Electrical Theory

Generator Theory

PJM State & Member Training Dept.

Objectives

- Describe the process of electromagnetic induction
- Identify the major components of an AC generator
- Apply the formula for rotational speed
- Describe generator governor control
- Discuss the characteristics that affect or limit generator performance
- Describe MVAR and MW flow
- Describe the synchronization process of a generator

Basic Operating Principles

- ***Electromagnetic Induction*** is the principle used by a generator to convert mechanical energy into electrical energy
- For this to happen, three things are needed:
  - A magnetic field
  - A current-carrying conductor
  - A relative motion between the two
- This is the fundamental operating principle of generators, motors, transformers, inductors, and solenoids

Basic Operating Principles

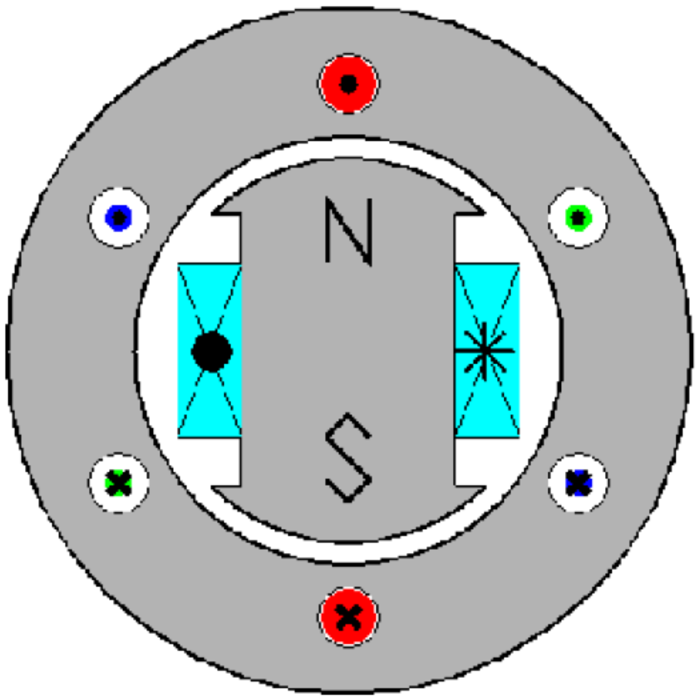
- Generators use energy from the prime mover to turn the generator's ***rotor*** (moving portion) inside the generator's ***stator*** (static portion)
  - Steam in a fossil or nuclear unit
  - Water flow in a hydroelectric unit
  - Fuel flow in a combustion turbine unit
  - Wind flow in a wind generator
- A DC current flows through the ***field windings*** of the ***rotor*** creating a magnetic field
- As the rotor spins, it acts via electromagnetic induction to induce a voltage in the ***armature windings*** of the ***stator***

Basic Operating Principles

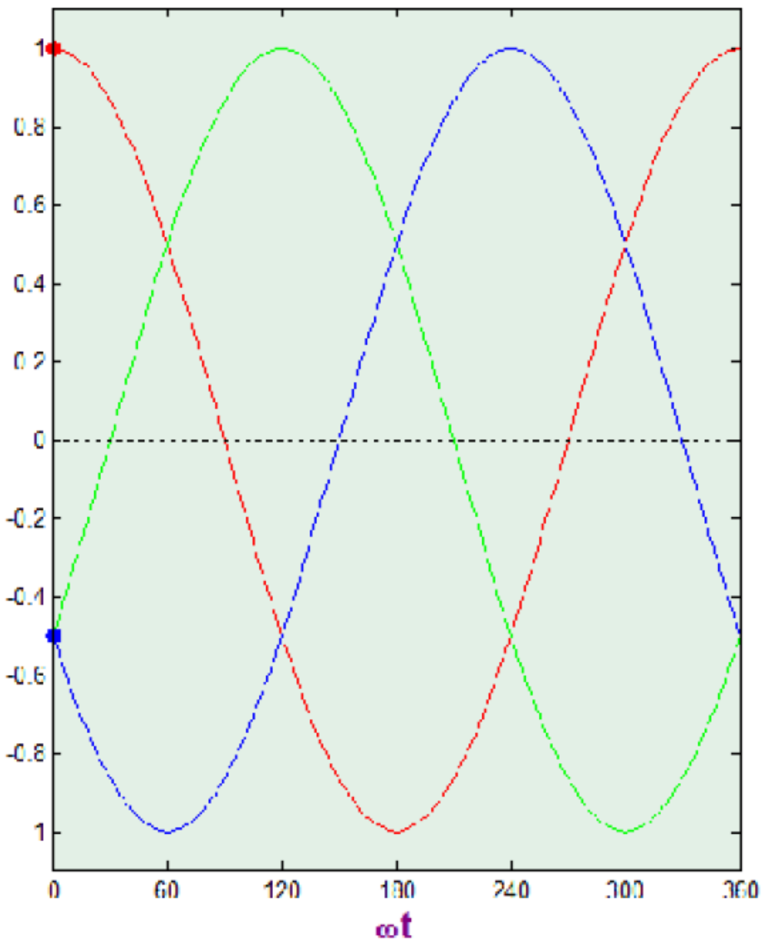
- Output voltage of the generator is controlled by changing the strength of the magnetic field of the rotor
- This is accomplished by controlling the amount of **direct current (DC)** or **excitation current** that is supplied to the rotor’s field winding
- The **excitation current** is supplied by the **exciter**
- The stator’s output to the system is a three-phase **alternating current (AC)** since the direction of the magnetic field changes in relation to the windings as the rotor turns 360 degrees
- One rotation is equal to a complete cycle of power

Basic Operating Principles

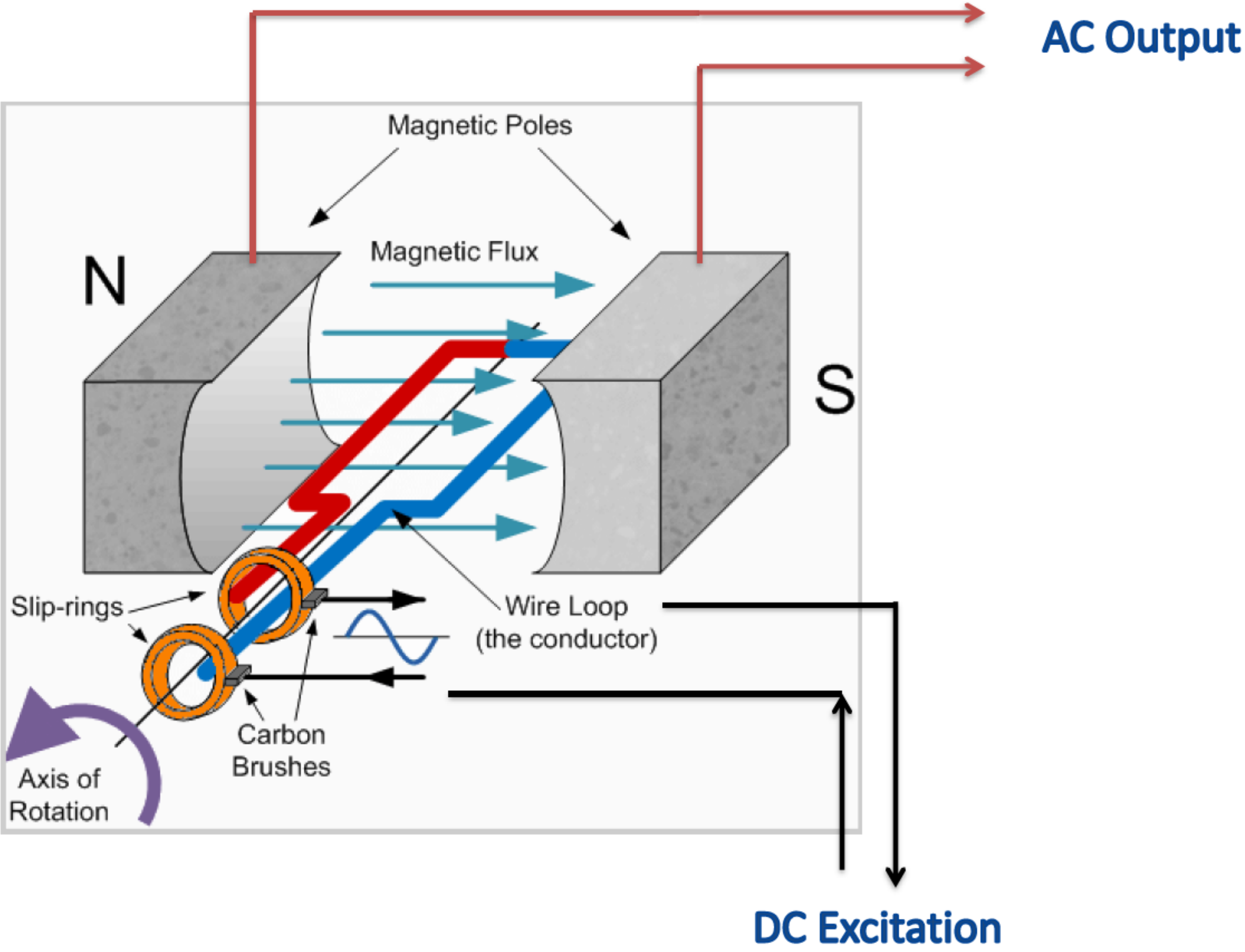
Bismark Phasor Sim



Phase A Phase B Phase C



Basic Operating Principles



A.C. Generator Components

- Rotating Magnetic Field (Rotor)
- Series of Stationary Conductors (Stator)
- Source of D.C. Voltage (Exciter)

Rotor

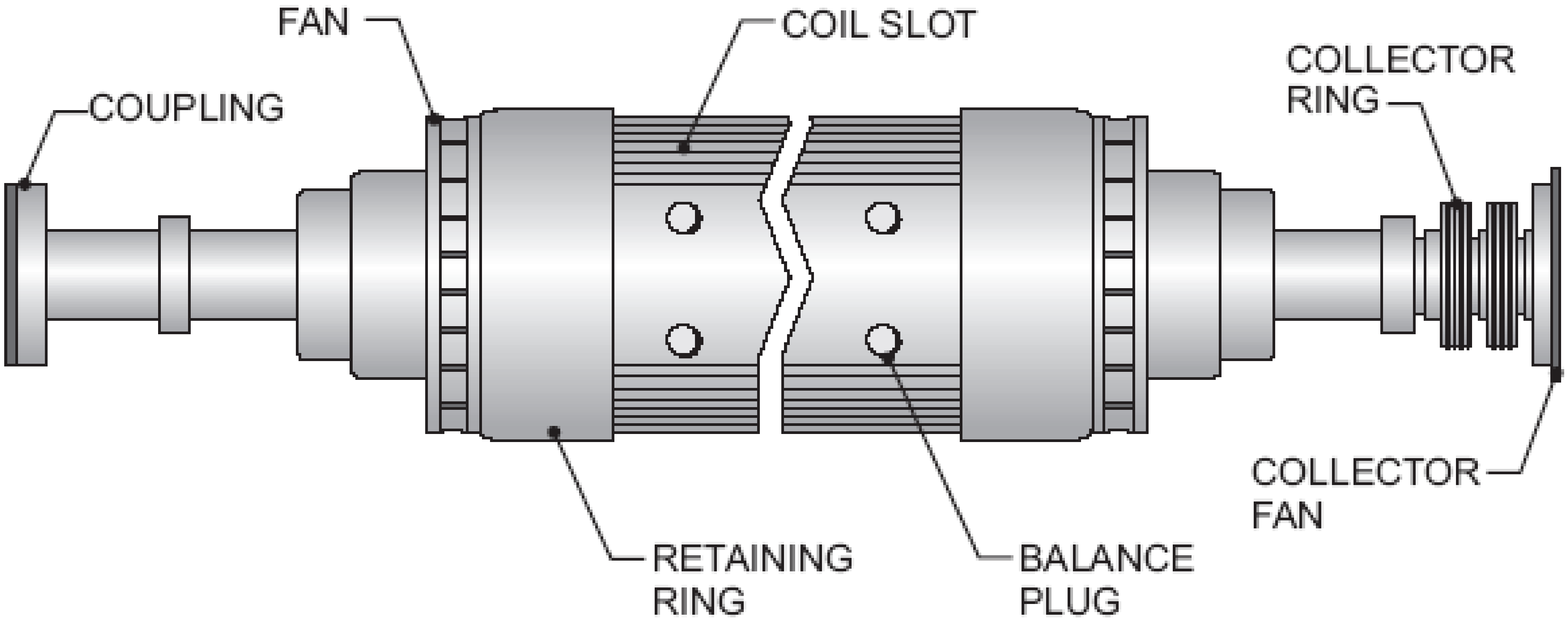


Figure 1. Generator field

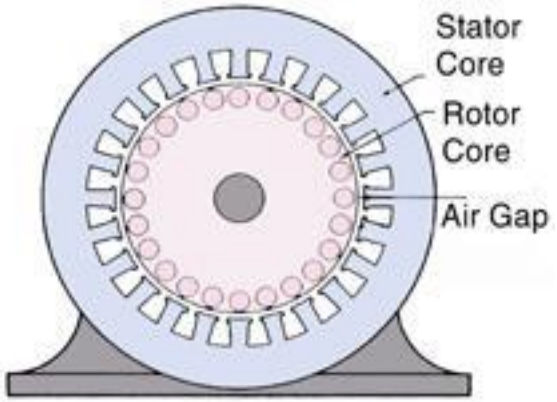
Rotor

- The rotating field is required to produce a given number of lines of magnetic flux which is obtained by: **Ampere-turns**

- Ampere-turns is the product of the number of turns in the rotor winding and the current that flows in the winding

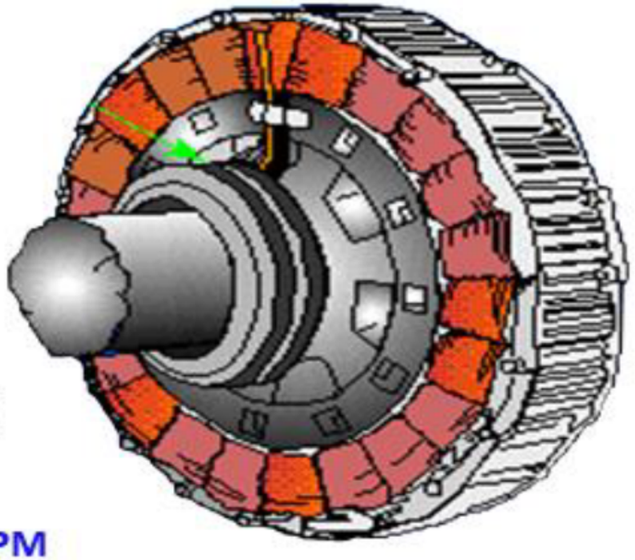
Rotor

- Generator rotors are made of solid steel forgings with slots cut along the length for the copper windings
- Insulated winding bars are wedged into the slots and connected at each end of the rotor and are arranged to act as one continuous wire to develop the magnetic field



Rotor

SLIP RINGS



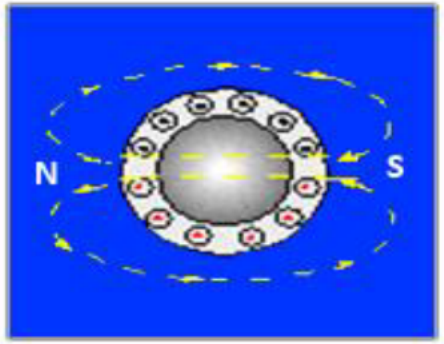
TURBINE DRIVEN
ROTOR

HIGH SPEED = 1200 RPM
OR MORE

SALIENT-POLE
ROTOR

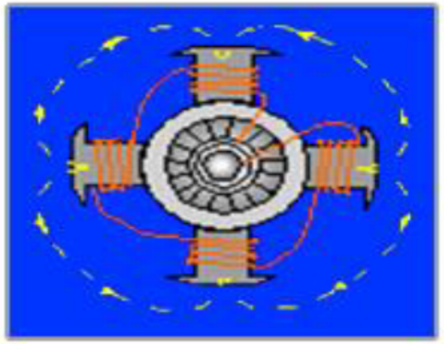
LOW SPEED = 1200 RPM
OR LESS

CROSS - SECTION



LINES OF
MAGETIC
FORCE

SCHEMATIC



Rotor

- Rotor design constraints include:
  - Temperature:
    - Ampere-turn requirements for the field increase with an increase in rating, which entails a combined increase in heating in the coil
  - Mechanical force:
    - Ampere-turn requirements for the field increase with an increase in rating causing a higher centrifugal load
  - Electrical insulation:
    - In older units, slot insulation is a primary thermal barrier, and as current increases, becomes a greater obstacle

Rotor

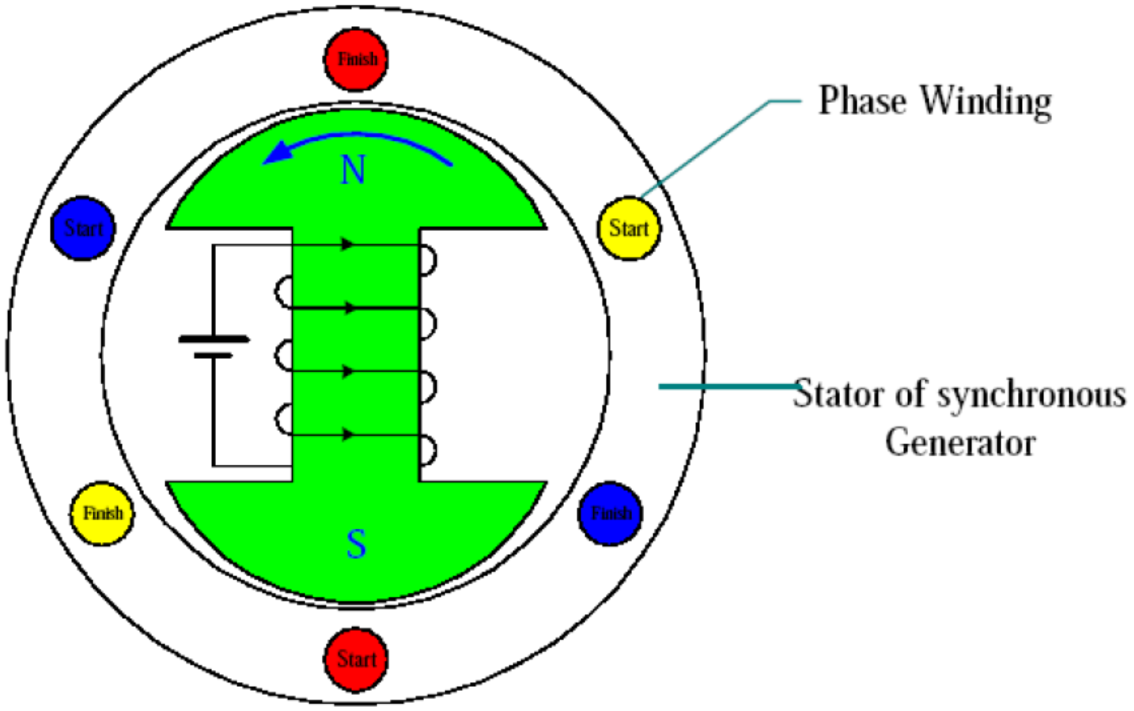
Advantage:

- Air gap between the stator and rotor can be adjusted so that the magnetic flux can be sinusoidal including the waveform

Disadvantage:

- Because of its weak structure it is not suitable for high-speed generation
- It is also expensive to fabricate
- Requires damper windings to prevent rotor oscillations during operations
- Due to low speed, they are constructed with a higher number of poles to achieve system frequency

Salient Pole Three Phase Synchronous Generator



Rotor

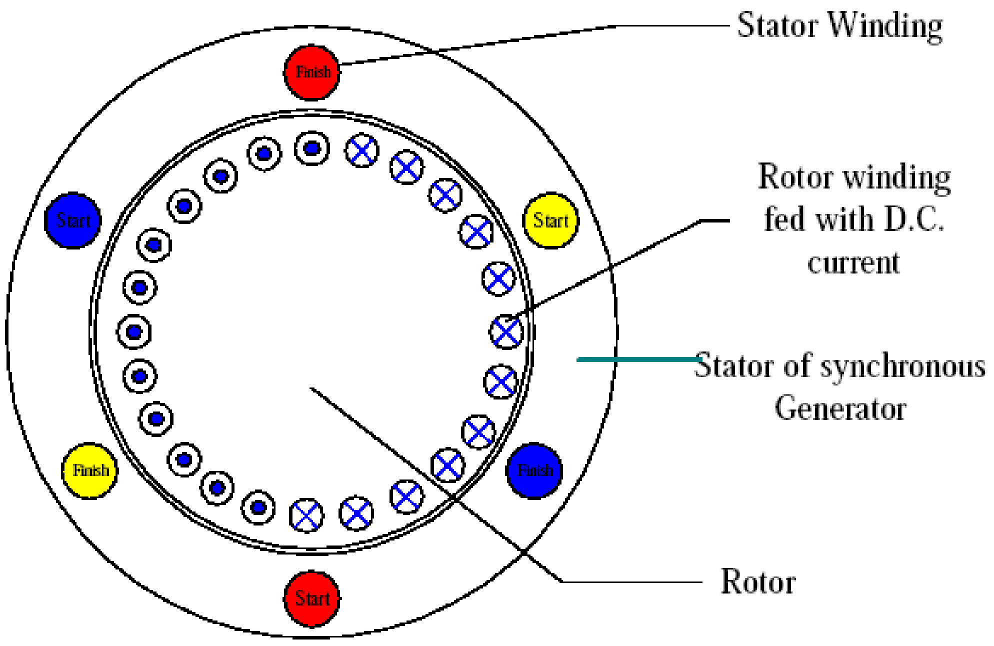
Advantage:

- Cheaper than a salient-pole
- Its symmetrical shape, is better for high-speed application
- Losses in the windings are reduced
- Noise produced is less

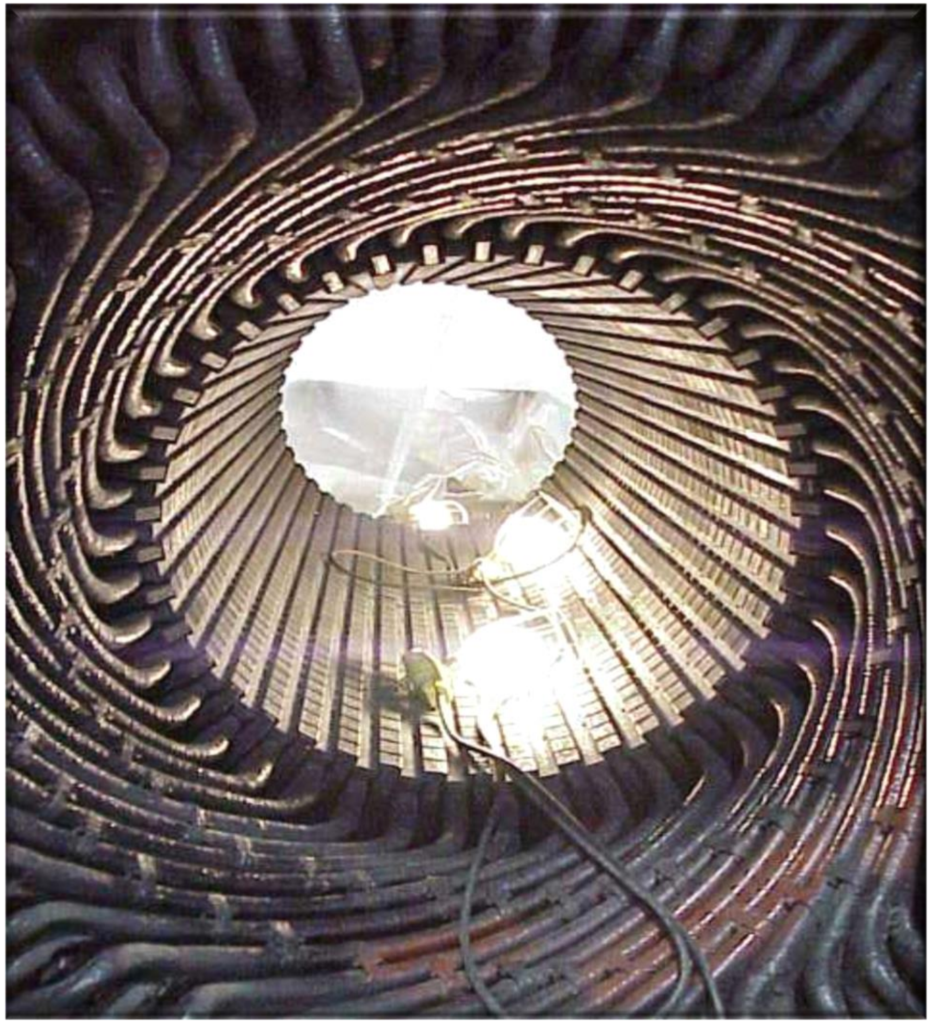
Disadvantage:

- Air gap is uniform
- Generated voltage is polygonal giving way to the susceptibility of harmonics

Cylindrical Rotor Synchronous Generator



Stator

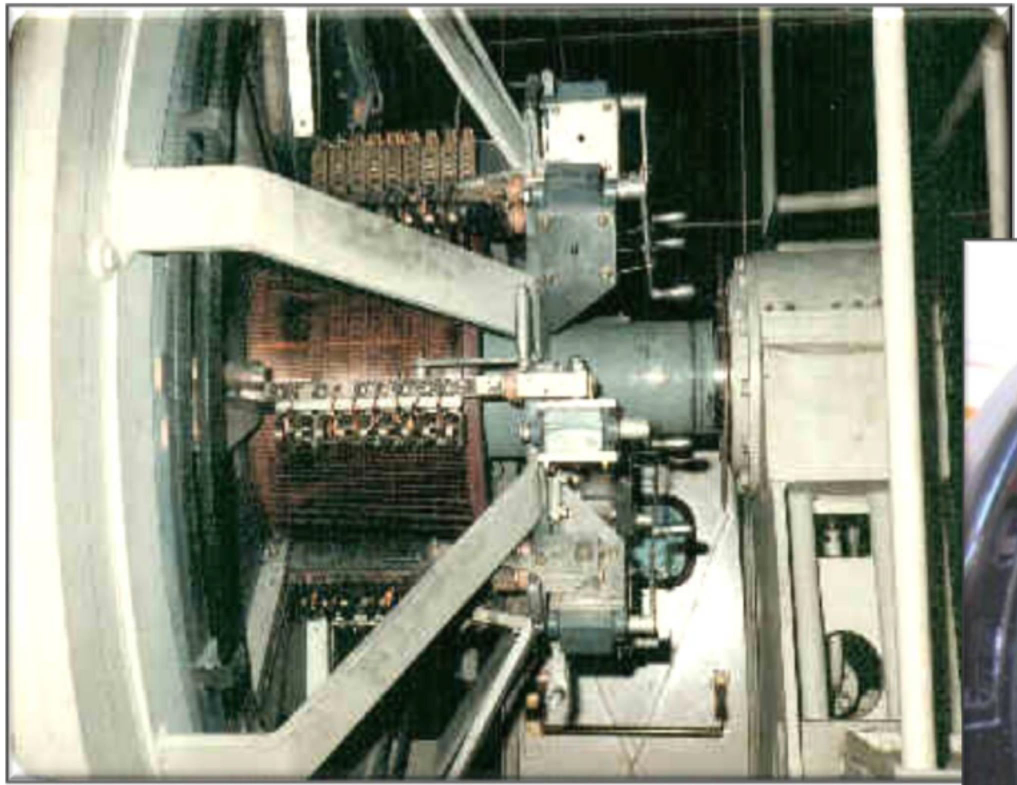


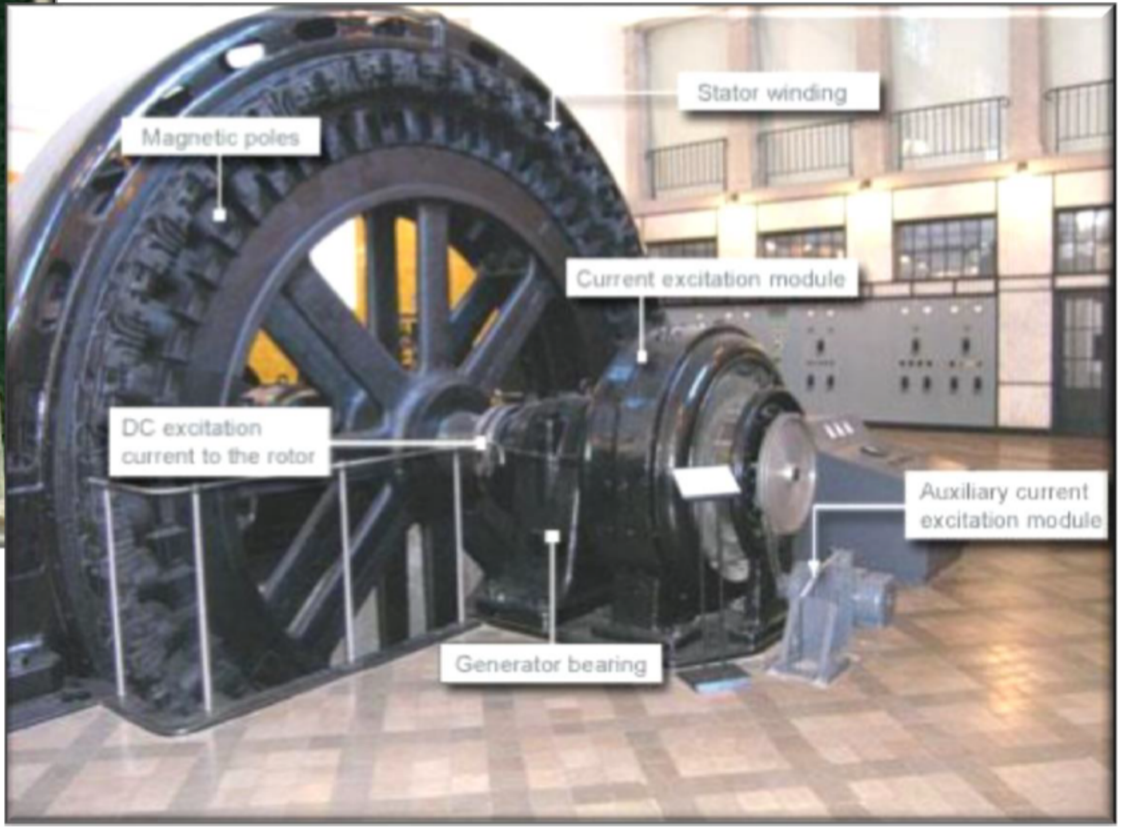
Stator

- Two-Pole Generators:
  - In a two-pole generator, there are three armature winding coils installed in the stator
  - North and south poles of the rotor are 180˚ apart
- Four-Pole Generators:
  - In a four-pole generator, there are six armature winding coils installed in the stator
  - North and south poles of the rotor are 90˚ apart
- A generator which is connected to the grid has a constant speed dictated by grid frequency

Bismark AC Generator Sim

Exciter




Stator winding
Magnetic poles
Current excitation module
DC excitation
current to the rotor
Auxiliary current
excitation module
Generator bearing

Exciter

- The function of the excitation system is to provide direct current for the generator rotor/field windings through slip rings to produce the magnetic field

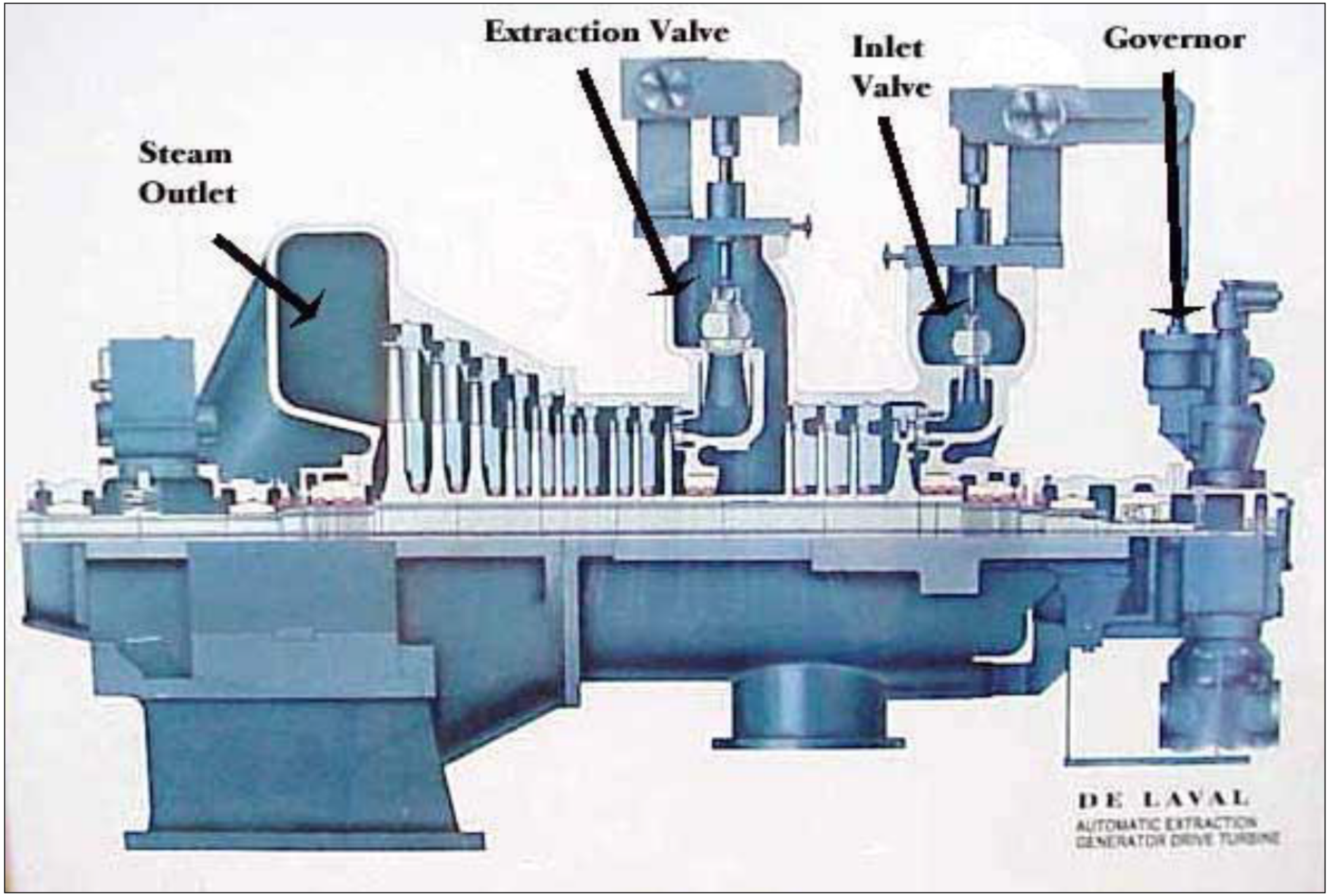
- Maintains generator voltage, controls MVAR flow, and assists in maintaining power system stability

- During load changes or disturbances on the system, the exciter must respond, sometimes rapidly, to maintain the proper voltage at the generator terminals

Generator Governor Control

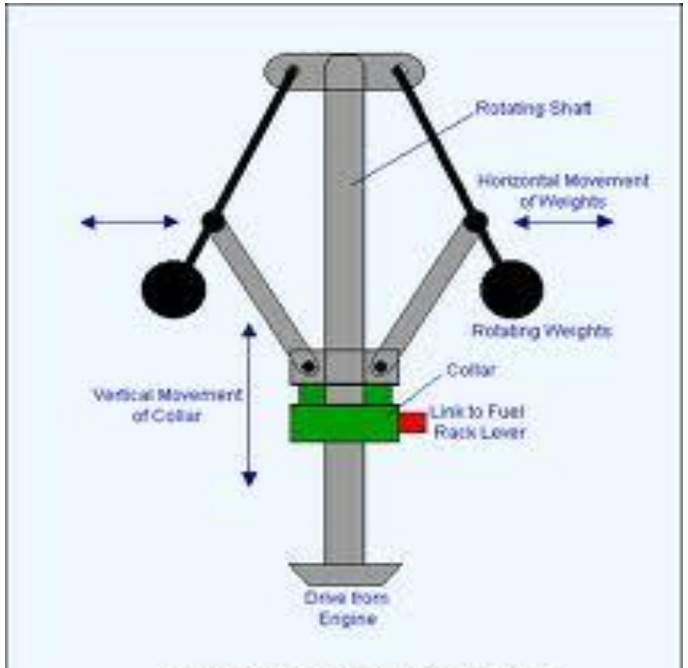
- Governors control generator shaft speed
- Adjust generation for small changes in load
- Operate by adjusting the input to the prime mover
  - Steam flow for fossil
  - Water flow for hydro
  - Fuel flow for combustion turbine
- Amount of governor control varies according to plant design
- Equivalent to a car’s cruise control

Generator Governor Control



Generator Governor Control

- The Watt centrifugal governor was the mechanical means for governor control
  - Used weights that moved radially as rotational speed increased that pneumatically operated a servo-motor
  - Electrohydraulic governing has replaced the mechanical governor because of:
    - High response speed
    - Low deadband
    - Accuracy in speed and load control

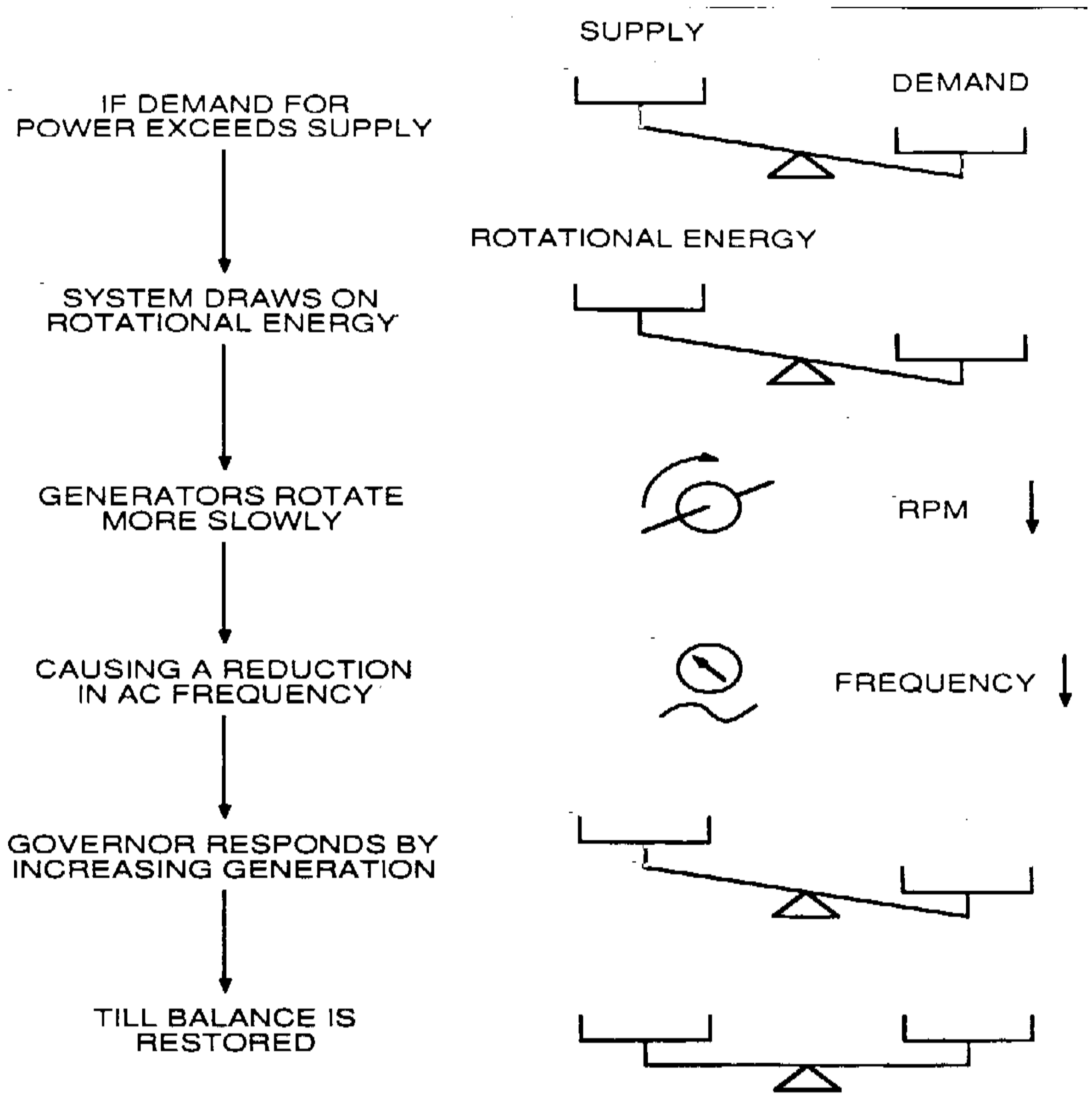


Simplified diagram of diesel engine governor

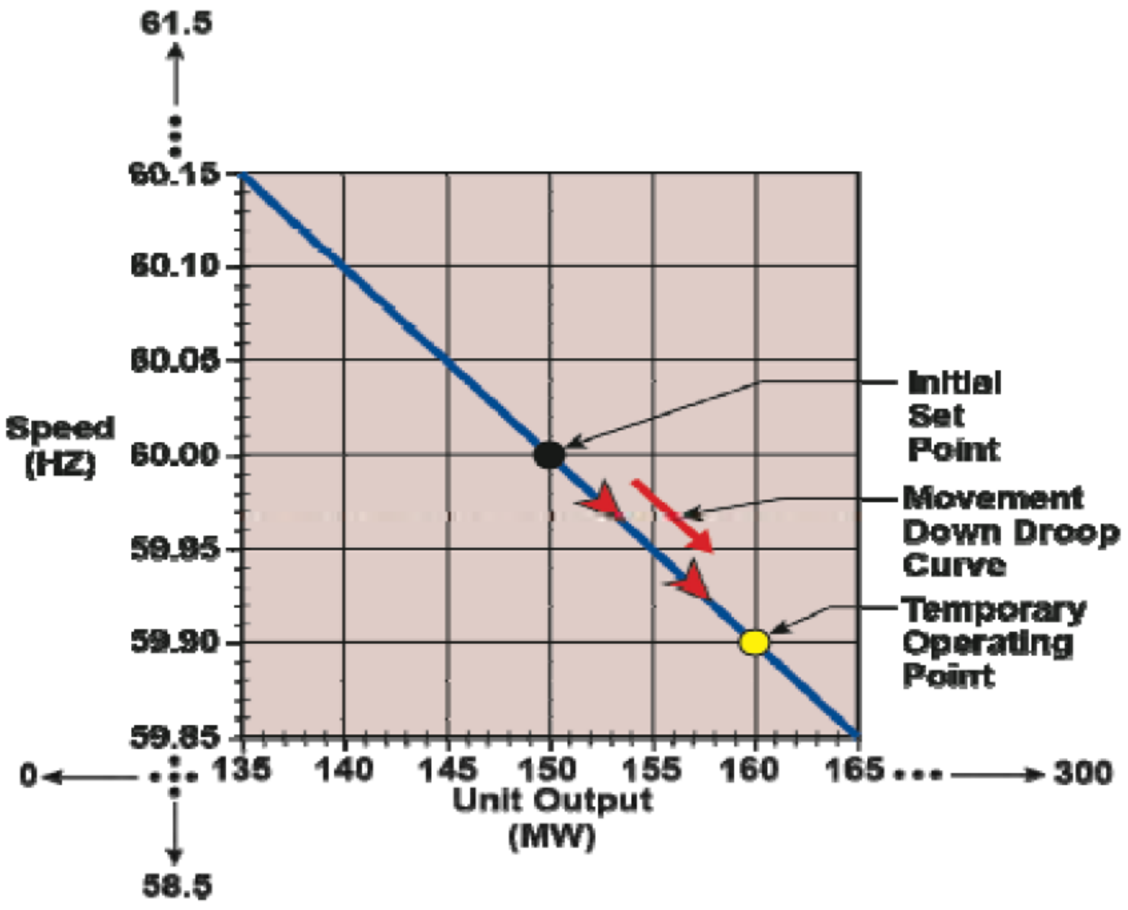
Governor Control

- When a generator synchronizes to the system
  - It couples itself to hundreds of other machines rotating at the same electrical speed
  - Each of these generators have a “droop” feature added to their governor
  - This allows generators to respond in proportion to their size whenever there is a disturbance, or load-resource mismatch

Governor Control

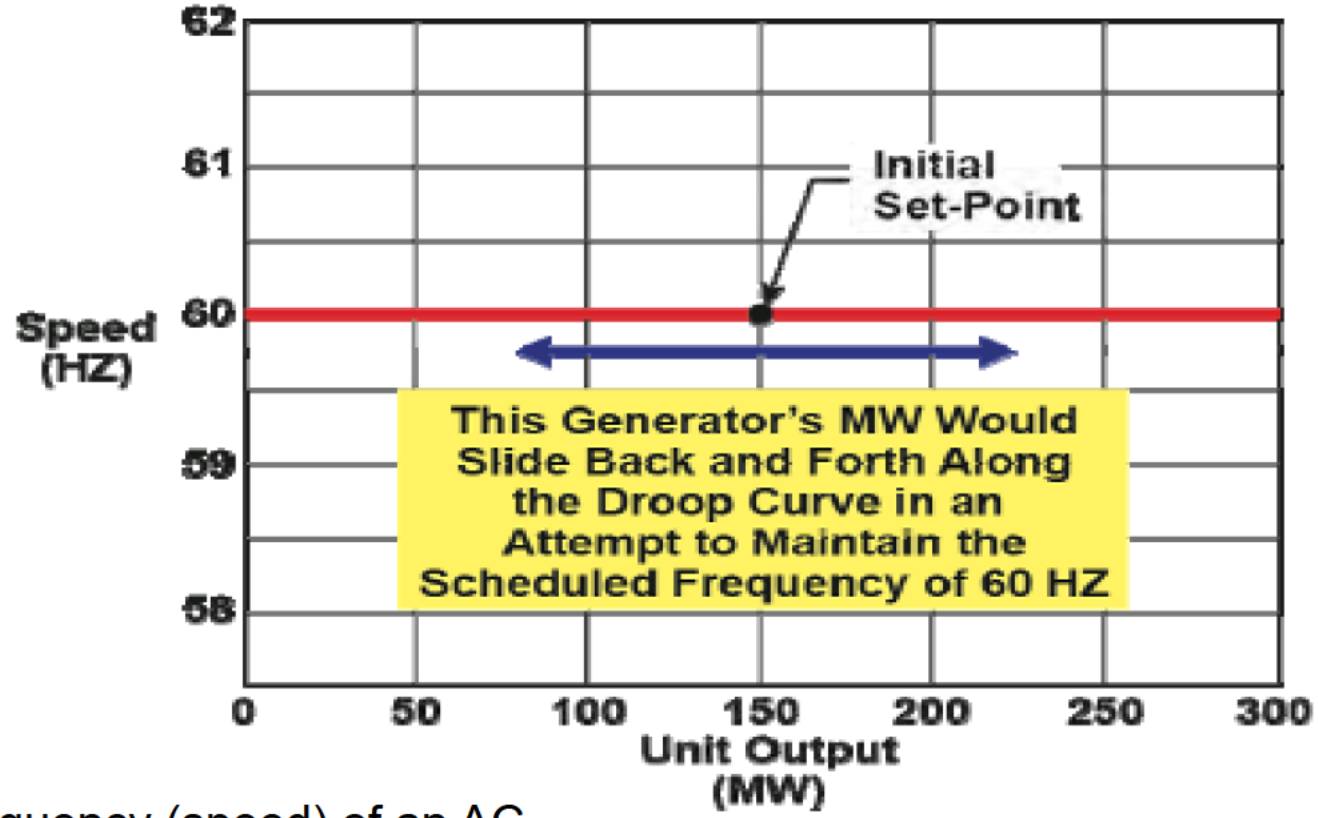


Governor Control – Droop Speed Mode



EPRI

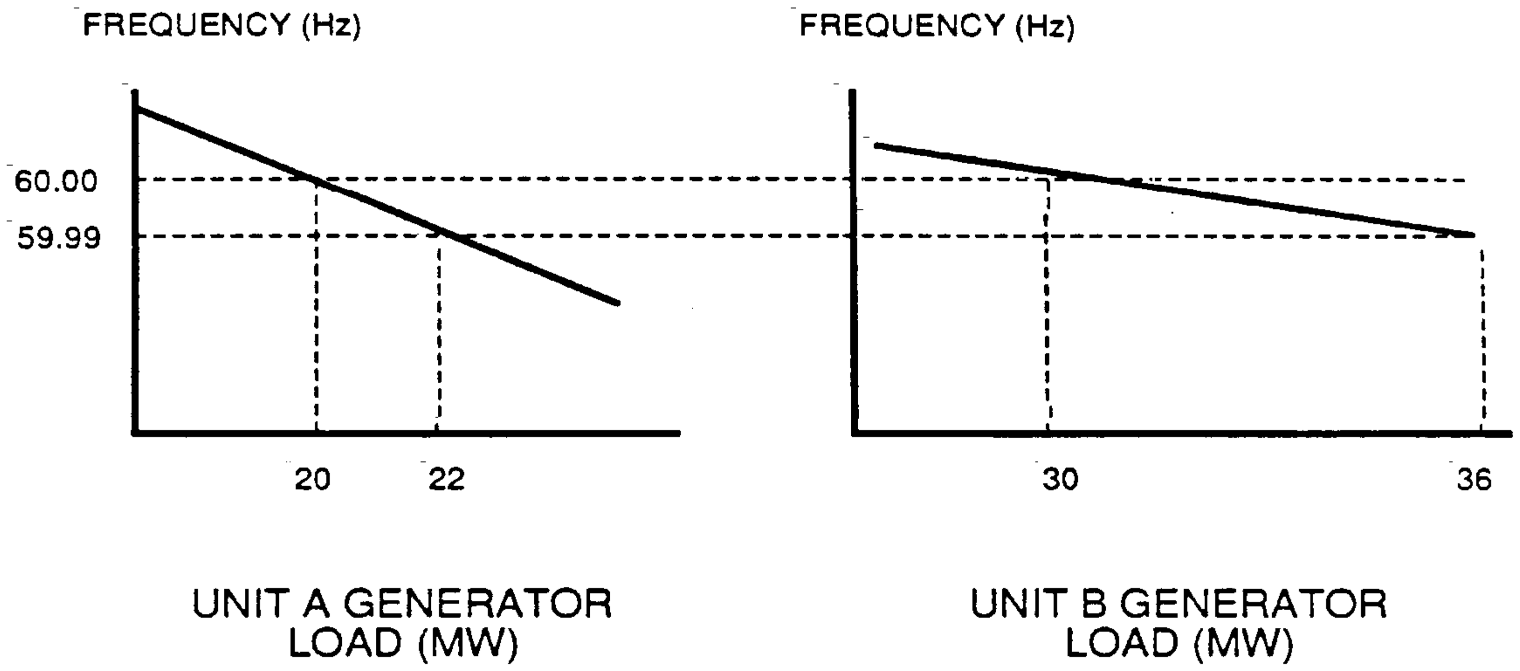
Governor Control – Isochronous Mode



Controls the frequency (speed) of an AC generator

EPRI

Generator Governor Control: Droop



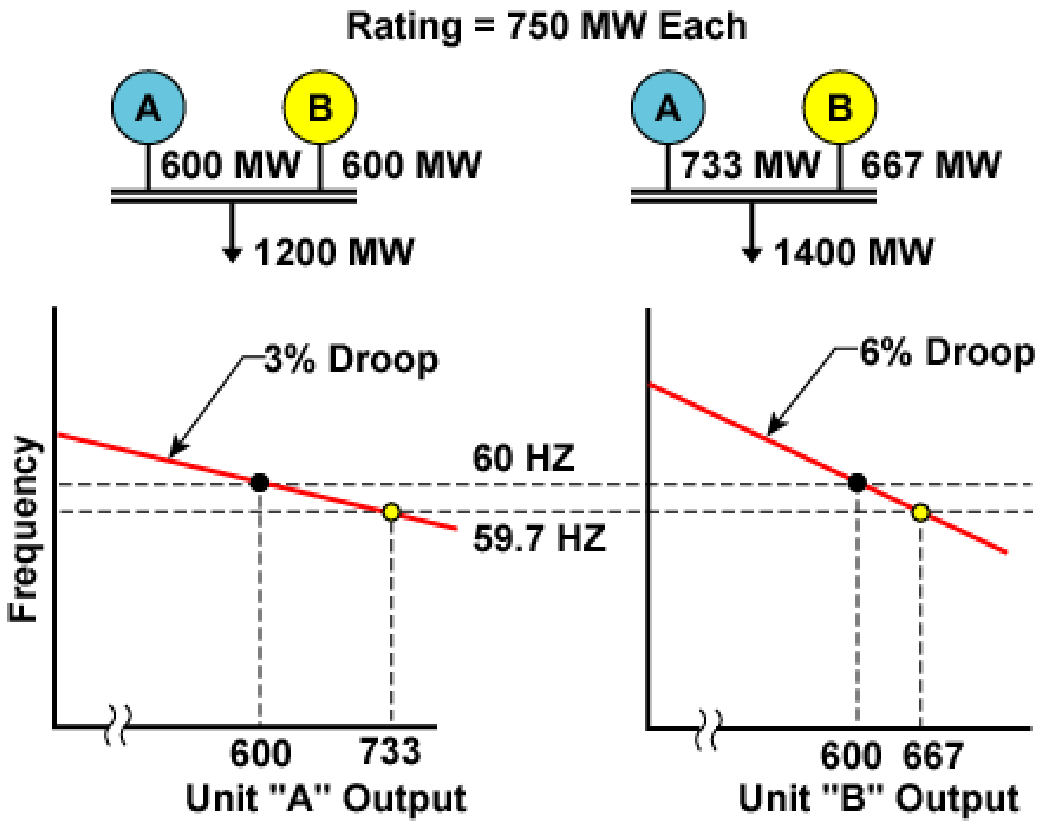
LOAD PICK-UP FOR A:

2MW FOR 0.01 Hz

LOAD PICK-UP FOR B:

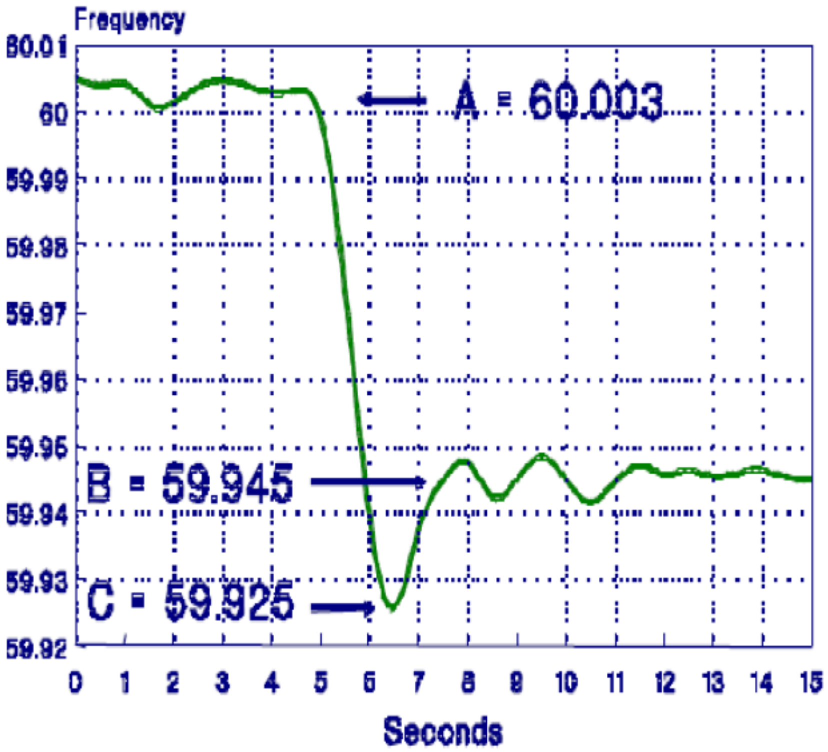
6MW FOR 0.01 Hz

Governor Control



Generator Governor Control

Frequency Response



- Load
  - Rate of frequency decline from points A to C is slowed by “load rejection” and inertia
- Generators
  - Generator governor action halts the decline in frequency and causes the “knee” of the excursion, and brings the frequency back to point B from point C

It is important to note that frequency will not recover from point B to 60 Hz until the deficient control area replaces the amount of lost generation

Generator Governor Control: Droop

- Adding a droop characteristic to a governor forces generators to respond to frequency disturbances in proportion to their size
- Droop settings enable many generators to operate in parallel while all are on governor control and not compete with one another for load changes

Governor Control

- Deadband
  - An additional feature displayed by generators
  - The amount of frequency change a governor must “see” before it starts to respond
  - Natural feature of the earliest governors caused by gear lash (looseness or slop in the gear mechanism)
  - Serves a useful purpose by preventing governors from continuously “hunting” as frequency varies ever so slightly

Generator Characteristics

- Generator limitation factors
  - Power capability of the prime mover
  - Heating of generator components (I2R losses)
  - Necessity to maintain a strong enough magnetic field to transfer power from the rotor to the generator output

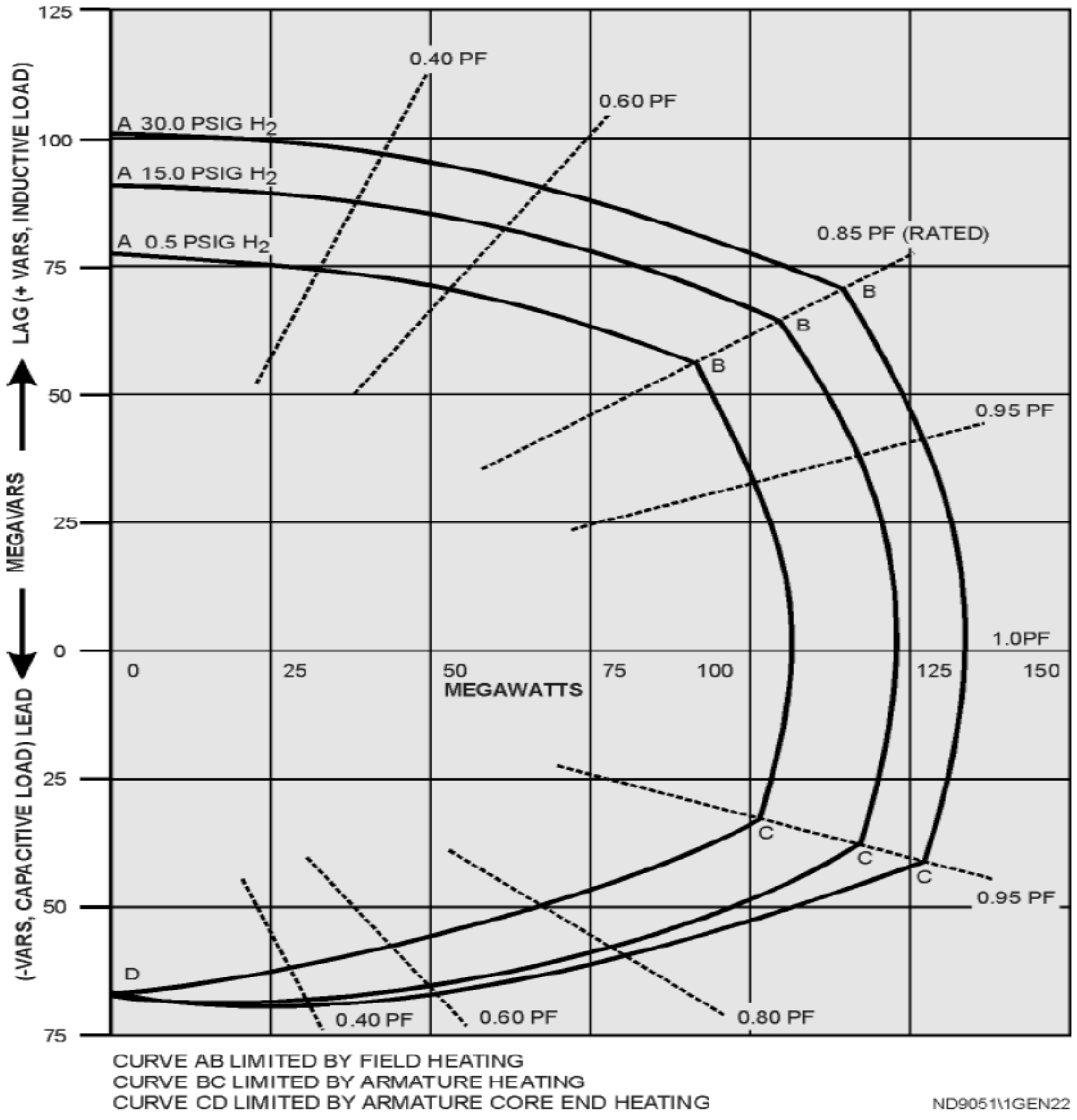
Generator Characteristics

- Heating of generator components
  - Heat generated within the armature windings is directly related to the magnitude of the armature current
  - Heat generated in the rotor is directly related to the magnitude of the field current
  - Heat dissipated by the generator is limited by the cooling system design

Generator Characteristics

- Magnetic field strength
  - Controlled by excitation voltage
  - If excitation voltage is lowered:
    - Voltage induced in A.C. windings is lowered
    - More VARS absorbed by generator from system
    - Undervoltage can cause overcurrent conditions in the stator and lead to armature or stator heating
  - Capability curves provide Max/Min limits

Capability Curve



Reactive Capability Curve

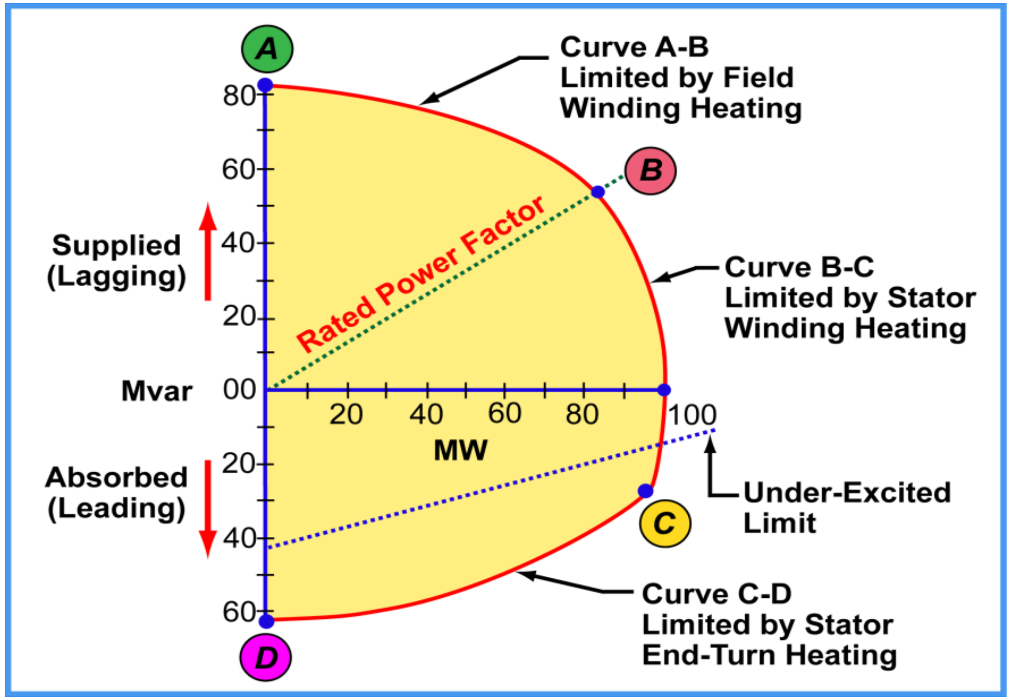
- Generating Unit Reactive Capability is a measurement of the reactive power able to be delivered by a generating unit to the transmission system
- It is defined by the MW versus MVAR points of a generator capability curve
- For real-time changes, each Generation Owner should also notify PJM and the respective Transmission Owners via phone

Reactive Capability Curve

Reactive Capability (or “D”) Curves

- Generators Report "Continuous Unit Reactive Capability Curve"
  - Realistic usable capability sustainable during continuous unit operation
  - Based on actual operating experience

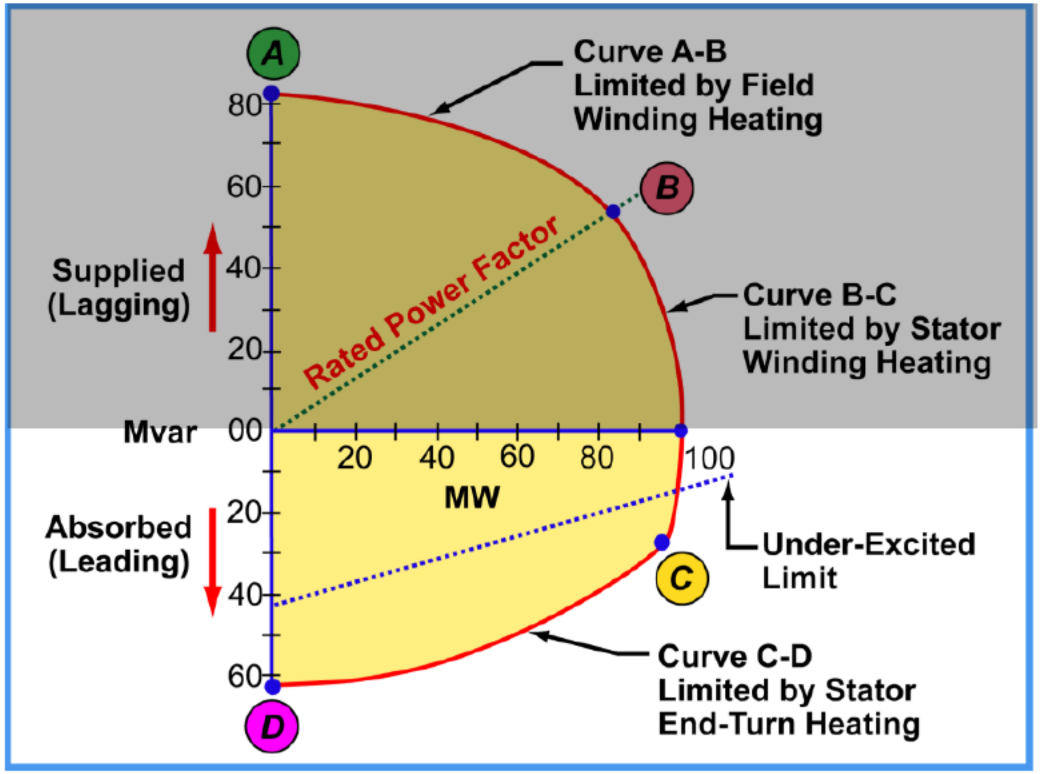
    (or testing)
  - Takes into consideration any normal unit or plant restrictions at 95˚ F ambient or above



Reactive Capability Curve

Generating Unit

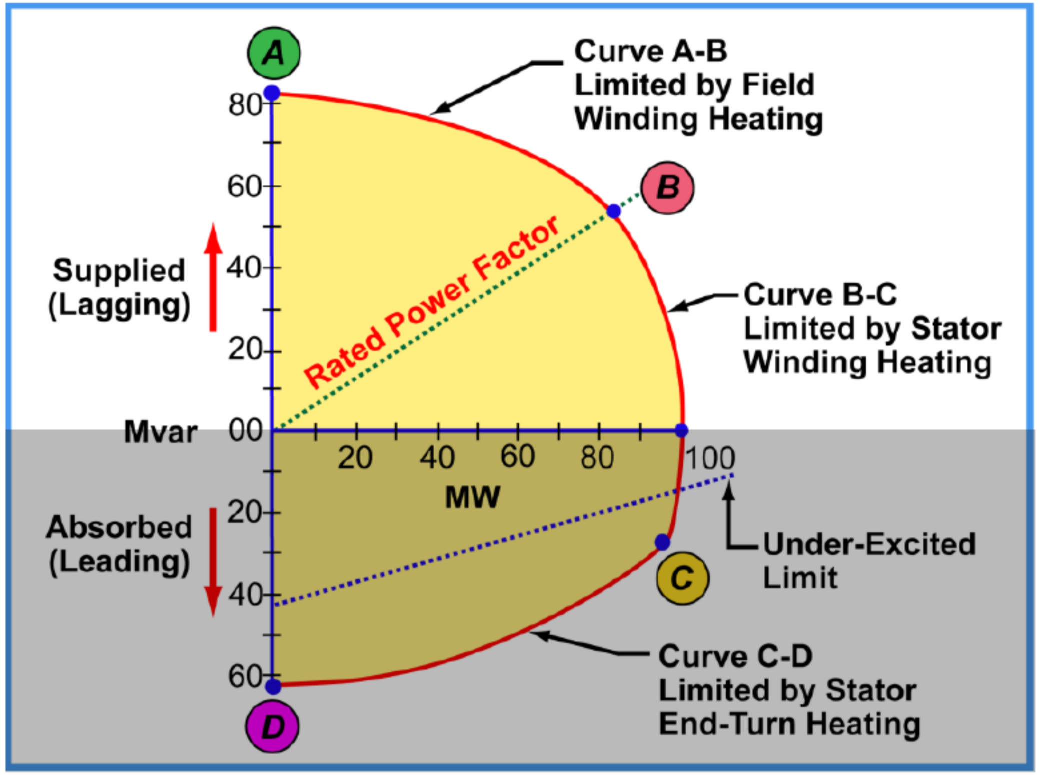
- Unit Over-Excitation
  - Limit on field heating, limits MVAR generation
  - Rotor overheating is I^2R heating caused by DC current over-excitation



Reactive Capability Curve

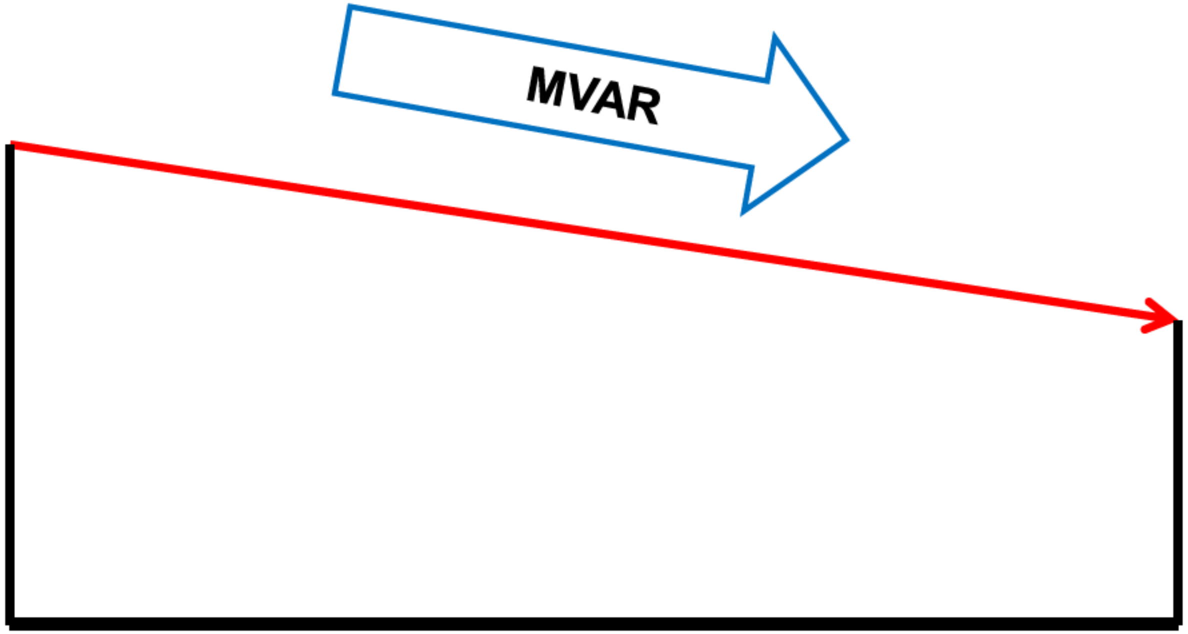
Generating Unit

- Unit Under-excitation
  - Limit on end turn heating
  - Unit instability
    - Field strength too weak, unit goes unstable
    - Area Stability concerns
      - Salem
      - PS South



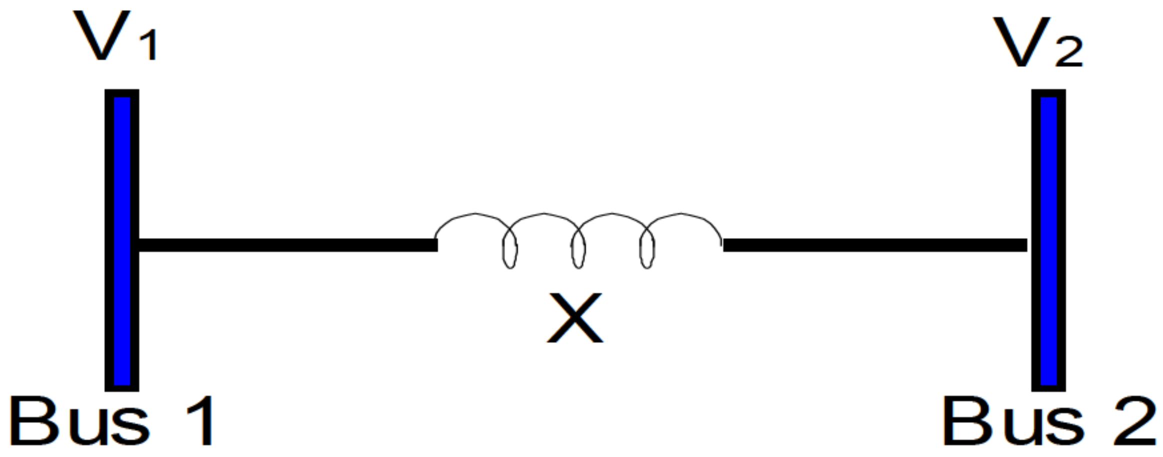
MVAR Flow & Voltage

- MVARs flow “downhill” based on voltage
- Flow from high per unit voltage to low per unit voltage



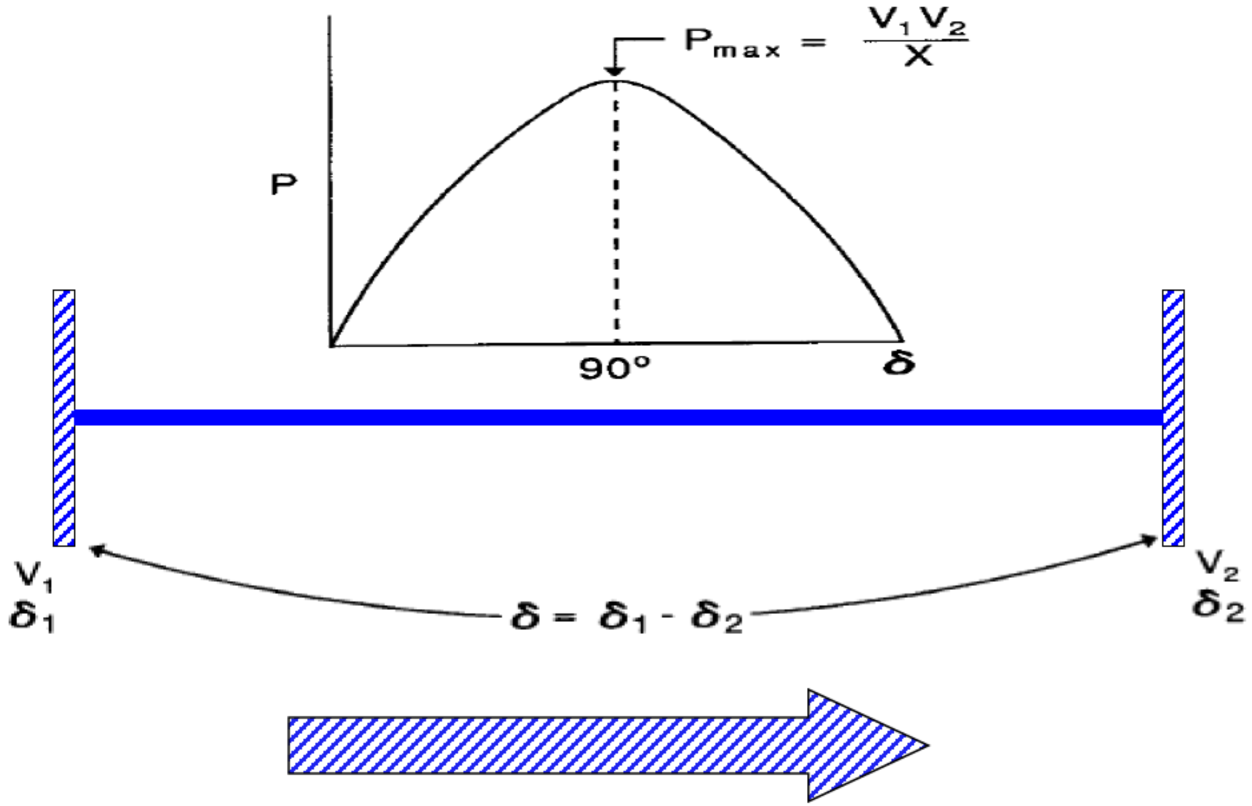
MVAR Flow & Voltage

- MVAR flow between buses is determined by magnitude difference between bus voltages
- Voltage magnitude difference is driving for MVAR flow
- The greater the voltage drop or rise between 2 locations – the greater the MVAR flow



$$\text{VARs} = \frac{V_1\,(V_1 - V_2)}{X}$$

MW Flow & Power Angle



$$P = \frac{V_1 V_2}{X} \text{ SIN } (\delta)$$

MW Flow & Power Angle

- MW flow between buses is determined by phase angle difference between voltages at the buses
- Phase angle difference between voltages is called Power Angle which is represented by the symbol Delta δ

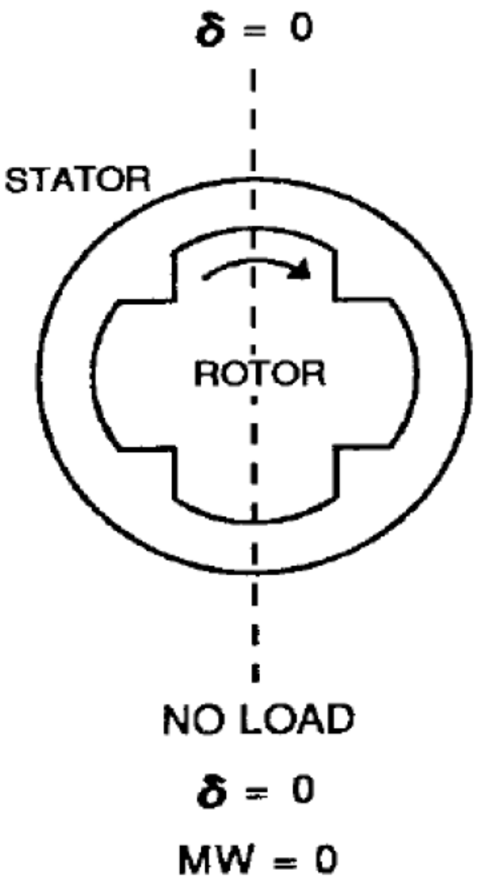
$$P = \frac{V_1 V_2}{X} \text{ SIN } (\delta)$$

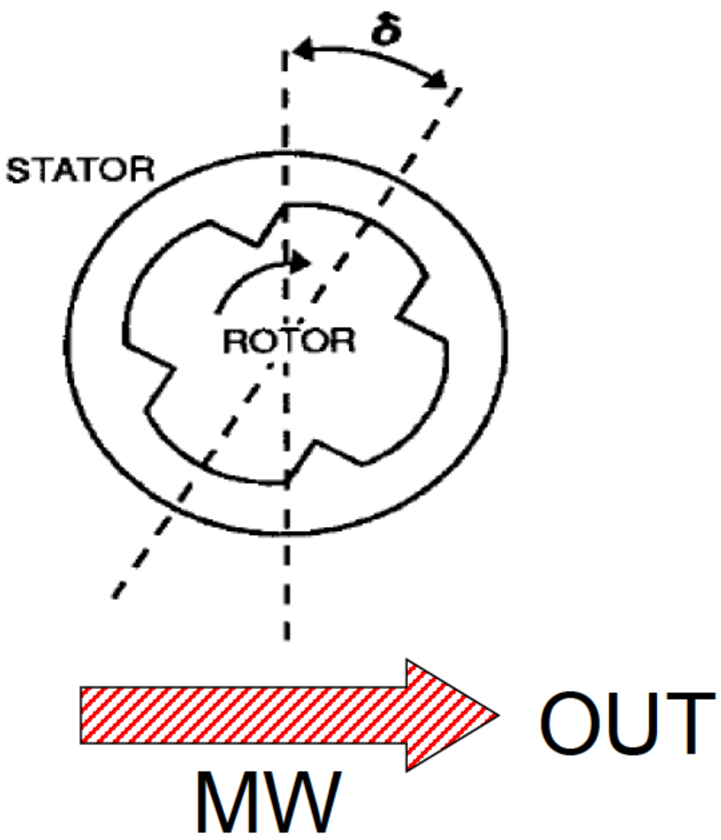
Generator MW Flow & Power Angle

- Rotor Angle
  - On a transmission system is similar to rotor angle
    - Load or Torque angle
  - No Load
    - Field pole of rotor is “in phase” with stator armature windings
    - $\delta = 0$
  - Load Added
    - Rotor advances with respect to the stator
    - MW’s flow out of the machine

Bismark Torque Angle Sim

MW Flow & Power Angle





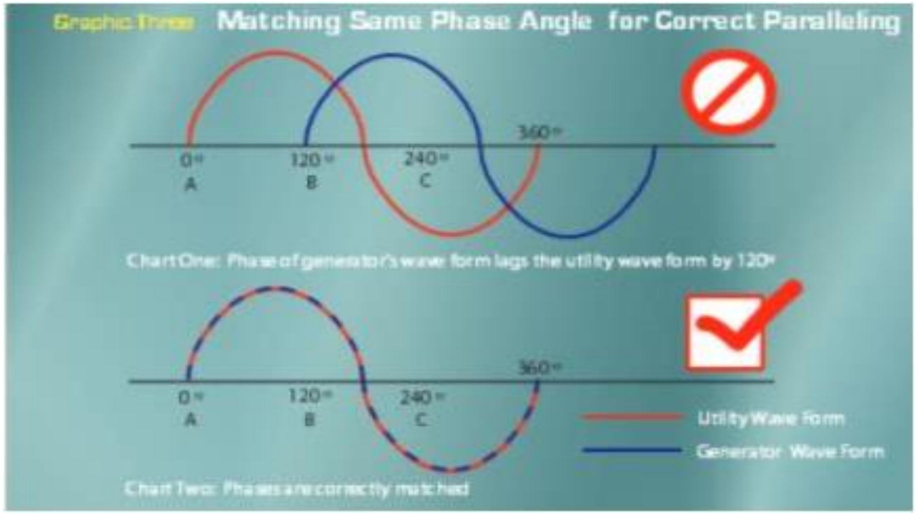
Generator Synchronization

- Synchronization is the process of precisely coordinating or matching two or more activities, devices, or processes in time

- Synchronization, in the electric industry, is the process of matching the speed, frequency, and voltage of a generator or other source to a “running” network
  - Conditions must be met to prevent unwanted and excessive energy flows when paralleling

Generator Synchronization

- The objective of synchronization is to match speed and phase position so there is little or no transfer of energy when paralleling a unit to a system or two systems
  - Voltage Magnitude (MVAR)
  - Frequency Magnitude (MW)
  - Phase Angle Deviation (MW)
  - Phase Sequence (Current)



Generator Synchronization

- Manual synchronizing is performed by plant or field operators by manually adjusting frequency and voltage of the generator or area to be paralleled and ultimately closing the circuit breaker to tie the “incoming” system to the “running” system

- For manual synchronization, meter panels are used to provide information
  - Individual bus and generator frequency meters
  - Individual bus and generator AC voltmeters
  - Synchroscope
  - Two indicating lamps

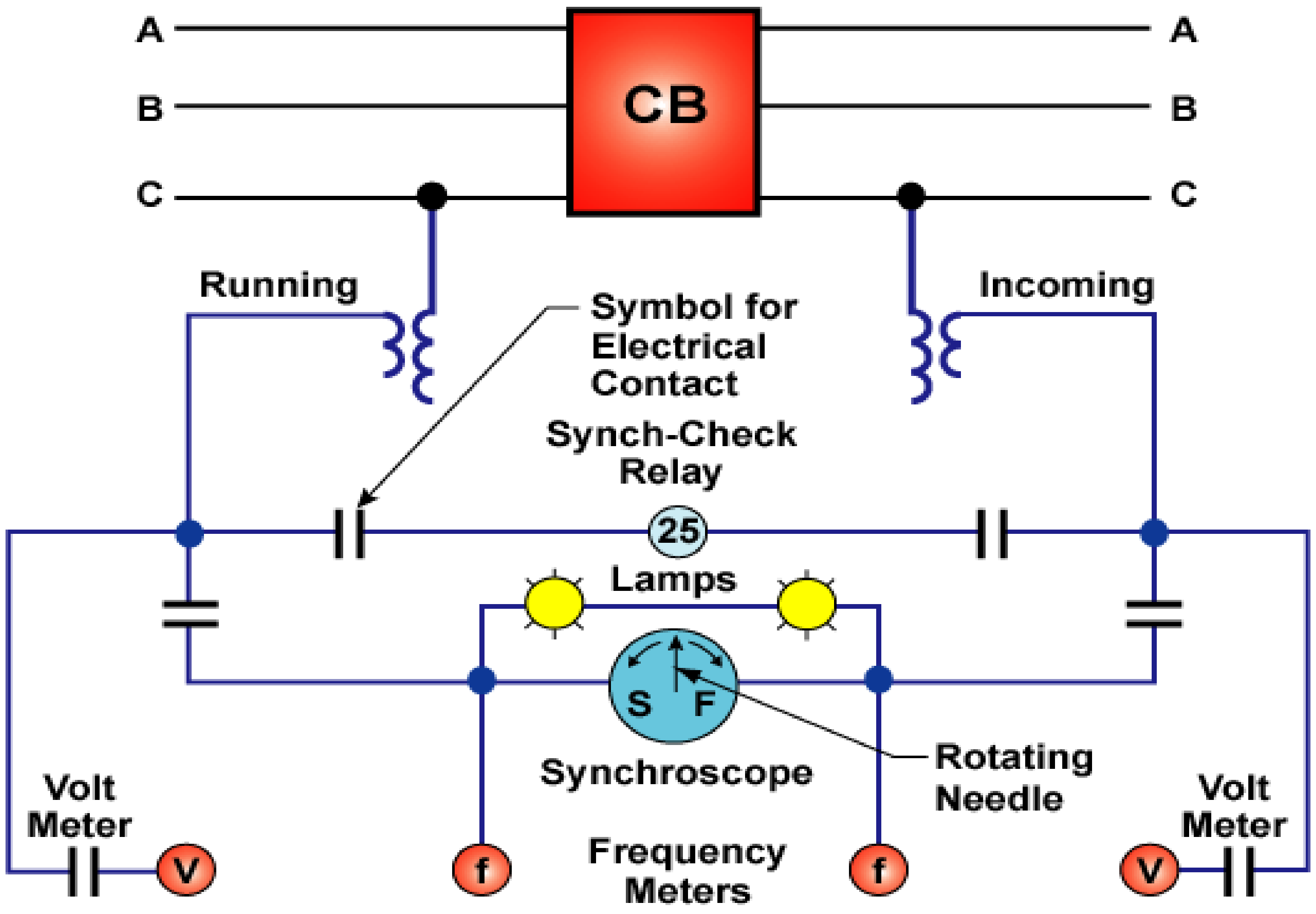
Generator Synchronization

- Synchroscope is a multiple parameter information source
  - Indicates a frequency difference between the generator or area and the “running” system (slip rate)
    - Indicates if the generator or area frequency is running slower or faster than the “running” area
  - Indicating incandescent lamps demonstrate that the “incoming” and “running” system are in phase

Bismark Synch Lab

Generator Synchronizing

Voltage
Frequency
Phase Angle



Questions?

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Member Community

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