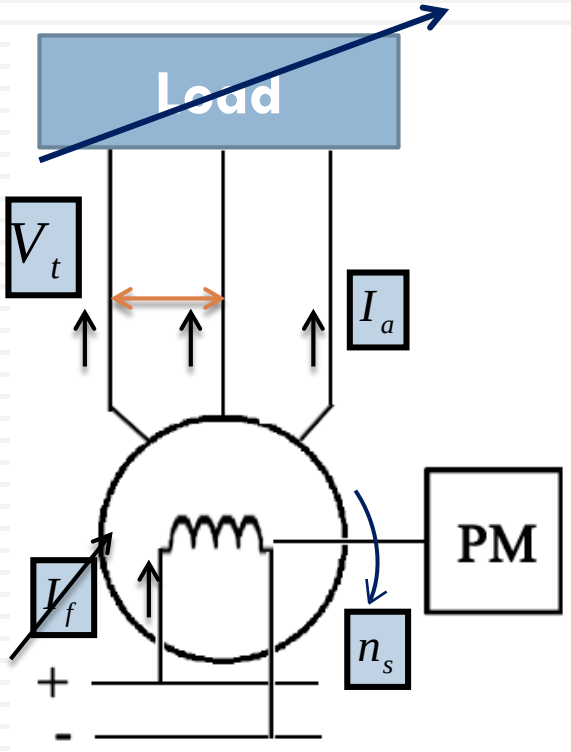
# Synchronous Generator: Modes of Operation



## 1. Stand-alone (isolated) Generators

*To keep $V_t$ constant, $I_f$ should be adjusted at each condition*




**Leading Load**

**As the load power (S) increases, $I_f$ should decrease (under-excited)**

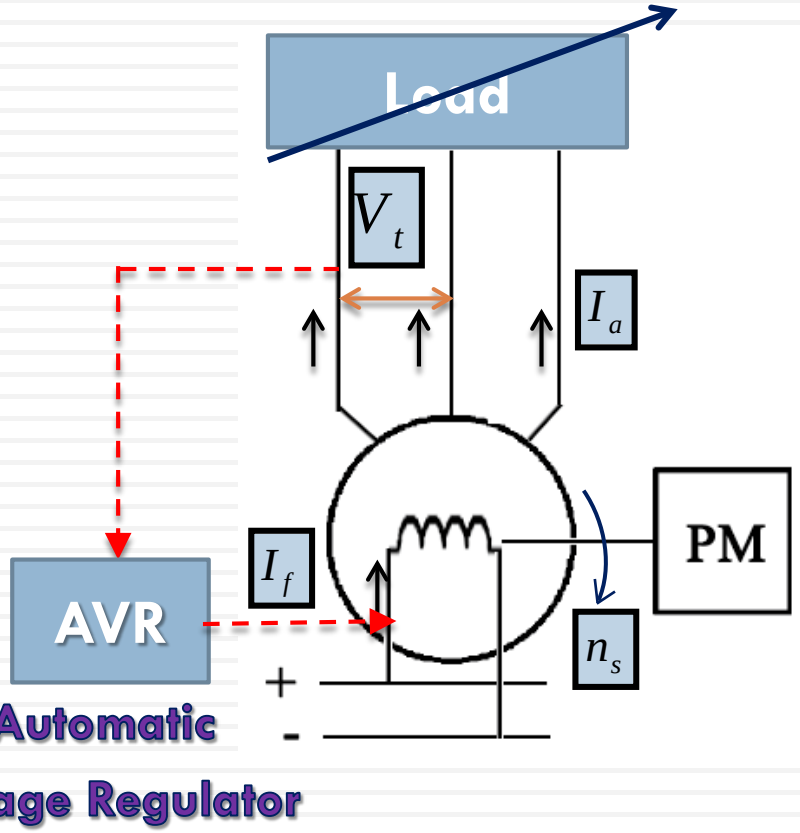
# Synchronous Generator: Modes of Operation



## 1. Stand-alone (isolated) Generators

### Voltage Regulation

$$VR = \frac{V_{nl} - V_{rated}}{V_{rated}}$$



# Synchronous Generator: Modes of Operation



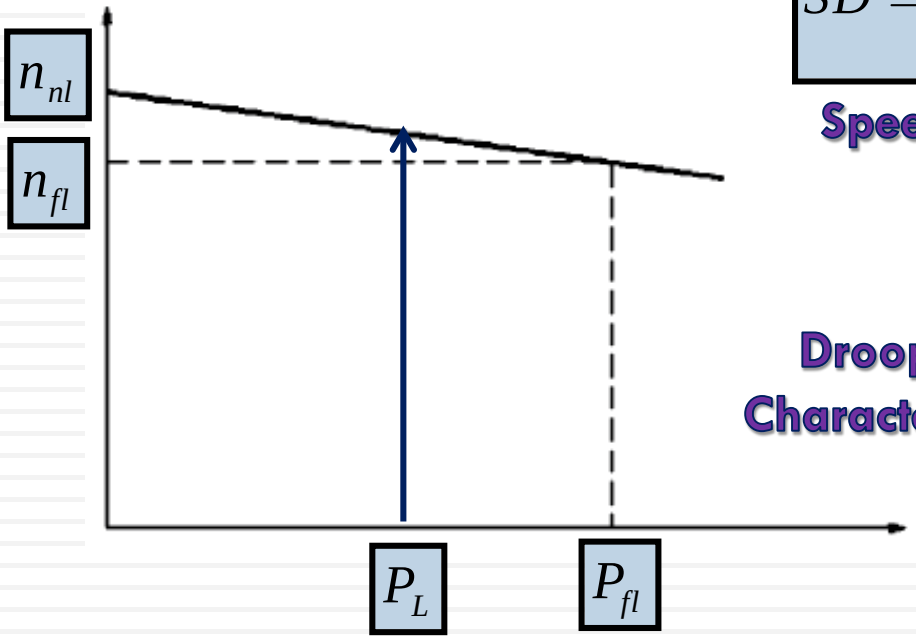
## 1. Stand-alone (isolated) Generators

### Prime-mover (Speed) Regulation

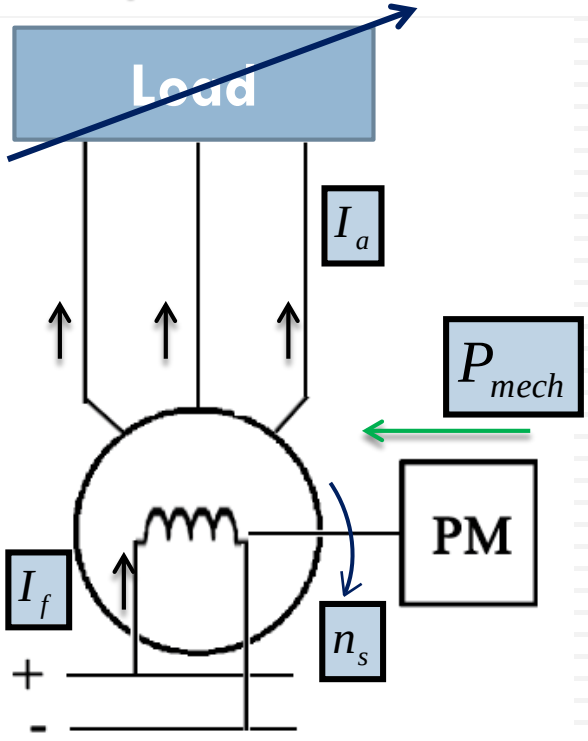
*as the power drawn from the PM increases, speed decreases.*

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}}$$

**Speed Droop**




**Drooping Characteristics**

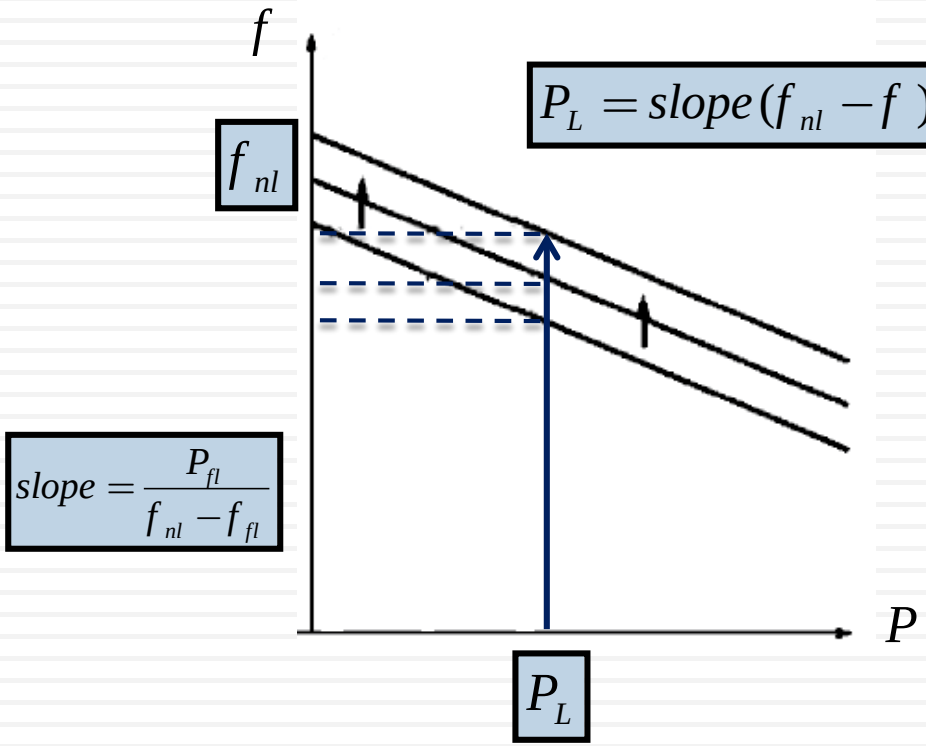


# Synchronous Generator: Modes of Operation

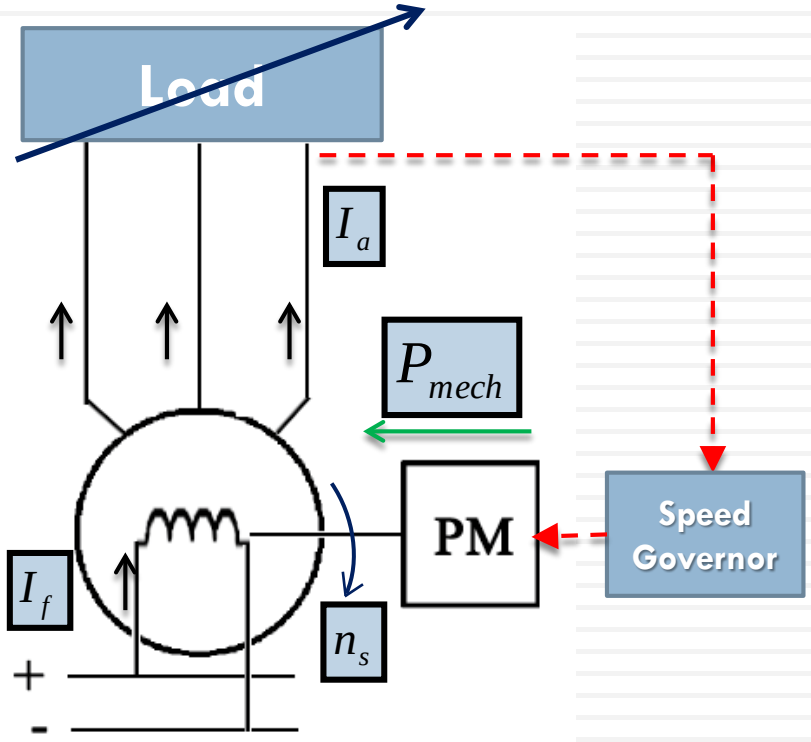


## 1. Stand-alone (isolated) Generators

### Prime-mover (Speed) Regulation



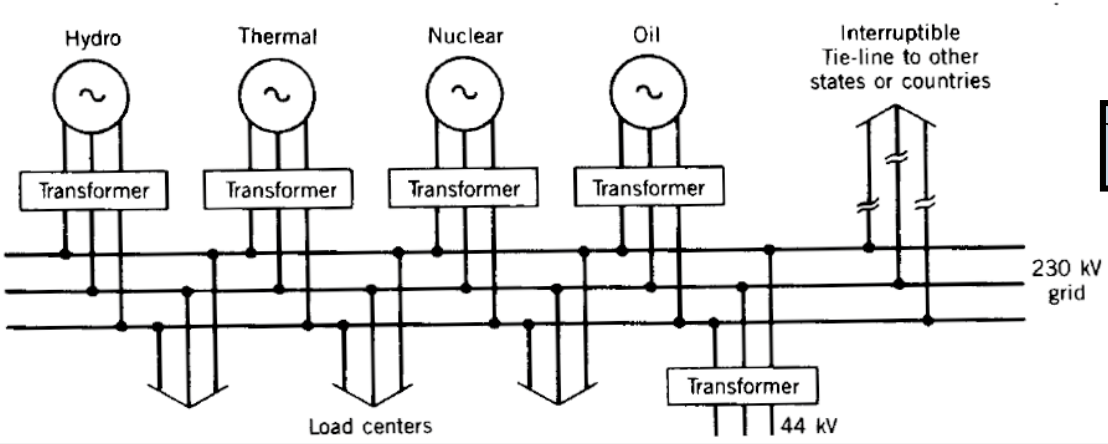

Drooping Characteristics



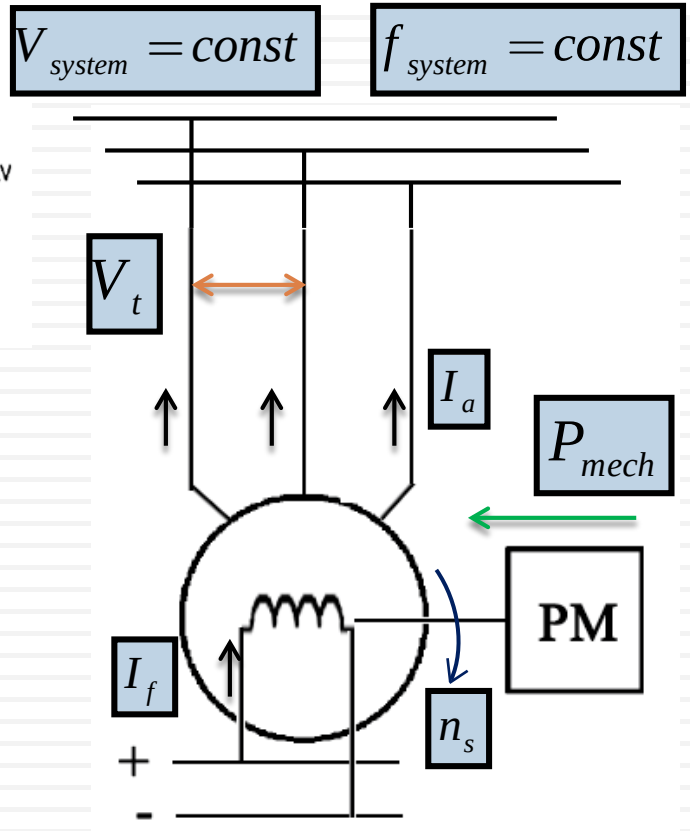
# **Synchronous Generator:** Modes of Operation



## 2. Parallel Operation with Large Power Systems




**Infinite Bus Bar - Grid**



# Synchronous Generator: Modes of Operation

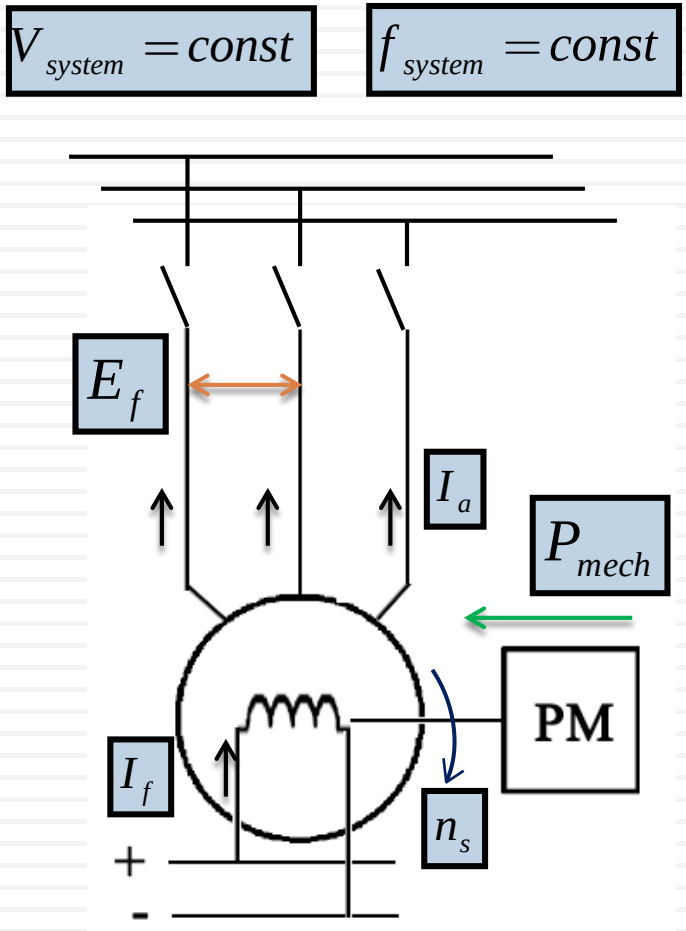


## 2. Parallel Operation with Large Power Systems

### Synchronization

*Before switching, the following must be achieved:*

1. $E_f = V_{system}$
2. $f_G = f_{system}$
3. *Same phase sequence.*
4. *Proper instance of switching (two phasor diagrams coincide)*



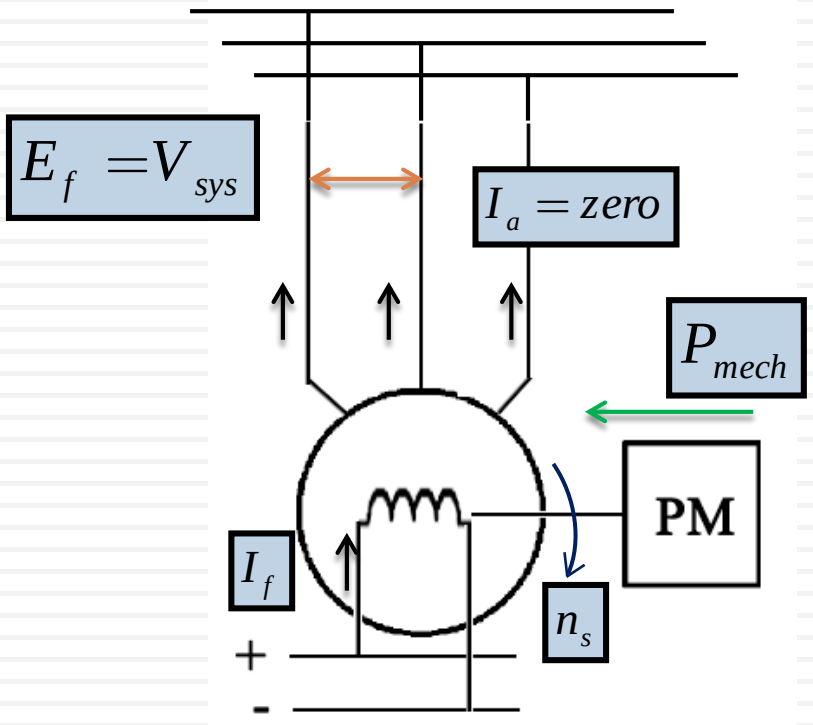
# **Synchronous Generator:** Modes of Operation



## 2. Parallel Operation with Large Power Systems

### a. Floating Condition


$$P = Q = zero$$

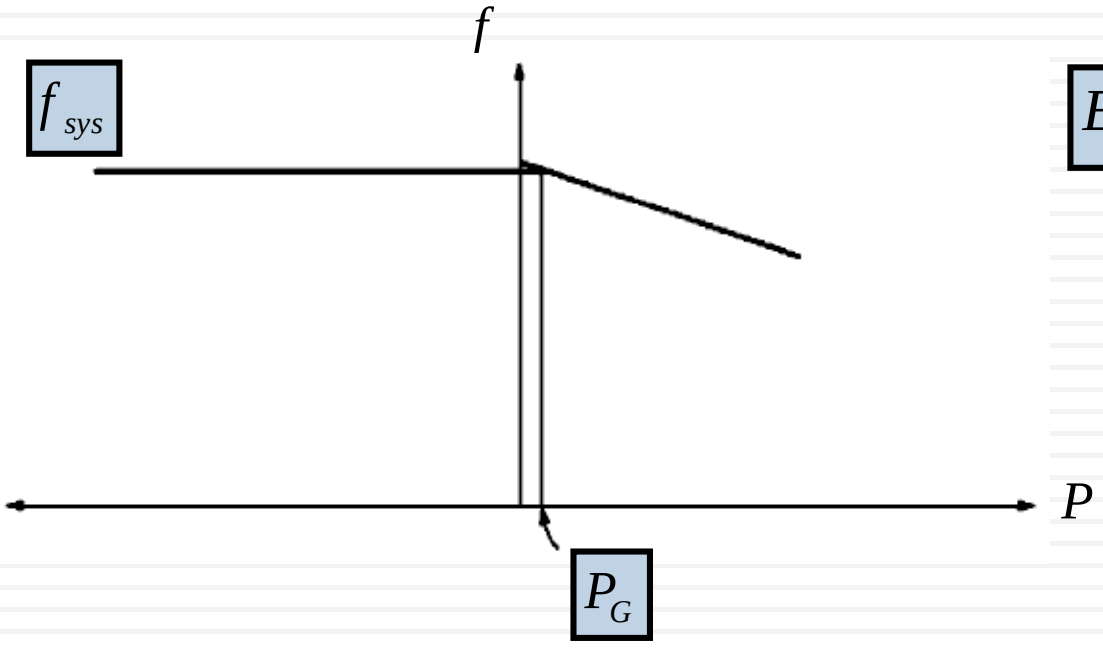


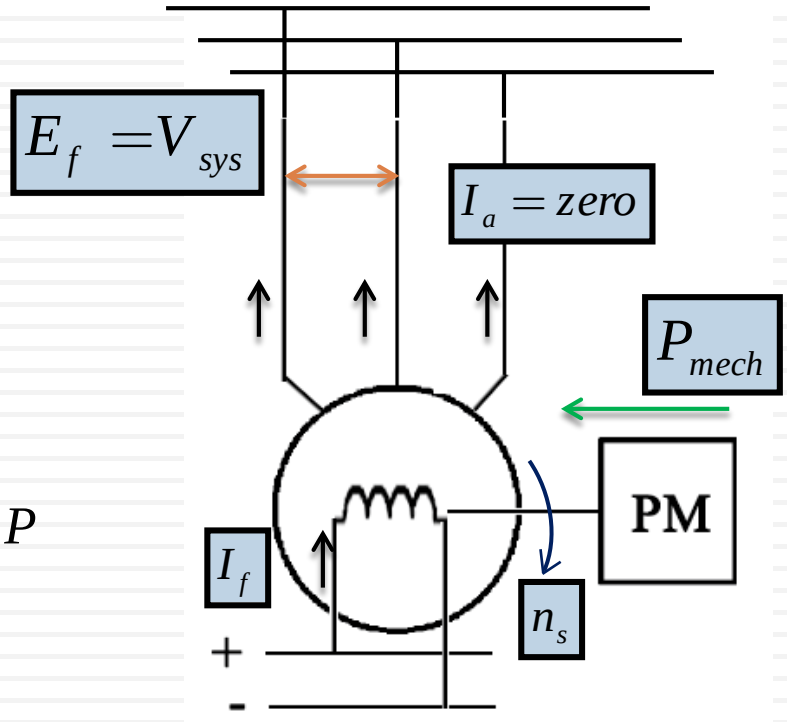
# Synchronous Generator: Modes of Operation



## 2. Parallel Operation with Large Power Systems

### a. Floating Condition



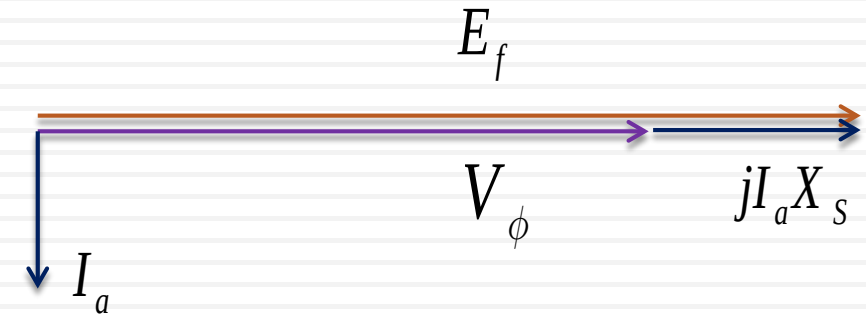
# Synchronous Generator: Modes of Operation



## 2. Parallel Operation with Large Power Systems

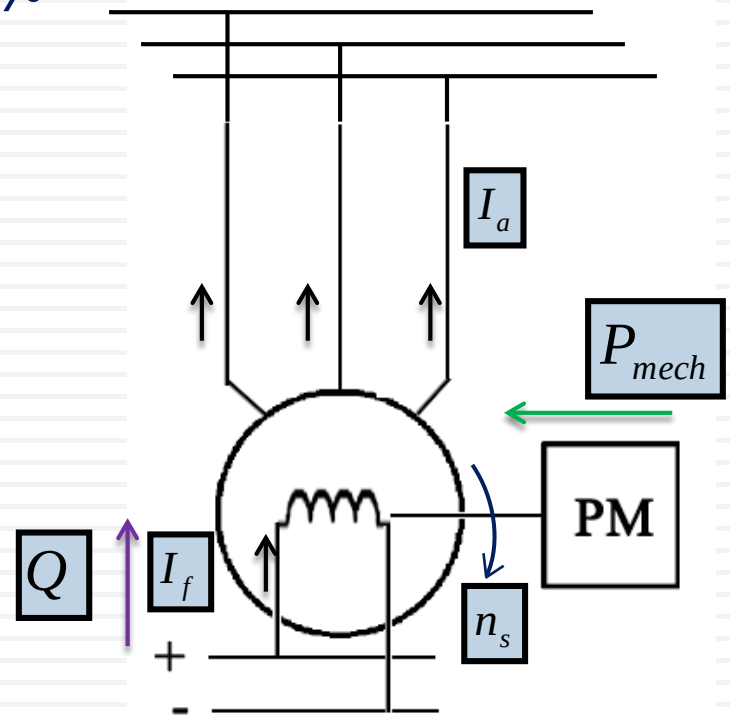
### b. Controlling Field Current ($I_f$)

*At zero prime-mover power ($f_{nl}=f_{sys}$)*




$$P = zero$$

$$Q = \sqrt{3}V_t I_a$$



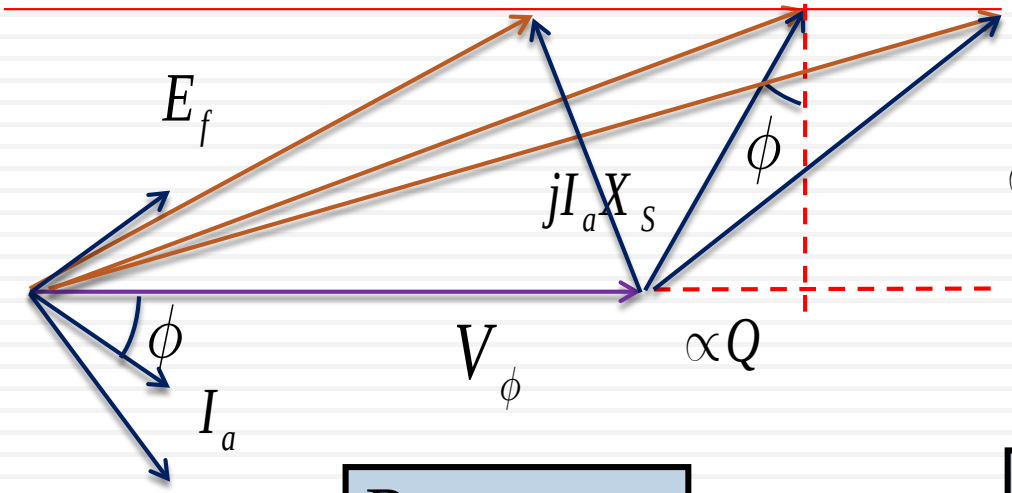

**As $I_f$ increase, Q increases**

# Synchronous Generator: Modes of Operation

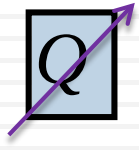


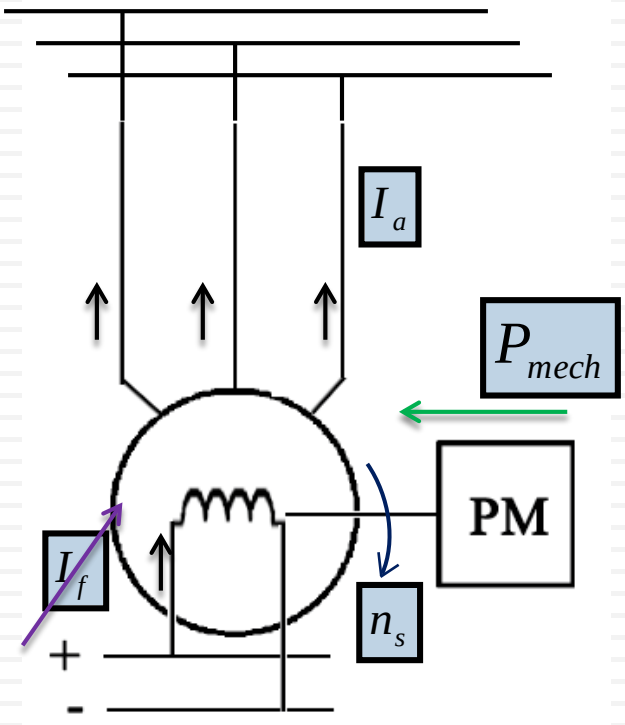
## 2. Parallel Operation with Large Power Systems

### b. Controlling Field Current ($I_f$)




$P = const.$



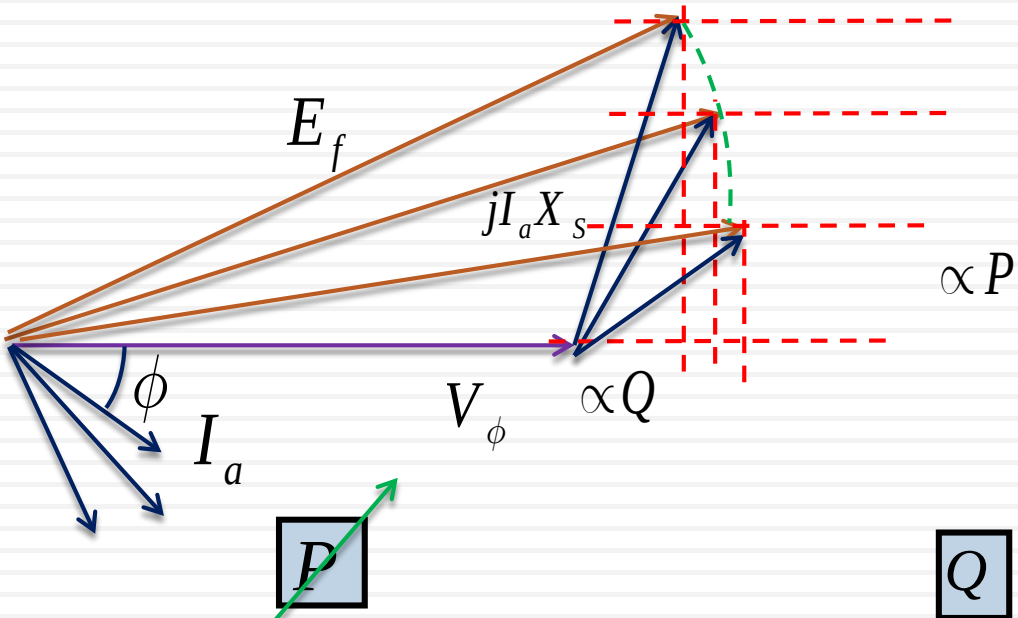

**$I_f$ controls Q**

# Synchronous Generator: Modes of Operation

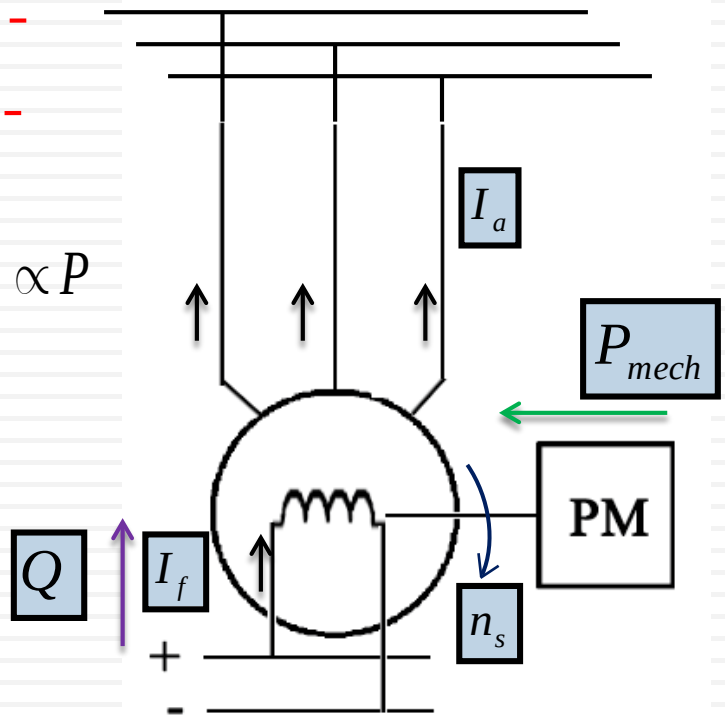


## 2. Parallel Operation with Large Power Systems

### c. Controlling the Prime-mover($P_{mech}$)




prime mover controls P and affects Q

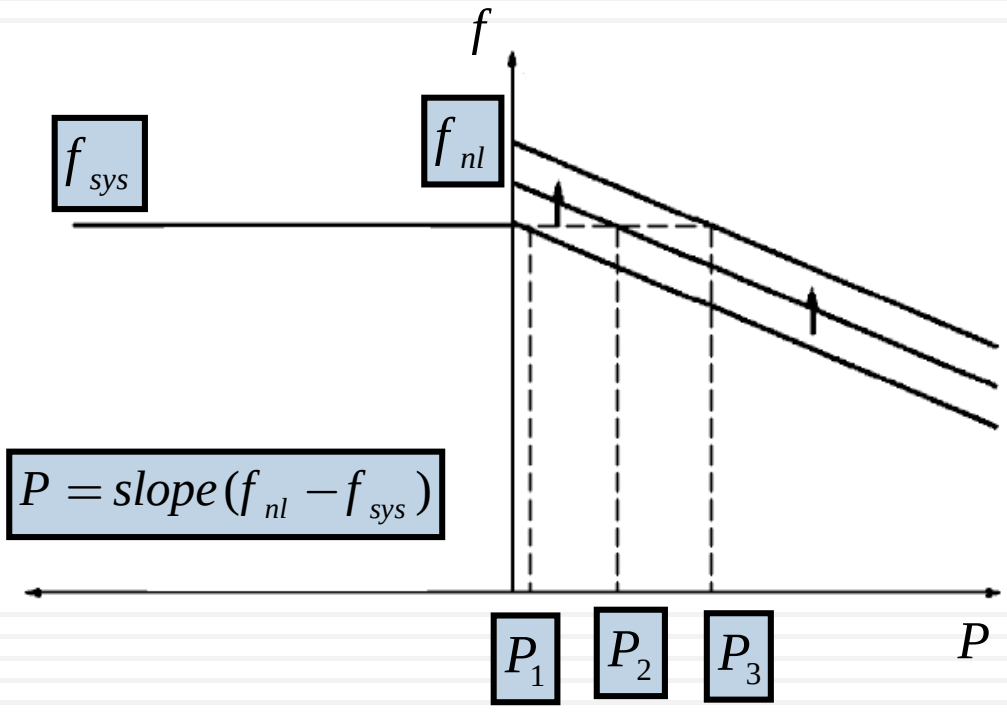


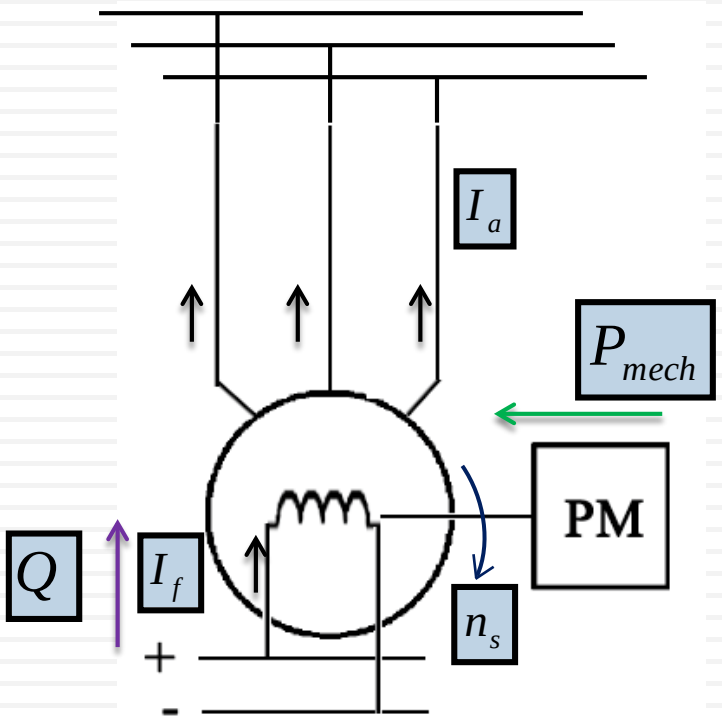
# Synchronous Generator: Modes of Operation



## 2. Parallel Operation with Large Power Systems

### c. Controlling the Prime-mover($P_{mech}$)

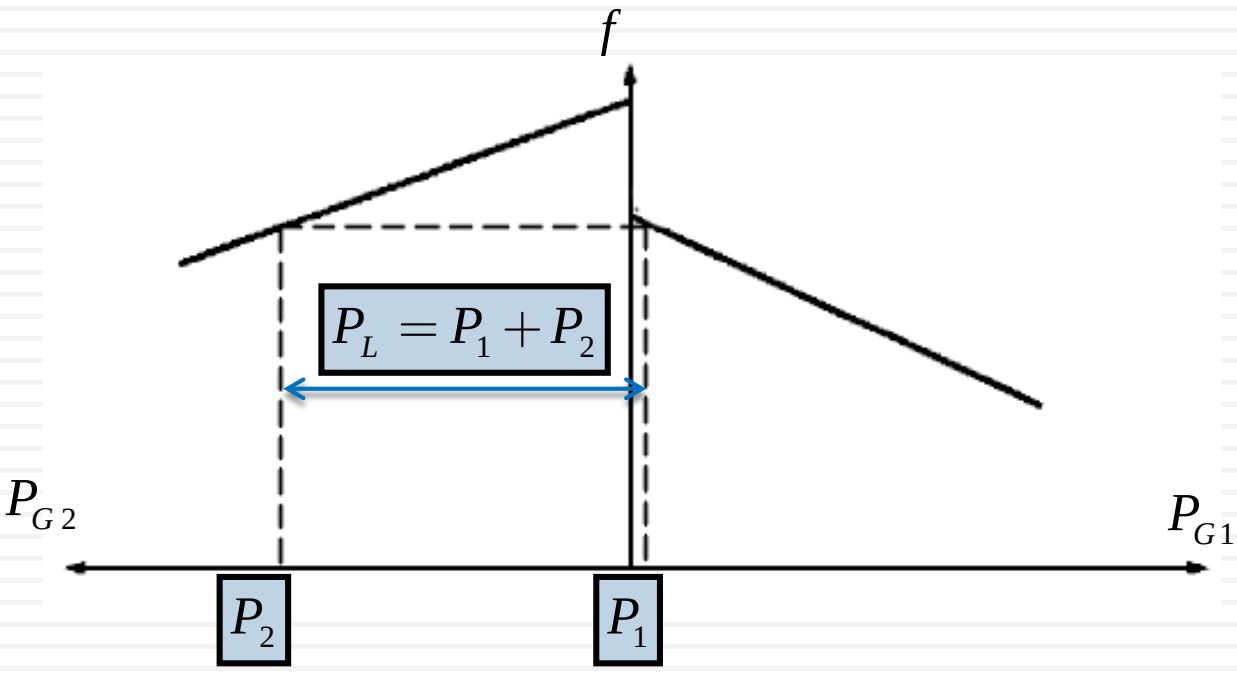


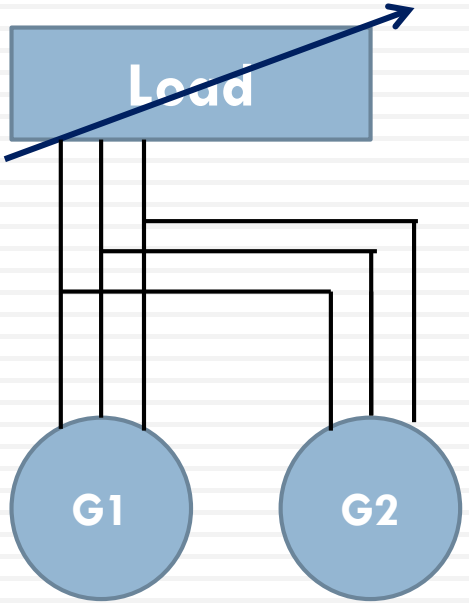



# Synchronous Generator: Modes of Operation



## 3. Parallel Operation of Two Generators



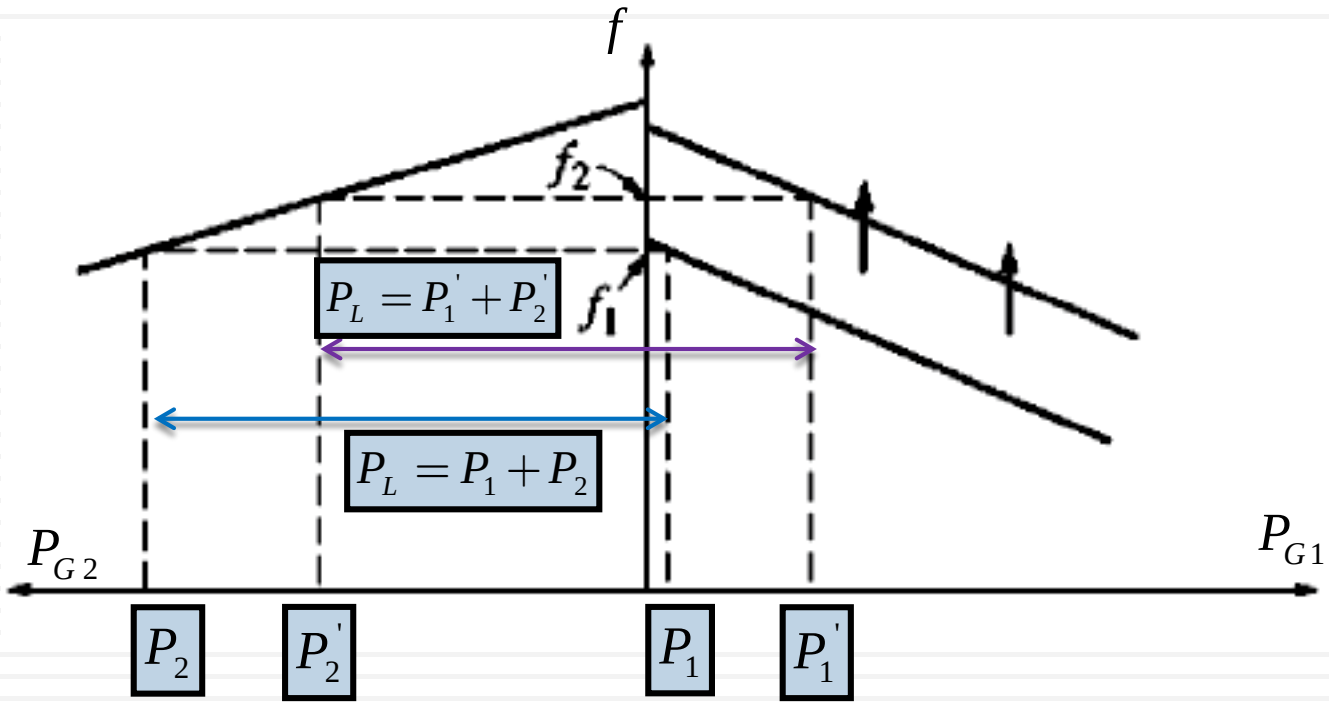

$$P_L = P_1 + P_2$$

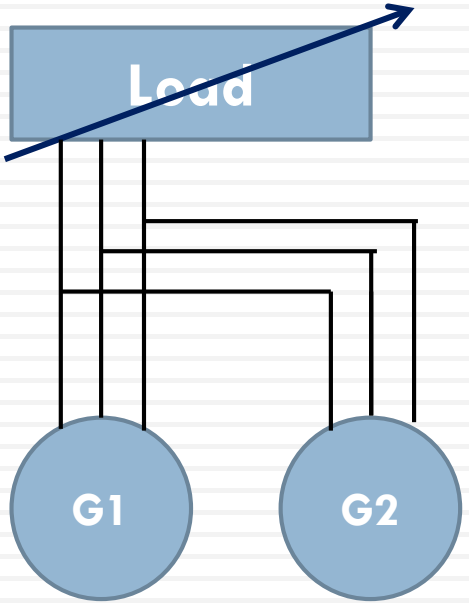
$$Q_L = Q_1 + Q_2$$

# Synchronous Generator: Modes of Operation



## 3. Parallel Operation of Two Generators




$$P_L = P_1 + P_2$$

$$Q_L = Q_1 + Q_2$$

# Synchronous Generator: Generator Stability



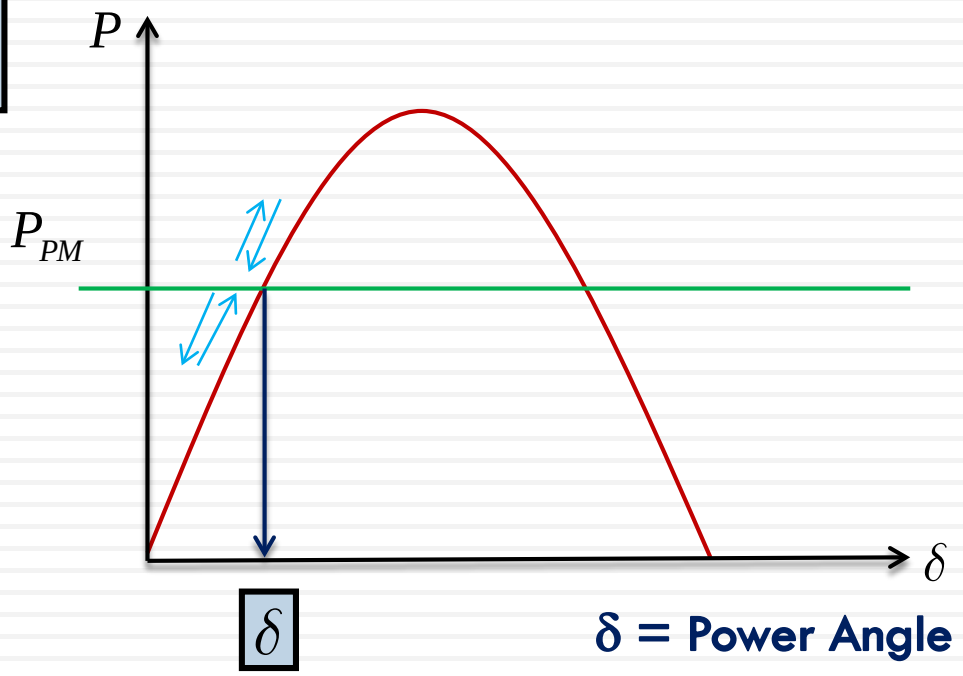
$$P = \frac{3V_\phi E_f \sin\delta}{X_S} \qquad T_d = \frac{3V_\phi E_f \sin\delta}{\omega_s X_S}$$

$$T_{PM} - T_d = J\frac{d\omega}{dt}$$

$T_{PM} > T_d$ **Acceleration**

$T_{PM} < T_d$ **Deceleration**

$T_{PM} = T_d \Rightarrow \delta = const.$



# **Synchronous Generator:** Generator Stability



## Synchronizing Power (Torque)

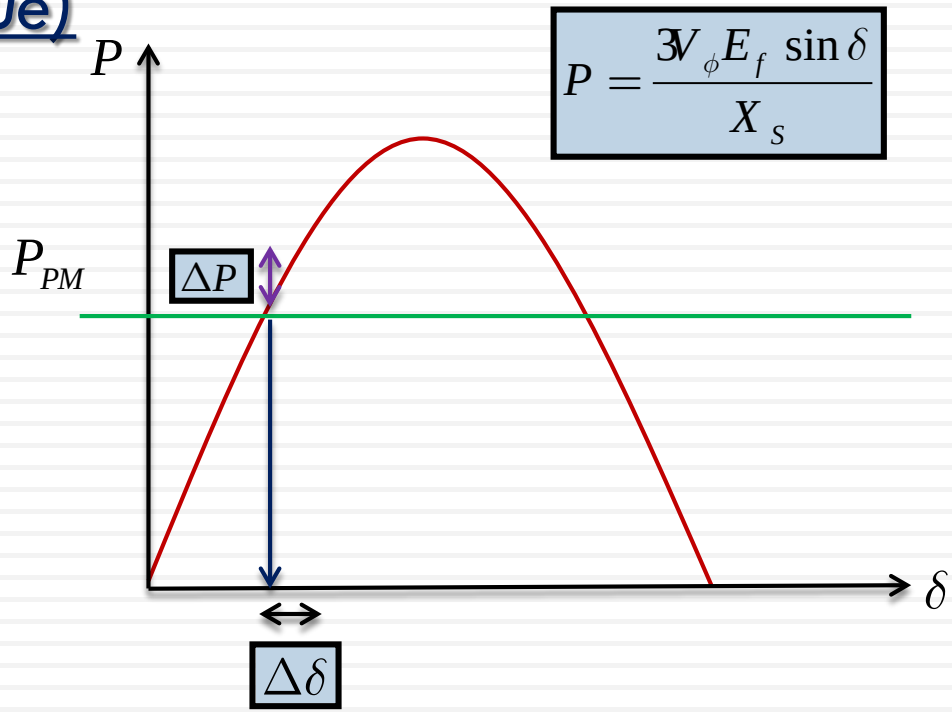
*In case of disturbances:*

$$\Delta P = P_{syn} = \frac{\partial P}{\partial \delta}\Delta\delta$$

$$\frac{\partial P}{\partial \delta} = \frac{3V_\phi E_f \cos\delta}{X_S}$$

$$\Delta T = T_{syn} = \frac{\partial T}{\partial \delta}\Delta\delta$$

$$\frac{\partial T}{\partial \delta} = \frac{3V_\phi E_f \cos\delta}{\omega_S X_S}$$



# **Synchronous Generator:** Generator Rating



*Voltage (V, kV)*

*Frequency (Hz)*

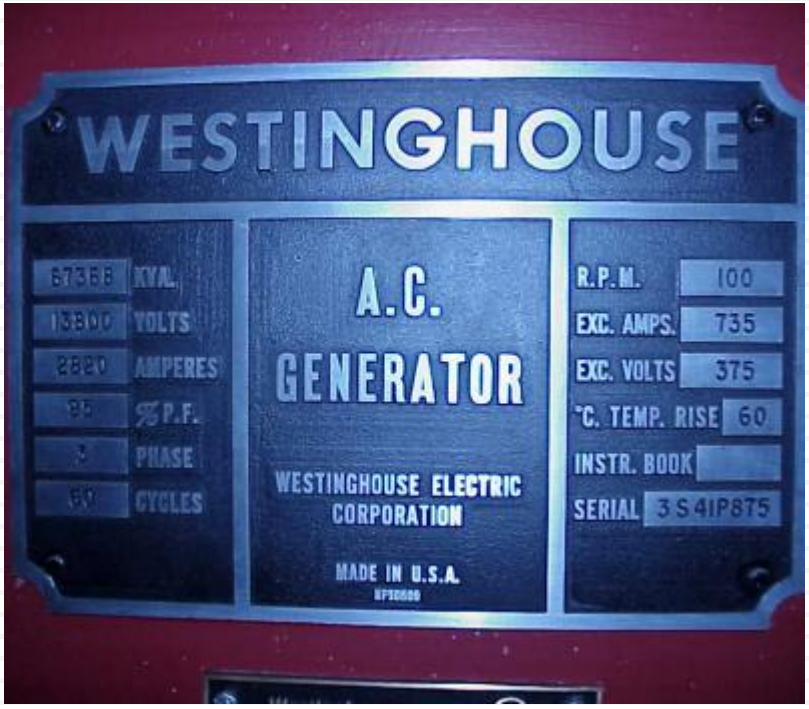
*Speed (rpm)*

*Apparent Power (kVA, MVA)*

*Power Factor*

*Field Current (A)*

*Service Factor*



# **Synchronous Generator:** Generator Rating



*Rated Speed: depends on the prime-mover maximum speed, the number of poles should be adjusted according to the speed range to produce the required system frequency.*

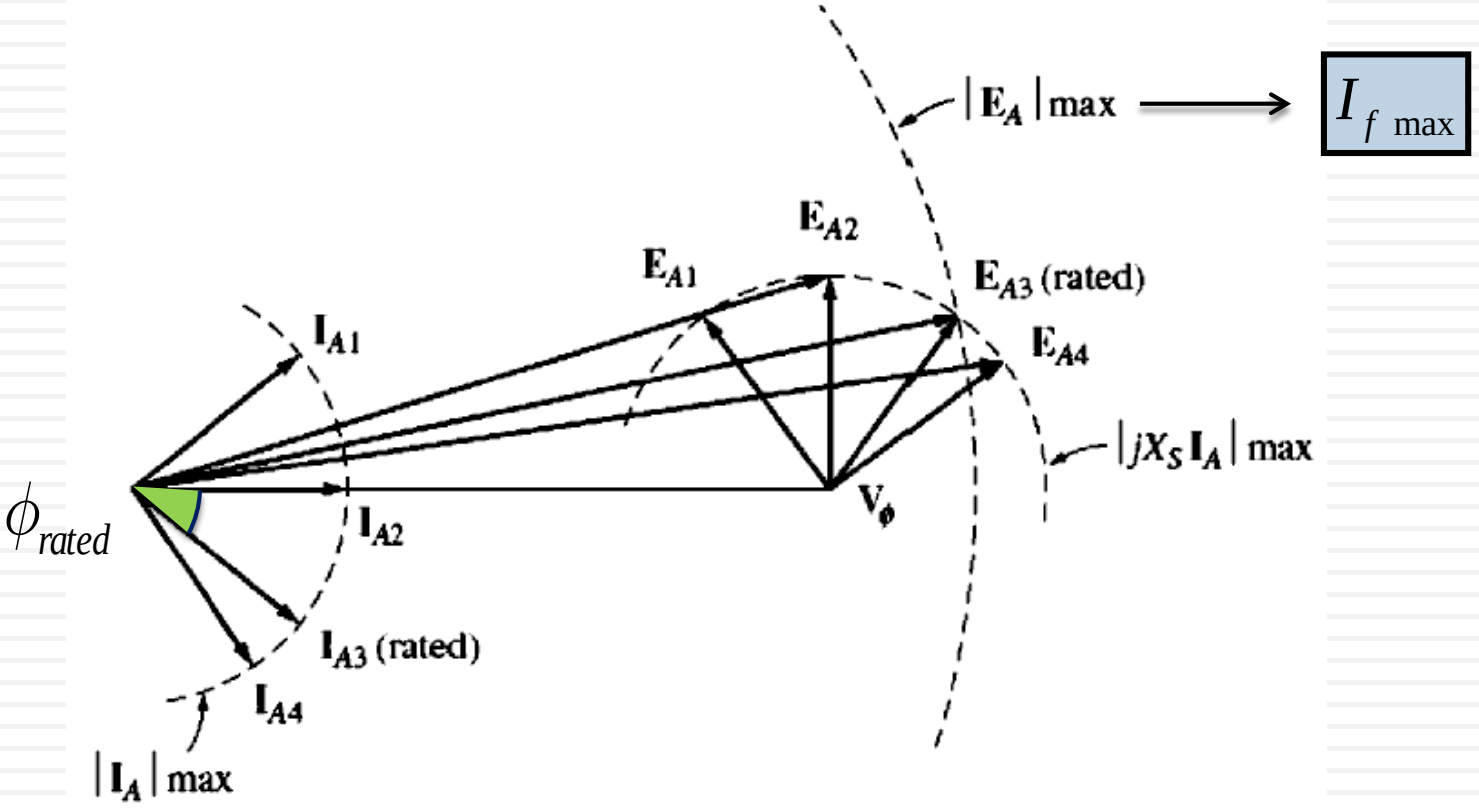
*Rated Apparent Power: depends on the maximum permissible shaft torque (i.e. $P_{PMmax}$), the maximum permissible armature current ($I_{amax}$)and the maximum permissible field current ($I_{fmax}$).*

$$S_{rated} = 3V_{\phi rated} I_{a\max}$$

# Synchronous Generator: Generator Rating



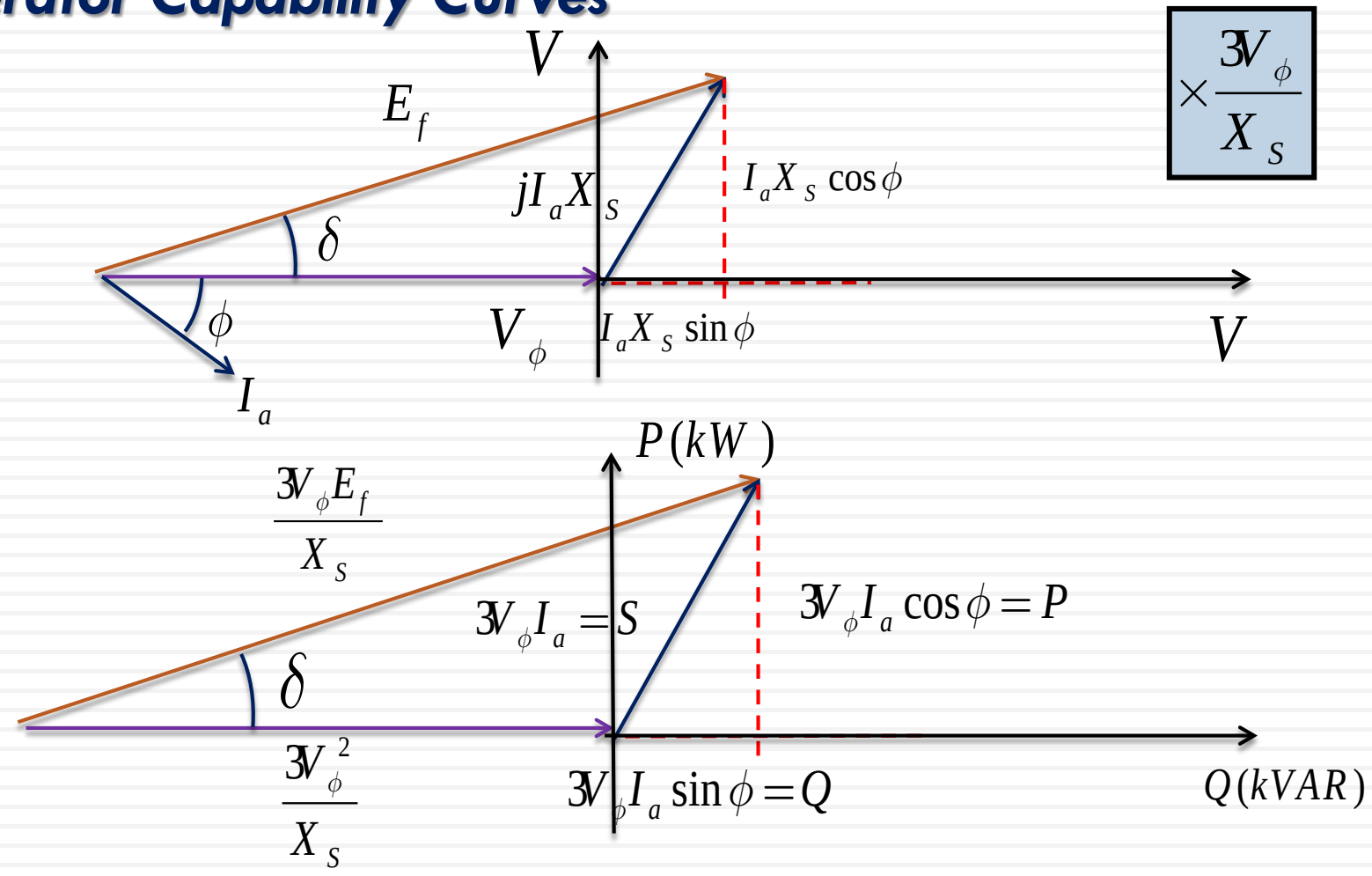
*Rated Power Factor: the least lagging pf at which the armature and field currents are maximum.*



# Synchronous Generator: Generator Rating



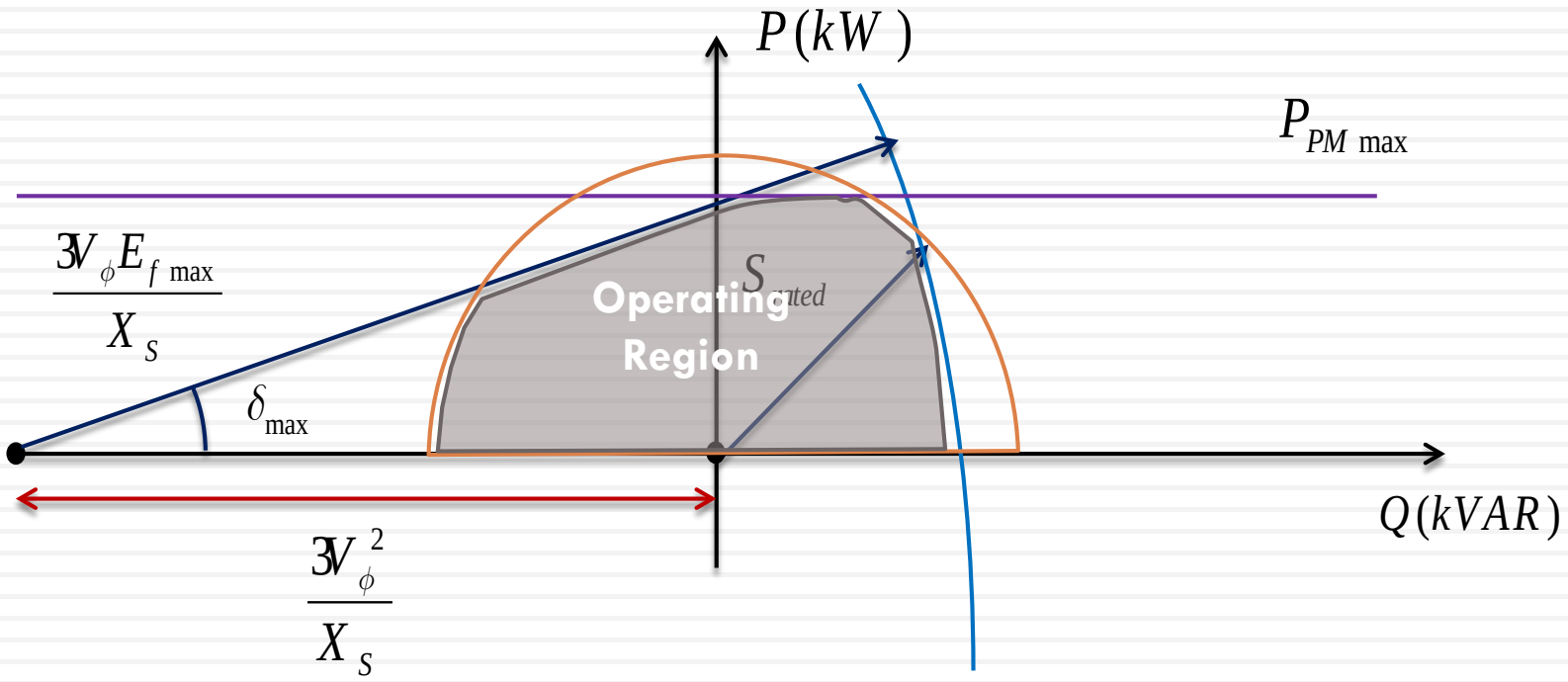
## Generator Capability Curves



# Synchronous Generator: Generator Rating



## Generator Capability Curves



# **Synchronous Generator:** Practical Aspects



*Voltage (V, kV)*

*Frequency (Hz)*

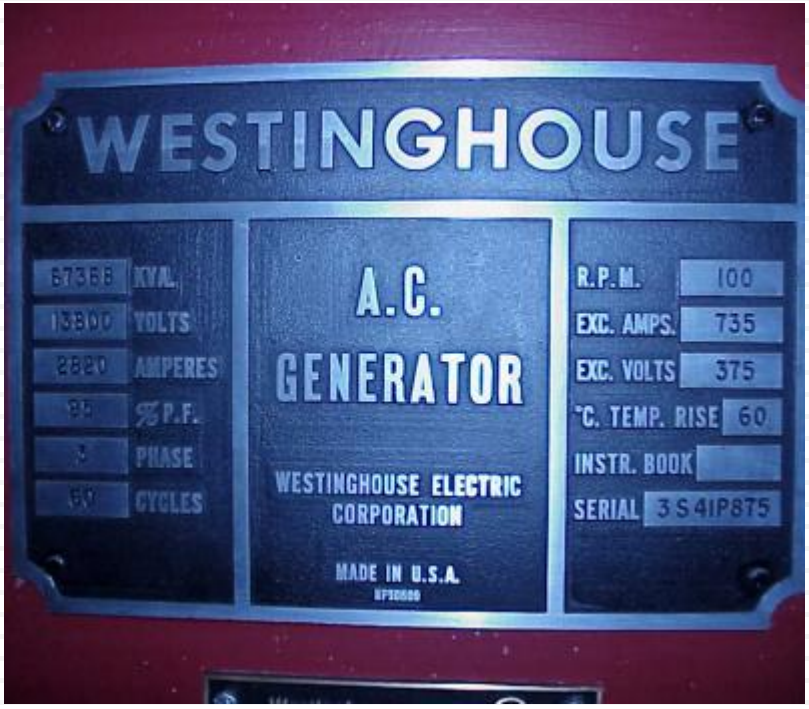
*Speed (rpm)*

*Apparent Power (kVA, MVA)*

*Power Factor*

*Field Current (A)*

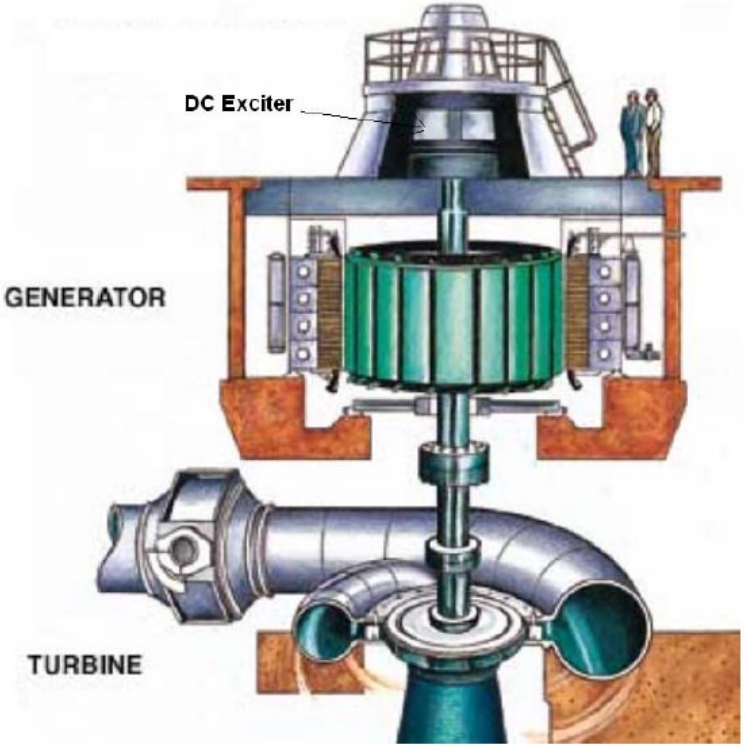
*Service Factor*



# Synchronous Generator: Practical Aspects



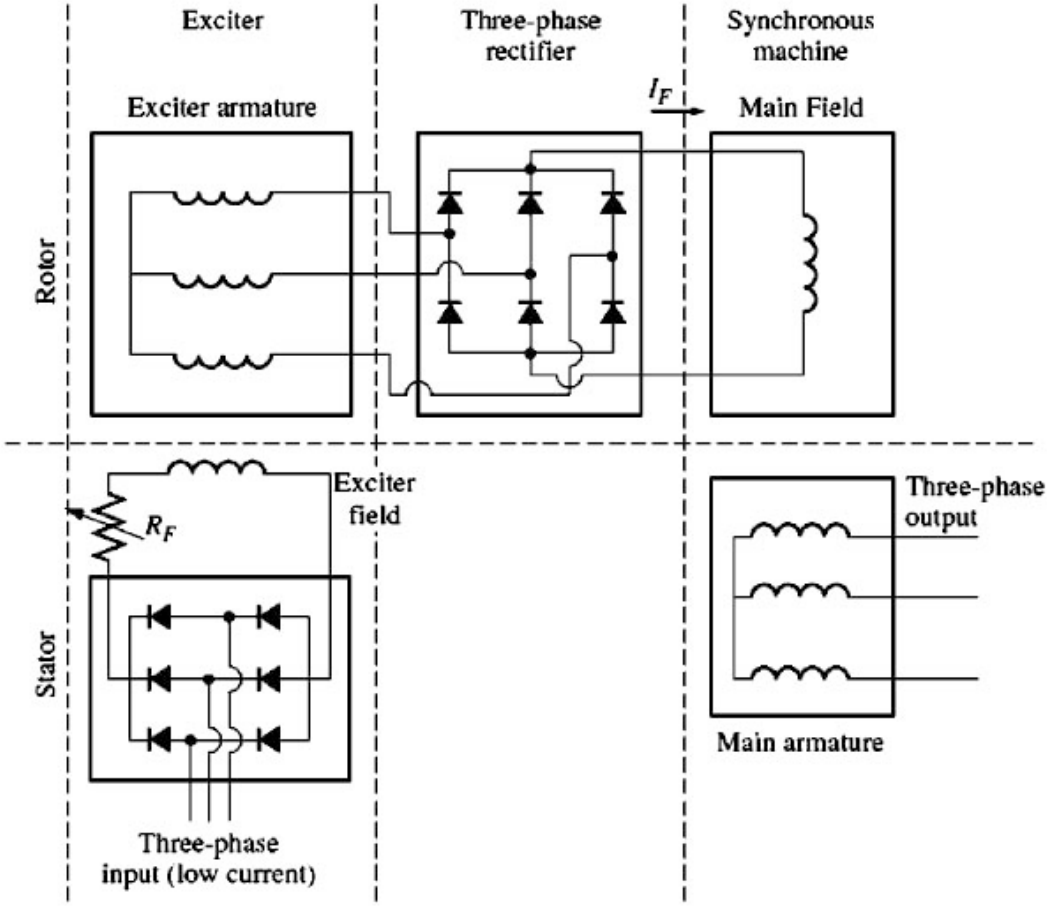
## Excitation Systems




# Synchronous Generator: Practical Aspects



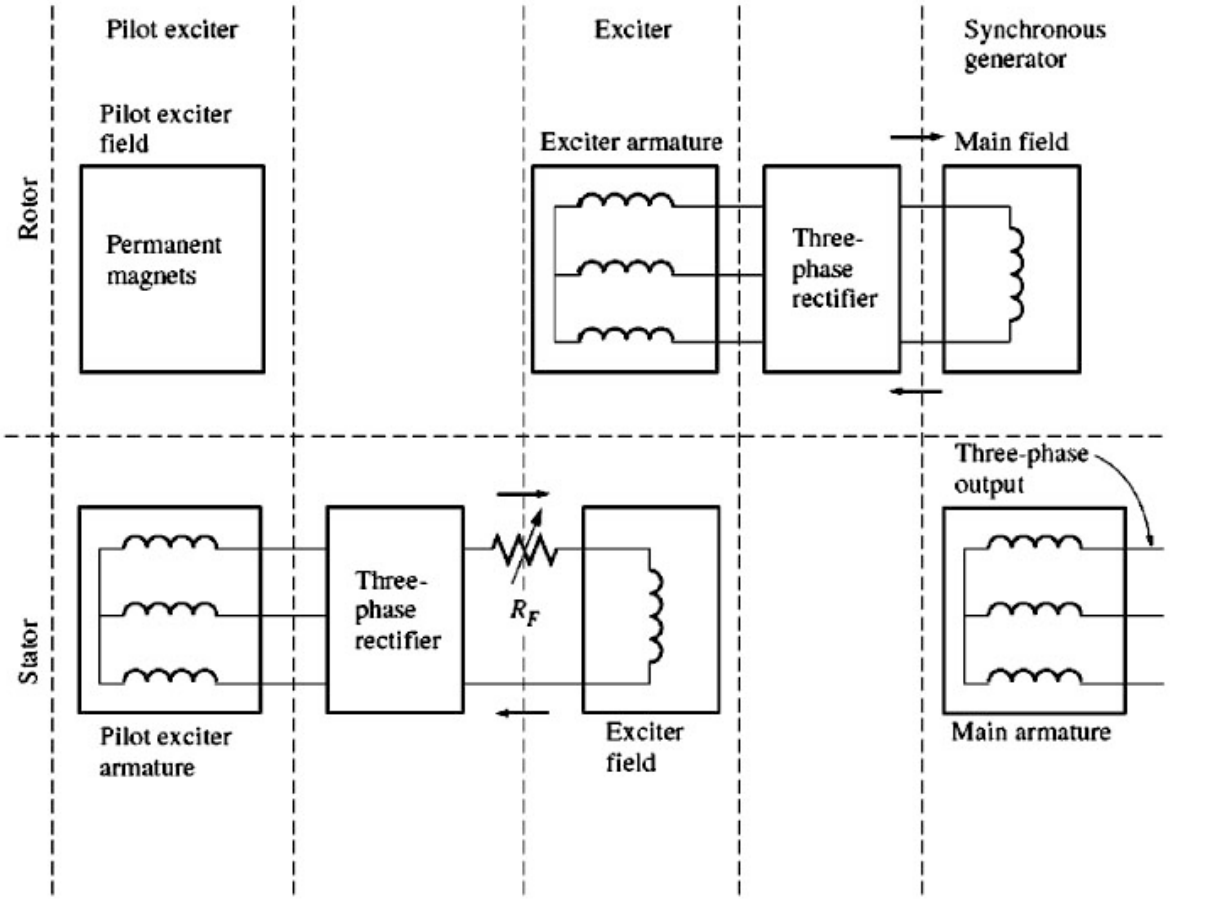
## Excitation Systems: Brushless Excitation



# Synchronous Generator: Practical Aspects



## Excitation Systems: Brushless Excitation



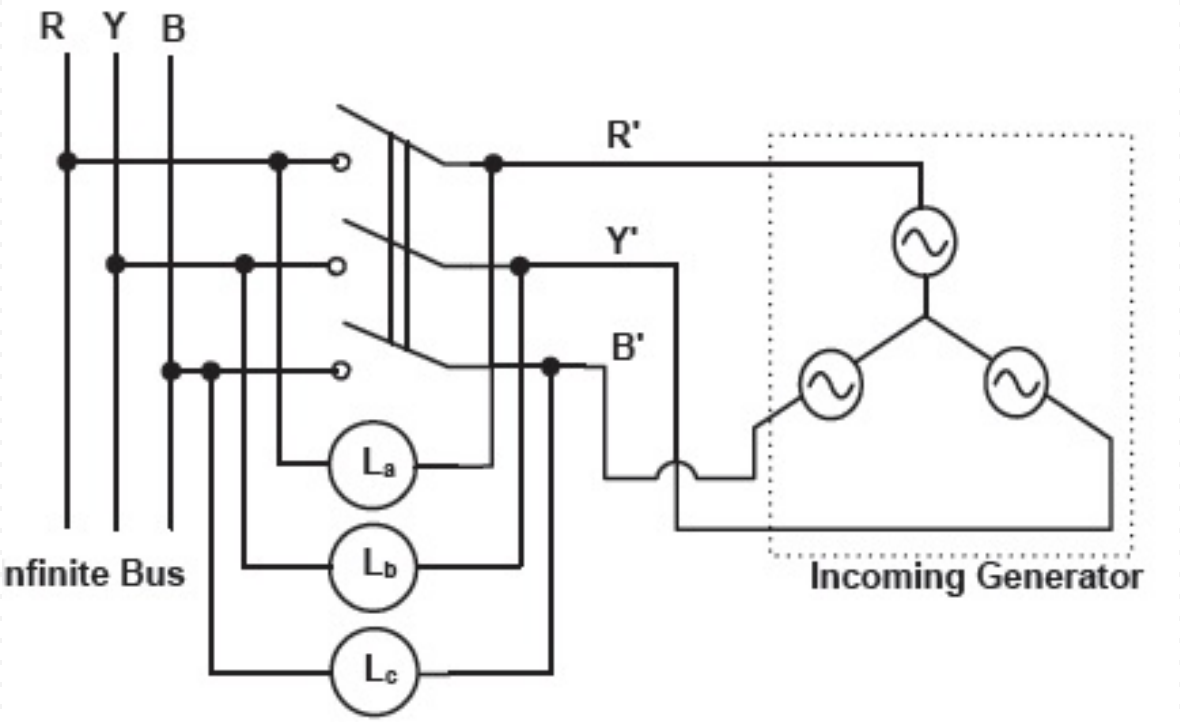
# Synchronous Generator: Practical Aspects



## Synchronization

### Dark Lamp Method

$L_a$ , $L_b$ & $L_c$ are dark



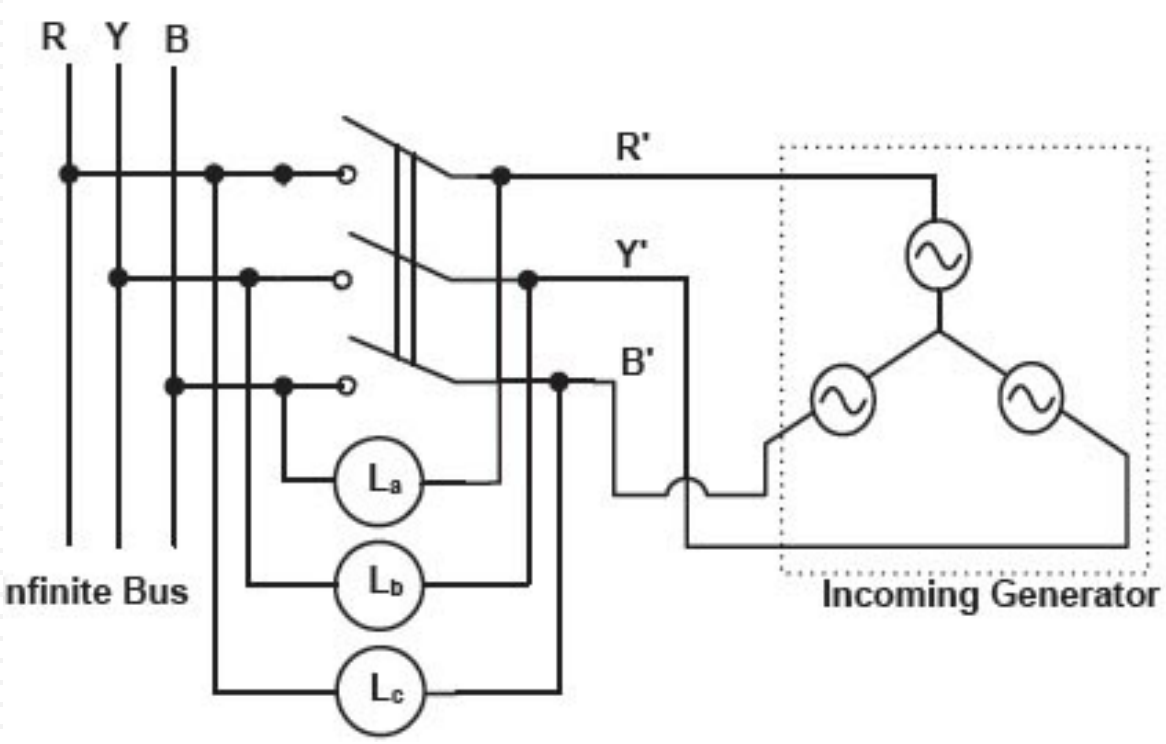
# Synchronous Generator: Practical Aspects



## Synchronization

### *Transposed Lamp Method*

*$L_b$ is dark while $L_a$ and $L_c$ are at maximum brightness*

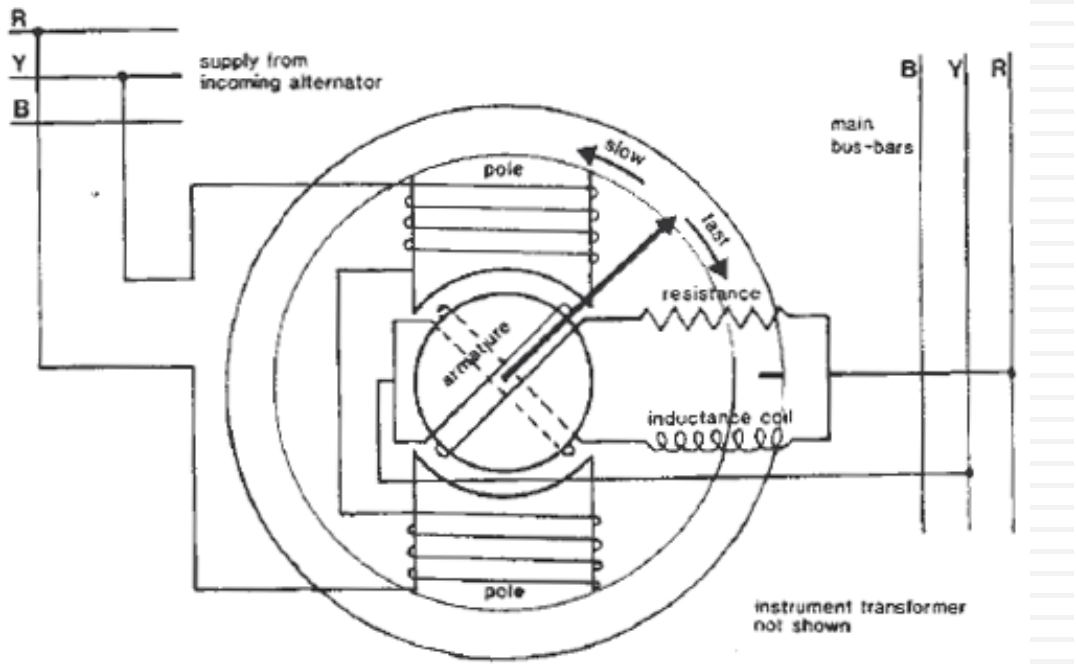


# Synchronous Generator: Practical Aspects



## Synchronization

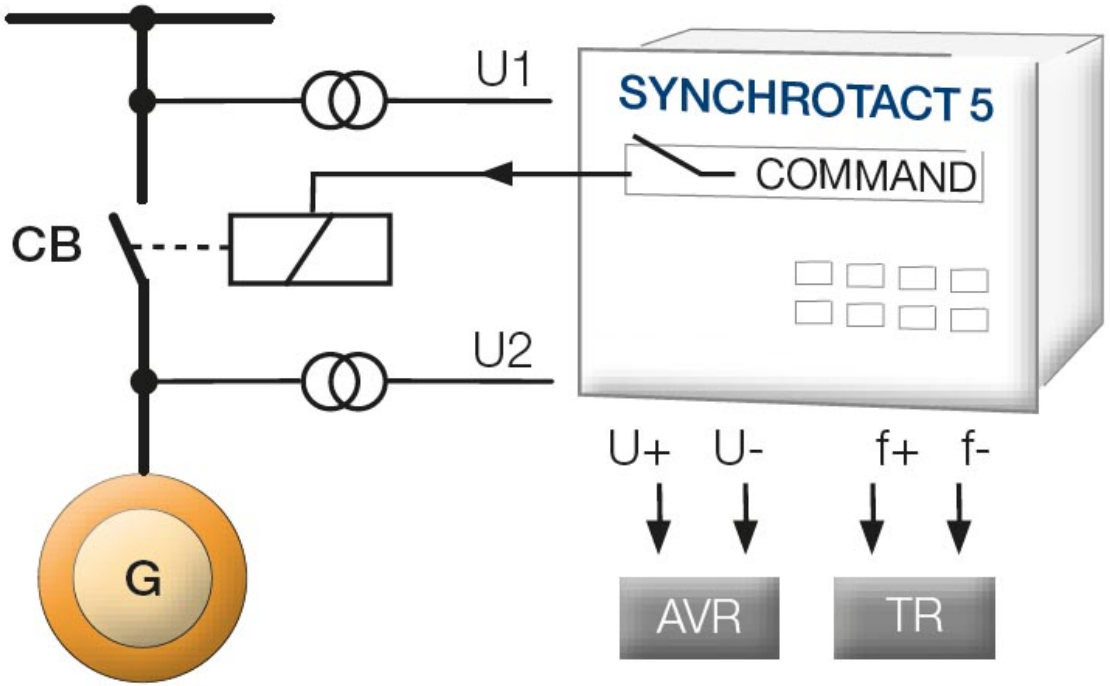
### Synchroscope




# Synchronous Generator: Practical Aspects



## Synchronization




Automatic Voltage Regulator

Speed Governor