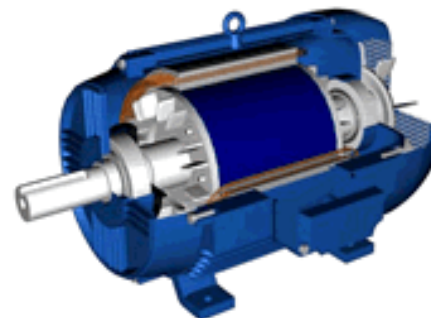
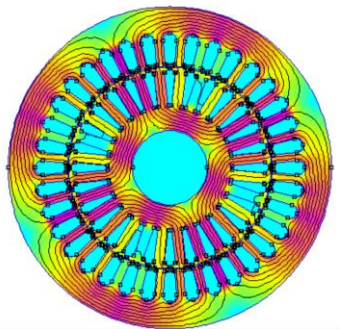


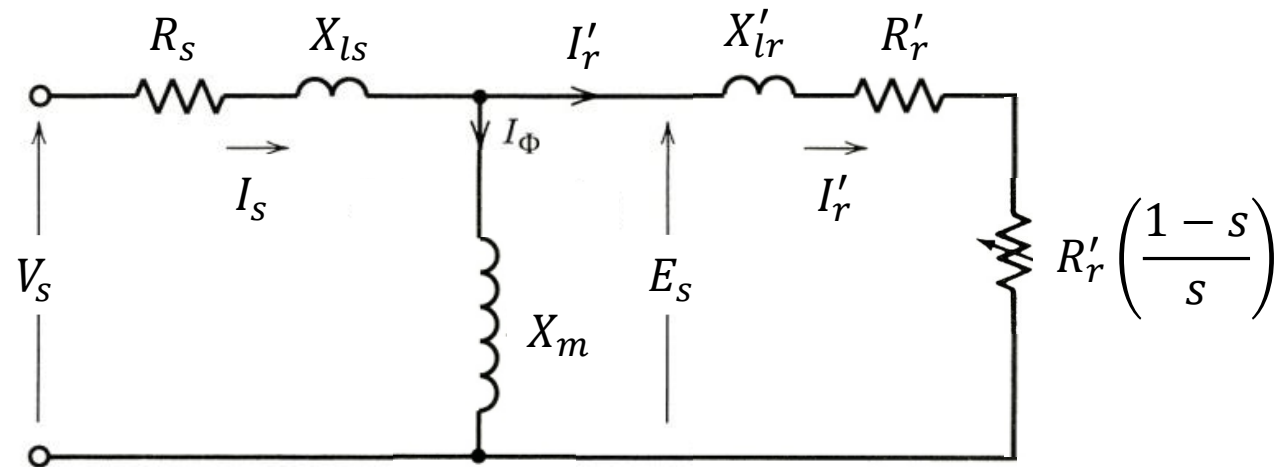
Aula 16: Características de conjugado do MIT

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Circuito equivalente – motor de indução



❑ Potência desenvolvida:

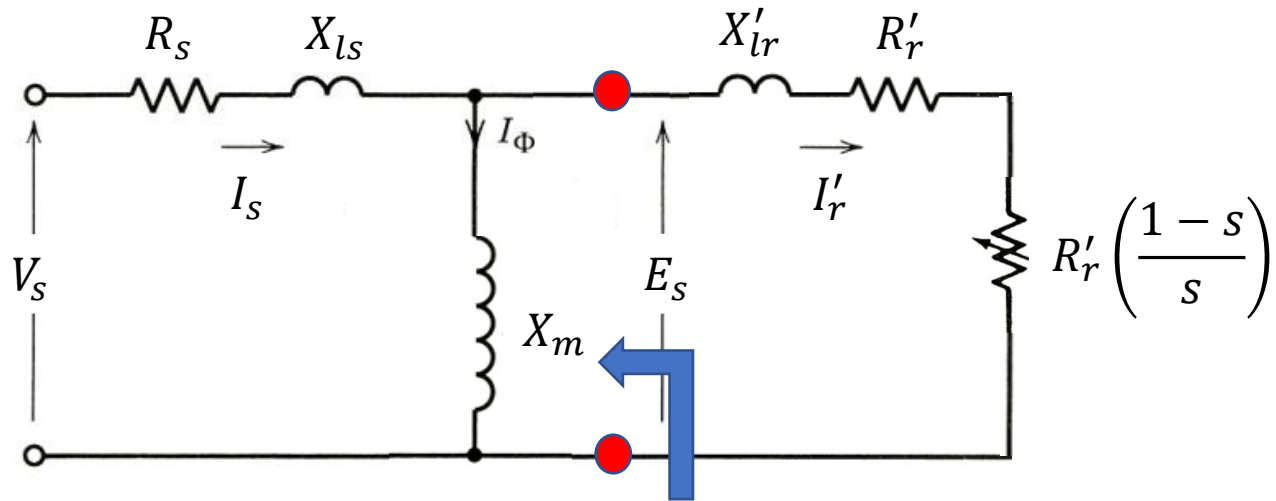
$$P_d = 3 \frac{R'_r}{s} I_r'^2 (1 - s)$$

❑ Conjugado desenvolvido:

$$T_d = \frac{P_d}{\omega_m} = 3 \frac{R'_r}{s \omega_m} I_r'^2 (1 - s)$$

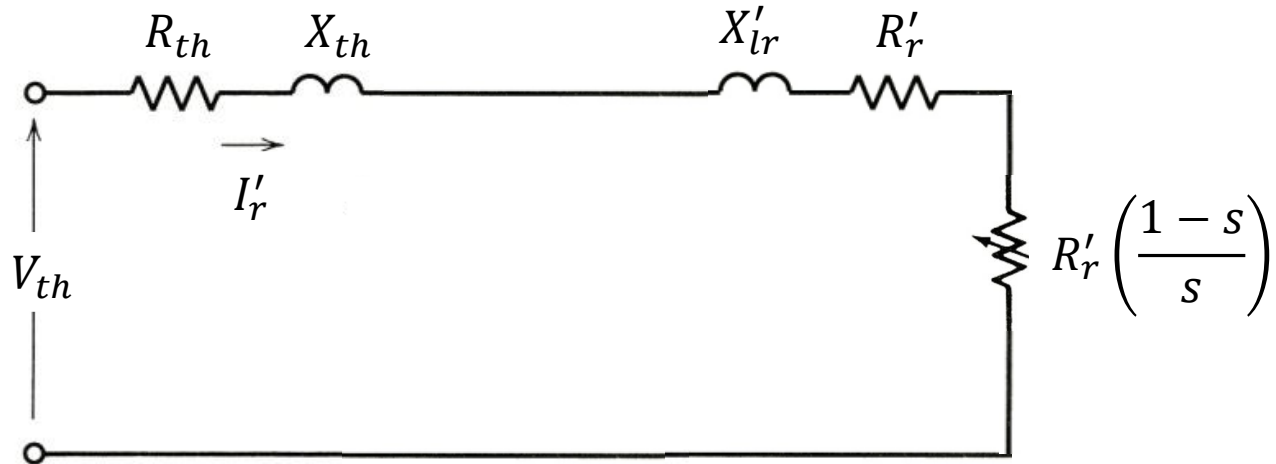
Fonte: P. C. Sen. “Principles of Electrical Machines and Power Electronics”.

Circuito Equivalente de Thévenin



$$V_{th} = \frac{X_m}{\sqrt{R_s^2 + (X_{ls} + X_m)^2}} V_1$$

$$V_{th} \approx \frac{X_m}{X_{ls} + X_m} V_1$$



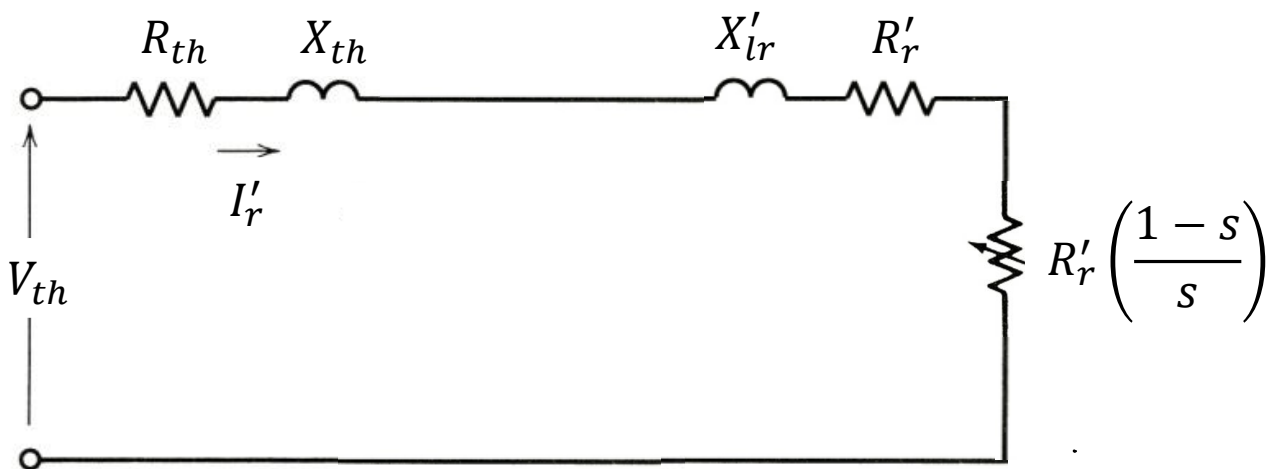
$$Z_{th} = R_{th} + jX_{th} = \frac{jX_m(R_s + jX_{ls})}{R_s + j(X_{ls} + X_m)}$$

$$R_{th} \approx R_s \left(\frac{X_m}{X_{ls} + X_m} \right)^2$$

$$X_{th} \approx X_{ls}$$

Fonte: P. C. Sen. "Principles of Electrical Machines and Power Electronics".

Expressão do Conjugado Desenvolvido



$$I'_r = \frac{V_{th}}{\sqrt{\left(R_{th} + \frac{R'_r}{s}\right)^2 + (X_{th} + X'_{lr})^2}}$$

Fonte: P. C. Sen. "Principles of Electrical Machines and Power Electronics".

$$T_d = \frac{P_d}{\omega_m} = 3 \frac{R'_r}{s \omega_m} I'^2_r (1 - s) = 3 \frac{V_{th}^2}{\left(R_{th} + \frac{R'_r}{s}\right)^2 + (X_{th} + X'_{lr})^2} \frac{R'_r}{s} \frac{1 - s}{\omega_m}$$

$$T_d = \frac{3}{\omega_s} \frac{V_{th}^2}{\left(R_{th} + \frac{R'_r}{s}\right)^2 + (X_{th} + X'_{lr})^2} \frac{R'_r}{s}$$

Assíntotas da relação conjugado versus escorregamento

□ Para baixos escorregamentos ($s \rightarrow 0$):

$$T_d = \frac{3}{\omega_s} \frac{V_{th}^2}{\left(R_{th} + \frac{R'_r}{s}\right)^2 + (X_{th} + X'_{lr})^2} \frac{R'_r}{s} \approx \frac{3}{\omega_s} \frac{V_{th}^2}{\left(\frac{R'_r}{s}\right)^2} \frac{R'_r}{s} = \frac{3}{\omega_s} \frac{V_{th}^2}{R'_r} s$$

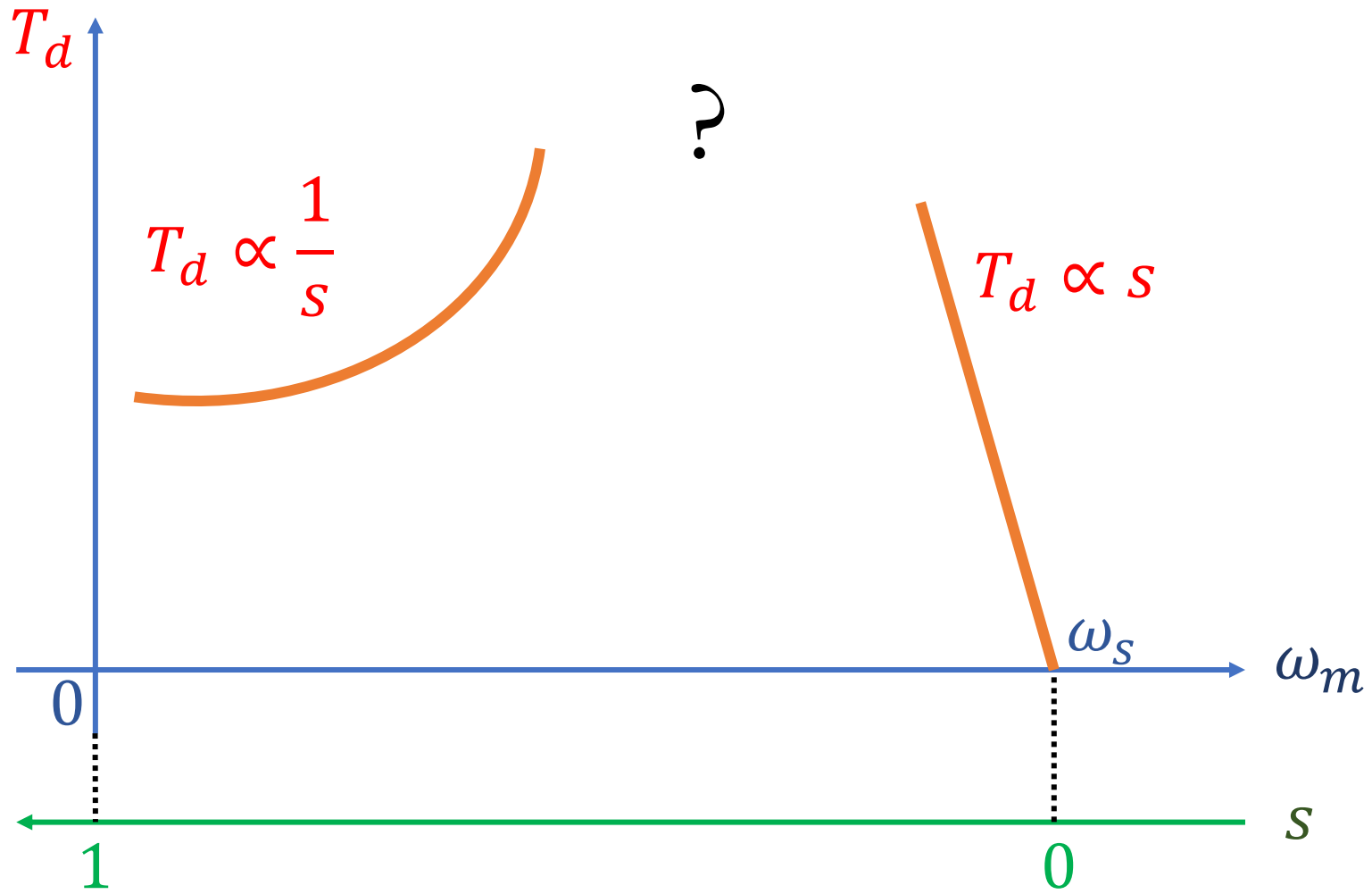
Neste caso, $T_d \propto s$

□ Para altos valores de escorregamento:

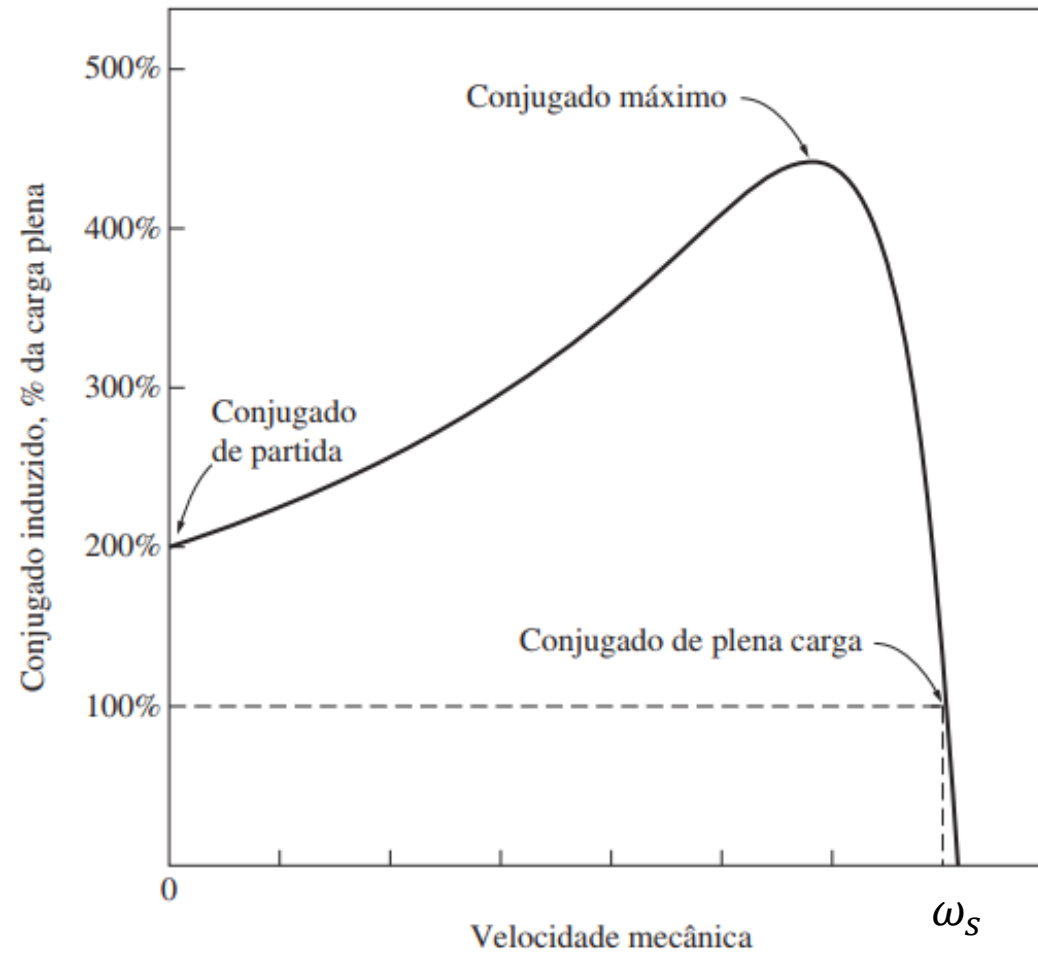
$$T_d = \frac{3}{\omega_s} \frac{V_{th}^2}{\left(R_{th} + \frac{R'_r}{s}\right)^2 + (X_{th} + X'_{lr})^2} \frac{R'_r}{s} \approx \frac{3}{\omega_s} \frac{V_{th}^2}{(X_{th} + X'_{lr})^2} \frac{R'_r}{s}$$

Neste caso, $T_d \propto 1/s$

Curva T_d versus ω_m



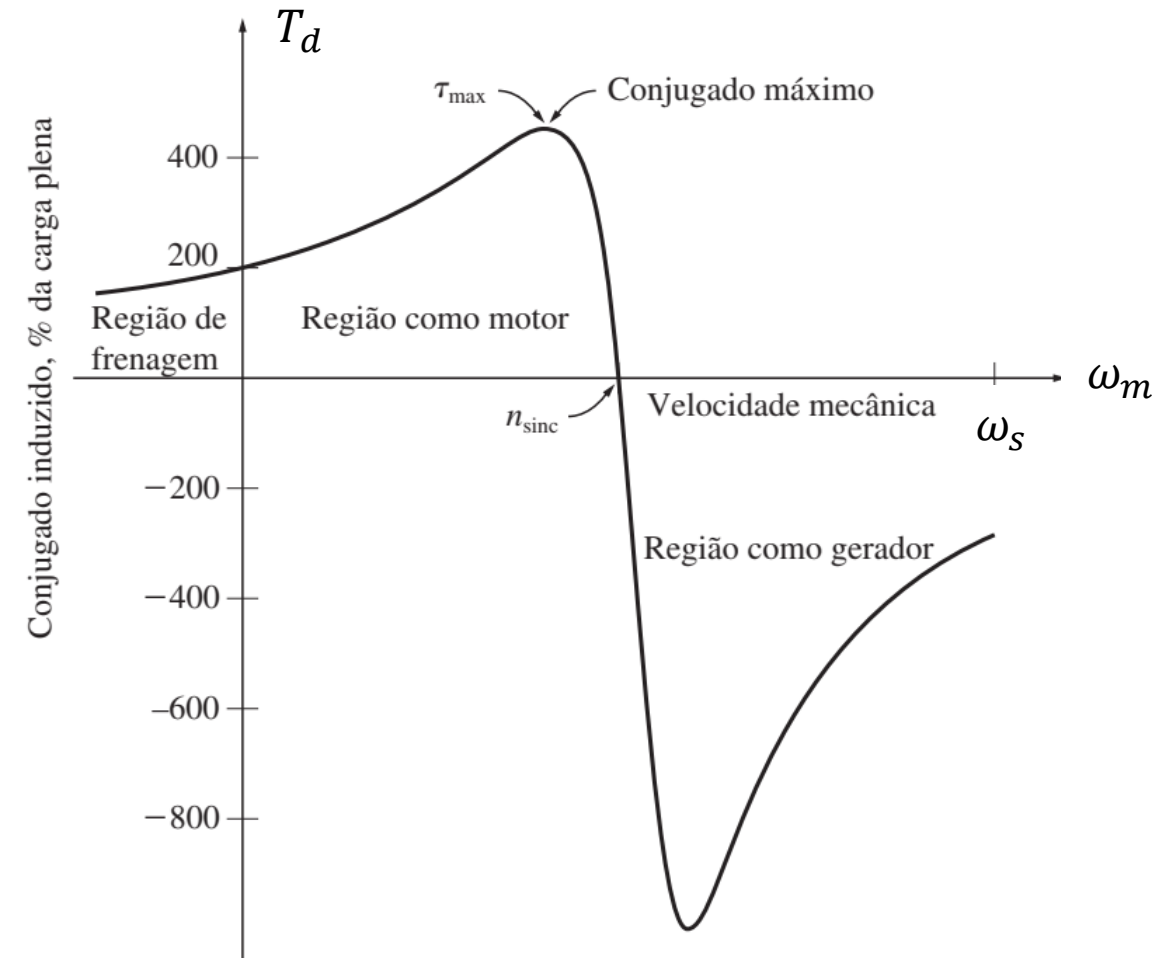
Curva T_d versus ω_m



S. J. Chapman. "Fundamentos de Máquinas Elétricas".


Curva T_d versus ω_m “Completa”

- ❑ Conjugado nulo na velocidade síncrona;
- ❑ Ponto de conjugado máximo;
- ❑ Conjugado de partida;
- ❑ Região de frenagem ($s > 1$);
- ❑ Operação como gerador ($s < 0$).

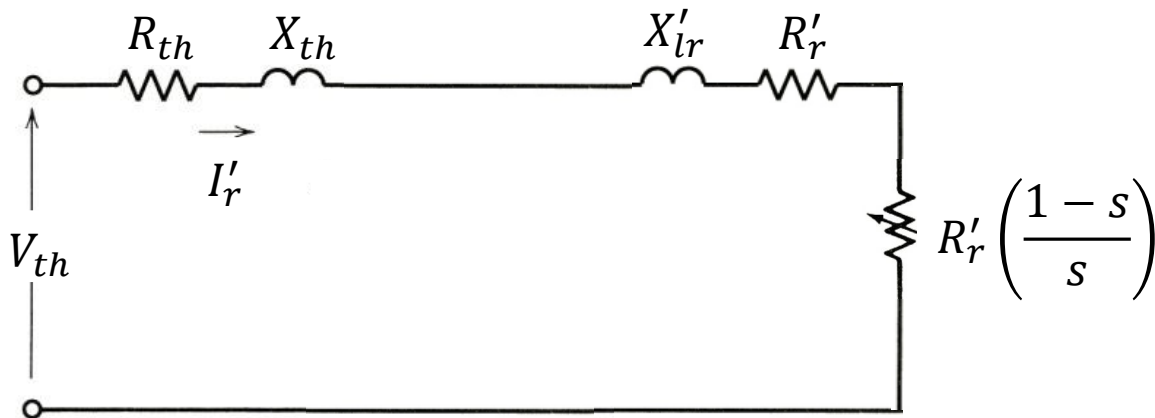


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Ponto de conjugado máximo

□ Acontece no ponto de máxima transferência de potência para $\frac{R'_r}{s}$ 

$$\frac{R'_r}{s_{T_{max}}} = \sqrt{R_{th}^2 + (X_m + X'_{lr})^2} \rightarrow s_{T_{max}} = \frac{R'_r}{\sqrt{R_{th}^2 + (X_m + X'_{lr})^2}}$$



$$T_{max} = \frac{3 V_{th}^2}{2 \omega_s \left(R_{th} + \sqrt{R_{th}^2 + (X_{th} + X'_{lr})^2} \right)}$$

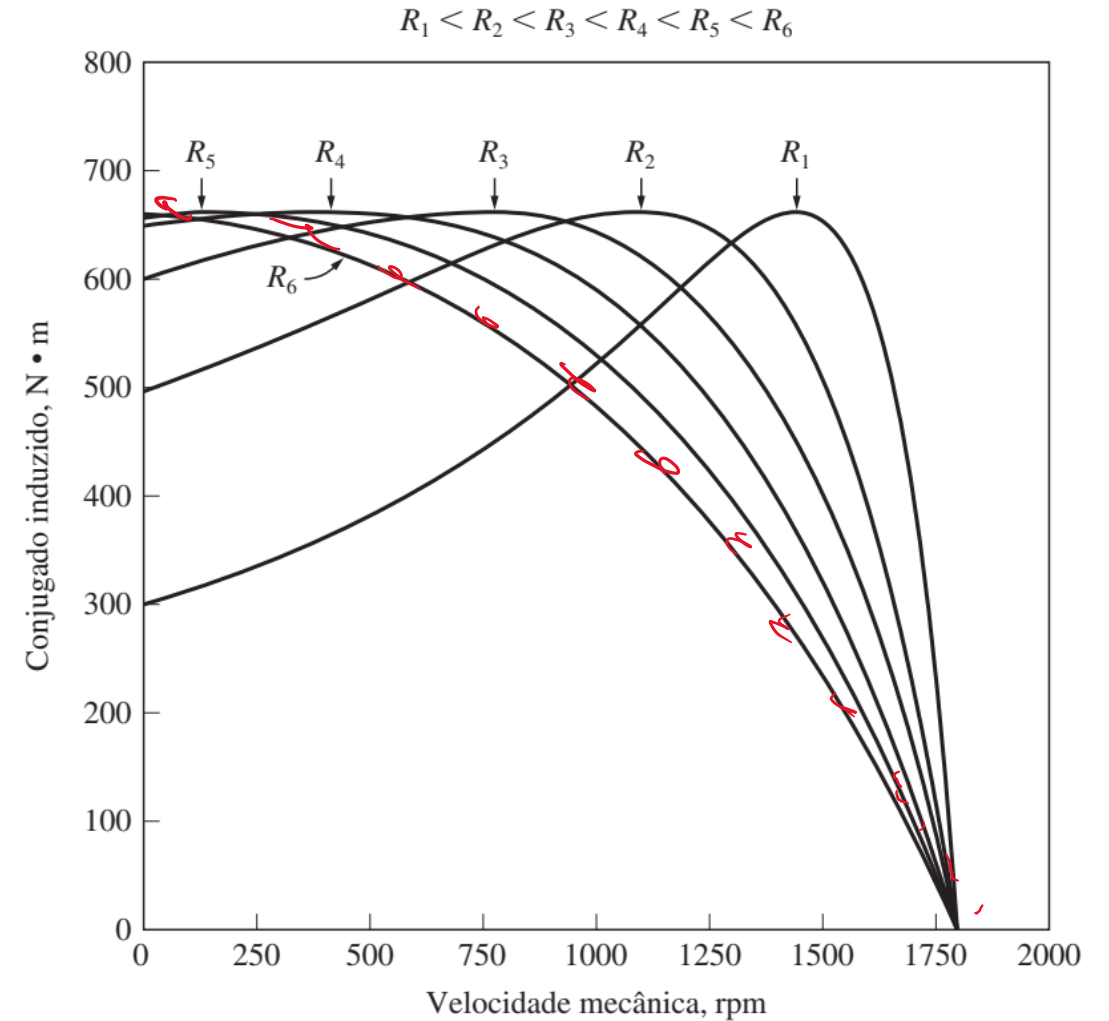
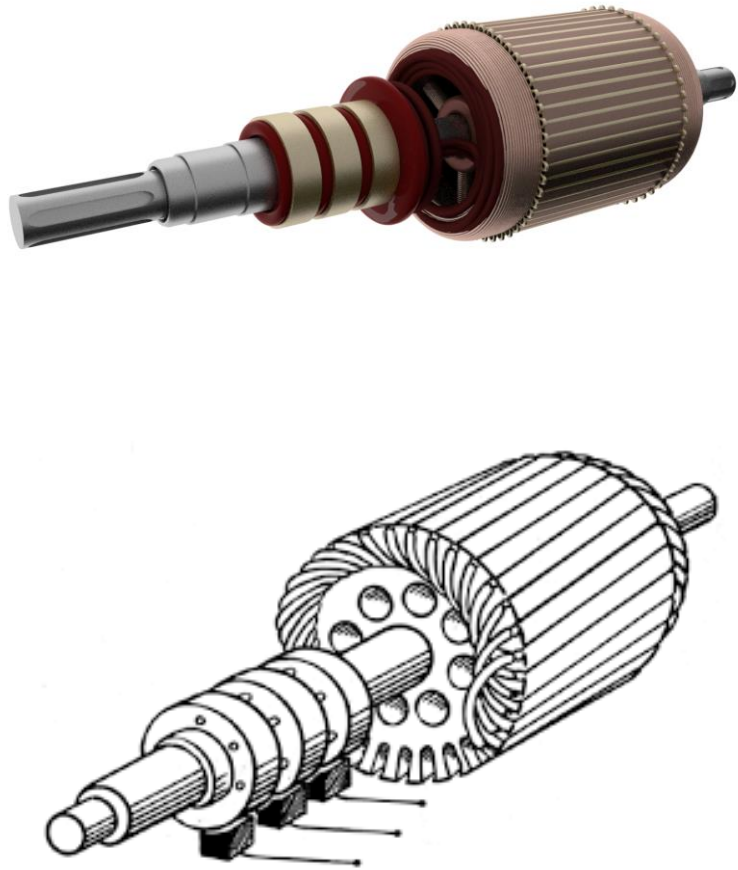
Conclusões Parciais

- ❑ Para uma dada máquina:
 - O escorregamento (e a velocidade) correspondente ao conjugado máximo depende da resistência de rotor;
 - O valor do conjugado máximo não depende da resistência de rotor.

$$s_{T_{max}} = \frac{R'_r}{\sqrt{R_{th}^2 + (X_m + X'_{lr})^2}}$$

$$T_{max} = \frac{3 V_{th}^2}{2 \omega_s \left(R_{th} + \sqrt{R_{th}^2 + (X_{th} + X'_{lr})^2} \right)}$$

Efeito da inserção de resistência no rotor



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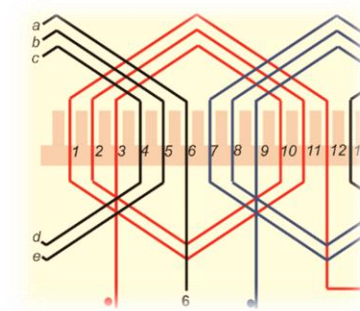
https://www.youtube.com/channel/UCe9KOSGORXh_hDBIcxMU2Nw



Estimate - Sistemas
Fotovoltaicos

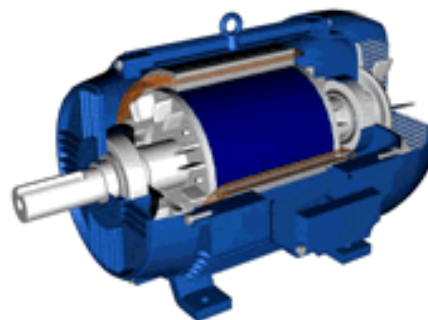
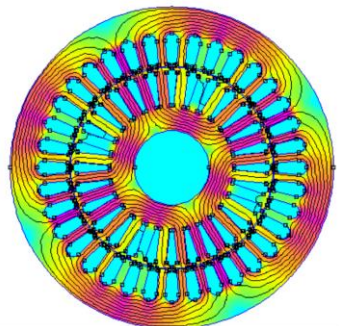


<https://play.google.com/store/apps/details?id=br.developer.gesep.estimate>



Aula 16: Características de conjugado do MIT

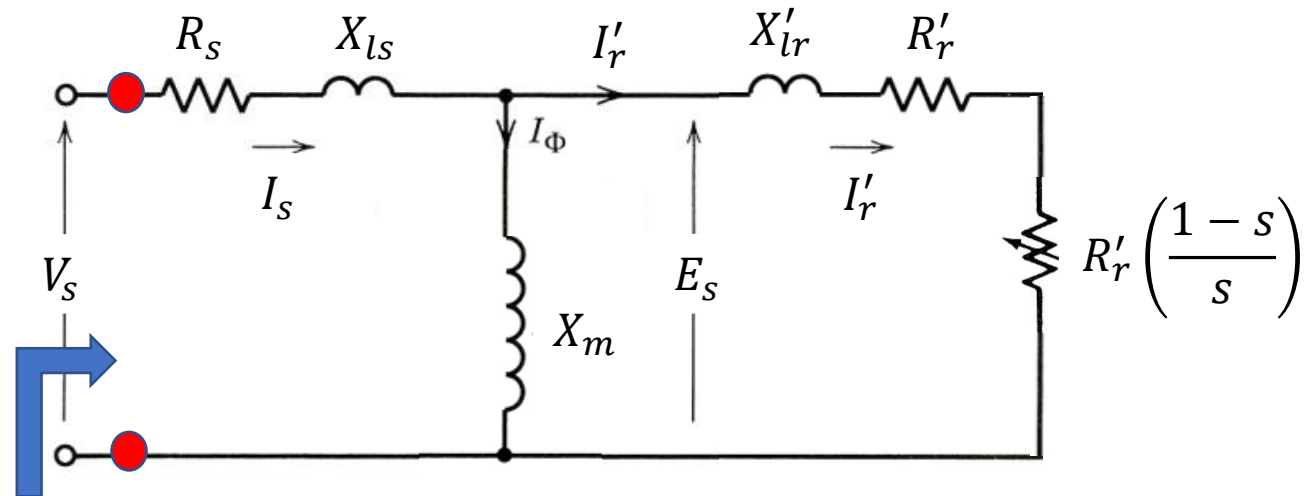
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Corrente de estator



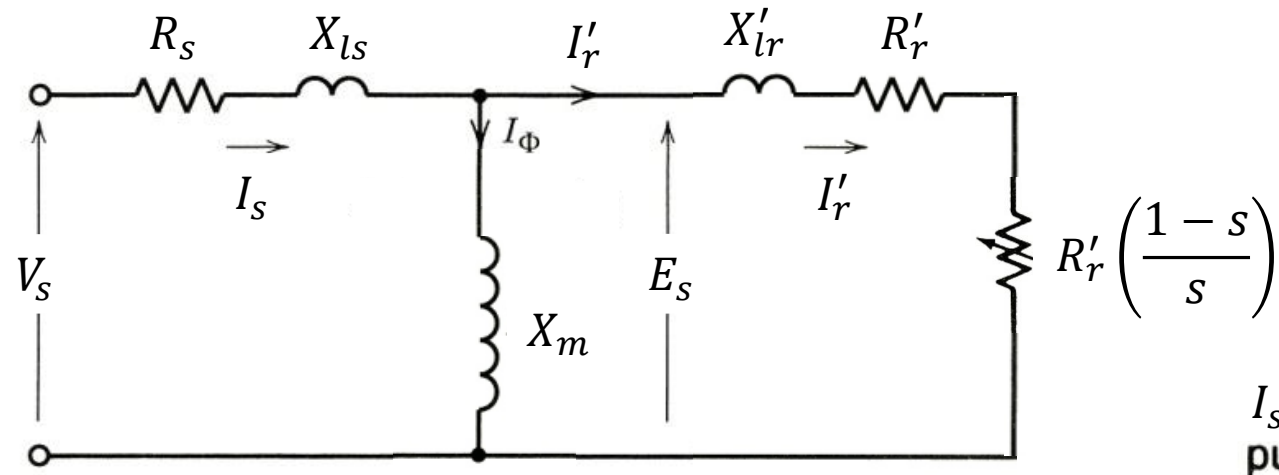
$$I_s = \frac{V_s}{Z_s}$$

Onde:

$$Z_s = R_s + jX_{ls} + \frac{jX_m \left(\frac{R'_r}{s} + jX'_{lr} \right)}{\frac{R'_r}{s} + jX'_{lr} + jX_m}$$

Fonte: P. C. Sen. "Principles of Electrical Machines and Power Electronics".

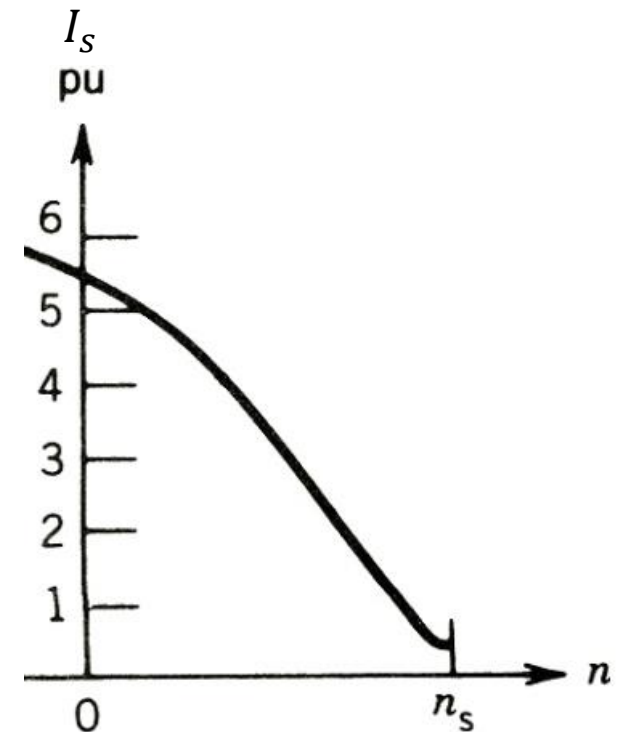
Corrente de estator - tendência



□ Se $s \rightarrow 0$, $I_s \approx I_\Phi$;

□ Se $s \rightarrow 1$, $I_s \approx I'_r$;

□ Corrente de partida (pode ser até 10 vezes a corrente nominal)

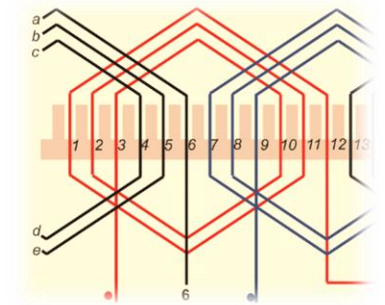


Fonte: P. C. Sen. "Principles of Electrical Machines and Power Electronics".

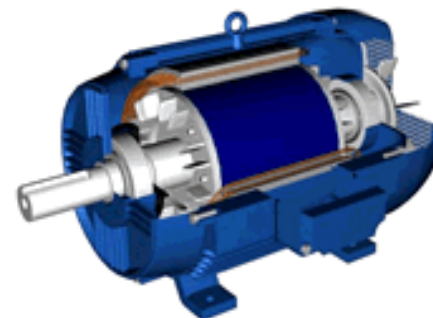
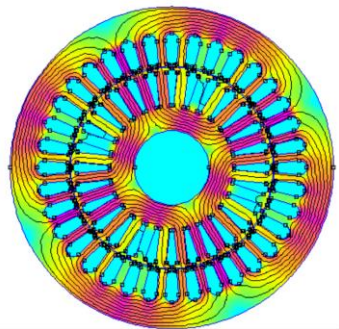
Métodos de redução de corrente de partida

- Partida estrela triângulo;
- Partida com autotransformador (chave compensadora);
- Inserção de resistência no rotor (rotor bobinado);
- Soft-Starter;
- Inversor de frequência.





Categorias de conjugado



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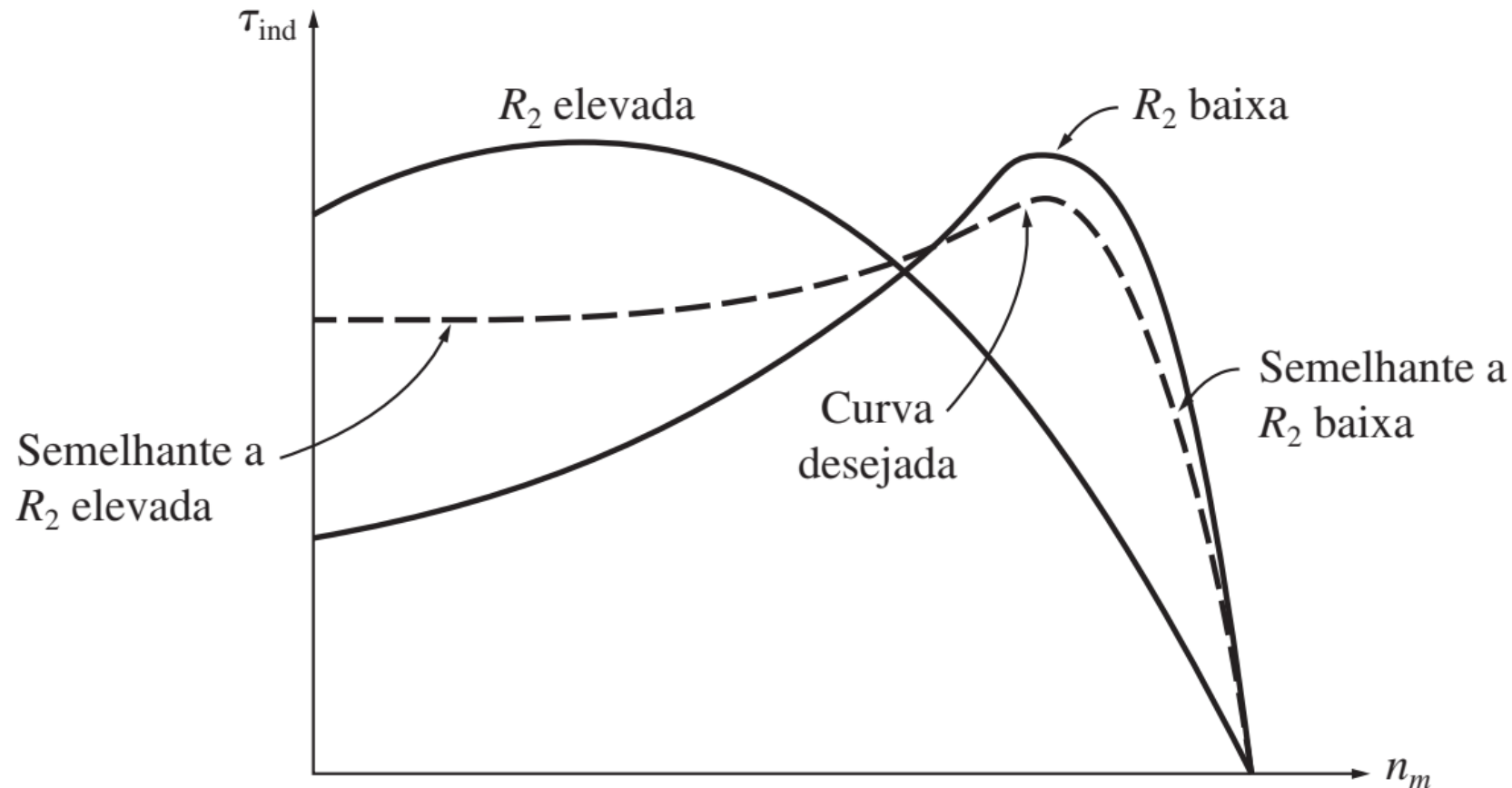
Conclusões parciais e relações de compromisso

- ❑ Torque de partida
 - Alto para valor adequado de R'_r (relativamente alto);
 - R'_r alto resulta em um maior escorregamento (menor eficiência).

- ❑ Corrente de partida
 - Maior quanto menor a impedância equivalente da máquina;
 - Métodos de partida.

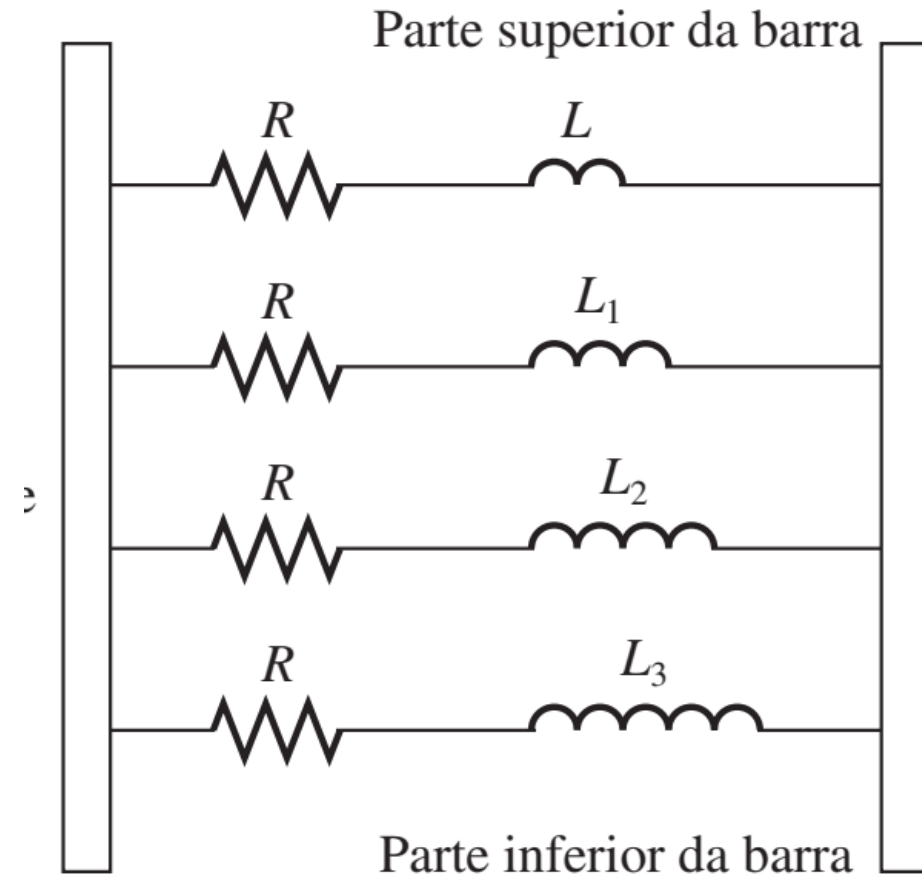
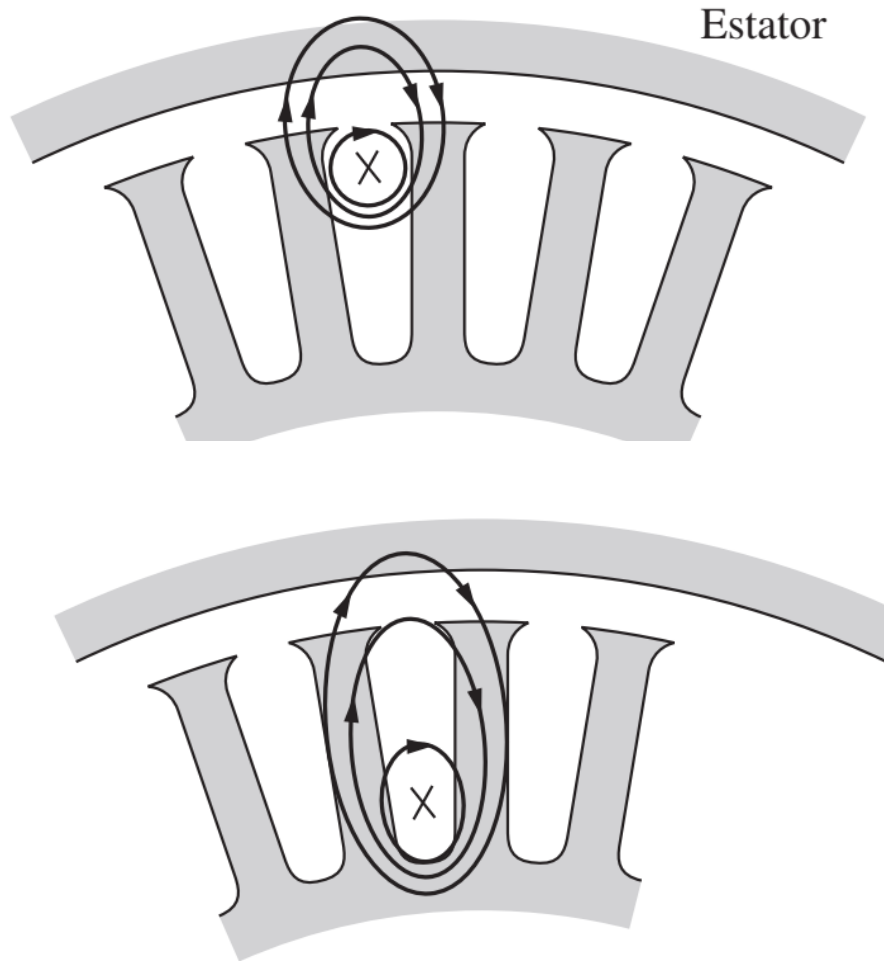
- ❑ Rotor bobinado
 - Baixa corrente de partida e conjugado elevado;
 - Motor mais caro;
 - Motor com maior custo de manutenção.

Características desejáveis



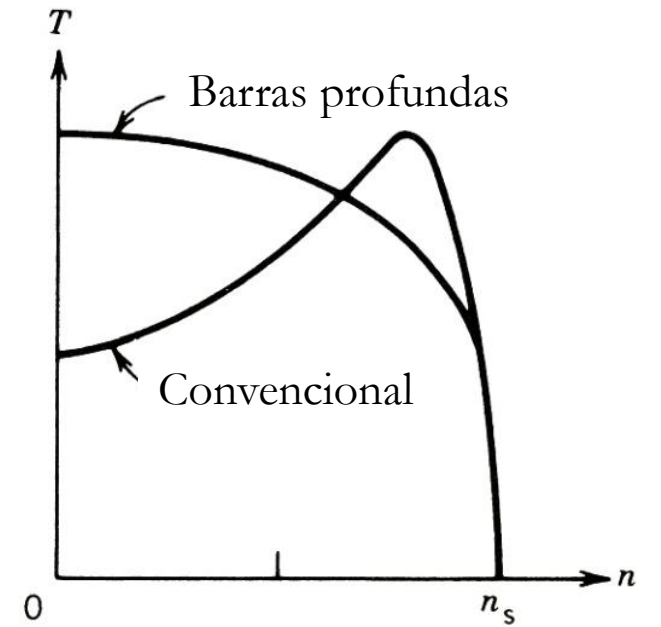
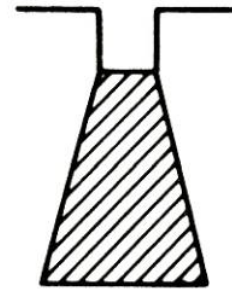
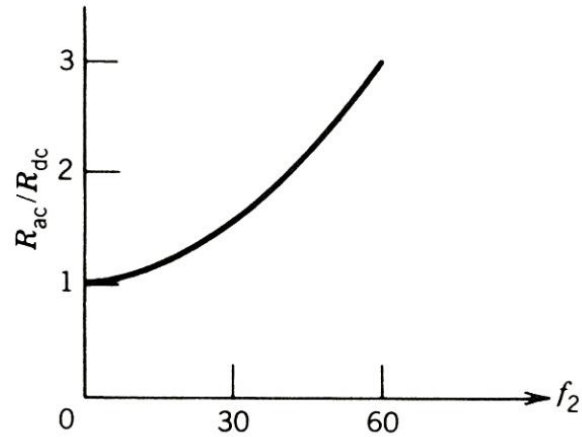
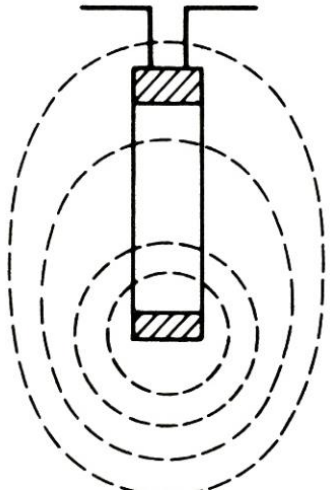
❑ Como obter esta característica em um motor com rotor em gaiola? **Projeto do rotor!**

Motor de barras profundas



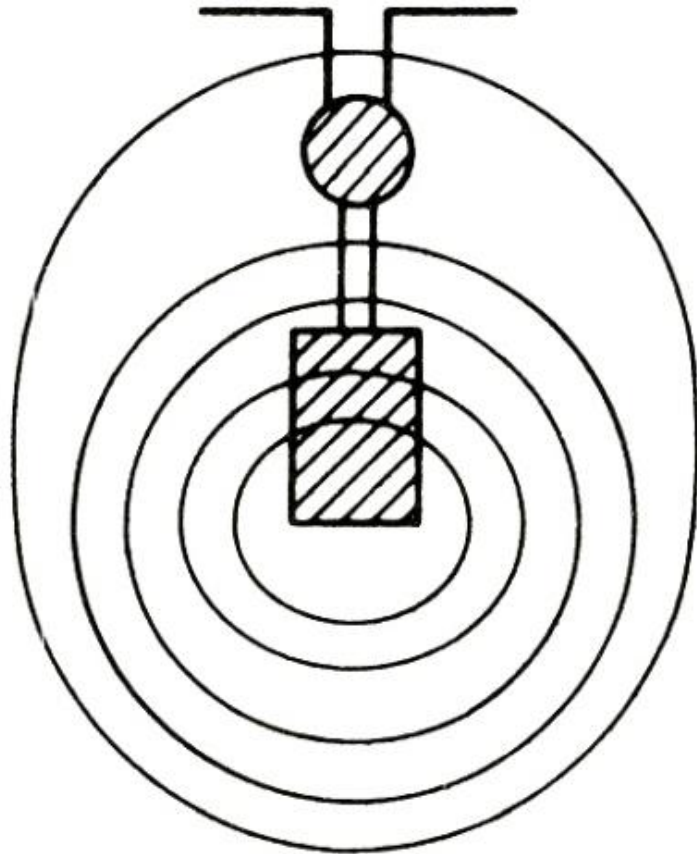
S. J. Chapman. "Fundamentos de Máquinas Elétricas".

Motor de barras profundas

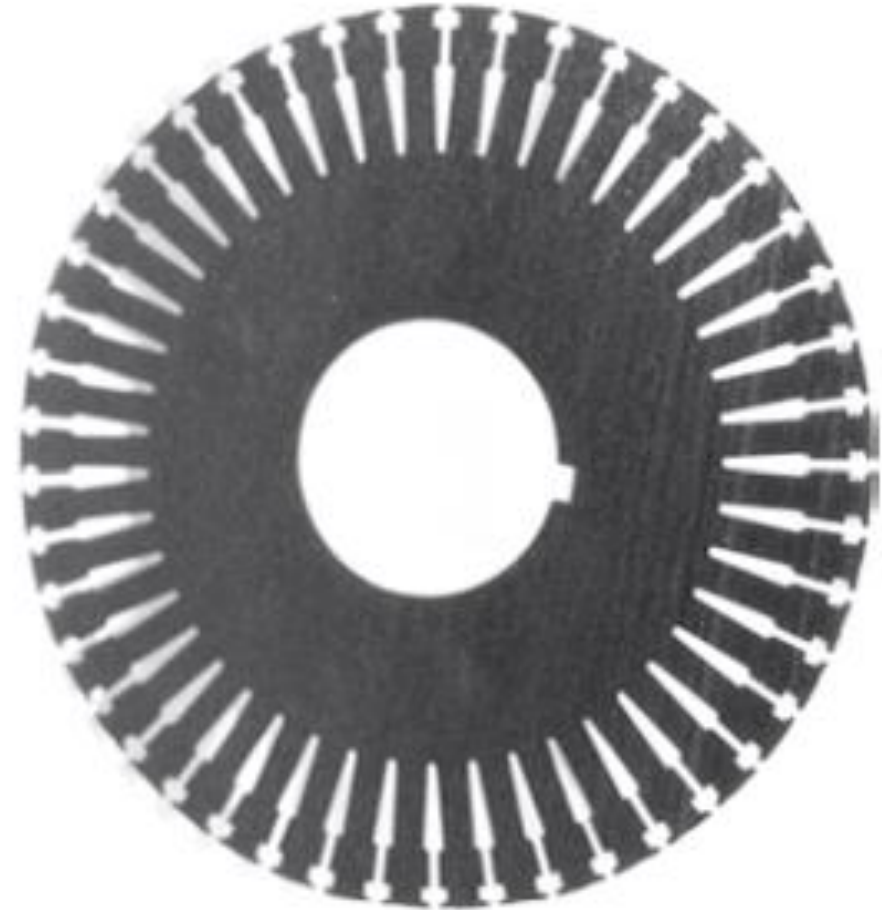


Fonte: P. C. Sen. "Principles of Electrical Machines and Power Electronics".

Motor de dupla gaiola

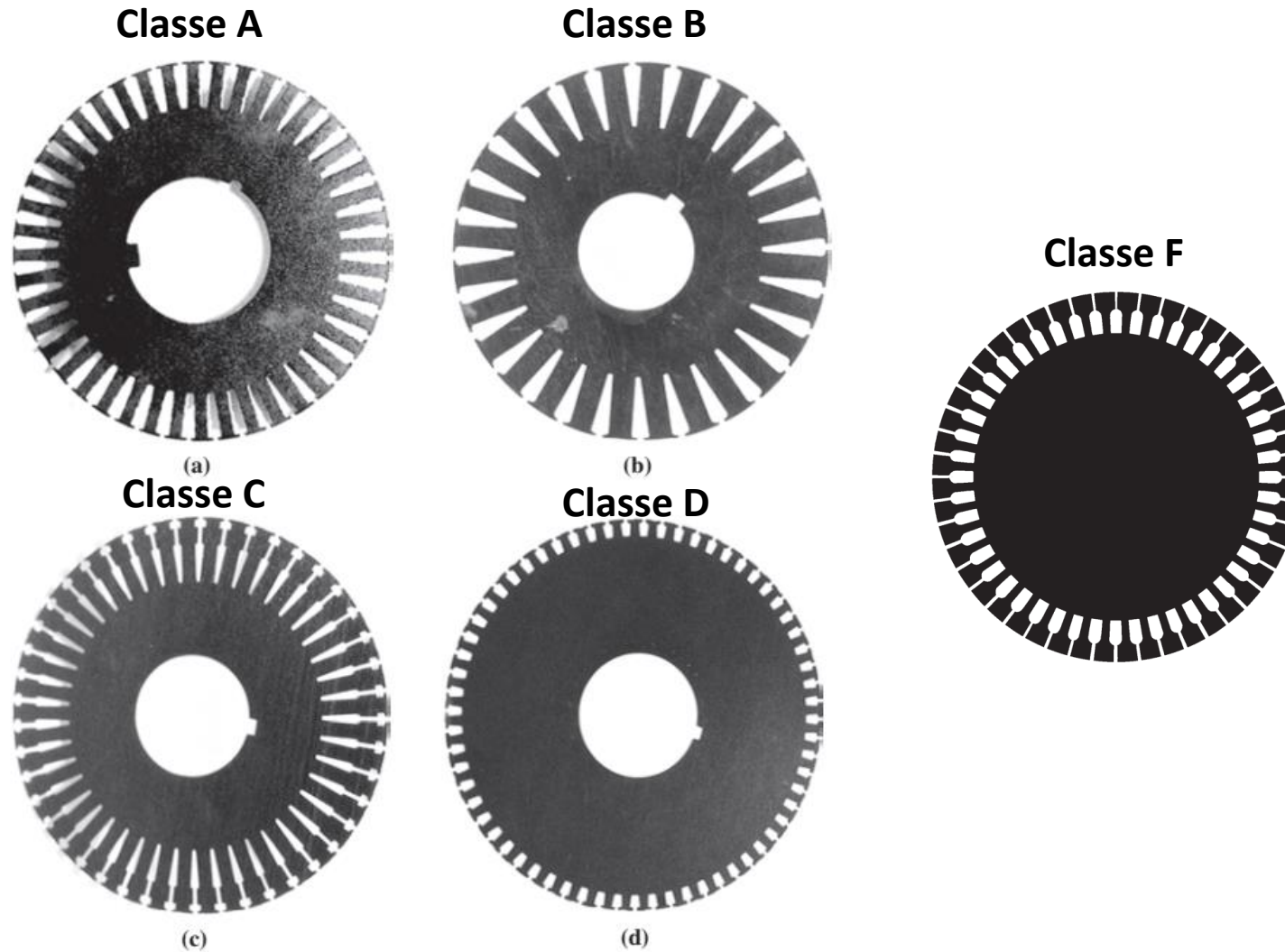


Fonte: P. C. Sen. "Principles of Electrical Machines and Power Electronics".



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Aspecto físico do rotor



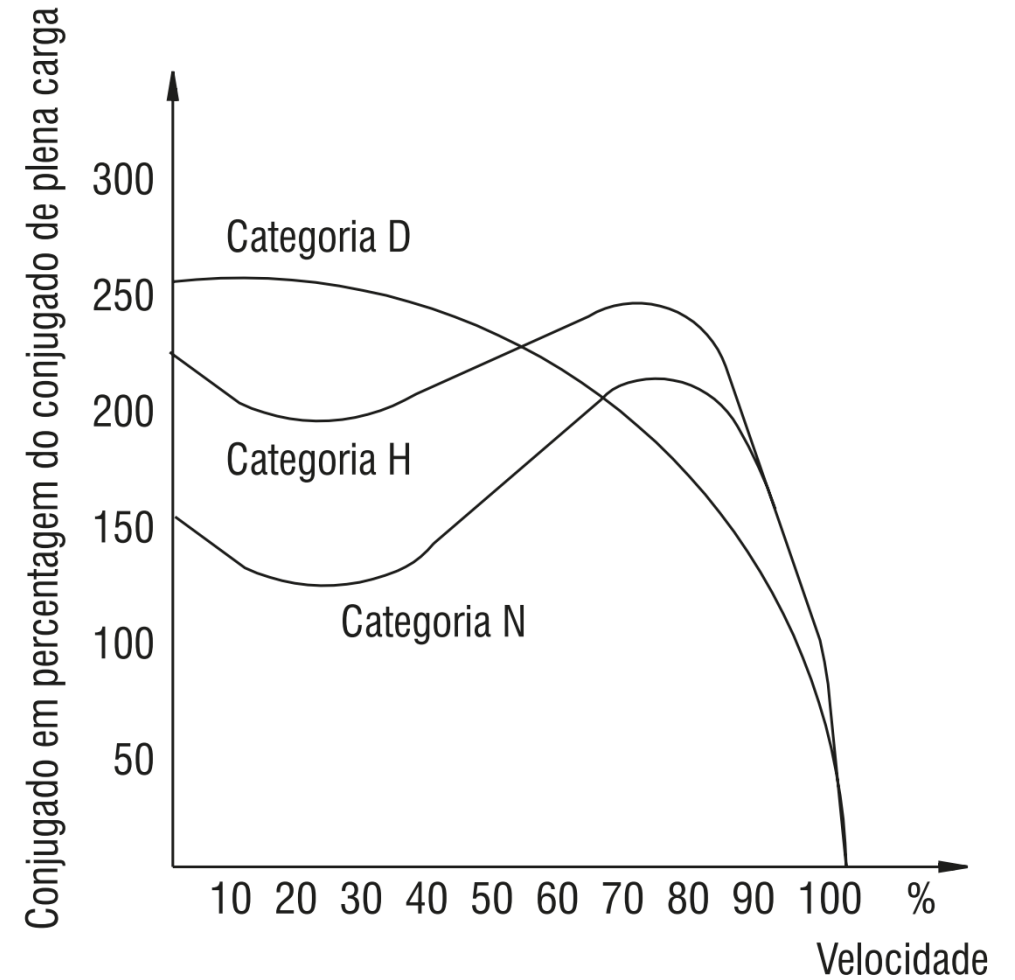
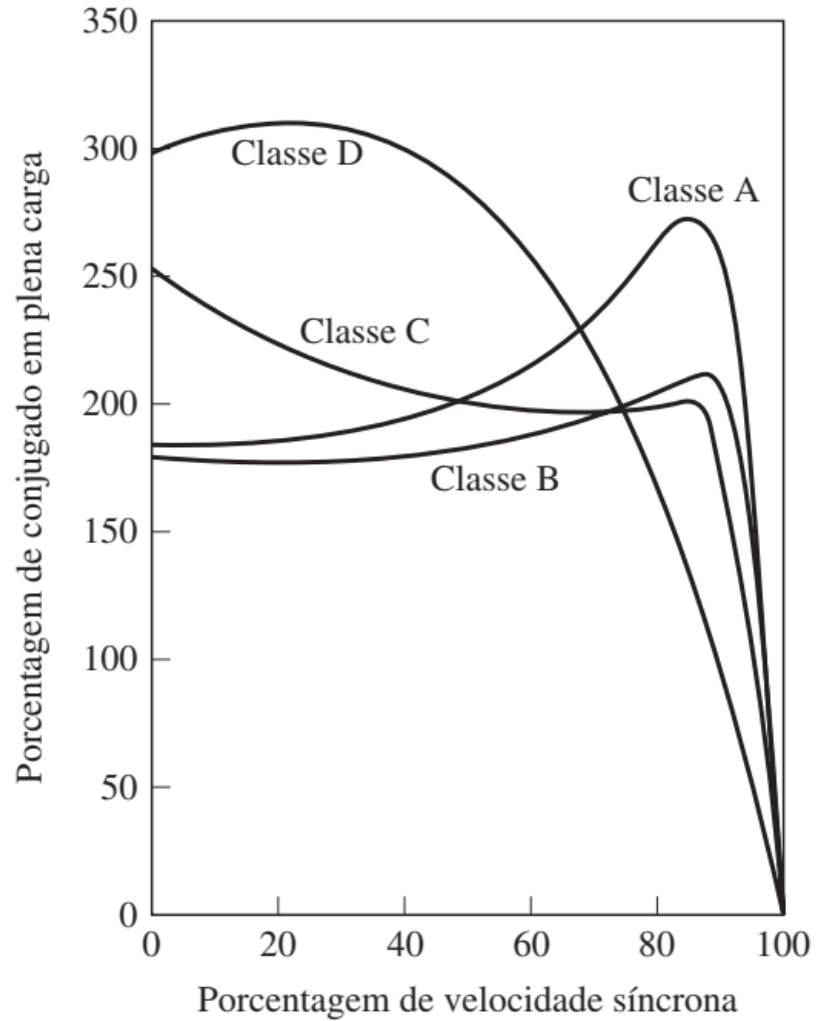
S. J. Chapman. "Fundamentos de Máquinas Eléctricas".

Categorias de conjugado de motores de indução trifásicos

	X_1 e X_2 em função de X_{RB}	
Tipo de rotor	X_1	X_2
Rotor bobinado	$0,5 X_{RB}$	$0,5 X_{RB}$
Classe A	$0,5 X_{RB}$	$0,5 X_{RB}$
Classe B	$0,4 X_{RB}$	$0,6 X_{RB}$
Classe C	$0,3 X_{RB}$	$0,7 X_{RB}$
Classe D	$0,5 X_{RB}$	$0,5 X_{RB}$

NEMA	ABNT NBR 17094
A	N
B	
C	H
D	D
E	-
F	-

Motor de dupla gaiola



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