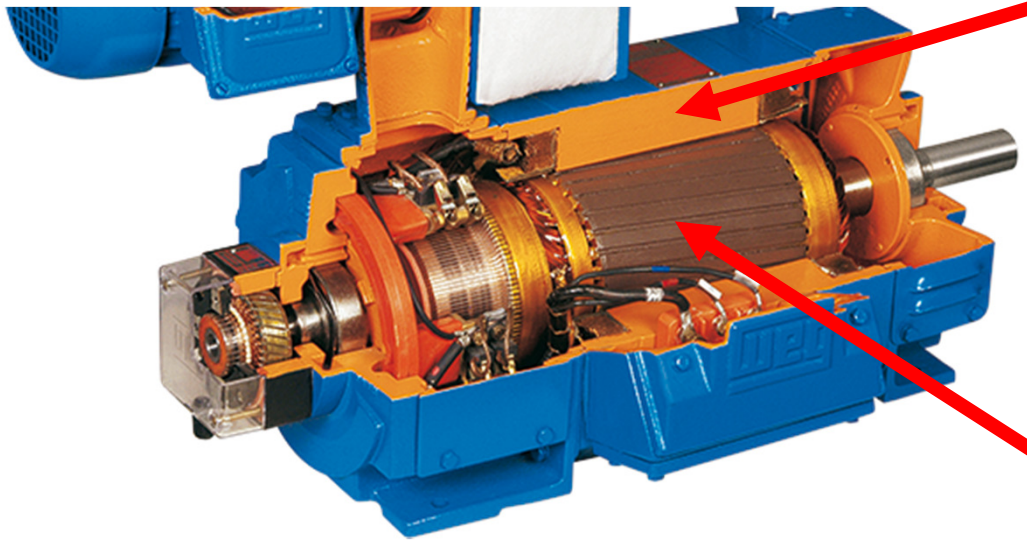
Máquinas Elétricas

- CC
- CA
  - Assíncronas (Indução)
    - **Estator**
  - Síncronas

Definição

- Circuito de Campo
  - Produz o campo magnético principal
- Circuito de Armadura
  - Circuito imerso no campo principal

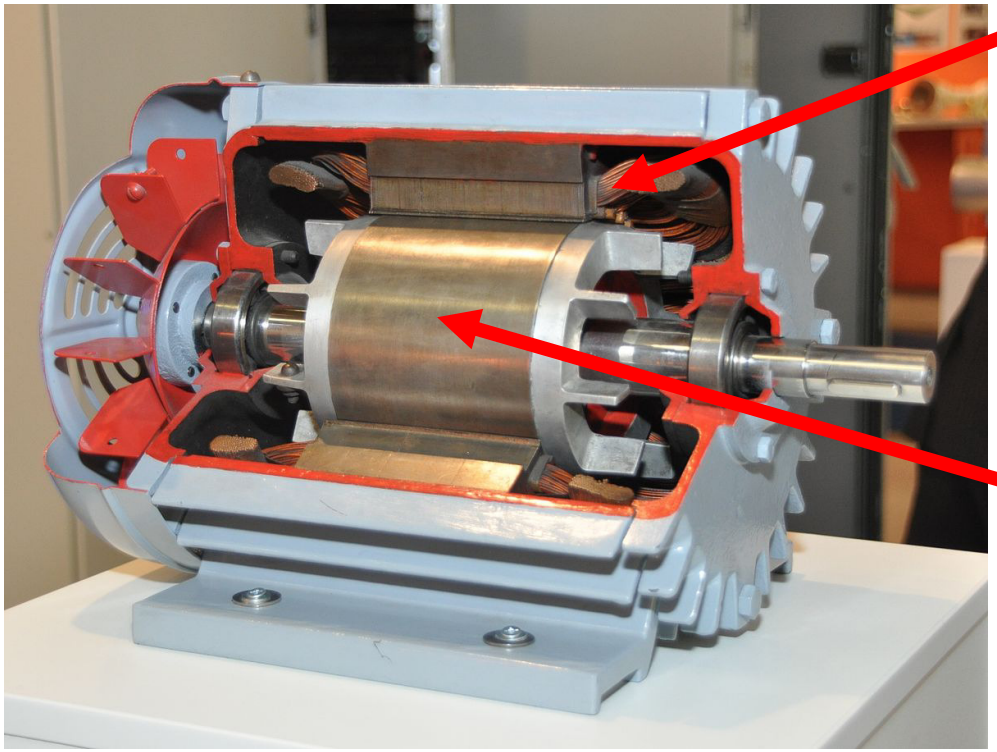
Máquinas CC



Circuito de Campo: Estator

Circuito de Armadura: Rotor

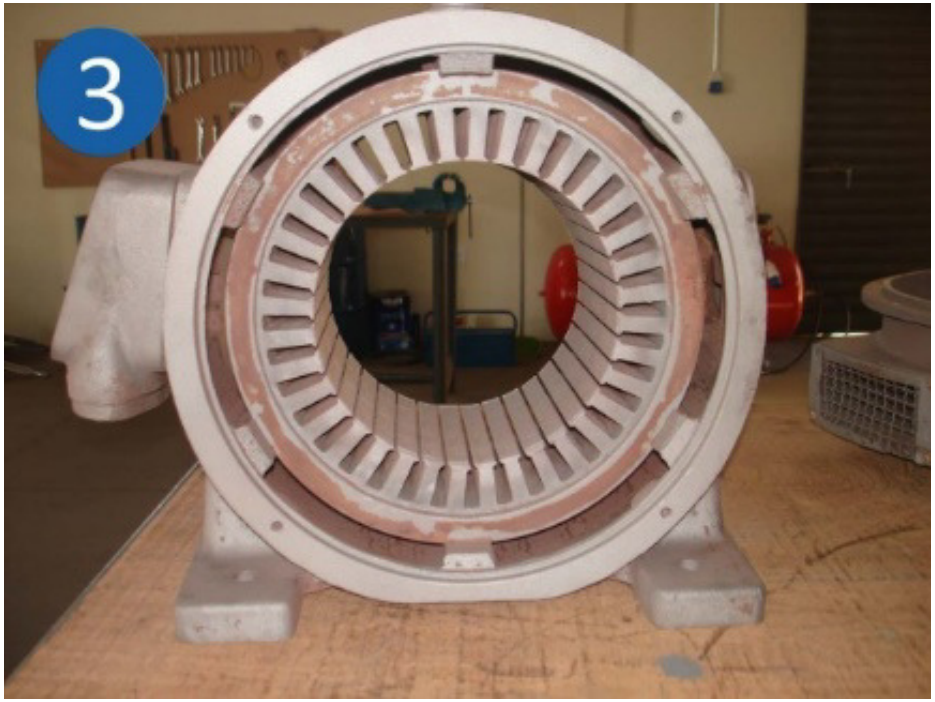
Máquinas CA

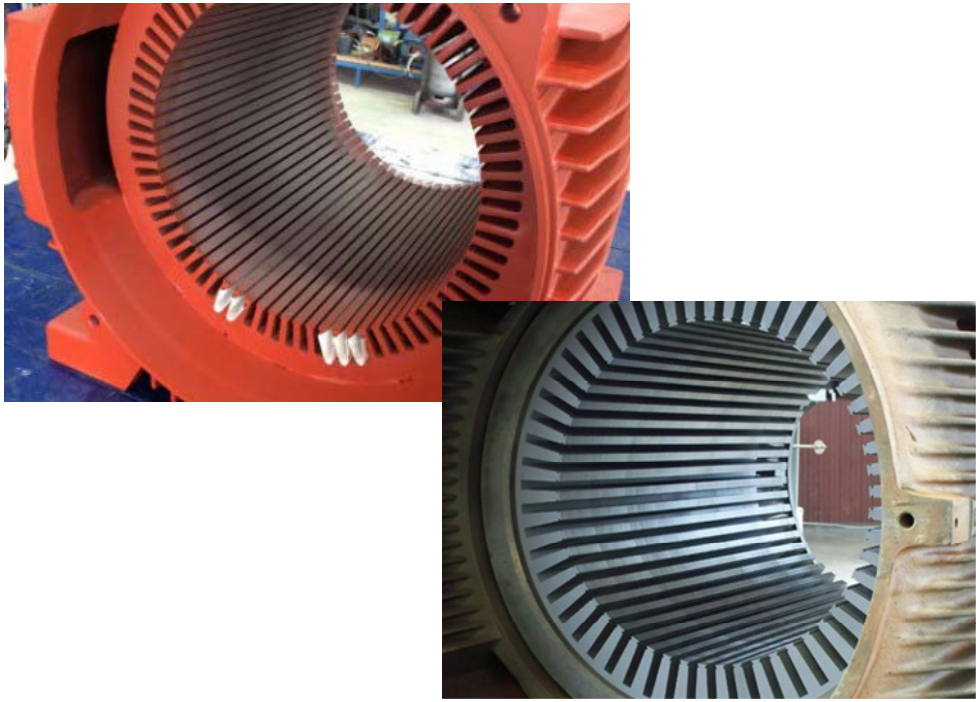


Circuito de Armadura: Estator

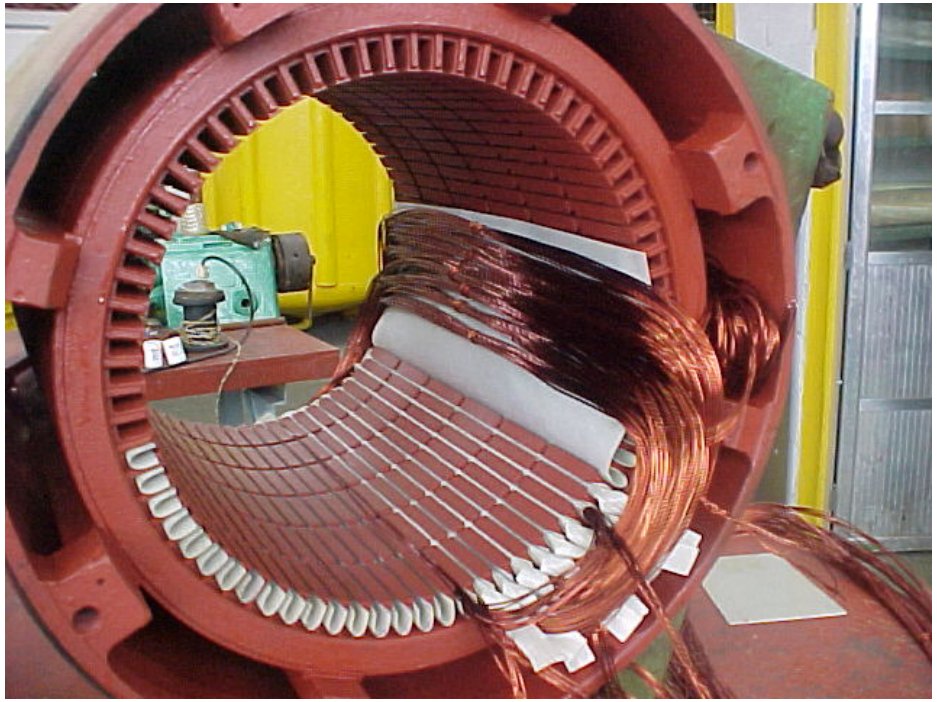
Circuito de Campo: Rotor

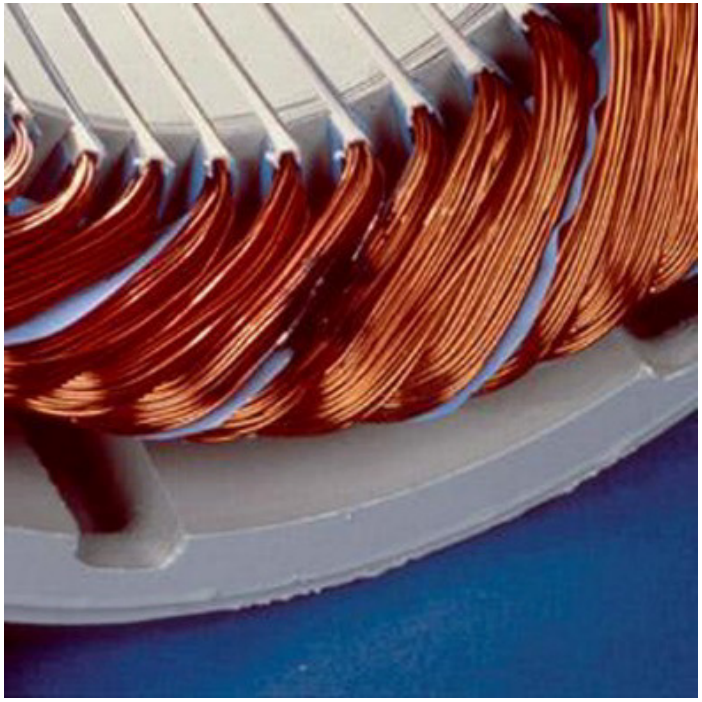
Estator das Máquinas CA





Estator das Máquinas CA

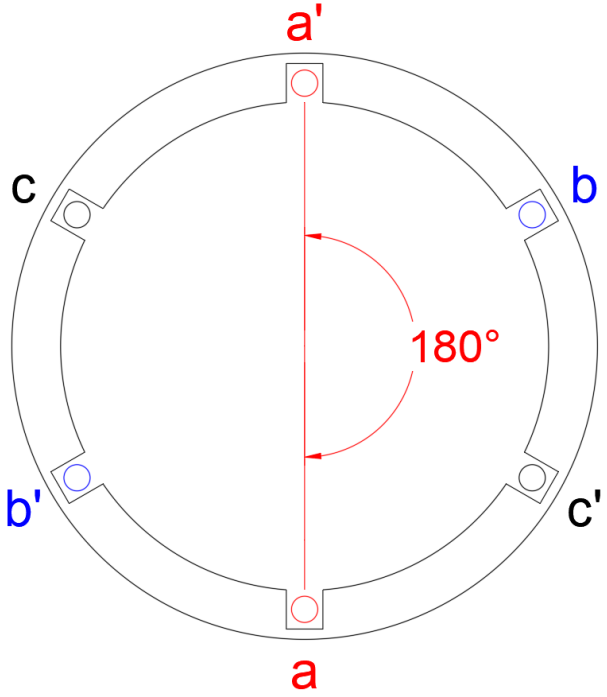




Campo Magnético
Enrolamento Concentrado e Enrolamento Distribuído

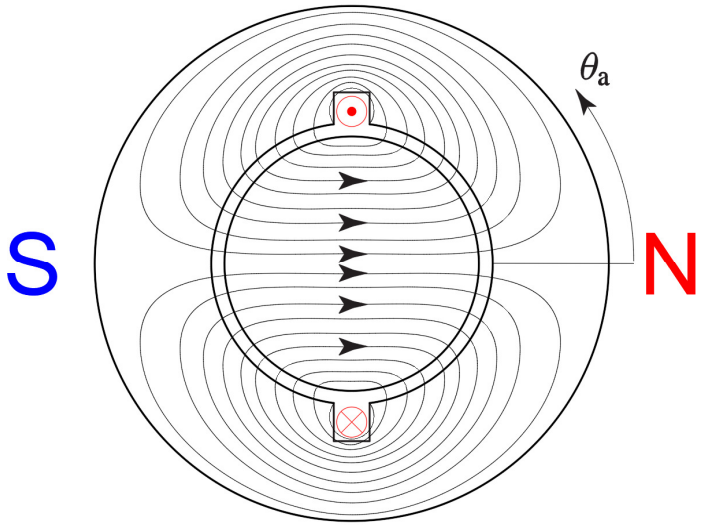
Estator

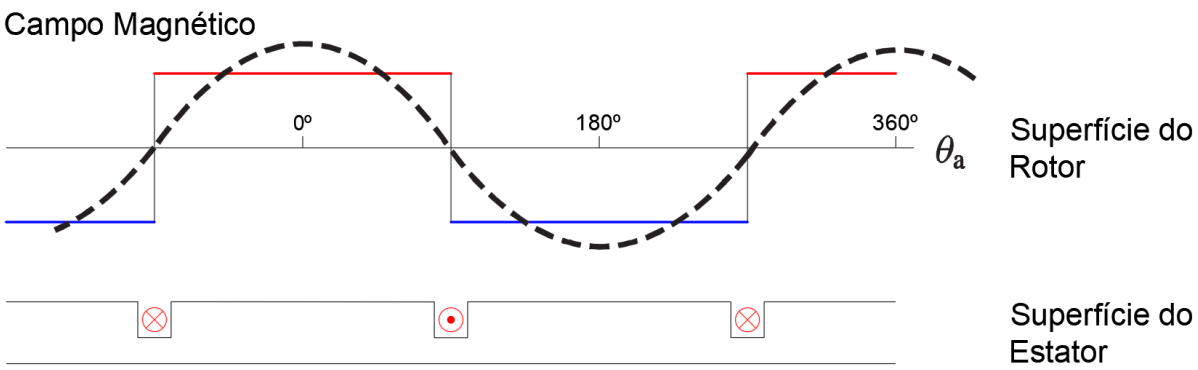
- Bobinas de Passo Pleno
  - Seus terminais estão dispostos a 180º.



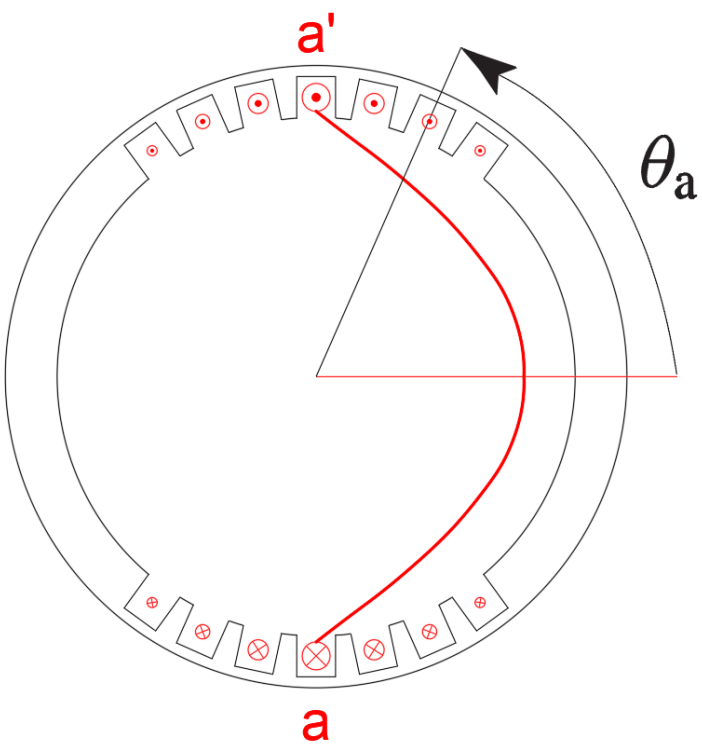
- Enrolamento Concentrado
  - Enrolamento no qual o número de ranhuras por pólo-fase é unitário.

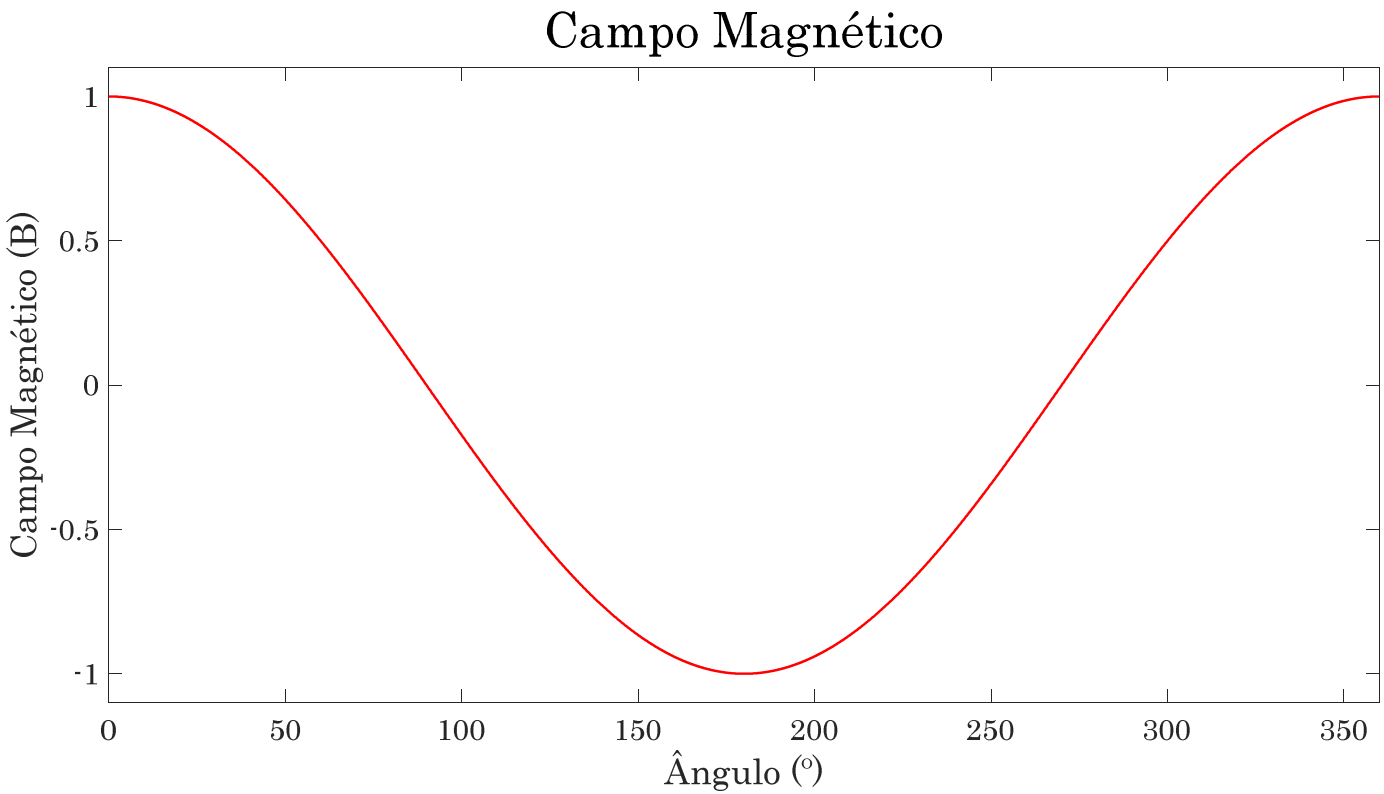
Enrolamento Concentrado Excitado por CC





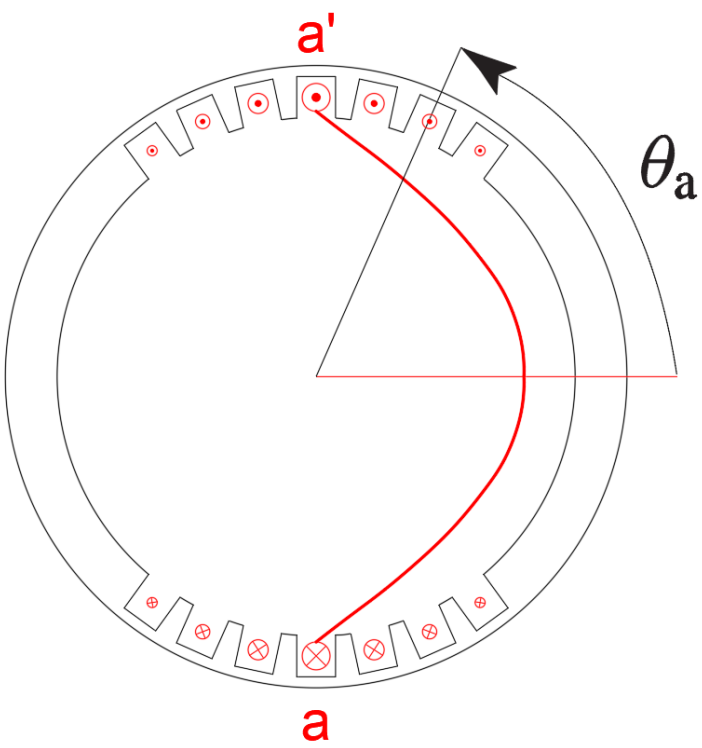
Enrolamento Distribuído Excitado por CC

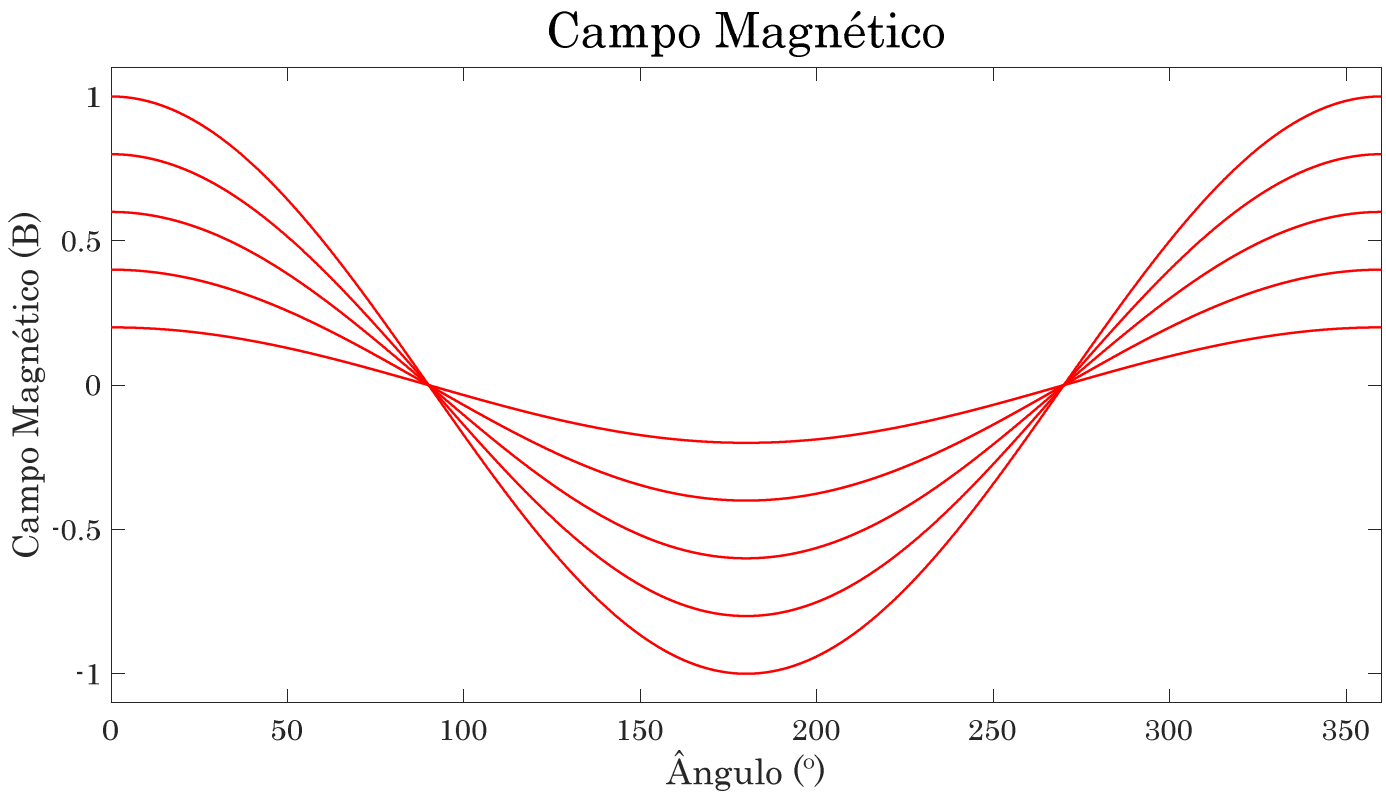




Campo varia senoidalmente em relação a θ.

Enrolamento Distribuído Excitado por CA

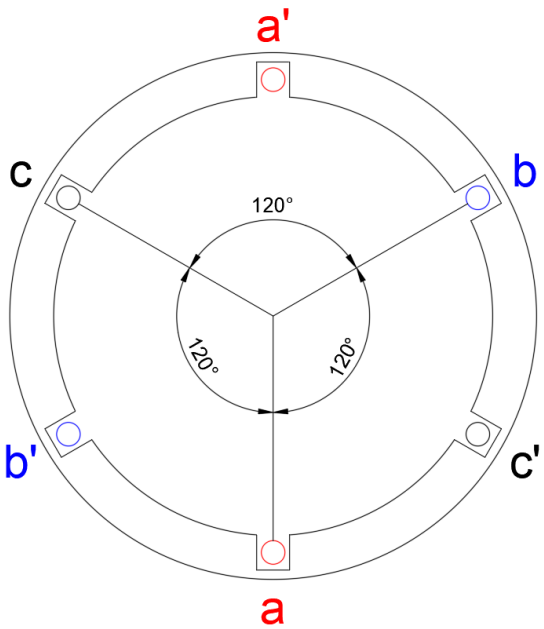




Campo pulsante: varia senoidalmente em relação a θ e a t.

Desenvolvimento do Conceito de Campo Girante

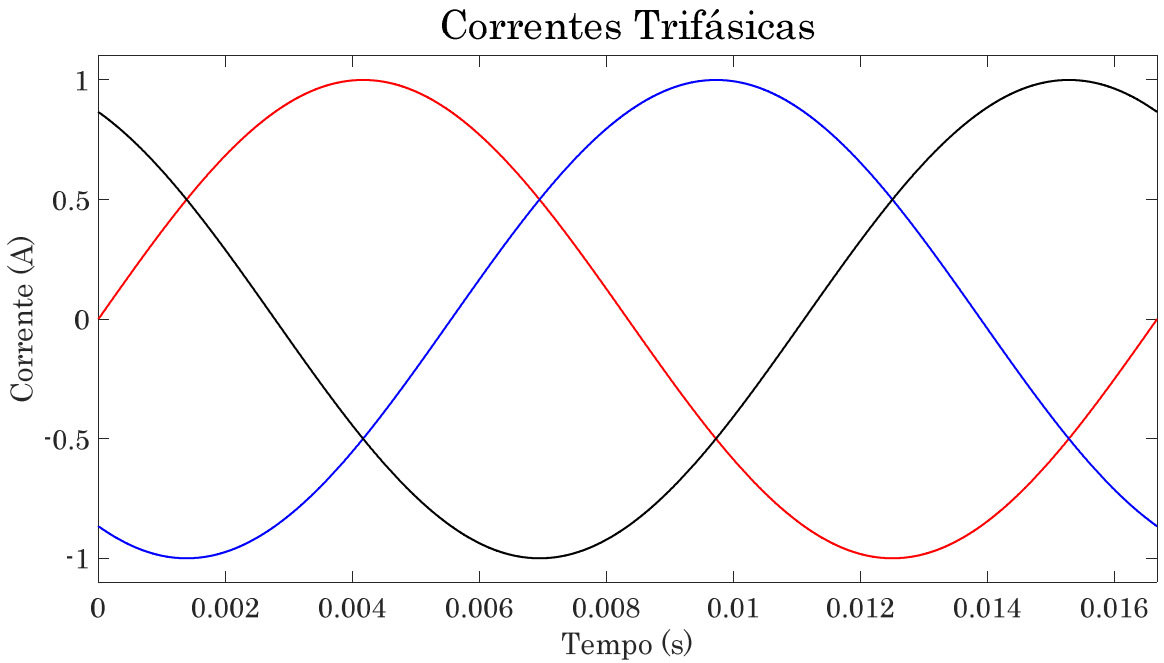
Correntes Aplicadas nas Bobinas do Estator



$i_{aa'}(t) = I_M sen(\omega t)\ A$

$i_{bb'}(t) = I_M sen(\omega t - 120°)\ A$

$i_{cc'}(t) = I_M sen(\omega t - 240°)\ A$



No gráfico: I_M=1 A

Campo Magnético no Estator

$H_{aa'}(t) = H_M sen(\omega t)\angle 0°\ Ae/m$

$H_{bb'}(t) = H_M sen(\omega t - 120°)\angle 120°\ Ae/m$

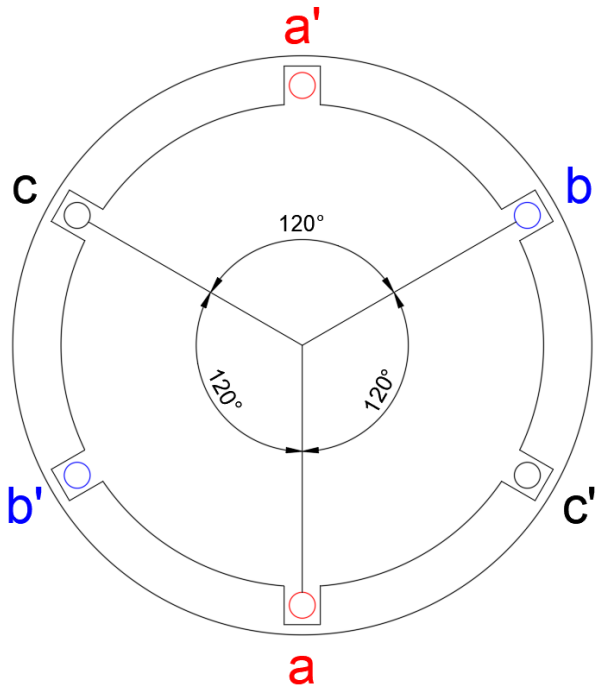
$H_{cc'}(t) = H_M sen(\omega t - 240°)\angle 240°\ Ae/m$

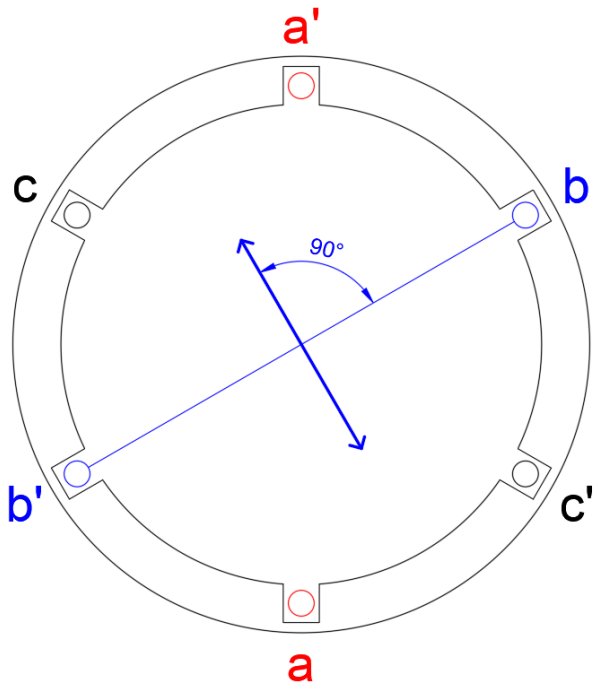
$$\boldsymbol{B} = \mu \boldsymbol{H}$$

$B_{aa'}(t) = B_M sen(\omega t)\angle 0°\ T$

$B_{bb'}(t) = B_M sen(\omega t - 120°)\angle 120°\ T$

$B_{cc'}(t) = B_M sen(\omega t - 240°)\angle 240°\ T$



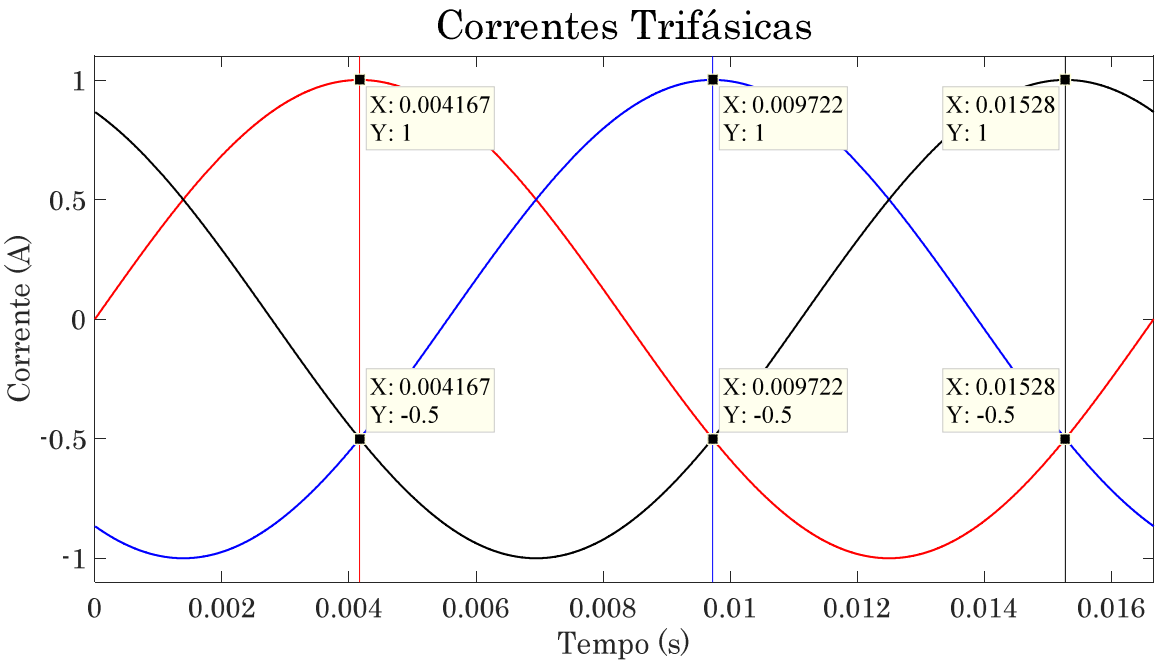


Correntes Aplicadas nas Bobinas do Estator

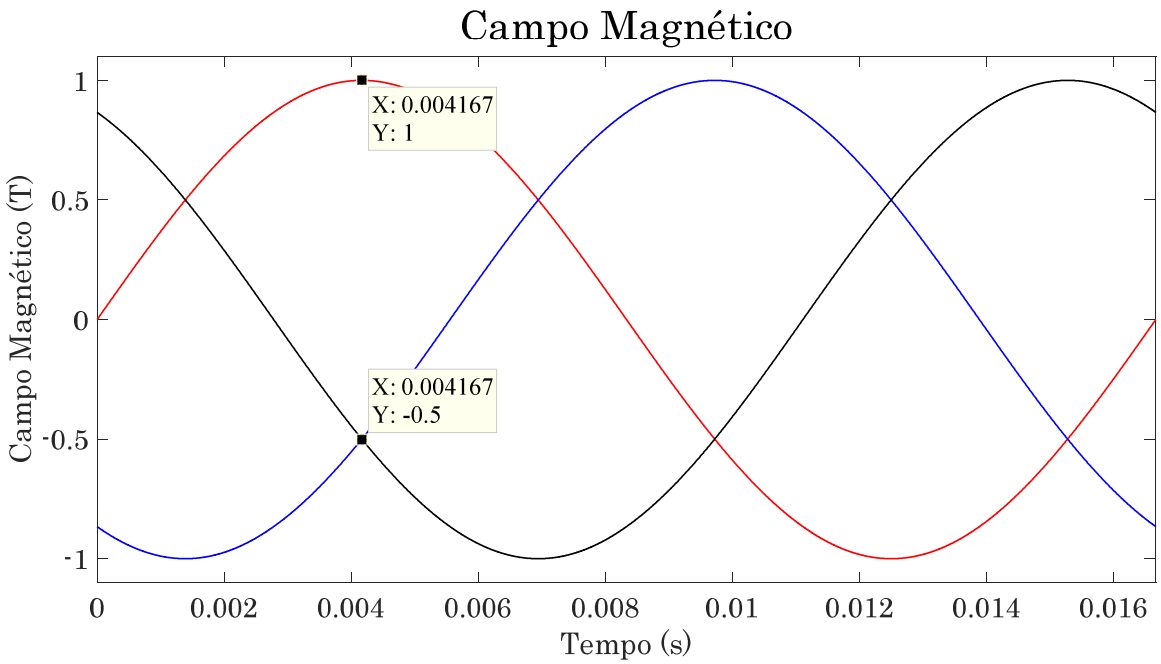
$i_{aa'}(t) = I_M sen(\omega t)\ A$

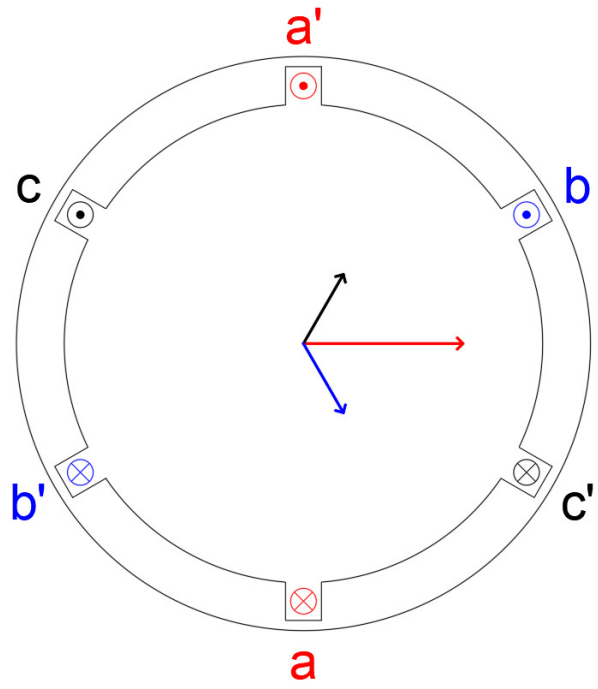
$i_{bb'}(t) = I_M sen(\omega t - 120°)\ A$

$i_{cc'}(t) = I_M sen(\omega t - 240°)\ A$



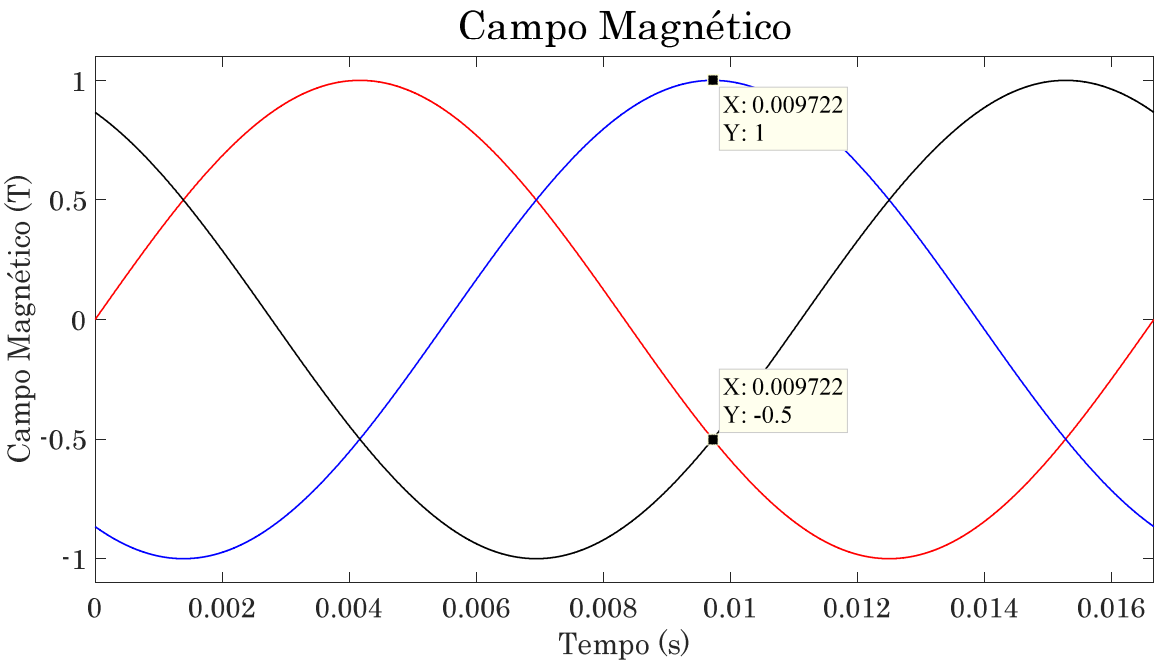
Campo Magnético no Estator

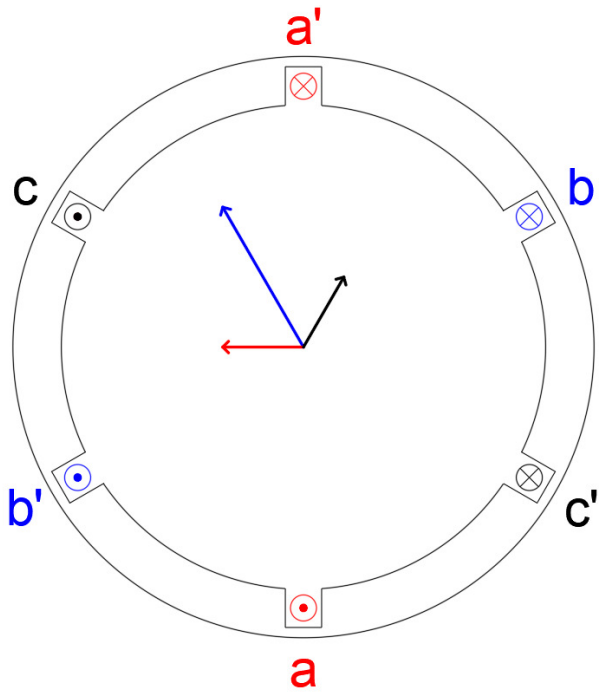




Considerando unitária a amplitude do campo

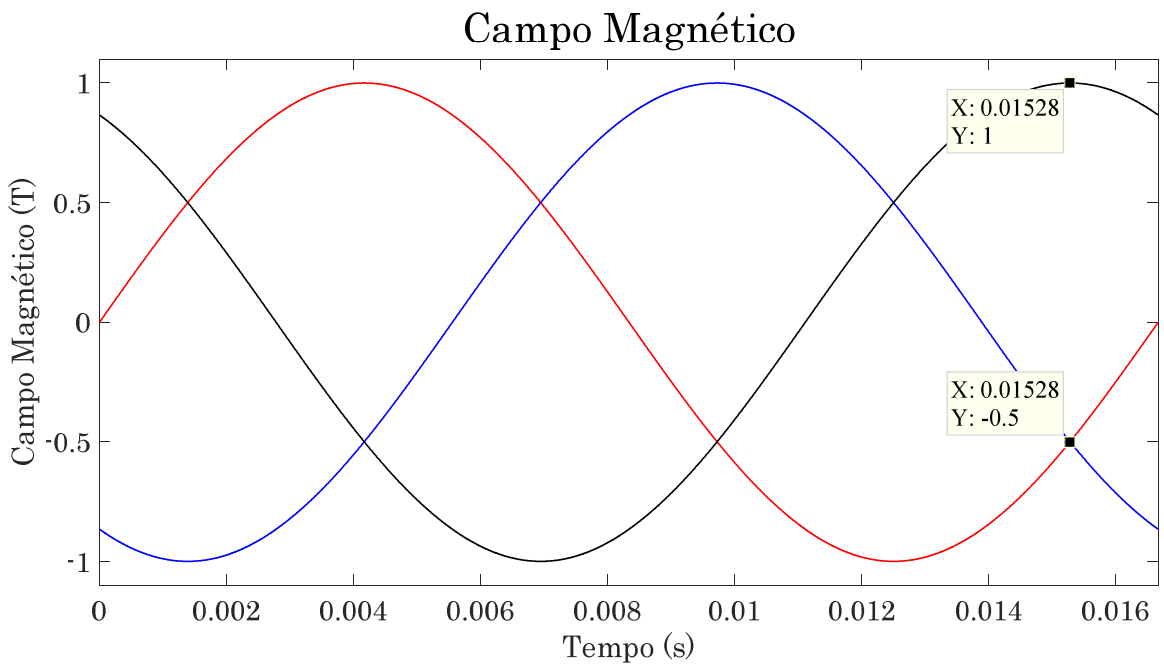
Campo Magnético no Estator

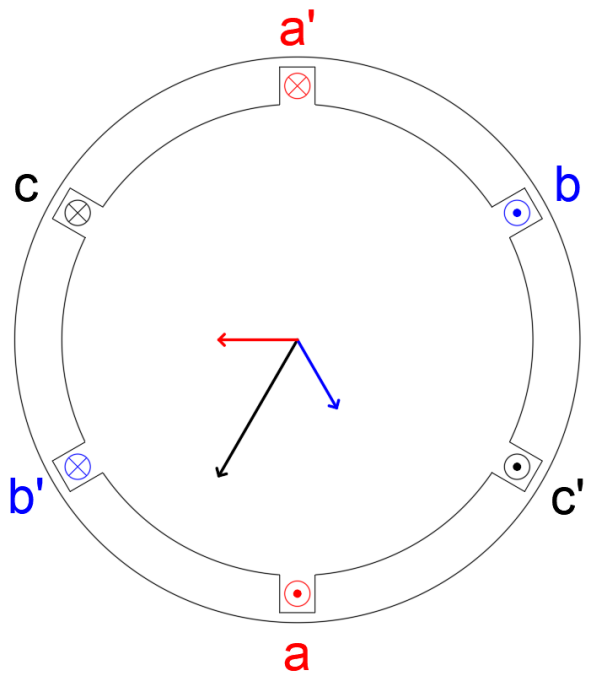




Considerando unitária a amplitude do campo

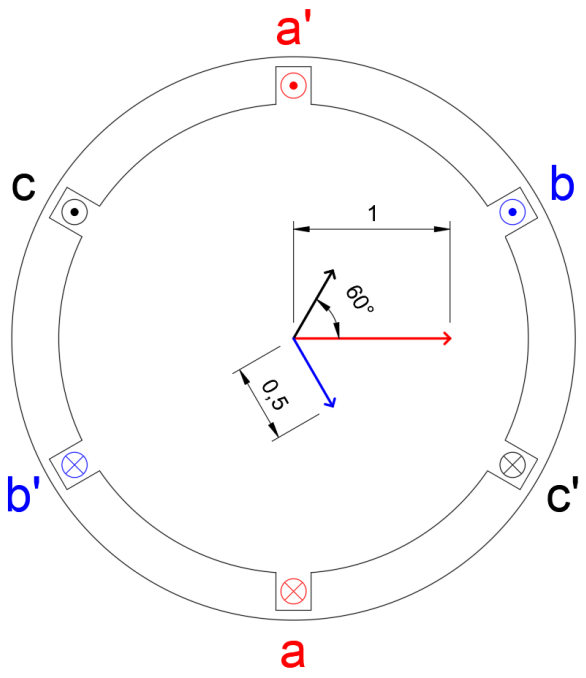
Campo Magnético no Estator

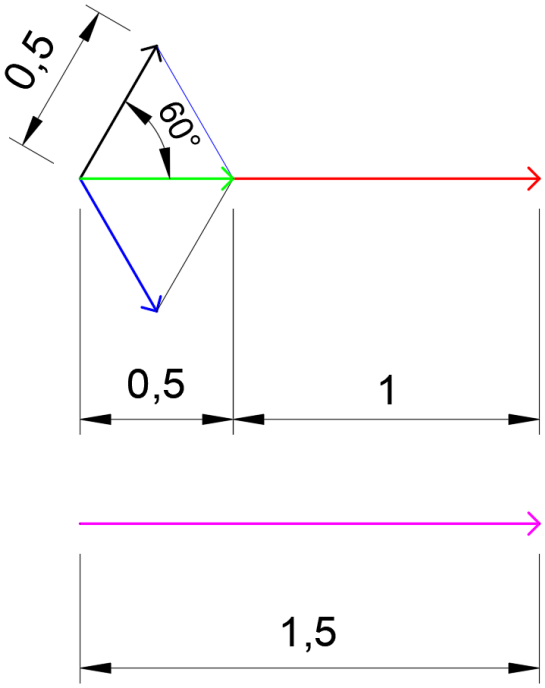




Considerando unitária a amplitude do campo

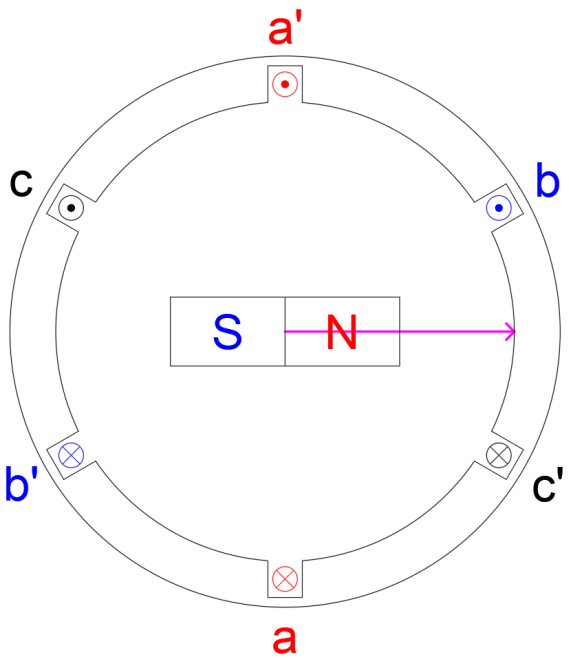
Campo Magnético no Estator

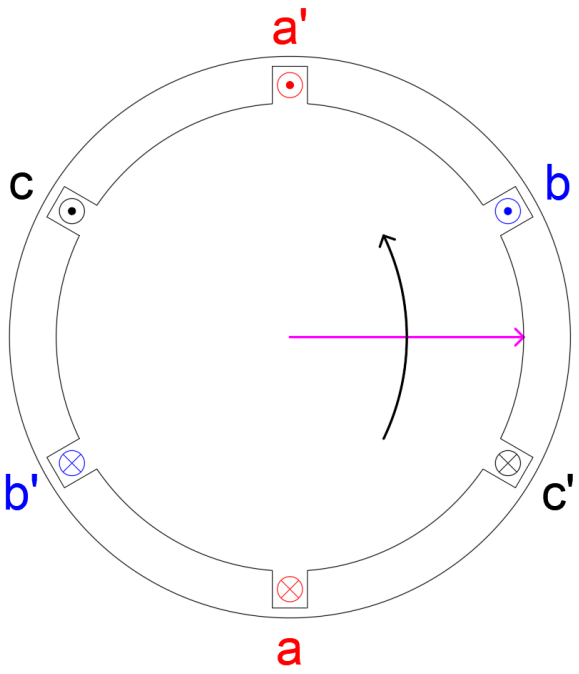




Considerando unitária a amplitude do campo

Campo Magnético Resultante no Estator





Como Inverter o Sentido de Rotação do Campo?

Análise da Fmm

Método Analítico

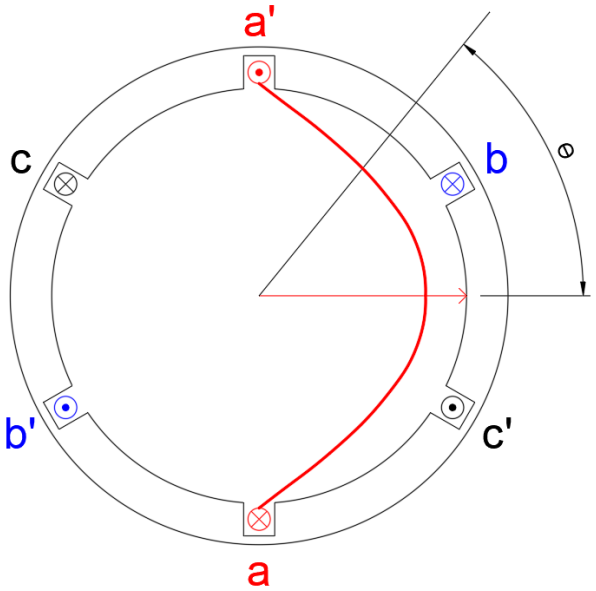
- Um enrolamento distribuído por fase.

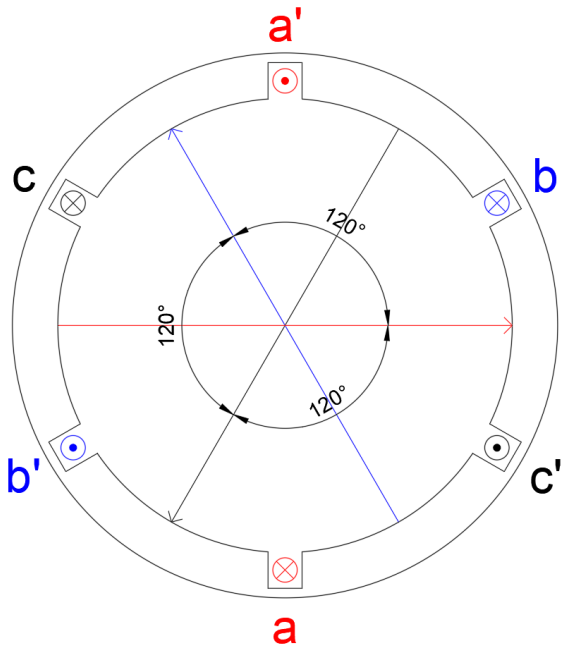
$$F(\theta) = F_a(\theta) + F_b(\theta) + F_c(\theta)$$

$$F_a(\theta) = Ni_a\cos(\theta)$$

$$F_b(\theta) = Ni_b\cos(\theta - 120)$$

$$F_c(\theta) = Ni_c\cos(\theta + 120)$$





Método Analítico

$$F(\theta) = Ni_a \cos(\theta) + Ni_b \cos(\theta - 120) + Ni_c \cos(\theta + 120)$$

Substituindo as correntes que estão em função do tempo:

$$i_a(t) = I_M cos(\omega t)\ A$$

$$i_b(t) = I_M cos(\omega t - 120°)\ A$$

$$i_c(t) = I_M cos(\omega t + 120°)\ A$$

$$cosAcosB = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B)$$

Método Analítico

$$F(\theta) = Ni_a \cos(\theta) + Ni_b \cos(\theta - 120) + Ni_c \cos(\theta + 120)$$

Substituindo as correntes que estão em função do tempo:

$$i_a(t) = I_M cos(\omega t)\ A$$

$$i_b(t) = I_M cos(\omega t - 120°)\ A$$

$$i_c(t) = I_M cos(\omega t + 120°)\ A$$

$$F(\theta) = NI_M cos(\omega t) \cos(\theta) +$$

$$NI_M cos(\omega t - 120°) \cos(\theta - 120) \ +$$

$$NI_M cos(\omega t + 120°) \cos(\theta + 120)$$

Método Analítico

$$F(\theta) = NI_M cos(\omega t)\cos(\theta) +$$

$$NI_M cos(\omega t - 120°)\cos(\theta - 120) \; +$$

$$NI_M cos(\omega t + 120°)\cos(\theta + 120)$$

Utilizando a identidade: $cosAcosB = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B)$

$$NI_M cos(\omega t)\cos(\theta) =$$

$$\frac{1}{2} NI_M \{\cos(\omega t - \theta) + \cos(\omega t + \theta)\}$$

Método Analítico

$$F(\theta) = NI_M cos(\omega t)\cos(\theta) +$$

$$NI_M cos(\omega t - 120°)\cos(\theta - 120) \; +$$

$$NI_M cos(\omega t + 120°)\cos(\theta + 120)$$

Utilizando a identidade: $cosAcosB = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B)$

$$NI_M cos(\omega t - 120)\cos(\theta - 120) =$$

$$\frac{1}{2}NI_M \{\cos(\omega t - 120 - \theta + 120) + \cos(\omega t - 120 + \theta - 120)\} =$$

$$\frac{1}{2}NI_M \{\cos(\omega t - \theta) + \cos(\omega t + \theta - 240)\}$$

Método Analítico

$$F(\theta) = NI_M cos(\omega t)\cos(\theta) +$$

$$NI_M cos(\omega t - 120°)\cos(\theta - 120) \; +$$

$$NI_M cos(\omega t + 120°)\cos(\theta + 120)$$

Utilizando a identidade: $cosAcosB = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B)$

$$NI_M cos(\omega t + 120)\cos(\theta + 120) =$$

$$\frac{1}{2} NI_M \{\cos(\omega t + 120 - \theta - 120) + \cos(\omega t + 120 + \theta + 120)\} =$$

$$\frac{1}{2} NI_M \{\cos(\omega t - \theta) + \cos(\omega t + \theta + 240)\}$$

Método Analítico

$$F(\theta,t) = \frac{1}{2}NI_M\cos(\omega t-\theta) + \frac{1}{2}NI_M\cos(\omega t+\theta) +$$

$$\frac{1}{2}NI_M\cos(\omega t-\theta) + \frac{1}{2}NI_M\cos(\omega t+\theta-240) +$$

$$\frac{1}{2}NI_M\cos(\omega t-\theta) + \frac{1}{2}NI_M\cos(\omega t+\theta+240)$$

$$\cos(A+B) = \cos(A)\cos(B) - \operatorname{sen}(A)\operatorname{sen}(B)$$

$$\cos(A-B) = \cos(A)\cos(B) + \operatorname{sen}(A)\operatorname{sen}(B)$$

Método Analítico

$\cos(\omega t + \theta)$

$$\cos(\omega t + \theta - 240) = \cos(\omega t + \theta)\cos(240) + \operatorname{sen}(\omega t + \theta)\operatorname{sen}(240) = -\frac{1}{2}\cos(\omega t + \theta) - \frac{\sqrt{3}}{2}\operatorname{sen}(\omega t + \theta)$$

$$\cos(\omega t + \theta + 240) = \cos(\omega t + \theta)\cos(240) - \operatorname{sen}(\omega t + \theta)\operatorname{sen}(240) = -\frac{1}{2}\cos(\omega t + \theta) + \frac{\sqrt{3}}{2}\operatorname{sen}(\omega t + \theta)$$

$$\cos(\omega t + \theta) - \frac{1}{2}\cos(\omega t + \theta) - \frac{\sqrt{3}}{2}\operatorname{sen}(\omega t + \theta) - \frac{1}{2}\cos(\omega t + \theta) + \frac{\sqrt{3}}{2}\operatorname{sen}(\omega t + \theta) = \mathbf{0}$$

Método Analítico

$$F(\theta,t) = \frac{1}{2}NI_M\cos(\omega t-\theta) + \frac{1}{2}NI_M\cos(\omega t+\theta) +$$

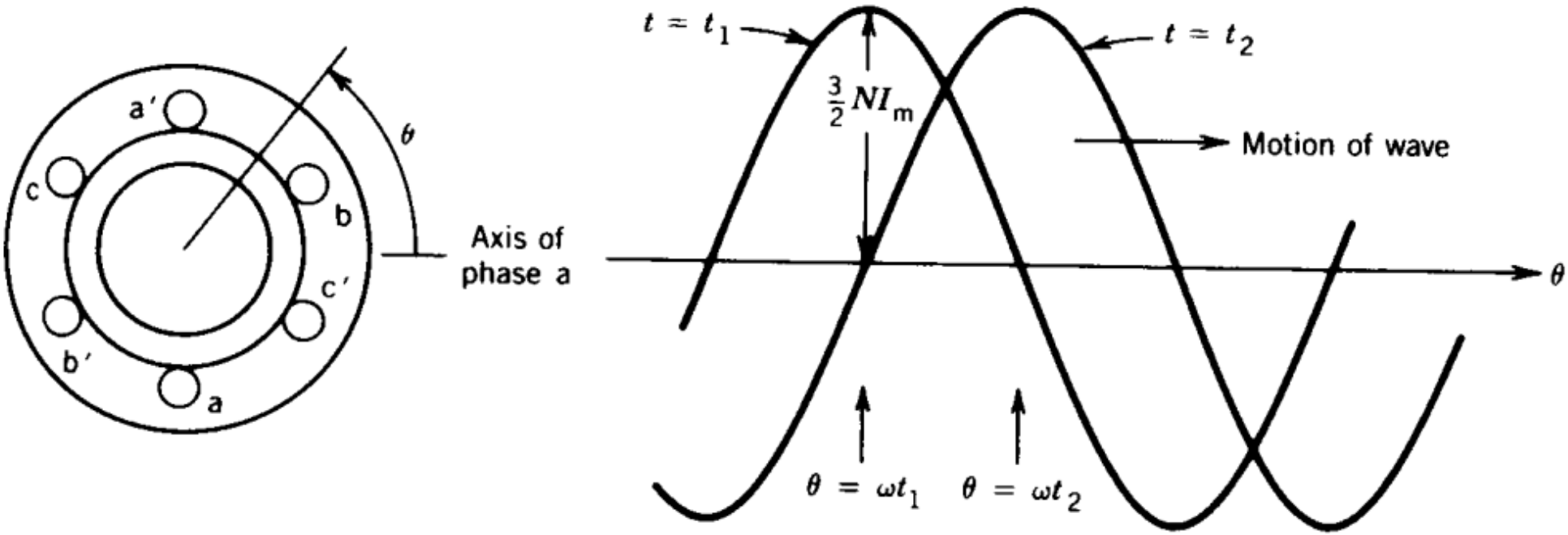
$$\frac{1}{2}NI_M\cos(\omega t-\theta) + \frac{1}{2}NI_M\cos(\omega t+\theta-240) +$$

$$\frac{1}{2}NI_M\cos(\omega t-\theta) + \frac{1}{2}NI_M\cos(\omega t+\theta+240)$$

$$F(\theta,t) = \frac{3}{2}NI_M\cos(\omega t-\theta)$$

Força Resultante

- $F(\theta, t) = \frac{3}{2} N I_M \cos(\omega t - \theta)$

- Fmm no entreferro:
  - Velocidade angular: ω
  - Pico: $\theta = \omega t$
  - A cada instante de tempo possui distribuição senoidal ao redor do entreferro.

Força Resultante no Entreferro