Synchronous Machines

Three phase synchronous generator

- **Reasons for need of synchronous generator**
- Dual voltages can be obtained from three phase supply; for example, 380 V three phase line voltage for heavy power applications and 220 V single phase voltage for domestic and light current applications
- It is economic to use three phase power, only three conductors are required to transmit three-phase currents for balanced three-phase load compared with six conductors for three single phase loads.
- A rotating magnetic field will be produced when three phase currents are fed to the stator of a 3-phase induction motor, thus providing cheap and convenient mechanical power for industry
- The synchronous generator can generate leading power factor kVA which can compensate the lagging power factor of the power transmission system

Basic construction of three phase synchronous generator

- A 3-phase synchronous generator is essentially composed of a stationary stator and a rotating rotor

- The stator is made of soft iron to provide the magnetic field a path with low permeability, the iron is laminated to reduce eddy current and hysteresis iron loss. The stator had a similar construction as that of a 3-phase induction motor. Three phase windings installed in the stator slots which are placed at 120 electrical degree apart

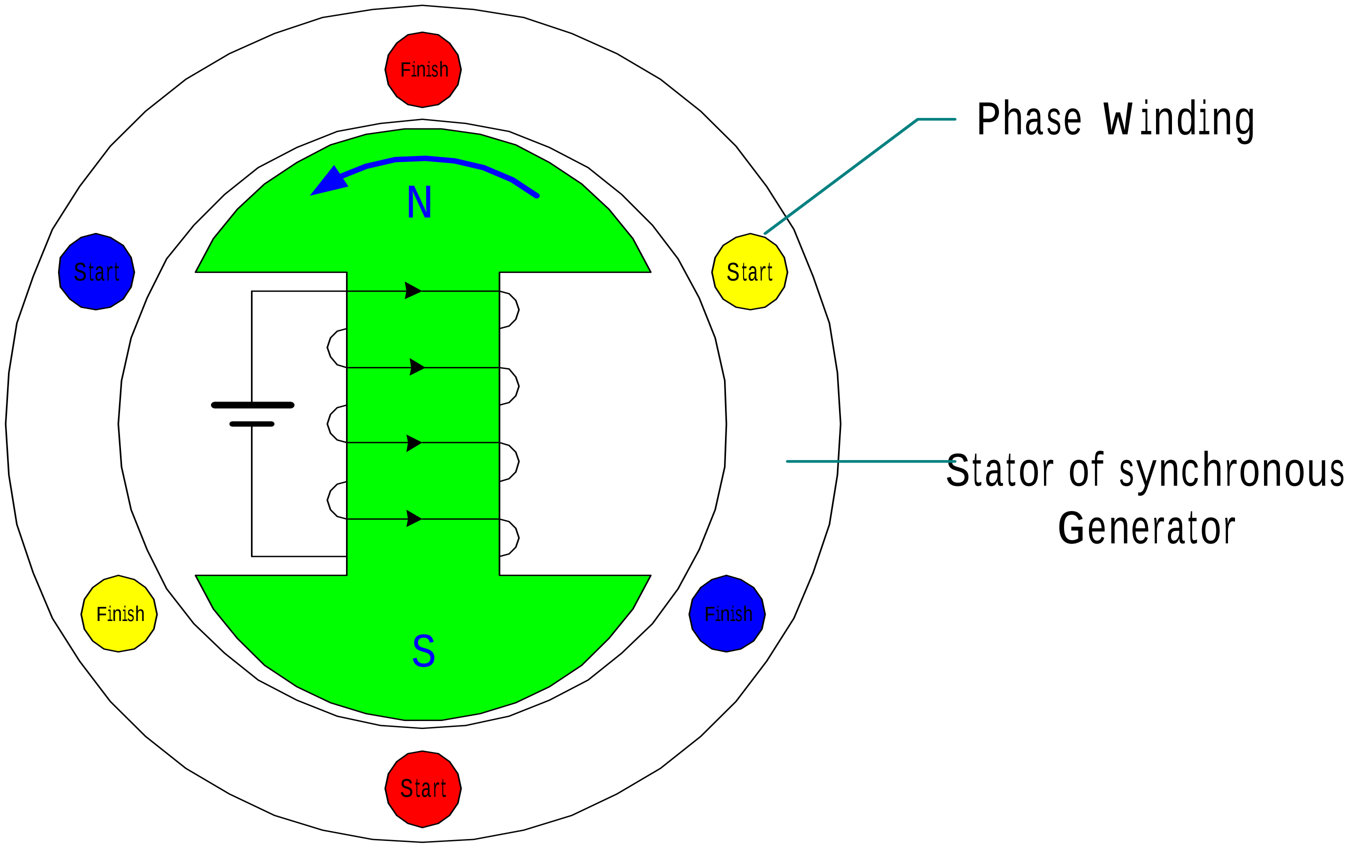
- The rotor is an electromagnet placed inside the stator, the rotor has the same number of poles as that of the stator. There are two types of rotor construction; the salient pole and the cylindrical rotor.

Types of three phase synchronous generator

- The salient pole generator has a salient pole rotor structure, this machine is ideal for slow running power generation at 50 - 60 Hz. The salient pole is wound with D.C. winding and current is fed to the rotor via slip rings. The salient pole has a nearly sinusoidal air gap so that the machine will produce sinusoidal output.

- The cylindrical rotor generator has a cylindrical rotor, the rotor is wound with windings fed with D.C. currents. The number of windings in each slot is so selected that the magnetic flux is close to sinusoidal distribution. However, the output waveform is still polygonal in shape and there is a high harmonic contents in the generated voltage.

Salient pole three phase synchronous generator



Salient pole synchronous generator

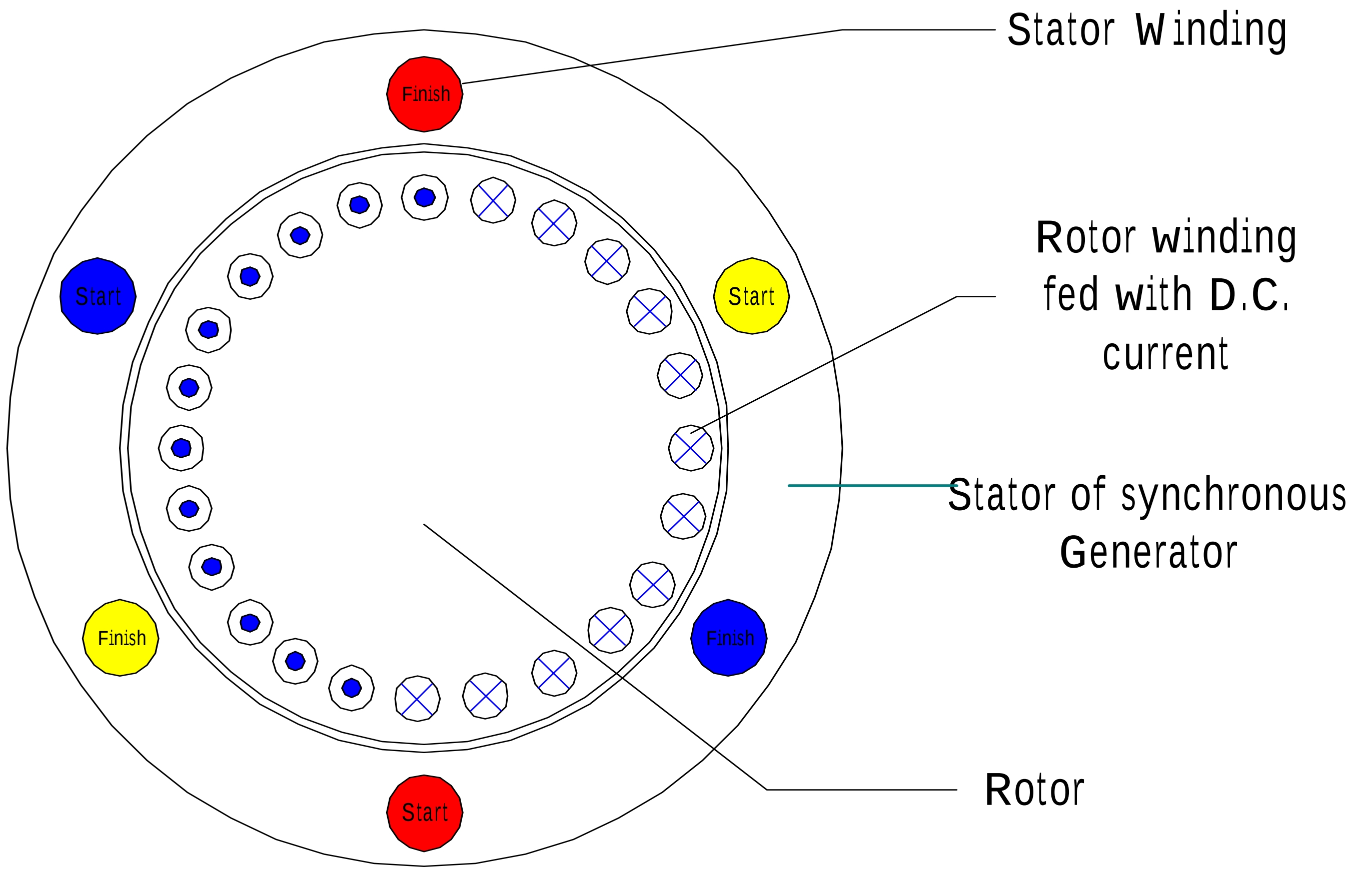
Advantages:

- The air gap between the stator and the rotor can be adjusted so that the magnetic flux is sinusoidal in distribution. As a result the output waveform will also be sinusoidal in nature

Disadvantages:

- The salient pole has a weak structure so that this machine is not suitable for high speed application such as the turbo-generator on air-plane.
- The salient pole generator is expensive

Cylindrical rotor synchronous generator



Cylindrical rotor synchronous generator

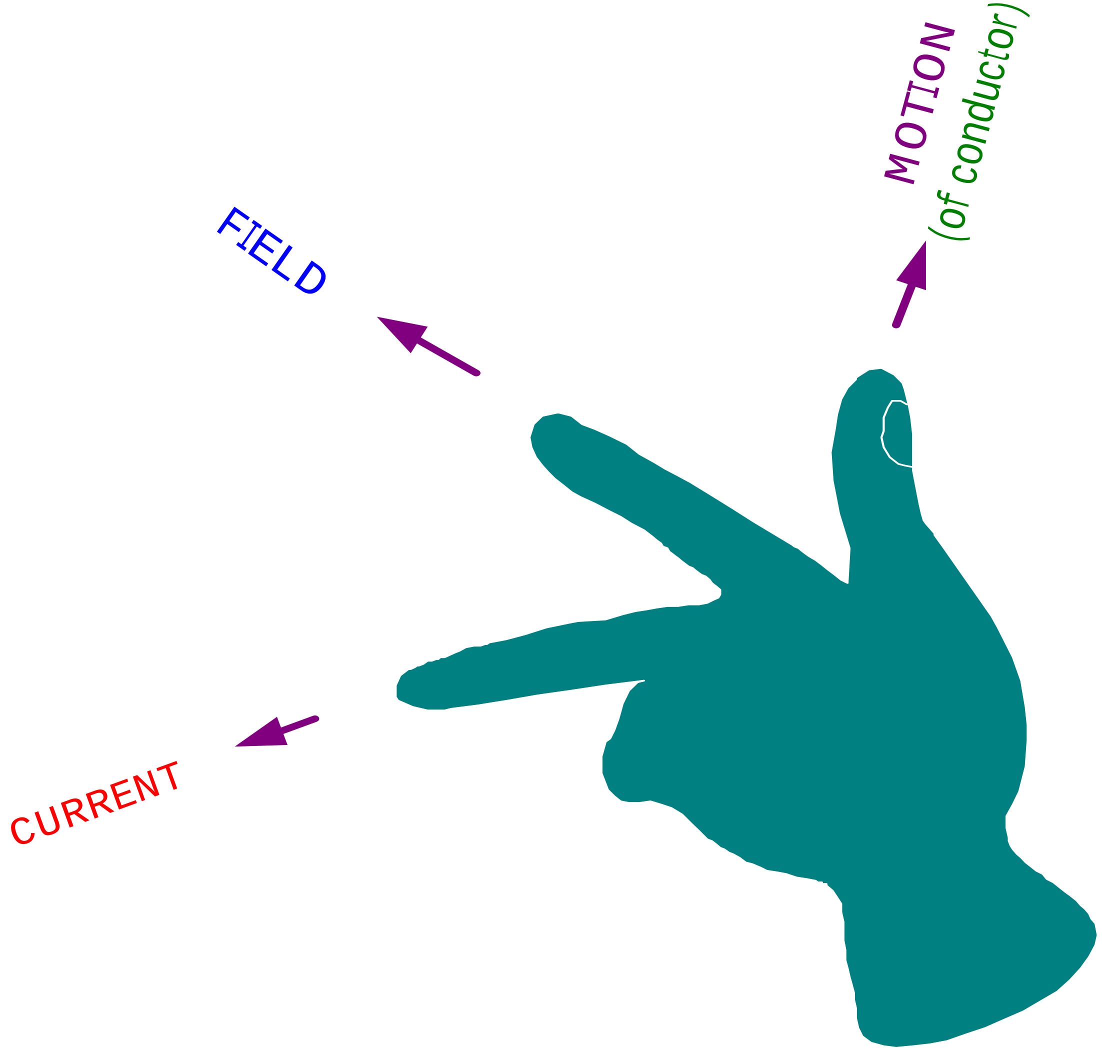
Advantages:

- The cylindrical rotor is cheaper than the salient pole rotor
- The cylindrical rotor is robotic in design, because it is symmetrical in shape, dynamically balance can be easily obtained. Hence it can be used for high speed application, say, coupled to turbo-engine such as the generator in an air-craft.

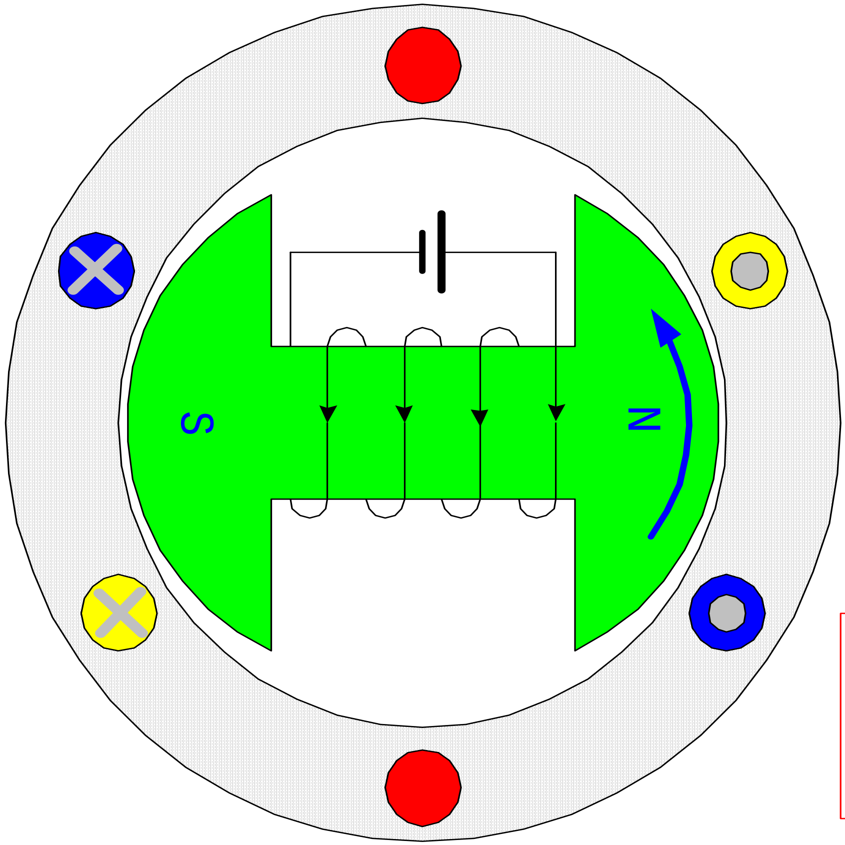
Disadvantages:

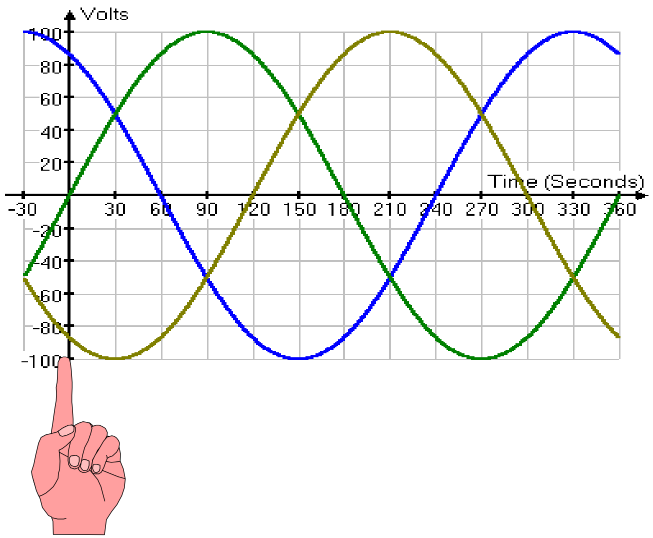
- The air gap is uniform for the rotor, the generated voltage will have a polygonal waveform depending on the number of windings on each of the rotor slots. Though the shape of the polygon is adjusted to be nearly sinusoidal, the output waveform still defers from the sine wave and therefore the harmonic content of the cylindrical rotor generator is high compared with that of the salient pole design

Fleming's Right Hand Rule for generator



Three phase voltages produced by the salient pole generator

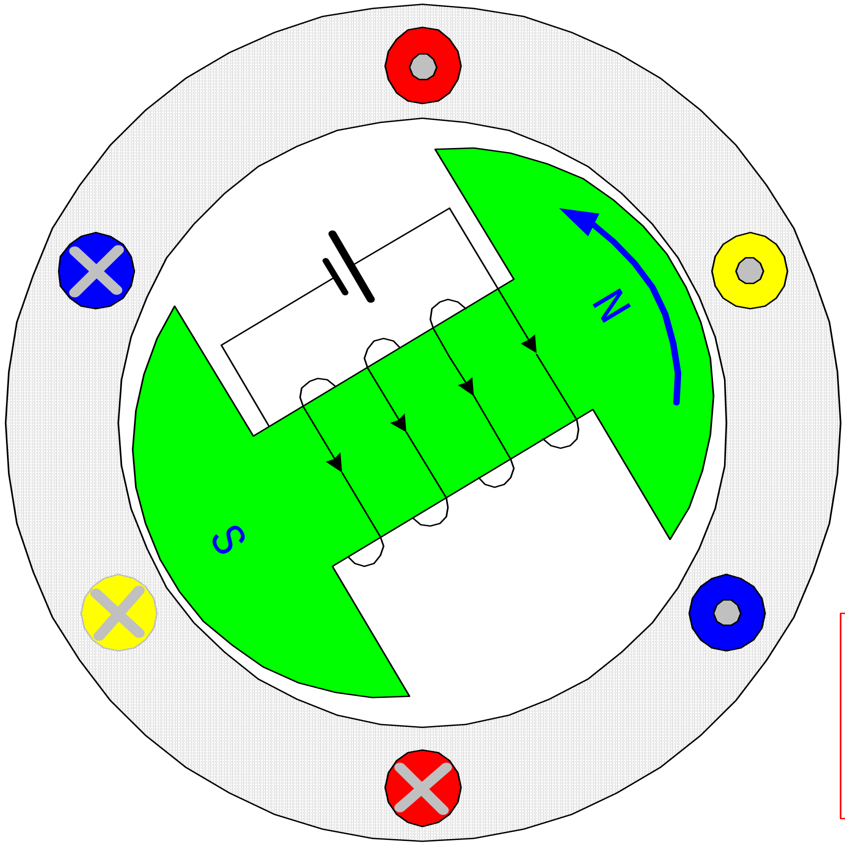


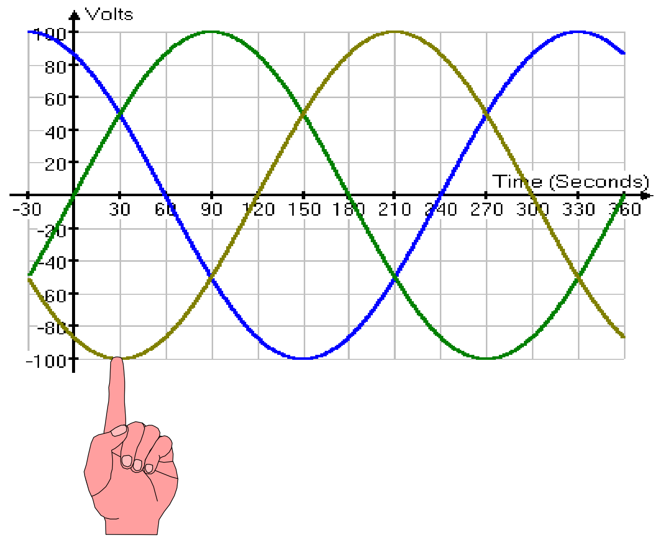


Time : t = 0

Red phase = 0 V
Yellow Phase = -86.6 V
Blue Phase = +86.6 V

Three phase voltages produced by the salient pole generator

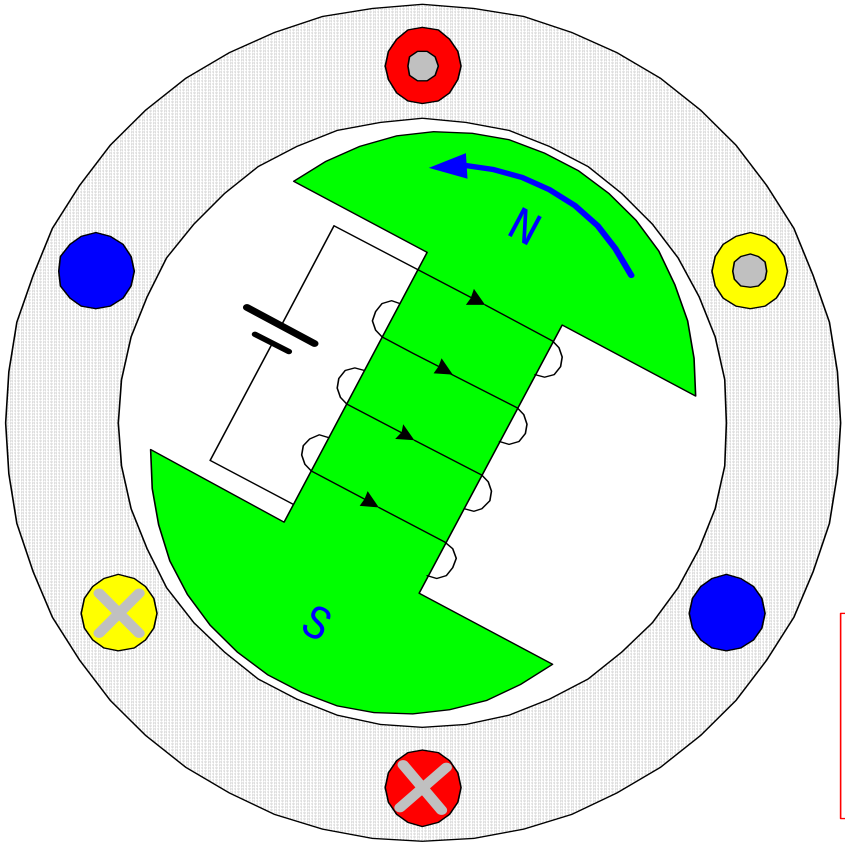


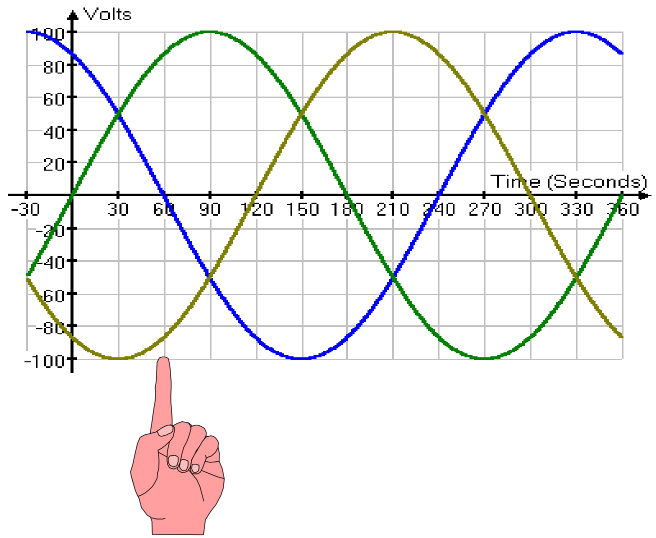


Time : t = 30 Sec

Red phase = 50 V
Yellow Phase = - 100 V
Blue Phase = + 50 V

Three phase voltages produced by the salient pole generator

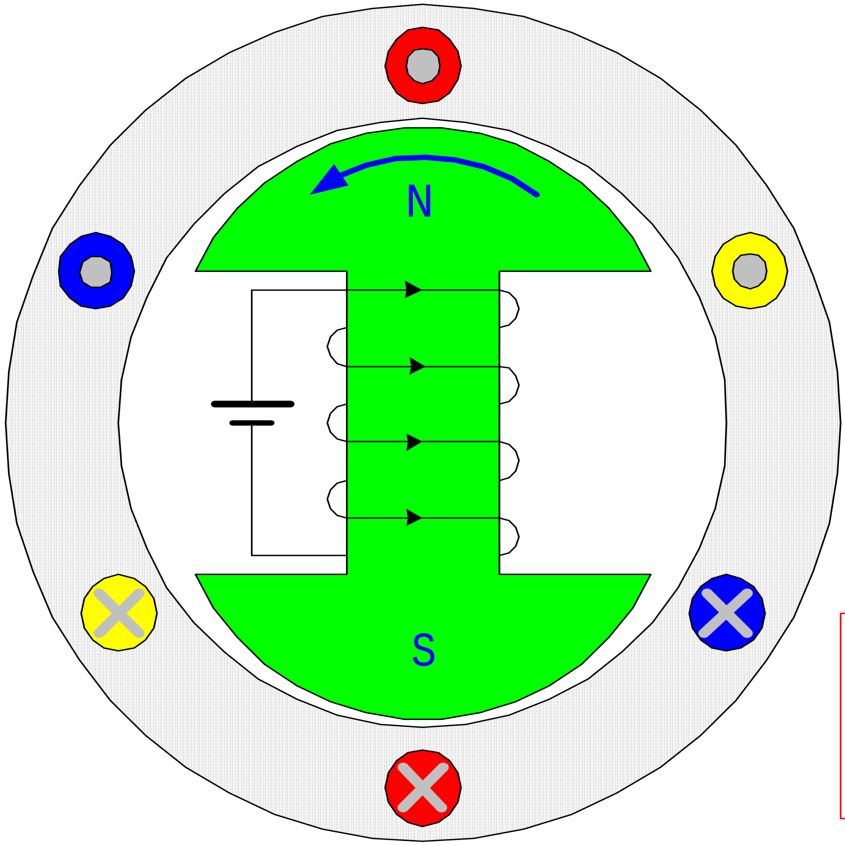


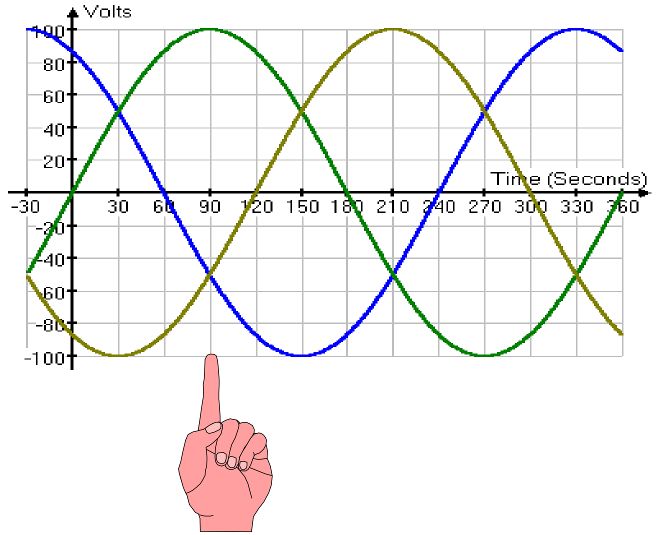


Time : t = 60 sec

Red phase = +86.6 V
Yellow Phase = -86.6 V
Blue Phase = 0 V

Three phase voltages produced by the salient pole generator

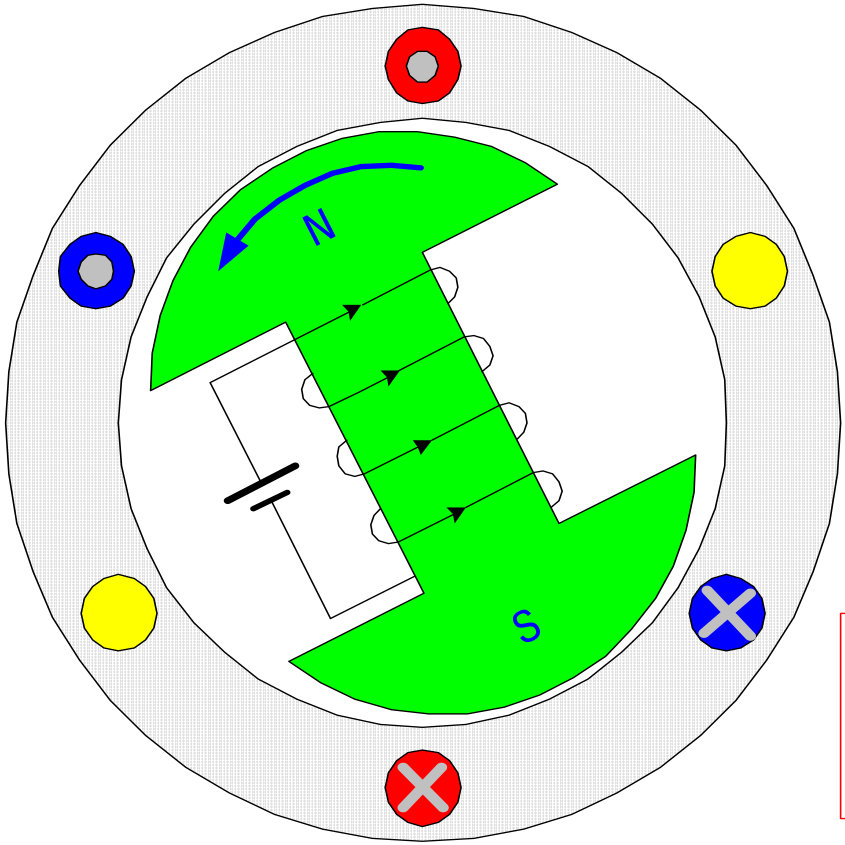


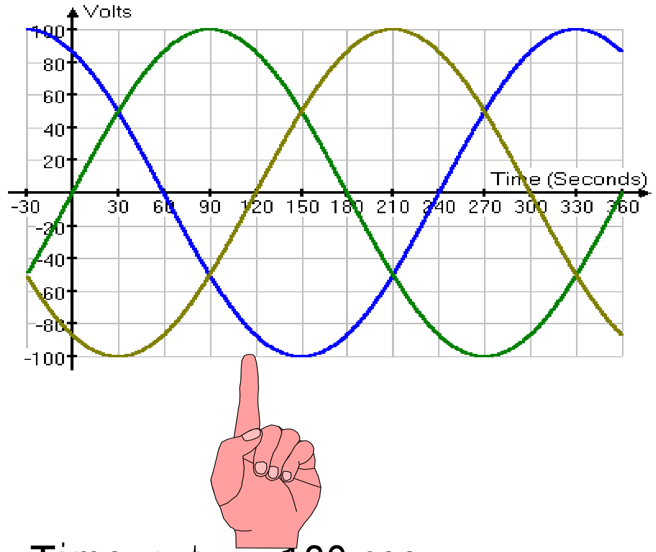


Time : t = 90 sec

Red phase = +100 V
Yellow Phase = - 50 V
Blue Phase = - 50 V

Three phase voltages produced by the salient pole generator

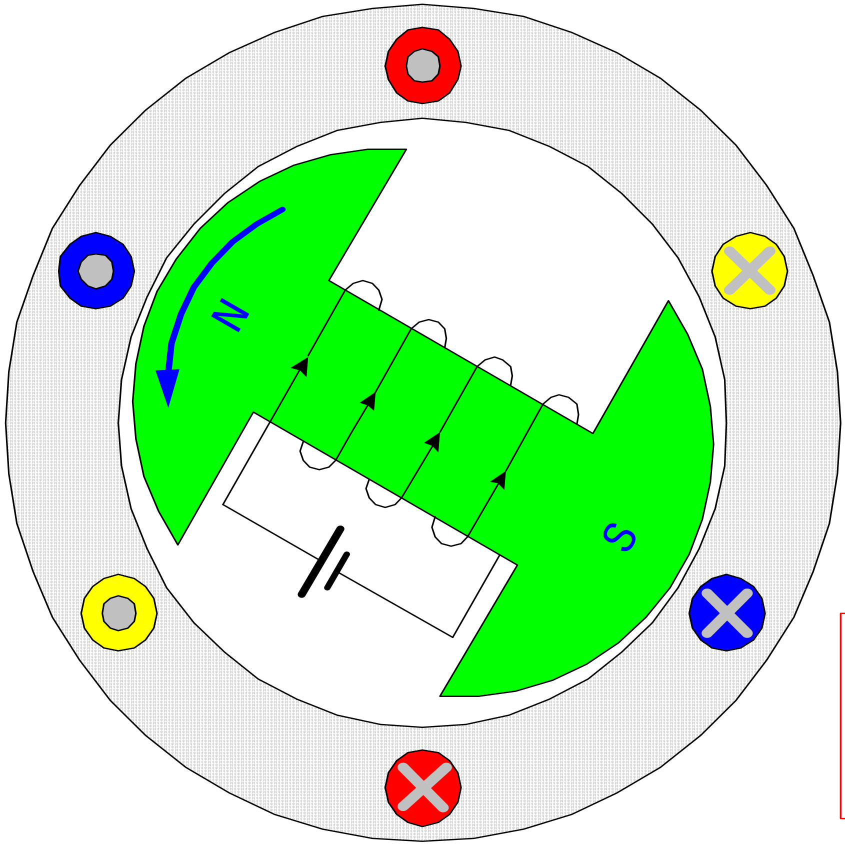


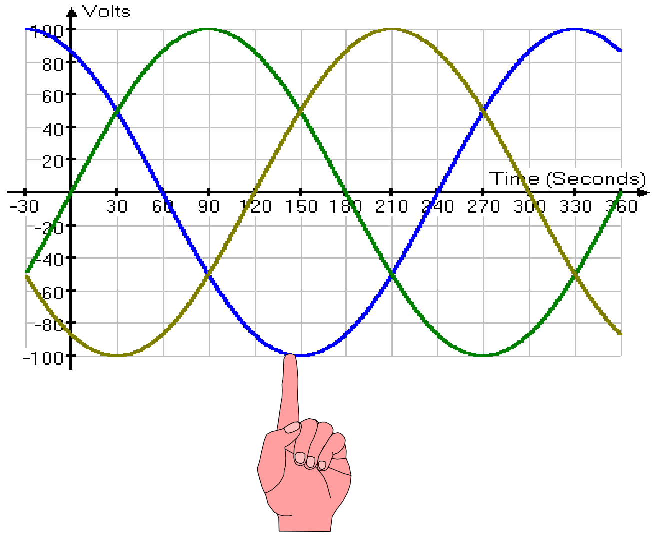


Time : t = 120 sec

Red phase = +86.6 V
Yellow Phase = 0 V
Blue Phase = -86.6 V

Three phase voltages produced by the salient pole generator

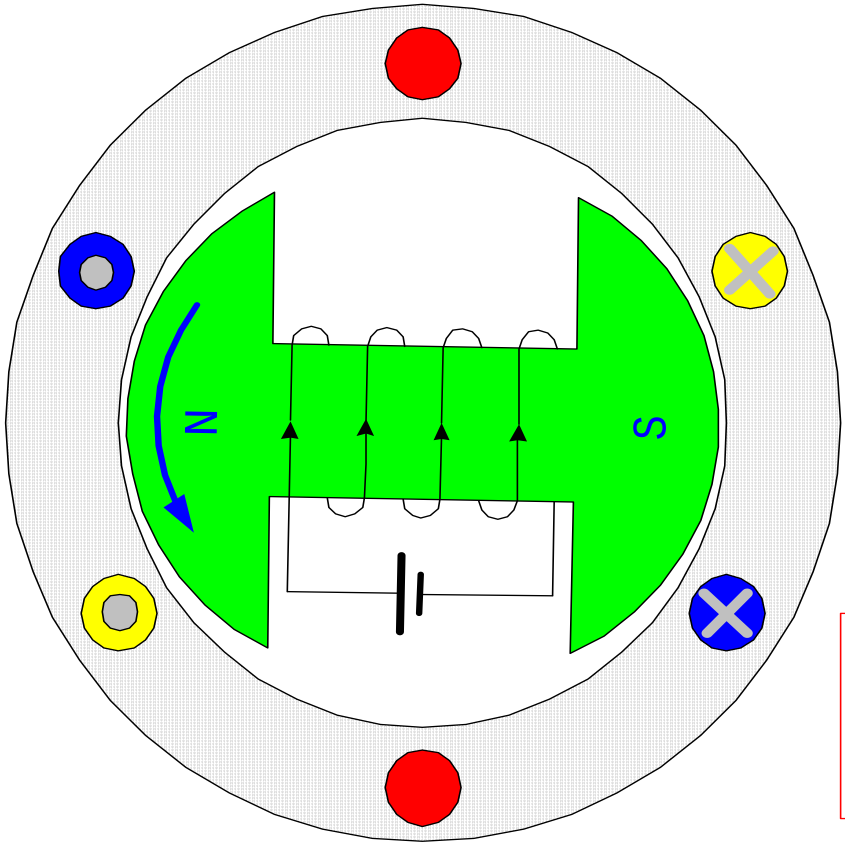


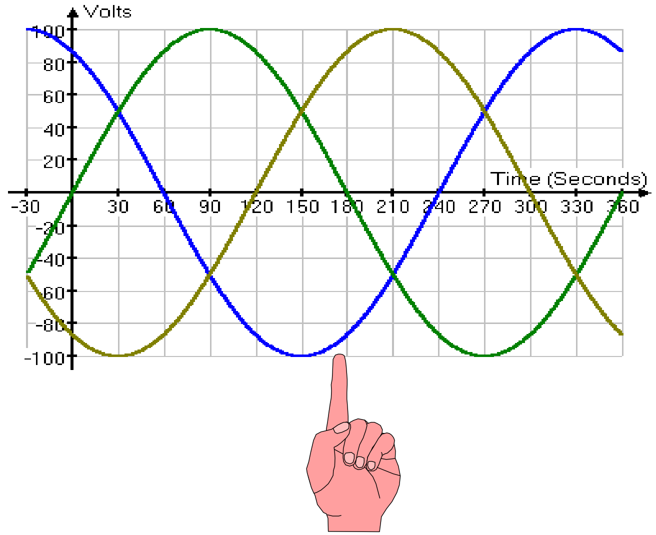


Time : t = 150 sec

Red phase = +50 V
Yellow Phase = +50 V
Blue Phase = -100 V

Three phase voltages produced by the salient pole generator

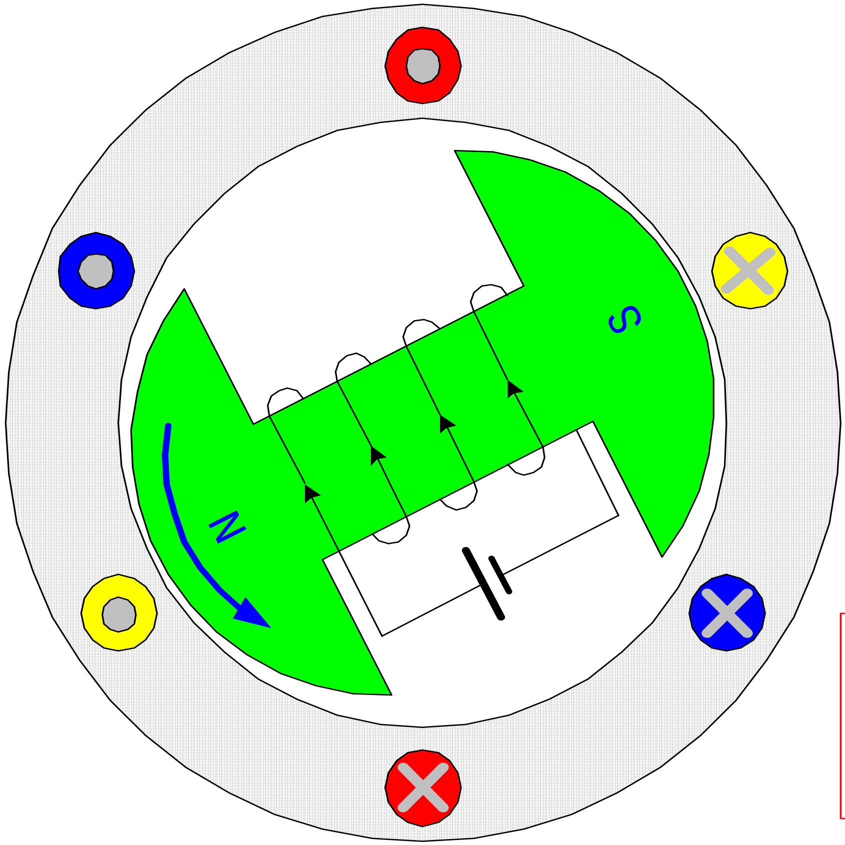


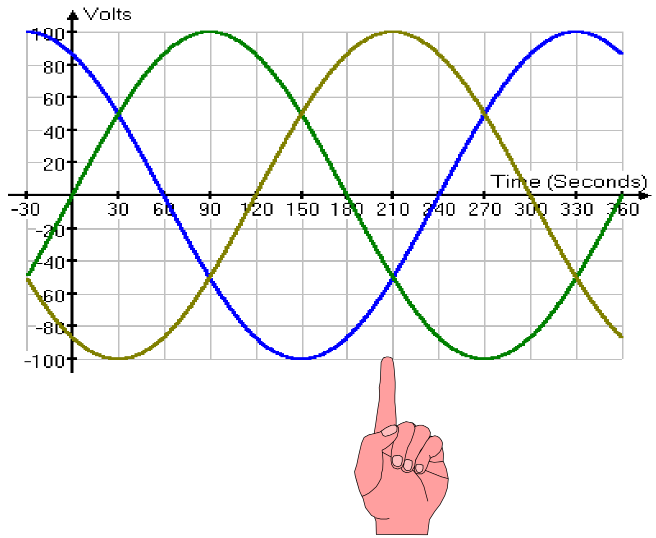


Time : t = 180 sec

Red phase = 0 V
Yellow Phase = +86.6 V
Blue Phase = -86.6 V

Three phase voltages produced by the salient pole generator





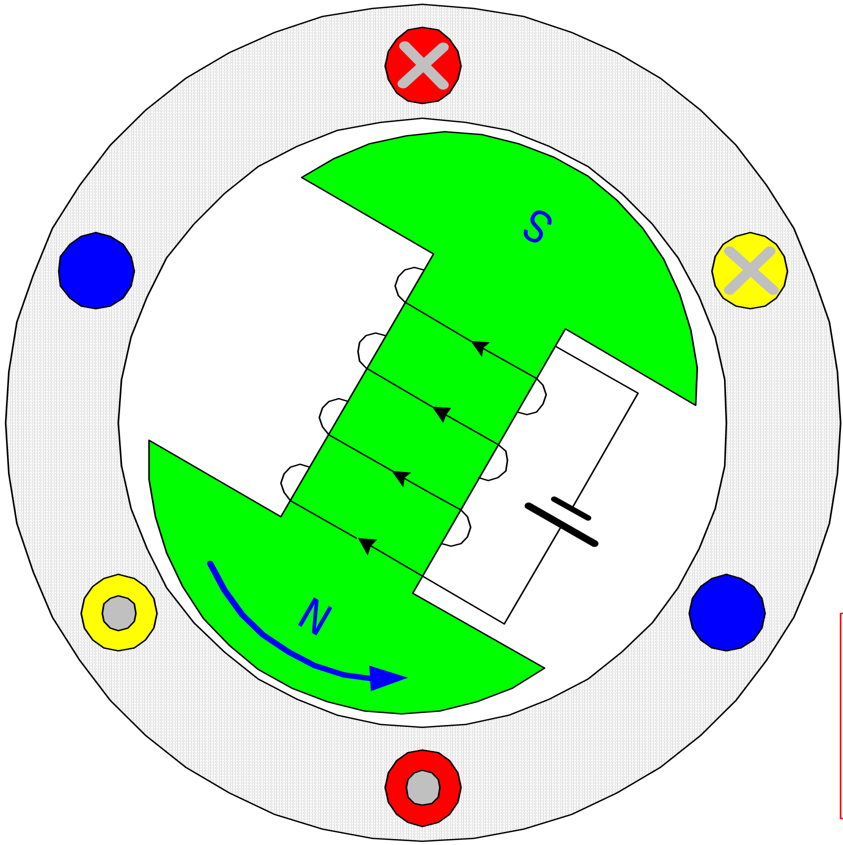
Time : t = 210 sec

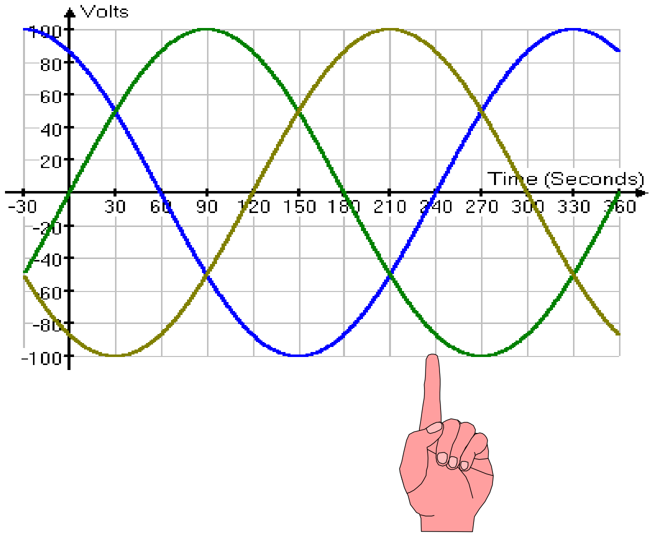
Red phase = -50 V

Yellow Phase = +100 V

Blue Phase = -50 V

Three phase voltages produced by the salient pole generator





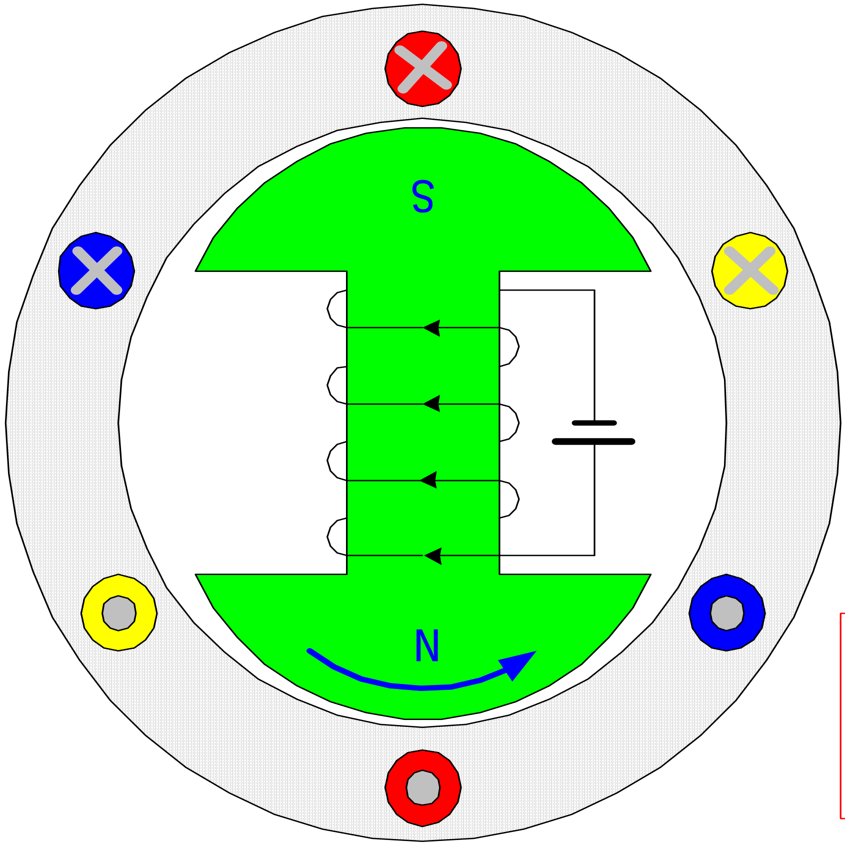
Time : t = 240 sec

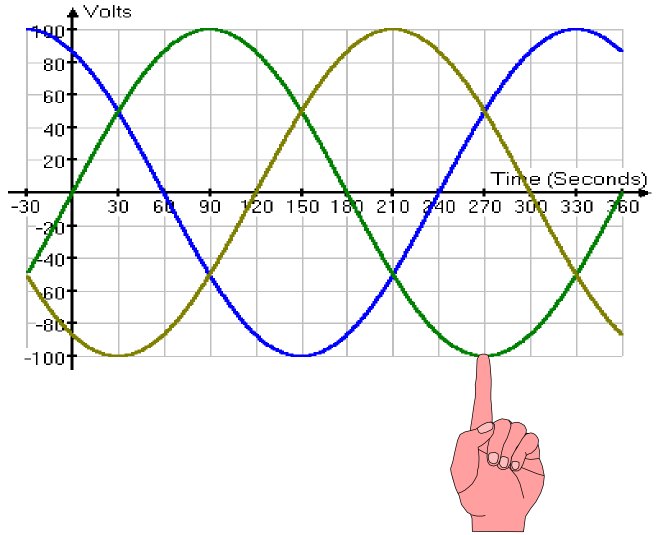
Red phase = -86.6 V

Yellow Phase = +86.6 V

Blue Phase = 0 V

Three phase voltages produced by the salient pole generator

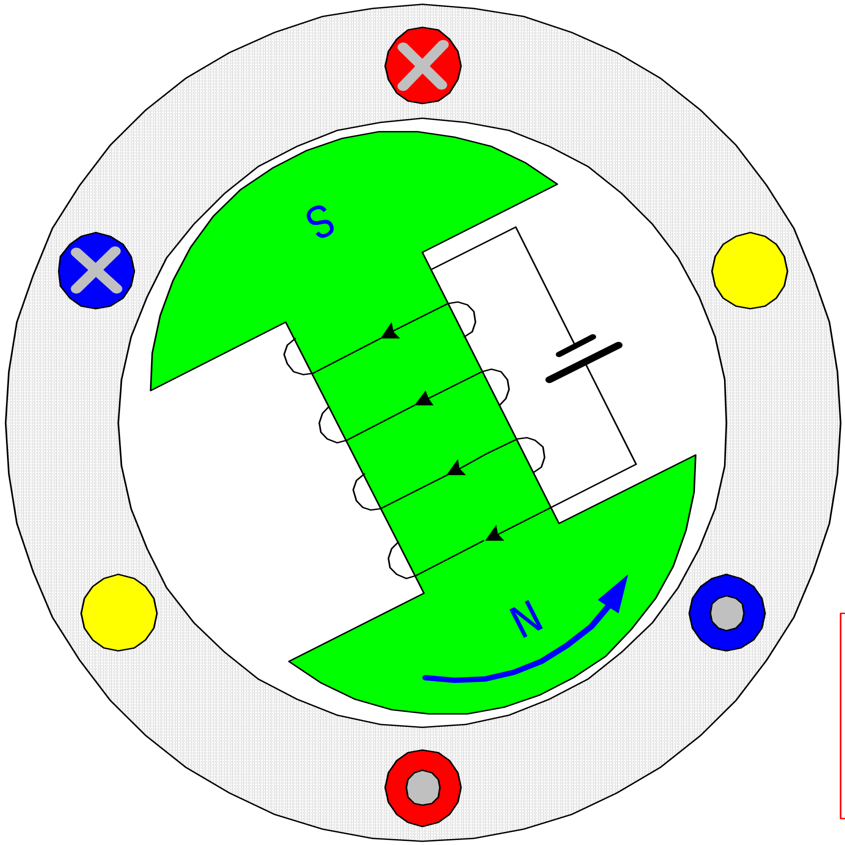


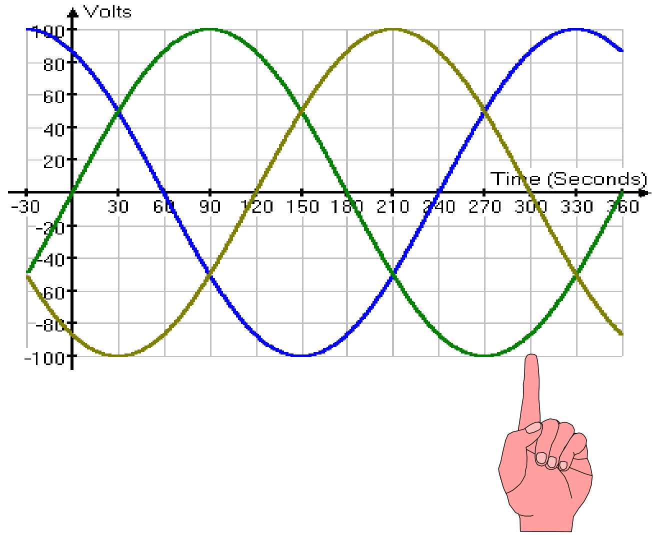


Time : t = 270 sec

Red phase = -100 V
Yellow Phase = +50 V
Blue Phase = +50 V

Three phase voltages produced by the salient pole generator

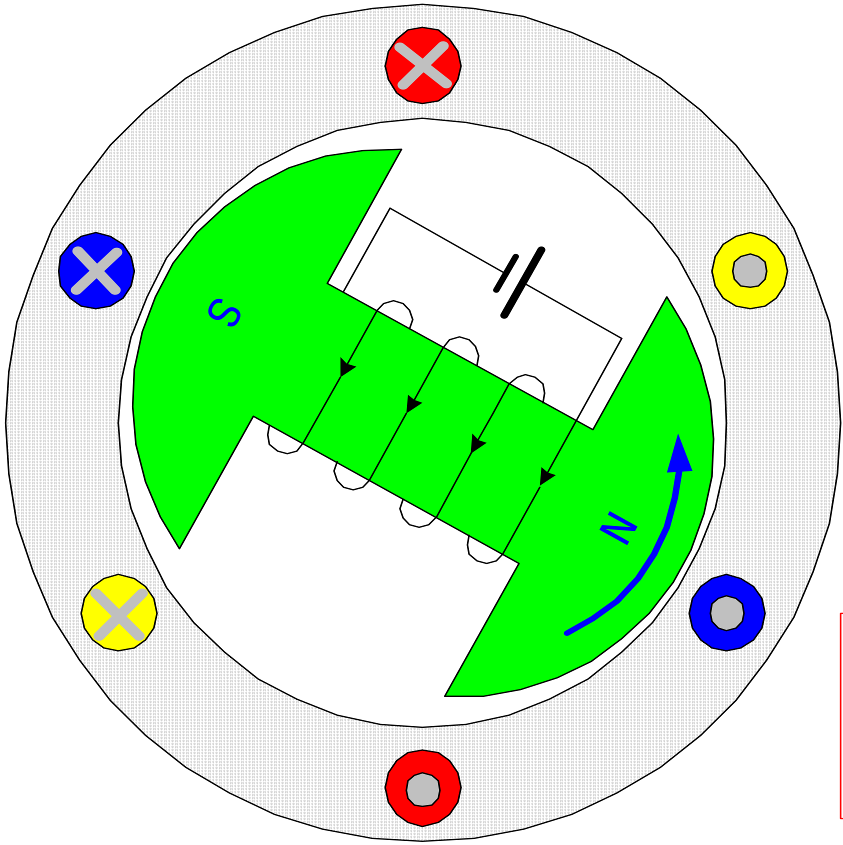


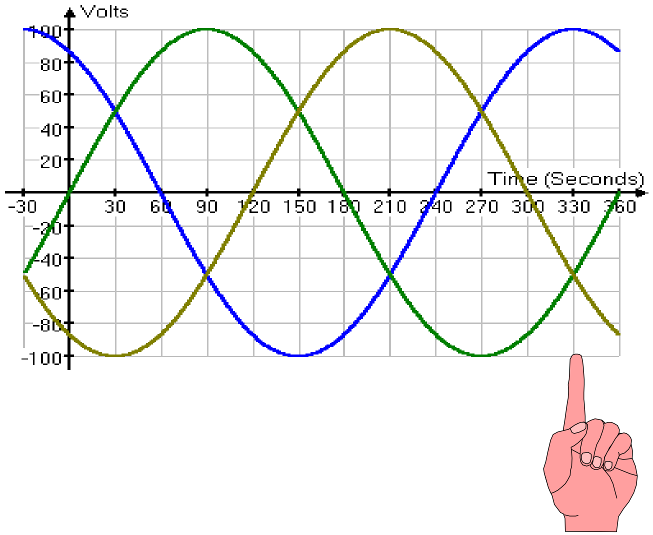


Time : t = 300 sec

Red phase = -86.6 V
Yellow Phase = 0 V
Blue Phase = +86.6 V

Three phase voltages produced by the salient pole generator

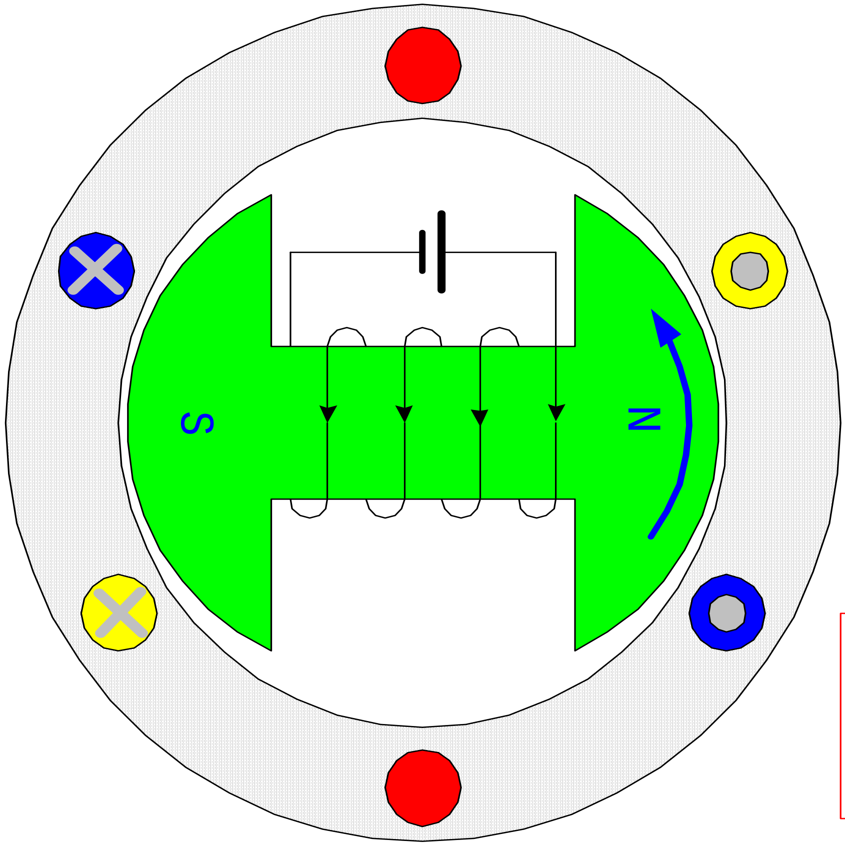


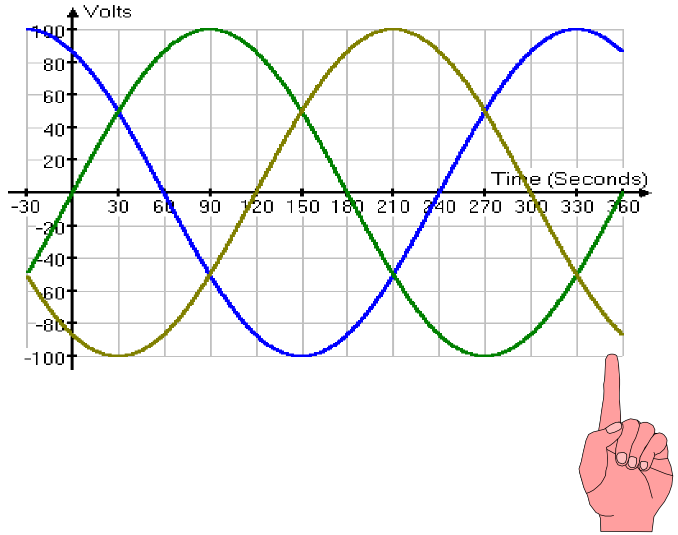


Time : t = 330 sec

Red phase = -50 V
Yellow Phase = -50 V
Blue Phase = +100 V

Three phase voltages produced by the salient pole generator





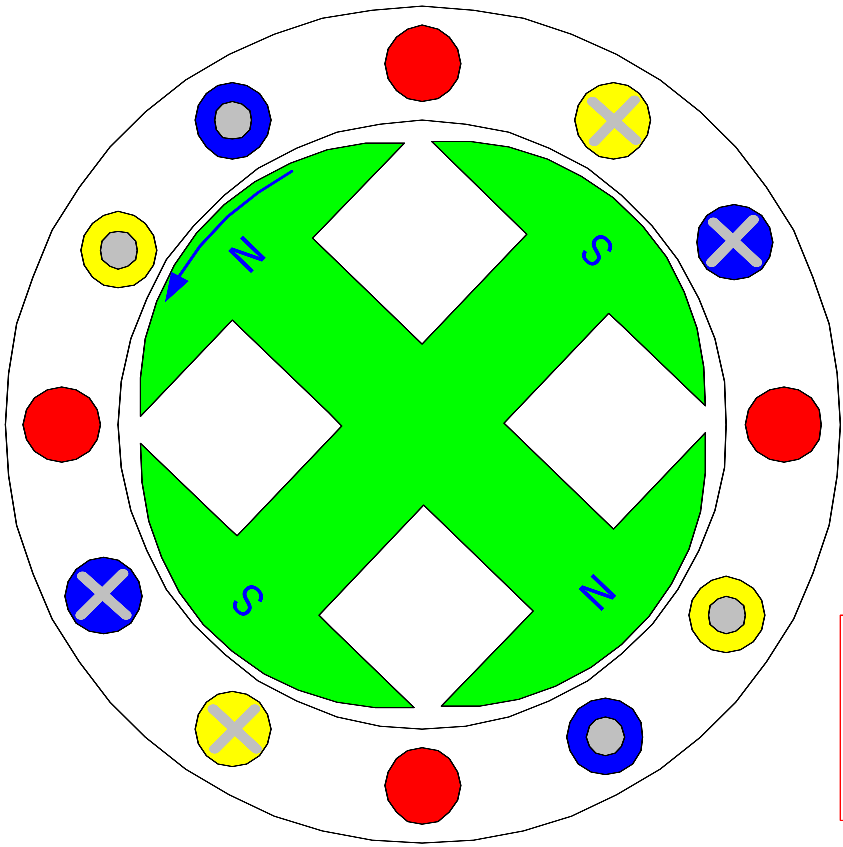
Time : t = 360 sec

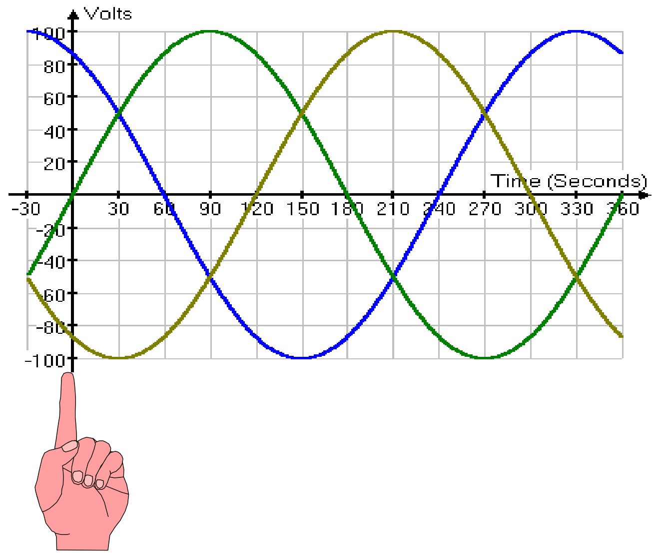
Red phase = 0 V
Yellow Phase = -86.6 V
Blue Phase = +86.6 V

Four pole salient pole synchronous generator

- A four pole synchronous generator is a repetition of the two pole generator
- For four pole generator, the rotor consists of four magnetic poles
- Since there is a total of four magnetic pole reversal for every one revolution of the rotor, the speed of the four pole machine is only half of that of the two pole machine for the same voltage output
- There are six winding coils installed in the stator for a four pole generator, as compared with a set of three winding coils for a two pole generator

Three phase voltages produced by a 4-pole salient pole synchronous generator

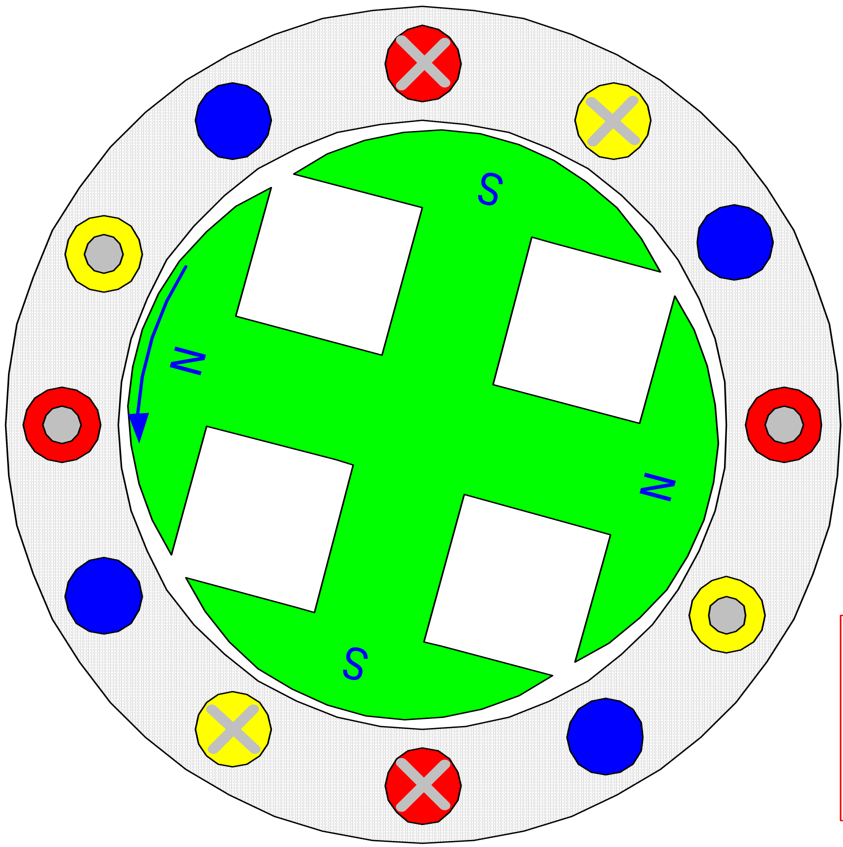


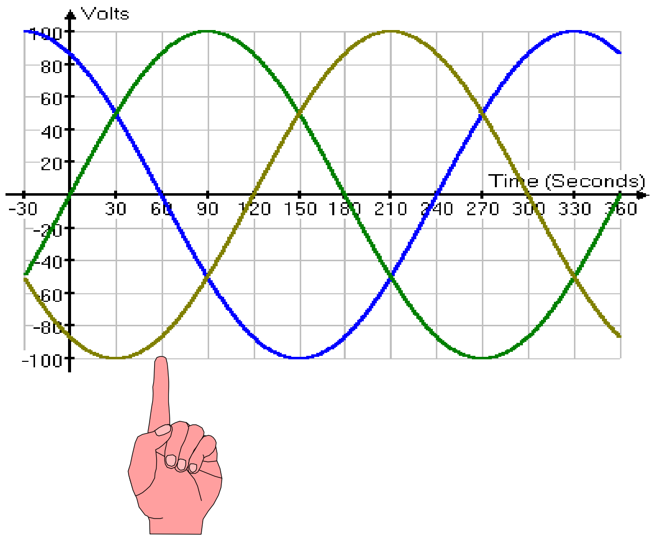


Time : t = 0

Red phase = 0 V
Yellow Phase = -86.6 V
Blue Phase = +86.6 V

Three phase voltages produced by a 4-pole salient pole synchronous generator

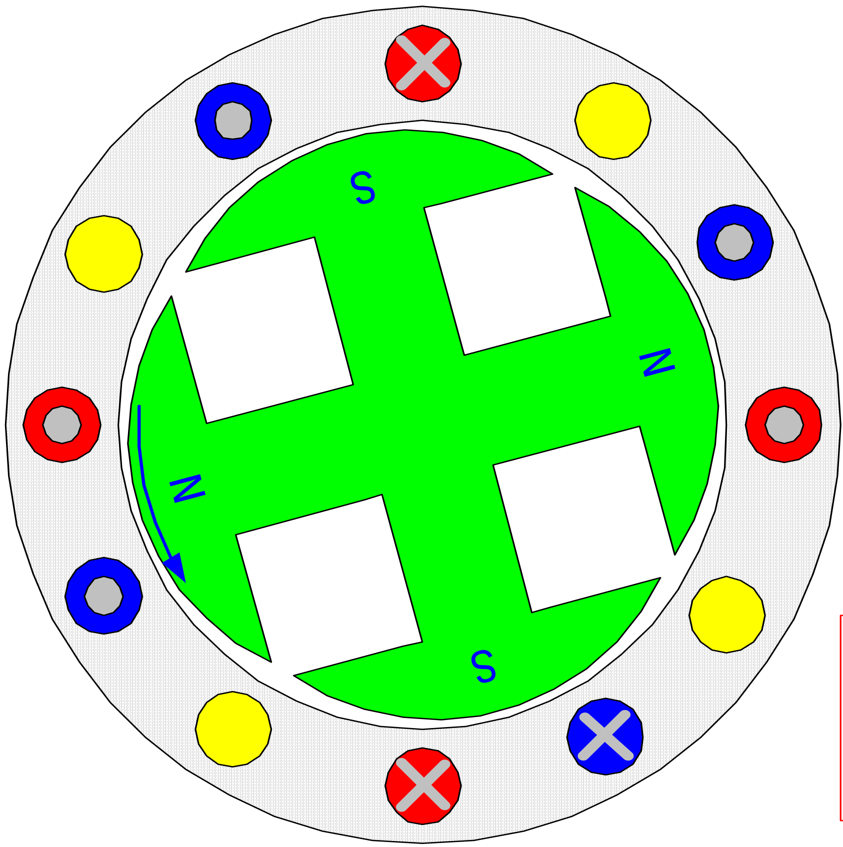


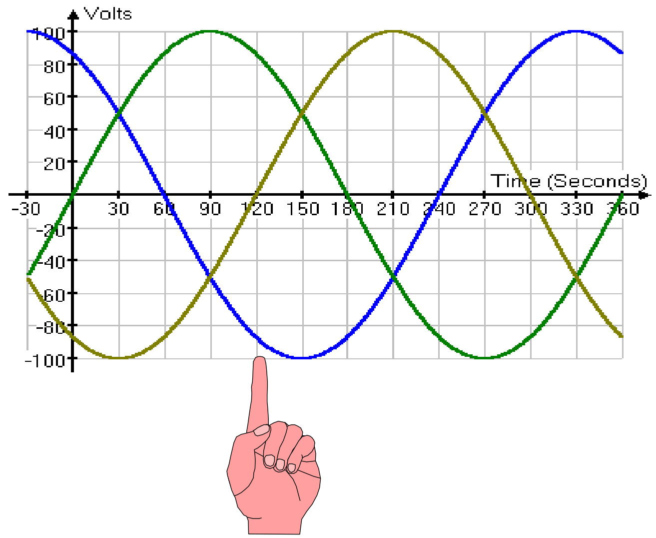


Time : t = 60

Red phase = +86.6 V
Yellow Phase = -86.6 V
Blue Phase = 0 V

Three phase voltages produced by a 4-pole salient pole synchronous generator

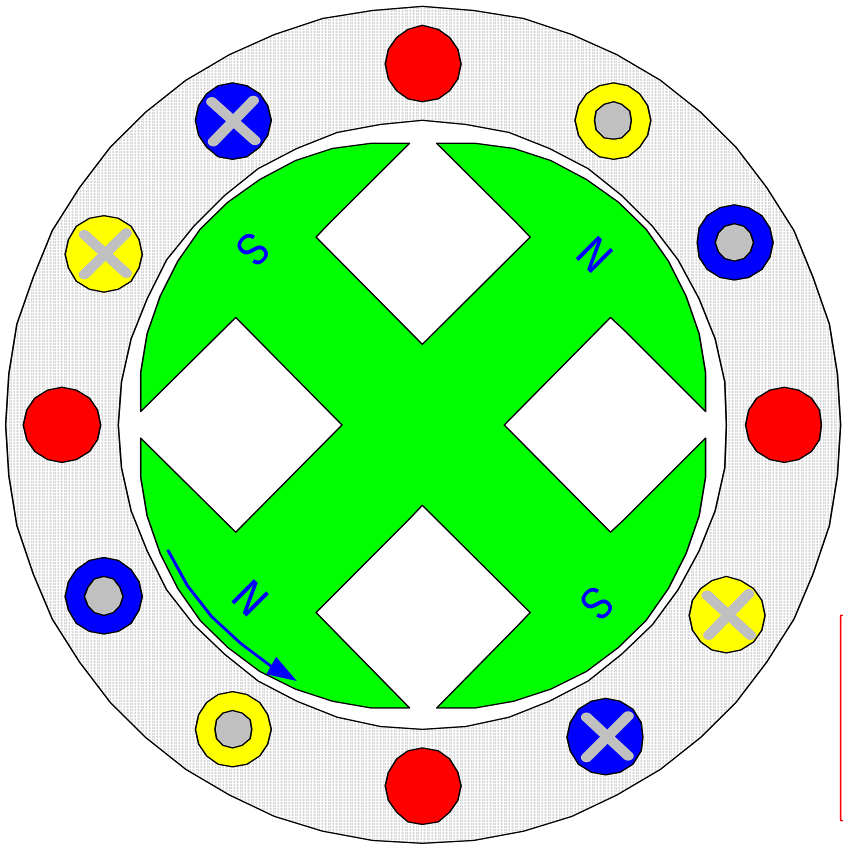


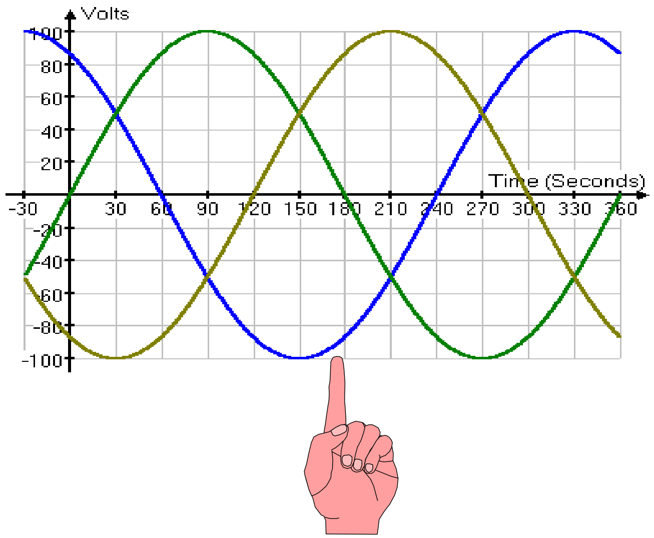


Time : t = 120

Red phase = +86.6 V
Yellow Phase = 0 V
Blue Phase = -86.6 V

Three phase voltages produced by a 4-pole salient pole synchronous generator





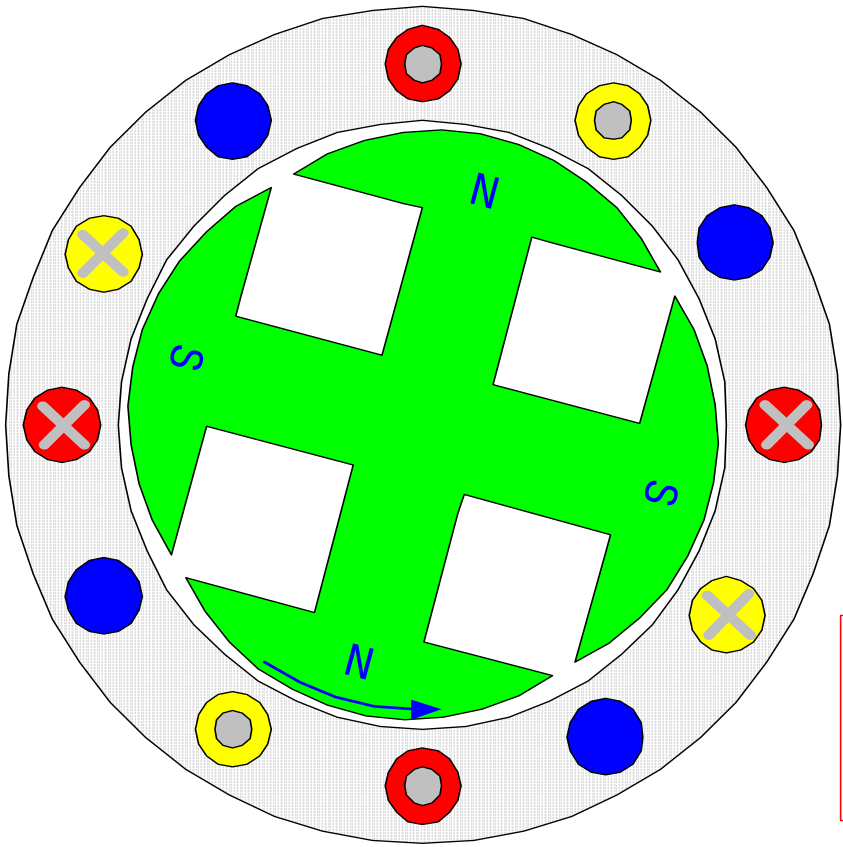
Time : t = 180

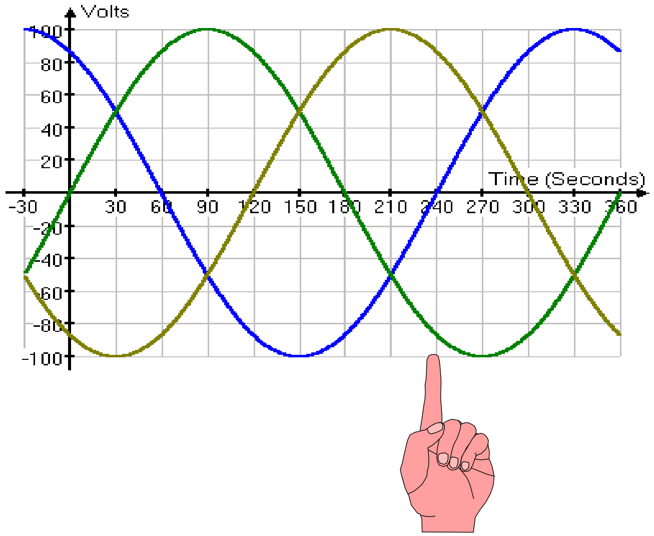
Red phase = 0 V

Yellow Phase = +86.6 V

Blue Phase = -86.6 V

Three phase voltages produced by a 4-pole salient pole synchronous generator

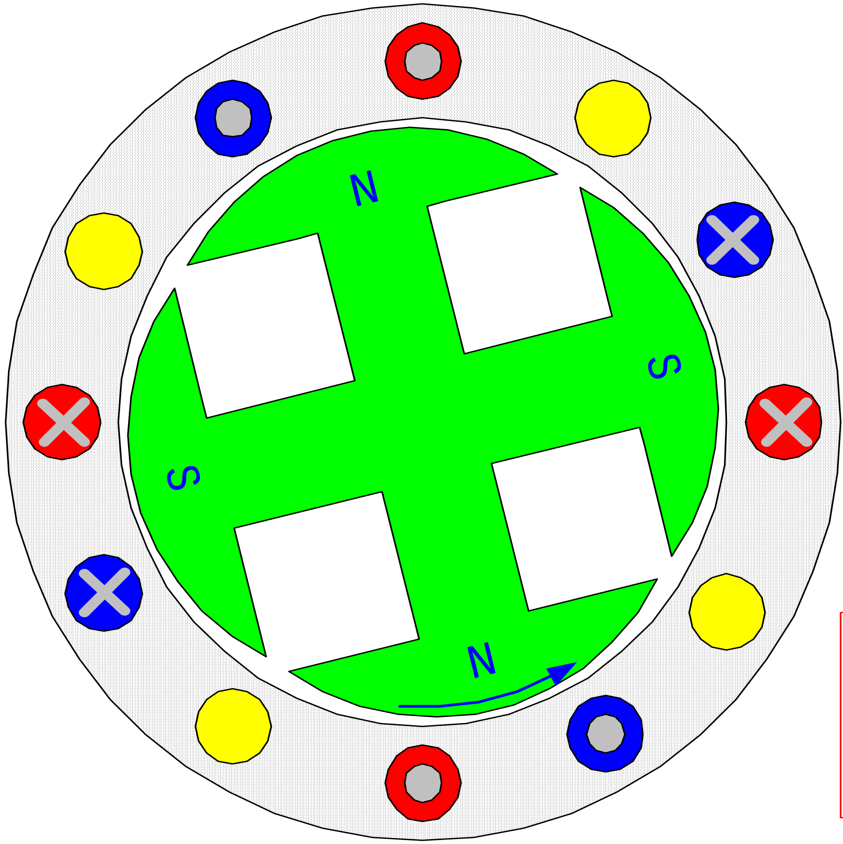


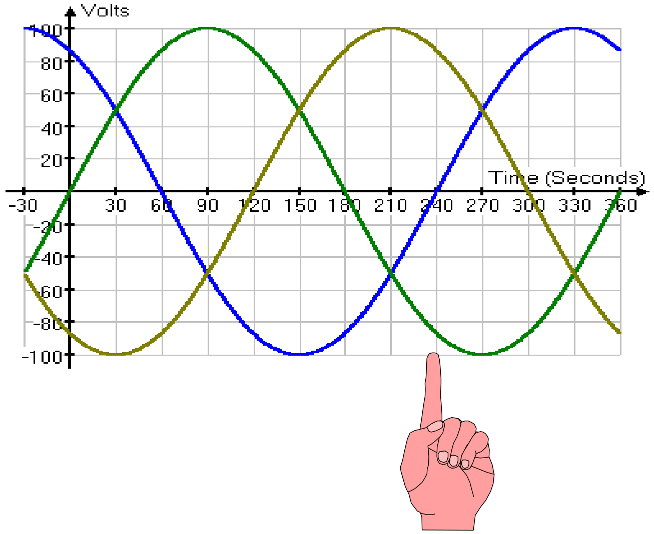


Time : t = 240

Red phase = -86.6 V
Yellow Phase = +86.6 V
Blue Phase = 0 V

Three phase voltages produced by a 4-pole salient pole synchronous generator

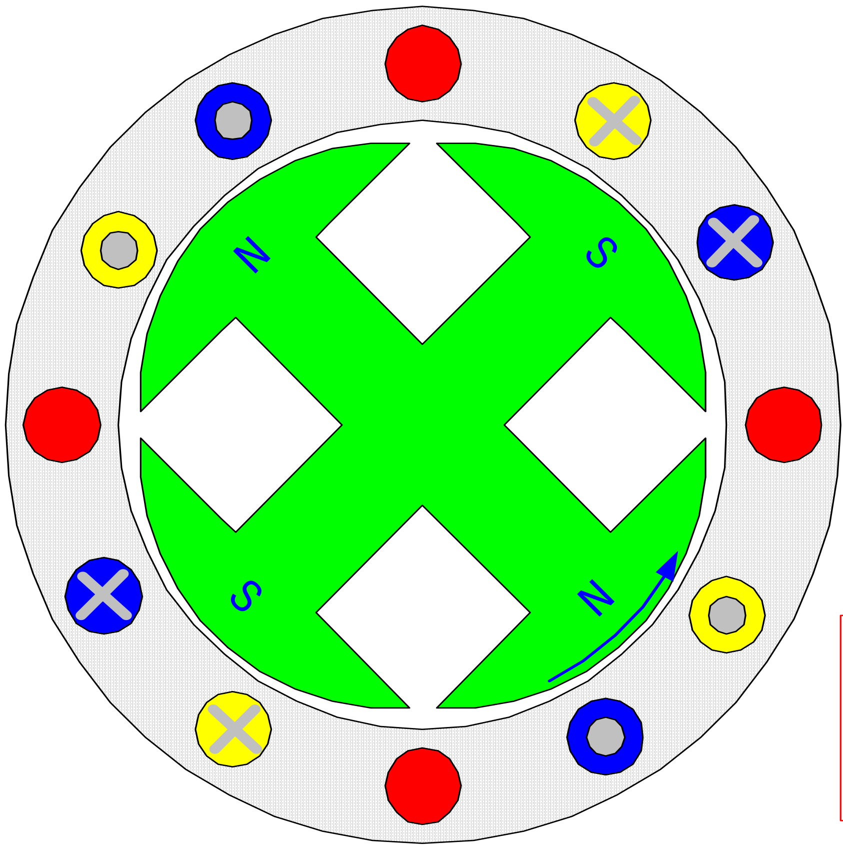


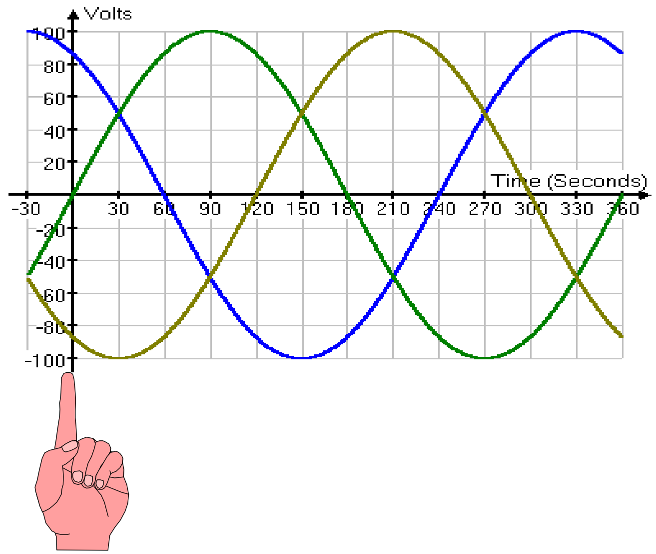


Time : t = 300

Red phase = -86.6 V
Yellow Phase = 0 V
Blue Phase = +86.6 V

Three phase voltages produced by a 4-pole salient pole synchronous generator

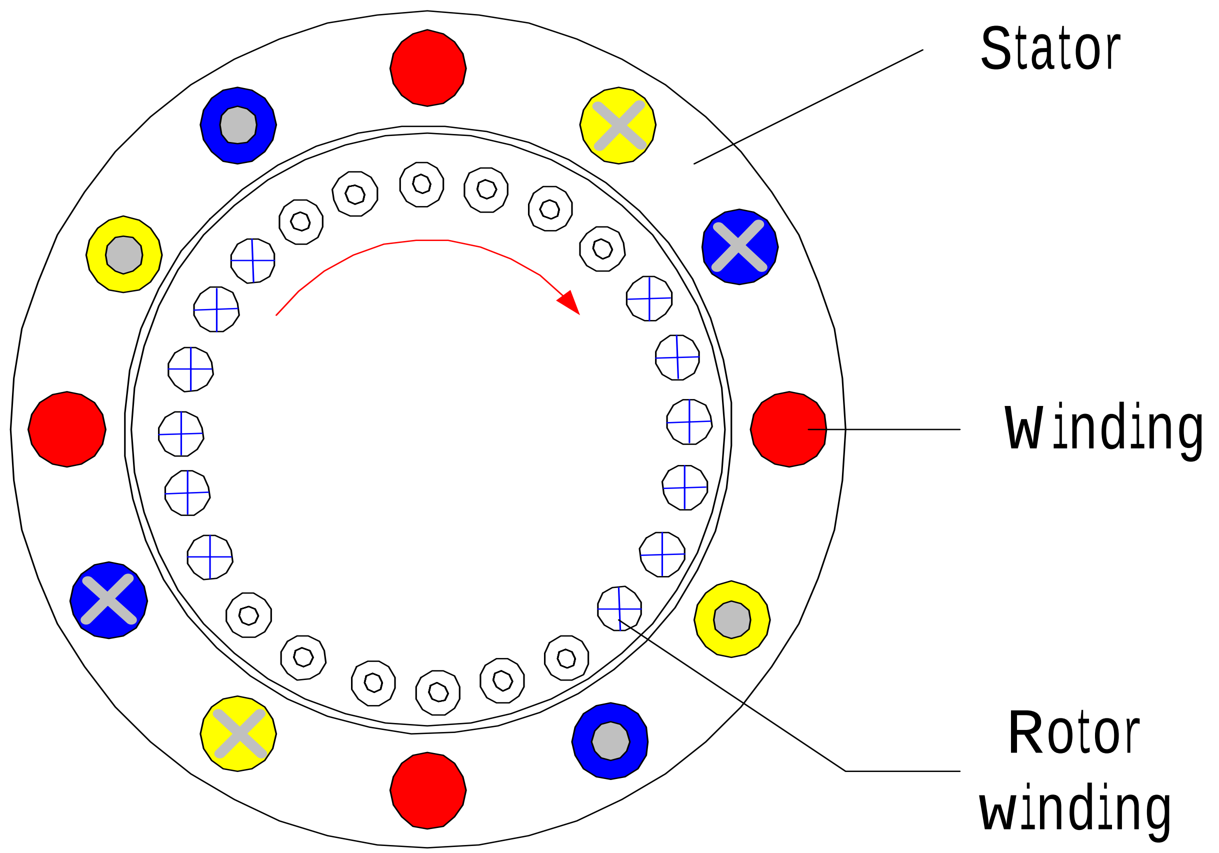




Time : t = 360

Red phase = 0 V
Yellow Phase = -86.6 V
Blue Phase = +86.6 V

4-pole cylindrical rotor synchronous generator



Ideal synchronous generator

- Like the transformer, we start with ideal generator, so that all other non-ideal element can be added to the ideal generator for analysis

- An ideal synchronous generator has the following characteristics:
  - It is connected to infinite busbar, i.e. the output is at constant voltage and frequency
  - The magnetic field characteristic is linear and has no saturation
  - The air gap is linear so that the reluctance is linear over the magnetic pole surface
  - There is no winding resistance and leakage reactance

Transformer e.m.f. and motional e.m.f induced in the stator winding of a synchronous machine

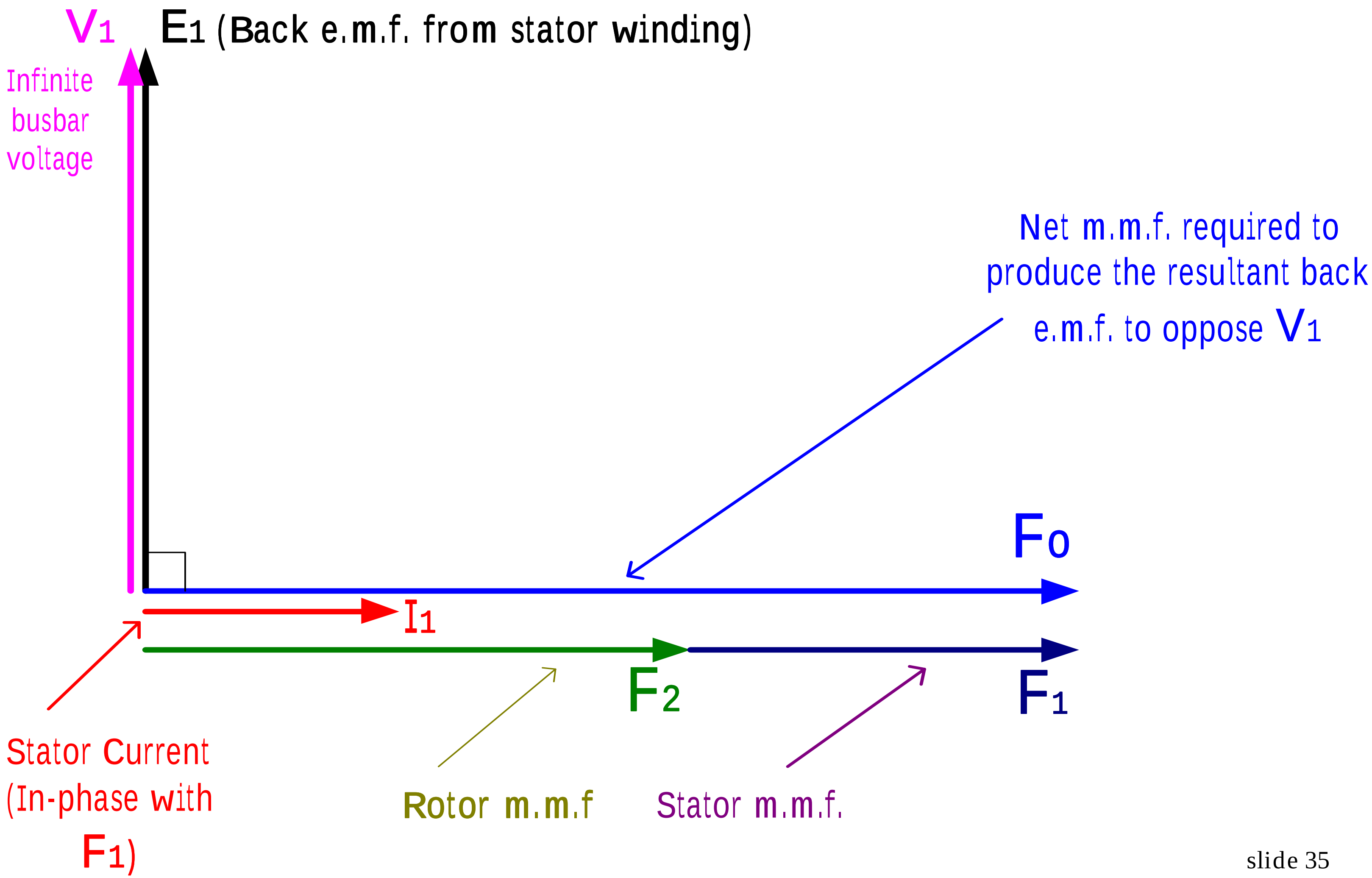
- A synchronous generator is made up of iron core and stator windings. Just like the transformer, when the stator winding of a synchronous machine is connected to an infinite busbar, the stator winding will draw a no-load magnetizing current to develop a magnetic flux through the stator and rotor core, Since this magnetizing current is an alternating current, a transformer back e.m.f. is induced in the stator winding and its direction will oppose the infinite busbar voltage.
- Unlike the transformer core which is stationary, the rotor of the synchronous generator is rotating at synchronous speed. The rotor is magnetized by a d.c. excitation current supplied through the slip rings. The magnetic field of the rotor is rotating at synchronous speed so that its magnetic flux trasverse against the stator winding. A rotational (motional) e.m.f. is induced in the stator. Because the rotor is travelling at synchronous speed, this induced e.m.f will have the same frequency as the transformer e.m.f. induced in the stator.

Ideal synchronous machine on No-load (under-excitation)

- When an ideal synchronous machine is connected to an infinite busbar, the stator winding will draw an excitation current to develop a transformer e.m.f.
- At the same time, a rotational e.m.f. is induced in the stator winding due to rotor excitation.
- Since the transformer e.m.f. and the rotational e.m.f. is having the same frequency, the two e.m.f will be added together, the resultant voltage will oppose the voltage of the infinite busbar. At balance, we have

  Tranformer e.m.f. + Rotational e.m.f. = Infinite busbar voltage
- Under-excitation is the case where the induced voltage due to the rotor excitation alone is smaller than the busbar voltage. The excessive busbar voltage will cause the stator to draw in a lagging magnetizing current to produce the required transformer back e.m.f.

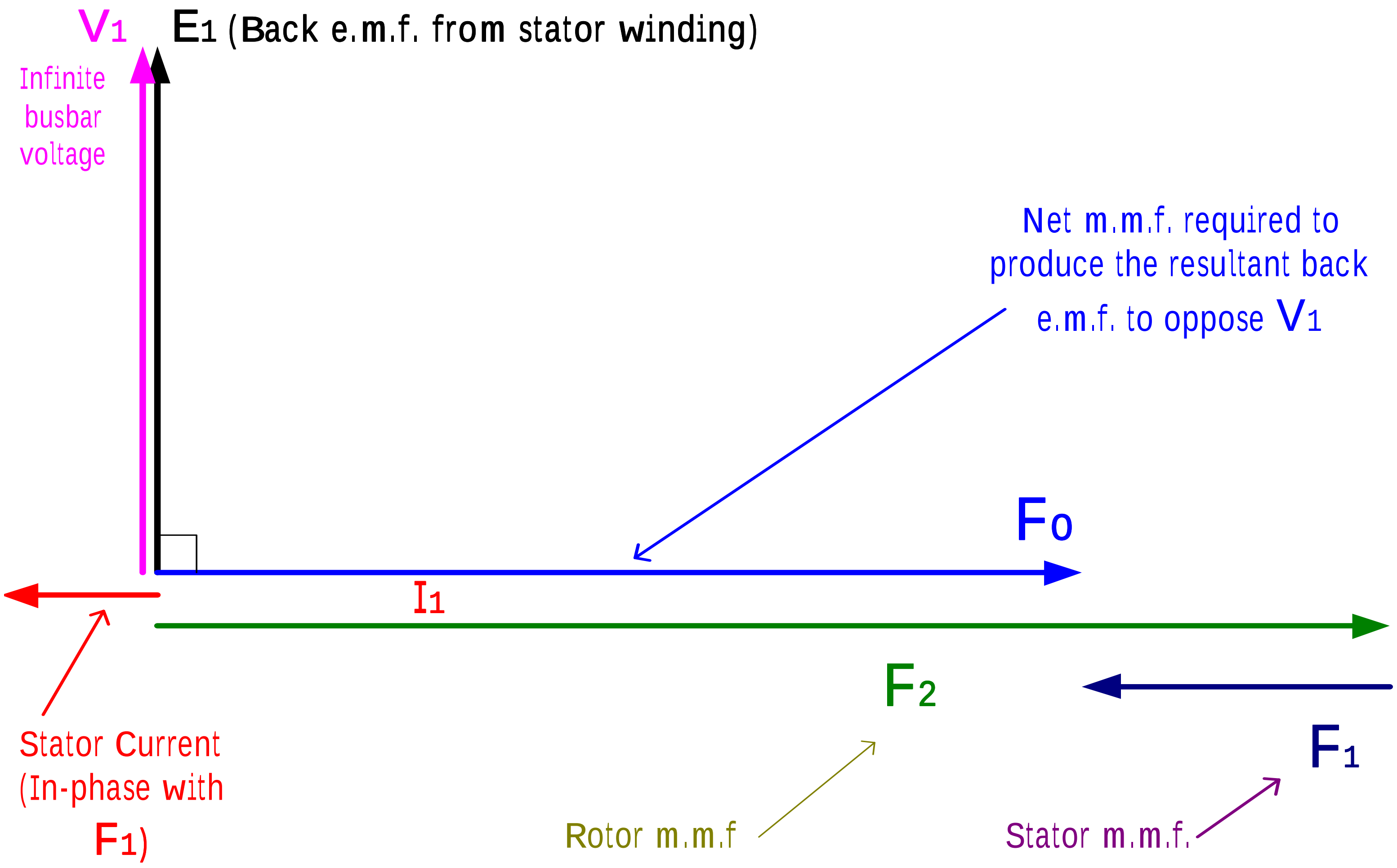
M.m.f. Phasor diagram for synchronous machine on No-load (Under-excitation)



Ideal synchronous machine on No-load (Over-excitation)

- If the excitation on the rotor winding alone is large enough to produce a rotational e.m.f. which itself is larger than the voltage of the infinite busbar, we called this case as over-excitation.
- Since the stator winding induced e.m.f. is larger than the busbar voltage, the stator winding is forced to draw in a leading power factor de-magnetizing stator current to produce the negative voltage, which when substracted to the over-excited rotational e.m.f. will balance the infinite busbar voltage.
- The magnitude of this leading stator current is adjustable and it depends on the degree of over excitation. Thus an Un-loaded over-excited synchronous machine can be used alone as a variable synchronous compensator for power factor correction of the power distribution networks

M.m.f. Phasor diagram for synchronous machine on No-load (Over-excitation)



Ideal synchronous machine on Generator mode (Under-excitation)

- The rotor axis is in phase with F2, the rotor magnetizing flux
- The infinite busbar voltage is in phase with Fo
- When the synchronous machine is driven by an external prime mover, such as steam turbine, hydro-electric or diesel machine, the rotor is brought ahead of the infinite busbar axis. For a generator

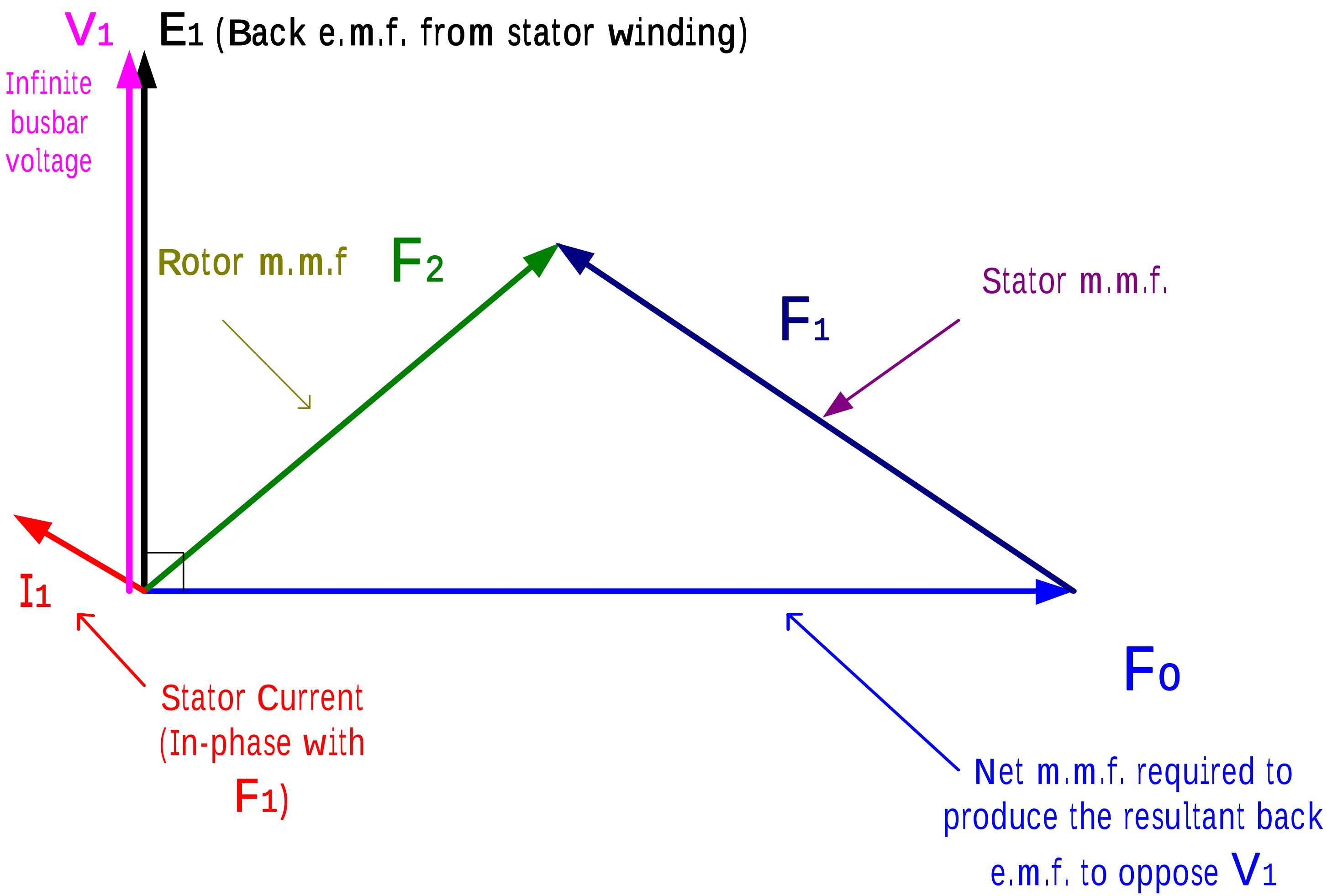
  V = E - IaZs

  Ia = Stator armature current, Zs = Synchronous Impedance

  $F_1 - F_2 = Fo$

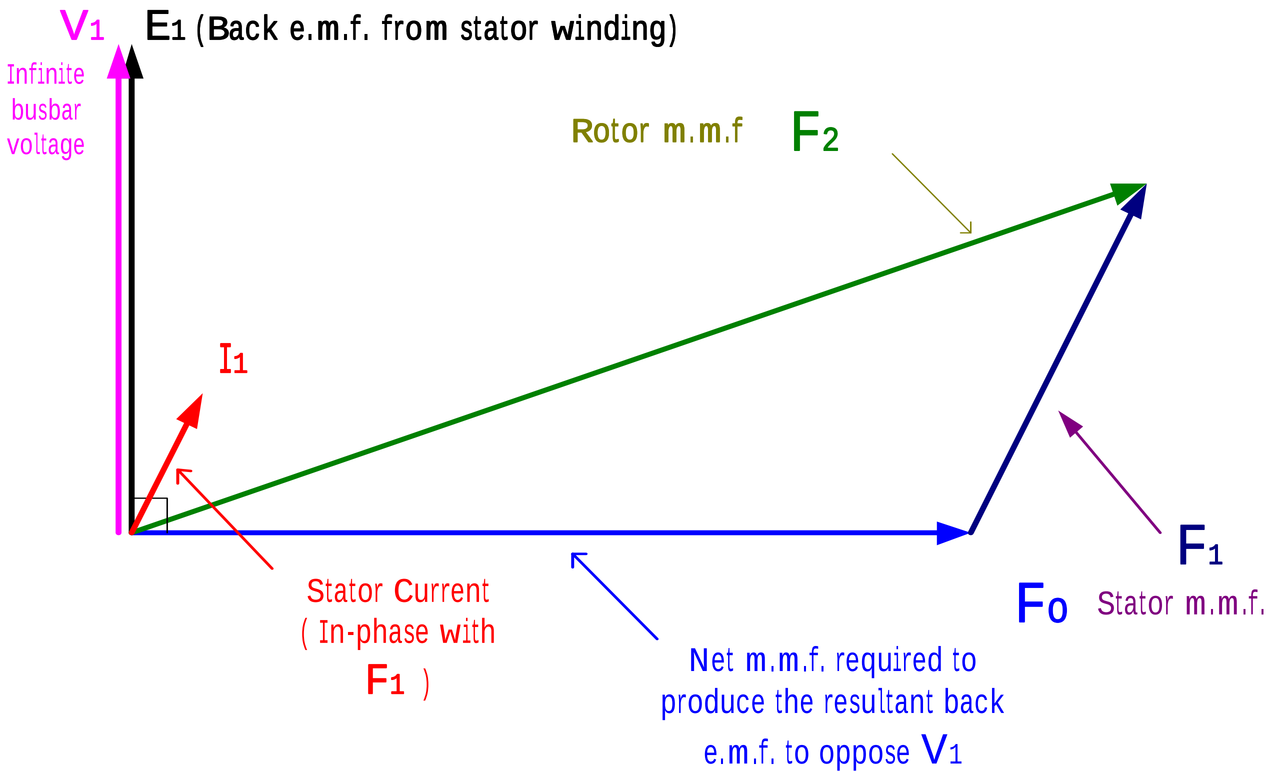
- F_1 is forced to take a leading power factor direction, now the stator deliver active current to the infinite busbar. A restraining torque is exerted on the rotor until a balance is obtained. The rotor sustain a load angle with respect to the infinite busbar phase angle.

M.m.f. Phasor diagram for synchronous machine on Generator mode (Under-excitation)



M.m.f. Phasor diagram for synchronous machine on Generator mode (Over-excitation)

- Since Fo = F_1 - F_2 for a generator, the same phasor relationship holds for the case of over-excitation, but this time the stator current become lagging.

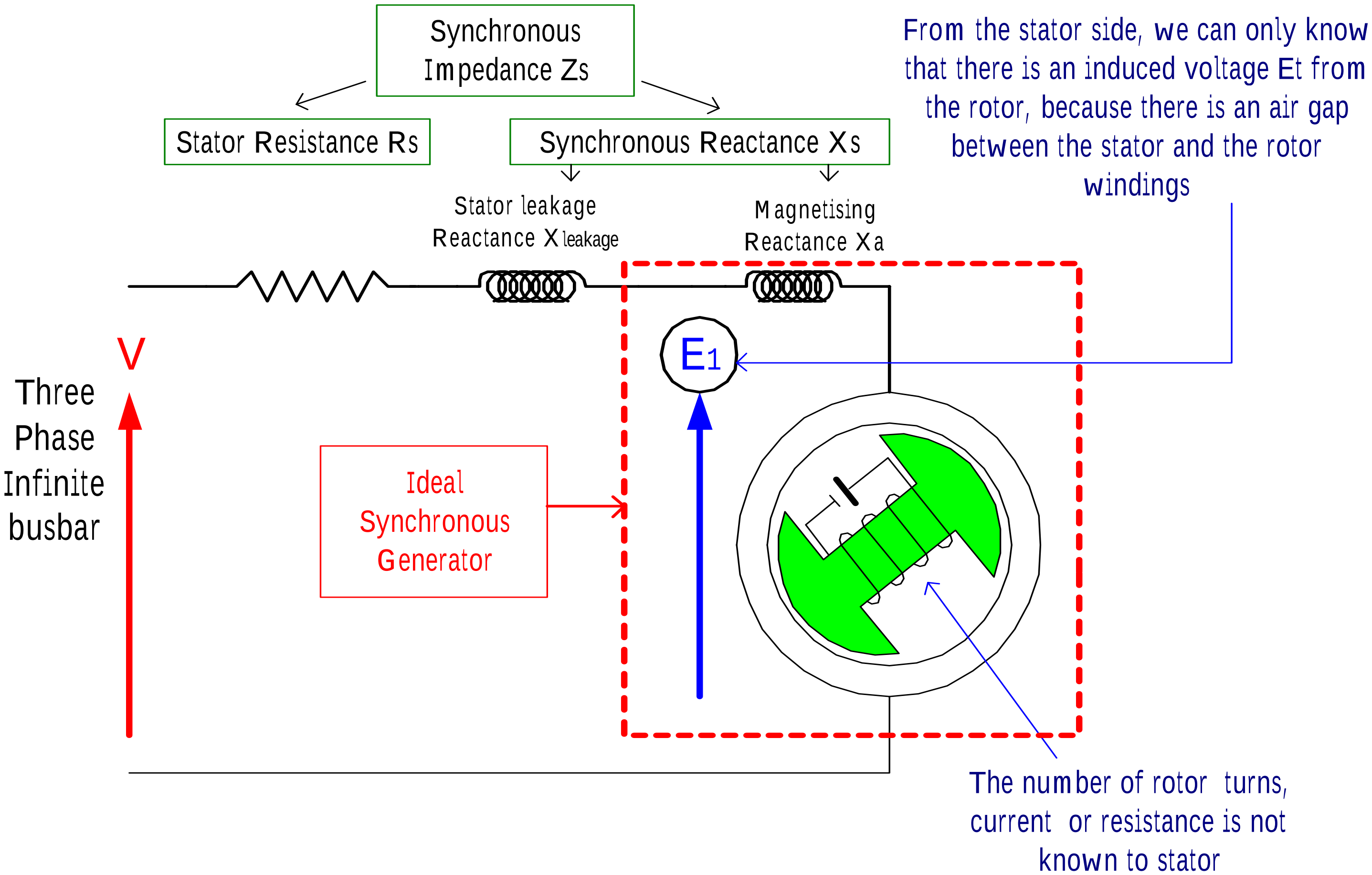


E.m.f. relationship for ideal synchronous generator

- From the relation $F_o = F_1 - F_2$, if the iron core have a non-linear magnetic characteristic, we know that we must first add the magnitude of both F1 and F2 to find Fo before we can determine the correct value of induced e.m.f . E1 from the magnetization curve.

- However, if we assume that the magnetic characteristic of the iron core is linear, we do not need to have the above consideration. Instead, we can first find the value of Et induced from F2 from the magnetization characteristic. Then we find the value of Ea induced by F1 from the magnetisation characteristic. We add Et and Ea together to form E1 to balance the voltage V from the infinite busbar.

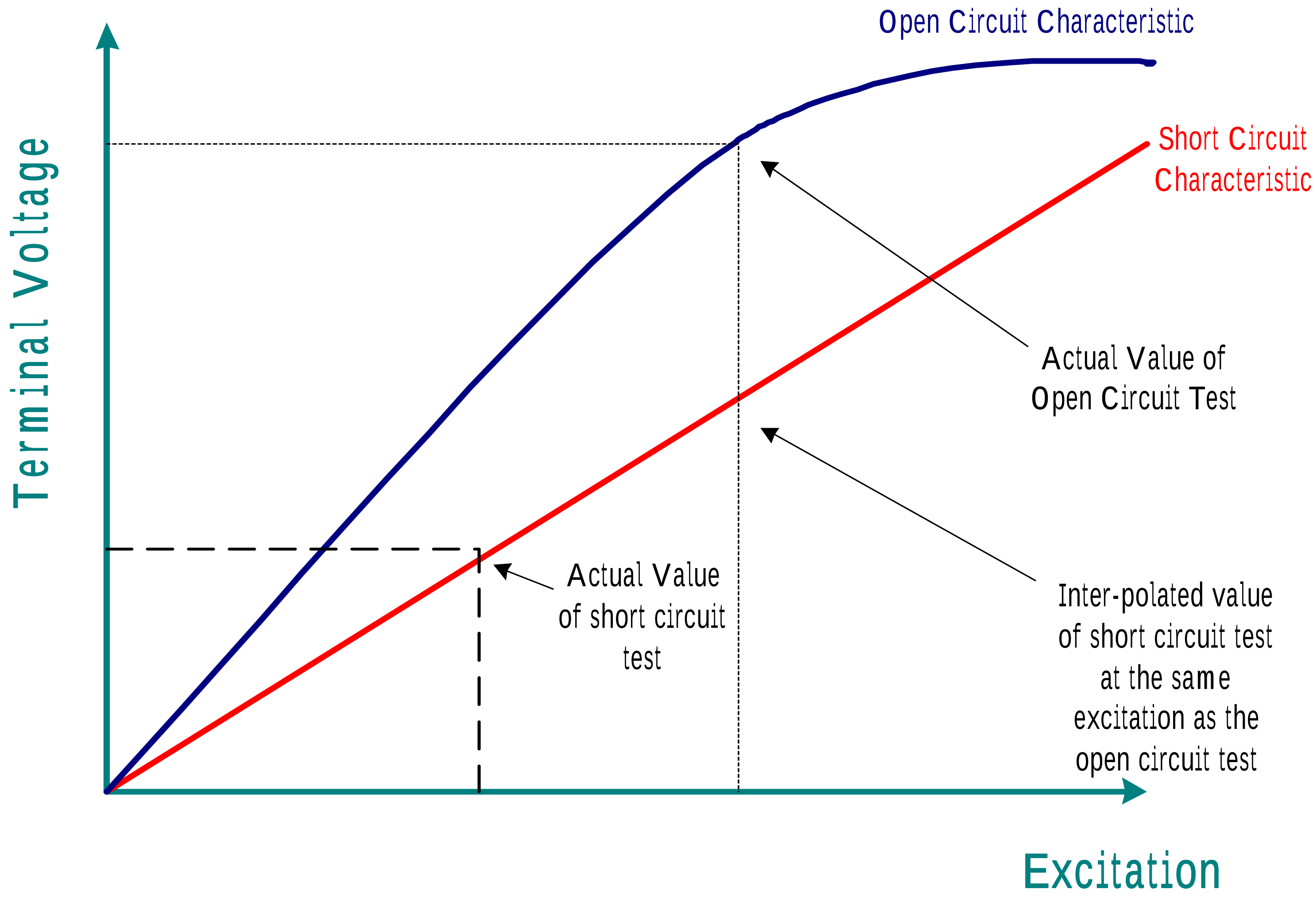
Equivalent circuit for linear analysis of three phase synchronous machine



Open circuit and short circuit test to determine the value of synchronous Impedance

- We can use Ohm's Law to find out the value of the synchronous impedance.
- The open circuit voltage of the synchronous generator is first measured to read Vopen circuit. Then the generator is short circuited to measure Iopen circuit. The value of synchronous impedance is found from Zs = Vopen circuit / Ishort circuit (at the same excitation)
- The curve for short circuit current is always a straight line because during short circuit, the short circuit current is a demagnetizing current. As a result, the magnetic field is never saturated. Hence, we can find the value of Ishort circuit by interpolation even the two tests are not carried out at the same value of excitation.

Graphical method to determine the value of synchronous impedance



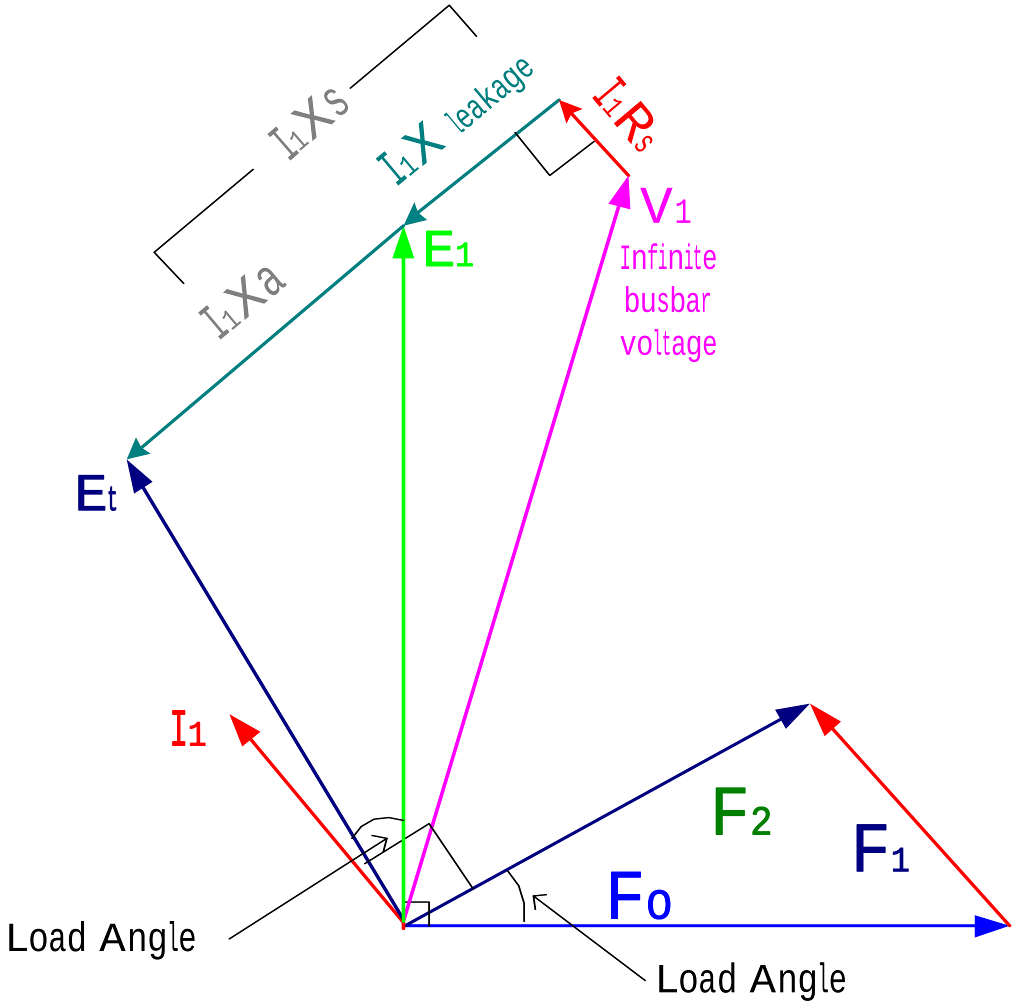
E.m.f. phasor diagram

- We often use e.m.f. phasor diagram to illustrate the phase relationship between the various phasors in a synchronous generator

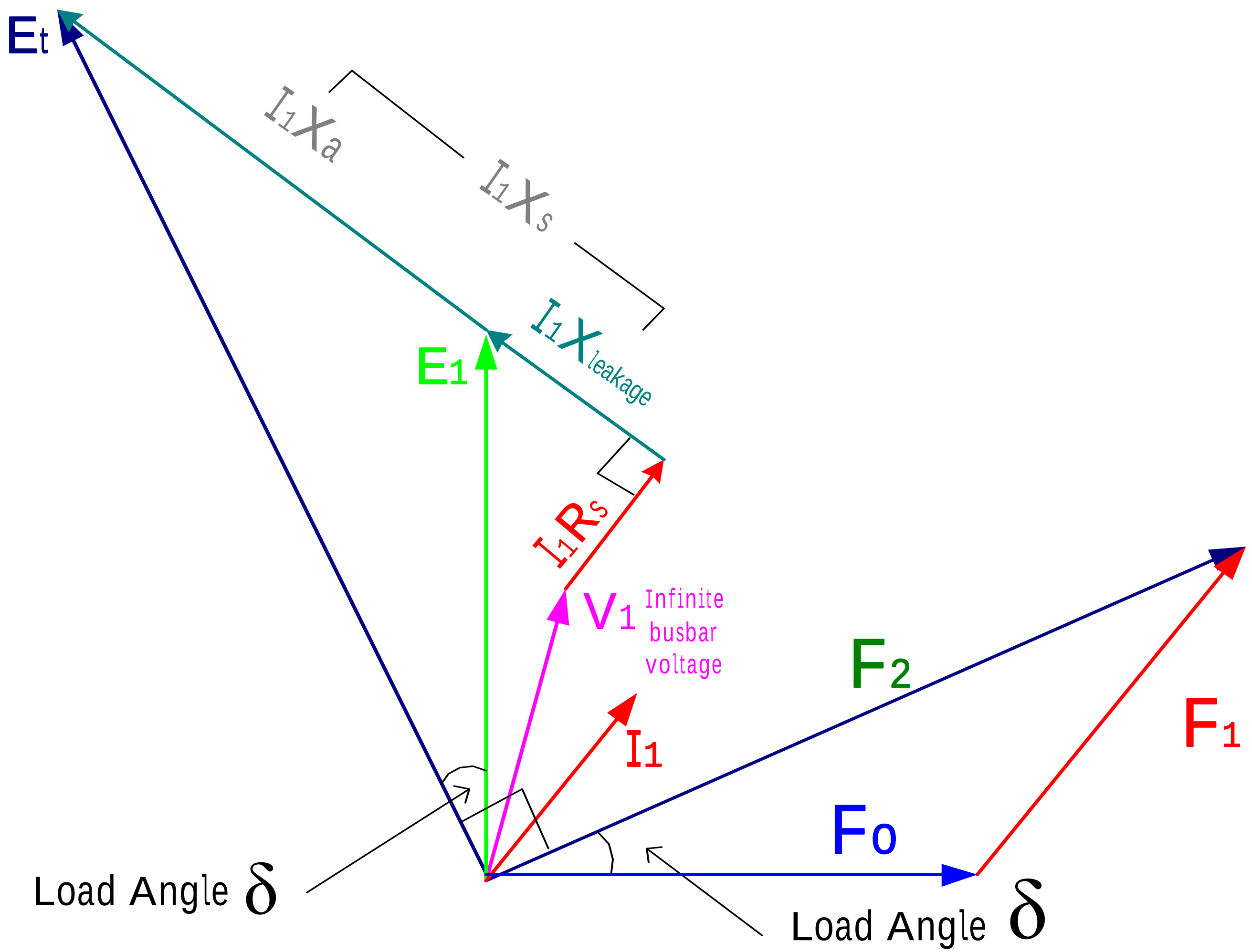
- For a generator, the generator internal voltage E_t is (physically) larger than the infinite busbar voltage V,
  - $E_t = E_1 + I_1X_a$
  - $E_1 = V + I_1 R_s + I_1 X$ leakage
  - $E_t = V + I_1 R_s + I_1 X_a + I_1 X$ leakage

- In fact the actual value of E_t may be smaller than the actual value of V as in the case of an under-excited generator where the stator current is leading

E.m.f. phasor diagram of under excited synchronous generator



E.m.f. phasor diagram of over-excited synchronous generator



Load angle of a synchronous generator

- The load angle δ of a synchronous generator is the physical mechanical angle between the stator rotating field and the rotor axis

- This angle is very important for a generator, if the angle approaches the limiting angle of 90 degrees, than the machine will become unstable as further increase in the electrical load will render the generator out of synchronism

- Since the rotor axis is directly related to F2 or Et and the stator rotating field is directly related to Fo or E1, the load angle is equal to the phase angle between F2 and Fo. Similarly, the load angle is also equal to the angle between Et and E1. For approximation purposes we take the load angle as the angle between V and Et

Alternative e.m.f. phasor diagram

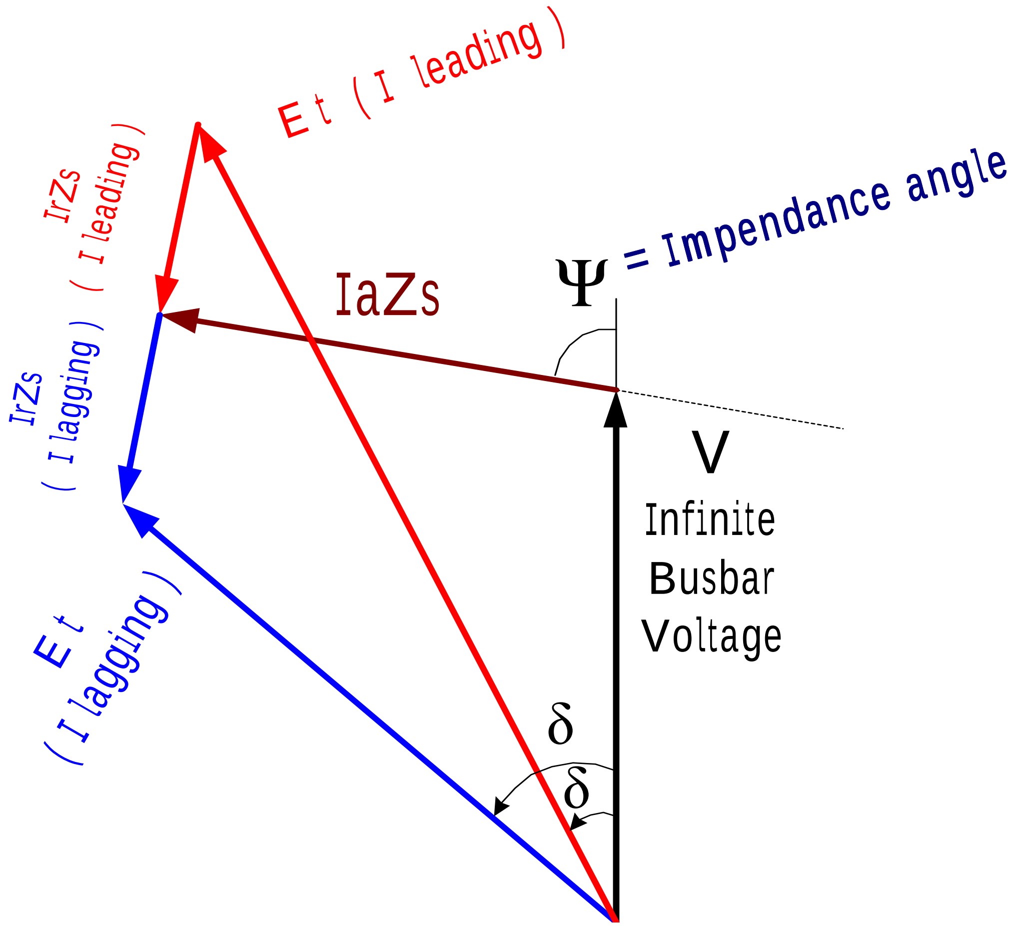
- Instead of breaking the synchronous impedance into synchronous reactance and synchronous resistance. We can breakdown the stator current into active and reactive current components, while at the same time we do not resolve synchronous impedance
- Instead of writing the equation $E_t = V + I_1 Rs + I_1 Xs$

  We can write the equation as $Et = V\angle 0° + IaZs\angle\Psi + IrZs\angle\Psi \pm 90°$

  Where $\Psi =$ Impedance angle $= Tan^{-1}\dfrac{Xs}{Rs}$ **+** = leading, **-** = lagging

- If we draw e.m.f. phasor diagrams according to this formula, we can use it to calculate synchronous generator problems easily since active and reactive power are separately dealt with

Alternative E.m.f. phasor diagram of synchronous generator



Voltage Regulation for a synchronous generator

- Voltage regulation for a synchronous generator is defined as the change in terminal voltage when rated load in kVA at a given power factor is removed, the field excitation remains constant
- Per Cent Regulation $= \frac{Et - V_{full-load}}{V_{full-load}} \times 100\ \%$

- Et is the voltage caused by the rotor excitation

  V is the rated full load voltage, which is usually the voltage at the infinite busbar

Mathematic formula for voltage Regulation

- From the following phasor diagrams, we observe that the voltage regulation for a synchronous generator is given by:
- i) Lagging power factor

$$Et = \sqrt{(V_{full-load} \times Cos\phi + I \times Rs)^2 + (V_{full-load} \times Sin\phi + I \times Xs)^2}$$

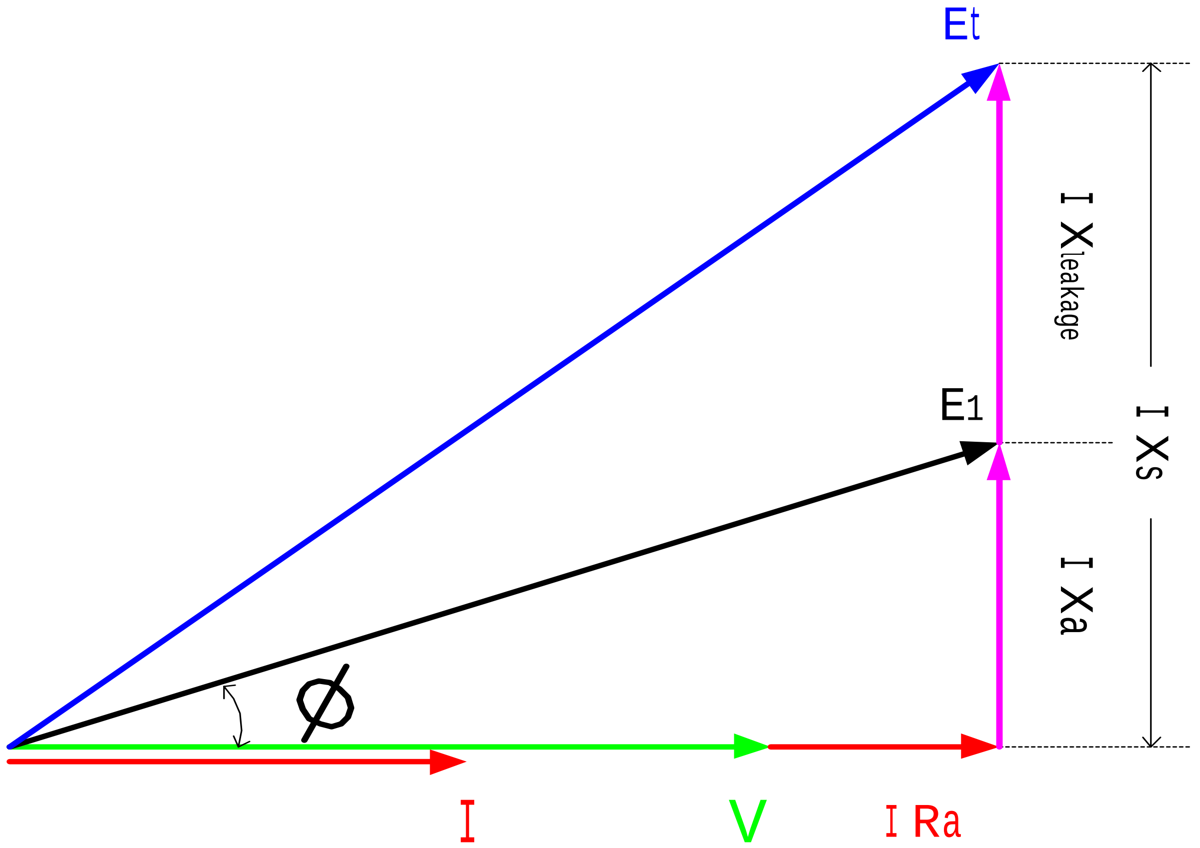
- ii) Leading power factor

$$Et = \sqrt{(V_{full-load} \times Cos\phi + I \times Rs)^2 + (V_{full-load} \times Sin\phi - I \times Xs)^2}$$

- iii) unity power factor

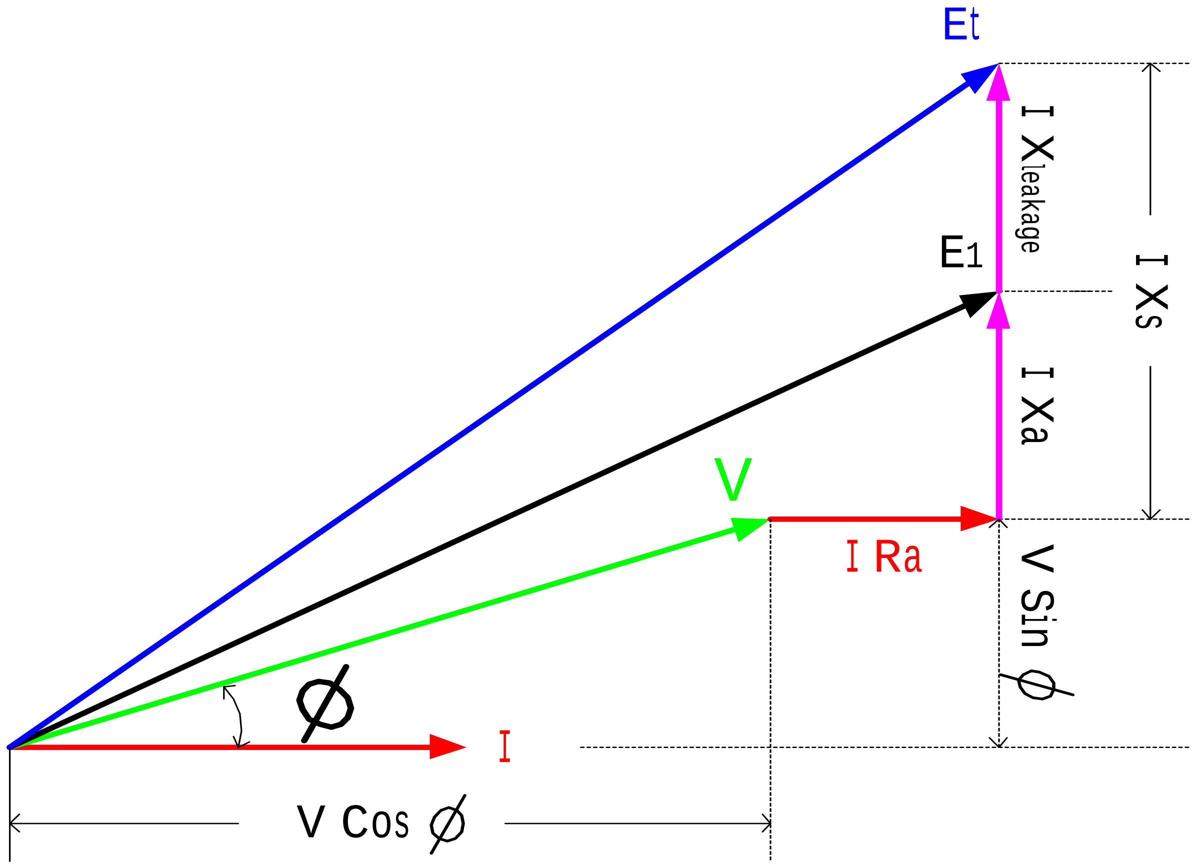
$$Et = \sqrt{(V_{full-load} + I \times Rs)^2 + (I \times Xs)^2}$$

Calculation of voltage regulation-Unity Power Factor



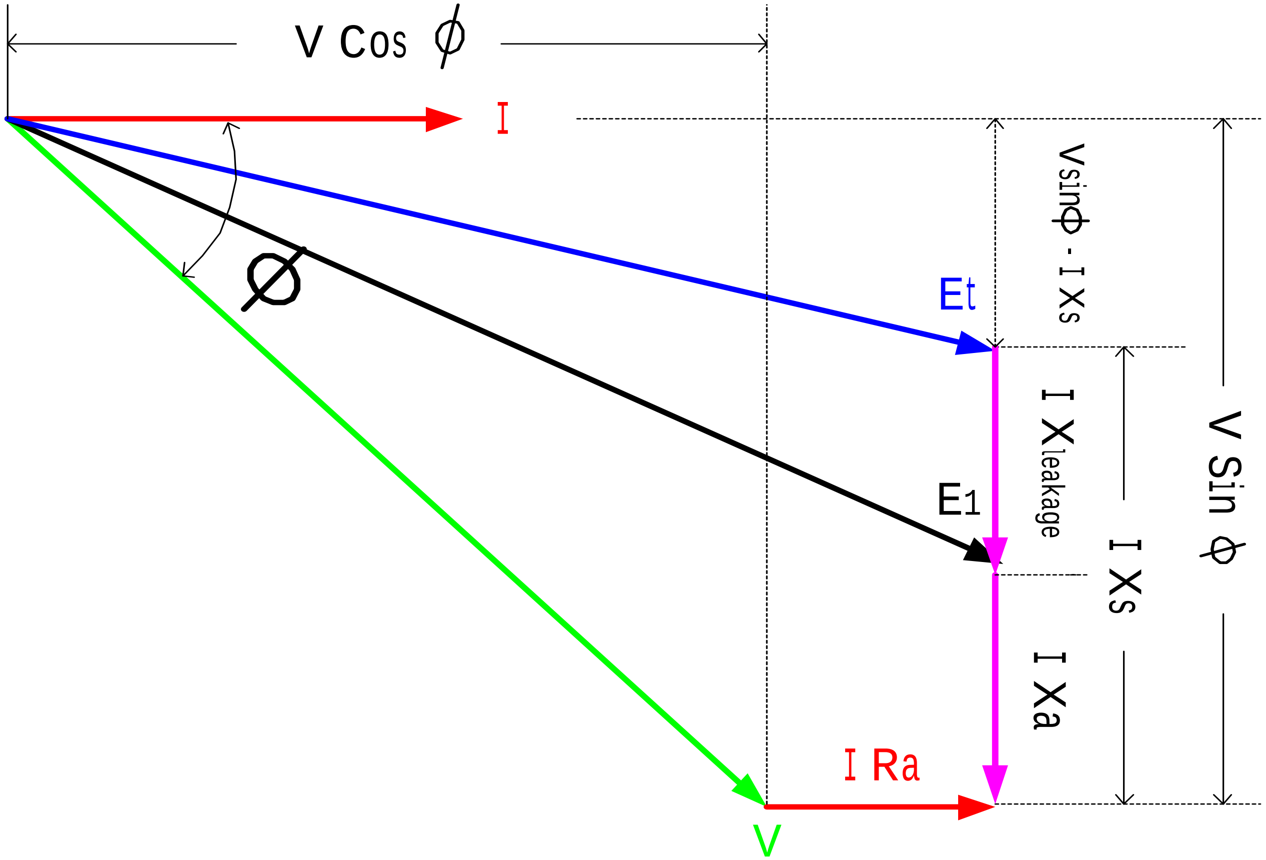
$$Et = \sqrt{\left(V_{full\ -\ load} + I \times Rs\right)^2 + \left(I \times Xs\right)^2}$$

Calculation of voltage regulation-lagging power factor



$$Et = \sqrt{(V_{full-load} \times Cos\phi + I \times Rs)^2 + (V_{full-load} \times Sin\phi + I \times Xs)^2}$$

Calculation of voltage regulation-leading power factor



$$Et = \sqrt{(V_{full-load} \times Cos\phi + I \times Rs)^2 + (V_{full-load} \times Sin\phi - I \times Xs)^2}$$