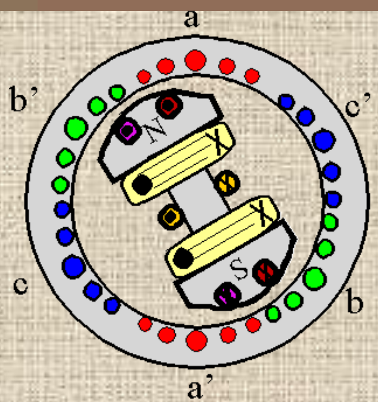
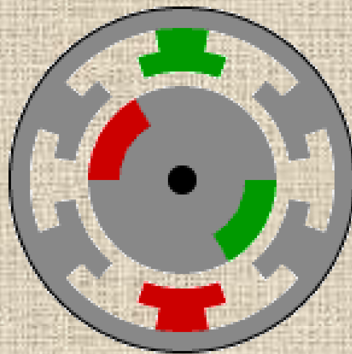
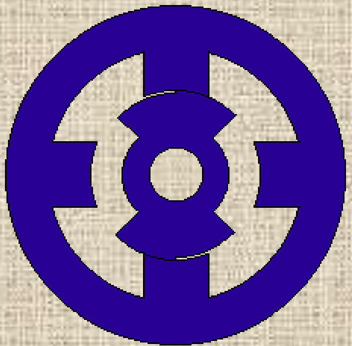
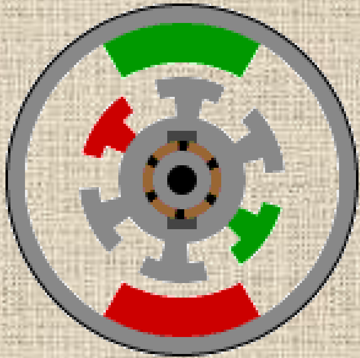
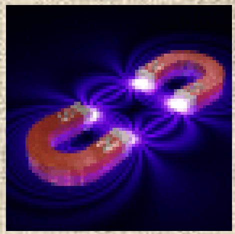
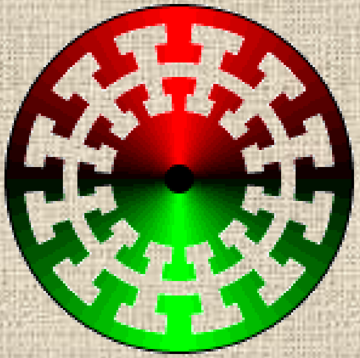


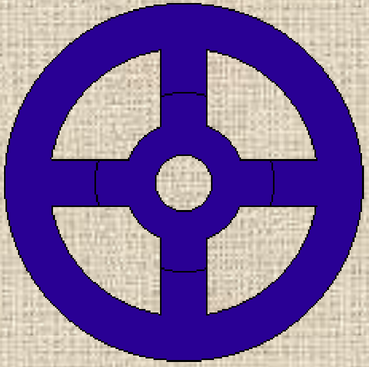
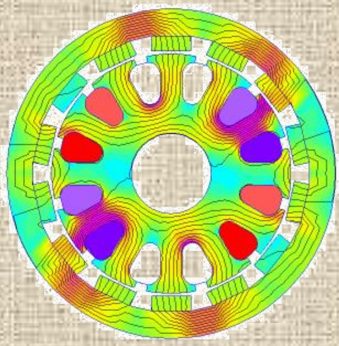
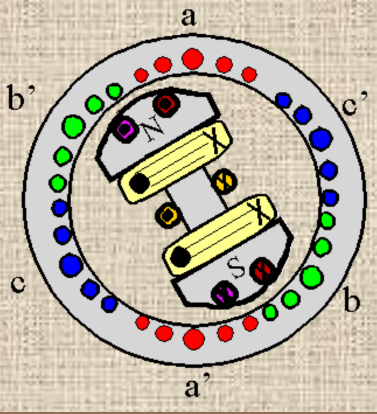




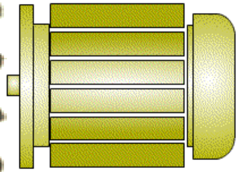


# EE552 ELECTRICAL MACHINES III

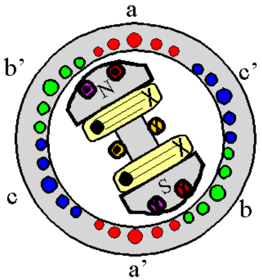


# LECTURE 11



# LECTURE NOTES

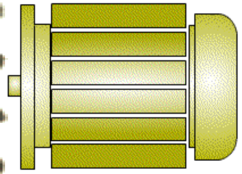


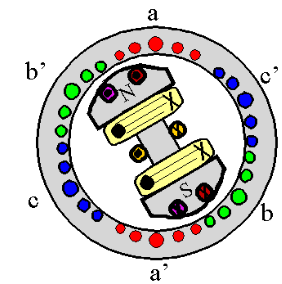

# ELECTRICAL MACHINES III

## EE552

## SPRING 2018

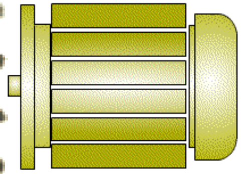
## Dr : MUSTAFA AL-REFAI



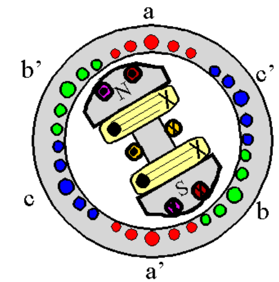



# LECTURE 11

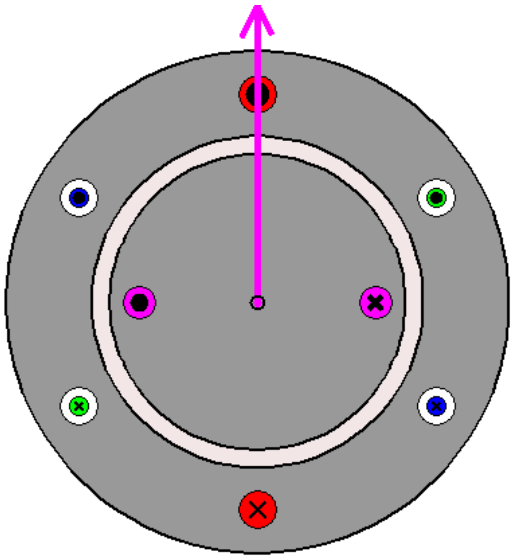
## SYNCHRONOUS GENERATOR



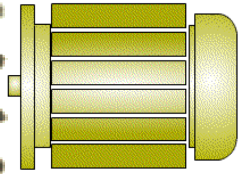
# ALTERNATOR



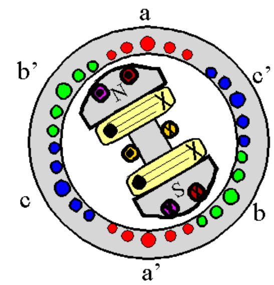

- The elementary 3-phase 2-pole round rotor synchronous generator has a stator equipped with 3 coils displaced $120^{o}$ from each other; although shown as concentrated, they actually are distributed.



- When the rotor is excited with dc and rotated, the resultant field will also rotate so that sinusoidal voltages are generated in the 3 stator phases.

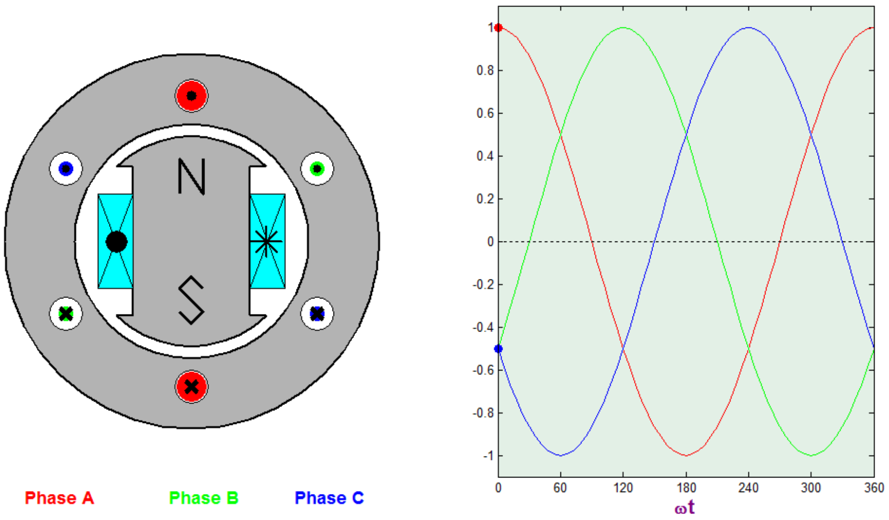


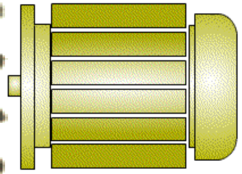
# ALTERNATOR



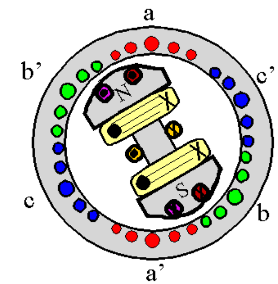

**The elementary 3-phase 2-pole synchronous generator has a stator equipped with 3 coils displaced 120º from each other; although shown as concentrated, they actually are distributed.**

**When the rotor is excited with dc and rotated, the resultant field will also rotate so that sinusoidal voltages are generated in the 3 stator phases, displaced 120º in time and having a frequency directly related to rotor speed.**

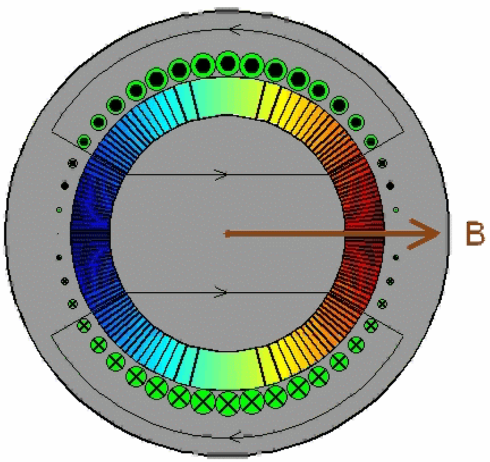




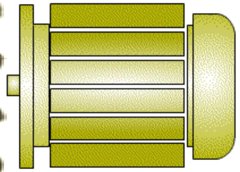
# FLUX PLOT



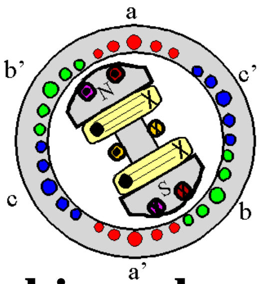

**A rotating sinusoidally distributed winding is excited with a constant current. The flux plot in the air gap also rotates. Where the lines are crowded, the corresponding magnetic field density B is high, and where the concentration of lines is reduced so is B. Thus the air gap B-field is sinusoidally distributed in space and is also rotating. It can be represented by a rotating space vector of constant magnitude pointing to where the field is maximum positive.**



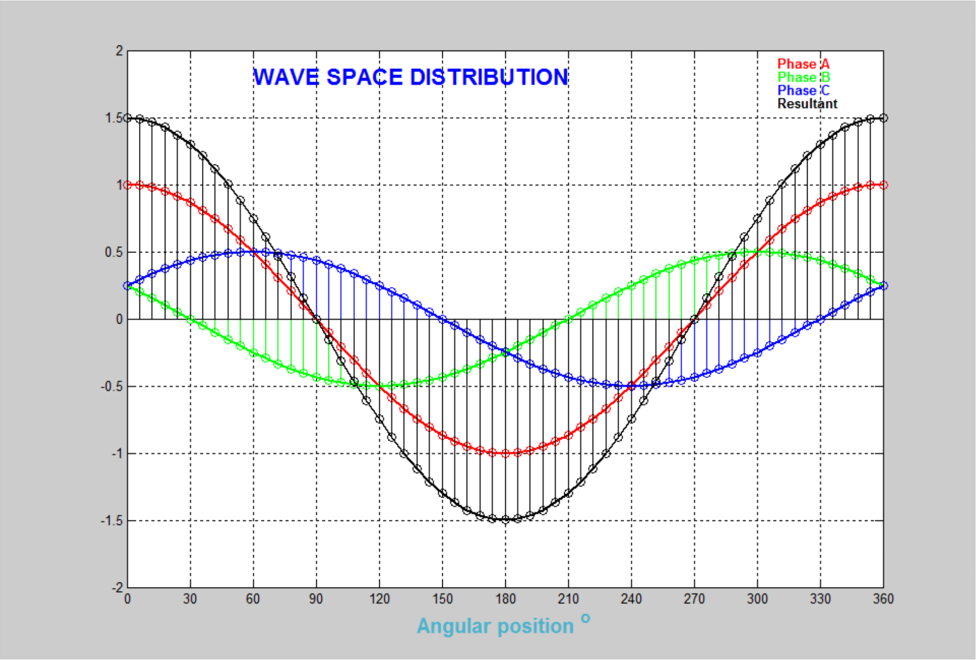

AIR GAP FLUX PLOT

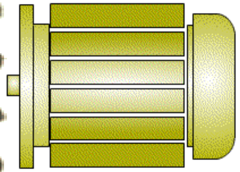


# WAVE SPACE DISTRIBUTIONS

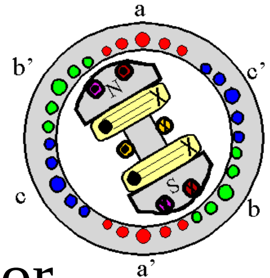



**Under balanced 3-phase sinusoidal excitation of an ac machine, the field space distribution produced by each phase is a sinusoidally distributed pulsating wave centered in its axis. The ABC [RGB] axes are 120$^{o}$ apart. The resultant field (in black) is a traveling wave of constant amplitude moving at a speed which corresponds to the excitation frequency.**





# The induced voltage in a 3-phase set of coils

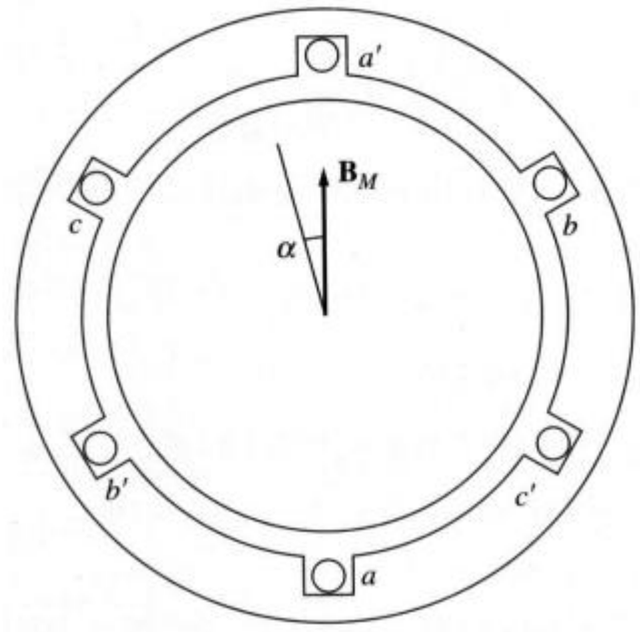



In three coils, each of $N_C$ turns, placed around the rotor magnetic field, the induced in each coil will have the same magnitude and phases differing by 120° :

$$e_{aa'}(t) = N_C \phi \omega_m \cos \omega_m t$$

$$e_{bb'}(t) = N_C \phi \omega_m \cos\left(\omega_m t - 120°\right)$$

$$e_{cc'}(t) = N_C \phi \omega_m \cos\left(\omega_m t - 240°\right)$$

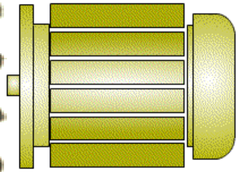



Peak voltage: $E_{\max} = N_C \phi \omega_m$

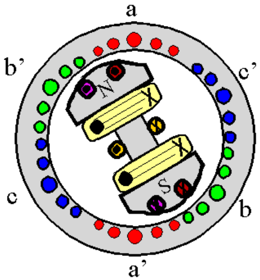
$$E_{\max} = 2\pi N_C \phi f$$

RMS voltage:

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



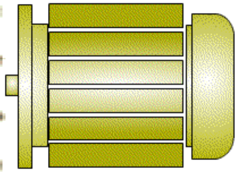
# Synchronous Machines – e.m.f equation



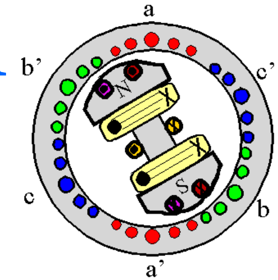

**The magnitude of the e.m.f induced in each stator (armature) winding is given by the flux-linking emf equation for ac fields**

$$E_{rms} = 4.44 K_w f N_a \Phi_p$$

$K_w$ – winding factor = Kp.Kd
f – frequency
$N_a$ – number of stator windings turns per phase
$\Phi_P$ – flux per pole



# SYNCHRONOUS GENERATOR INTERNAL GENERATED VOLTAGE



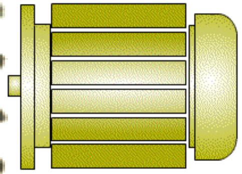

- **Induced voltage depends on flux φ, frequency or speed of rotation f, & machine's construction**
- **Last equation can be rewritten as:**

  $E_A = K\,\varphi\,\omega$

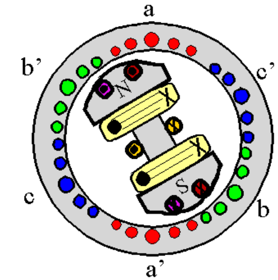
  $K = N_C/\sqrt{2}$ (if $\omega = \omega_e$)

  $K = N_C\,p/\sqrt{2}$ (if $\omega = \omega_m$)

- **Note: $E_A$ proportional to flux & speed, while flux depend on current in rotor winding $I_F$, therefore $E_A$ is related to $I_F$ & its plot named: magnetization curve, or O/C characteristic**



# Internal generated voltage of a synchronous generator

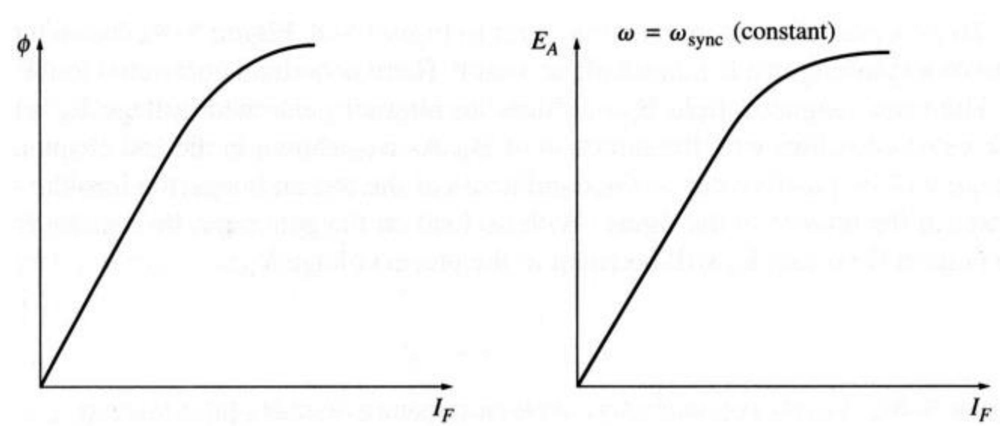



**The magnitude of internal generated voltage induced in a** in one phase **is**

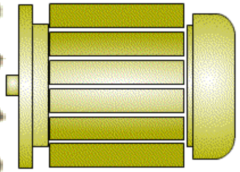
$$E_A = \sqrt{2}\pi N_C \phi f = K\phi\omega$$

**where K is a constant representing the construction of the machine,φ is flux in it and w is its rotation speed.**

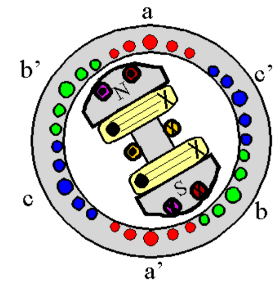
**Since flux in the machine depends on the field current through it, the internal generated voltage is a function of the rotor field current.**




Magnetization curve (open-circuit characteristic) of a synchronous machine

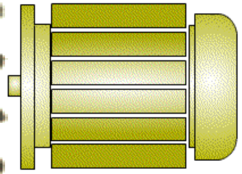


# Equivalent circuit of a synchronous generator

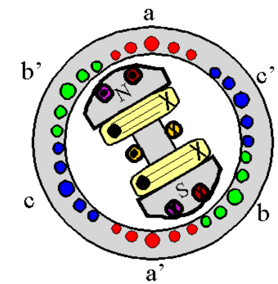



**The internally generated voltage in a single phase of a synchronous machine $E_A$ is not usually the voltage appearing at its terminals. It equals to the output voltage $V_\phi$ only when there is no armature current in the machine. The reasons that the armature voltage $E_A$ is not equal to the output voltage $V_\phi$ are:**

1. **Distortion of the air-gap magnetic field caused by the current flowing in the stator (armature reaction);**
2. **Self-inductance of the armature coils;**
3. **Resistance of the armature coils;**
4. **Effect of salient-pole rotor shapes.**

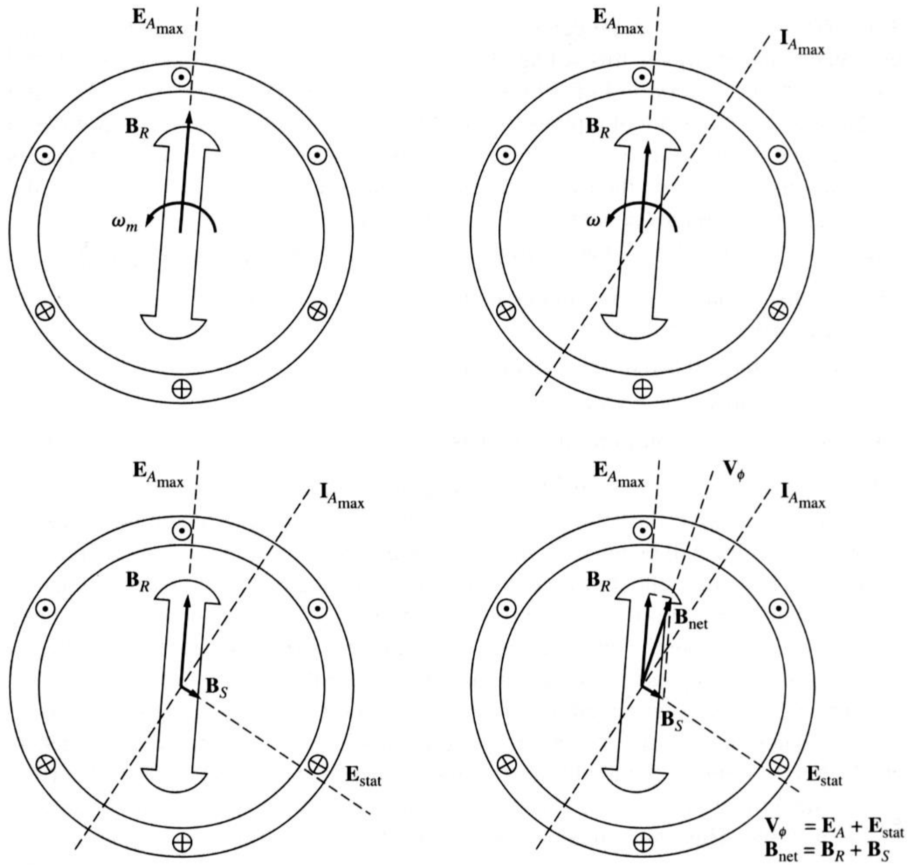


# Equivalent circuit of a synchronous generator cont…

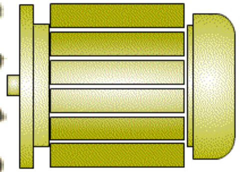



**Armature reaction (the largest effect):**

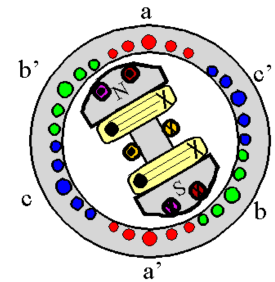
**When the rotor of a synchronous generator is spinning, a voltage $E_A$ is induced in its stator. When a load is connected, a current starts flowing creating a magnetic field in machine's stator. This stator magnetic field $B_S$ adds to the rotor (main) magnetic field $B_R$ affecting the total magnetic field and, therefore, the phase voltage.**




Lagging load



# Equivalent circuit of a synchronous generator cont…




Assuming that the generator is connected to a lagging load, the load current $I_A$ will create a stator magnetic field $B_S$, which will produce the armature reaction voltage $E_{stat}$. Therefore, the phase voltage will be

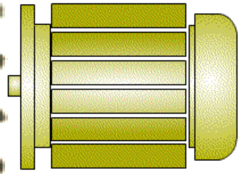
$$V_\phi = E_A + E_{stat}$$

The net magnetic flux will be

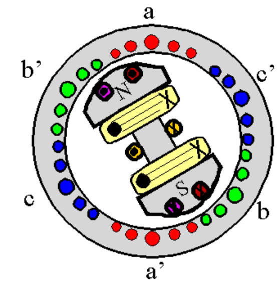
$$B_{net} = B_R + B_S$$

Rotor field Stator field

Note that the directions of the net magnetic flux and the phase voltage are the same.



# Equivalent circuit of a synchronous generator cont…

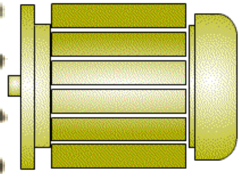



## Self inductance

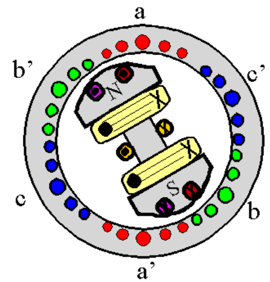
With a cylindrical stator, the self-inductance of the field winding is independent of the rotor position $\theta_m$ when the harmonic effects of stator slot openings are neglected. Hence

$$\mathrm{L}_{ff} = L_{ff\,0} + L_{fl}$$

**where the italic L is used for an inductance which is independent of $\mathrm{L}_{ff}$. The component $L_{ff\,0}$ corresponds to that portion of $\theta_{me}$ due to the space-fundamental component of air-gap flux.**



# Equivalent circuit of a synchronous generator cont…

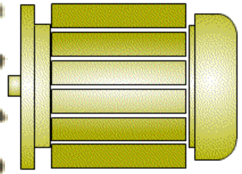



## Stator-to-Rotor Mutual Inductances

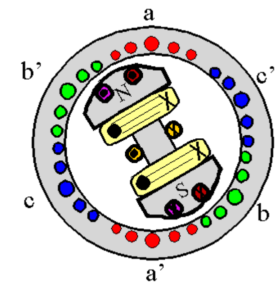
The stator-to-rotor mutual inductances vary periodically with 0me, the electrical angle between the magnetic axes of the field winding and the armature phase a as shown in In next fig. With the space-mmf and air-gap flux distribution assumed sinusoidal, the mutual inductance between the field winding f and phase a varies as $\cos\theta_{me}$ ; thus

$$\mathrm{L}_{af} = \mathrm{L}_{fa} = L_{af} \cos\theta_{me}$$

Similar expressions apply to phases b and c, with $\theta_{me}$ replaced by $\theta_{me}$ - 120 ° and $\theta_{me}$ +120 °, respectively.



# Equivalent circuit of a synchronous generator cont…

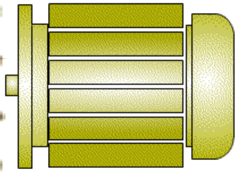



**With the rotor rotating at synchronous speed ws, the rotor angle will vary as**

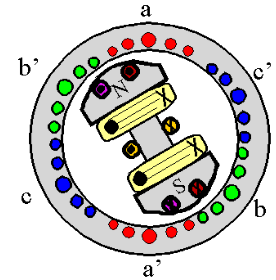
$$\theta_{me} = \frac{p}{2}\theta_m = \omega_e t + \delta_{e0}$$

Here, (poles/2)ws is the electrical frequency

and $\delta_{e0}$ is the electrical angle of the rotor at time t =0.



# SYNCHRONOUS-MACHINE INDUCTANCES; EQUIVALENT CIRCUTS




Mutual inductances:

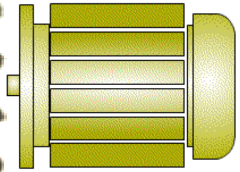
$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = L_{aa0}\cos\frac{2\pi}{3} = -\frac{1}{2}L_{aa0}$$

$$L_{af} = L_{fa} = L_{af}\cos\theta_{me} \qquad \theta_{me} = \frac{p}{2}\theta_m = \omega_e t + \delta_{e0}$$

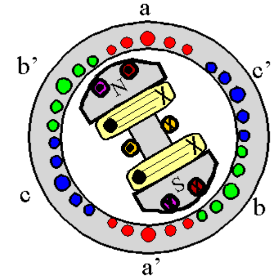
$$L_{af} = L_{fa} = L_{af}\cos(\omega_e t + \delta_{e0})$$

$$L_{bf} = L_{fb} = L_{af}\cos(\omega_e t + \delta_{e0} - \frac{2\pi}{3})$$

$$L_{cf} = L_{fc} = L_{af}\cos(\omega_e t + \delta_{e0} + \frac{2\pi}{3})$$



# SYNCHRONOUS-MACHINE INDUCTANCES; EQUIVALENT CIRCUITS cont…

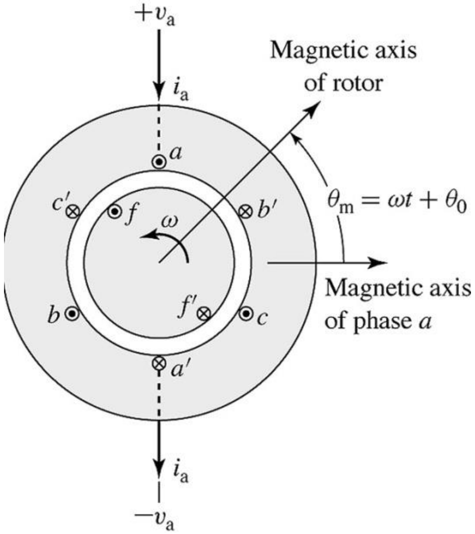



$$\lambda_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + L_{af} i_f$$

$$\lambda_b = L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + L_{bf} i_f$$

$$\lambda_c = L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + L_{cf} i_f$$

$$\lambda_f = L_{fa} i_a + L_{fb} i_b + L_{fc} i_c + L_{ff} i_f$$



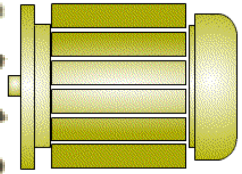

Self inductances:

Fundamental component

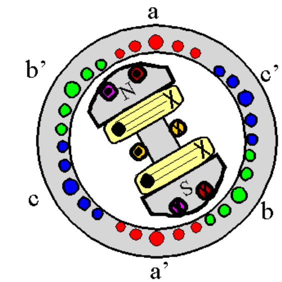
$$L_{aa} = L_{bb} = L_{cc} = L_{aa0} + L_{al}$$

$$L_{ff} = L_{ff0} + L_{fl}$$

Leakage flux component



# SYNCHRONOUS-MACHINE INDUCTANCES; EQUIVALENT CIRCUTS




$$
\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \\ \lambda_f \end{bmatrix} =
\begin{bmatrix}
L_{aa0}+L_{al} & -\frac{1}{2}L_{aa0} & -\frac{1}{2}L_{aa0} & L_{af}\cos(\omega_e t+\delta_{e0}) \\
-\frac{1}{2}L_{aa0} & L_{aa0}+L_{al} & -\frac{1}{2}L_{aa0} & L_{af}\cos(\omega_e t+\delta_{e0}-\frac{2\pi}{3}) \\
-\frac{1}{2}L_{aa0} & -\frac{1}{2}L_{aa0} & L_{aa0}+L_{al} & L_{af}\cos(\omega_e t+\delta_{e0}+\frac{2\pi}{3}) \\
L_{af}\cos(\omega_e t+\delta_{e0}) & L_{af}\cos(\omega_e t+\delta_{e0}-\frac{2\pi}{3}) & L_{af}\cos(\omega_e t+\delta_{e0}+\frac{2\pi}{3}) & L_{ff0}+L_{fl}
\end{bmatrix}
\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix}
$$

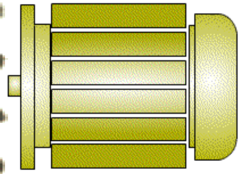
For balanced system $\qquad i_a + i_b + i_c = 0$

$$\lambda_a = (L_{aa0}+L_{al})i_a + \frac{1}{2}L_{aa0}i_a + \mathrm{L}_{af}i_f$$

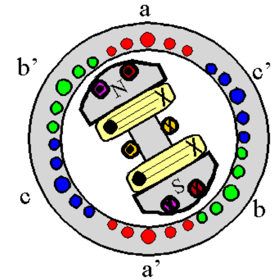
$$\lambda_a = \underbrace{(\frac{3}{2}L_{aa0}+L_{al})}\, i_a + \mathrm{L}_{af}i_f$$

$$\lambda_a = L_s i_a + \mathrm{L}_{af}i_f$$

$L_s$ : Defined as synchronous inductance. It is the effective inductance seen by phase a under steady state balanced conditions.



# EQUIVALENT CIRCUTS




Terminal voltage for phase a

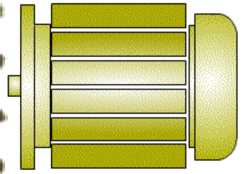
$$v_a = R_a i_a + \frac{d\lambda_a}{dt} = R_a i_a + L_s \frac{di_a}{dt} + \frac{d(\mathrm{L}_{af} i_f)}{dt} = R_a i_a + L_s \frac{di_a}{dt} + e_{af}$$

$$\mathrm{L}_{af} = L_{af} \cos(\omega_e t + \delta_{e0})$$

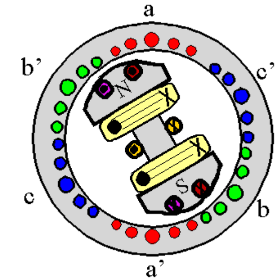
$$e_{af} = -\omega_e L_{af} I_f \sin(\omega_e t + \delta_{e0}) \qquad E_{af} = \frac{\omega_e \mathrm{L}_{af} I_f}{\sqrt{2}}$$

In complex form:

$$\hat{E}_{af} = j \frac{\omega_e \mathrm{L}_{af} I_f}{\sqrt{2}} e^{j\delta_{e0}}$$



# EQUIVALENT CIRCUTS

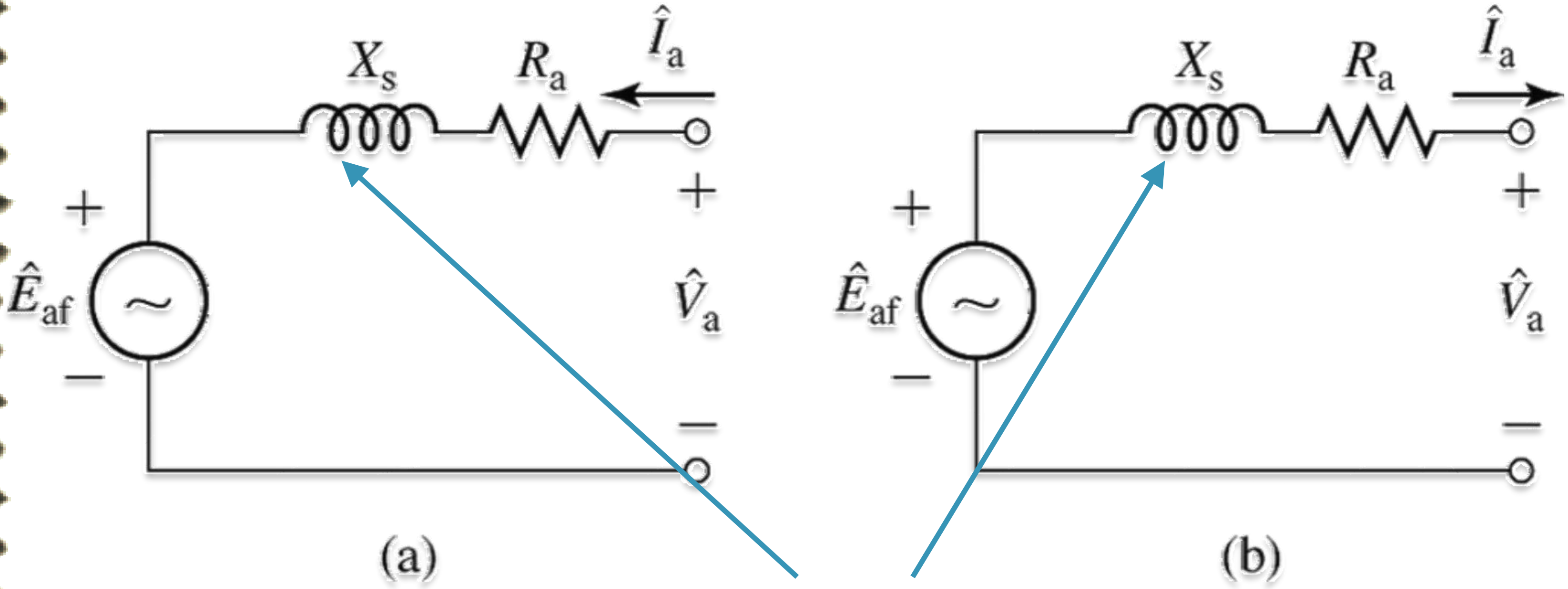



**Motor:**

$$\hat{V}_a = R_a \hat{I}_a + j\,X_s \hat{I}_a + \hat{E}_{af}$$

**Generator:**

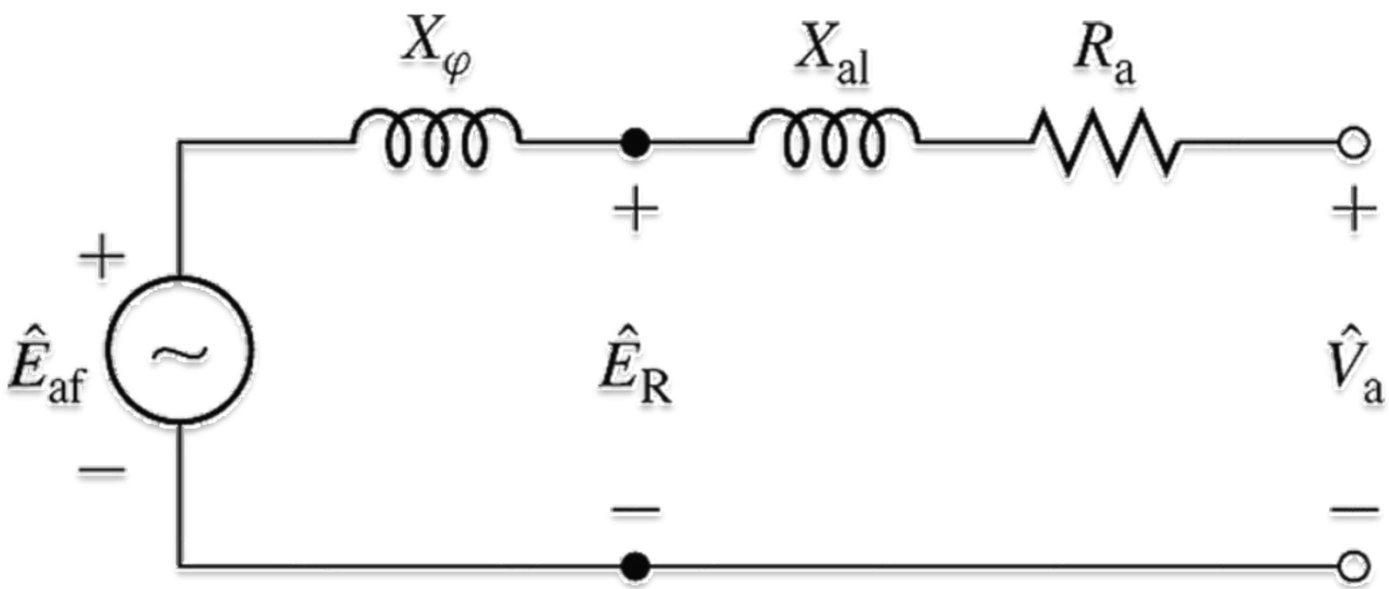
$$\hat{V}_a = \hat{E}_{af} - R_a \hat{I}_a - j\,X_s \hat{I}_a$$

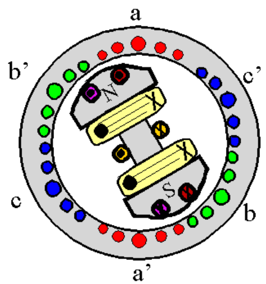



Synchronous Reactance

# EQUIVALENT CIRCUTS

**Synchronous-machine equivalent circuit showing air-gap and leakage components of synchronous reactance and air-gap voltage.**




a
b'
c'
N
S
c
b
a'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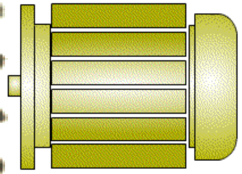

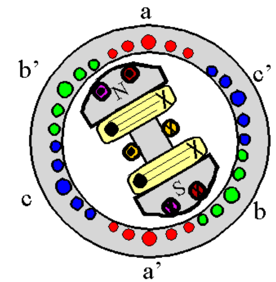
a
b’
c’
N
S
c
b
a’


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# END of LECTURE 11