



Basics of Electricity

Generator Theory

PJM State & Member Training Dept.

Objectives



The student will be able to:

- 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

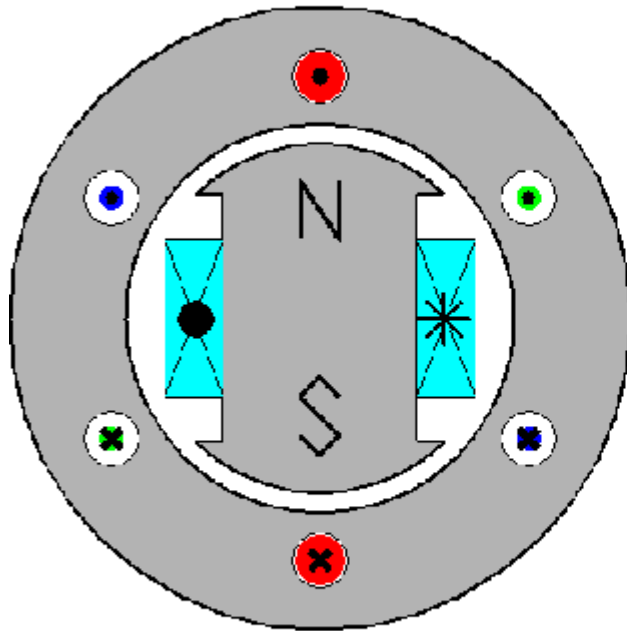
Basic Operating Principles

- 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

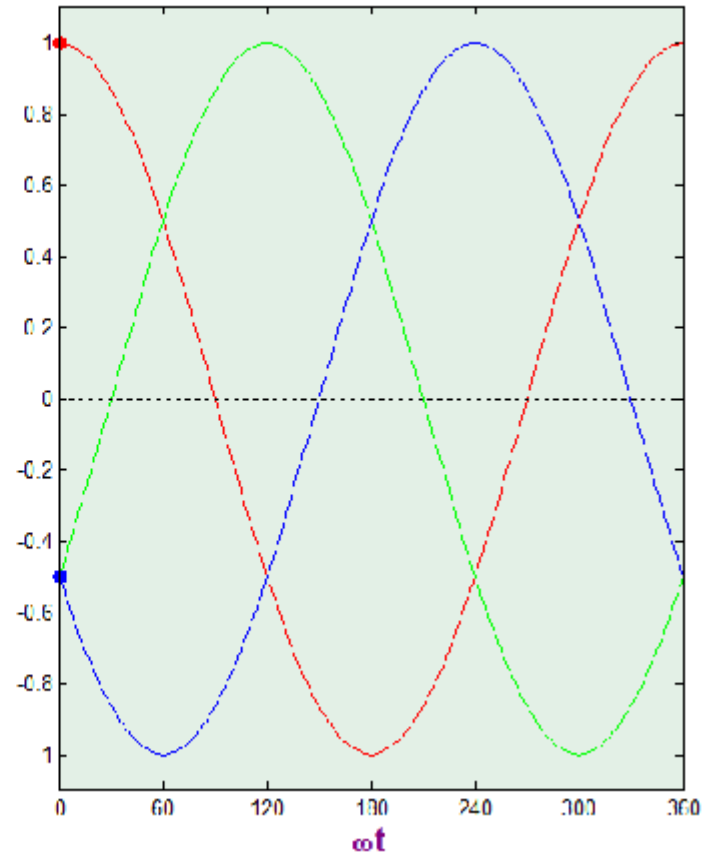
Basic Operating Principles



Phase A

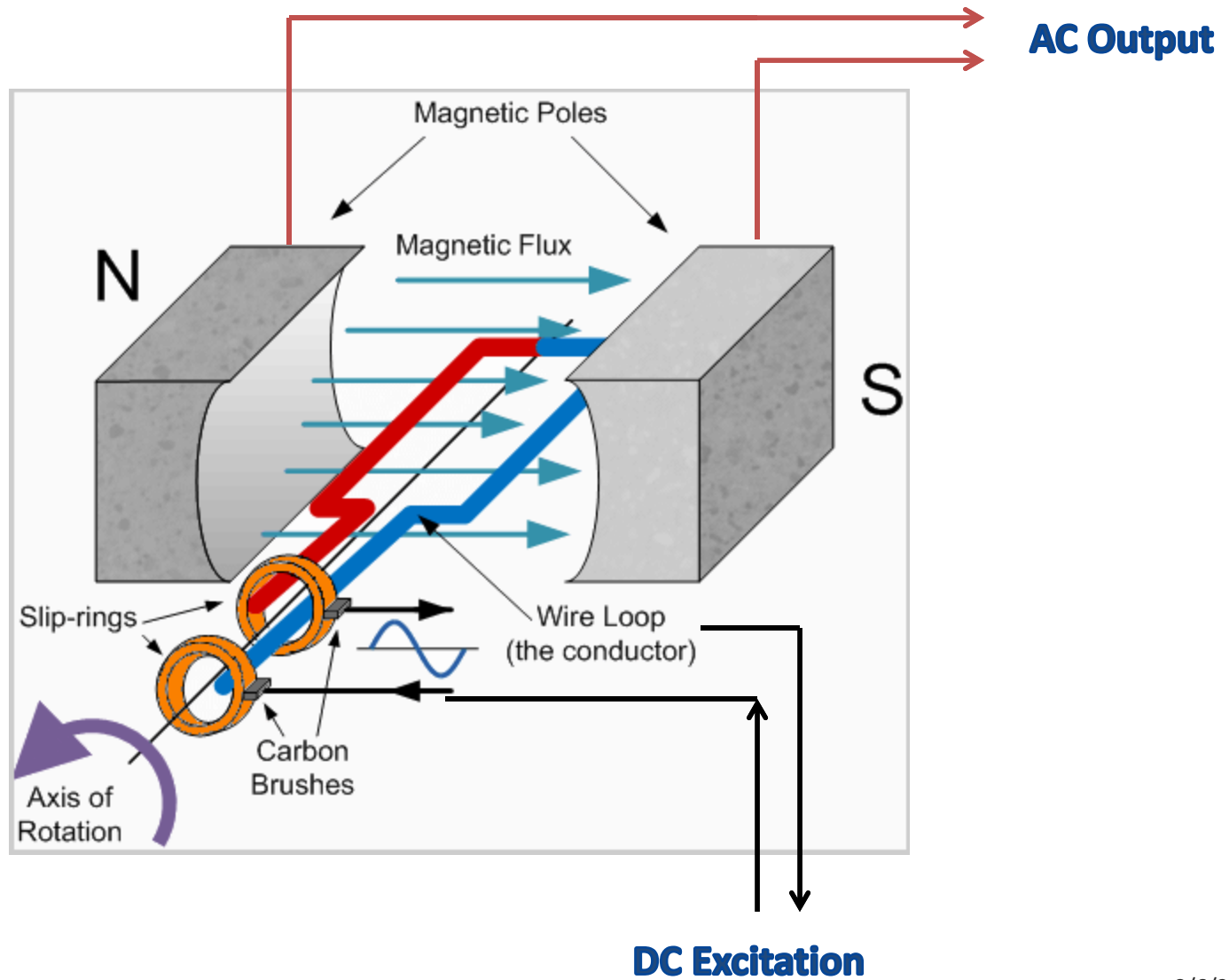
Phase B

Phase C



Bismark Phasor Sim

Basic Operating Principles



A.C. Generator Components: Rotor

- Rotating Magnetic Field
- Series of Conductors

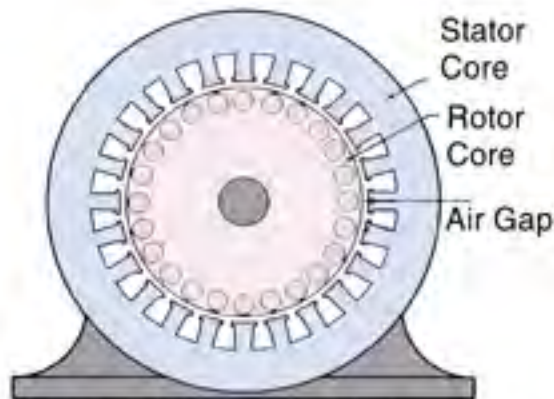


A.C. Generator Components: Rotor

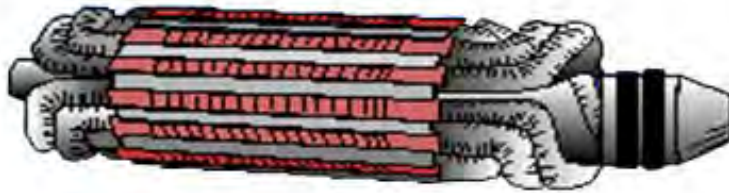
- The basic function of the rotor is to produce a magnetic field of the size and shape necessary to induce the desired output voltage in the stator
- The rotating field is required to produce a given number of lines of magnetic flux which is obtained by: **Ampere-turns**
- Ampere-turns is the product of the number of turns in the rotor winding and the current that flows in the winding

A.C. Generator Components: 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



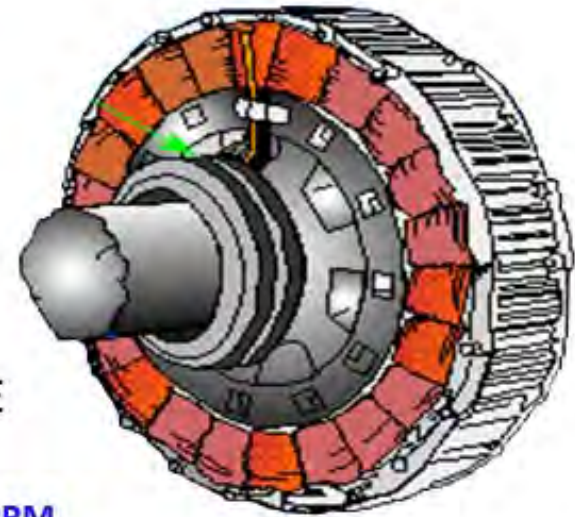
A.C. Generator Components: Rotor



TURBINE DRIVEN ROTOR

HIGH SPEED = 1200 RPM OR MORE

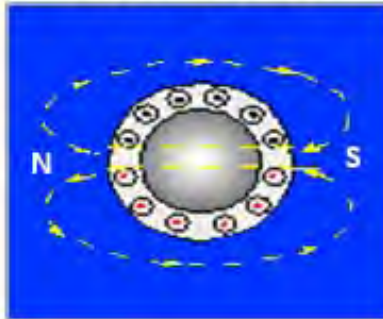
SLIP RINGS



SALIENT-POLE ROTOR

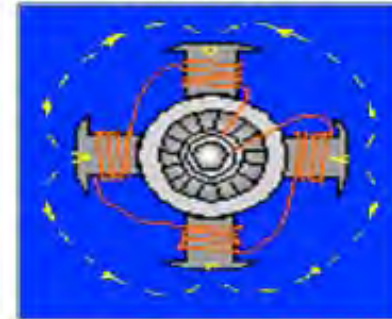
LOW SPEED = 1200 RPM OR LESS

CROSS - SECTION



LINES OF MAGETIC FORCE

SCHEMATIC



A.C. Generator Components: 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

A.C. Generator Components: Rotor

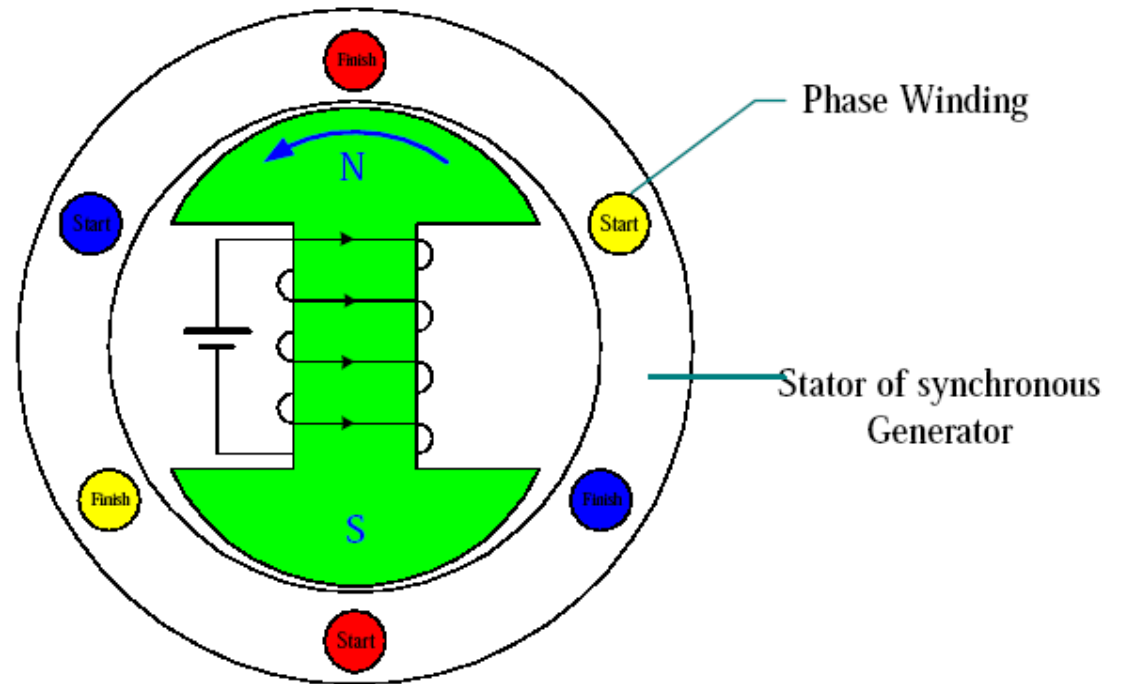
Advantage:

- 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



A.C. Generator Components: Rotor

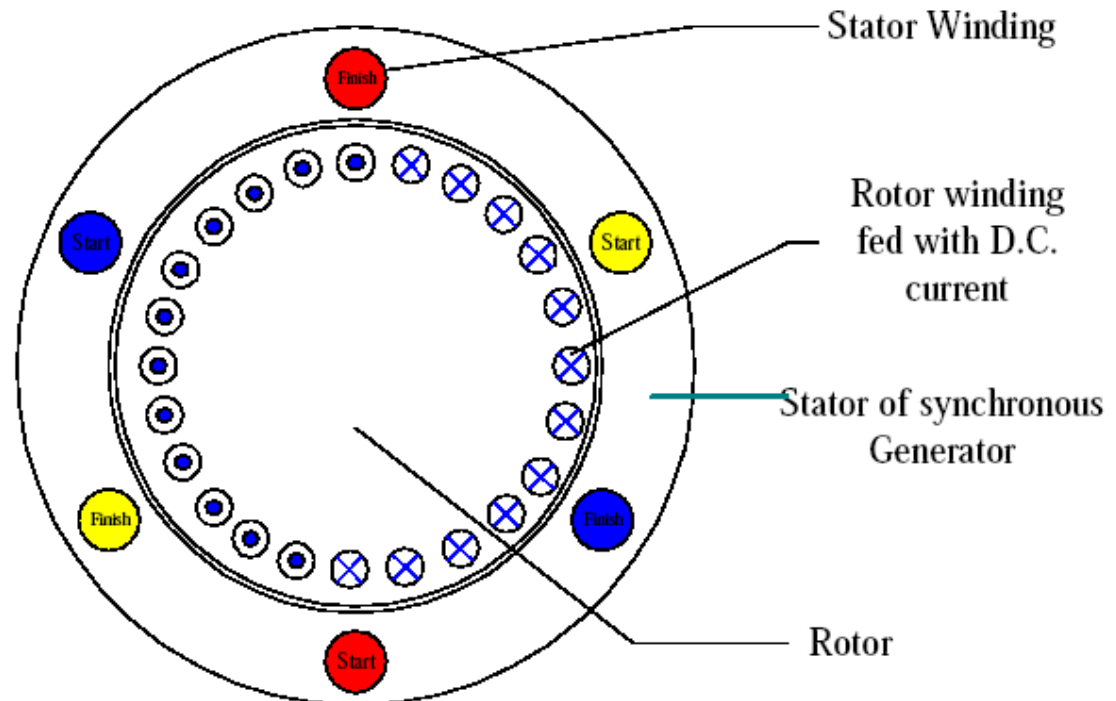
Advantage:

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

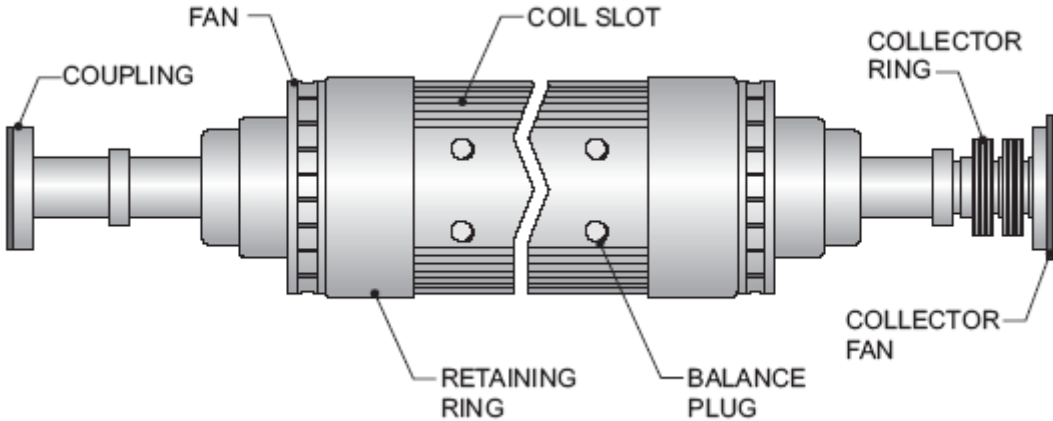
Disadvantage:

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

Cylindrical rotor synchronous generator



A.C. Generator Components: Rotor



A.C. Generator Components: Stator



A.C. Generator Components: Stator

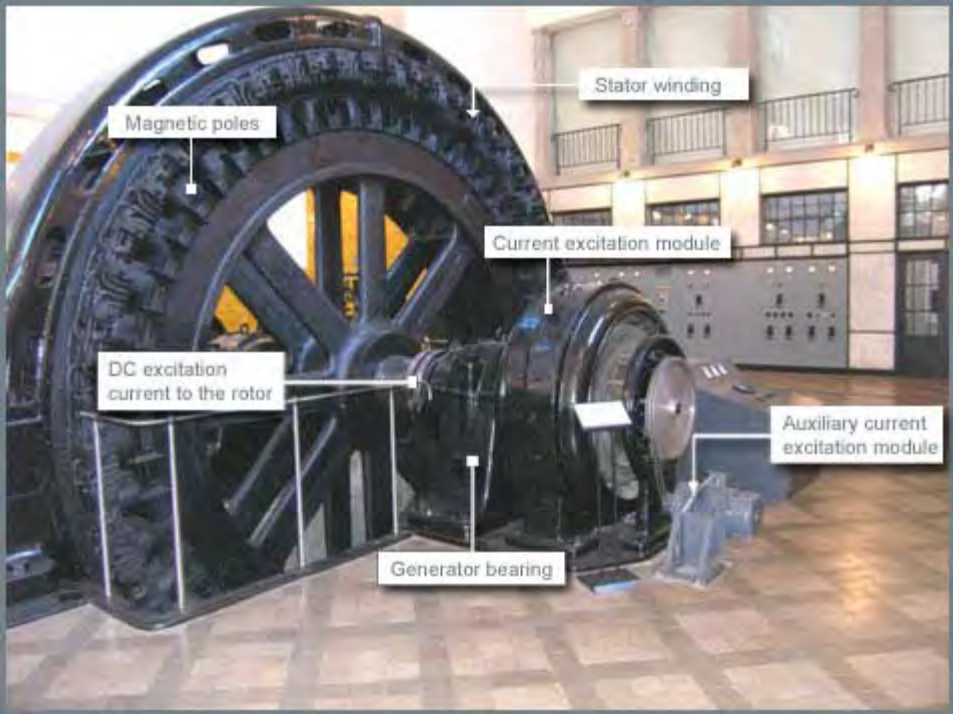
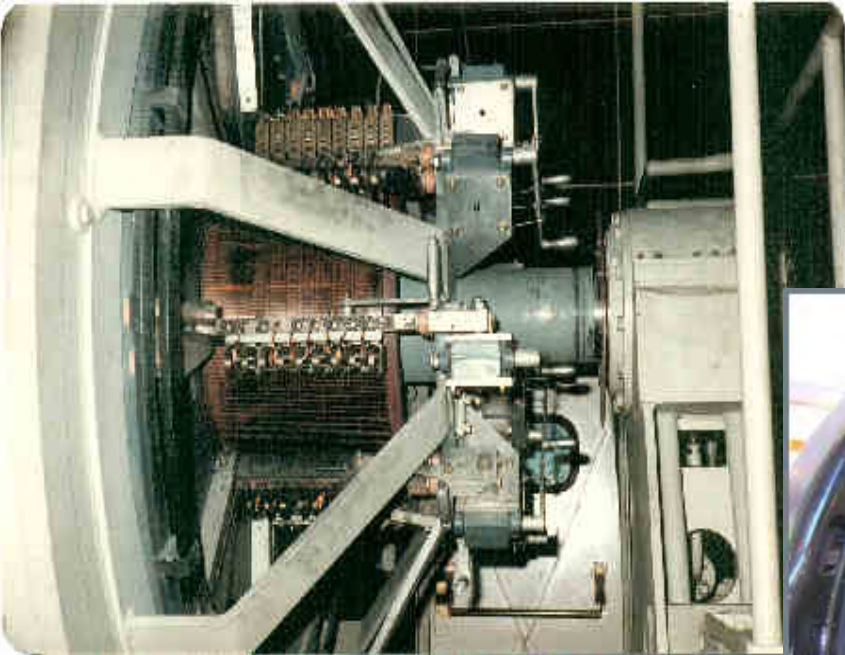
- The stator is the stationary part of the generator that is comprised of a series of stationary windings or “poles”(phases)
- Basic function of the stator core is to provide a return path for the lines of magnetic flux, and support the coils of the stator winding
- The stator core is made of soft iron to provide the magnetic field path with a high permeability
- The iron is laminated to reduce eddy currents (opposing field) and hysteresis (power losses)

A.C. Generator Components: 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



A.C. Generator Components: Exciter



A.C. Generator Components: 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 Rotational Speed

- Frequency is dependent on:

- Number of field poles
- Speed of the generator

- $f = (N)(P)/120$, where

f = frequency (Hz)

N = rotor speed (rpm)

P = total number of poles

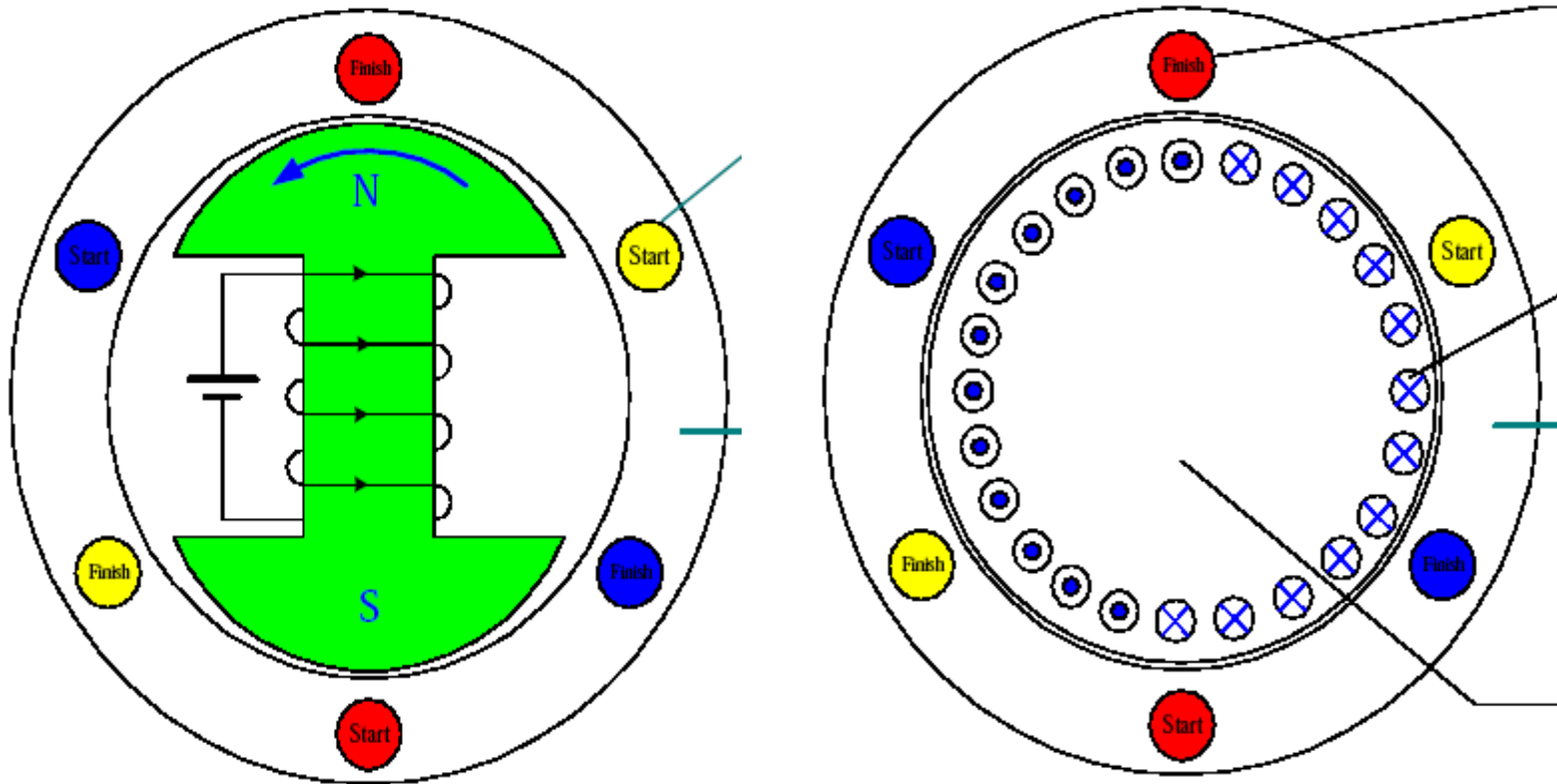
120 = Conversion from minutes to seconds and from “poles” to “pole pairs”

(60 seconds/1 minute) x (2 poles/pole pair)

Generator Rotational Speed

Example: 2 Poles

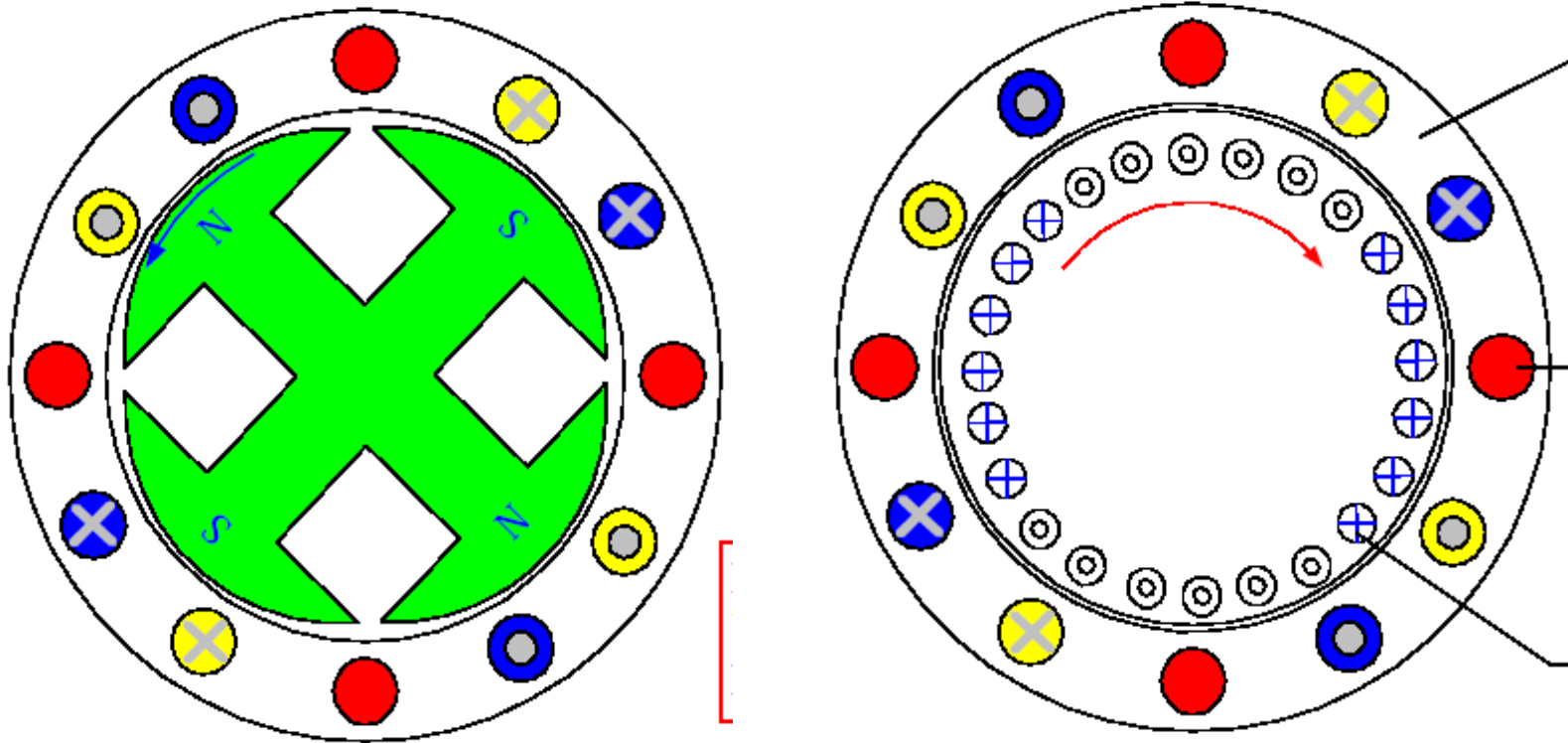
$$60 \text{ Hz} = (3600 \text{ RPM})(2 \text{ Poles})/120$$



Generator Rotational Speed

Example: 4 Poles

$$60 \text{ Hz} = (1800 \text{ RPM})(4 \text{ Poles})/120$$

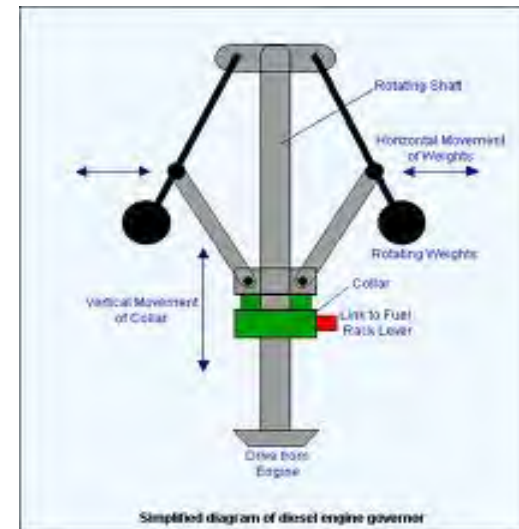


Generator Governor Control

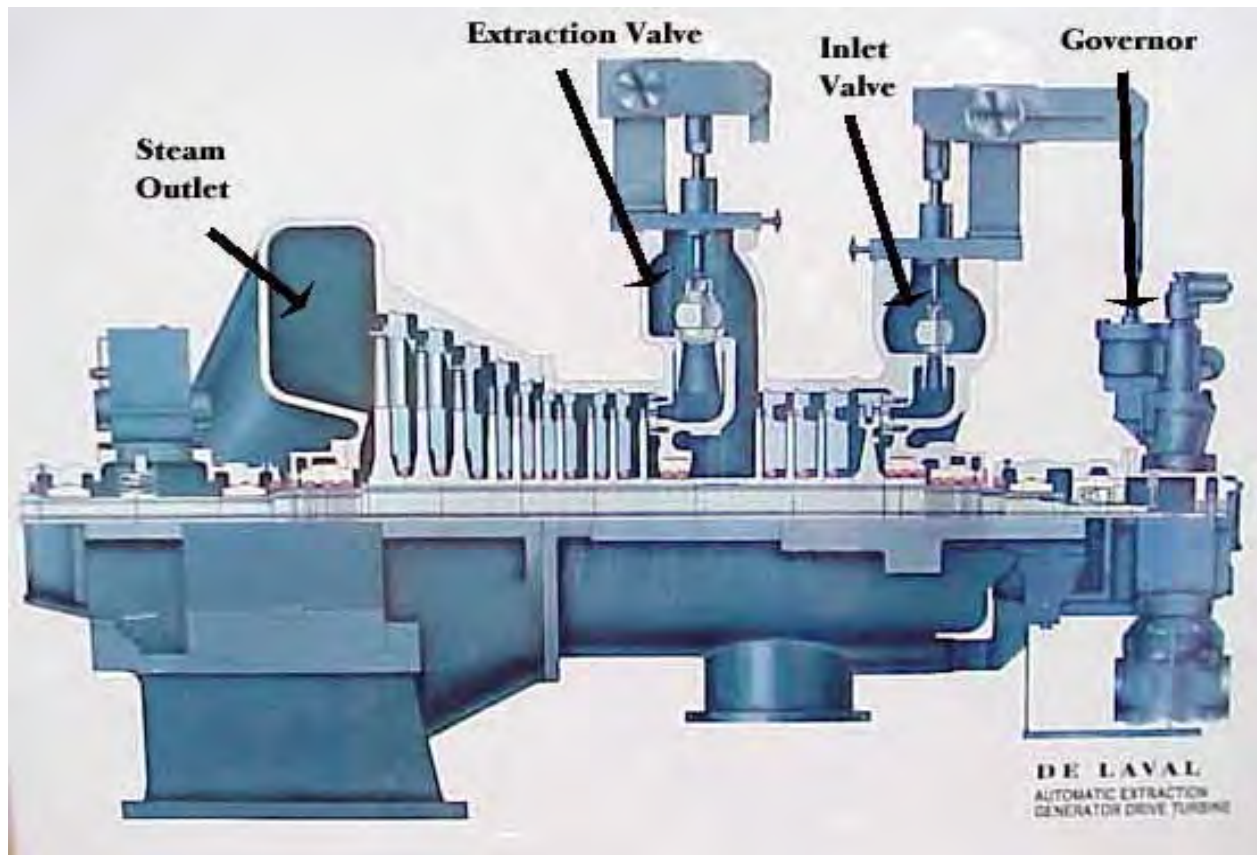
- Governors control generator shaft speed
- Adjust generation for small changes in load
- Operate by adjusting the input to the prime mover
 - Steam flow for fossil
 - Water flow for hydro
 - Fuel flow for combustion turbine
- Amount of governor control varies according to plant design
- Equivalent to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

Generator Governor Control

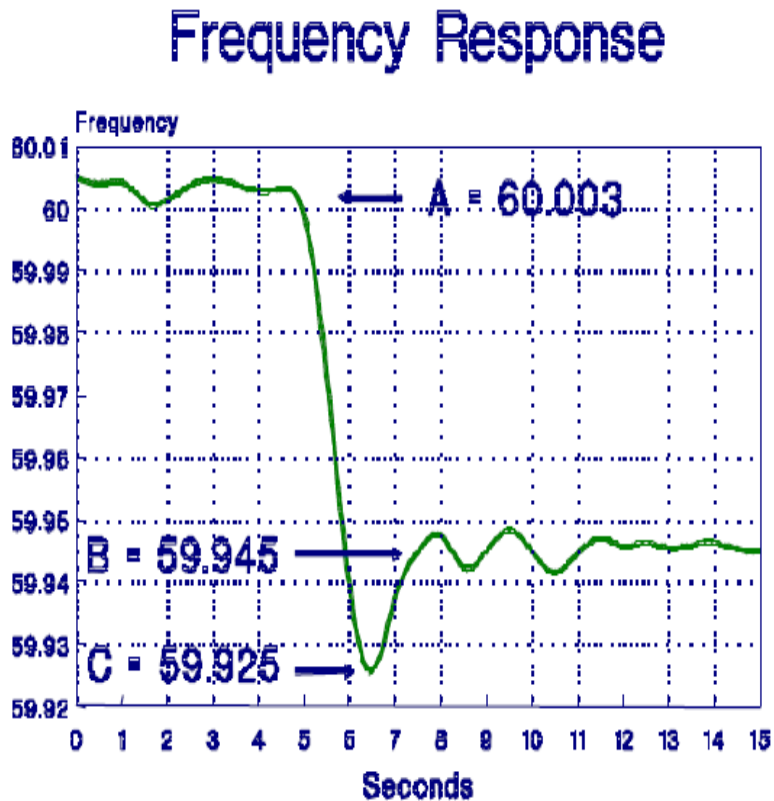
- The Watt centrifugal governor was the mechanical means for governor control
 - Used weights that moved radially as rotational speed increased that pneumatically operated a servo-motor
 - Electrohydraulic governing has replaced the mechanical governor because of:
 - High response speed
 - Low deadband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



Generator Governor Control



Generator Governor Control



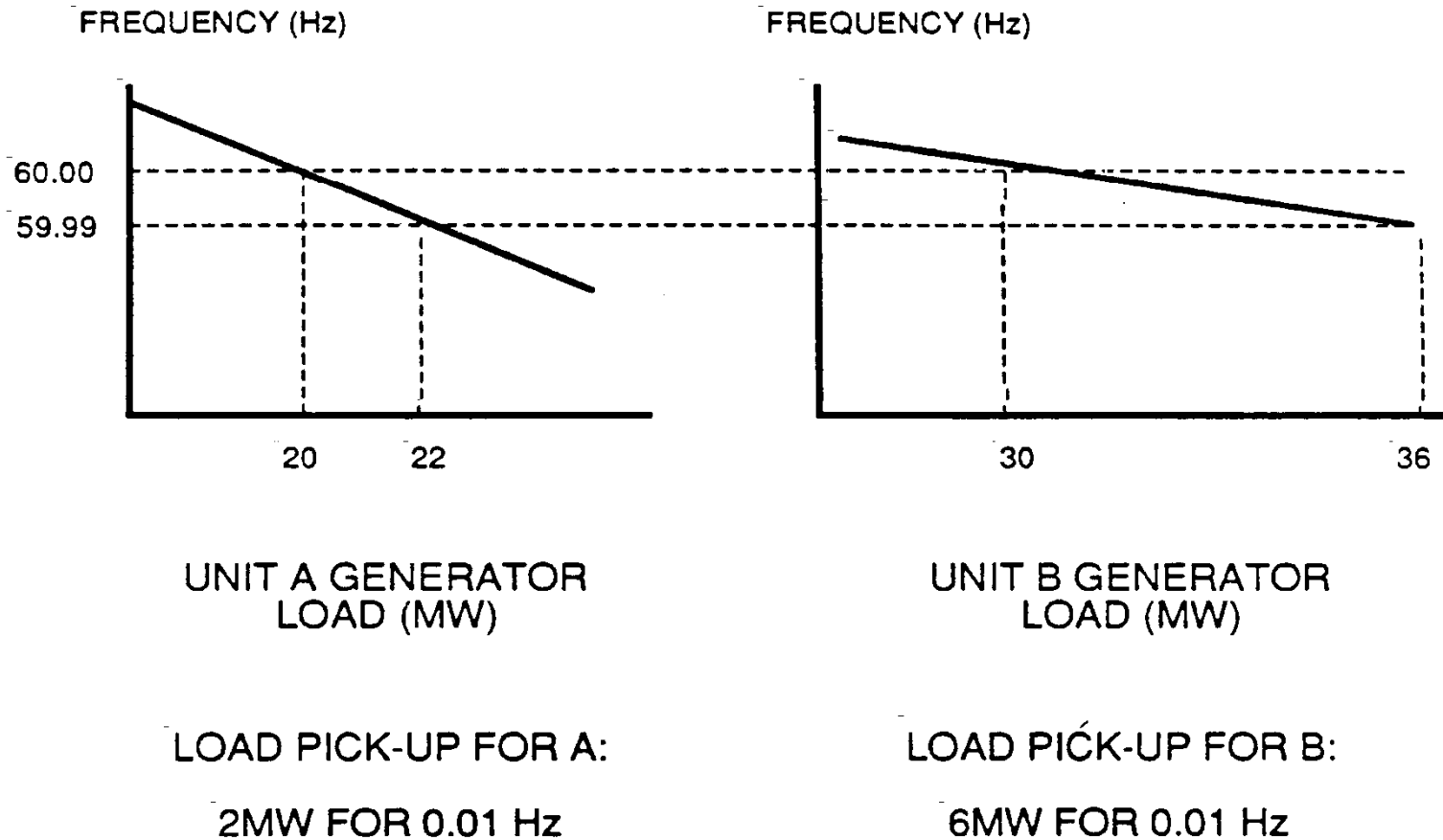
- Load
 - Rate of frequency decline from points A to C is slowed by “load rejection”
- Generators
 - Generator governor action halts the decline in frequency and causes the “knee” of the excursion, and brings the frequency back to point B from point C

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

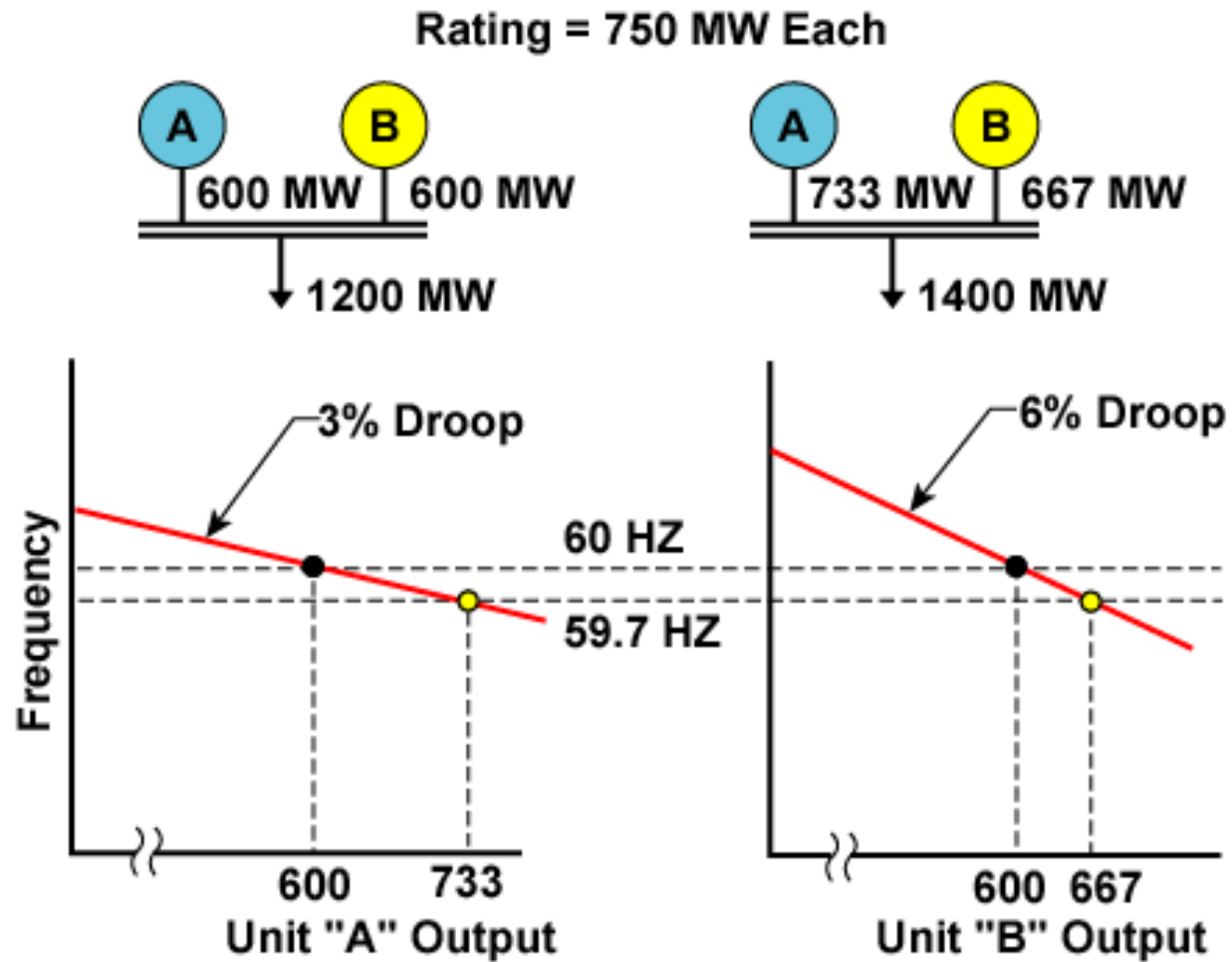
Generator Governor Control: Droop

- 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

Generator Governor Control: Droop



Generator Governor Control: Droop



Generator Governor Control: Deadband

- Deadband
 - An additional feature displayed by governors
 - The amount of frequency change a governor must “see” before it starts to respond
 - Really a natural feature of the earliest governors caused by friction and 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 (I^2R losses)
 - Necessity to maintain a strong enough magnetic field to transfer power from the rotor to the generator output

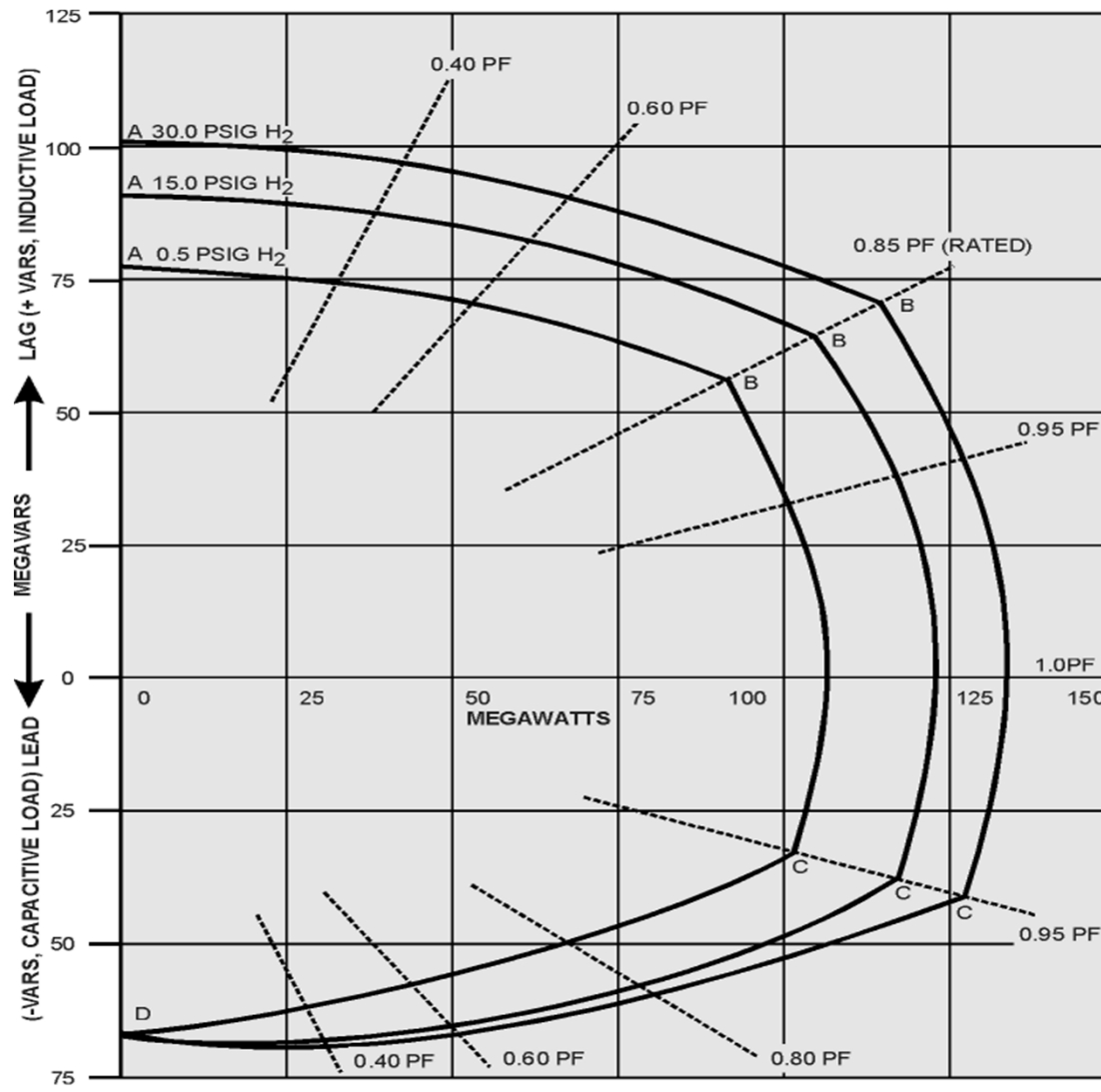
Generator Characteristics

- Heating of generator components
 - Heat generated within the armature and field windings is directly related to the magnitude of current flowing through them
 - Generator losses:
 - Based on resistance of the field winding of the rotor
 - Based on resistance and inductive reactance of the armature windings of the stator causing a voltage drop that subtracts from the output voltage
 - 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



CURVE AB LIMITED BY FIELD HEATING
 CURVE BC LIMITED BY ARMATURE HEATING
 CURVE CD LIMITED BY ARMATURE CORE END HEATING

ND9051\1GEN22

Nameplate Data

Main Generator "Nameplate" Characteristic Data	
• Rated Output	• 496,000 kVA
• Rated Voltage	• 22,000 v
• Rated Stator Current	• 13,017 amps
• Rated Field Current	• 3,017 amps
• Power Factor	• 0.9
• Poles	• 2
• Phases	• 3
• Electrical Connection	• Wye
• Rated Speed	• 3,600 RPM
• Rated Frequency	• 60 Hz
• Rated Hydrogen Pressure	• 48 psig
• Rated Hydrogen Purity	• 97%

Generator Capability Curve

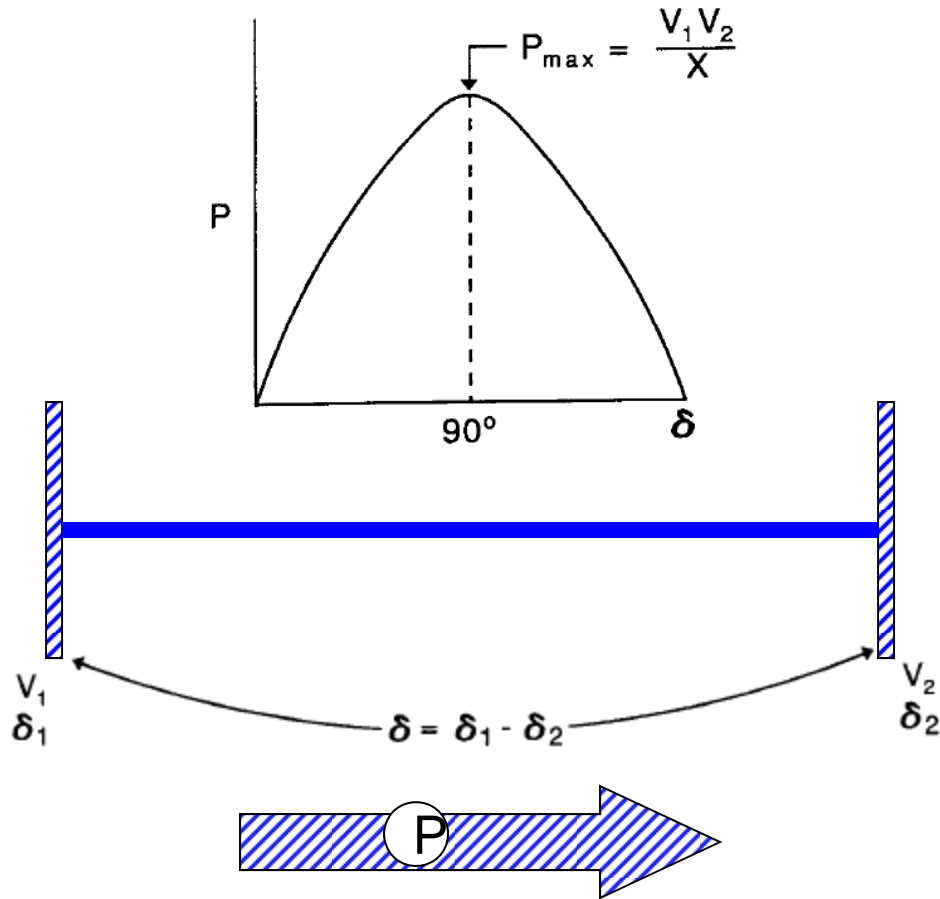
- The steady-state capability of a generator as it is influenced by the power factor is divided into three major components on the curve
- Region A-B: Zero power factor lagging to rated power factor
 - Generator is over-excited
 - Field current is at rated value
 - Capability limitation is field overheating
- Region B-C: Rated power factor lagging through unity to 0.95 power factor leading
 - Capability limitation is dependent on the stator current
 - Maximum nameplate stator amperes should not be exceeded

Generator Capability Curve

- Region C-D: leading power factor operation
 - Excessive heating in the stator end-iron due to flux leakage from the core
 - Capability limitation is end-iron heating
 - This is also an underexcitation region and capability is further reduced by the voltage squared during reduced terminal voltage operation

Generator MW Flow & Power Angle

Power Angle



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

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

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

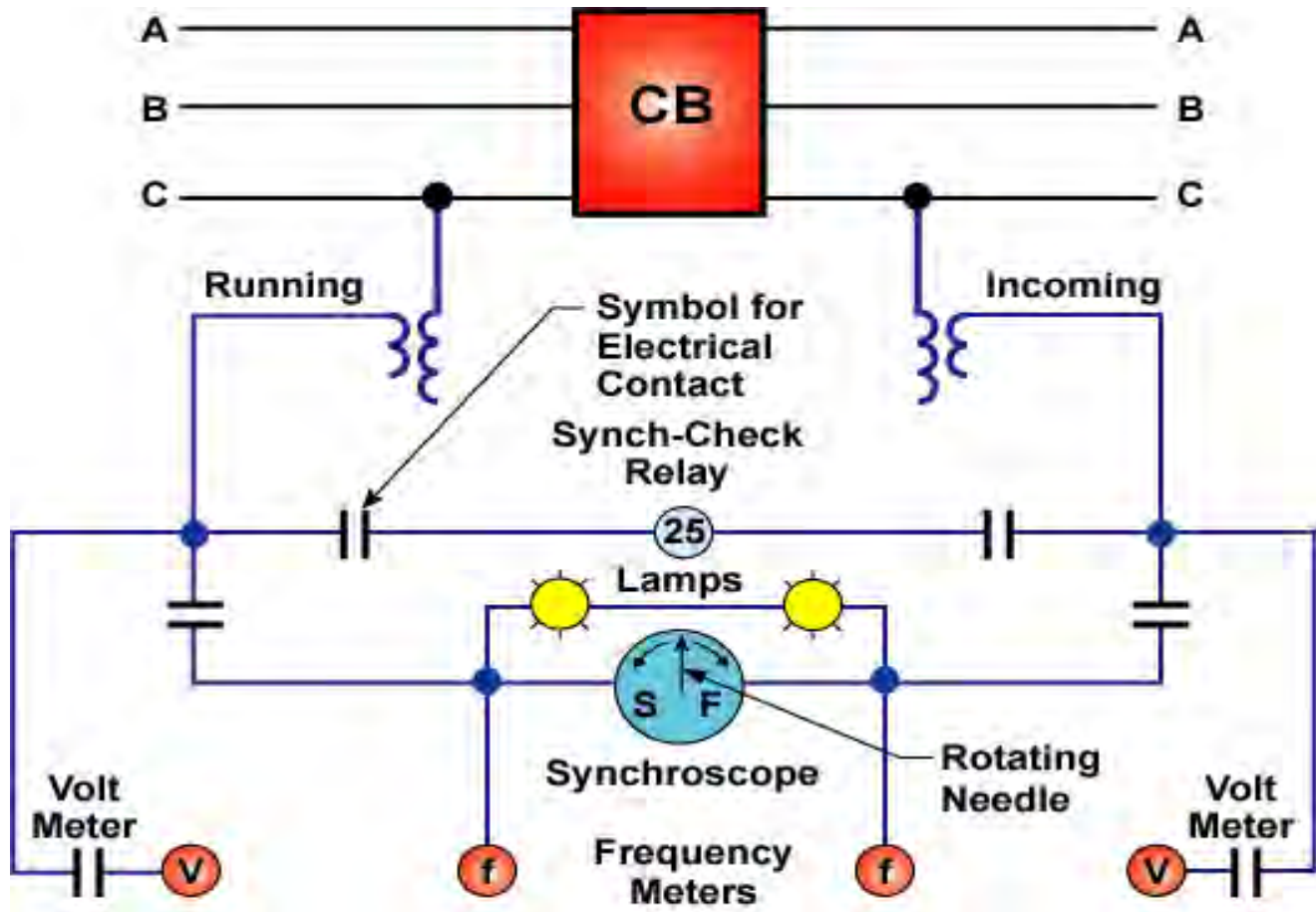
Generator Synchronization

- 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



Summary

- Defined electromagnetic induction and how mechanical energy is converted into electrical energy
- Explained the major components of an AC Generator
- Applied the formula for generator rotational speed
- Described generator governor control to include the droop and deadband characteristics
- Described generator characteristics that can limit the performance of a generator
- Described MVAR and MW flow
- Described the process of synchronizing a generator to the system

Questions?

Resources and References

- Rustebakke, Homer M. (1983). Electric Utility Systems and Practices. New York: John Wiley and Sons
- Miller, Robert H., & Malinowski, James H. (1993). Power System Operation. New York: McGraw-Hill Inc.

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PJM has made all efforts possible to accurately document all information in this presentation. The information seen here does not supersede the PJM Operating Agreement or the PJM Tariff both of which can be found by accessing:

<http://www.pjm.com/documents/agreements/pjm-agreements.aspx>

For additional detailed information on any of the topics discussed, please refer to the appropriate PJM manual which can be found by accessing:

<http://www.pjm.com/documents/manuals.aspx>