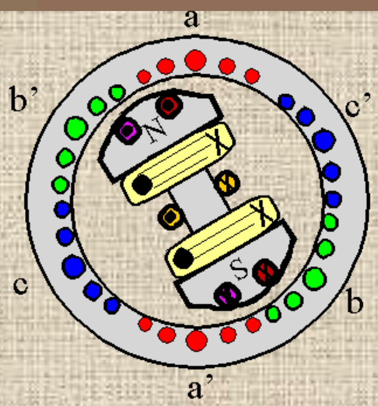
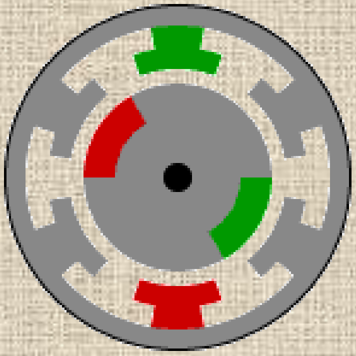
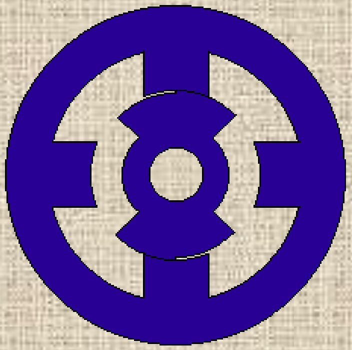
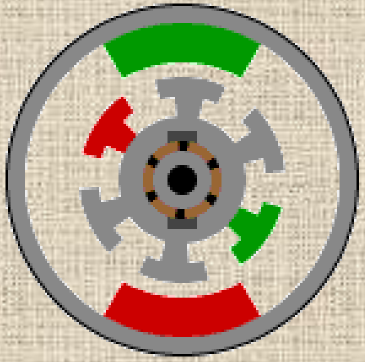
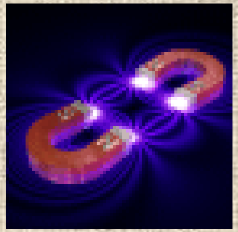


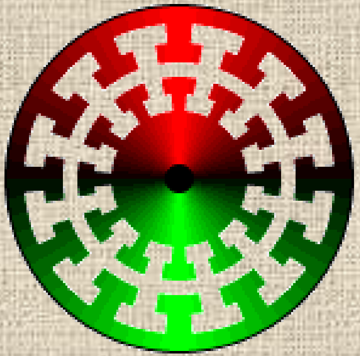




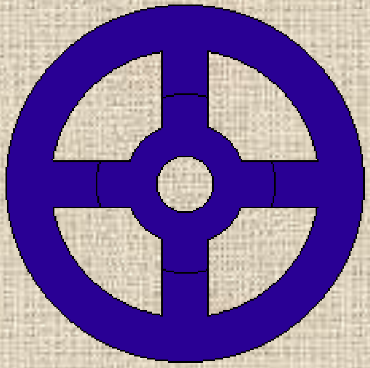


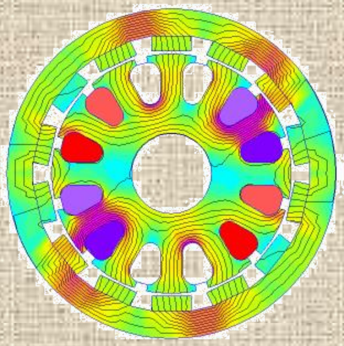


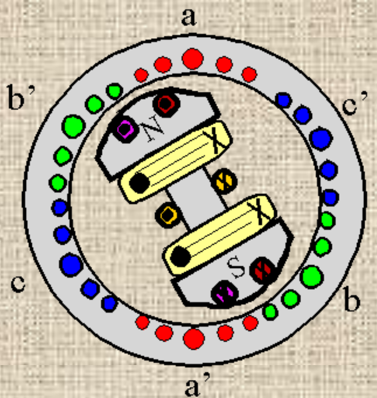
EE552 ELECTRICAL MACHINES III

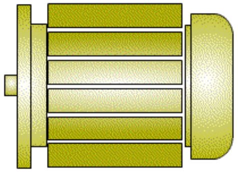


LECTURE 15

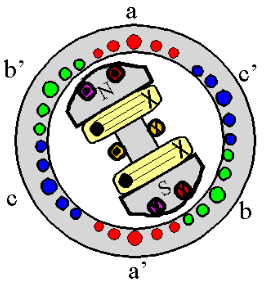








LECTURE NOTES

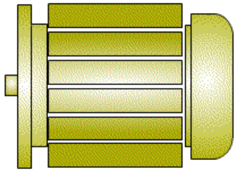


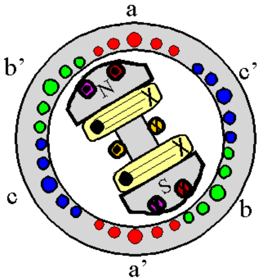
ELECTRICAL MACHINES III

EE552

SPRING 2018

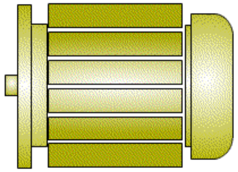
Dr : MUSTAFA AL-REFAI



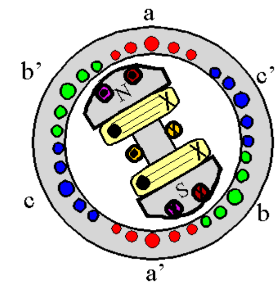


LECTURE 15

SYNCHRONOUS GENERATOR



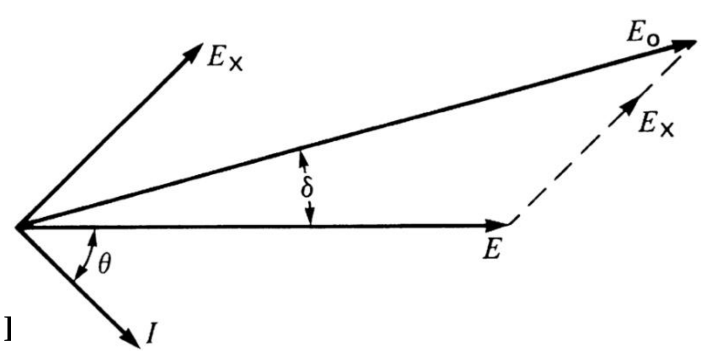
Synchronous generator under load

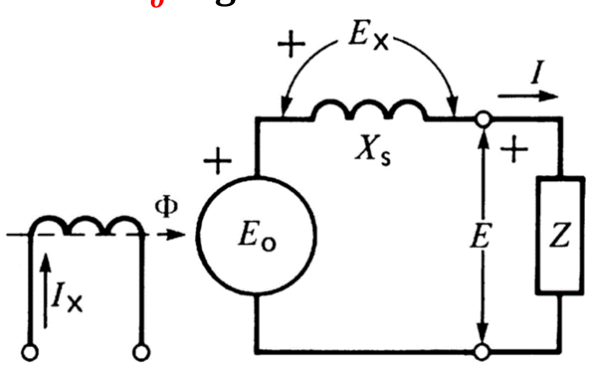


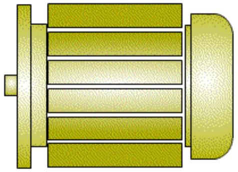
- Behavior of a synchronous generator depends upon the type of load it has to supply. Loads, can be of two basic categories:
  1) Isolated loads, supplied by a single generator 2) The infinite bus
- For isolated loads; Consider a generator that supplies power to a load with a lagging *pf*. For phasor diagram, we list the following facts:

1) Current I lags behind terminal voltage E by an angle θ.
2) Cosine θ = power factor of the load.
3) Voltage E_x across the synchronous reactance leads current I by $90°$. Given by the expression $E_x = jIX_s$.
4) Voltage E_o generated by the flux Φ is equal to the phasor sum of $E + E_s$.
5) Both E_o and E_x are voltages that exist inside the synchronous generator windings and cannot be measured directly.
6) Flux Φ is that produced by the dc exciting current I_x

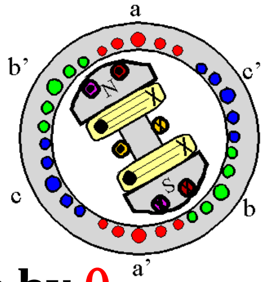
- Phasor diagram shows E_o leads E by δ degrees & E_o is greater than E



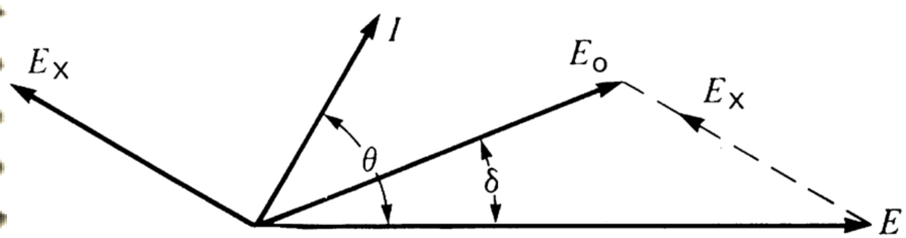


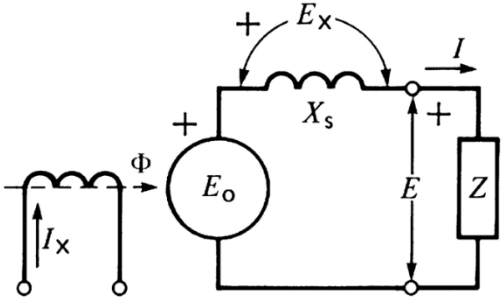


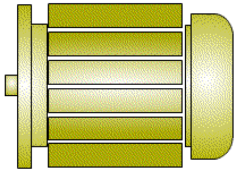
Synchronous generator under load



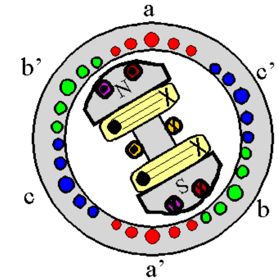
- If the load is capacitive, current *I* leads the terminal voltage by θ.
- In the new phasor diagram, the voltage E_x across the synchronous reactance is still 90° ahead of the current.
- E_o is again equal to the phasor sum of E and E_x.
- The terminal voltage is now *greater* than the induced voltage E_o, which is a very surprising result.
- The inductive reactance X_s enters into partial resonance with the capacitive reactance of the load.
- It may appear we are getting something for nothing, the higher terminal voltage does not yield any more power.
- If the load is entirely capacitive, a very high terminal voltage can be produced with a small exciting current.



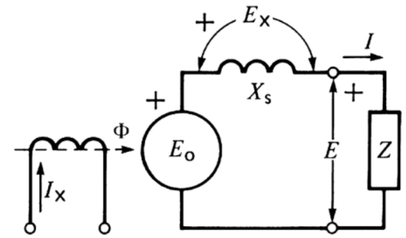




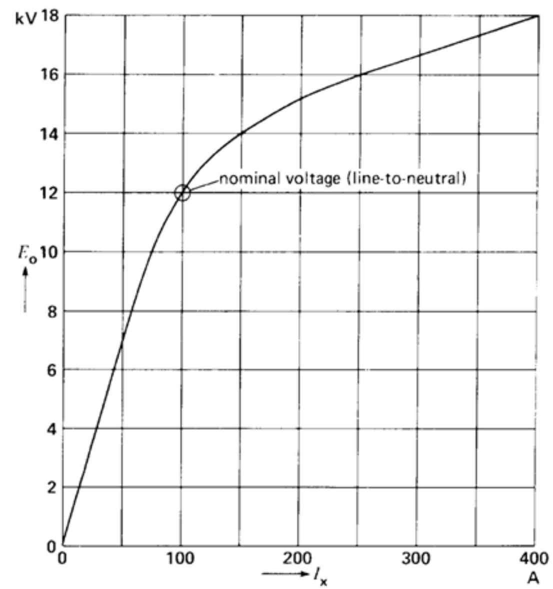
Example



A 36 MVA, 20.8 kV, 3-phase alternator has a synchronous reactance of 9Ω and a nominal current of 1 kA. The no-load saturation curve giving the relationship between E_O and I_x is given. If the excitation is adjusted so that the terminal voltage remains fixed at 21 kV, calculate the exciting current required and draw the phasor diagram for the following conditions:



a) No-load
b) Resistive load of 36 MW
a) Capacitive load of 12 Mvar



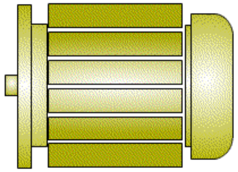
We shall immediately simplify the circuit to show only one phase. The line-to-neutral terminal voltage for all cases is fixed at

$$E = 20.8/\sqrt{3} = 12\text{ kV}$$

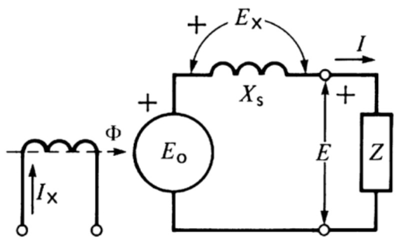
a) At no-load there is no voltage drop in the synchronous reactance; consequently,

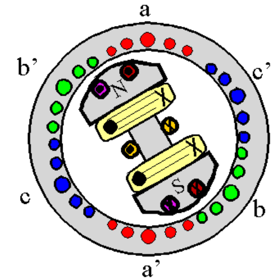
$$E_o = E = 12\ kV$$

Excitation current : $I_x = 100\ A$



Example





b) With a resistive load of 36 MW:

The power per phase is: ***P = 36/3 = 12 MW***

The full-load line current is: ***I = P/E = 12 x*** $\boldsymbol{10^6}$***/12 000 = 1000 A = 1kA***

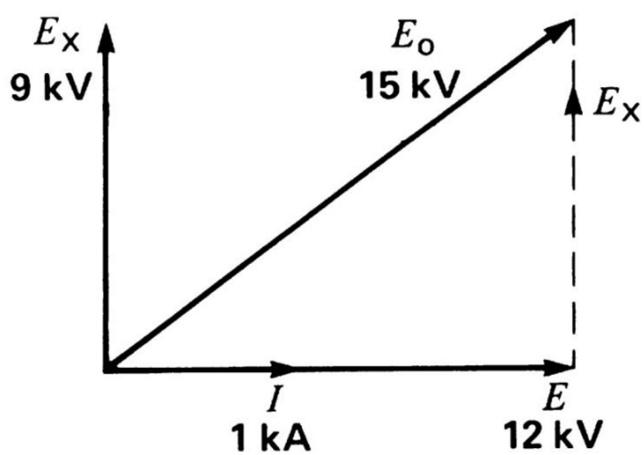
Current is in phase with the terminal voltage. The voltage across X_s **is**

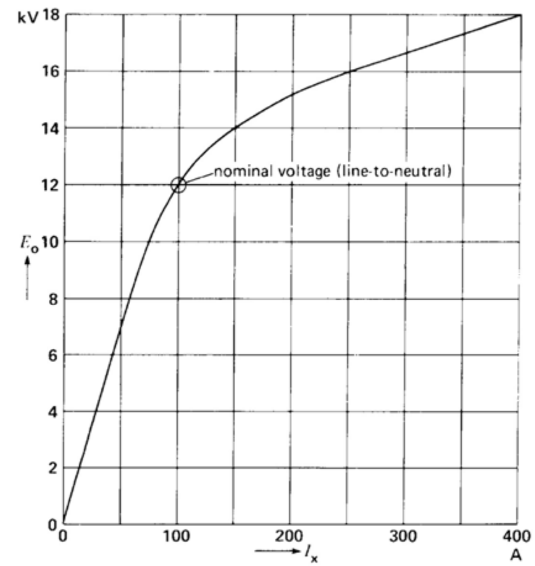
$$E_x = jIX_s = j1000 \times 9 = 9\ kV \angle 90°$$

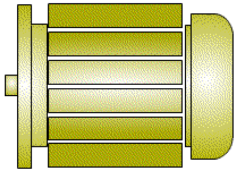
This voltage is 90° ahead of ***I*****. The voltage** E_0 **generated by** I_x **is equal to the phasor sum of** ***E*** **and** E_x**. Referring to the phasor diagram, its value is**

$$E_O = \sqrt{E^2 + E_X^2} = \sqrt{12^2 + 9^2} = 15kV$$

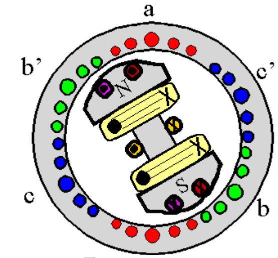
The required exciting current is: $I_x = 200\ A$







Example

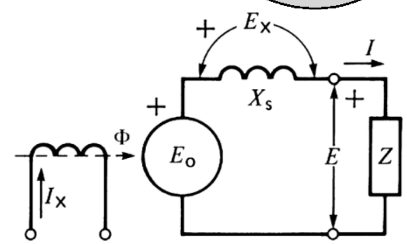


c) **With a capacitive load of 12 Mvar:**

The reactive power per phase is: $Q = 12/3 = 4$ MVAR

$I = Q/E = 4 \times 10^6/12\,000. = 333$ A

The voltage across X_s is : $E_x = jIX_s = j333 \times 9 = 3$ kV $\angle 90^o$



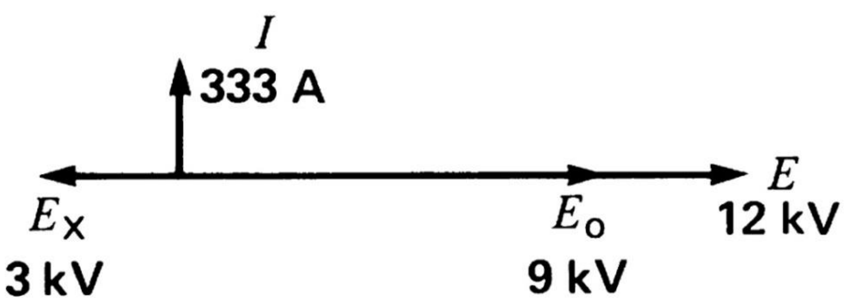
As before E_x leads I by 90°

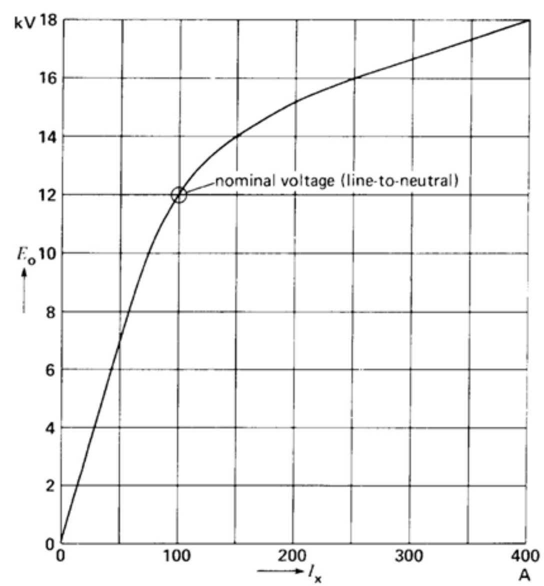
The voltage E_O generated by I_x is equal to the phasor sum of E and E_x.

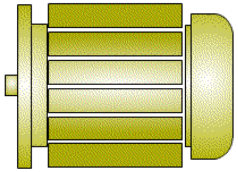
$E_o = E + E_x = 12 + (-3) = 9$kV

The corresponding exciting current is : $I_x = 70$ A

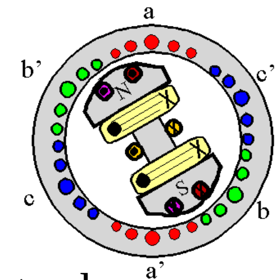
Note that E_O is again less than the terminal voltage E.







The Synchronous generator operating alone: Example



Example 7.2: A 480 V, 60 Hz, Y-connected six-pole synchronous generator has a per-phase synchronous reactance of 1.0 Ω. Its full-load armature current is 60 A at 0.8 PF lagging. Its friction and windage losses are 1.5 kW and core losses are 1.0 kW at 60 Hz at full load. Assume that the armature resistance (and, therefore, the I^2R losses) can be ignored. The field current has been adjusted such that the no-load terminal voltage is 480 V.

a. What is the speed of rotation of this generator?

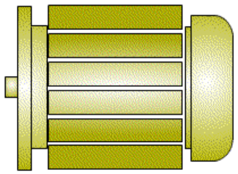
b. What is the terminal voltage of the generator if

   1. It is loaded with the rated current at 0.8 PF lagging;
   2. It is loaded with the rated current at 1.0 PF;
   3. It is loaded with the rated current at 0.8 PF leading.

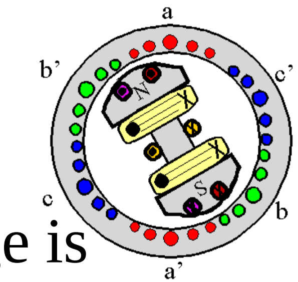
c. What is the efficiency of this generator (ignoring the unknown electrical losses) when it is operating at the rated current and 0.8 PF lagging?

d. How much shaft torque must be applied by the prime mover at the full load? how large is the induced countertorque?

e. What is the voltage regulation of this generator at 0.8 PF lagging? at 1.0 PF? at 0.8 PF leading?



The Synchronous generator operating alone: Example



Since the generator is Y-connected, its phase voltage is

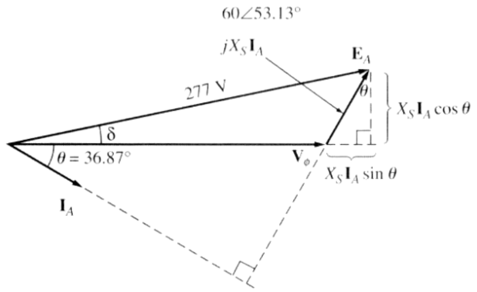
$$V_\phi = V_T / \sqrt{3} = 277\,V$$

At no load, the armature current $I_A = 0$ and the internal generated voltage is $E_A = 277$ V and it is constant since the field current was initially adjusted that way.

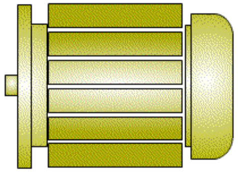
a. The speed of rotation of a synchronous generator is

$$n_m = \frac{120}{P} f_e = \frac{120}{6} 60 = 1200\ rpm$$

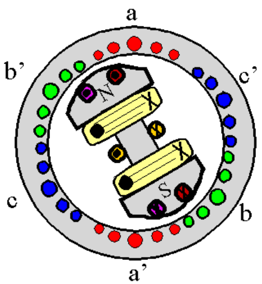
which is $\omega_m = \frac{1200}{60} 2\pi = 125.7\ rad/s$



b.1. For the generator at the rated current and the 0.8 PF lagging, the phasor diagram is shown. The phase voltage is at 0^0, the magnitude of E_A is 277 V,



The Synchronous generator operating alone: Example



and that $jX_S I_A = j \cdot 1 \cdot 60\angle -36.87° = 60\angle 53.13°$

Two unknown quantities are the magnitude of V_ϕ and the angle δ of E_A. From the phasor diagram:

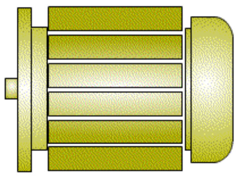
$$E_A^2 = \left(V_\phi + X_S I_A \sin\theta\right)^2 + \left(X_S I_A \cos\theta\right)^2$$

Then:

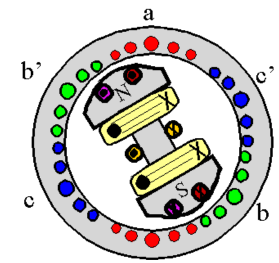
$$V_\phi = \sqrt{E_A^2 - \left(X_S I_A \cos\theta\right)^2} - X_S I_A \sin\theta = 236.8\,V$$

Since the generator is Y-connected,

$$V_T = \sqrt{3} V_\phi = 410\,V$$

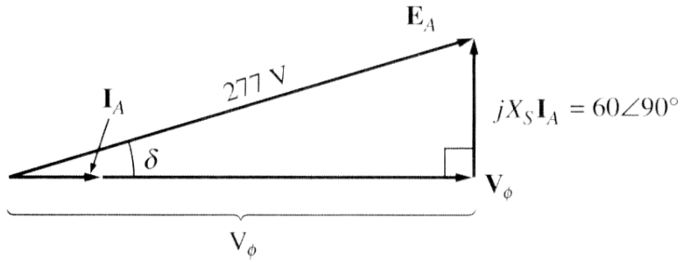


The Synchronous generator operating alone: Example



b.2. For the generator at the rated current and the 1.0 PF, the phasor diagram is shown.

Then:



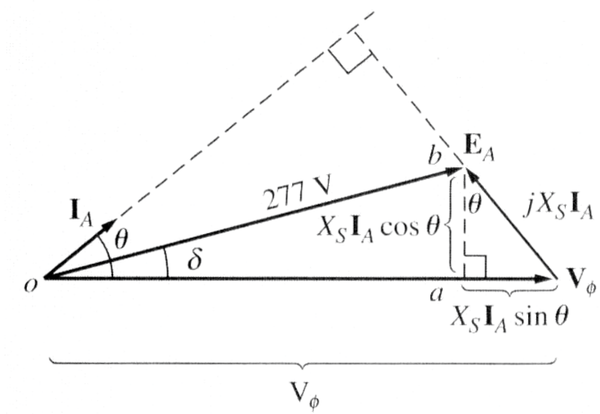
$$V_\phi = \sqrt{E_A^2 - (X_S I_A \cos\theta)^2} - X_S I_A \sin\theta = 270.4V$$

and

$$V_T = \sqrt{3}V_\phi = 468.4V$$

b.3. For the generator at the rated current and the 0.8 PF leading, the phasor diagram is shown.

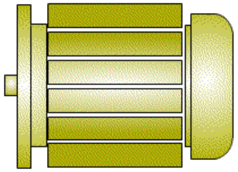
Then:



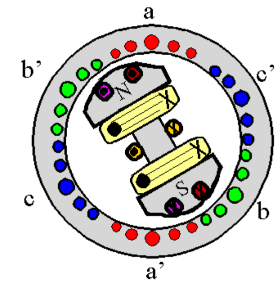
$$V_\phi = \sqrt{E_A^2 - (X_S I_A \cos\theta)^2} - X_S I_A \sin\theta = 308.8V$$

and

$$V_T = \sqrt{3}V_\phi = 535V$$



The Synchronous generator operating alone: Example



c. The output power of the generator at 60 A and 0.8 PF lagging is

$$P_{out} = 3V_{\phi}I_A \cos\theta = 3\cdot 236.8\cdot 60\cdot 0.8 = 34.1\,kW$$

The mechanical input power is given by

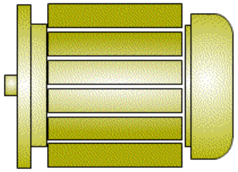
$$P_{in} = P_{out} + P_{elec\,loss} + P_{core\,loss} + P_{mech\,loss} = 34.1 + 0 + 1.0 + 1.5 = 36.6\,kW$$

The efficiency is

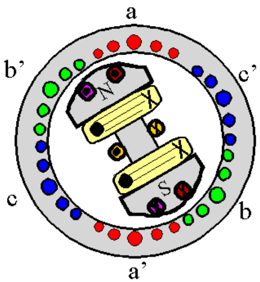
$$\eta = \frac{P_{out}}{P_{in}}\cdot 100\,\% = \frac{34.1}{36.6}\cdot 100\% = 93.2\%$$

d. The input torque of the generator is

$$\tau_{app} = \frac{P_{in}}{\omega_m} = \frac{36.6}{125.7} = 291.2\ \ N\text{-}m$$



The Synchronous generator operating alone: Example



The induced countertorque of the generator is

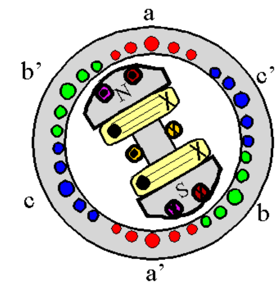
$$\tau_{app} = \frac{P_{conv}}{\omega_m} = \frac{34.1}{125.7} = 271.3 \;\; N\text{-}m$$

e. The voltage regulation of the generator is

Lagging PF: $$VR = \frac{480 - 410}{410} \cdot 100\% = 17.1\%$$

Unity PF: $$VR = \frac{480 - 468}{468} \cdot 100\% = 2.6\%$$

Lagging PF: $$VR = \frac{480 - 535}{535} \cdot 100\% = -10.3\%$$


a
b’
c’
c
b
a’
N
S


PresenterMedia

END OF LECTURE 15