Motors Generators and Transformers

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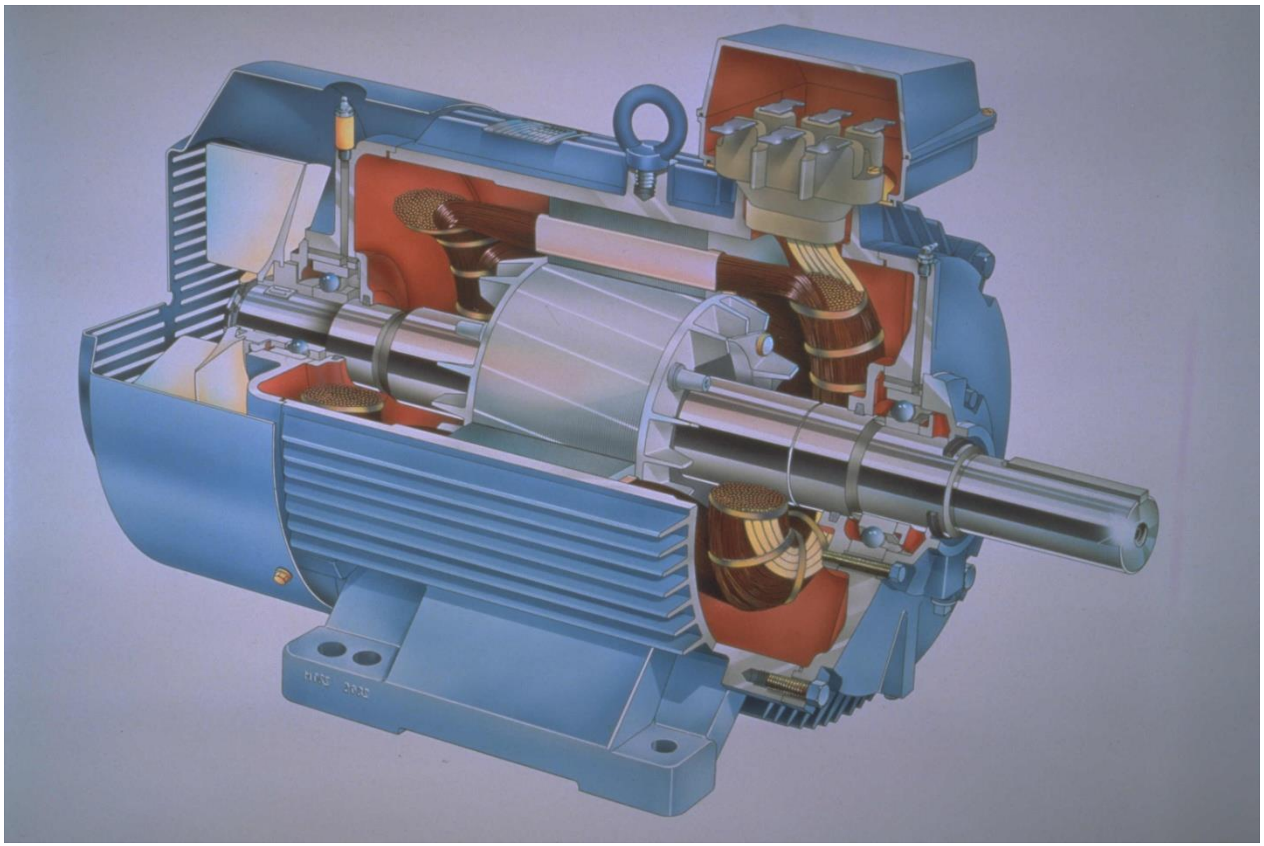
Induction Motors



Introduction

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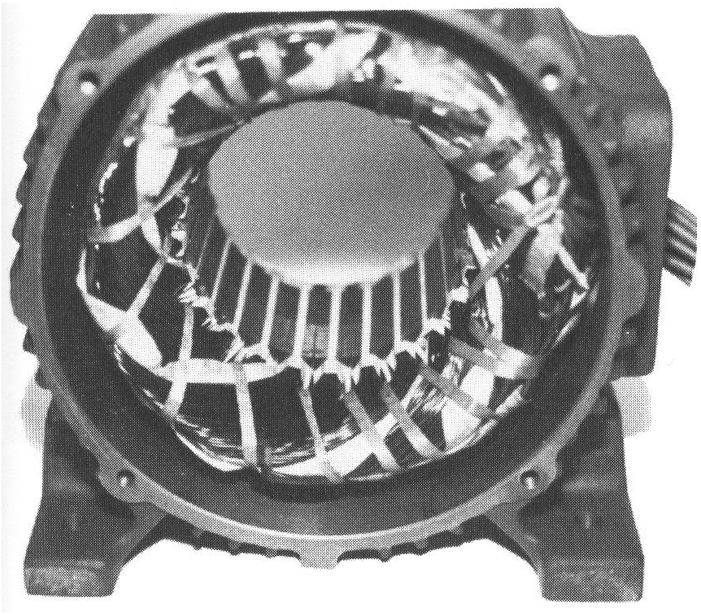
- Three-phase induction motors are the most common and frequently encountered machines in industry

  - simple design, rugged, low-price, easy maintenance
  - wide range of power ratings: fractional horsepower to 10 MW
  - run essentially as constant speed from no-load to full load
  - Its speed depends on the frequency of the power source

- not easy to have variable speed control
- requires a variable-frequency power-electronic drive for optimal speed control

Construction

- An induction motor has two main parts
  - a stationary stator
    - consisting of a steel frame that supports a hollow, cylindrical core
    - core, constructed from stacked laminations, having a number of evenly spaced slots, providing the space for the stator winding



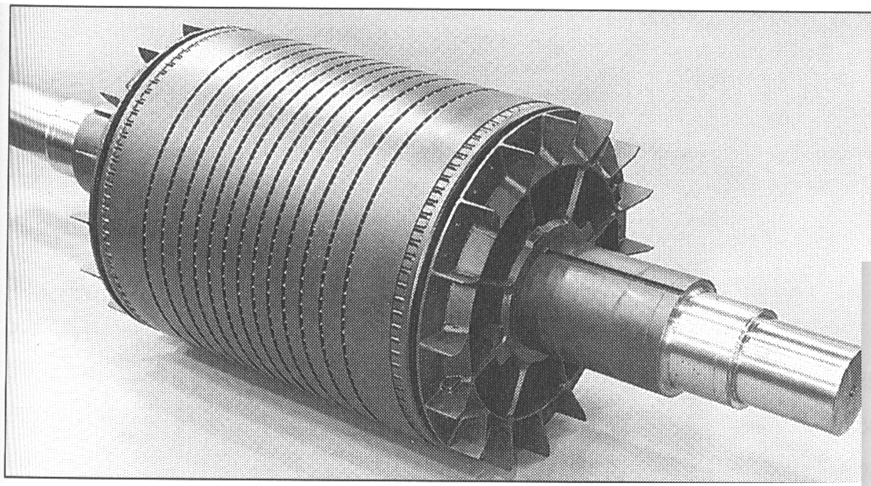
Stator of induction motor

Construction

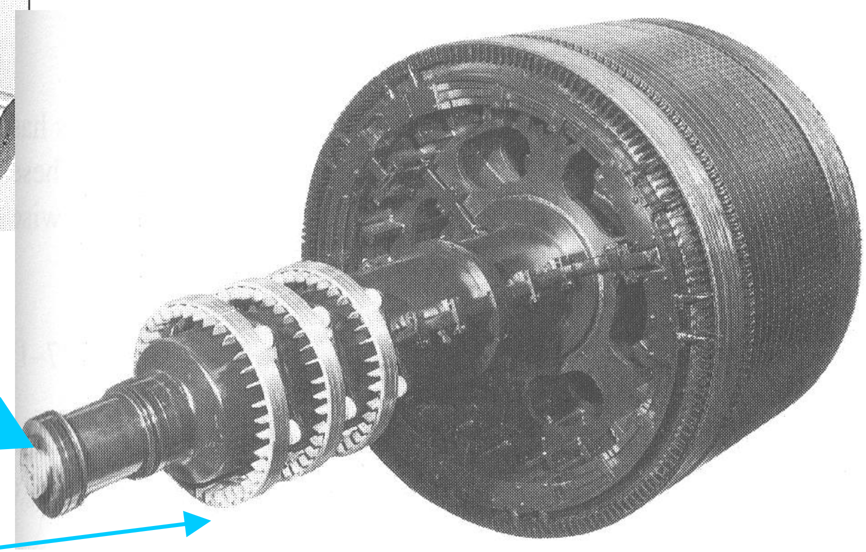
- a revolving rotor
  - composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
  - one of two types of rotor windings
  - conventional 3-phase windings made of insulated wire (wound-rotor) similar to the winding on the stator
  - aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)

- Two basic design types depending on the rotor design
  - squirrel-cage: conducting bars laid into slots and shorted at both ends by shorting rings.
  - wound-rotor: complete set of three-phase windings exactly as the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. In this way, the rotor circuit is accessible.

Construction



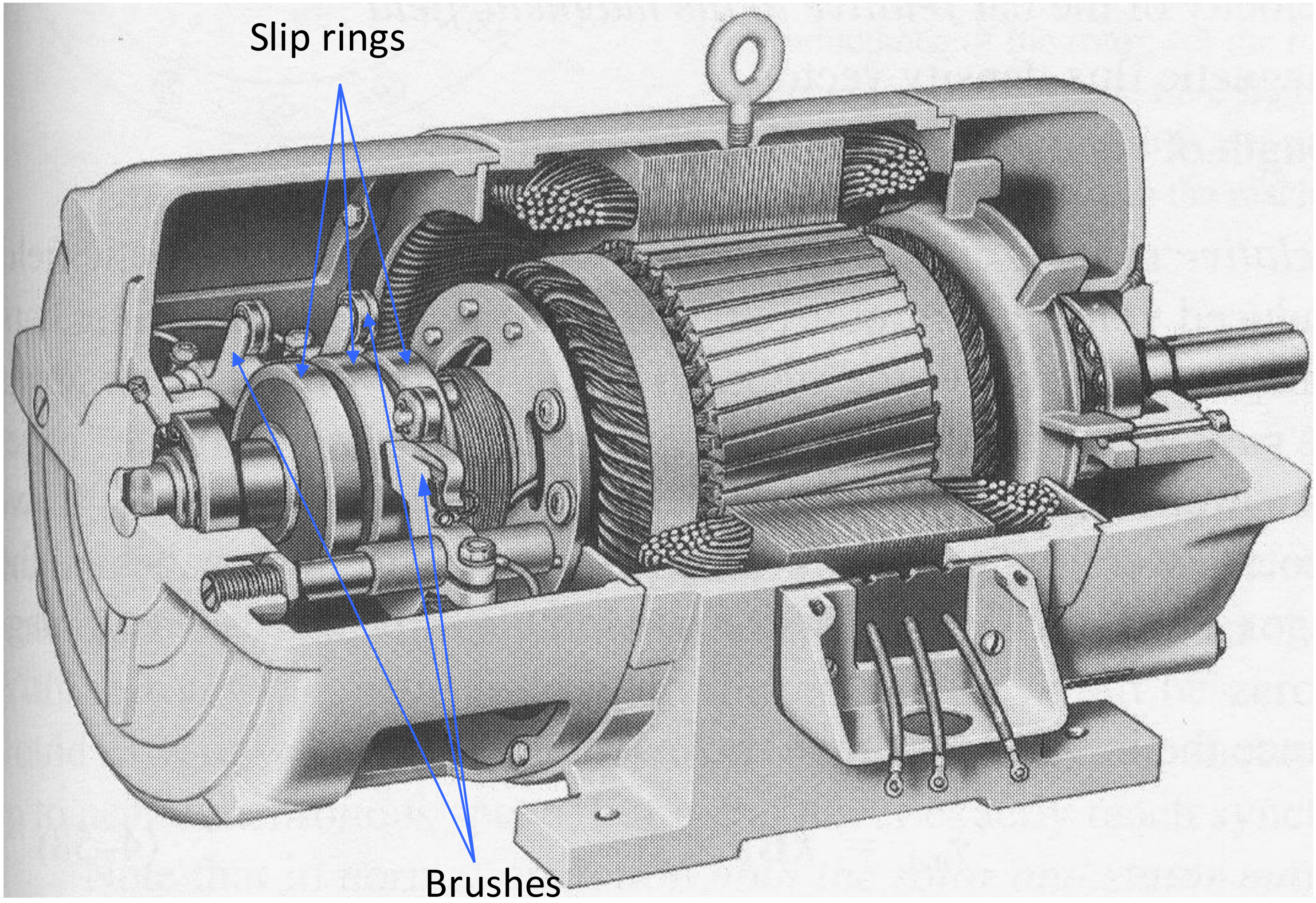
Squirrel cage rotor



Wound rotor

Notice the slip rings

Construction

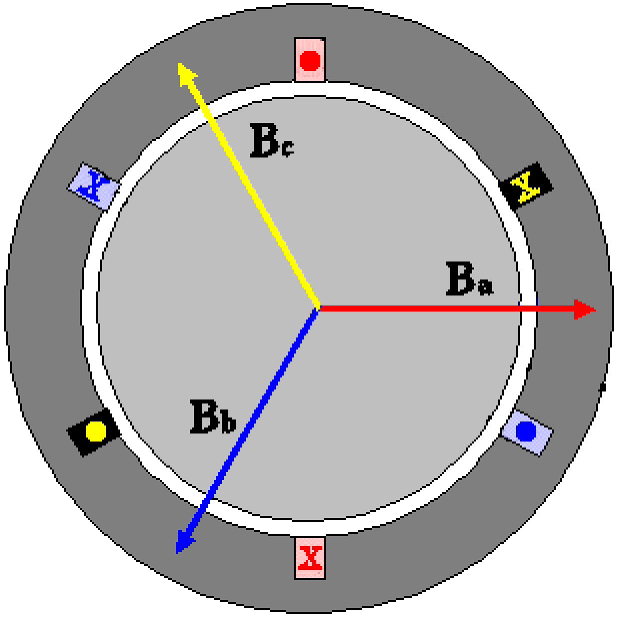


Cutaway in a typical wound-rotor Induction motor. Notice the brushes and the slip rings

Rotating Magnetic Field

- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

$$n_{sync} = \frac{120 f_e}{P} \quad rpm$$



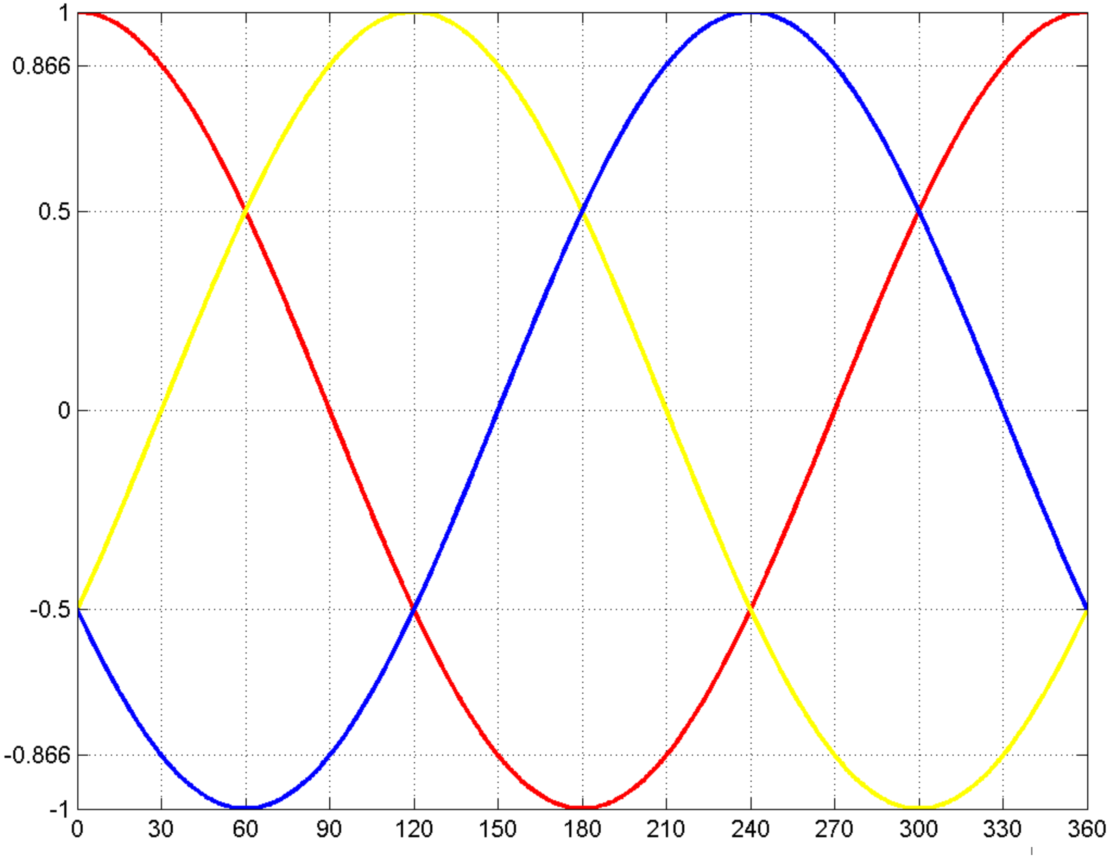
Where f_e is the supply frequency and

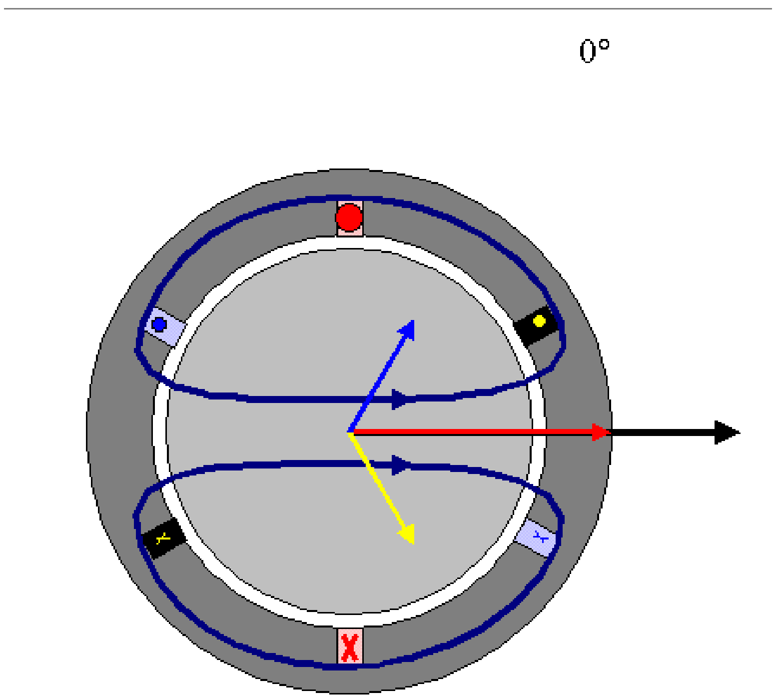
P is the no. of poles and n_{sync} is called the synchronous speed in *rpm* (revolutions per minute)

Synchronous speed

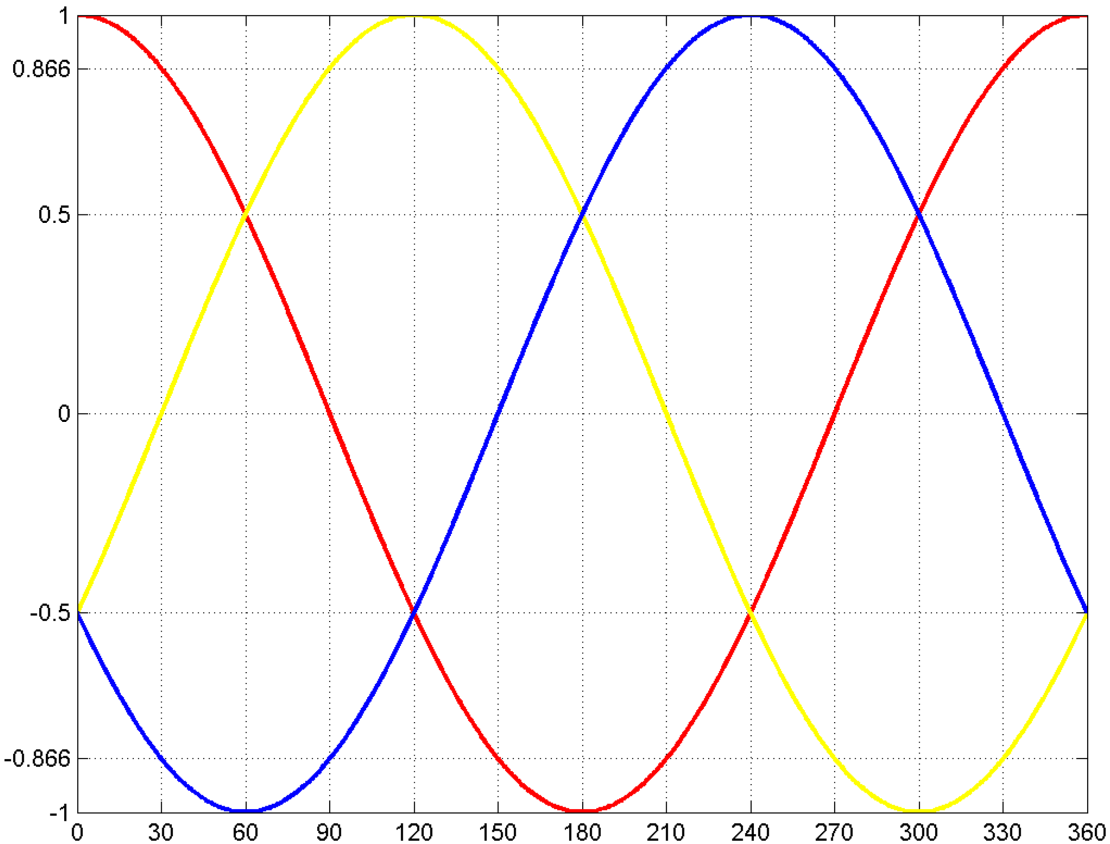
P	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

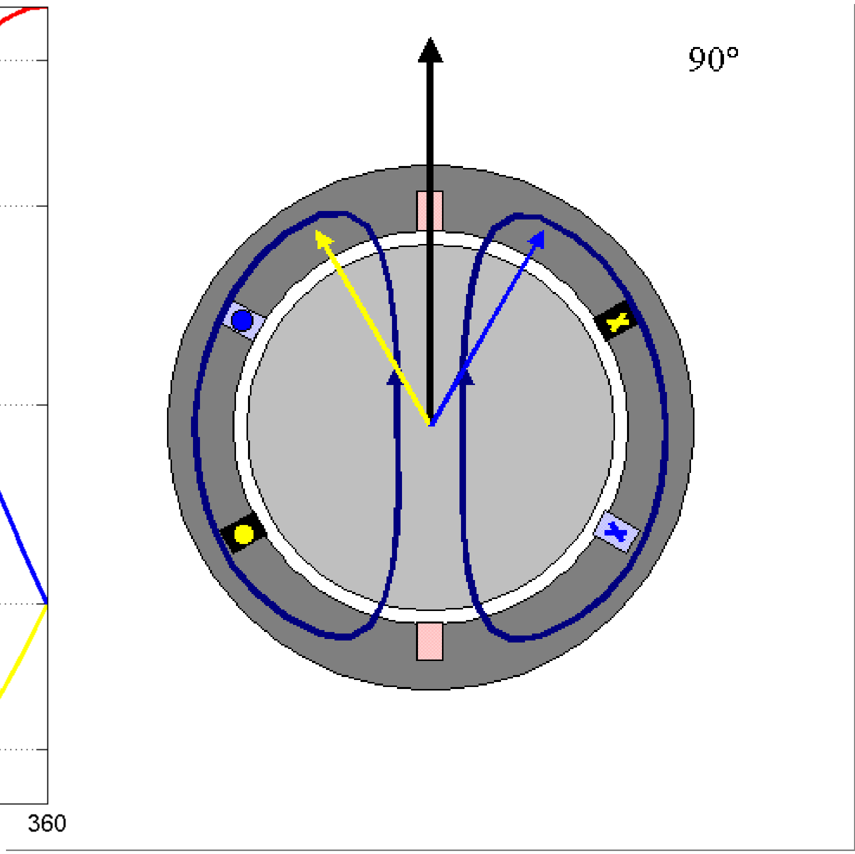
Rotating Magnetic Field





Rotating Magnetic Field





Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field
- A torque is produced as a result of the interaction of those two magnetic fields

$$\tau_{ind} = kB_R \times B_s$$

Where τ_{ind} is the induced torque and B_R and B_S are the magnetic flux densities of the rotor and the stator respectively

Induction motor speed

- At what speed will the IM run?
  - Can the IM run at the synchronous speed, why?
  - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
  - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

Induction motor speed

- So, the IM will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*

$$n_{slip} = n_{sync} - n_m$$

Where n_{slip}= slip speed

n_{sync}= speed of the magnetic field

n_m = mechanical shaft speed of the motor

Torque

- While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power.
- Any mechanical load applied to the motor shaft will introduce a Torque on the motor shaft. This torque is related to the motor output power and the rotor speed.

$$\tau_{load} = \frac{P_{out}}{\omega_m} \quad N.m$$

$$\omega_m = \frac{2\pi n_m}{60} \quad rad/s$$

Electric Generators

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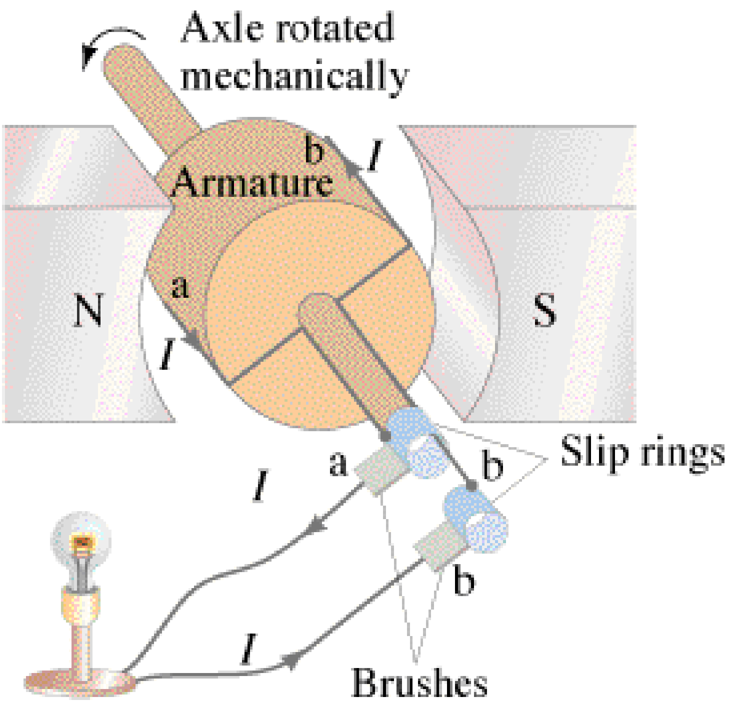
- **Convert mechanical energy into electrical energy.**
- **A direct result of Faraday's work on induction.**
- **Basically, the inverse of the electric motor which converts electrical energy to mechanical energy.**

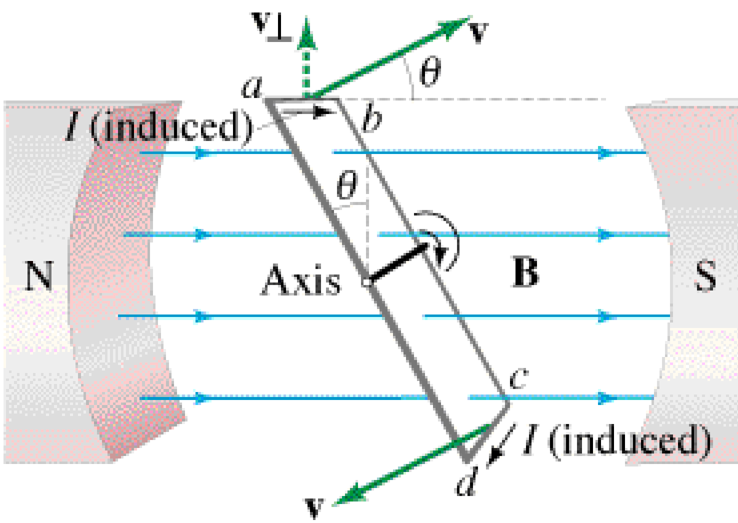
AC Generator

- We will look at a simple version



The output current is alternating and changes direction each half revolution.

AC Generator

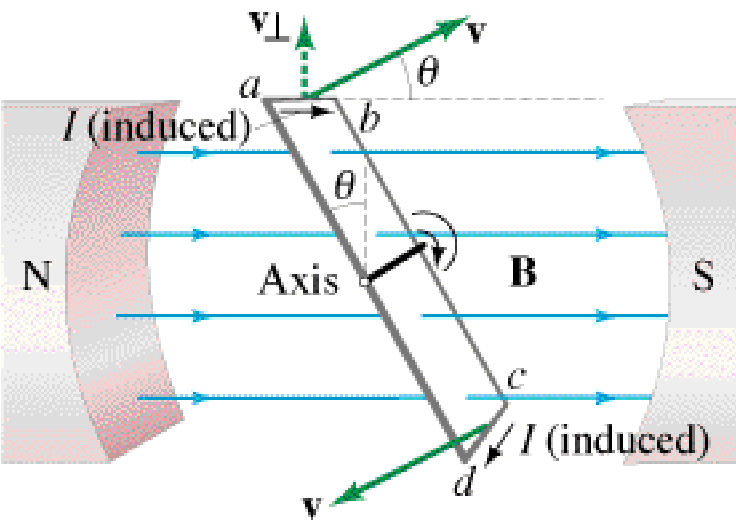


We saw earlier that we can consider Faraday's Law or we can just calculate the forces on the individual electrons making up the current. We'll do the latter here.

All the action takes place in the wire segments *ab* and *cd*.

The forces on electrons in *ad* and *bc* are sideways the the electrons don't move along the wire due to these forces.

AC Generator



The direction of current in *ab* is from *a* to *b*. At the bottom it is from *c* to *d*. Thus current will flow in the loop.

Last time we saw that the EMF causing this current in one wire is just $Blv_{perpendicular}$. Since we have two wires, the EMF is just twice this amount. If our coil has N turns then

$$\varepsilon = 2NBlv\sin\theta$$

Construction of synchronous machines

Synchronous machines are AC machines that have a field circuit supplied by an external DC source.

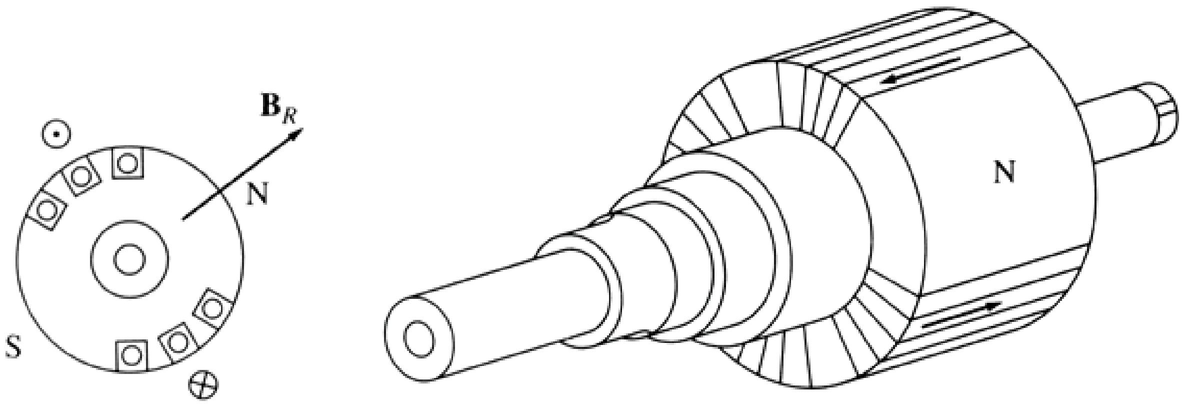
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

In a synchronous motor, a 3-phase set of stator currents produces a rotating magnetic field causing the rotor magnetic field to align with it. The rotor magnetic field is produced by a DC current applied to the rotor winding.

Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

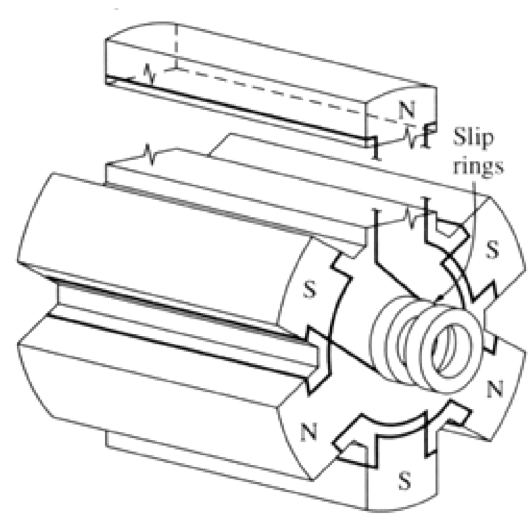
Construction of synchronous machines

The rotor of a synchronous machine is a large electromagnet. The magnetic poles can be either salient (sticking out of rotor surface) or non-salient construction.



End view Side view

Non-salient-pole rotor: usually two- and four-pole rotors.

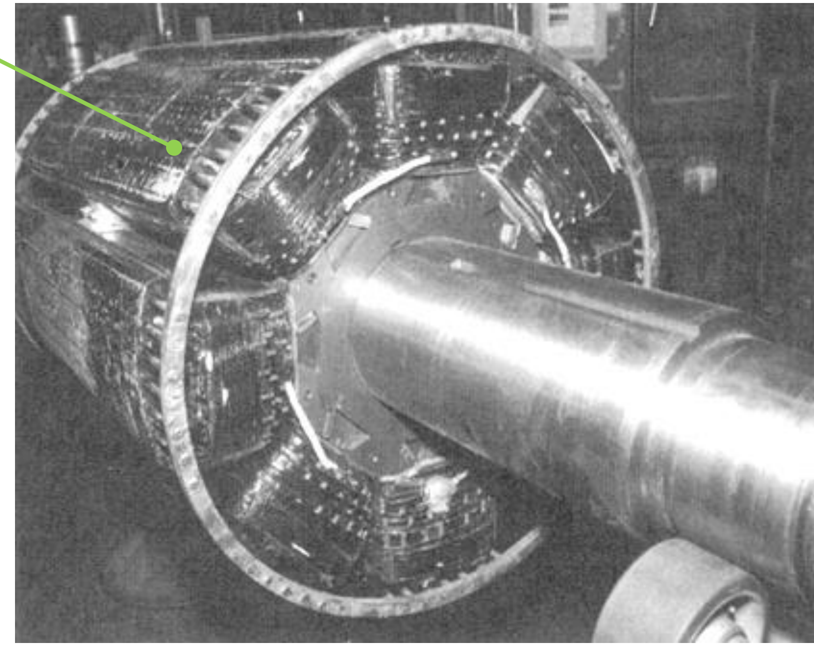


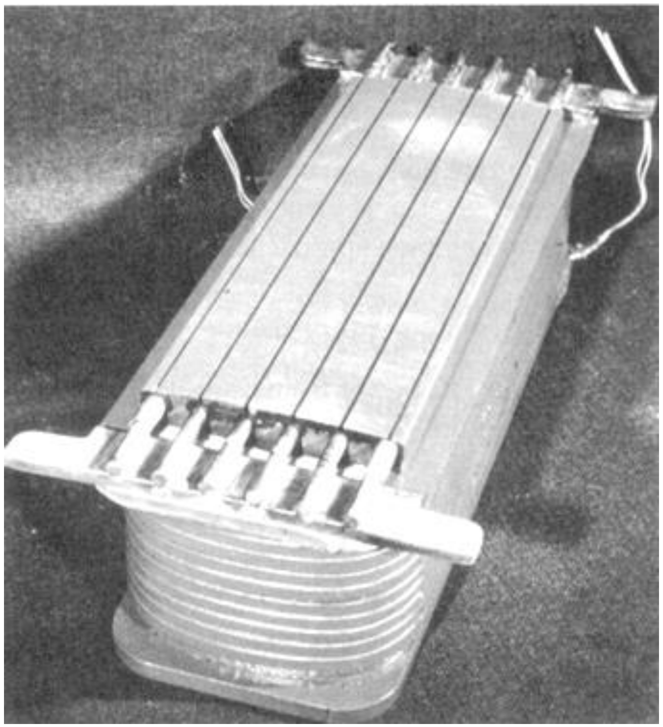
Salient-pole rotor: four and more poles.

Rotors are made laminated to reduce eddy current losses.

Construction of synchronous machines

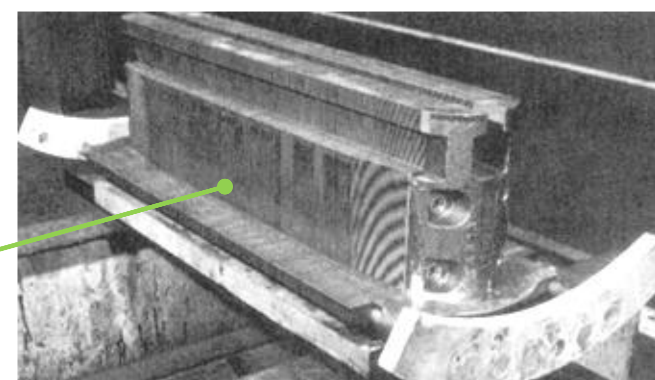
A synchronous rotor with 8 salient poles





Salient pole with field windings

Salient pole without field windings – observe laminations



Construction of synchronous machines

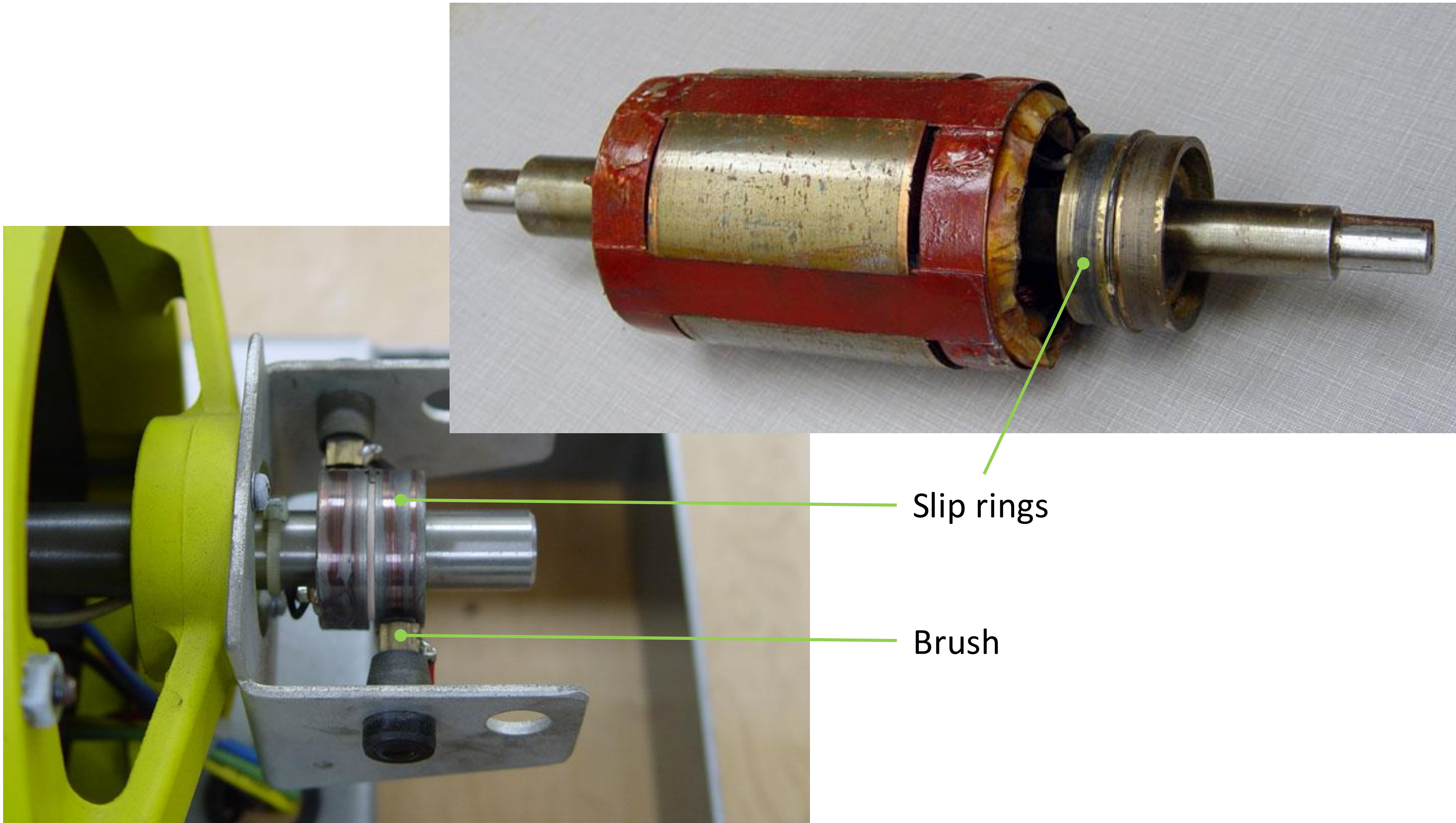
Two common approaches are used to supply a DC current to the field circuits on the rotating rotor:

1. Supply the DC power from an external DC source to the rotor by means of slip rings and brushes;

2. Supply the DC power from a special DC power source mounted directly on the shaft of the machine.

Slip rings are metal rings completely encircling the shaft of a machine but insulated from it. One end of a DC rotor winding is connected to each of the two slip rings on the machine's shaft. Graphite-like carbon brushes connected to DC terminals ride on each slip ring supplying DC voltage to field windings regardless the position or speed of the rotor.

Construction of synchronous machines



Construction of synchronous machines

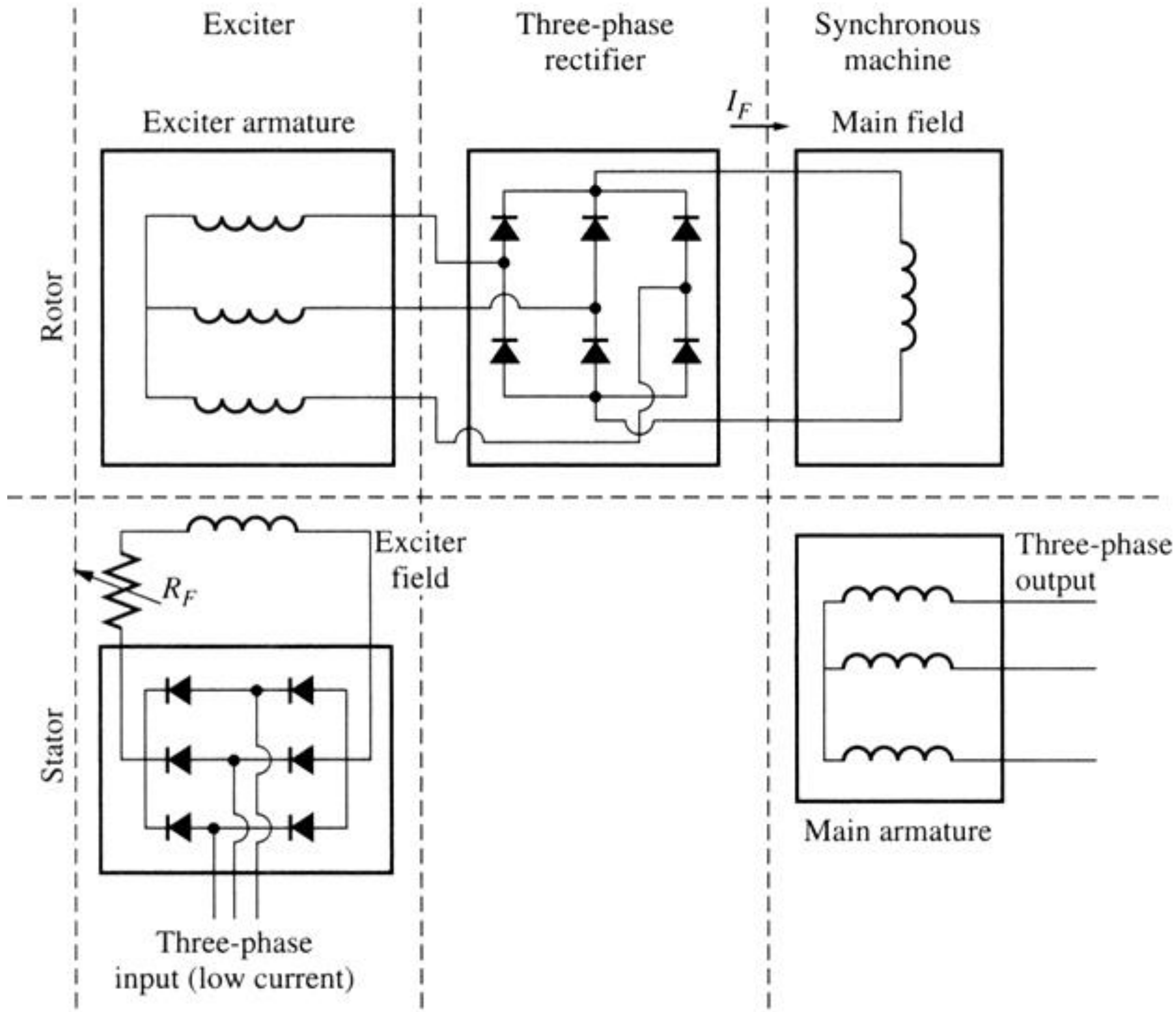
Slip rings and brushes have certain disadvantages: increased friction and wear (therefore, needed maintenance), brush voltage drop can introduce significant power losses. Still this approach is used in most *small* synchronous machines.

On large generators and motors, brushless exciters are used.
A brushless exciter is a small AC generator whose field circuits are mounted on the stator and armature circuits are mounted on the rotor shaft. The exciter generator's 3-phase output is rectified to DC by a 3-phase rectifier (mounted on the shaft) and fed into the main DC field circuit. It is possible to adjust the field current on the main machine by controlling the small DC field current of the exciter generator (located on the stator).

Since no mechanical contact occurs between the rotor and the stator, exciters of this type require much less maintenance.

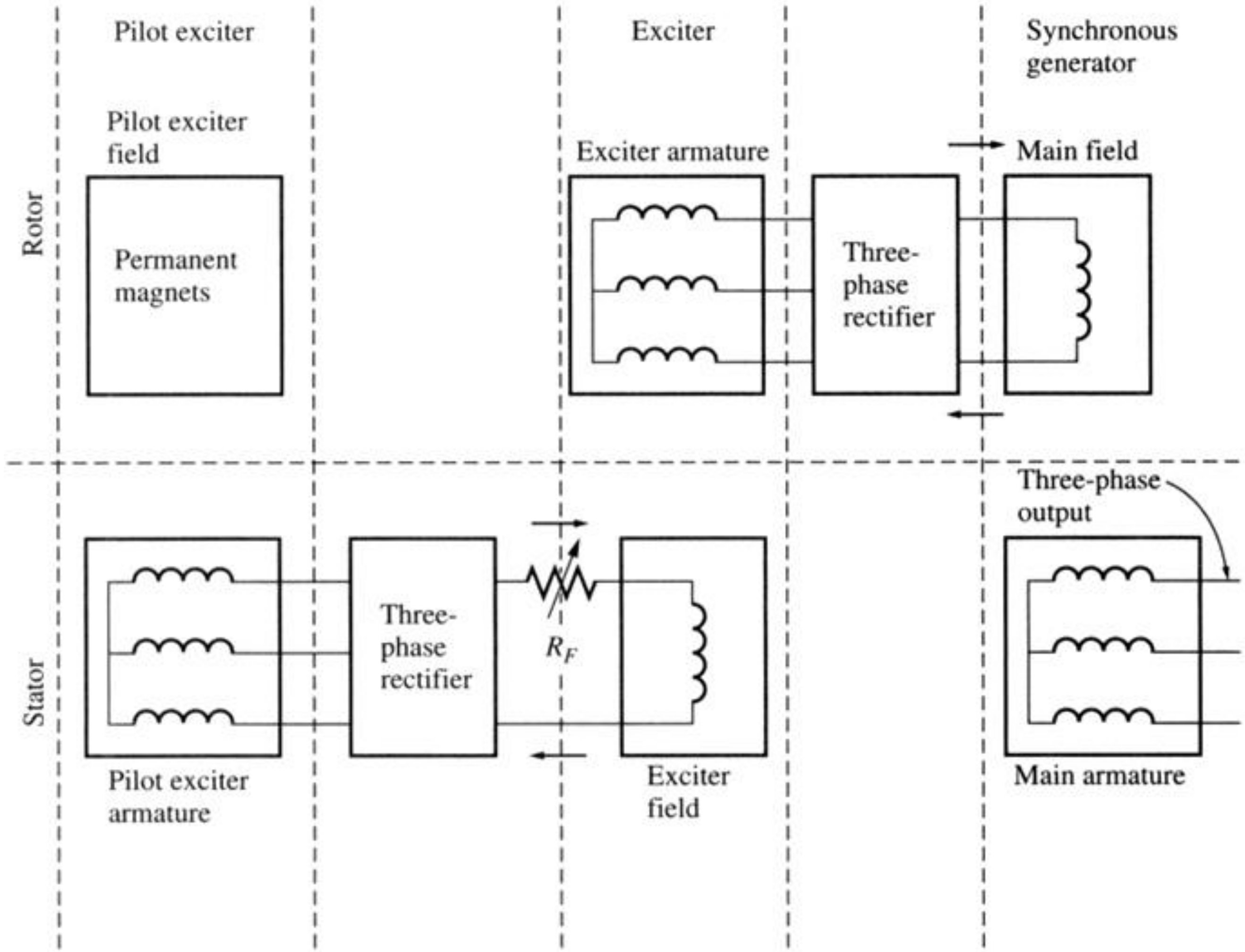
Construction of synchronous machines

A brushless exciter: a low 3-phase current is rectified and used to supply the field circuit of the exciter (located on the stator). The output of the exciter's armature circuit (on the rotor) is rectified and used as the field current of the main machine.



Construction of synchronous machines

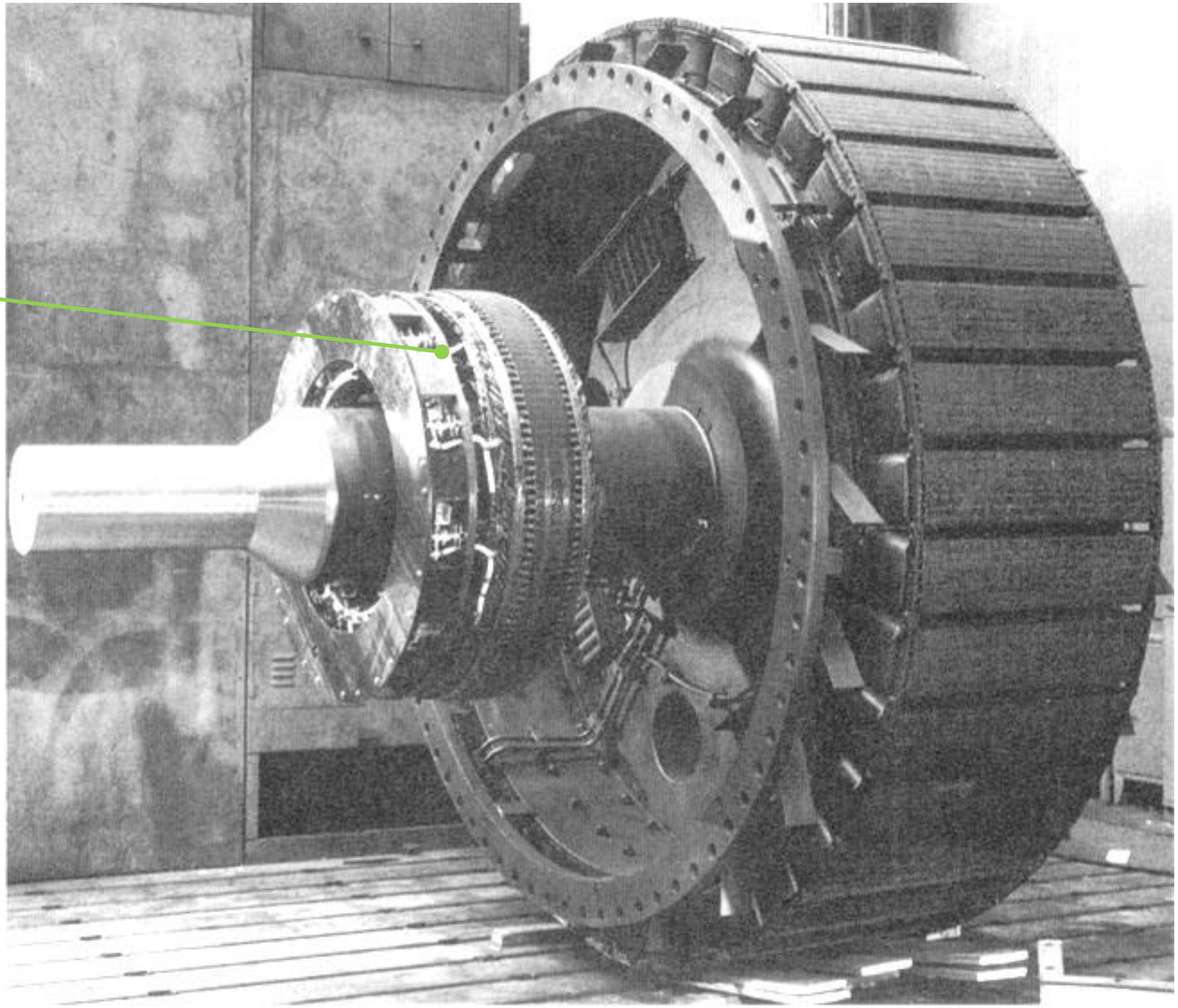
To make the excitation of a generator completely independent of any external power source, a small pilot exciter is often added to the circuit. The pilot exciter is an AC generator with a permanent magnet mounted on the rotor shaft and a 3-phase winding on the stator producing the power for the field circuit of the exciter.



Construction of synchronous machines

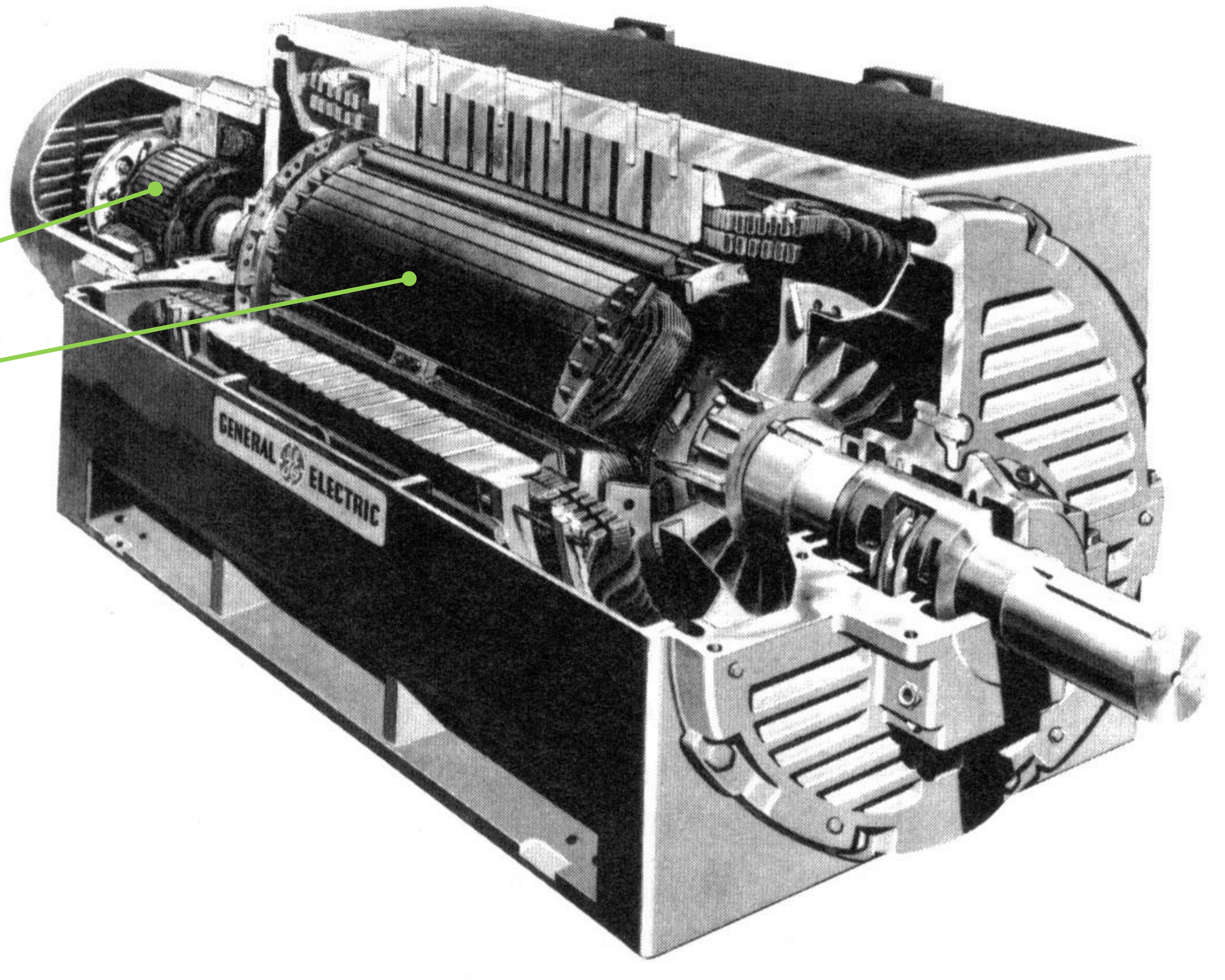
A rotor of large synchronous machine with a brushless exciter mounted on the same shaft.

Many synchronous generators having brushless exciters also include slip rings and brushes to provide emergency source of the field DC current.



Construction of synchronous machines

A large synchronous machine with the exciter and salient poles.



Rotation speed of synchronous generator

By the definition, synchronous generators produce electricity whose frequency is synchronized with the mechanical rotational speed.

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

Where f_e is the electrical frequency, Hz;
n_m is mechanical speed of magnetic field (rotor speed for synchronous machine), rpm;
P is the number of poles.

Steam turbines are most efficient when rotating at high speed; therefore, to generate 60 Hz, they are usually rotating at 3600 rpm and turn 2-pole generators.
Water turbines are most efficient when rotating at low speeds (200-300 rpm); therefore, they usually turn generators with many poles.

Transformers

What is a transformer?

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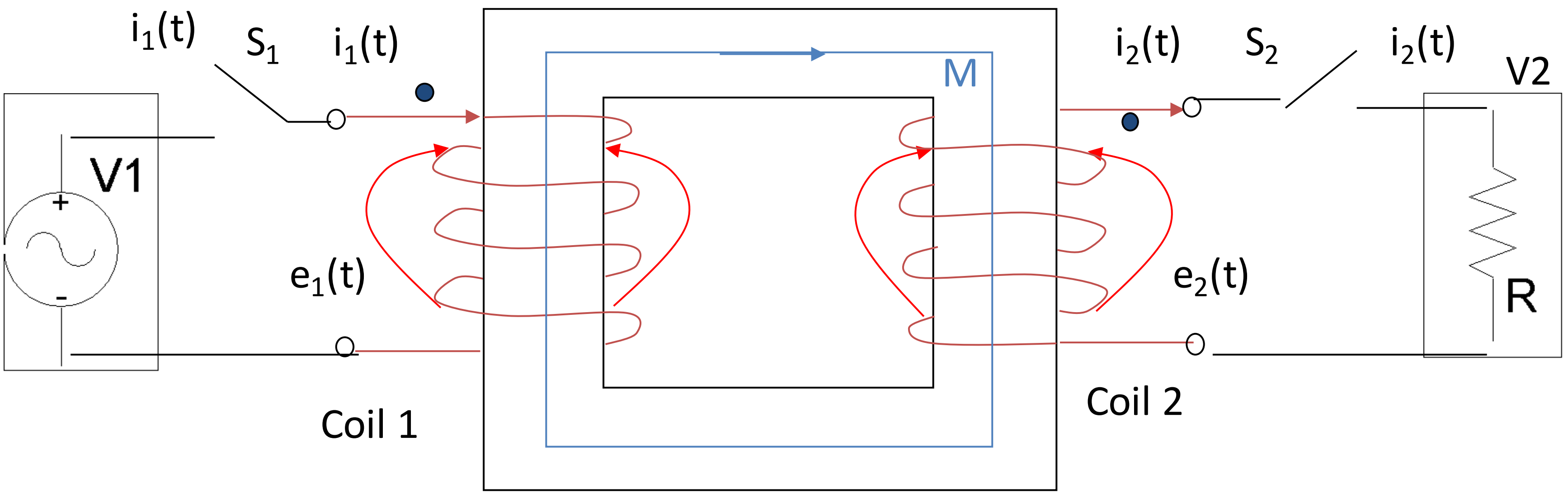
- A transformer can change electrical energy of a given voltage into electrical energy at a different voltage level. It consists of two coils arranged in such a way that the magnetic field surrounding one coil cuts through the other coil. When an **alternating voltage** is applied to (across) one coil, the **varying magnetic field** set up around that coil induces an alternating voltage in the other coil. Transformers will not work with direct current, since no changing magnetic field is produced, and therefore no current can be induced

Types of Transformers



(Primary has N_1 turns)

(Secondary has N_2 turns)

Types of Transformers

- $V2/V1 = N2/N1$
- Step Up Transformer
  - Voltages on Secondary (V2) > Voltages at Primary (V1)
  - Current at Secondary(I2) < Current at Primary (I1)

- Step Down Transformer
  - Voltages on Secondary (V2) < Voltages at Primary (V1)
  - Current at Secondary(I2) > Current at Primary (I1)

How Transformer Works

- Switch ‘S_1’ is closed and ‘S_2’ is open at t=0
  - The voltage induced across each coil is proportional to its number of turns

- Switch ‘S_2’ is now closed
  - A current now starts to flow in resistance R. This current is $i_2(t)$ (flows out of the dotted terminal).

$$i_2(t) = \frac{e_2(t)}{R} = \frac{V2(t)}{R}$$

- The current induced in each coil is inversely proportional to its number of turns.
- Instantaneous input power to the transformer = Instantaneous output power from the transformer
- Practical Example
  - $V1 = 11000$ V
  - $V2 = 415$V
  - $I1 = ?, I2 = ?$
  - $V1I1 = V2I2 = 3500$ KVA

Thank You