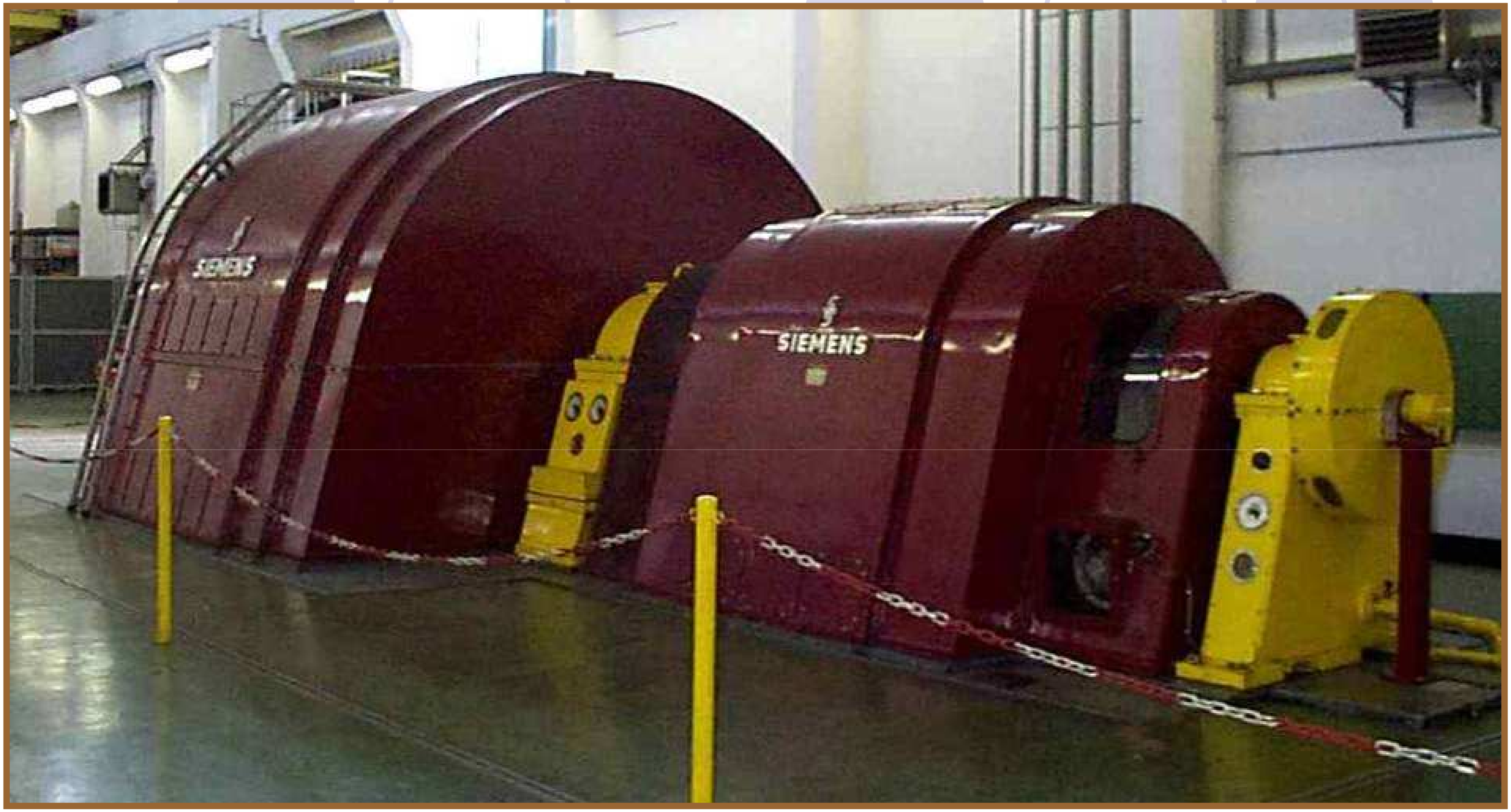
Synchronous Machines

Synchronous Machines

- *Synchronous generators* or *alternators* are used to convert mechanical power derived from steam, gas, or hydraulic-turbine to ac electric power
- Synchronous generators are the primary source of electrical energy we consume today
- Large ac power networks rely almost exclusively on synchronous generators
- *Synchronous motors* are built in large units compare to induction motors (Induction motors are cheaper for smaller ratings) and used for constant speed industrial drives

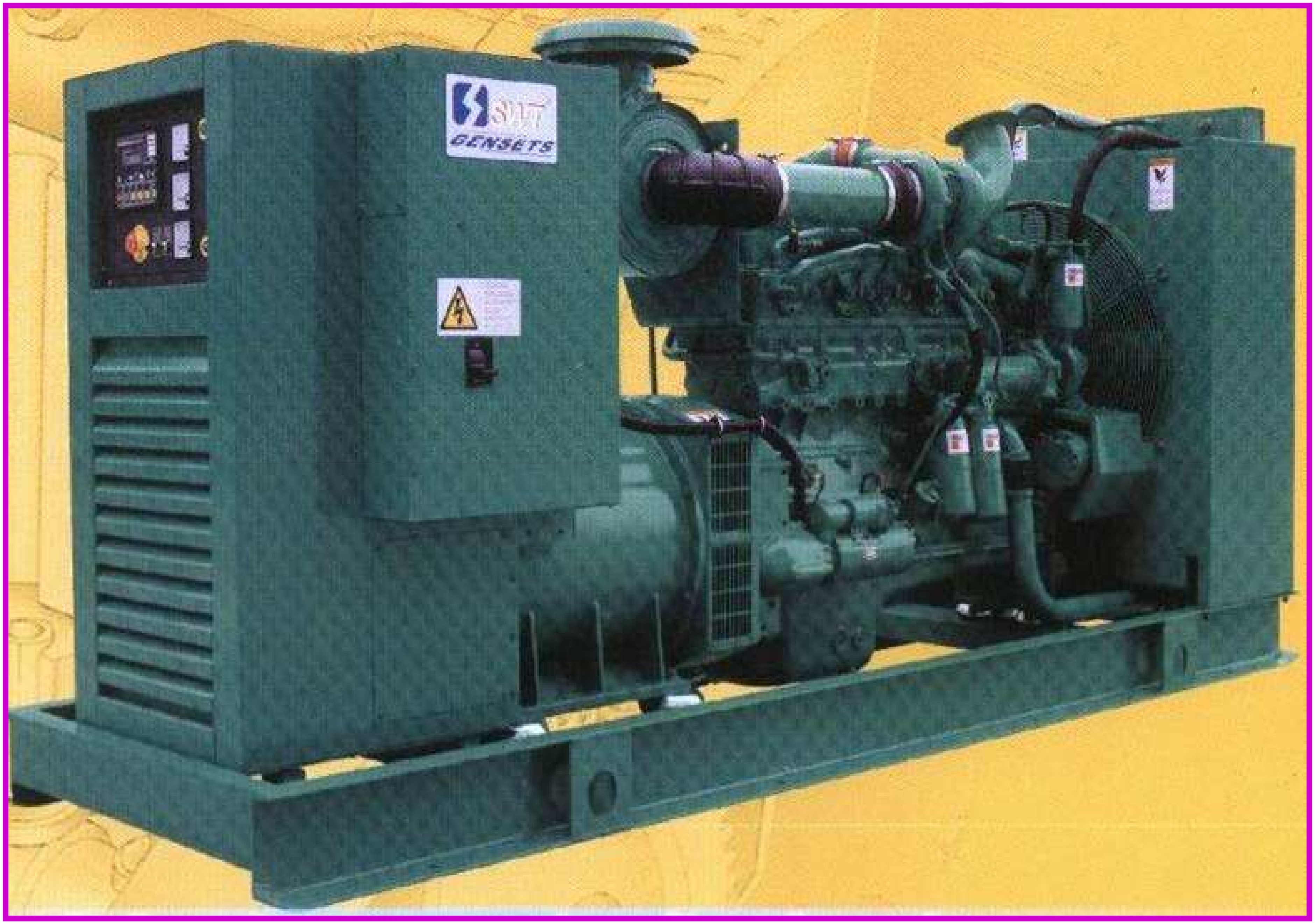

SIEMENS

500 KW Genset / Generator Set, powered with a Cummins VTA28G1 Engine

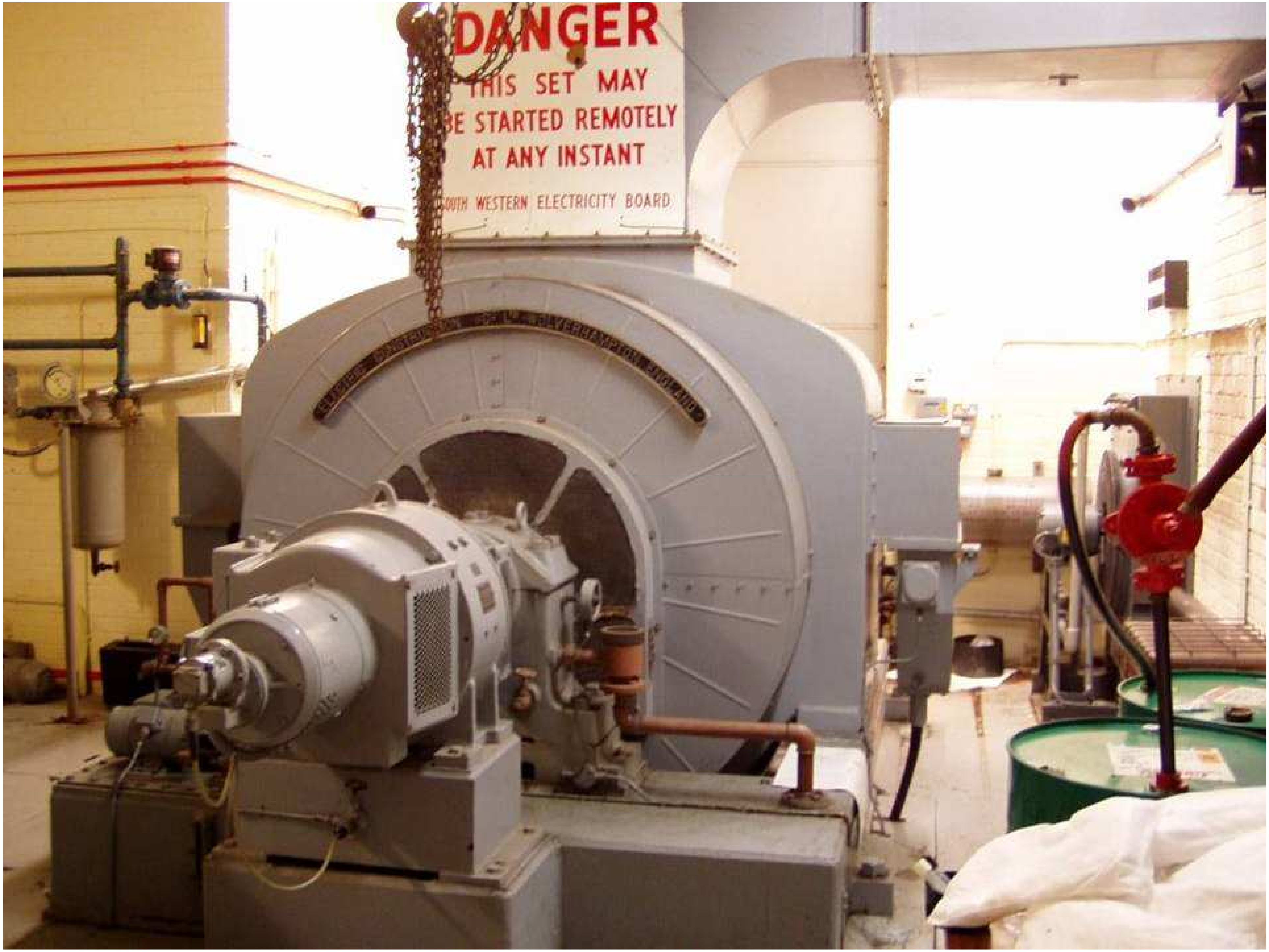

SIEMENS
SIEMENS

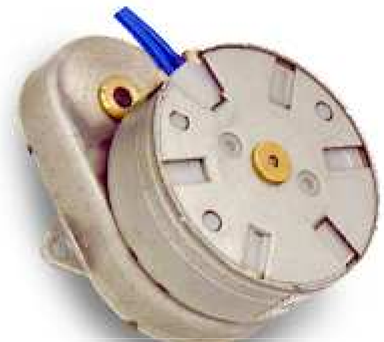

SIEMENS

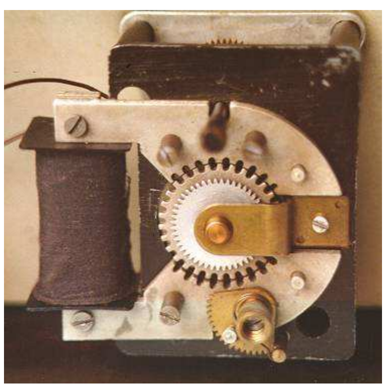
2 x 14MW Synchronous Motors
…apparently, they use permanent magnets!


GENSETS

3 phase Dunlite machine

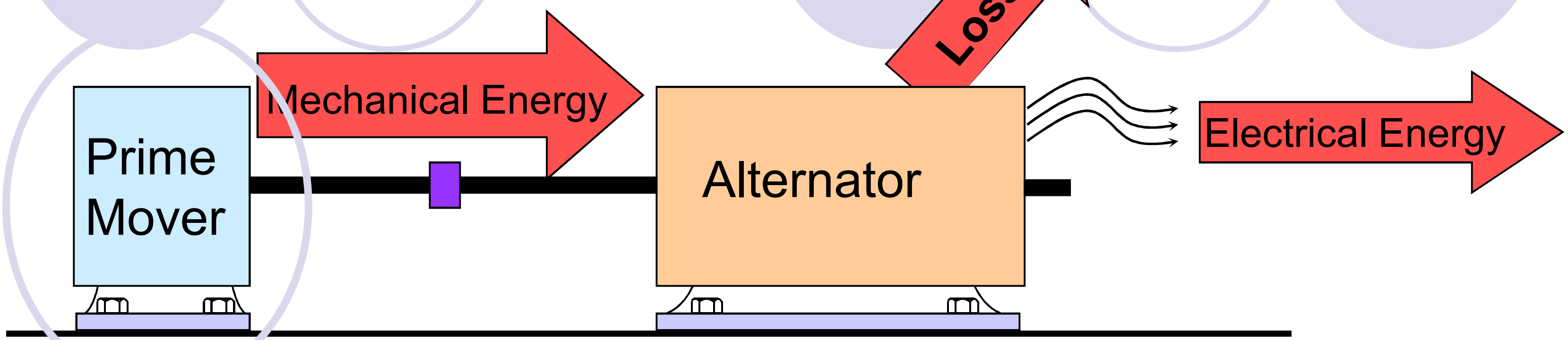

DANGER
THIS SET MAY
BE STARTED REMOTELY
AT ANY INSTANT
SOUTH WESTERN ELECTRICITY BOARD





Synchronous machines are not just the big units, but they can be small also.

Alternator



- Steam Turbine
- Small petrol engine
- Diesel Engine

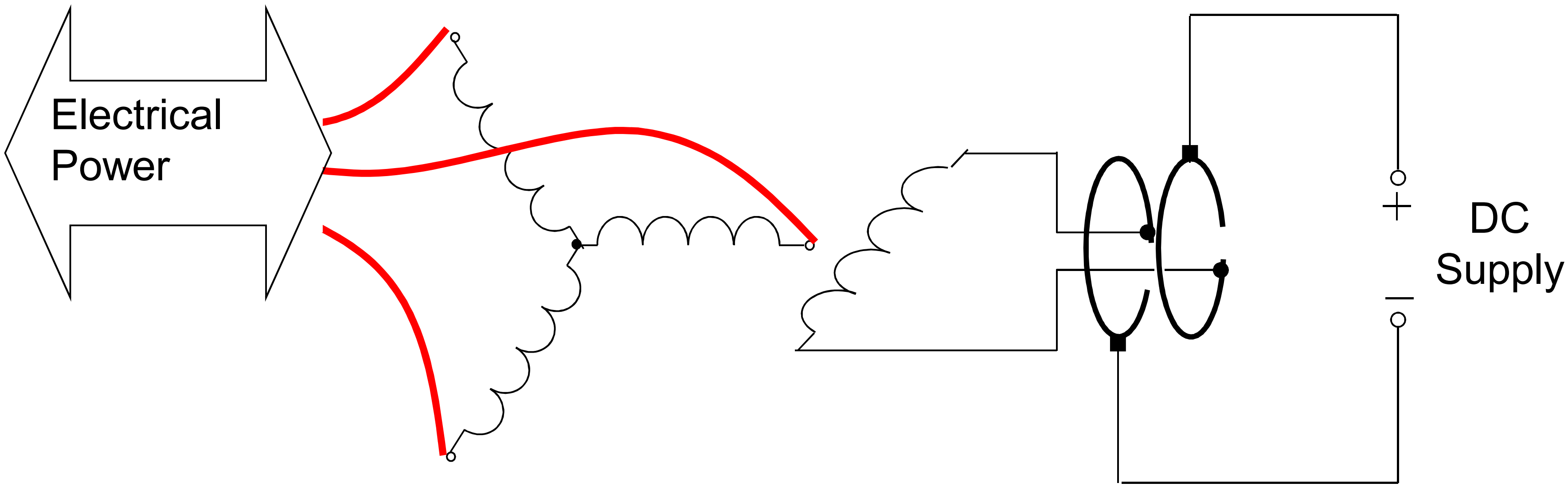
Alternator:

Pin = Pout + Losses

Alternator:

$$Eff\% = \frac{Pout}{Pin} \times 100$$

Synchronous Machine



Stator
- Identically wound to an induction motor.
- Connected to supply.

Rotor
- Constant DC field
- Connected to supply via sliprings.

Construction

- A DC current is applied to the rotor winding, which then produces a rotor magnetic field. The rotor is then turned by a prime mover (eg. Steam, water etc.) producing a rotating magnetic field.
- This rotating magnetic field induces a 3-phase set of voltages within the stator windings of the generator.
- "Field windings" applies to the windings that produce the main magnetic field in a machine, and
- "Armature windings" applies to the windings where the main voltage is induced.
- For synchronous machines, the field windings are on the rotor, so the terms "rotor windings" and "field windings" are used interchangeably.

Construction

- **Basic parts of a synchronous generator:**
  - **Rotor - dc excited winding**
  - **Stator - 3-phase winding in which the ac emf is generated.**
- **The manner in which the active parts of a synchronous machine are cooled determines its overall physical size and structure**

- **Stator of synchronous machines is the same as the stator of induction machines.**

Types of Rotor of synchronous Machines

The rotor of a synchronous generator is a large electromagnet and the magnetic poles on the rotor can either be salient or non salient construction. Non-salient pole rotors are normally used for rotors with 2 or 4 poles rotor (High Speed), while salient pole rotors are used for 4 or more poles rotor (Low Speed).

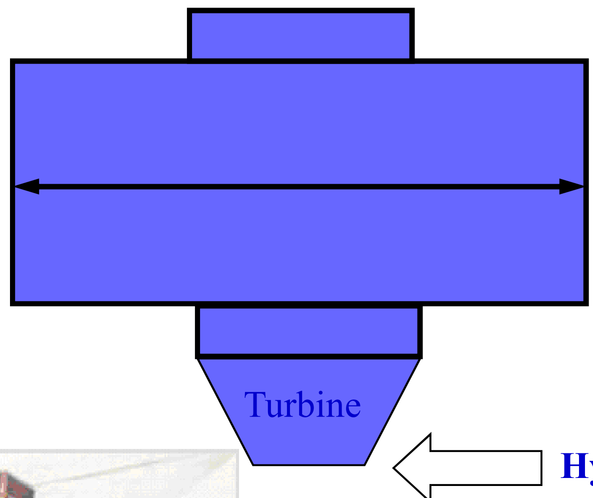
- **Salient-pole synchronous machine**
- **Non Salient Cylindrical or round-rotor synchronous machine**

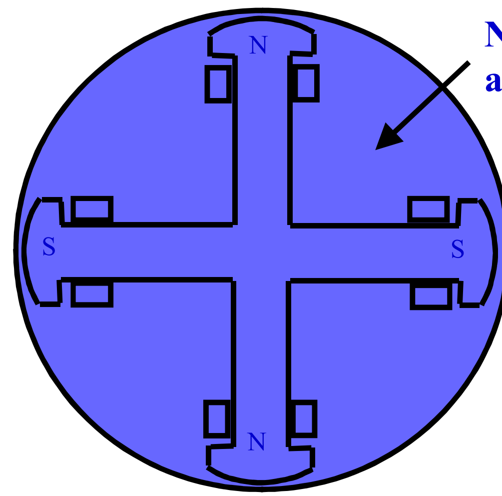
Salient Pole Rotors

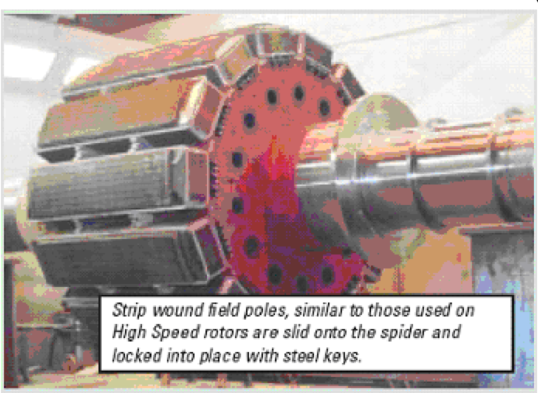
1. The salient rotor has protruding poles.
2. The salient rotor has several poles.
3. The salient rotor has large diameter (2 to 6m) to accommodate several poles and short axial length (1m).
4. Salient pole rotor are used for low speed Hydro generators.

Salient-Pole Synchronous Generator

1. **Most hydraulic turbines have to turn at low speeds (between 50 and 300 r/min)**
2. **A large number of poles are required on the rotor**

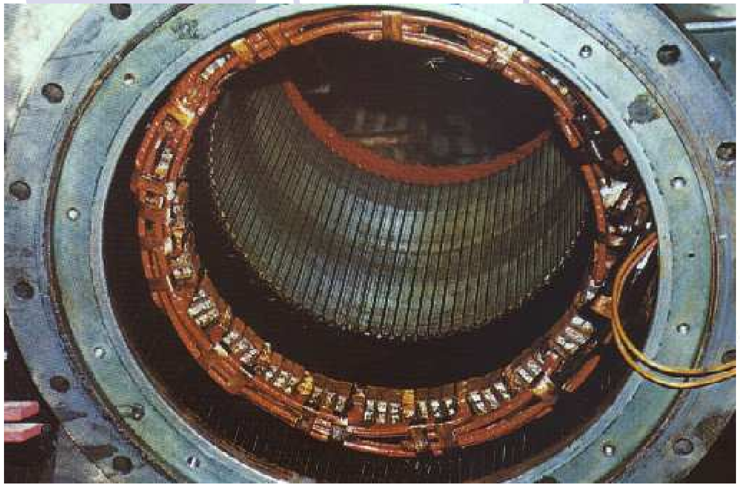




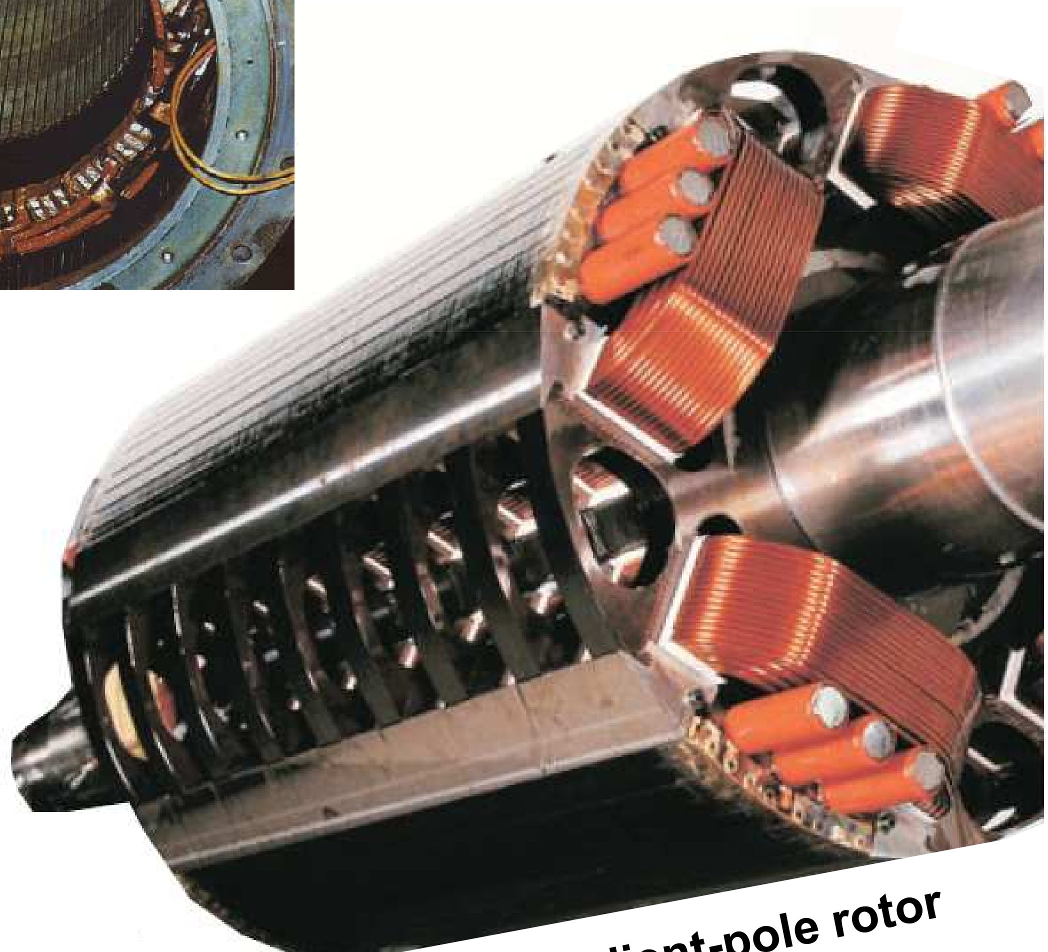


Hydro generator

Salient-Pole Synchronous Generator



Stator

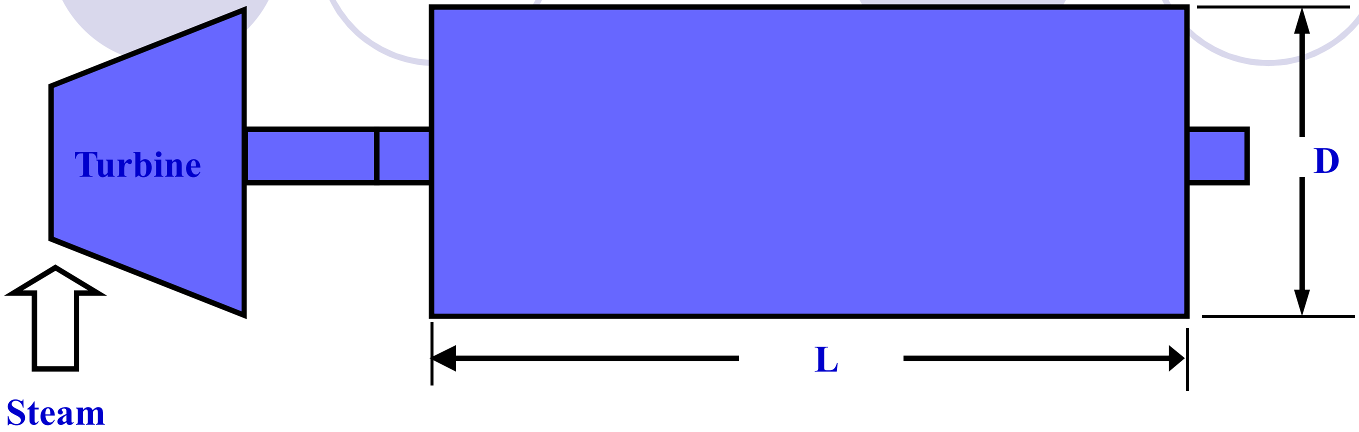


Salient-pole rotor

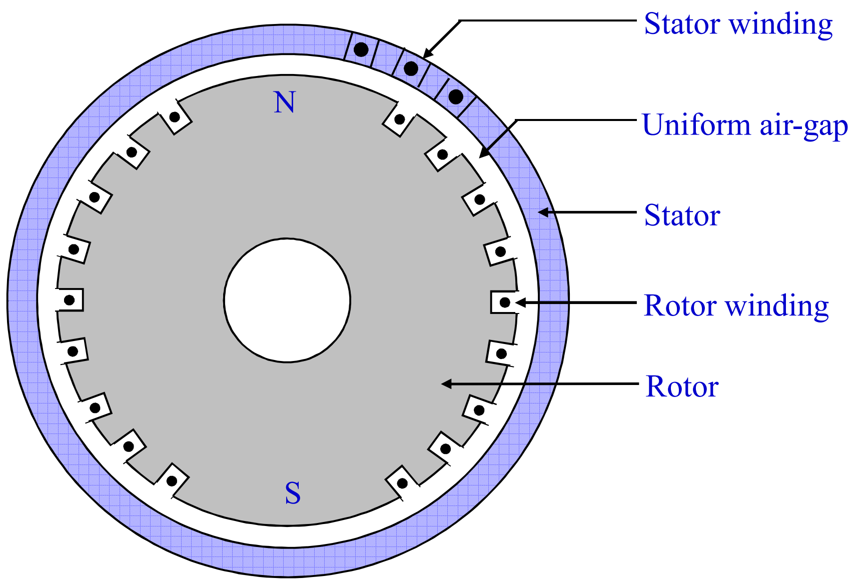
Cylindrical Type Rotor (Non Salient)

1. The cylindrical rotor has no protruding poles.
2. The rotor of cylindrical rotor generally has two poles.
3. The cylindrical rotor has low diameter (1.2m) and long lengths (2 to 5m).
4. Cylindrical rotors are used for high speed turbo generators, like gas and steam turbine generation system.

Cylindrical-Rotor Synchronous Generator

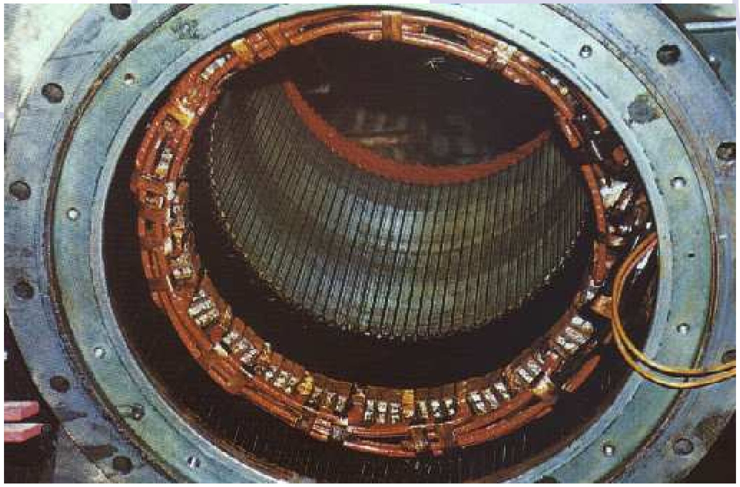


- High speed
- 3600 r/min $\Rightarrow$ 2-pole
- 1800 r/min $\Rightarrow$ 4-pole
- Direct-conductor cooling (using hydrogen or water as coolant)
- Rating up to 2000 MVA

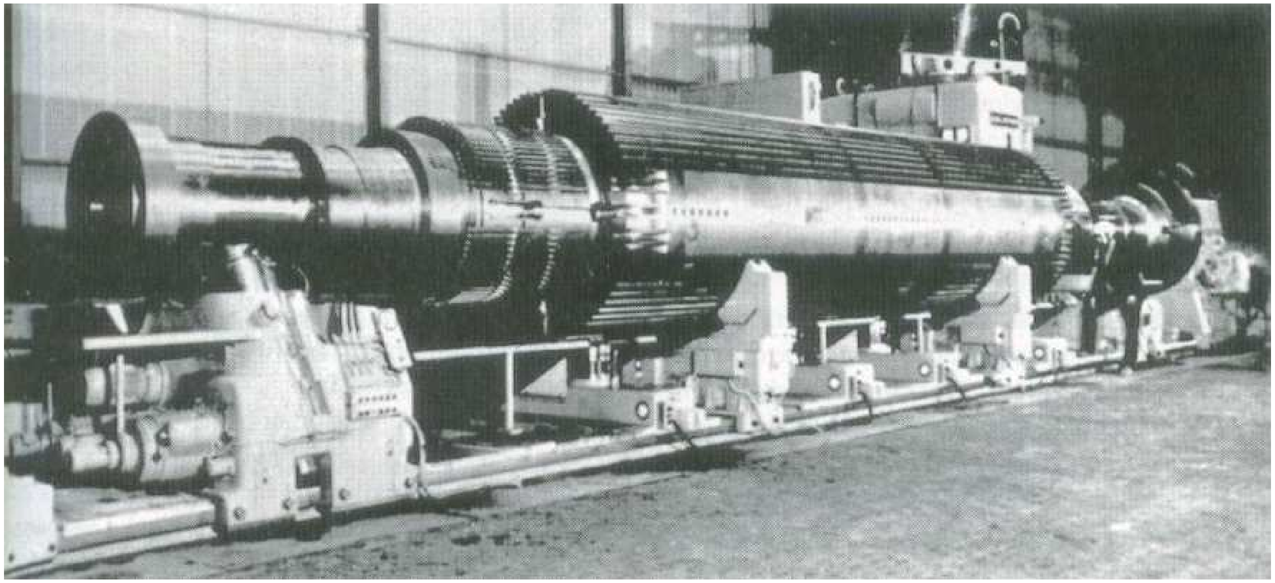


Turbo generator

Cylindrical-Rotor Synchronous Generator



Stator



Cylindrical rotor

Difference Between Salient & Non Salient Rotor Poles

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2. The salient rotor has several poles.
3. The salient rotor has large diameter (2 to 6m) to accommodate several poles and short axial length (1m).
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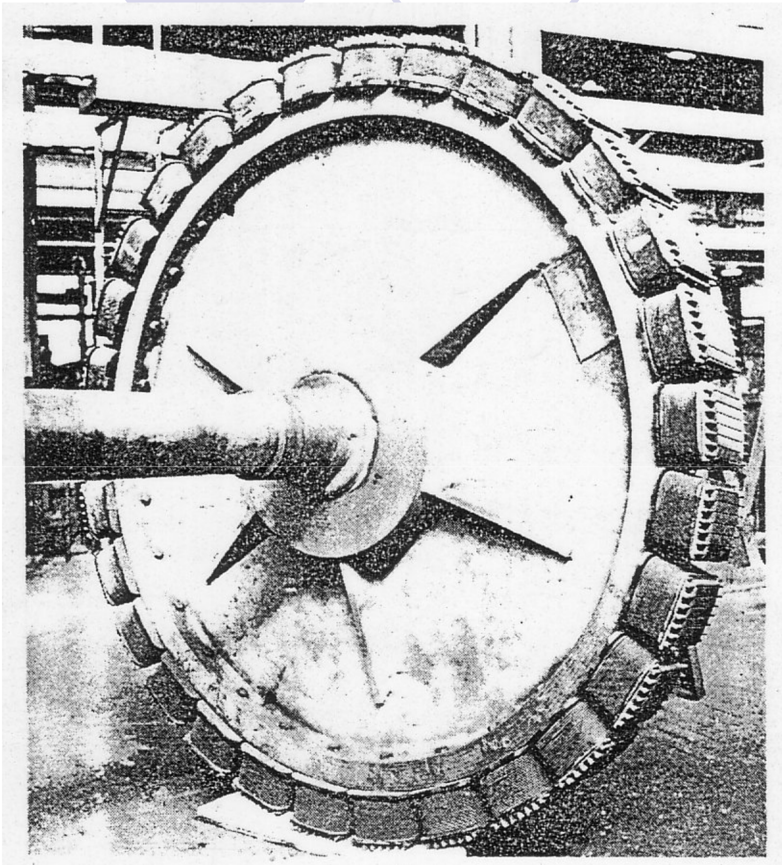
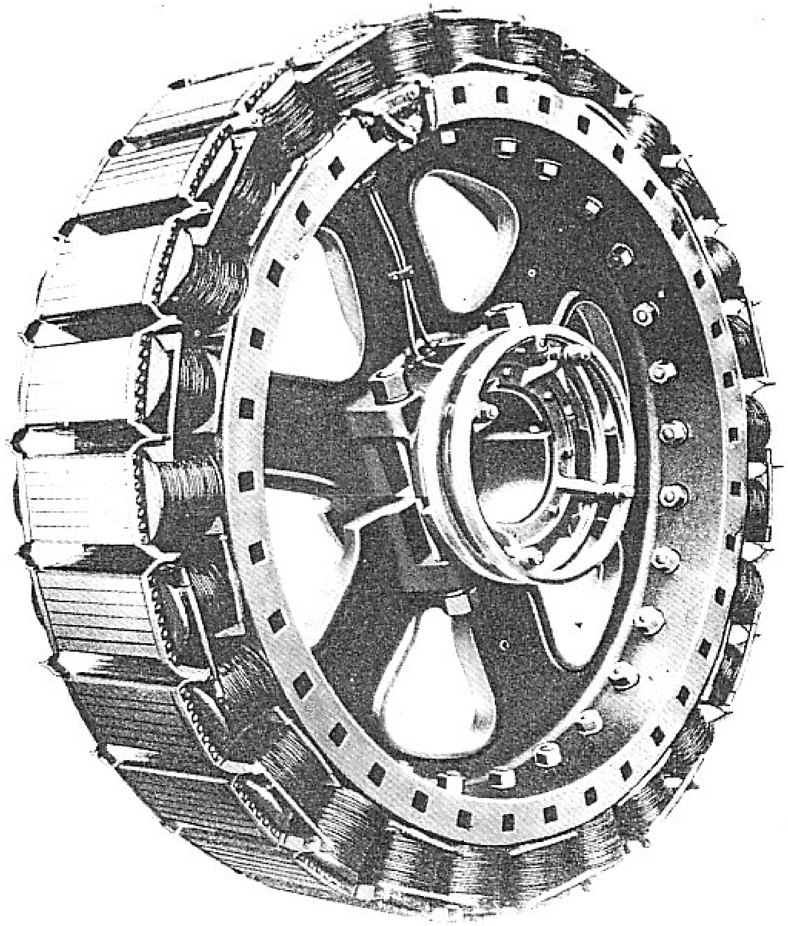
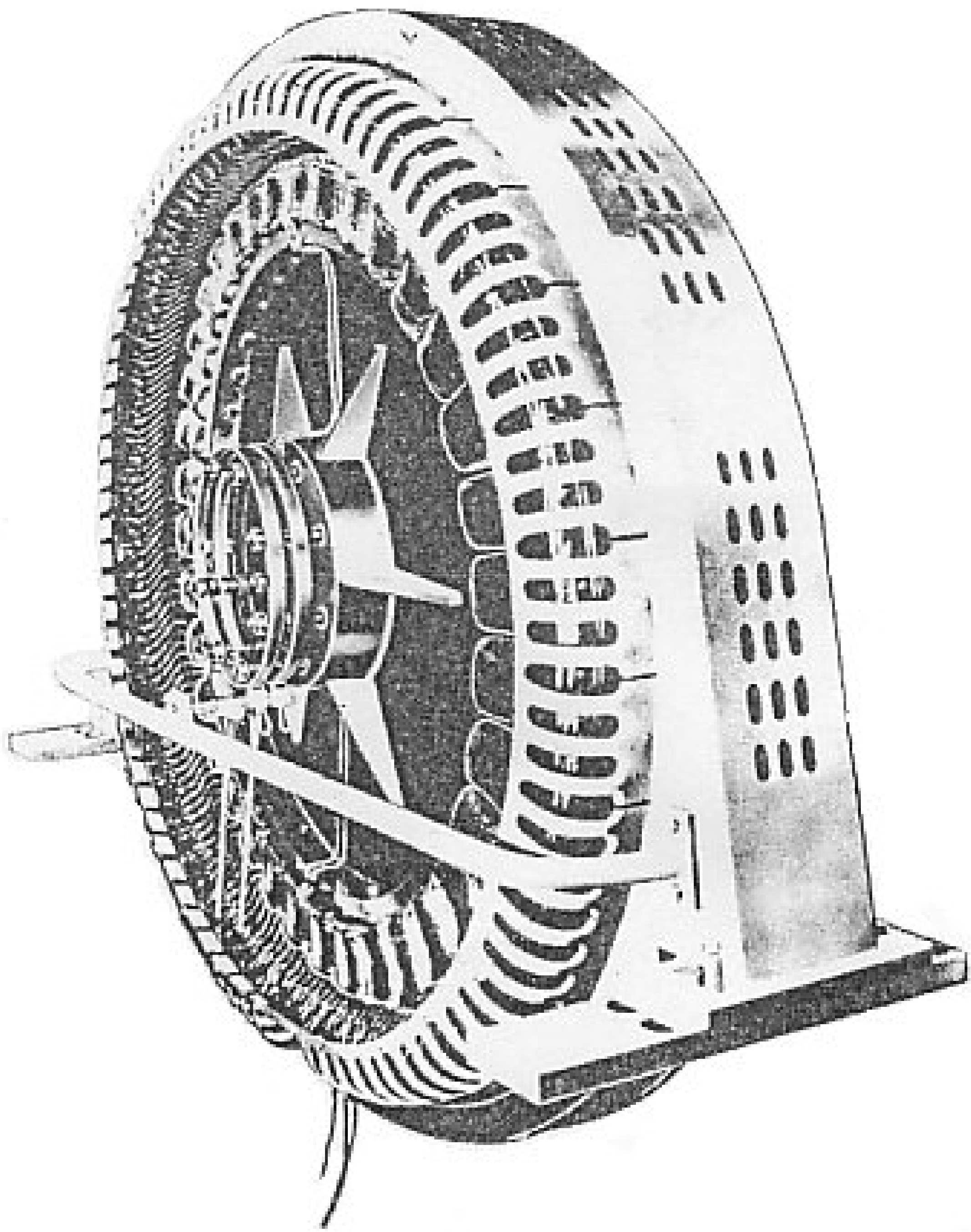
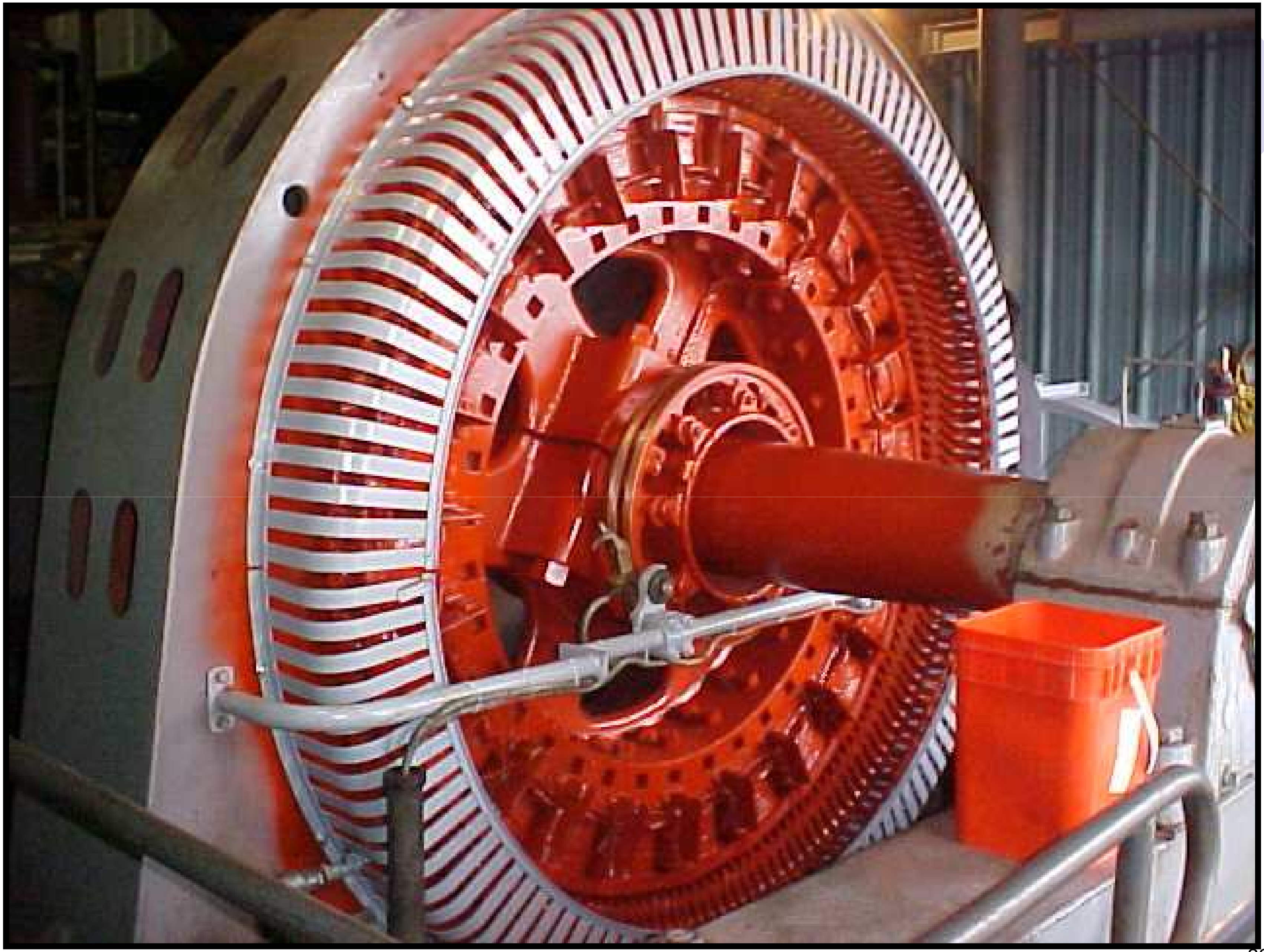
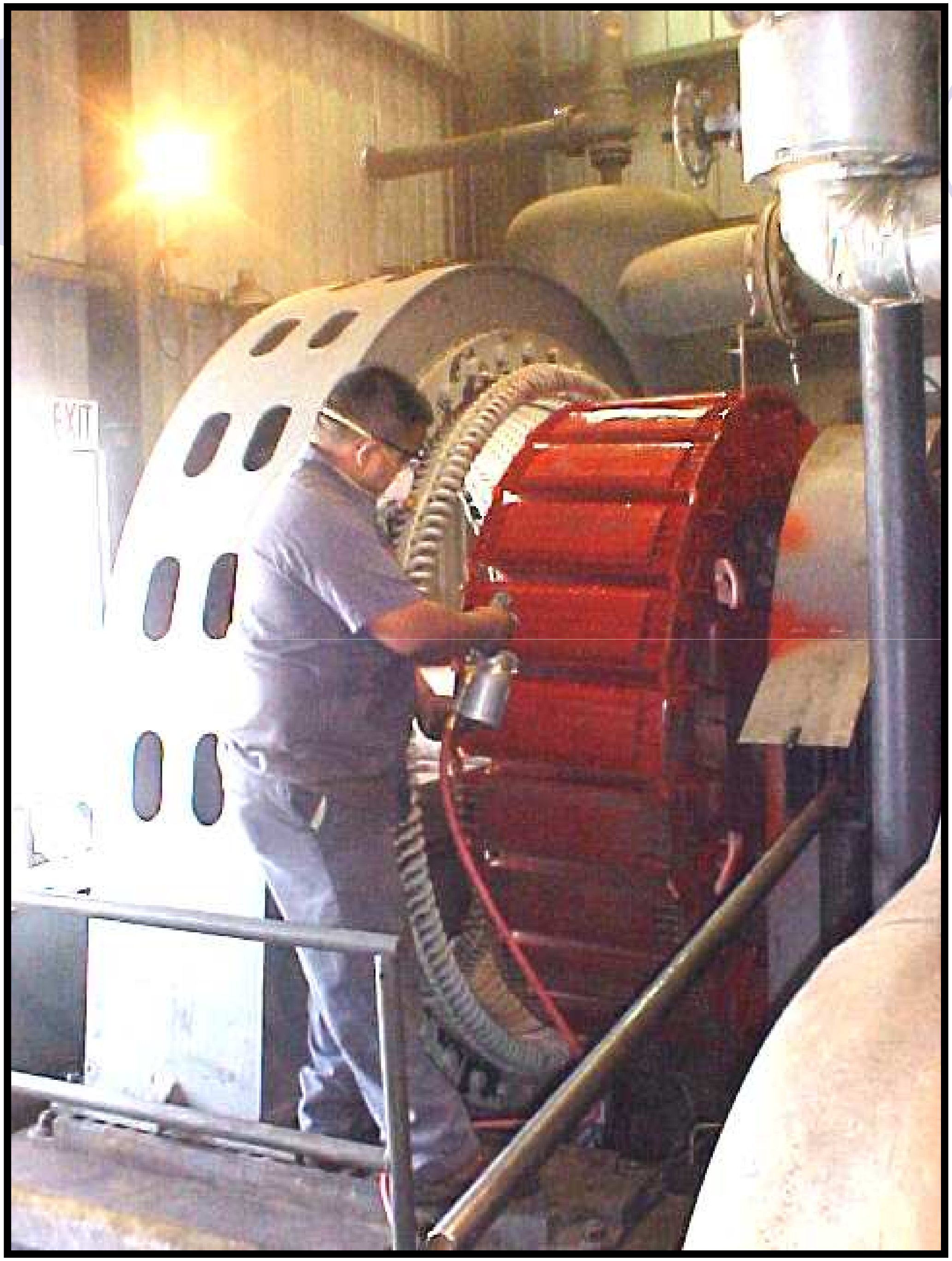
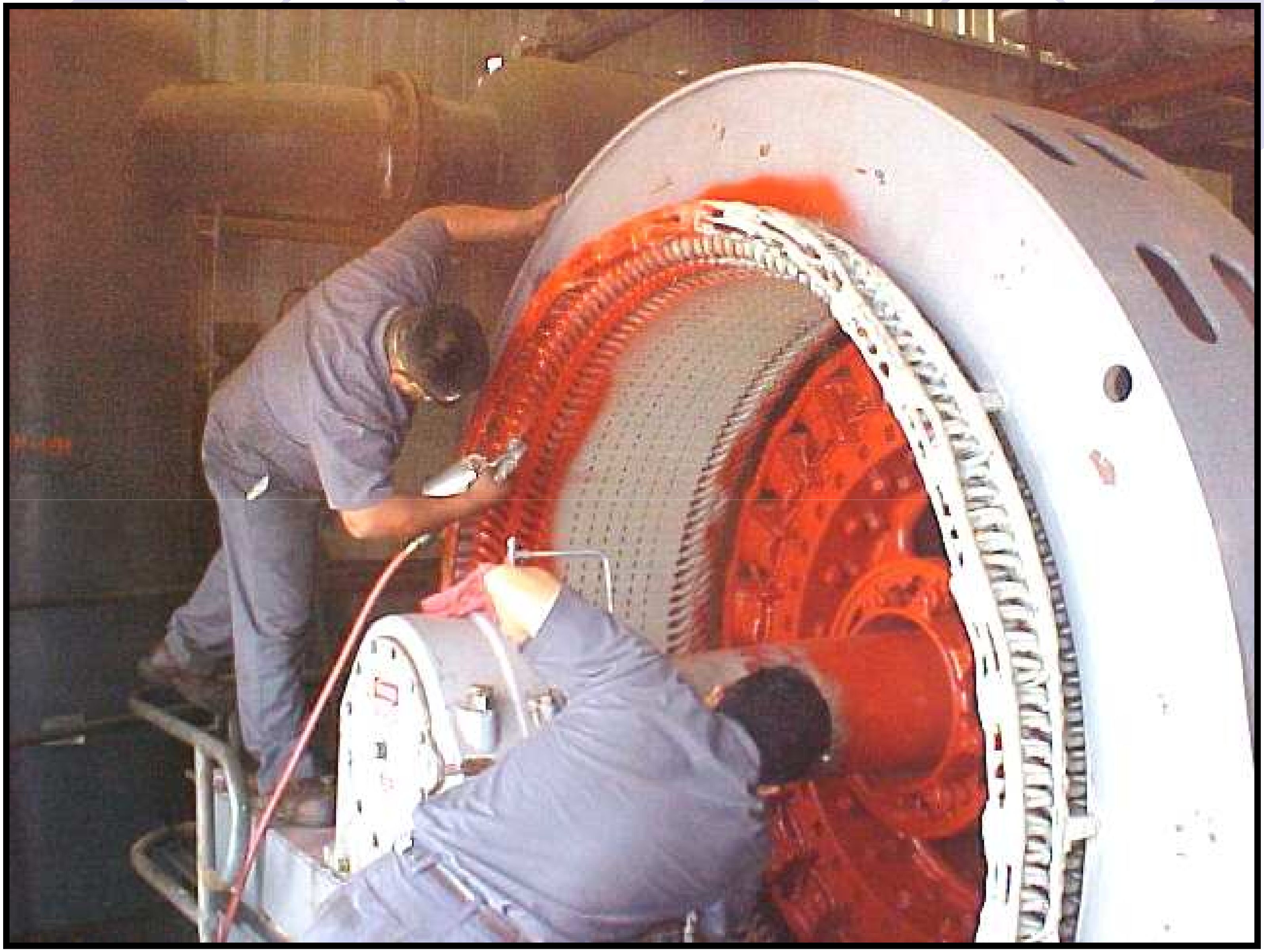


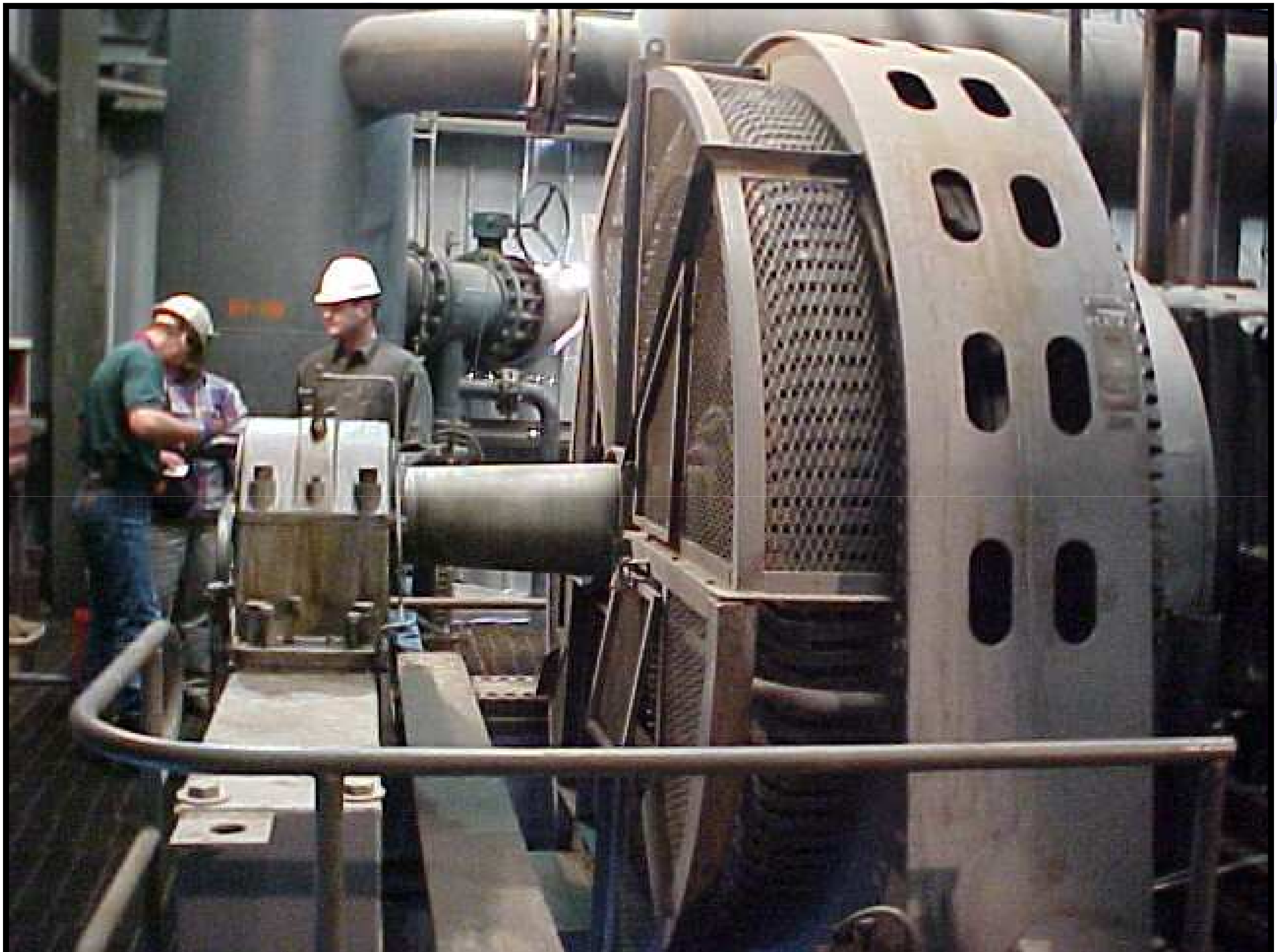




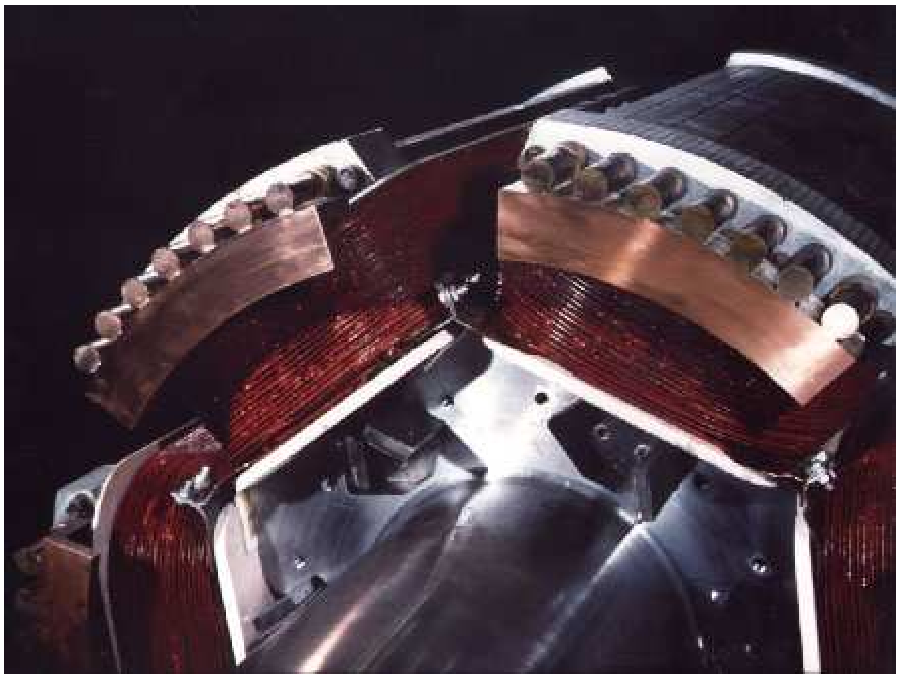


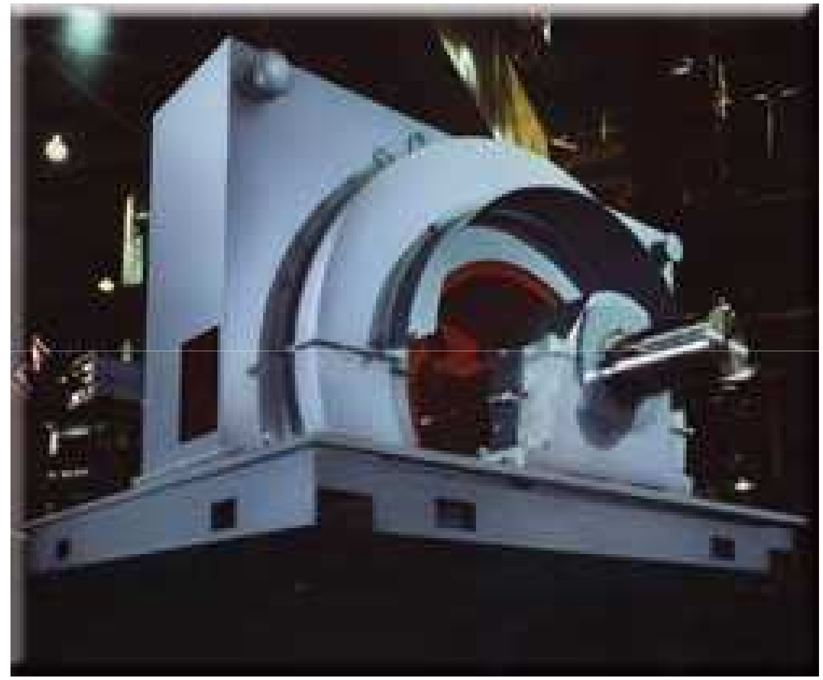

EXIT



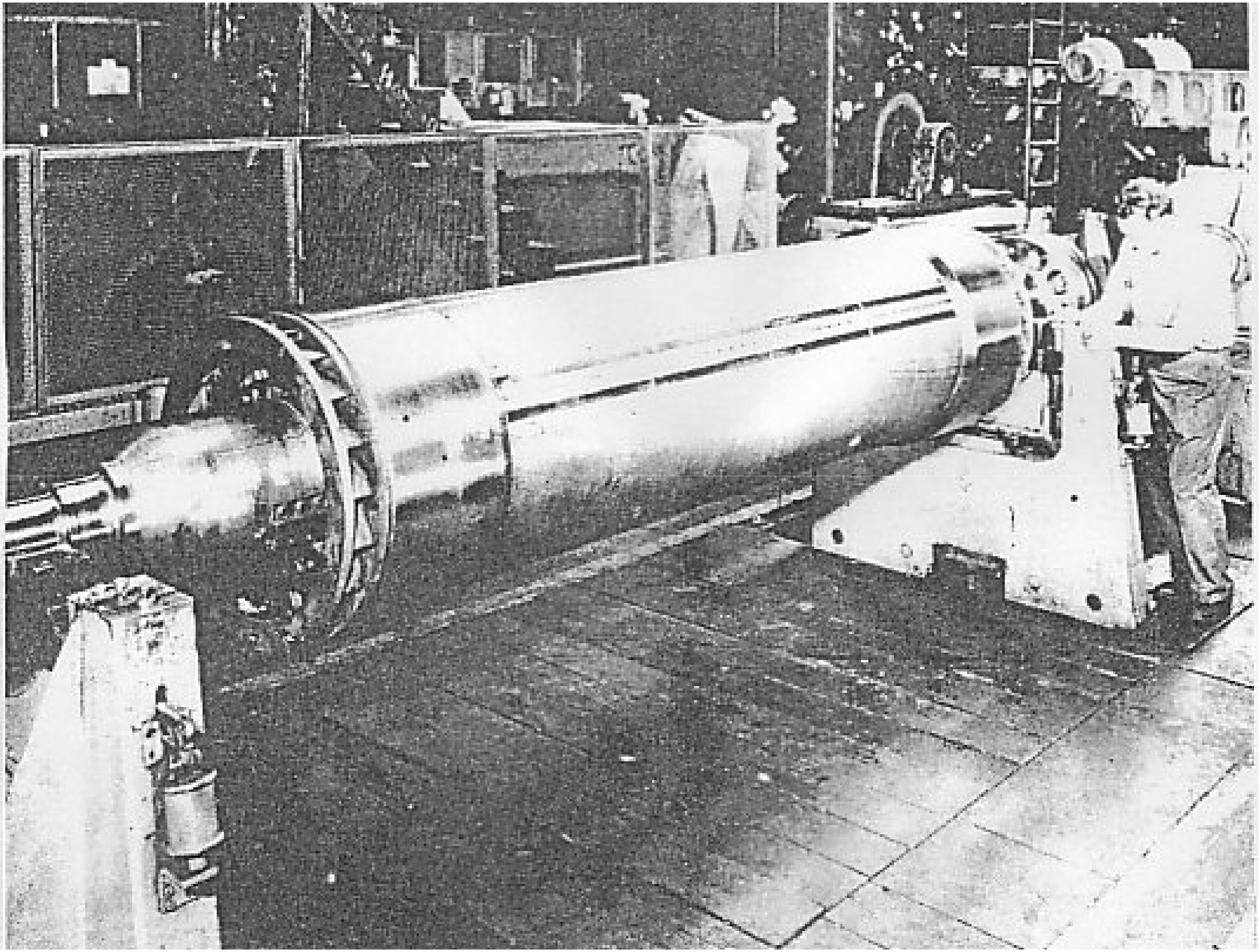


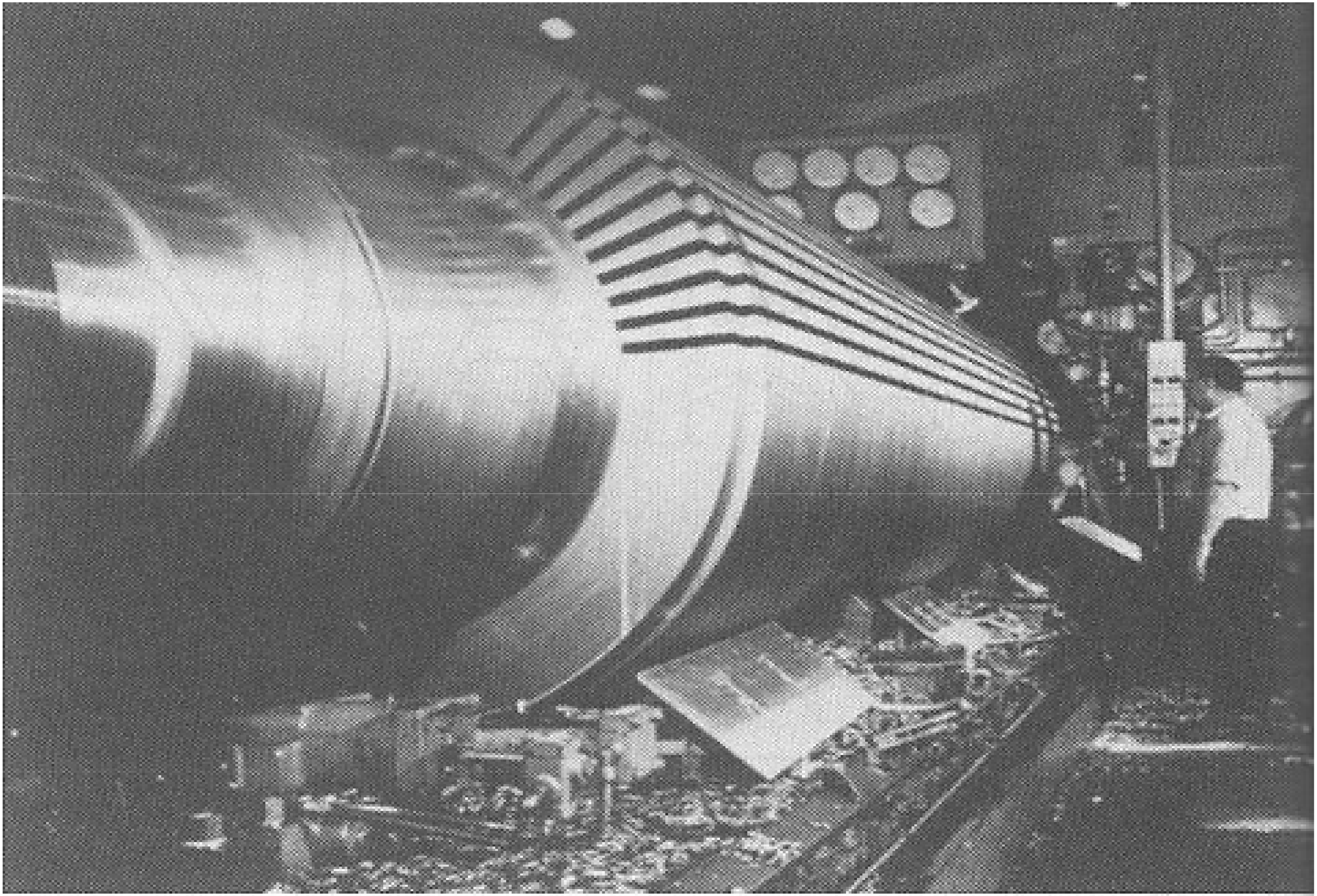
Small salient pole synchronous machine rotor



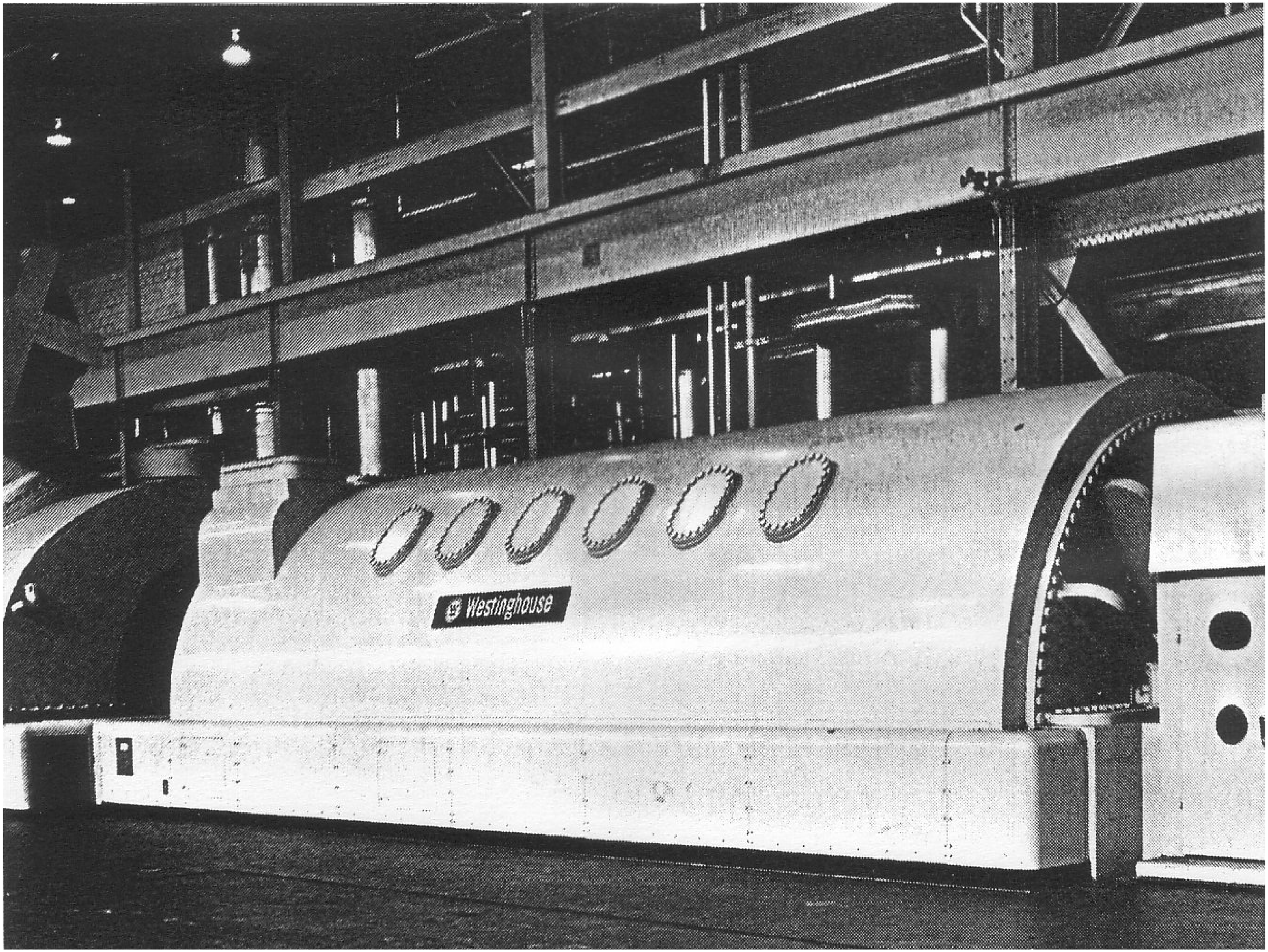


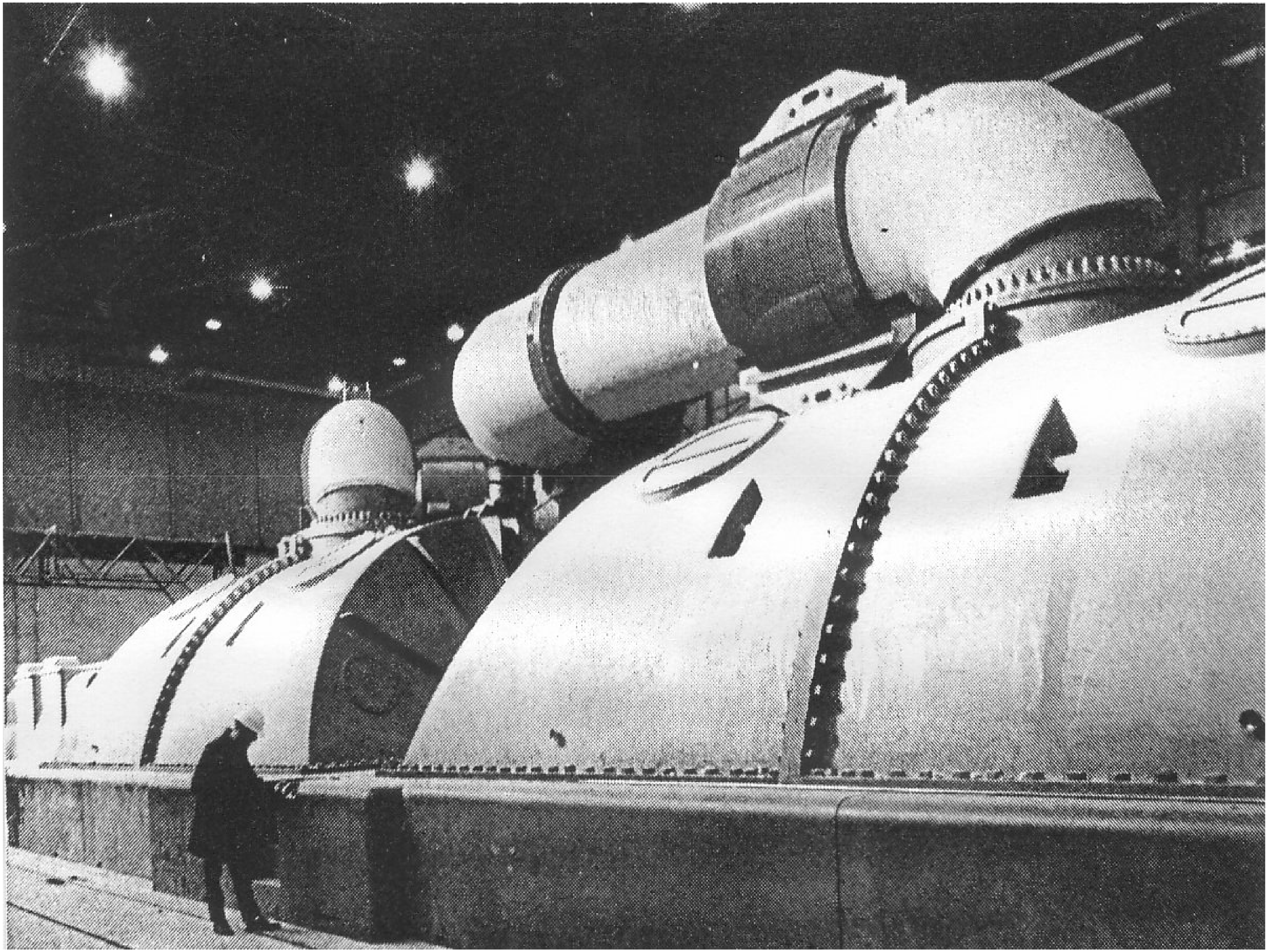
www.tecowestinghouse.com

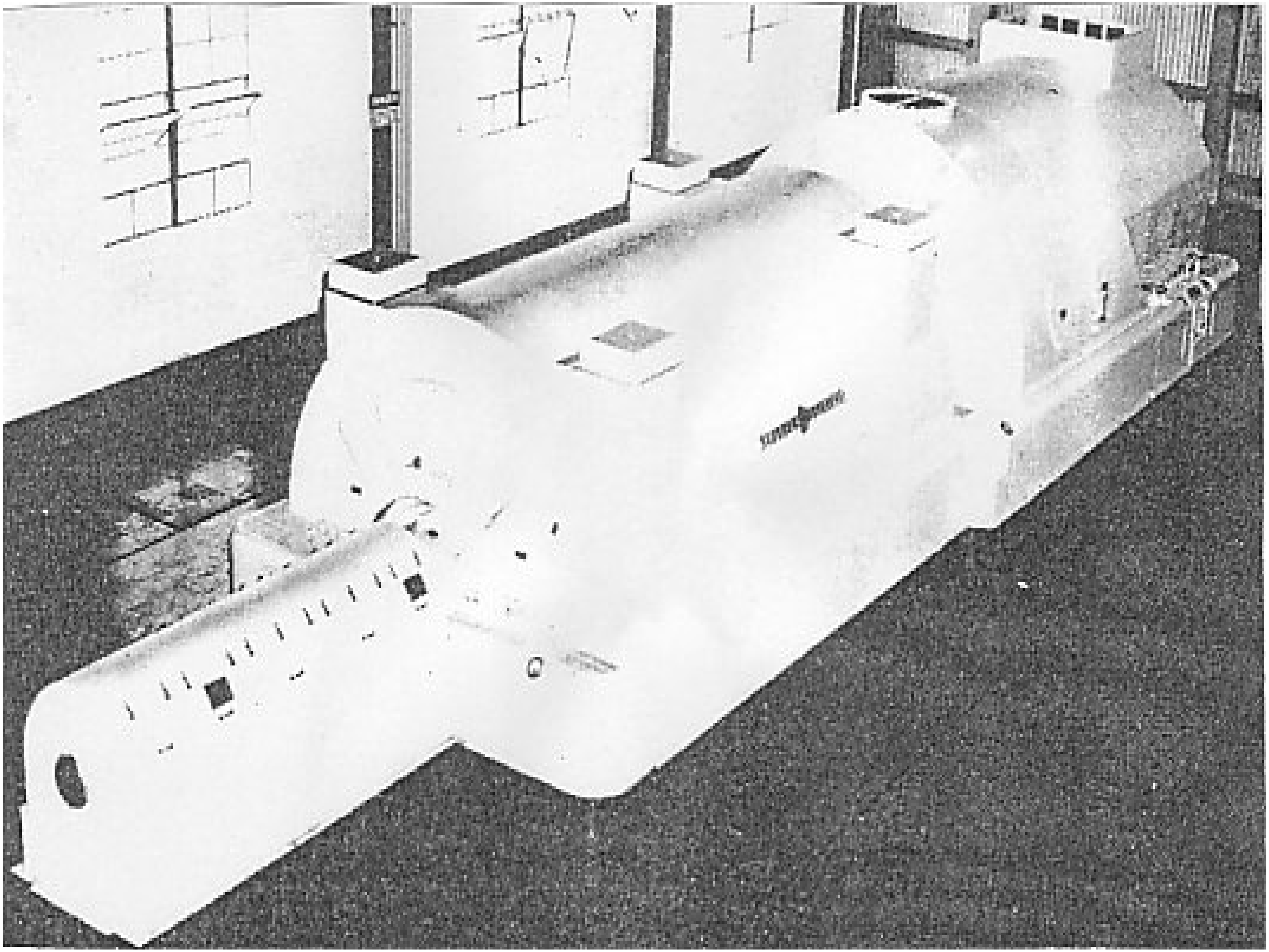


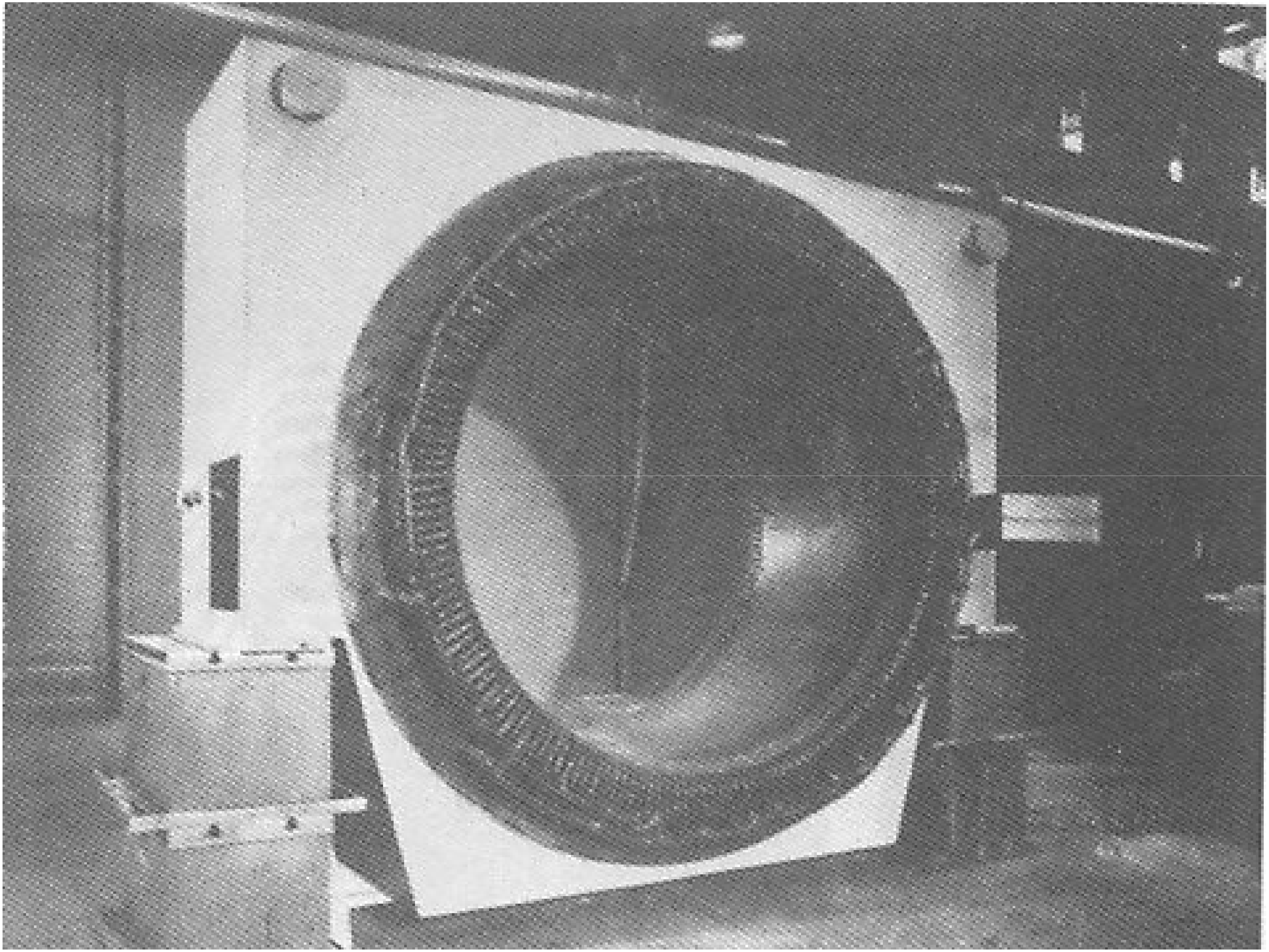


Slotting a large synchronous alternator rotor. (Courtesy of the General Electric Company.)


Westinghouse










Operation Principle

The rotor of the generator is driven by a prime-mover

↓

A dc current is flowing in the rotor winding which produces a rotating magnetic field within the machine

↓

The rotating magnetic field induces a three-phase voltage in the stator winding of the generator

Excitation System

- A dc current must be supplied to the field circuit on the rotor. Since the rotor is rotating, a special arrangement is required to get the dc power to its field windings.

  The common ways are:

- Supply the dc power from an external dc source to the rotor by means of slip rings and brushes.

- Supply the dc power from a special dc power source mounted directly on the shaft of the synchronous generator.

Slip rings & Brush

- Slip rings are metal rings completely encircling the shaft of a machine but insulated from it. One end of the dc rotor winding is tied to each of the 2 slip rings on the shaft of the synchronous machine, and a stationary brush rides on each slip ring.

- A "brush" is a block of graphite like carbon compound that conducts electricity freely but has very low friction, hence it doesn't wear down the slip ring. If the positive end of a dc voltage source is connected to one brush and the negative end is connected to the other, then the same dc voltage will be applied to the field winding at all times regardless of the angular position or speed of the rotor.

Some problems with slip rings and brushes

- They increase the amount of maintenance required on the machine, since the brushes must be checked for wear regularly.

- Brush voltage drop can be the cause of significant power losses on machines with larger field currents.

- Small synchronous machines – use slip rings and brushes.

- Larger machines – brushless exciters are used to supply the dc field current.

Brushless Excitation

- A brushless exciter is a small ac generator with its field circuit mounted on the stator and its armature circuit mounted on the rotor shaft.

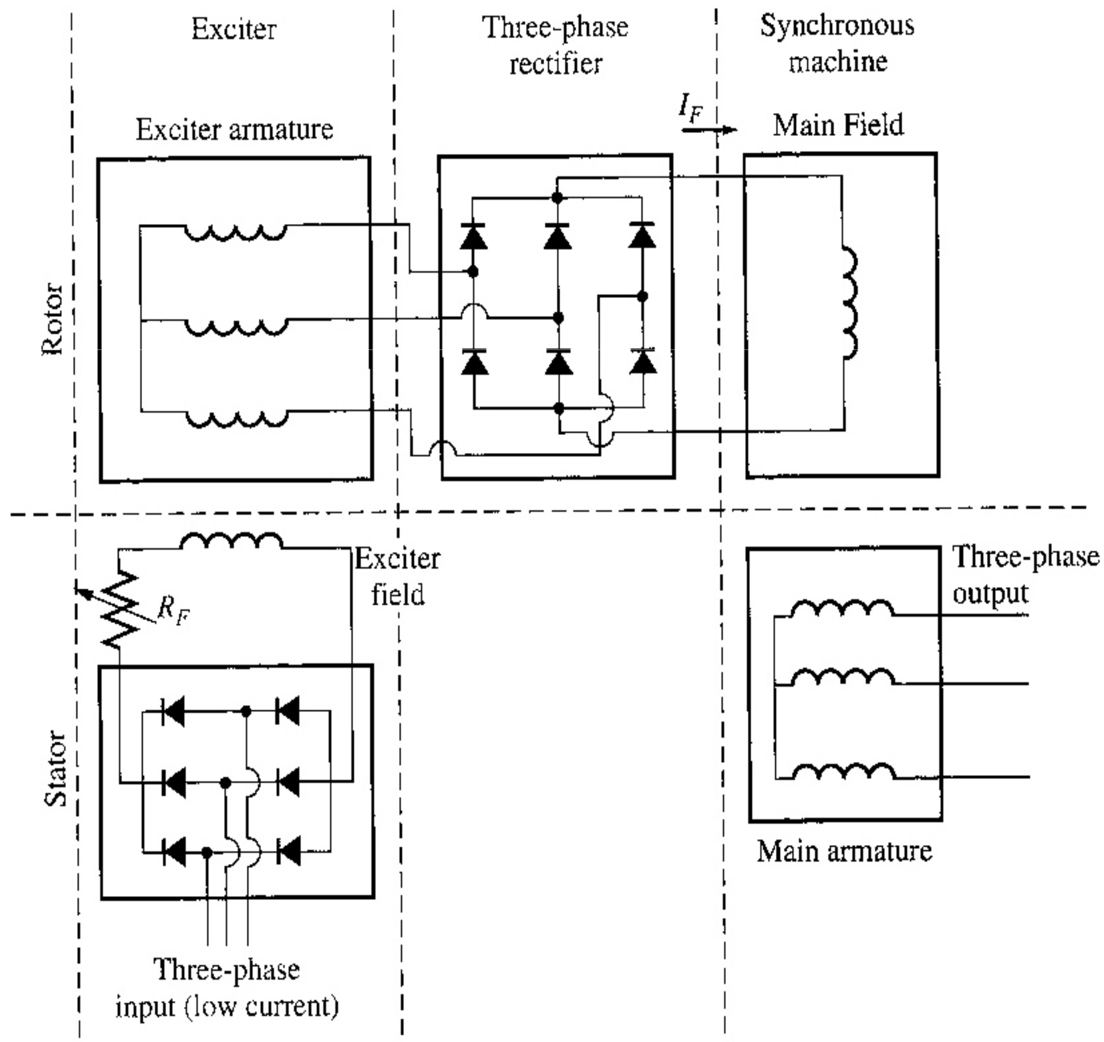
- The 3-phase output of the exciter generator is rectified to direct current by a 3-phase rectifier circuit also mounted on the shaft of the generator, and is then fed to the main dc field circuit. By controlling the small dc field current of the exciter generator (located on the stator), we can adjust the field current on the main machine without slip rings and brushes.

- Since no mechanical contacts occur between the rotor and stator, a brushless exciter requires less maintenance.

Brushless Excitation

Brushless Exciter Circuit:

A small 3-phase current is rectified and used to supply the field circuit of the exciter, which is located on the stator. The output of the armature circuit of the exciter (on the rotor) is then rectified and used to supply the field current of the main machine.



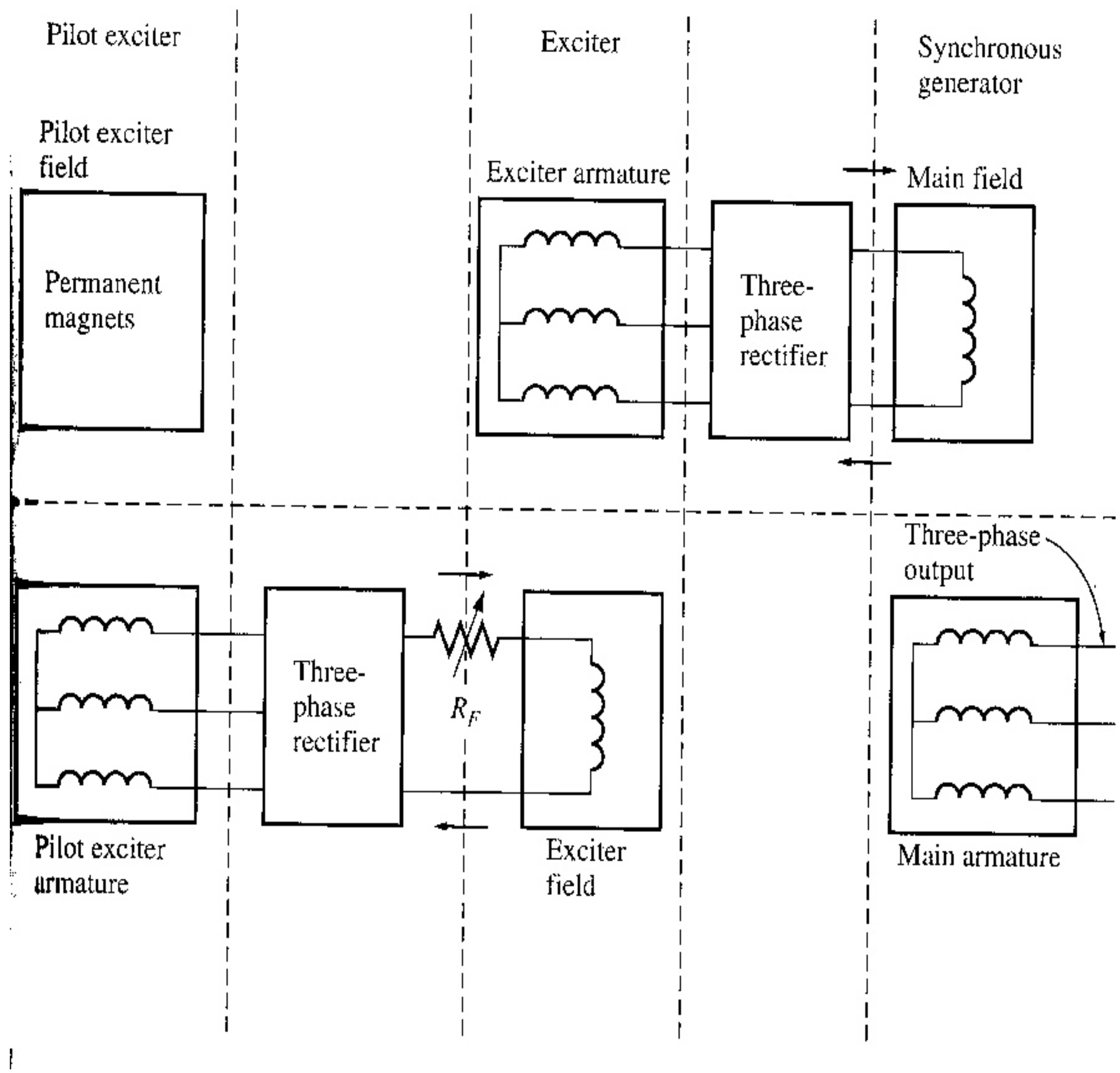
Pilot Excitation System

- To make the excitation of a generator completely independent of any external power sources, a small pilot exciter can be used.

- A pilot exciter is a small ac generator with permanent magnets mounted on the rotor shaft and a 3-phase winding on the stator. It produces the power for the field circuit of the exciter, which in turn controls the field circuit of the main machine. If a pilot exciter is included on the generator shaft, then no external electric power is required.

Pilot Excitation System Circuit

A brushless excitation scheme that includes a pilot exciter. The permanent magnets of the pilot exciter produce the field current of the exciter, which in turn produces the field current of the main machine.



Pilot Excitation System

Even though machines with brushless exciters do not need slip rings and brushes, they still include the slip rings and brushes so that an auxiliary source of dc field current is available in emergencies.

The Speed of Rotation of a Synchronous Generator

Synchronous generators are by definition *synchronous*, meaning that the electrical frequency produced is locked in or synchronized with the mechanical rate of rotation of the generator. A synchronous generator's rotor consists of an electromagnet to which direct current is supplied. The rotor's magnetic field points in the direction the rotor are turned. Hence, the rate of rotation of the magnetic field in the machine is related to the stator electrical frequency by:

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

where f_e = electrical frequency in Hz

P = number of poles

n_m = mechanical speed of the rotor, in r/min

Generated Voltage

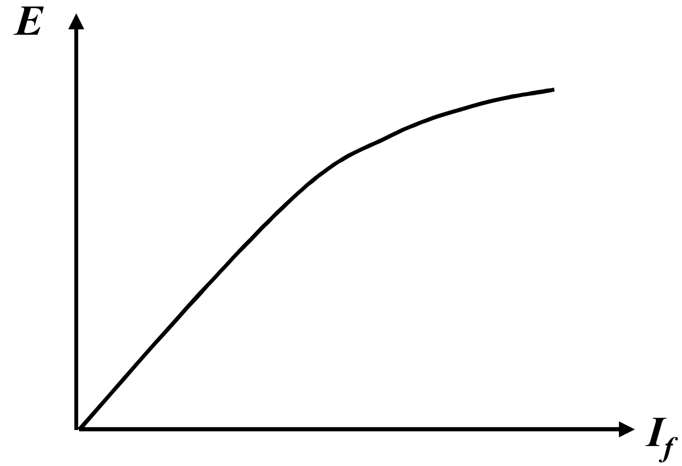
The generated voltage of a synchronous generator is given by

$$E = K_c \phi f_e$$

where ϕ = flux in the machine (function of I_f)

f_e = electrical frequency

K_c = synchronous machine constant



Saturation characteristic of a synchronous generator.

Voltage Regulation

A convenient way to compare the voltage behaviour of two generators is by their *voltage regulation* (*VR*). The *VR* of a synchronous generator at a given load, power factor, and at rated speed is defined as

$$VR = \frac{E_{nl} - V_{fl}}{V_{fl}} \times 100\%$$

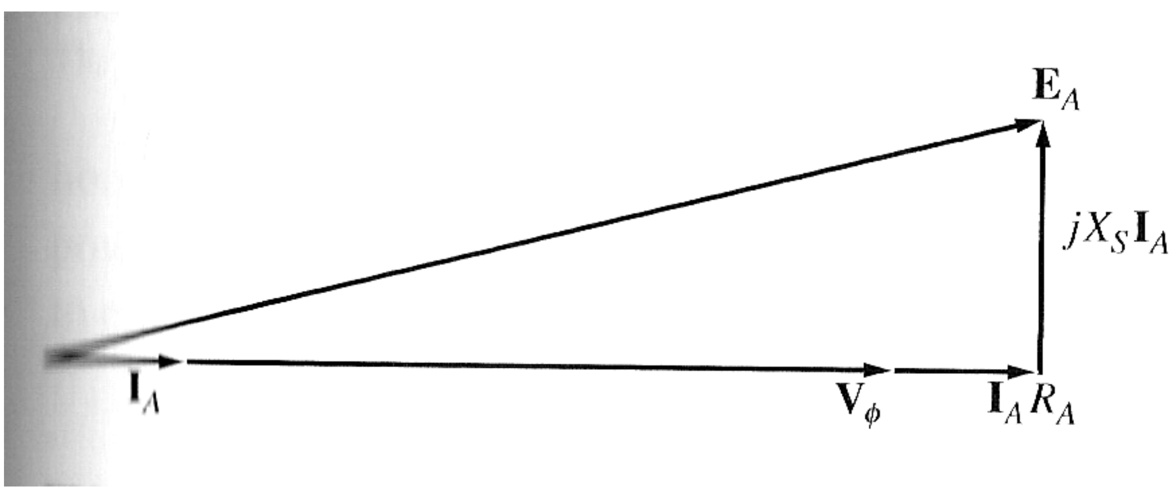
Where V_{fl} is the full-load terminal voltage, and E_{nl} is the no-load terminal voltage (internal voltage) at rated speed when the load is removed without changing the field current.

For lagging power factor (*PF*), *VR* is fairly positive, for unity *PF*, *VR* is small positive and for leading *PF*, *VR* is negative.

Phasor Diagram of a Synchronous Generator

For a given phase voltage and armature current, a larger internal voltage E_A is needed for lagging loads than for leading loads. Thus, a larger field current is needed to get the same terminal voltage because $E_A = k\Phi\omega$ because ω must be kept constant to keep constant frequency.

Alternatively, for a given field current and magnitude of load current, the terminal voltage is lower for lagging loads and higher for leading loads.

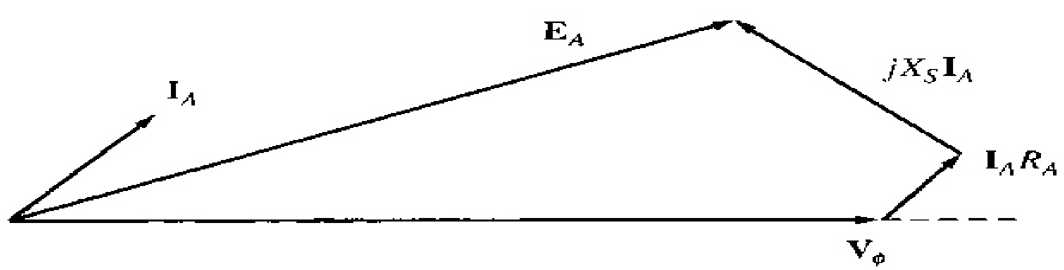


Unity power factor

Phasor Diagram of a Synchronous Generator

(a)

Lagging PF



(b)

Leading PF

SYNCHRONOUS GENERATORS Phasor Diagram

- Note: at specific phase voltage & armature current, a larger internal voltage E_A required for lagging loads than for leading loads
- Therefore a larger field current required with lagging loads to get same terminal voltage

$$E_A = K\varphi\omega$$

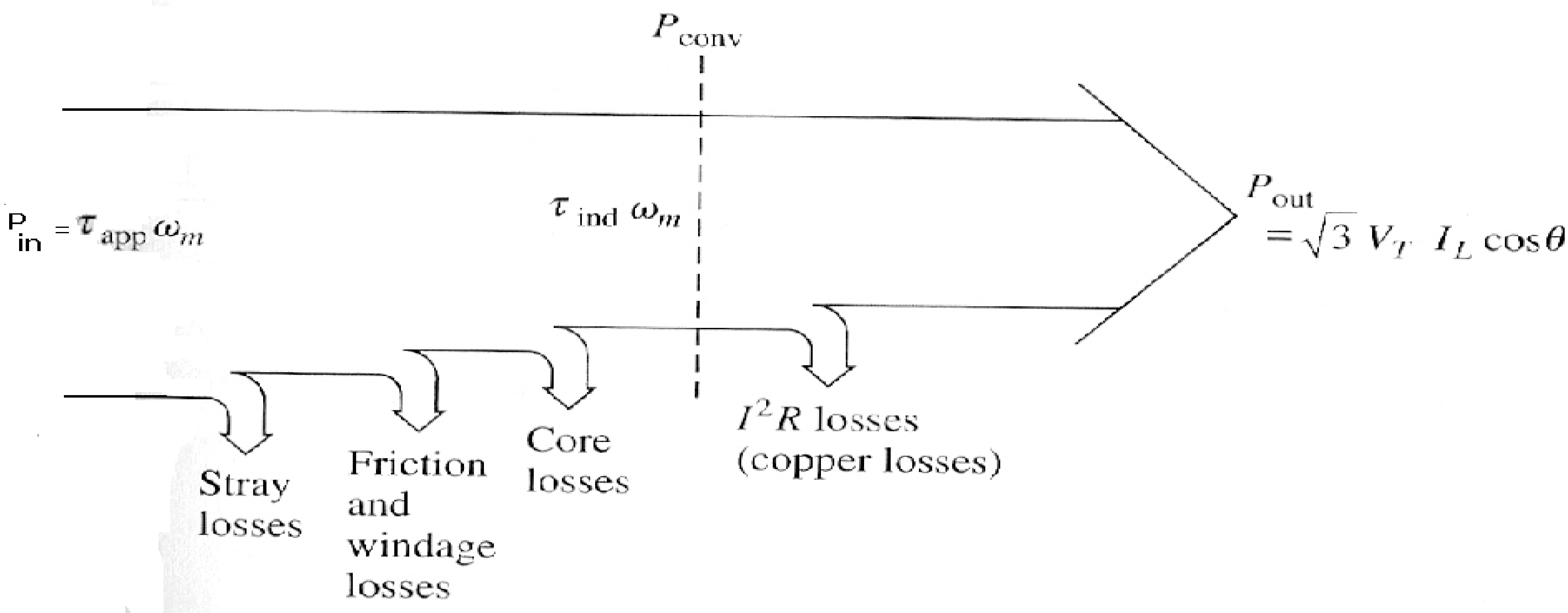
- Alternatively for a given I_F and load current , V_φ is lower for *lagging loads* & higher for *leading loads*
- In real synchronous machines, X_S *normally much larger than* R_A *& often neglected in qualitative study*

SYNCHRONOUS GENERATORS Power and Torque

- A synchronous generator is a synchronous machine used as generator
- converts mechanical energy to 3 phase electrical energy
- Source of mechanical energy is prime mover (a diesel engine , a steam turbine, …)
- Any source employed should have an almost constant speed regardless of load
- If it were not constant, the power system frequency would wander

SYNCHRONOUS GENERATORS Power and Torque

- Not all mechanical power going to a synchronous generator becomes electrical power the difference between input & output power represent losses, Power flow Diagram➔



SYNCHRONOUS GENERATORS Power and Torque

- Input mechanical power is shaft power in generator
- $P_{in} = T_{prime\text{-}mover}\,\omega_m$

  $(T_{prime\text{-}mover} \equiv T_{app})$
- $P_{conv} = T_{generated}\,\omega_m = 3E_A I_A \cos\gamma$

  (γ angle between E_A and I_A)

  $(T_{generated} \equiv T_{ind})$
- Difference between P_{in} and P_{conv} in generator represents mechanical, core, and stray losses of machine

SYNCHRONOUS GENERATORS Power and Torque

- Real elect. output power of syn. Gen. in line quantities:

$$P_{out}=\sqrt{3}\ V_T\ I_L\ \cos\theta$$

reactive power output:

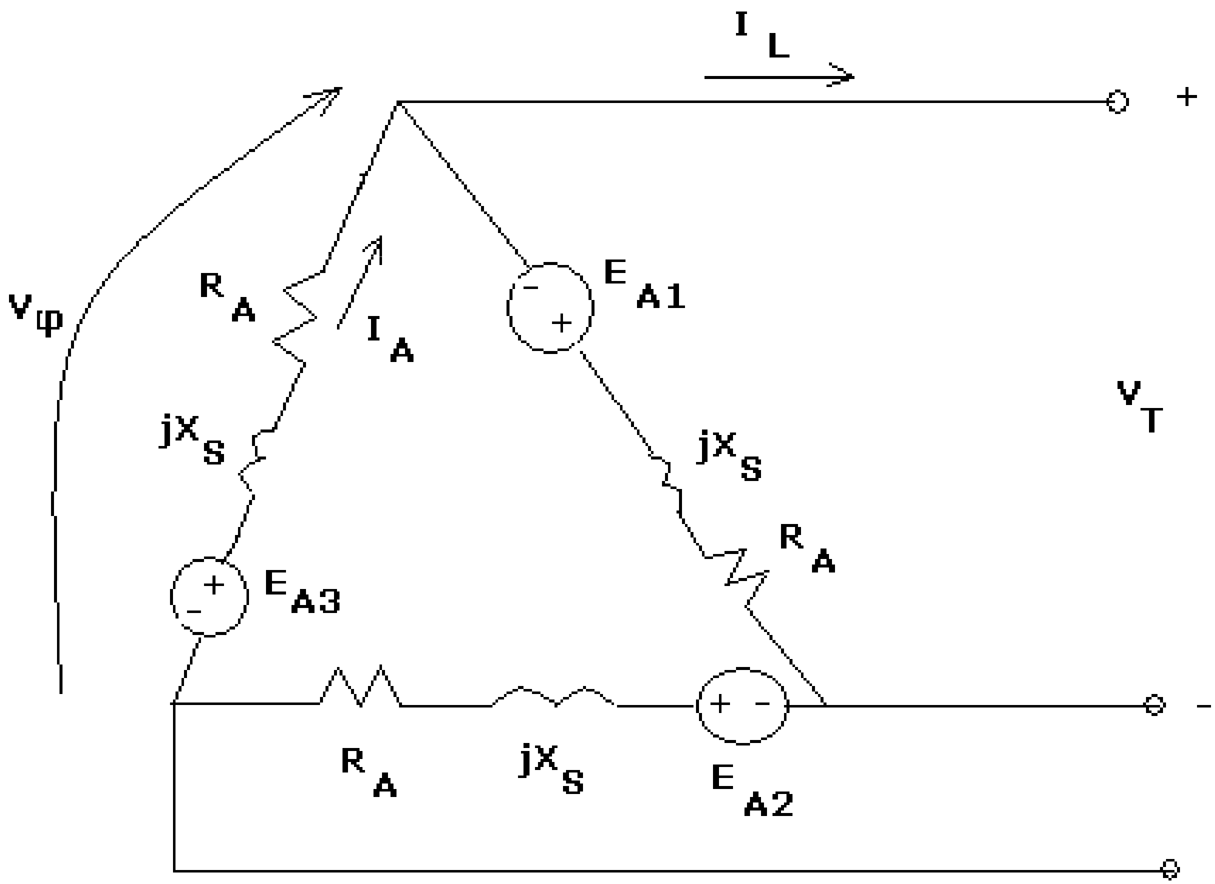
$$Q_{out}=\sqrt{3}\ V_T\ I_L\ \sin\theta$$

$$Q_{out}=\sqrt{3}\ V_\varphi\ I_A\ \sin\theta$$

ignoring armature resistance R_A (X_S>>R_A), a useful relation can be derive to approximate output power of Gen.

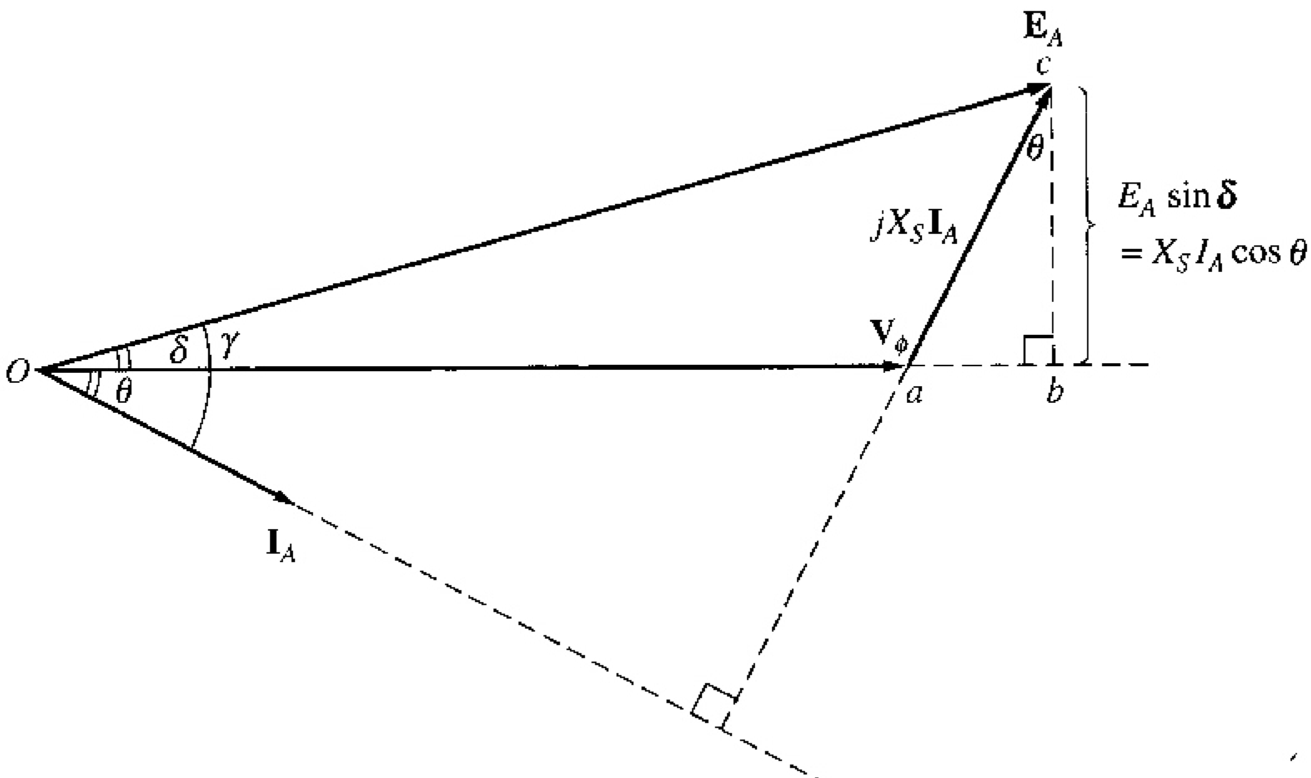
SYNCHRONOUS GENERATORS Power and Torque

- Generator Equivalent circuit for Δ connection



SYNCHRONOUS GENERATORS Power and Torque

- To derive that useful equation, when stator resistance ignored, phasor diagram employed



SYNCHRONOUS GENERATORS Power and Torque

- The vertical segment *bc* is $E_A \sin\delta$ or $X_S I_A \cos\theta$

  ➔ $$I_A \cos\theta = E_A \sin\delta / X_S$$
- Substituting this in equation of P_{out} ➔

  $$P = 3V_\varphi E_A \sin\delta / X_S$$
- since resistances assumed zero, losses not included in this equation (& it is both P_{conv} ,P_{out})
- Above equation shows power produced by a Syn. Gen. depends on angle δ (between V_φ,E_A), the torque angle
- Maximum power that Gen. can supply occurs when $\delta=90^\circ$. At this angle $\sin\delta=1$ ➔

  $$P_{max}=3V_\varphi E_A / X_S \qquad (1)$$

The Equivalent Circuit of a Synchronous Generator

- The internal voltage E_f produced in a machine is not usually the voltage that appears at the terminals of the generator.
- The only time E_f is same as the output voltage of a phase is when there is no armature current flowing in the machine.
- There are a number of factors that cause the difference between E_f and V_t:
  - The distortion of the air-gap magnetic field by the current flowing in the stator, called the armature reaction
  - The self-inductance of the armature coils.
  - The resistance of the armature coils.
  - The effect of salient-pole rotor shapes.

The Equivalent Circuit of a Synchronous Generator

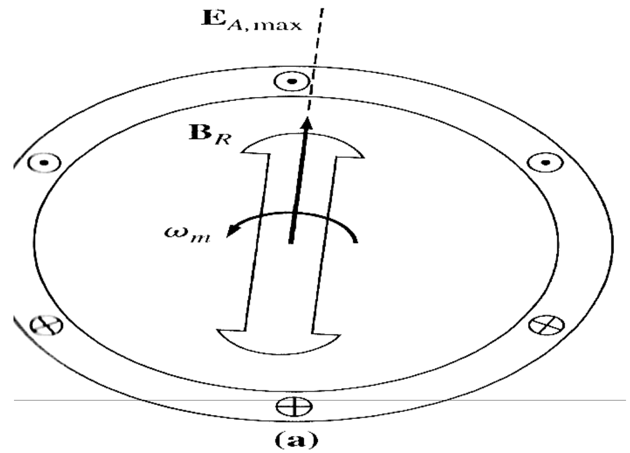
Armature Reaction

When the rotor is spun, a voltage E_A is induced in the stator windings. If a load is attached to the terminals of the generator, a current flows. But a 3-phase stator current flow will produce a magnetic field of its own. This stator magnetic field will distorts the original rotor magnetic field, changing the resulting phase voltage.

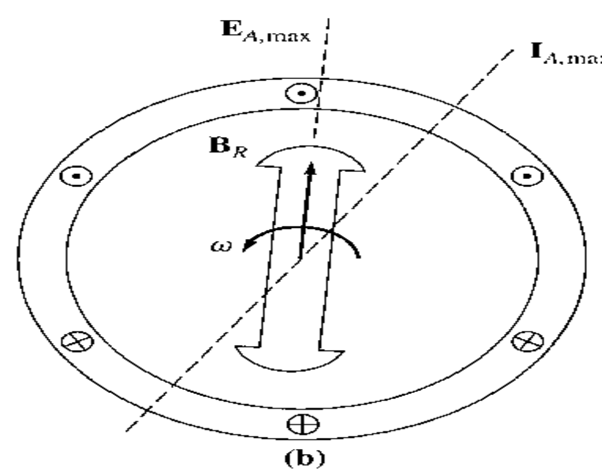
This effect is called armature reaction because the armature (stator) current affects the magnetic field, which produced it in the first place.

Armature Reaction

(a) A rotating magnetic field produces the internal generated voltage E_A.

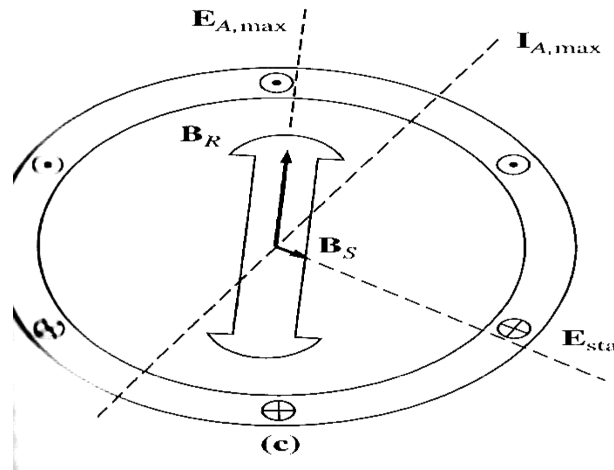


(b) The resulting voltage produces a lagging current flow when connected to a lagging load.

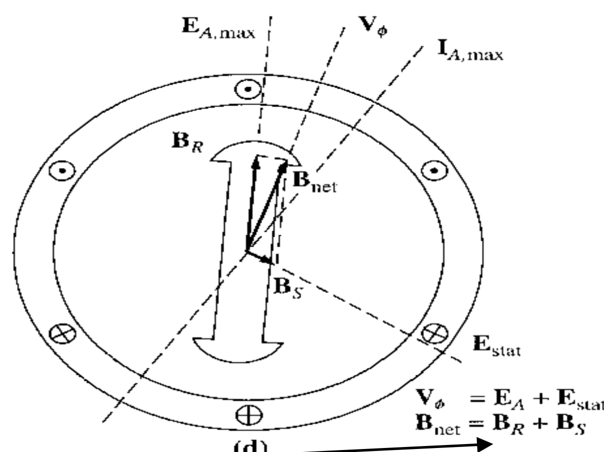


Armature Reaction

(c) The stator current produces its own magnetic field B_S which produces its own E_{stat} in the stator windings.

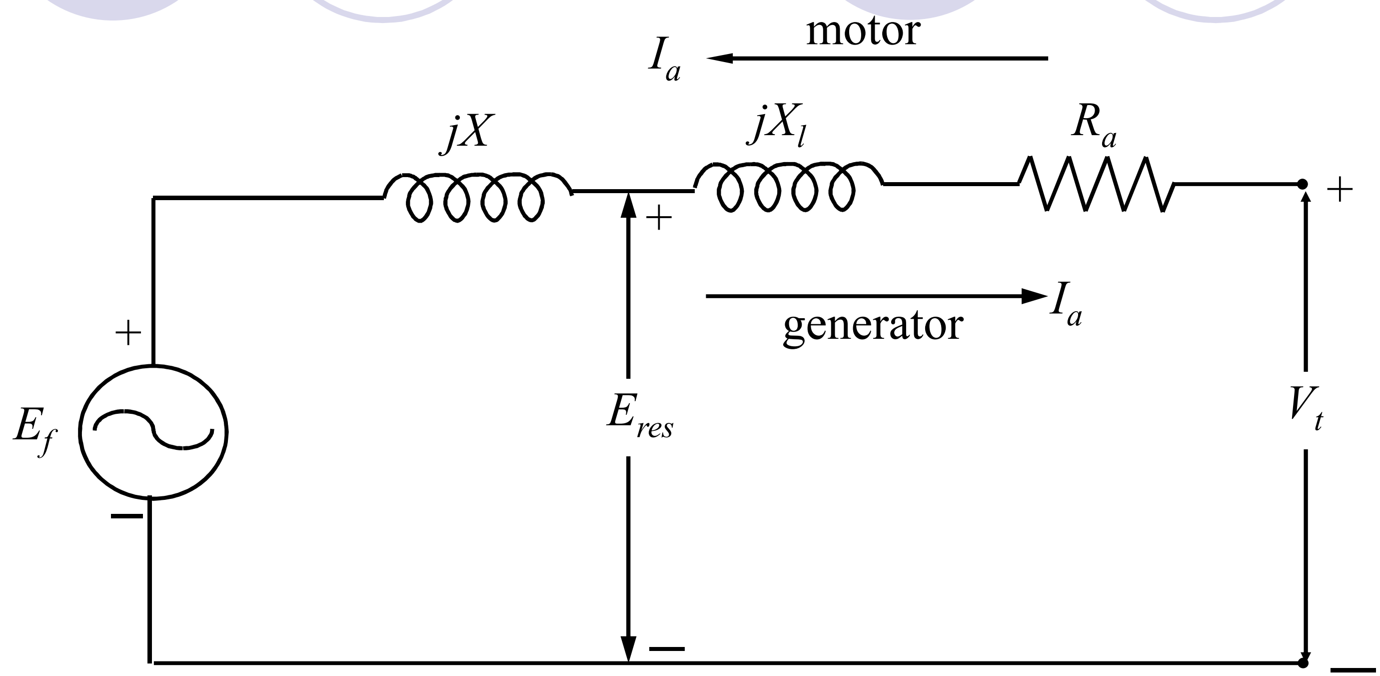


(d) The field BS adds to BR distorting it into B_{net}. The voltage E_{stat} adds to E_A, producing V_f at the output of the phase.



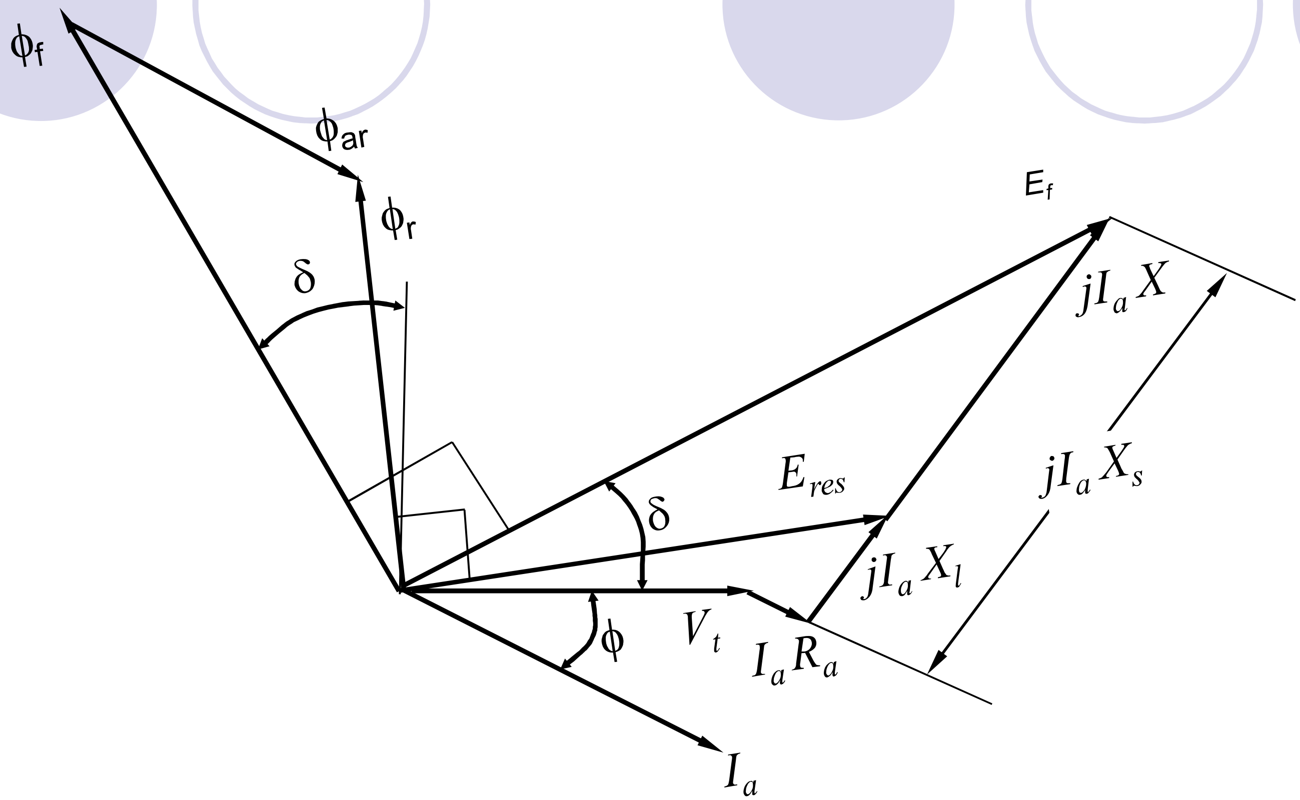
$$V_\phi = E_A + E_{stat}$$
$$B_{net} = B_R + B_S$$

Equivalent Circuit_2



Equivalent circuit of a cylindrical-rotor synchronous machine

Phasor Diagram

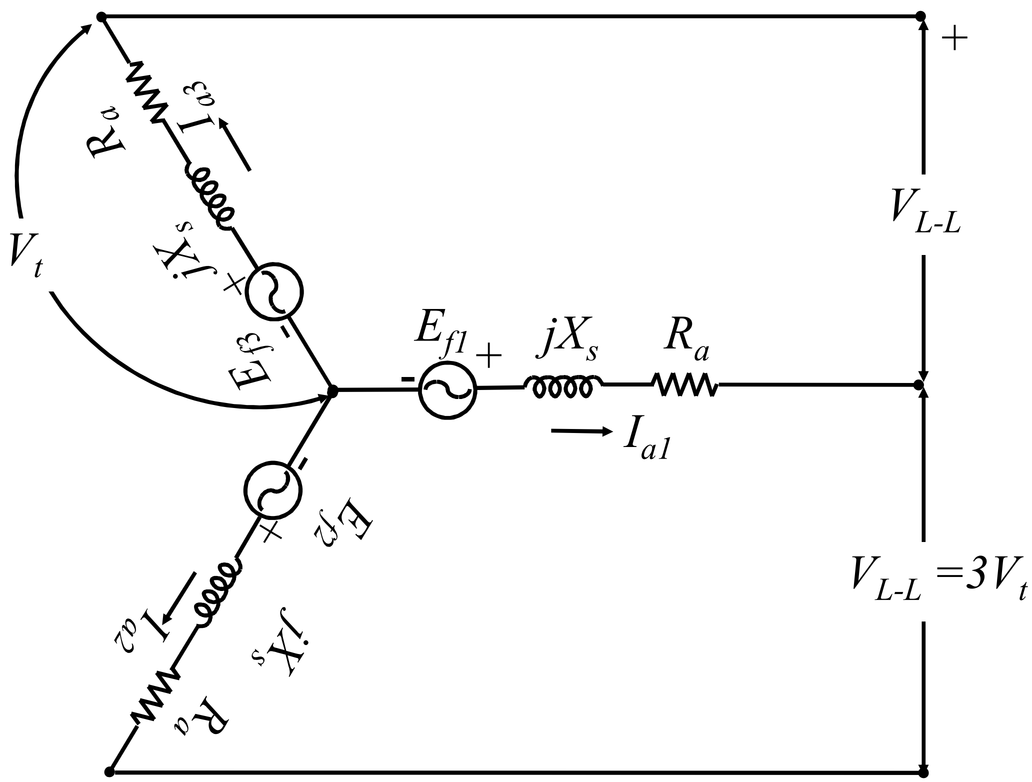


Phasor diagram of a cylindrical-rotor synchronous generator, for the case of lagging power factor

Lagging PF: $|V_t|<|E_f|$ for overexcited condition
Leading PF: $|V_t|>|E_f|$ for underexcited condition

Three-phase equivalent circuit of a cylindrical-rotor synchronous machine

The voltages and currents of the three phases are 120^o apart in angle, but otherwise the three phases are identical.

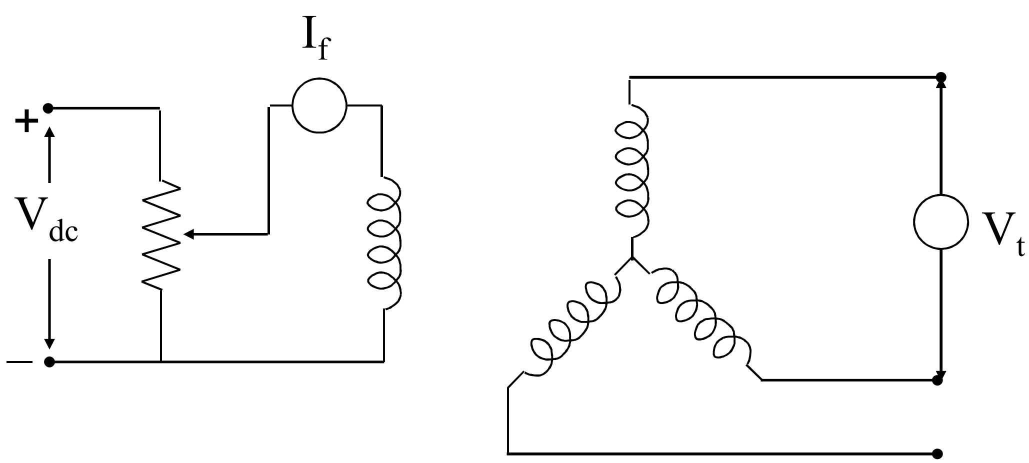


Determination of the parameters of the equivalent circuit from test data

- The equivalent circuit of a synchronous generator that has been derived contains three quantities that must be determined in order to completely describe the behaviour of a real synchronous generator:
  - The saturation characteristic: relationship between I_f and ϕ (and therefore between I_f and E_f)
  - The synchronous reactance, X_s
  - The armature resistance, R_a
- The above three quantities could be determined by performing the following three tests:
  - Open-circuit test
  - Short-circuit test
  - DC test

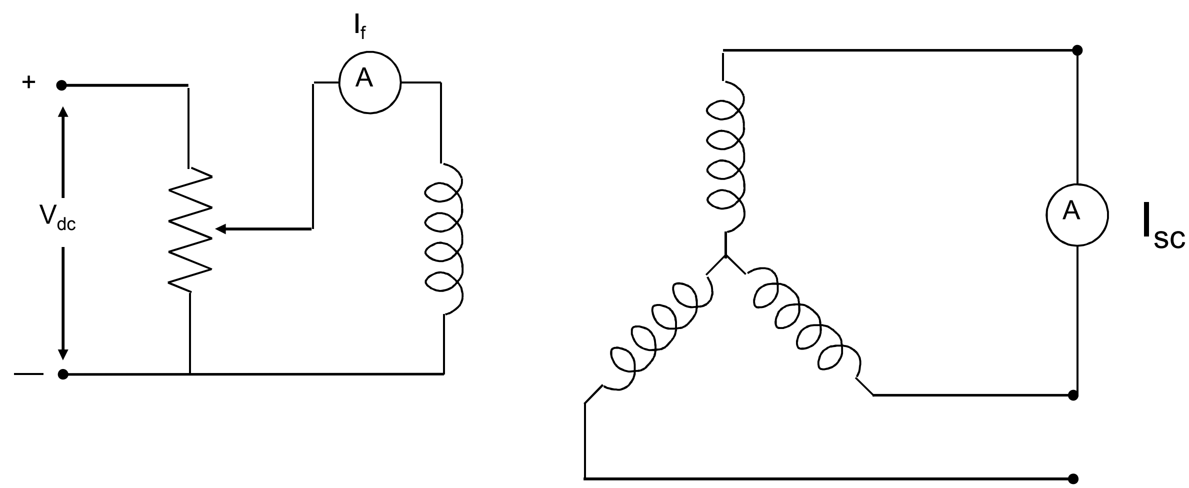
Open-circuit test

- The generator is turned at the rated speed
- The terminals are disconnected from all loads, and the field current is set to zero.
- Then the field current is gradually increased in steps, and the terminal voltage is measured at each step along the way.
- It is thus possible to obtain an open-circuit characteristic of a generator (E_f or V_t versus I_f) from this information



Short-circuit test

- Adjust the field current to zero and short-circuit the terminals of the generator through a set of ammeters.
- Record the armature current I_{sc} as the field current is increased.
- Such a plot is called short-circuit characteristic.



DC Test

- The purpose of the DC test is to determine R_a. A variable DC voltage source is connected between two stator terminals.
- The DC source is adjusted to provide approximately rated stator current, and the resistance between the two stator leads is determined from the voltmeter and ammeter readings
- then $$R_{DC} = \frac{V_{DC}}{I_{DC}}$$
- If the stator is Y-connected, the per phase stator resistance is

$$\boldsymbol{R_a = \frac{R_{DC}}{2}}$$

- If the stator is delta-connected, the per phase stator resistance is

$$\boldsymbol{R_a = \frac{3}{2} R_{DC}}$$

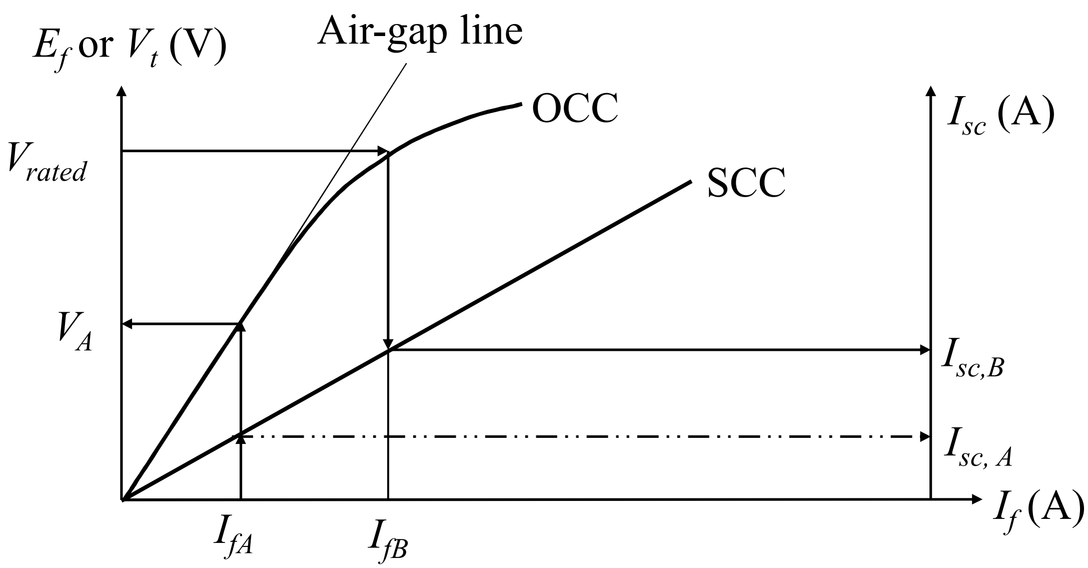
Determination of X_s

- For a particular field current I_{fA}, the internal voltage E_f $(=V_A)$ could be found from the occ and the short-circuit current flow $I_{sc,A}$ could be found from the scc.
- Then the synchronous reactance X_s could be obtained using

$$Z_{s,unsat} = \sqrt{R_a^2 + X_{s,unsat}^2} = \frac{V_A(=E_f)}{|I_{scA}|}$$

$$X_{s,unsat} = \sqrt{Z_{s,unsat}^2 - R_a^2}$$

: R_a is known from the DC test.



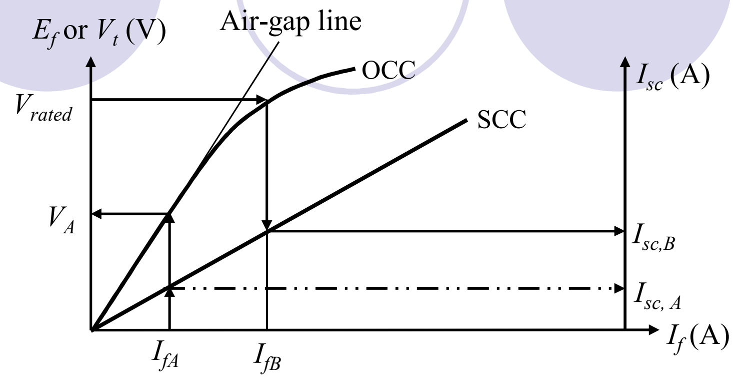
Since $X_{s,unsat} >> R_a$,

$$X_{s,unsat} \approx \frac{E_f}{I_{scA}} = \frac{V_{t,oc}}{I_{scA}}$$

X_s under saturated condition

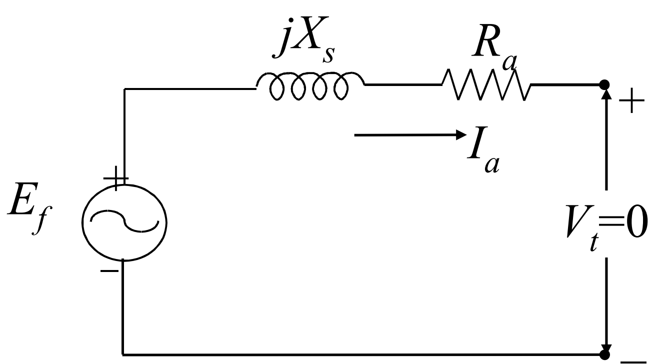
At $V = V_{rated}$,

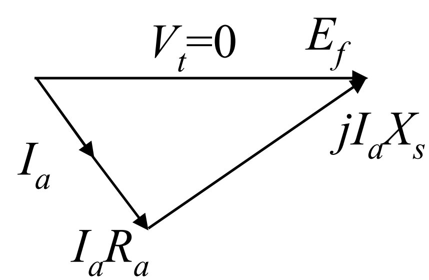
$$Z_{s,sat} = \sqrt{R_a^2 + X_{s,sat}^2} = \frac{V_{rated}\left(= E_f\right)}{\left|I_{scB}\right|}$$



$$X_{s,sat} = \sqrt{Z_{s,sat}^2 - R_a^2}$$ R_a is known from the DC test.

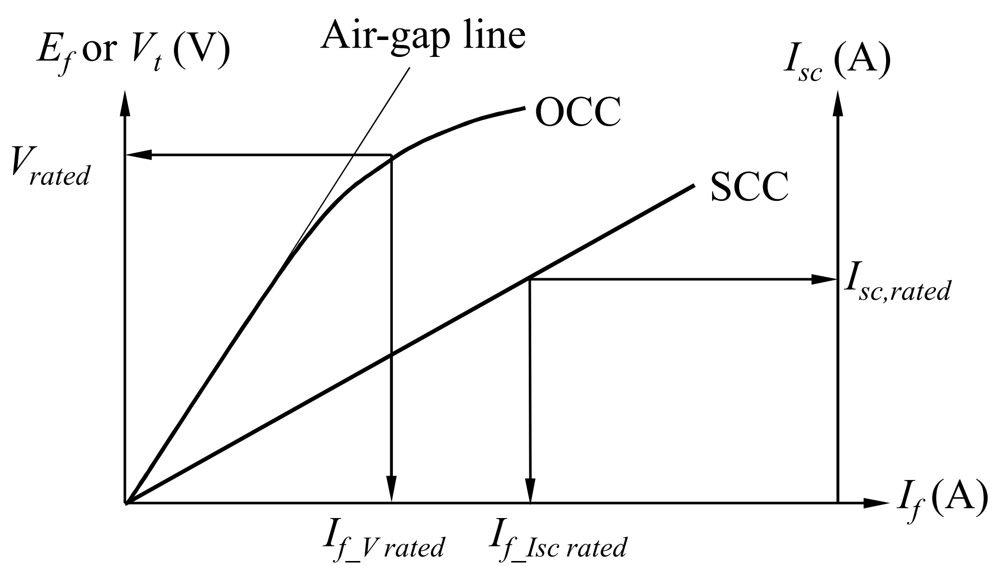
Equivalent circuit and phasor diagram under condition





Short-circuit Ratio

Another parameter used to describe synchronous generators is the short-circuit ratio (*SCR*). The SCR of a generator defined as the ratio of the *field current required for the rated voltage at open circuit* to the *field current required for the rated armature current at short circuit*. *SCR* is just the reciprocal of the per unit value of the saturated synchronous reactance calculated by



$$SCR = \frac{I_{f\_Vrated}}{I_{f\_Iscrated}} = \frac{1}{X_{s\_sat}\,[in\ p.u.]}$$

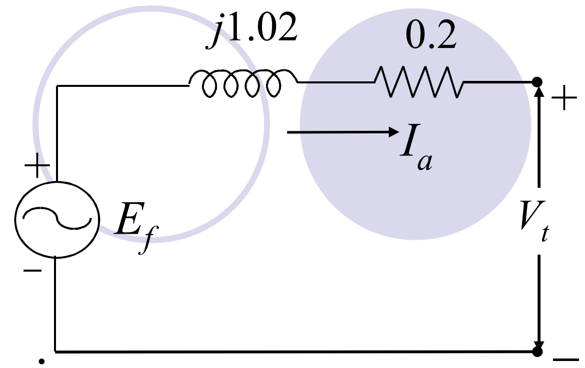
Example 1

A 200 kVA, 480-V, 60-Hz, 4-pole, Y-Connected synchronous generator with a rated field current of 5 A was tested and the following data was taken.

a) from OC test – terminal voltage = 540 V at rated field current
b) from SC test – line current = 300A at rated field current
c) from Dc test – DC voltage of 10 V applied to two terminals, a current of 25 A was measured.

1. Calculate the speed of rotation in r/min
2. Calculate the generated emf and saturated equivalent circuit parameters (armature resistance and synchronous reactance)

Solution to Example 1



1.

f_e = electrical frequency = $Pn_m/120$

f_e = 60Hz

P = number of poles = 4

n_m = mechanical speed of rotation in r/min.

So, speed of rotation $n_m = 120 f_e / P$

= (120 x 60)/4 = 1800 r/min

2. In open-circuit test, $I_a = 0$ and $E_f = V_t$

E_f = 540/1.732

= 311.8 V (as the machine is Y-connected)

In short-circuit test, terminals are shorted, $V_t = 0$

$E_f = I_a Z_s$ or $Z_s = E_f/I_a$ =311.8/300=1.04 ohm

From the DC test, $R_a = V_{DC}/(2I_{DC})$

= 10/(2X25) = 0.2 ohm

Synchronous reactance $Z_{s,sat} = \sqrt{R_a^2 + X_{s,sat}^2}$

$$X_{s,sat} = \sqrt{Z_{s,sat}^2 - R_a^2} = \sqrt{1.04^2 - 0.2^2} = 1.02$$

Problem 1

A 480-V, 60-Hz, Y-Connected synchronous generator, having the synchronous reactance of 1.04 ohm and negligible armature resistance, is operating alone. The terminal voltage at rated field current at open circuit condition is 480V.

1. Calculate the voltage regulation
    1. If load current is 100A at 0.8 PF lagging
    2. If load current is 100A at 0.8 PF leading
    3. If load current is 100A at unity PF
2. Calculate the real and reactive power delivered in each case.
3. State and explain whether the voltage regulation will improve or not if the load current is decreased to 50 A from 100 A at 0.8 PF lagging.

Operation of AC Generators in Parallel with Large Power Systems

- Isolated synchronous generator supplying its own load is very rare (emergency generators).
- In general applications more than one generator operating in parallel to supply loads.
- In Pakistani national grid hundreds of generators share the load on the system.

Parallel operation of synchronous generators

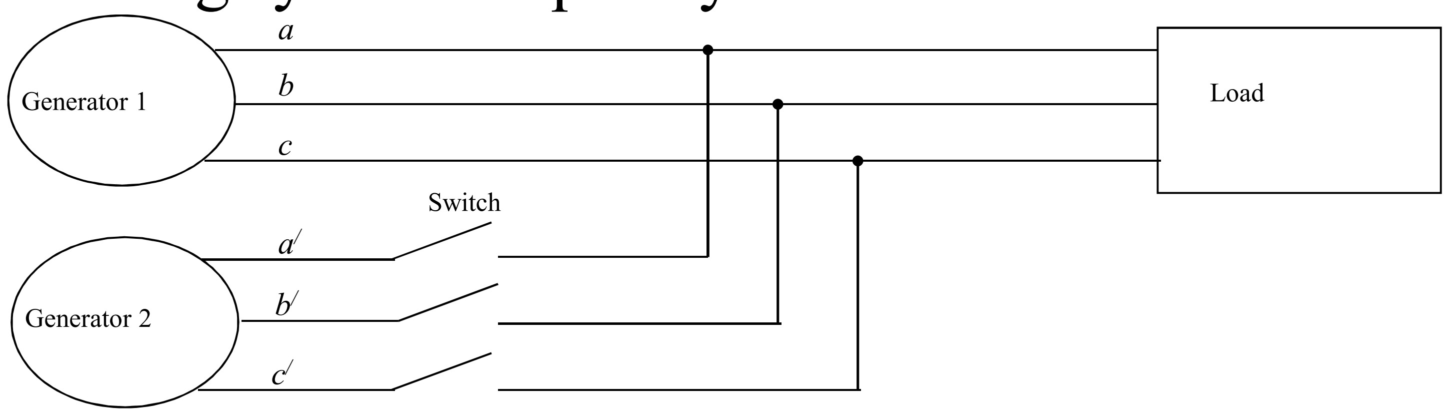
There are several major advantages to operate generators in parallel:

- Several generators can supply a bigger load than one machine by itself.
- Having many generators increases the reliability of the power system.
- It allows one or more generators to be removed for shutdown or preventive maintenance.
- If only one generator employed & not operating near full load, it will be relatively inefficient

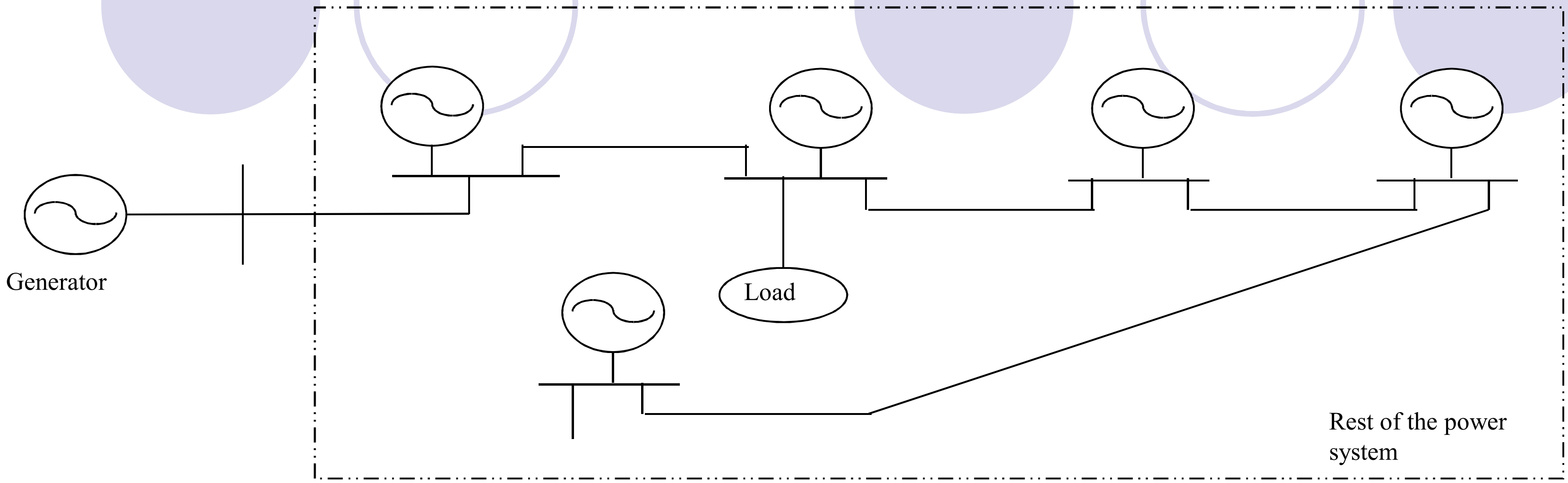
Synchronization

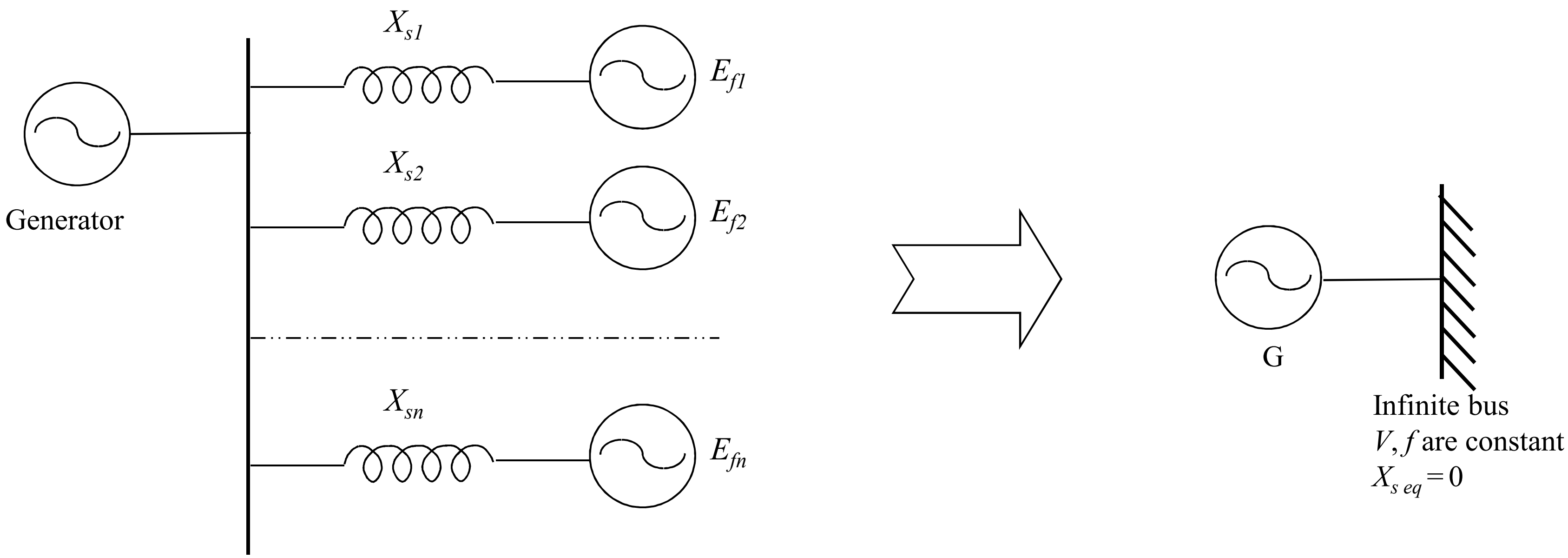
Before connecting a generator in parallel with another generator, it must be synchronized. A generator is said to be synchronized when it meets all the following conditions:

- The *rms line voltages* of the two generators must be equal.
- The two generators must have the same *phase sequence*.
- The *phase angles* of the two *a* phases must be equal.
- The *oncoming generator frequency* is equal to the running system frequency.



Synchronization





Concept of the infinite bus

When a synchronous generator is connected to a power system, the power system is often so large that nothing the operator of the generator does will have much of an effect on the power system. An example of this situation is the connection of a single generator to the Pakistan power grid. Our Pakistani power grid is so large that no reasonable action on the part of one generator can cause an observable change in overall grid frequency. This idea is idealized in the concept of an infinite bus. *An infinite bus is a power system so large that its voltage and frequency do not vary regardless of how much real or reactive power is drawn from or supplied to it.*

Procedure

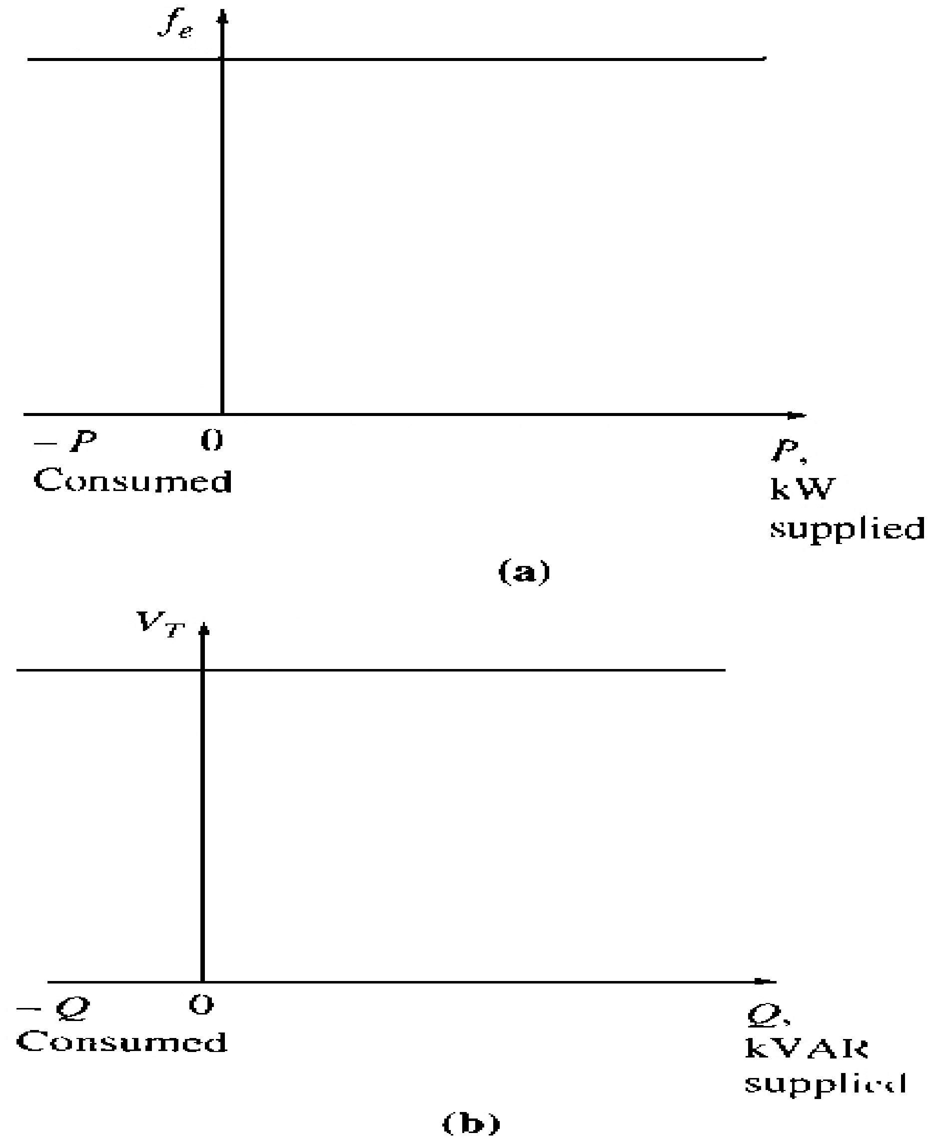
- ***First*** – verify terminal voltage of oncoming generator equals line voltage of system
- ***Second*** – verify that the phase sequence of the oncoming generator is the same as the phase sequence of the running system (motor, bulbs, synchroscope)
- ***Third*** – adjust the frequency of the oncoming unit to be slightly higher than the frequency of the running system. (Why ? Explained in coming slides)

Operation of AC Generators in Parallel with Large Power Systems

- When a synchronous Generator connected to a power system:

1-The real power versus frequency characteristic of such a system

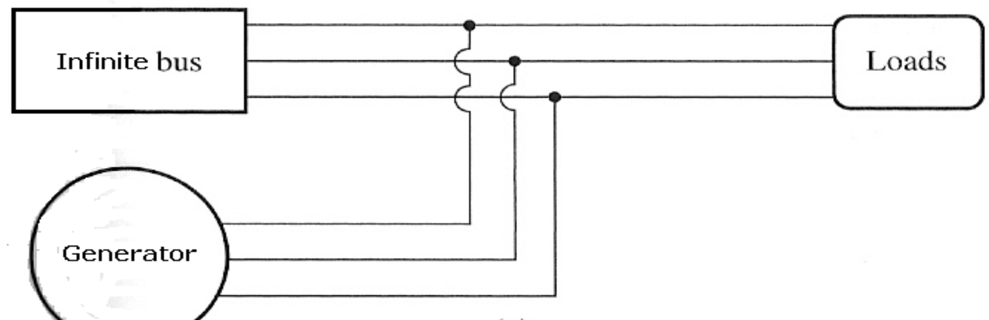
2-And the reactive power-voltage characteristic



Operation of AC Generators in Parallel with Large Power Systems

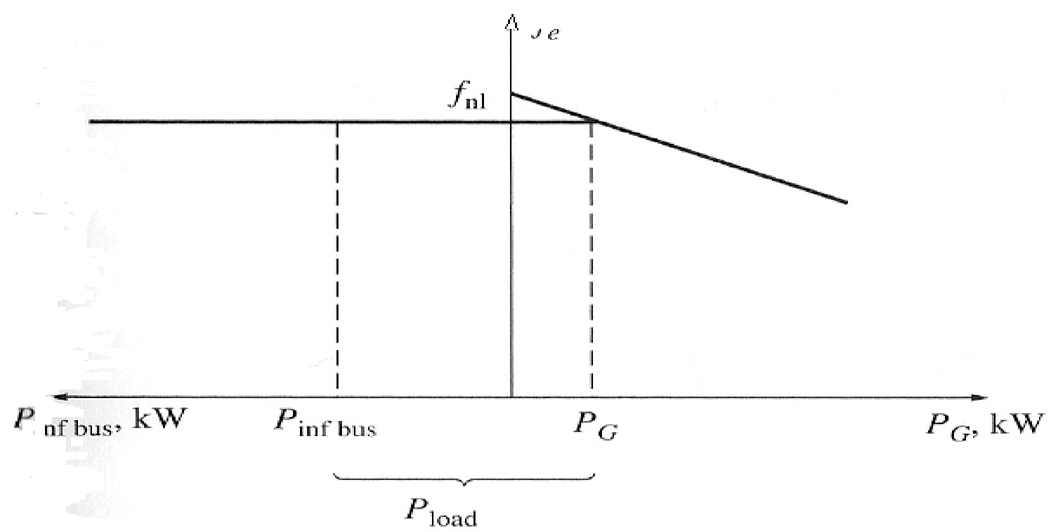
- Behavior of a generator connected to a large system.

  A generator connected in parallel with a large system as shown ➔



(a)

- Frequency & voltage of all machines must be the same, their real power-frequency (& reactive power-voltage) characteristics plotted back to back ➔



(b)

Operation of AC Generators in Parallel with Large Power Systems

- Assume generator just been paralleled with infinite bus, generator will be “floating” on the line, supplying a small amount of real power and little or no reactive power
- Suppose generator paralleled, however its frequency being slightly lower than system’s operating frequency ➔
- At this frequency power supplied by generator is less than system’s operating frequency, generator will consume energy and runs as motor .

Operation of AC Generators in Parallel with Large Power Systems

- In order that a generator comes on line and supply power instead of consuming it, we should ensure that oncoming machine's frequency is adjusted higher than running system's frequency.
- Many generators have "reverse-power trip" system.
- And if such a generator ever starts to consume power it will be automatically disconnected from line.

Active and reactive power-angle characteristics

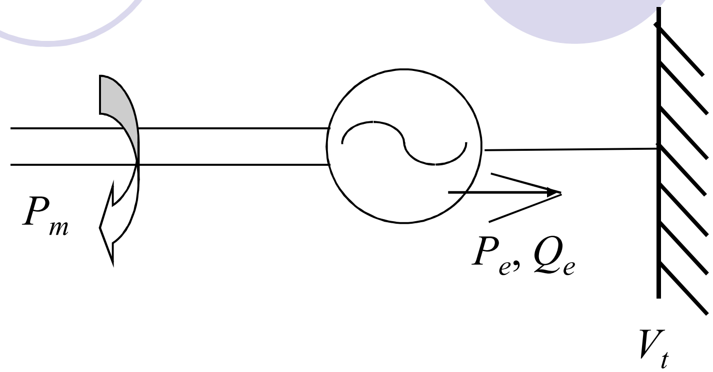
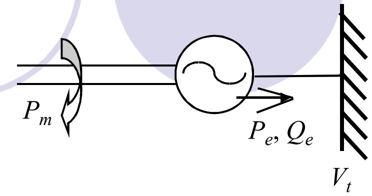


Fig. Synchronous generator connected to an infinite bus.

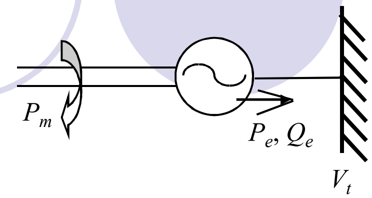
- P>0: generator operation
- P<0: motor operation
- Positive Q: delivering inductive vars for a generator action or receiving inductive vars for a motor action
- Negaive Q: delivering capacitive vars for a generator action or receiving capacitive vars for a motor action

Active and reactive power-angle characteristics



- The real and reactive power delivered by a synchronous generator or consumed by a synchronous motor can be expressed in terms of the terminal voltage V_t, generated voltage E_f, synchronous impedance Z_s, and the power angle or torque angle δ.
- Referring to Fig. 8, it is convenient to adopt a convention that makes positive real power P and positive reactive power Q delivered by an *overexcited generator*.
- The generator action corresponds to positive value of δ, while the motor action corresponds to negative value of δ.

Active and reactive power-angle characteristics



The complex power output of the generator in volt-amperes per phase is given by

$$S = P + jQ = \bar{V}_t \, I_a^*$$

where:

V_t = terminal voltage per phase

I_a^* = complex conjugate of the armature current per phase

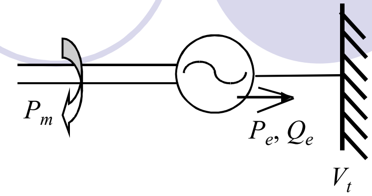
Taking the terminal voltage as reference

$$\bar{V}_t = V_t + j0$$

the excitation or the generated voltage,

$$\bar{E}_f = E_f(\cos\delta + j\sin\delta)$$

Active and reactive power-angle characteristics



and the armature current,

$$\bar{I}_a = \frac{\bar{E}_f - \bar{V}_t}{jX_s} = \frac{\left(E_f \cos\delta - V_t\right) + jE_f \sin\delta}{jX_s}$$

where X_s is the synchronous reactance per phase.

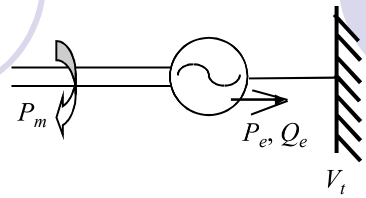
$$S = P + jQ = \bar{V}_t \bar{I}_a^* = V_t \left[\frac{\left(E_f \cos\delta - V_t\right) - jE_f \sin\delta}{-jX_s} \right]$$

$$= \frac{V_t E_f \sin\delta}{X_s} + j\frac{V_t E_f \cos\delta - V_t^2}{X_s}$$

$$\therefore \quad P = \frac{V_t E_f \sin\delta}{X_s} \qquad \&$$

$$Q = \frac{V_t E_f \cos\delta - V_t^2}{X_s}$$

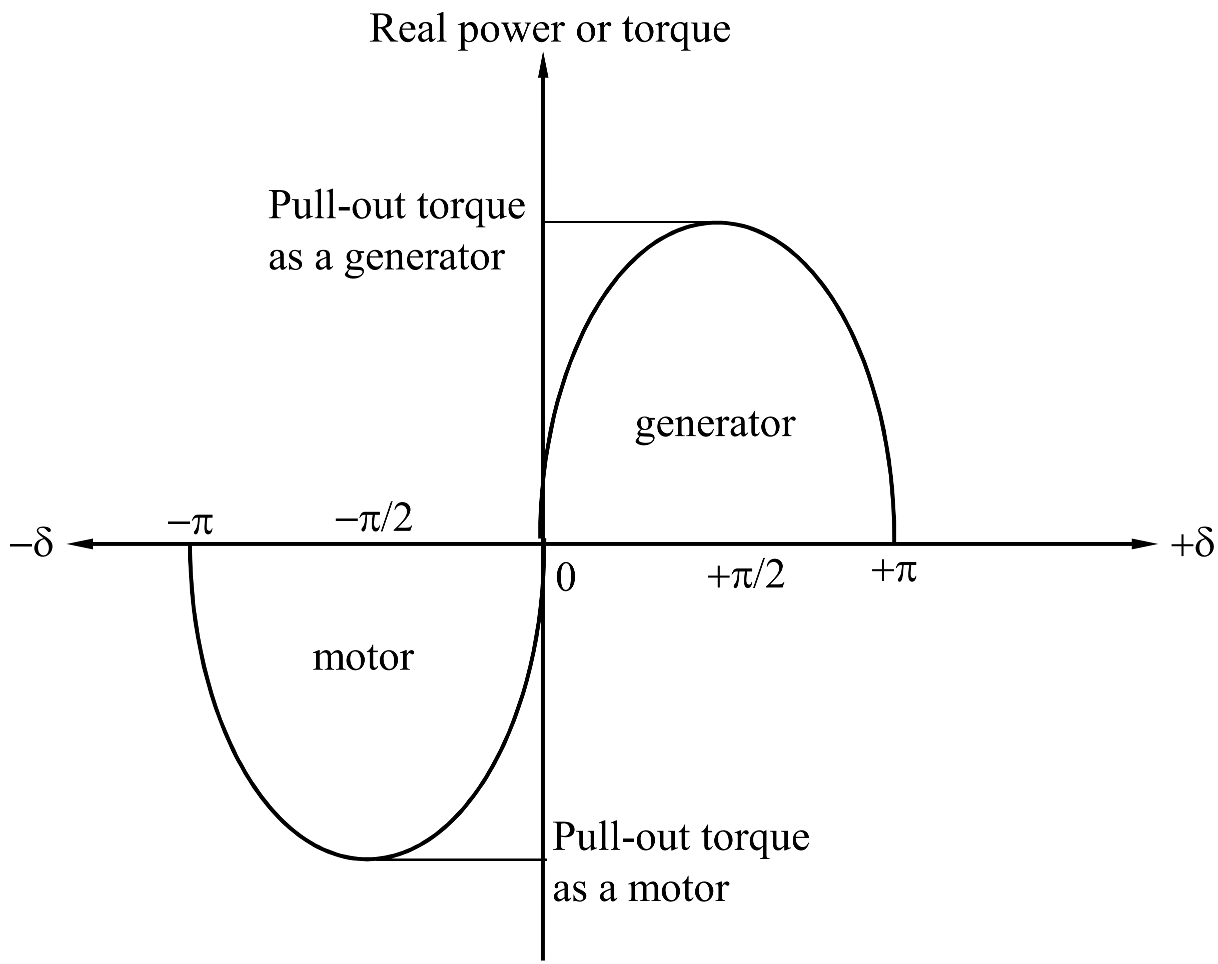
Active and reactive power-angle characteristics



$$\therefore \quad P = \frac{V_t E_f \sin\delta}{X_s} \qquad \& \qquad Q = \frac{V_t E_f \cos\delta - V_t^2}{X_s}$$

- The above two equations for active and reactive powers hold good for cylindrical-rotor synchronous machines for negligible resistance
- To obtain the total power for a three-phase generator, the above equations should be multiplied by 3 when the voltages are line-to-neutral
- If the line-to-line magnitudes are used for the voltages, however, these equations give the total three-phase power

Steady-state power-angle or torque-angle characteristic of a cylindrical-rotor synchronous machine (with negligible armature resistance).



Steady-state stability limit

Total three-phase power: $P = \dfrac{3V_t E_f}{X_s} sin\,\delta$

The above equation shows that the power produced by a synchronous generator depends on the angle δ between the V_t and E_f. The maximum power that the generator can supply occurs when $\delta=90^o$.

$$P = \frac{3V_t E_f}{X_s}$$

The maximum power indicated by this equation is called *steady-state stability limit* of the generator. If we try to exceed this limit (such as by admitting more steam to the turbine), the rotor will accelerate and lose synchronism with the infinite bus. In practice, this condition is never reached because the circuit breakers trip as soon as synchronism is lost. We have to resynchronize the generator before it can again pick up the load. Normally, real generators never even come close to the limit. Full-load torque angle of 15^o to 20^o are more typical of real machines.

Pull-out torque

The maximum torque or *pull-out torque* per phase that a two-pole round-rotor synchronous motor can develop is

$$T_{max} = \frac{P_{max}}{\omega_m} = \frac{P_{max}}{2\pi\left(n_s/60\right)}$$

where n_s is the synchronous speed of the motor in rpm

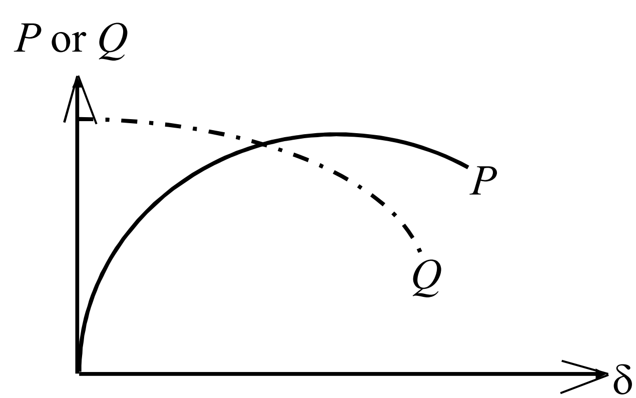


Fig. Active and reactive power as a function of the internal angle

Problem 2

A 208-V, 45-kVA, 0.8-PF leading, △-connected, 60-Hz synchronous machine having 1.04 ohm synchronous reactance and negligible armature resistance is supplying a load of 12 kW at 0.8 power factor leading. Find the armature current and generated voltage and power factor if the load is increased to 20 KW. Neglect all other losses.

Example 5-2 (pp291)

A 480 V, 60 Hz, -connected, four pole synchronous generator has the OCC shown below. This generator has a synchronous reactance of 0.1 ohm and armature resistance of 0.015 ohm. At full load, the machine supplies 1200 A and 0.8 pf lagging. Under full-load conditions, the friction and windage losses are 40 kW, and the core losses are 30 kW. Ignore field circuit losses.

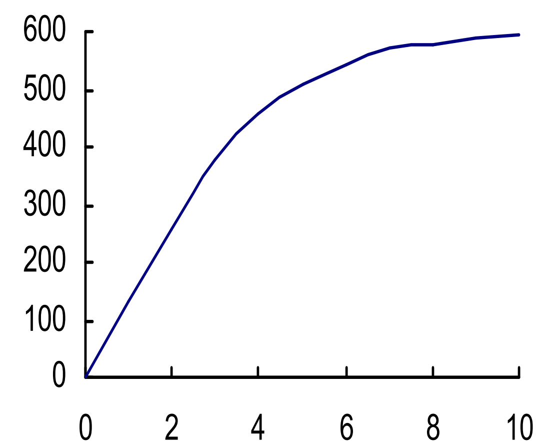
a) What is the speed of rotation of the generator?

b) How much field current must be supplied to the generator to make the terminal voltage 480 V at no load?

c) If the generator is now connected to a load and the load draws 1200 A at 0.8 pf lagging, how much field current will be required to keep the terminal voltage equal to 480 V?

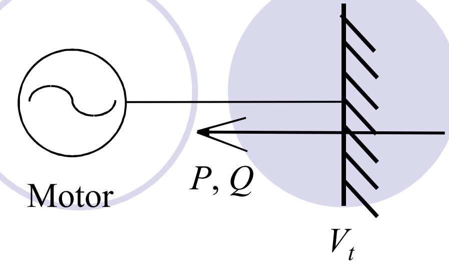
d) How much power is the generator now supplying? How much power is supplied to the generator by the prime-mover? What is the machine's overall efficiency?

e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?



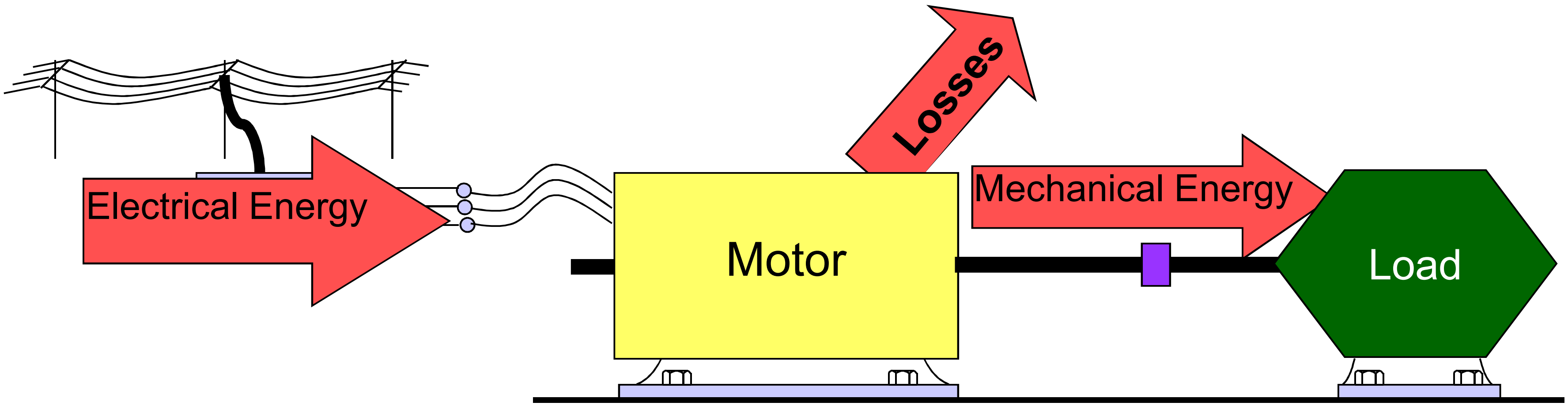
Synchronous Motor

Synchronous Motors



- A synchronous motor is the same physical machine as a generator, except that the direction of real power flow is reversed
- Synchronous motors are used to convert electric power to mechanical power
- Most synchronous motors are rated between 150 kW (200 hp) and 15 MW (20,000 hp) and turn at speed ranging from 150 to 1800 r/min. Consequently, these machines are used in heavy industry
- At the other end of the power spectrum, we find tiny single-phase synchronous motors used in control devices and electric clocks

Synchronous Motor



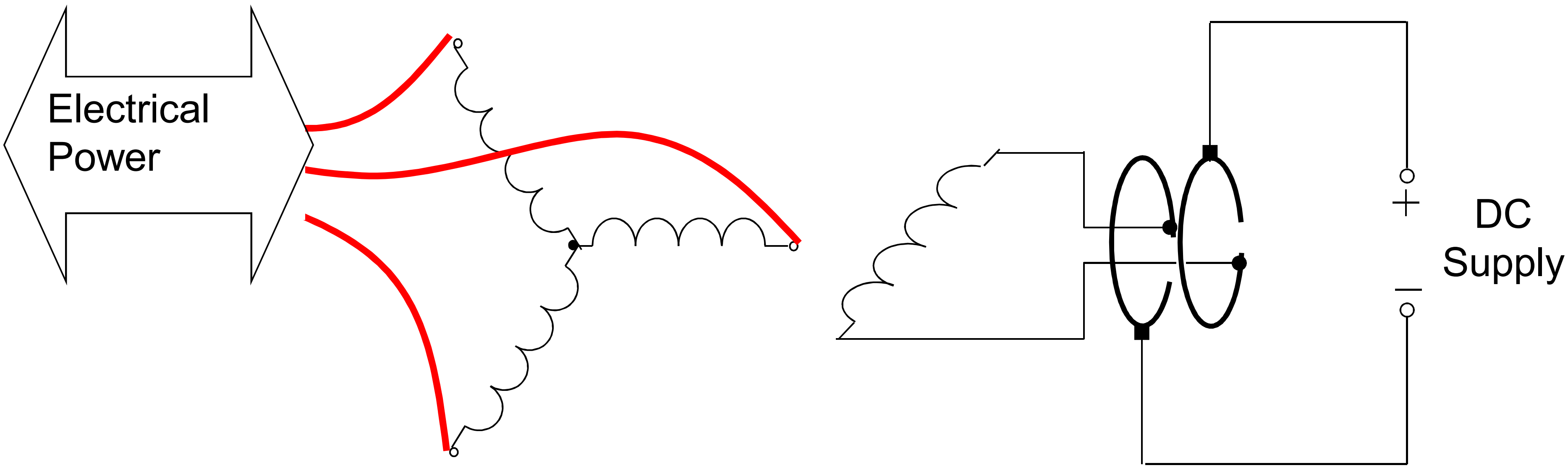
Motor

Pin = Pout + Losses

Motor:

$$Eff\% = \frac{Pout}{Pin} \times 100$$

Synchronous Machine



Stator
- Identically wound to an induction motor.
- Connected to supply.

Rotor
- Constant DC field
- Connected to supply via slip rings.

Operation Principle

- The field current of a synchronous motor produces a steady-state magnetic field B_R
- A three-phase set of voltages is applied to the stator windings of the motor, which produces a three-phase current flow in the windings. This three-phase set of currents in the armature winding produces a uniform rotating magnetic field of B_s
- Therefore, there are two magnetic fields present in the machine, and *the rotor field will tend to line up with the stator field*, just as two bar magnets will tend to line up if placed near each other.
- Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will try to catch up
- The larger the angle between the two magnetic fields (up to certain maximum), the greater the torque on the rotor of the machine

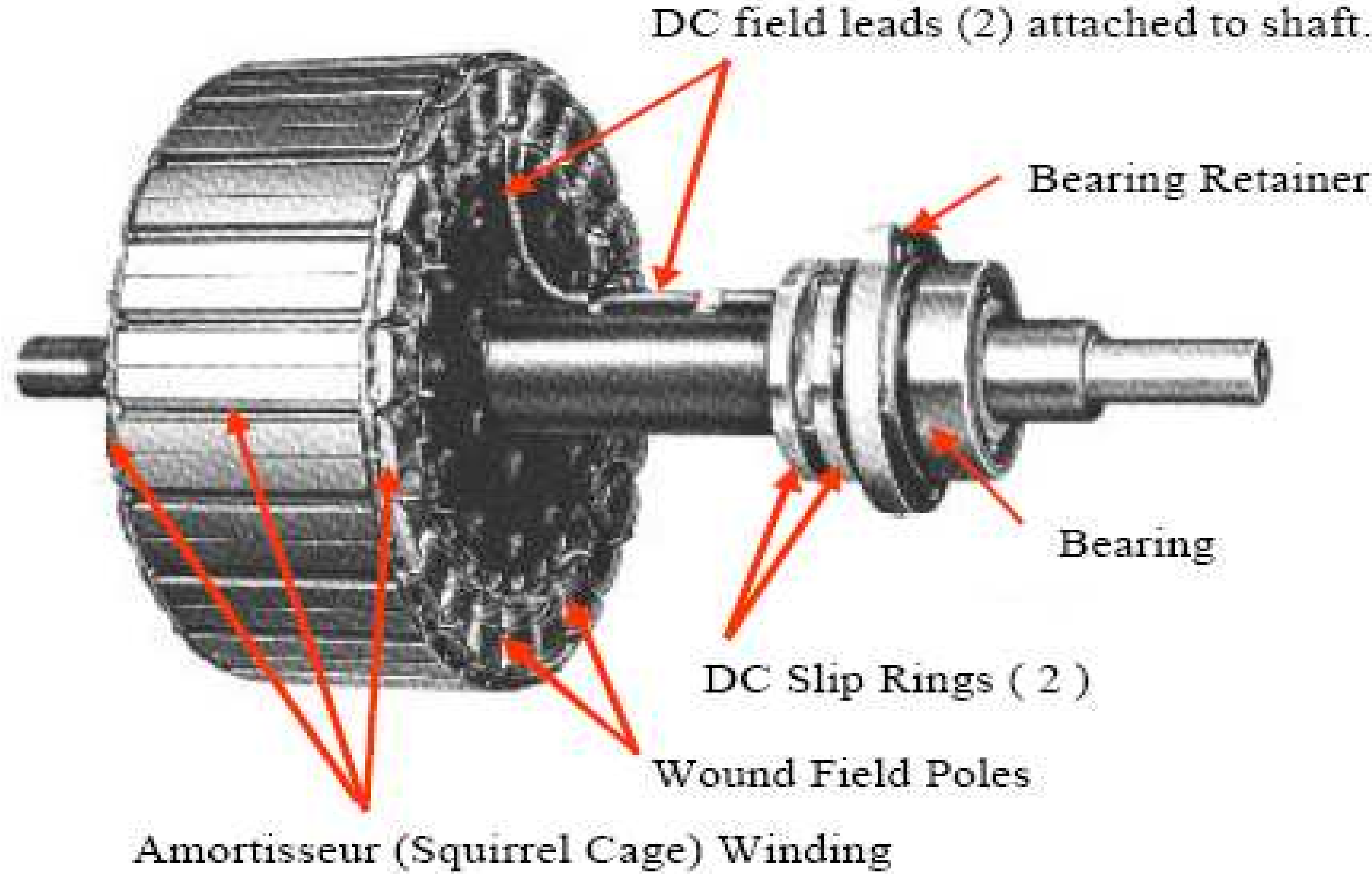
Synchronous Motor Rotors

The Salient-Pole unit shown at the right is a brush-type rotor that uses slip rings for application of the DC field current.

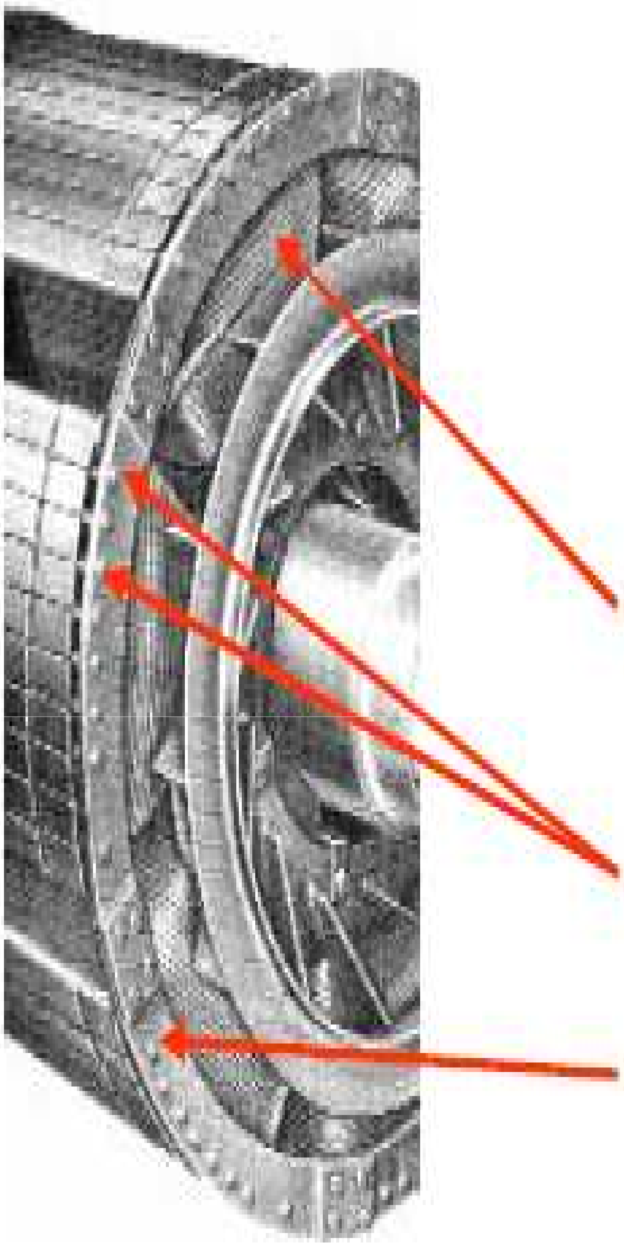
- Low voltage DC is used for the rotating field. 120 VDC and 250 VDC are typical.

- Slip ring polarity is not critical and should be periodically reversed to equalize the wear on the slip rings. The negative polarity ring will
  sustain more wear than the positive ring due to electrolysis.

- Slip rings are usually made of steel for extended life.



Electric Machinery Photo



Electric Machinery Photo

Detail of Amortisseur Winding

Synchronous motors start as an induction motor utilizing the Amortisseur winding which is a squirrel-cage-type winding with short-circuited rotor bars.

Wound Field Pole - Energized by separate source of DC for synchronous operation.

Squirrel-Cage Rotor Bars

Shorting Ring - One on each end of rotor.

why synchronous motor has zero starting ?

A synchronous motor is not self starting. when three phase current displaced in time by 120 degree is applied to the three phase stator windings displaced in space by 120 degree then a rotating magnetic field is produced in the air gap. The rotor tends to align with this rotating field, the rotor windings are supplied by dc .

So constant poles are produced on the rotor. Now suppose the instant when the rotating stator field has its north pole in line with the south pole of the rotor, the rotor will be attracted and tend to move with the stator. but due to its inertia before it starts to move with the stator the south pole of the stator comes in line with the rotor south pole, so now the rotor gets repelling force and it tends to move in the opposite direction as that of the stator. but again before it starts to move the stator north pole comes in line with the rotor south pole. thus overall the effect is that the syn. motor is not self starting. once it is brought to the syn speed by an external prime mover it rotates at syn. speed irrespective of the load.

Motor Under load General Perspective

When a synchronous motor runs at no-load, the rotor poles are directly opposite the stator poles and their axes coincide (Fig. 17.5). However, if we apply a mechanical load, the rotor poles fall slightly behind the stator poles, but the rotor continues to turn at synchronous speed. The mechanical angle α between the poles increases progressively as we increase the load (Fig. 17.6). Nevertheless, the magnetic attraction keeps the rotor locked to the revolving field, and the motor develops an ever more powerful torque as the angle increases.

Motor Under load General Perspective

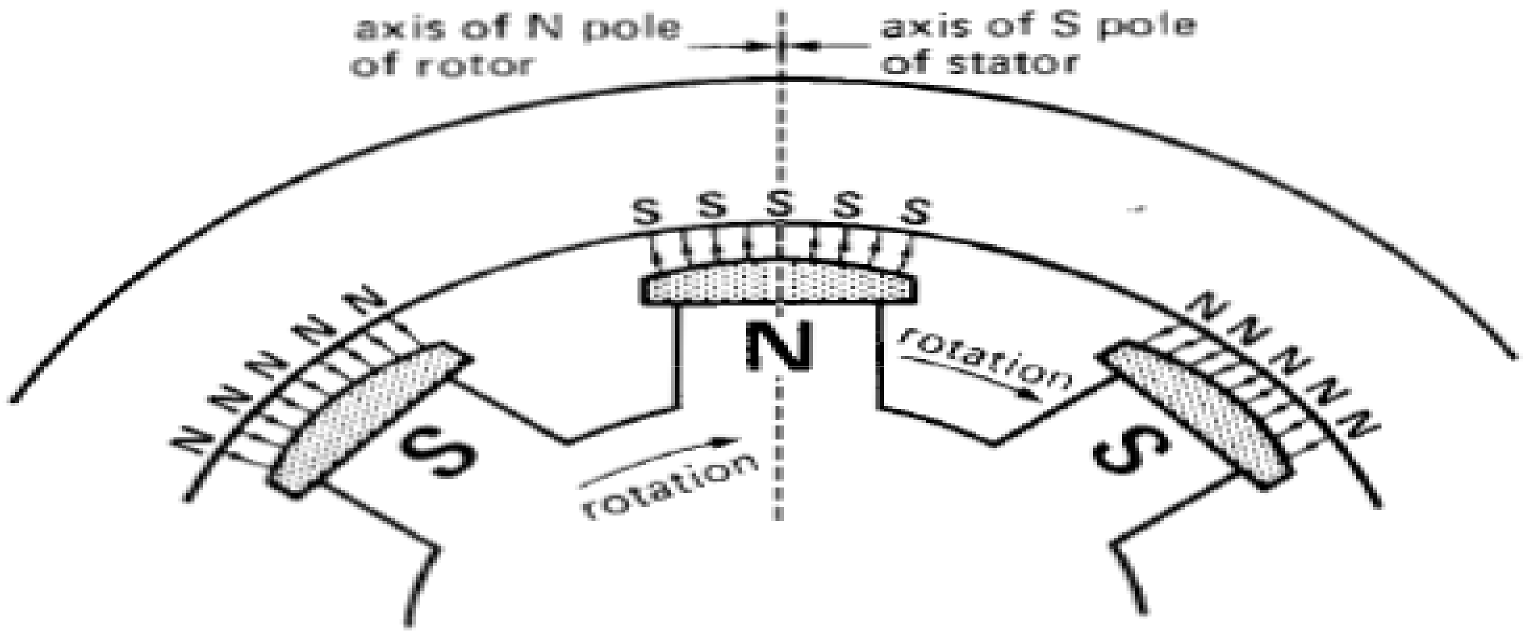


Figure 17.5
The poles of the rotor are attracted to the opposite poles on the stator. At no-load the axes of the poles coincide.

Motor Under load General Perspective

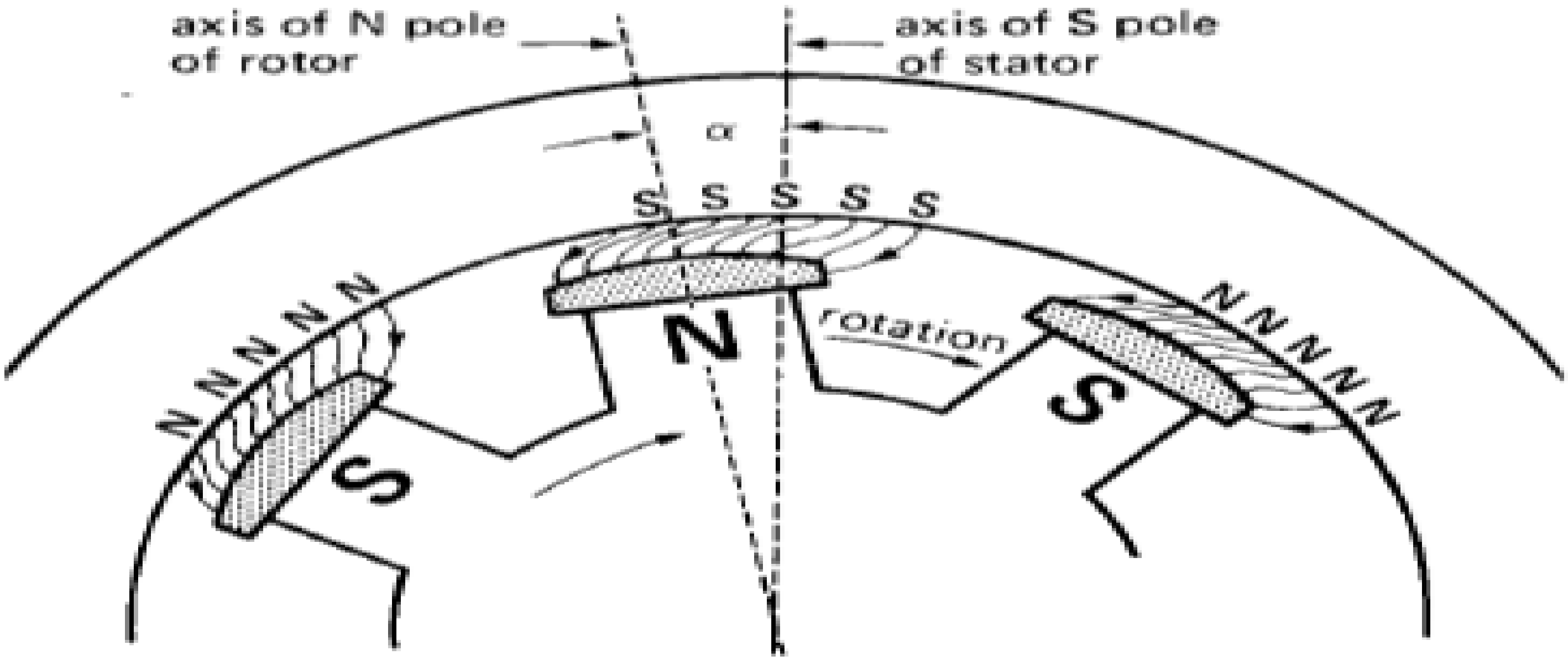


Figure 17.6
The rotor poles are displaced with respect to the axes of the stator poles when the motor delivers mechanical power.

Motor Under load General Perspective

But there is a limit. If the mechanical load exceeds the *pull-out torque* of the motor, the rotor poles suddenly pull away from the stator poles and the motor comes to a halt. A motor that pulls out of step creates a major disturbance on the line, and the circuit breakers immediately trip. This protects the motor because both the squirrel-cage and stator windings overheat rapidly when the machine ceases to run at synchronous speed.

Motor Under load General Perspective

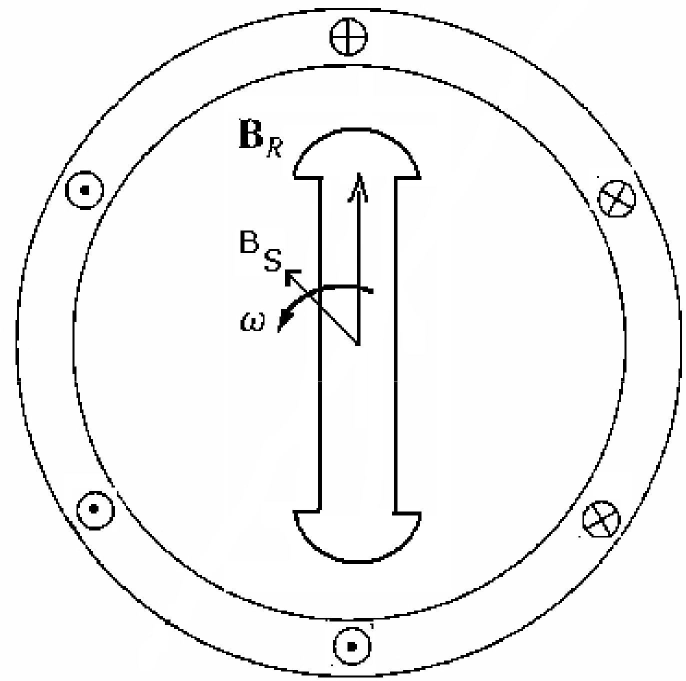
The pull-out torque depends upon the magneto-motive force developed by the rotor and the stator poles. The mmf of the rotor poles depends upon the dc excitation I_x, while that of the stator depends upon the ac current flowing in the windings. The pull-out torque is usually 1.5 to 2.5 times the nominal full-load torque.

The mechanical angle α between the rotor and stator poles has a direct bearing on the stator current. As the angle increases, the current increases. This is to be expected because a larger angle corresponds to

a bigger mechanical load, and the increased power can only come from the 3-phase ac source.

Synchronous Motors

- Synchronous machines employed to convert electric energy to mechanical energy
- To present the principles of Synchronous motor, a 2-pole synchronous motor considered
- It has the same basic speed, power, & torque equations as Syn. Gen.



$$\tau_{ind} = kB_R \times B_S = counterclockwise$$

Vector Diagram

- The equivalent circuit of a synchronous motor is exactly same as the equivalent circuit of a synchronous generator, except that the reference direction of I_a is reversed.
- The basic difference between motor and generator operation in synchronous machines can be seen either in the magnetic field diagram or in the phasor diagram.
- In a generator, E_f lies ahead of V_t, and B_R lies ahead of B_{net}. In a motor, E_f lies behind V_t, and B_R lies behind B_{net}.
- In a motor the induced torque is in the direction of motion, and in a generator the induced torque is a countertorque opposing the direction of motion

Vector Diagram

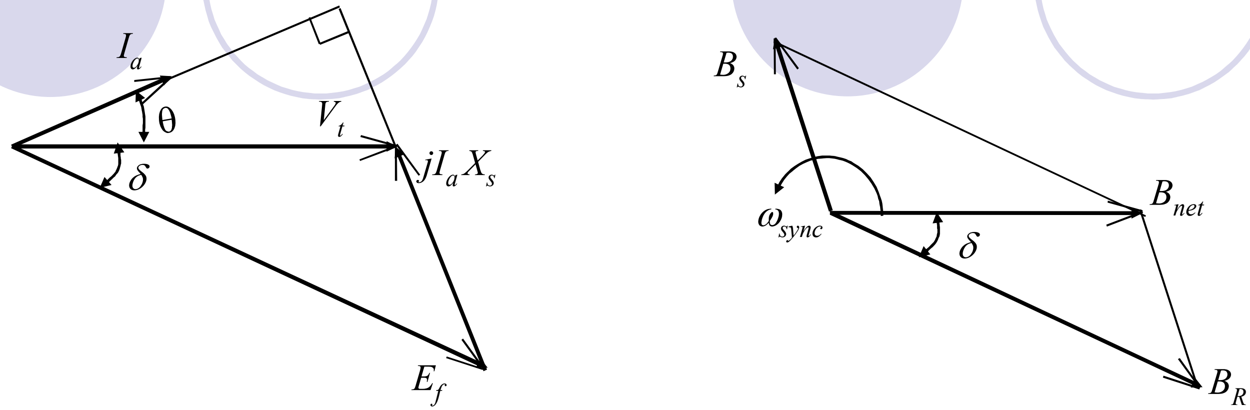


Fig. The phasor diagram (leading PF: overexcited and $|V_t|<|E_f|$) and the corresponding magnetic field diagram of a synchronous motor.

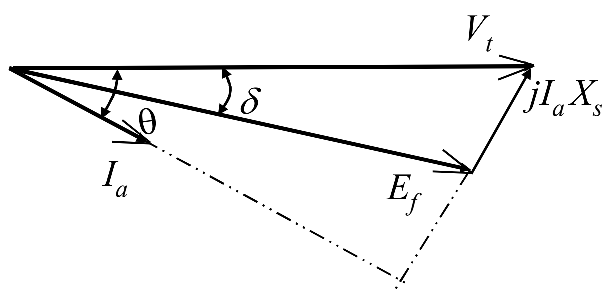


Fig. The phasor diagram of an underexcited synchronous motor (lagging PF and $|V_t|>|E_f|$).

Application of Synchronous Motors

Synchronous motors are usually used in large sizes because in small sizes they are costlier as compared with induction machines. The principal advantages of using synchronous machine are as follows:

- Power factor of synchronous machine can be controlled very easily by controlling the field current.
- It has very high operating efficiency and constant speed.
- For operating speed less than about 500 rpm and for high-power requirements (above 600KW) synchronous motor is cheaper than induction motor.

In view of these advantages, synchronous motors are preferred for driving the loads requiring high power at low speed; e.g; reciprocating pumps and compressor, crushers, rolling mills, pulp grinders etc.

Problem 5-22 (pp.343)

A 100-MVA, 12.5-kV, 0.85 power lagging, 50 Hz, two-pole, Y-connected, synchronous generator has a pu synchronous reactance of 1.1 and pu armature resistance of 0.012.

a) What are its synchronous reactance and armature resistance in ohms?
b) What is the magnitude of the internal voltage E_f at the rated conditions? What is its load angle δ at these conditions?
c) Ignoring losses in the generator, what torque must be applied to its shaft by the prime-mover at full load?

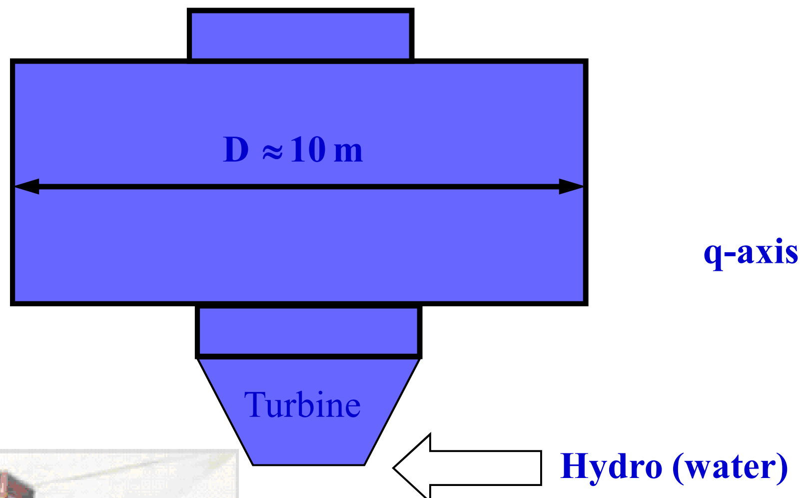
Problem 5-23 (pp.343)

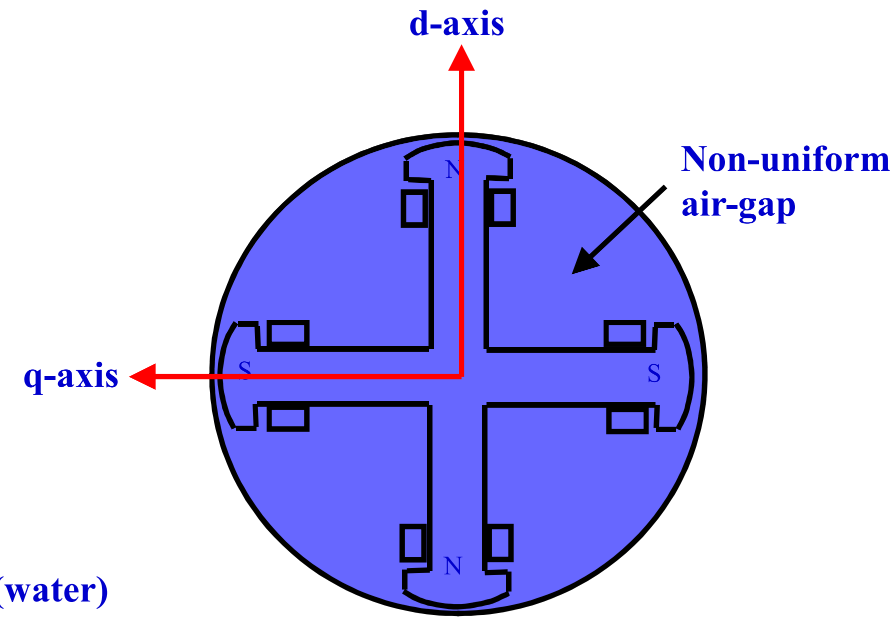
A three-phase, Y-connected synchronous generator is rated 120 MVA, 13.2 kV, 0.8 power lagging, and 60 Hz. Its synchronous reactance is 0.9 ohm and its armature resistance may be ignored.

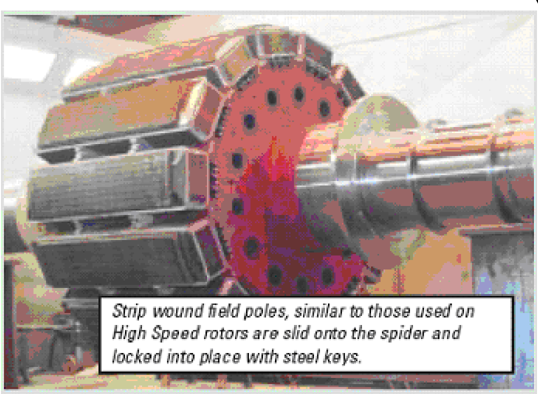
a) What is its voltage regulation at rated load?
b) What would the voltage and apparent power rating of this generator be if it were operated at 50 Hz with the same armature and field losses as it had at 60 Hz?
c) What would the voltage regulation of the generator be at 50 Hz?

Salient-Pole Synchronous Generator

1. Most hydraulic turbines have to turn at low speeds (between 50 and 300 r/min)
2. A large number of poles are required on the rotor

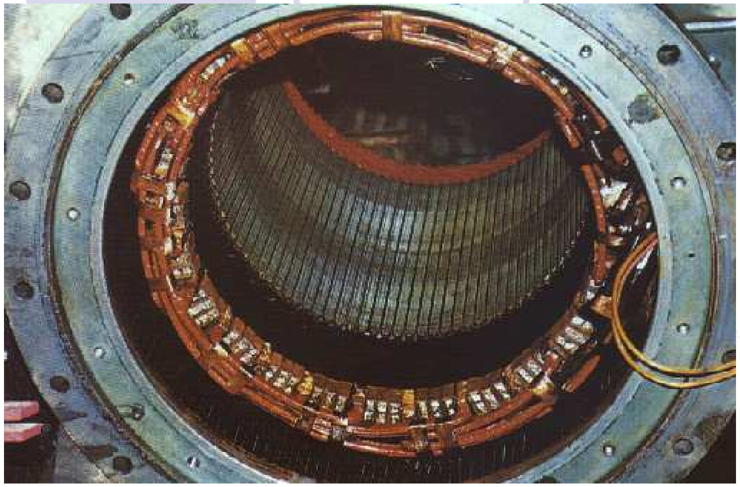




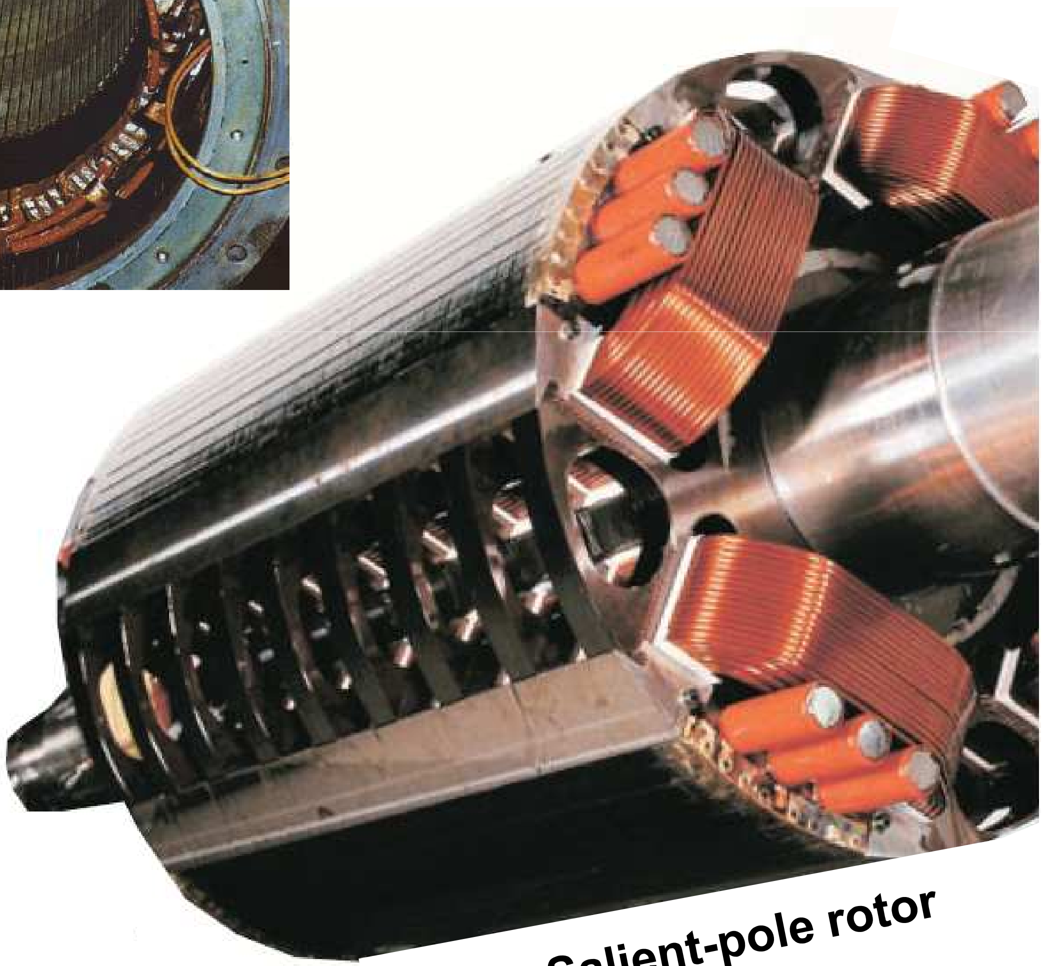


Hydro generator

Salient-Pole Synchronous Generator

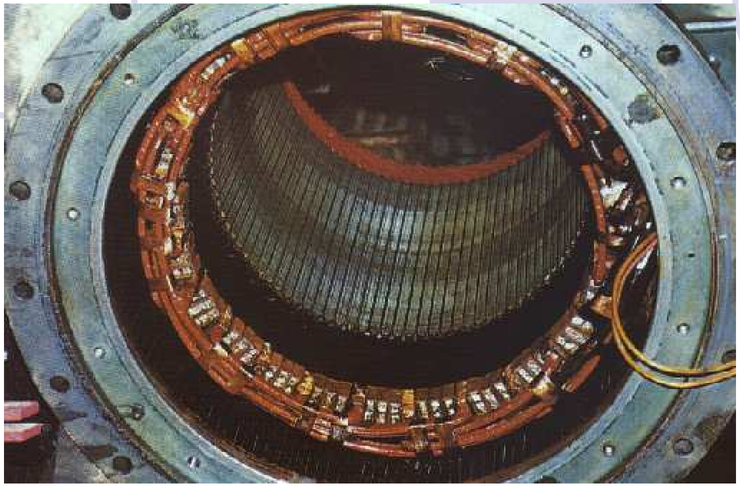


Stator

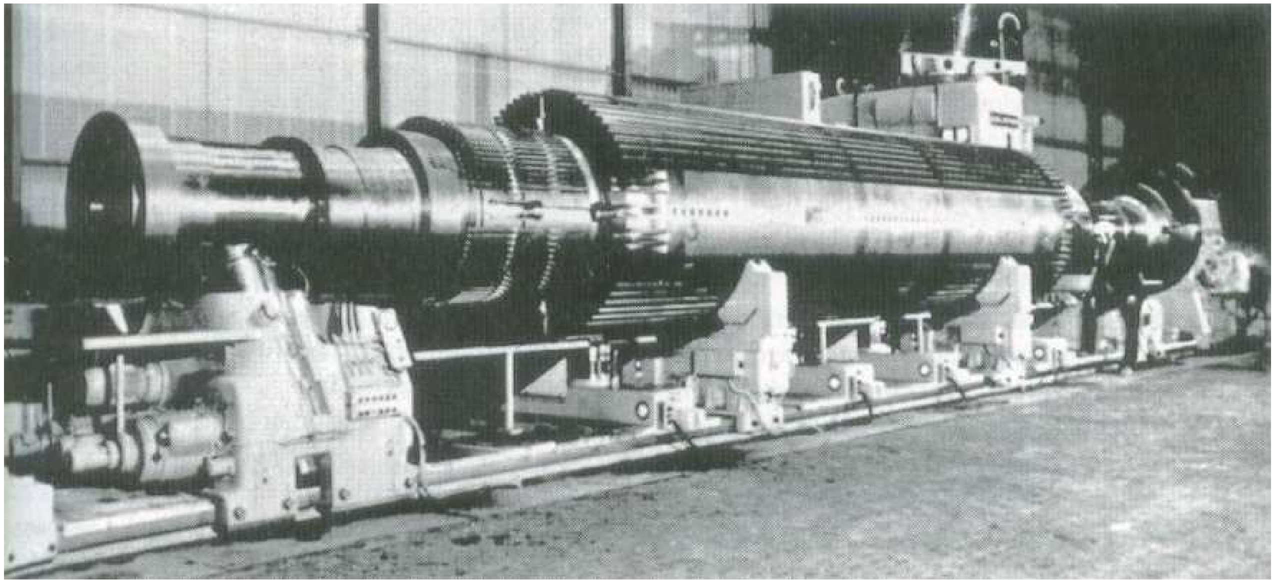


Salient-pole rotor

Cylindrical-Rotor Synchronous Generator



Stator



Cylindrical rotor