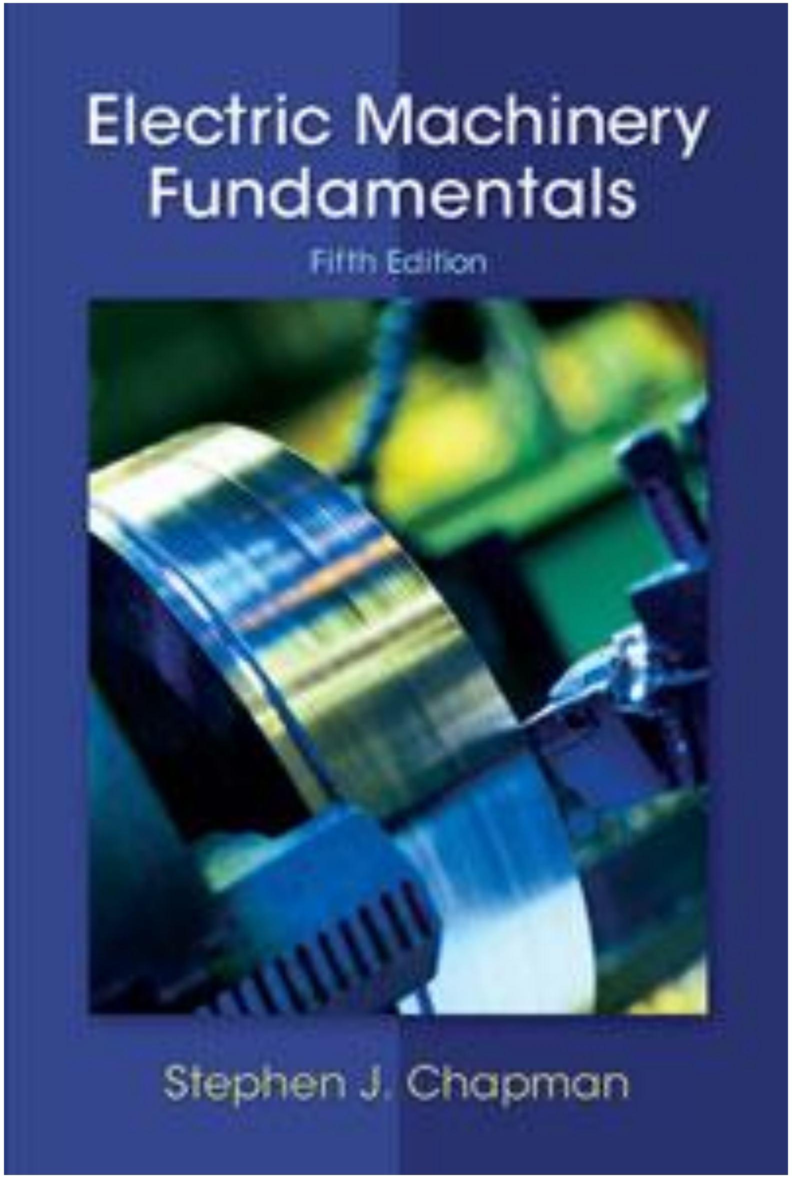


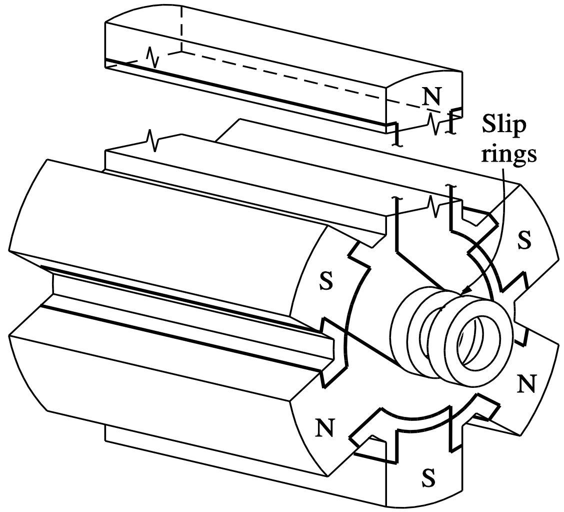
Synchronous Generators

Basic Topology

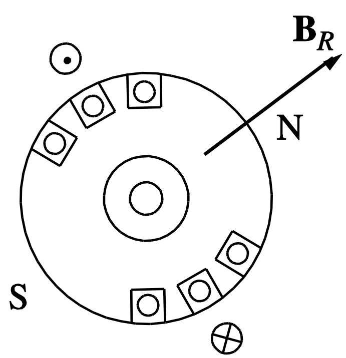
- In *stator*, there is a three-phase winding. Since the main voltage is induced in this winding, it is also called *armature winding*.
- In *rotor*, magnetic field is produced either by designing the rotor as a permanent magnet or by applying a dc current to a rotor winding to create an electromagnet. Since rotor is producing the main field, it is also called *field winding*. The rotor of the generator is then turned by a prime mover, producing a rotating magnetic field within the machine. This rotating magnetic field induces a three-phase set of voltages within the stator windings of the generator.

- For synchronous machines, the field windings are on the rotor, so the terms *rotor windings* and *field windings are used interchangeably. Similarly, the terms stator windings and armature windings are used interchangeably.* Two rotor designs are common: Salient and nonsalient.
- The magnetic poles on the rotor can be of either salient or nonsalient construction.
- Nonsalient-pole rotors are normally used for two- and four-pole rotors, while salient-pole rotors are normally used for rotors with four or more poles.

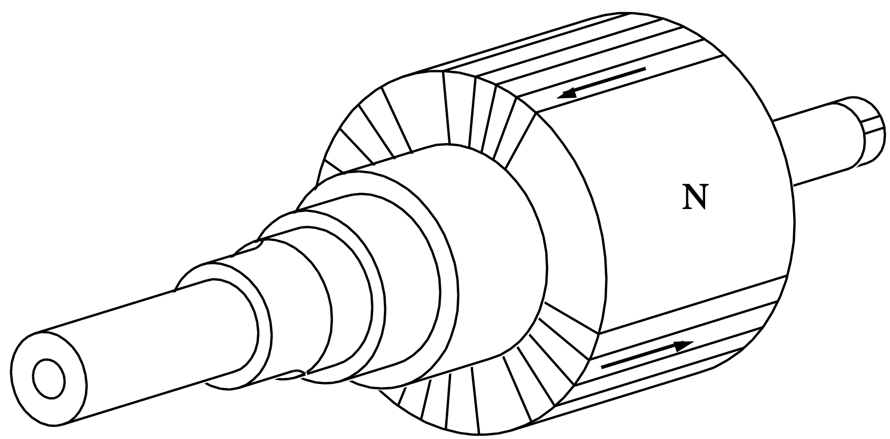
- Salient-pole rotor with “protruding” poles



- Round or Cylindrical rotor with a uniform air gap



End View



Side View

- A dc current must be supplied to the field circuit on the rotor if it is an electromagnet. Since the rotor is rotating, a special arrangement is required to get the dc power to its field windings. There are two common approaches to supplying this dc power:

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 synchronous generator.

- Slip rings and brushes create a few problems when they are used to supply dc power to the field windings of a synchronous machine. They increase the amount of maintenance required on the machine, since the brushes must be checked for wear regularly. In addition, brush voltage drop can be the cause of significant power losses on machines with larger field currents. Despite these problems, slip rings and brushes are used on all smaller synchronous machines, because no other method of supplying the dc field current is cost-effective.

- On larger generators and motors, *brushless exciters* are used to supply the dc field current to the machine. 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 three-phase output of the exciter generator is rectified to direct current by a three-phase rectifier circuit also mounted on the shaft of the generator, and is then fed into the main dc field circuit. By controlling the small dc field current of the exciter generator (located on the stator), it is possible to adjust the field current on the main machine without slip rings and brushes. This arrangement is shown schematically in Fig.1. Since no mechanical contacts ever occur between the rotor and the stator, a brushless exciter requires much less maintenance than slip rings and brushes.

Exciter Systems for Large Generators

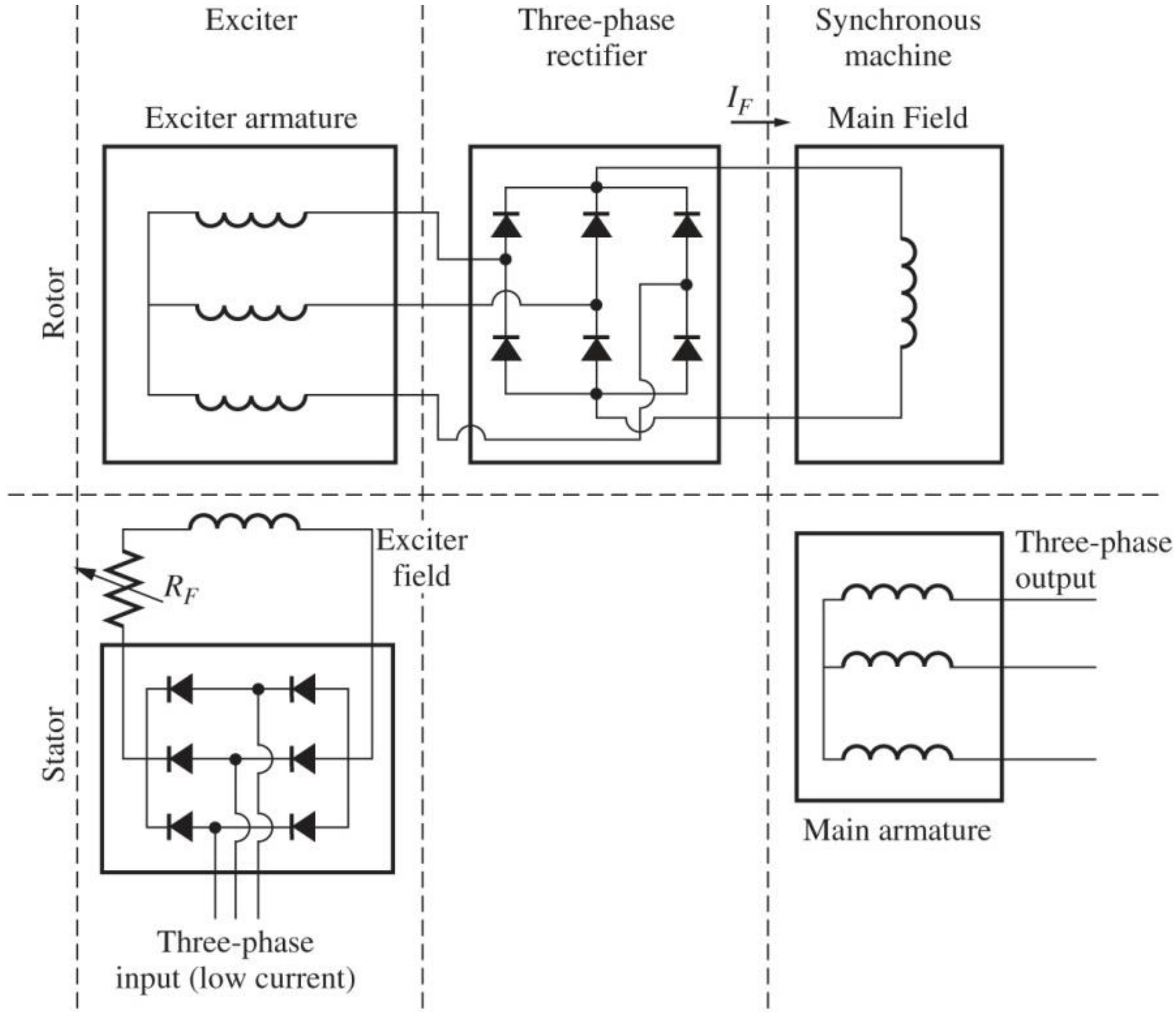


Figure 1: Brushless exciter circuit.

- To make the excitation of a generator completely independent of any external power sources, a small pilot exciter is often included in the system. A pilot exciter is a small ac generator with permanent magnets mounted on the rotor shaft and a three-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 to run the generator (see Fig.2).

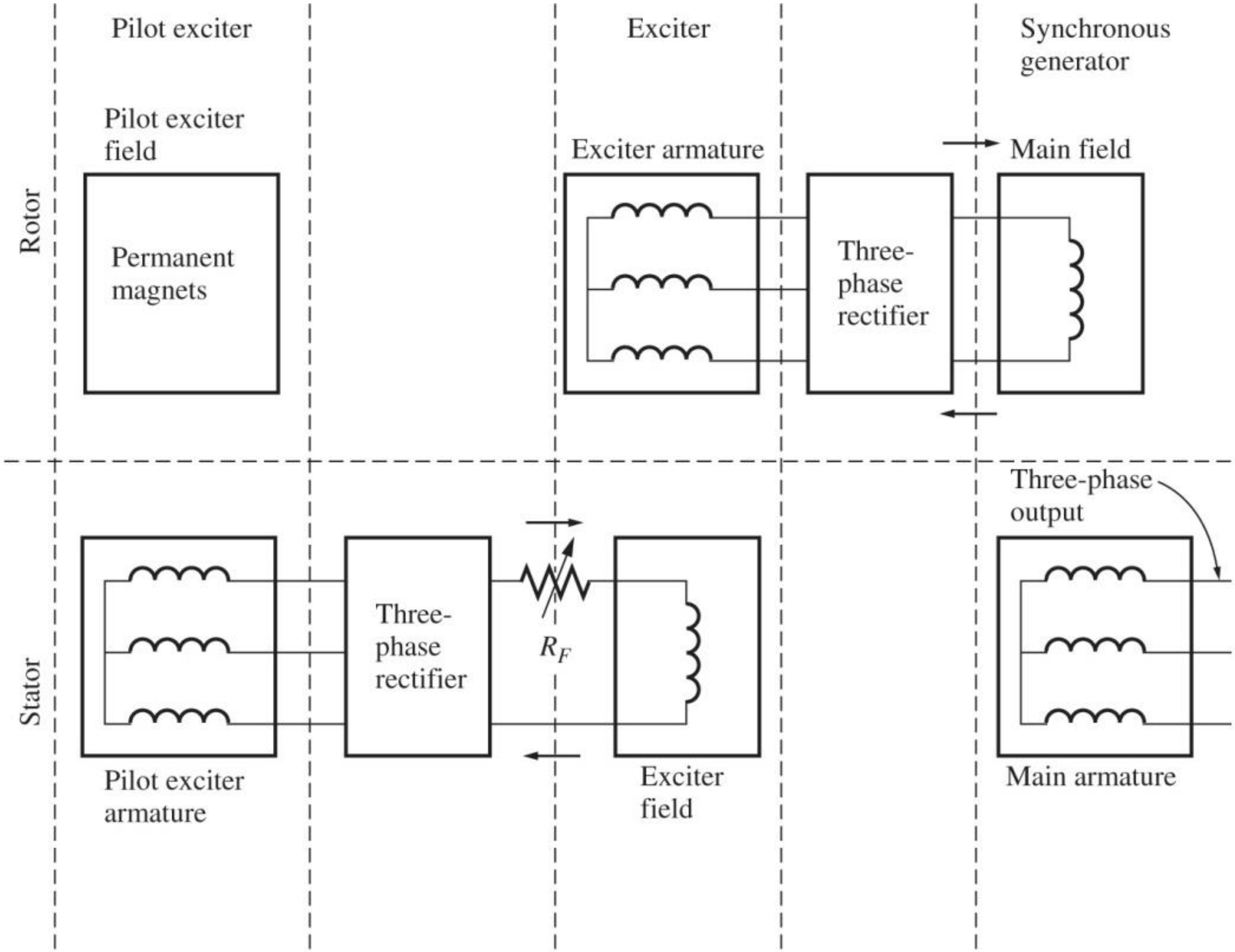


Figure 2: A brushless excitation scheme that includes a pilot exciter. The permanent magnets of the pilot generator produces a field current of the exciter which in turns produces the field current of the main machine.

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. The rate of rotation of the magnetic fields in the machine is related to the stator electrical frequency by;

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

Where;

f_e = electrical frequency, in Hz

n_m = mechanical speed of magnetic field, in rpm

= rotor speed, in rpm

P = number of poles

- Since the rotor turns at the same speed as the magnetic field, this equation relates the speed of rotor rotation to the resulting electrical frequency. Electric power is generated at 50 or 60 Hz, so the generator must turn at a fixed speed depending on the number of poles on the machine. For example, to generate 60-Hz power in a two-pole machine, the rotor *must turn at 3600 rpm. To generate 50-Hz power in* a four-pole machine, the rotor *must turn at 1500 rpm. The required rate of rotation* for a given frequency can always be calculated from above equation.

The Internal Generated Voltage of a Synchronous Generator

- It was shown previously, the magnitude of the voltage induced in a given stator phase was found to be

$$E_A = \sqrt{2}\pi N_C \phi f = \frac{N_C \phi}{\sqrt{2}} \omega$$

- $=4.44*f*N_c*\phi$

- The induced voltage is proportional to the rotor flux for a given rotor angular frequency in electrical Radians per second. This equation is sometimes rewritten in a simpler form that emphasizes the quantities that are variable during machine operation. This simpler form is;

$$E_A = K\phi\omega$$

- where K is a constant representing the construction of the machine.

- The internal generated voltage E_A is directly proportional to the flux and to the speed, but the flux itself depends on the current flowing in the rotor field circuit. The field circuit I_F is related to the flux in the manner shown in Fig.3 (a). Since the rotor flux depends on the field current I_F, the induced voltage E_A is related to the field current as shown below. This is generator magnetization curve or the open-circuit characteristics of the machine.

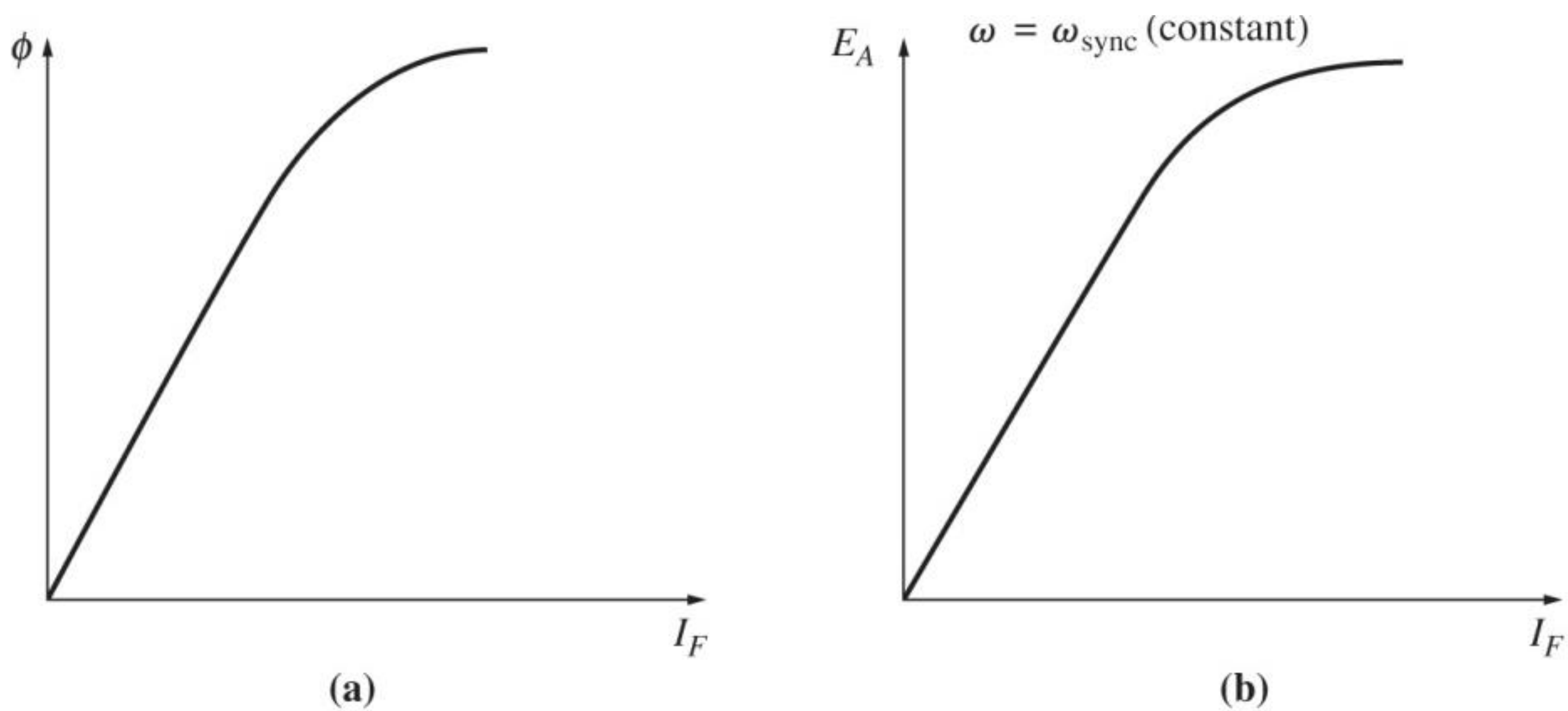
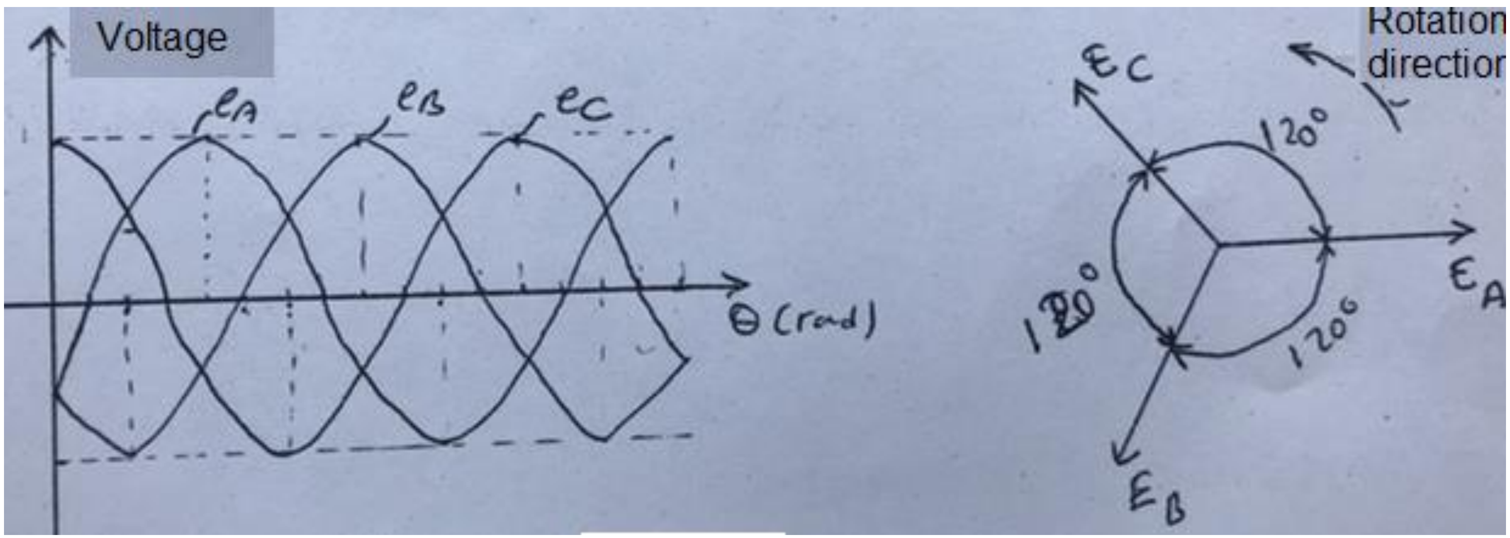


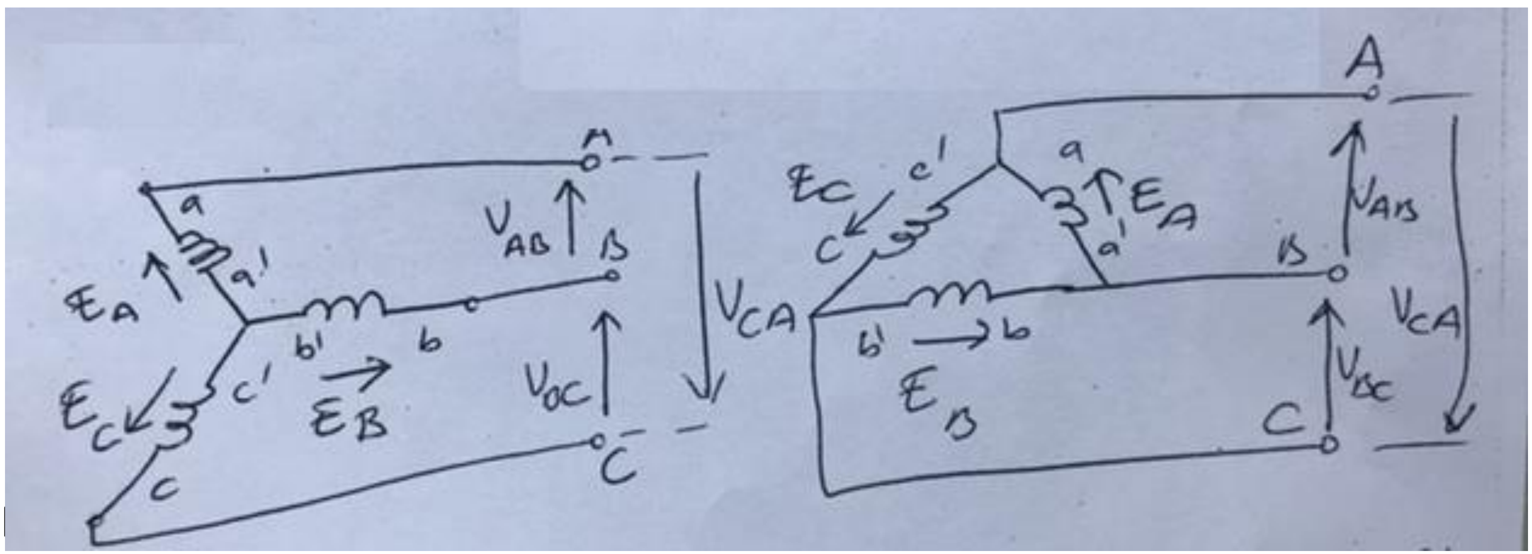
Figure 3: (a) Plot of flux versus field current for a synchronous generator. (b) The magnetization curve for the synchronous generator.

- As can be seen from Fig.4 the armature winding in a three-phase generator consists of three separate coils replaced in 120 degrees with each other.



- Figure 4: Output voltages and phasor diagram of the synchronous generator

- The three-phase winding in the stator can be connected in star or delta as shown in Fig.5.



- Each phase voltage is represented by amplitude, frequency and angle.

- The maximum value of each phase voltage is also given as;
- $E_{max}=B_m.\ell.\omega.r$ (Volt)
- Where;
- B_m: The maximum flux density produced by the rotor field winding (Tesla).
- ℓ: The length of the coil in the magnetic field (m).
- ω: Rotor angular velocity (rad/s).
- r: Radius of the armature (m).

- Example: The phase order of a three-phase synchronous generator is A, B and C. If B=1.2 T, P=2, ℓ=0.5 m, n=1500 rpm and D=0.4 m, calculate;
- a) Voltage of each phase
- b) Express the voltages as time depended
- c) Express the voltage as phasors
- Solution:
- a) $E_{max}=B_m.\ell.\omega.r = 1.2*0.5*(2\pi1500/60)*0.4/2 = 37.7$ Volt
- b) The generated voltages are sinusoidal. If we take the phase A as reference then, the phase B and C will lag the phase A by 120 degrees and 240 degrees, respectively.

$$f = \frac{P.n}{120} = \frac{2.1500}{120} = 25\,Hz$$

- ω=2πf = 2.π.25 = 157 rad/s

$$e_A = E_{max}\sin(\omega t) = 37.7\sin(157t)\,Volt$$

$$e_B = E_{max}\sin(\omega t - 120^o) = 37.7\sin(157t - 120^o)\,Volt$$

$$e_C = E_{max}\sin(\omega t - 240^o) = 37.7\sin(157t - 240^o)\,Volt$$

- c) We need to calculate rms values of the voltages for phasor representing.

$$E_{rms} = \frac{E_{max}}{\sqrt{2}} = 26.7\,Volt$$

- $E_A = 26.7 \angle 0$
- $E_B = 26.7 \angle -120$
- $E_C = 26.7 \angle -240$