



Universidade Federal do ABC

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Pós-graduação em Engenharia Elétrica

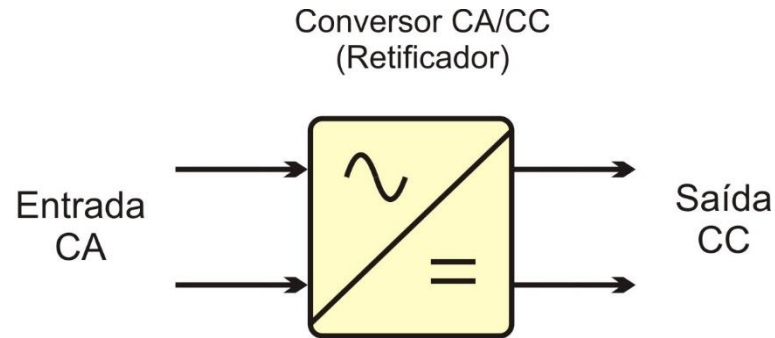
Aplicações de Conversores Estáticos de Potência

José L. Azcue Puma, Prof. Dr.

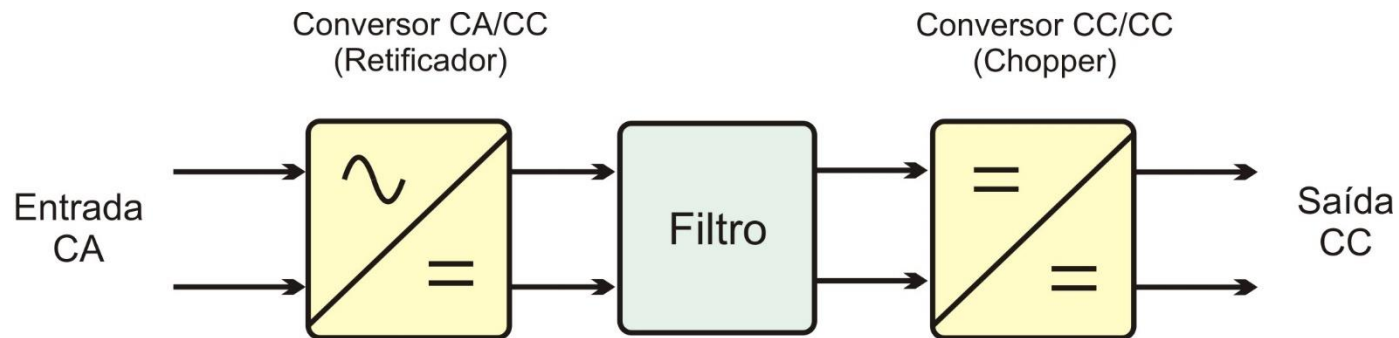
- ✓ *Acionamento de Maquinas CC*

Conversores para acionamento de motores

- **Acionamento de motores CC**

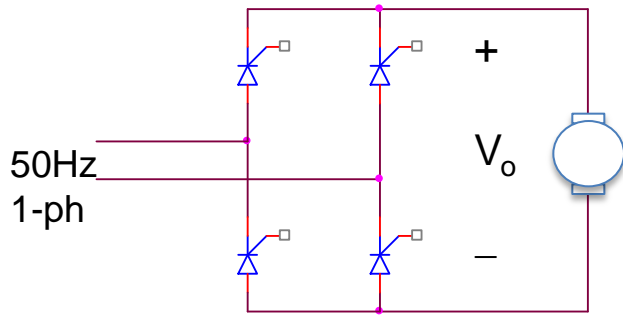


Conversor CA/CC (retificador controlado)



Conversor CA/CC-CC/CC

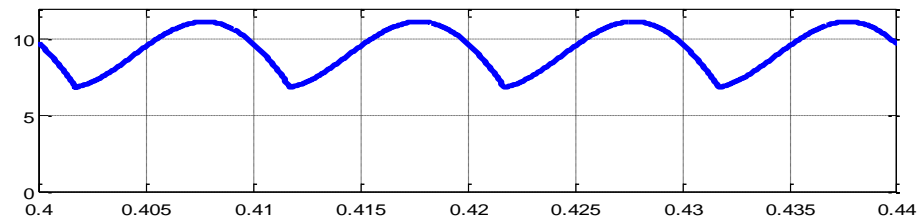
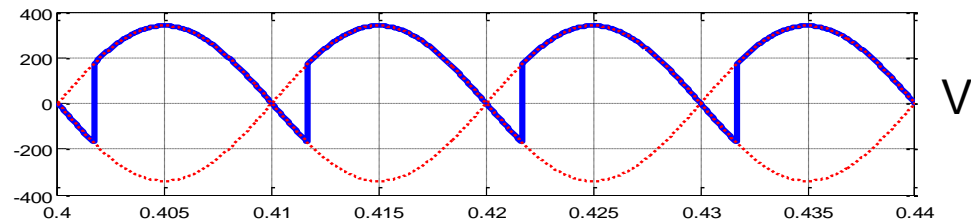
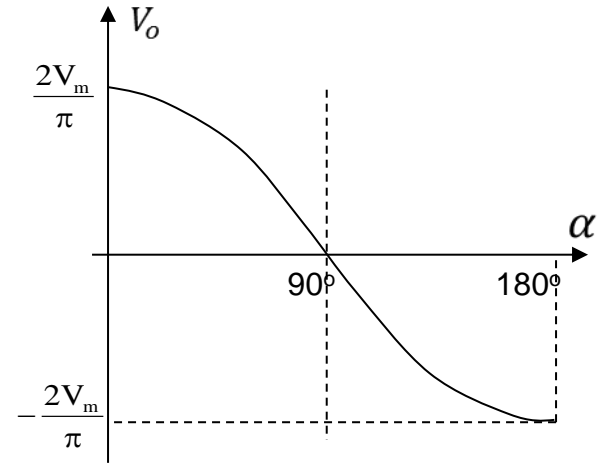
Acionadores CC



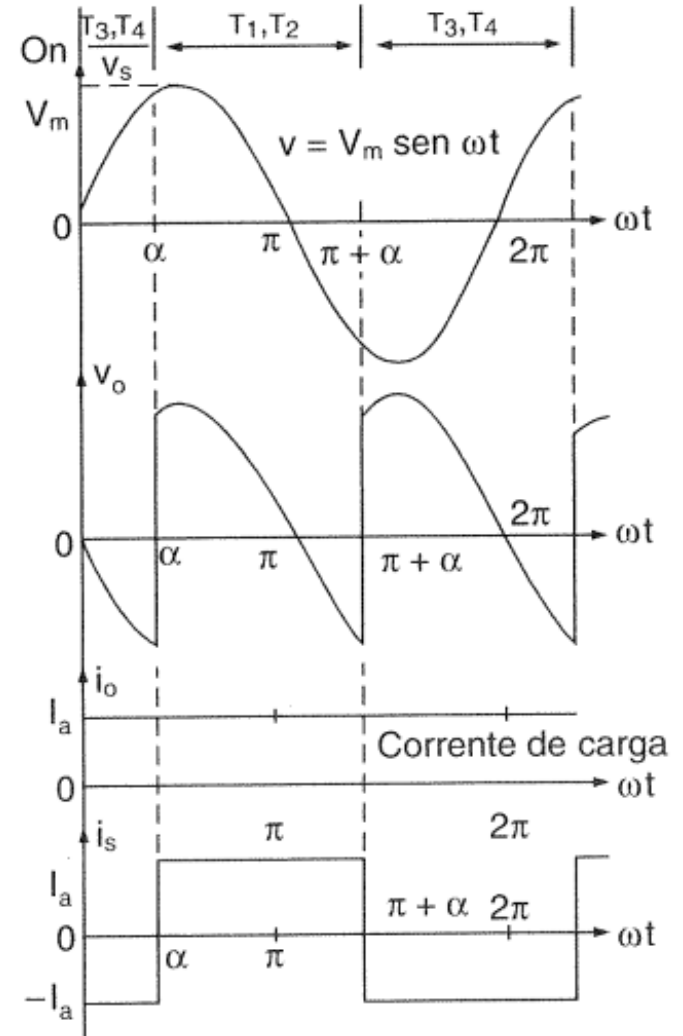
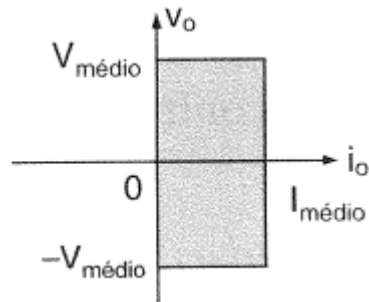
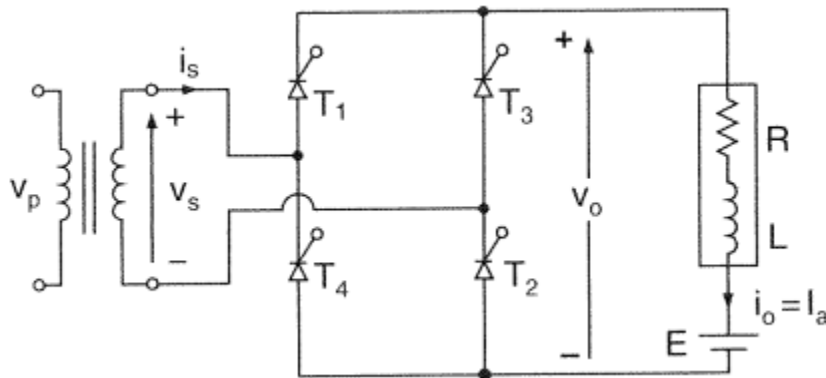
$$V_o = \frac{2V_m}{\pi} \cos \alpha$$

Tensão média

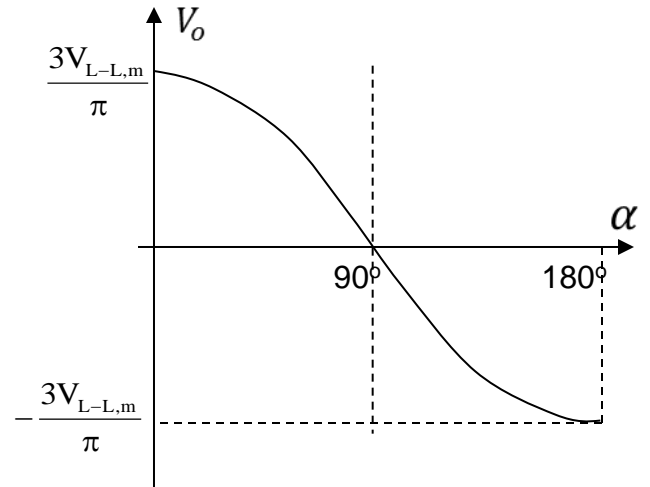
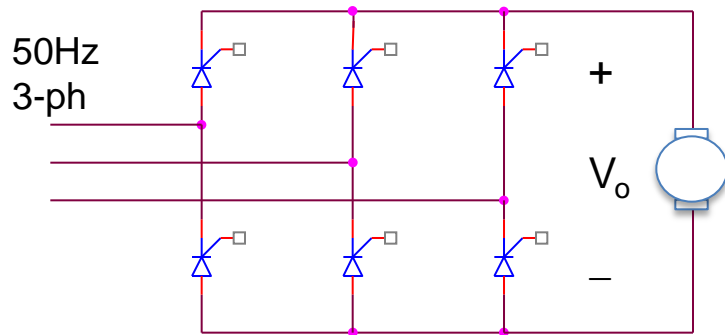
T=10 ms (50 Hz)



Retificador Controlado



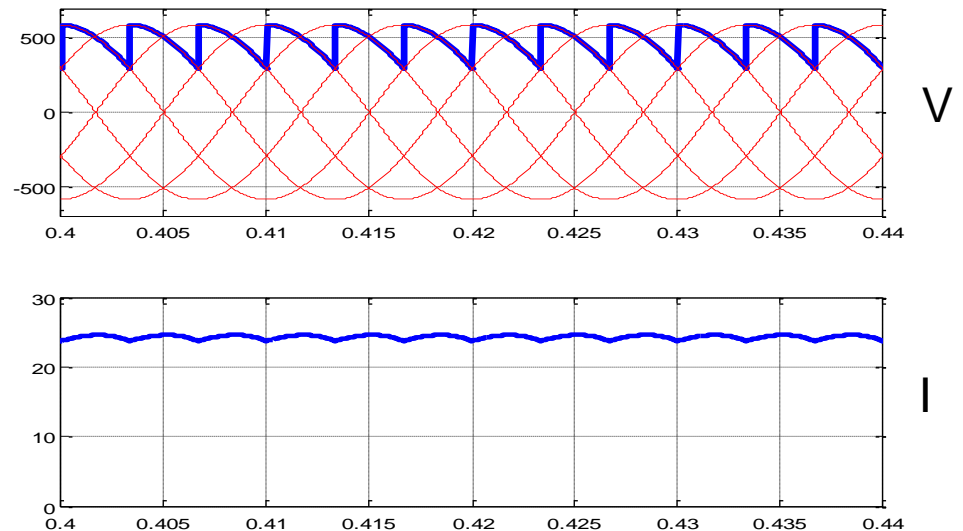
Acionadores CC



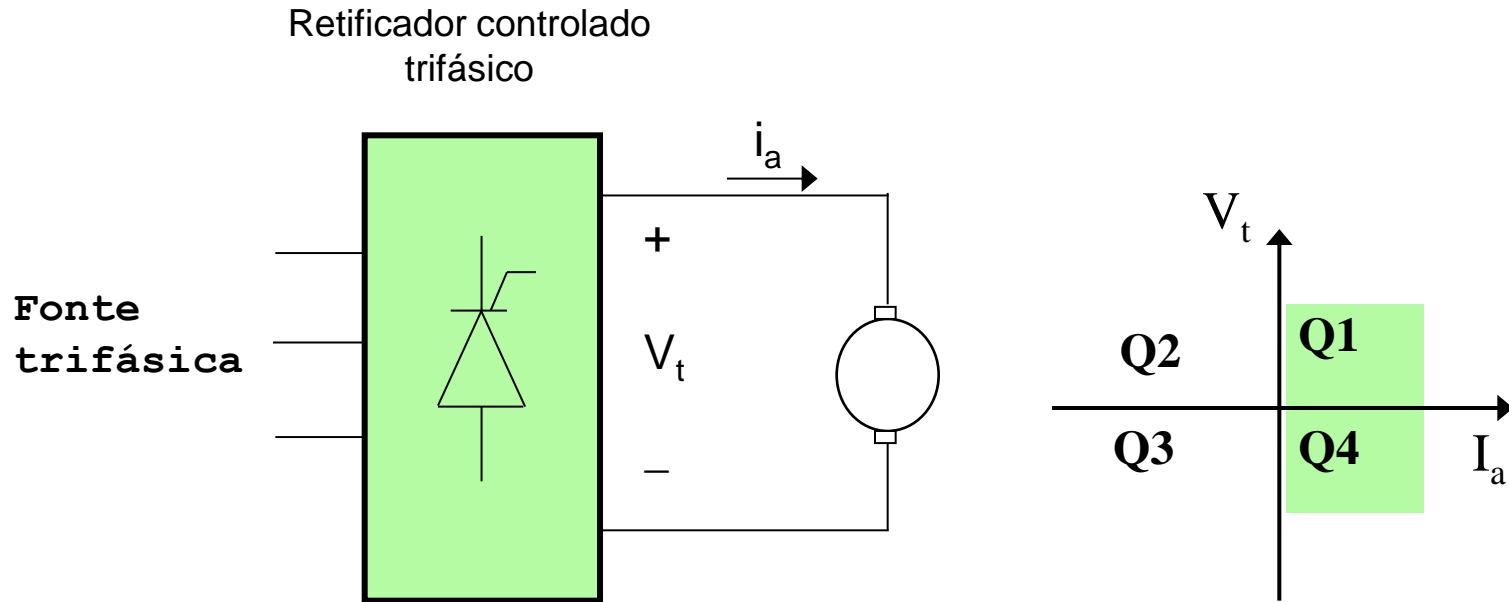
$$V_o = \frac{3V_{L-L,m}}{\pi} \cos \alpha$$

Tensão média

$T=3,33 \text{ ms}$

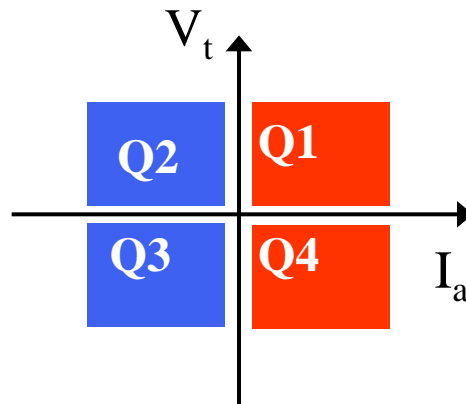
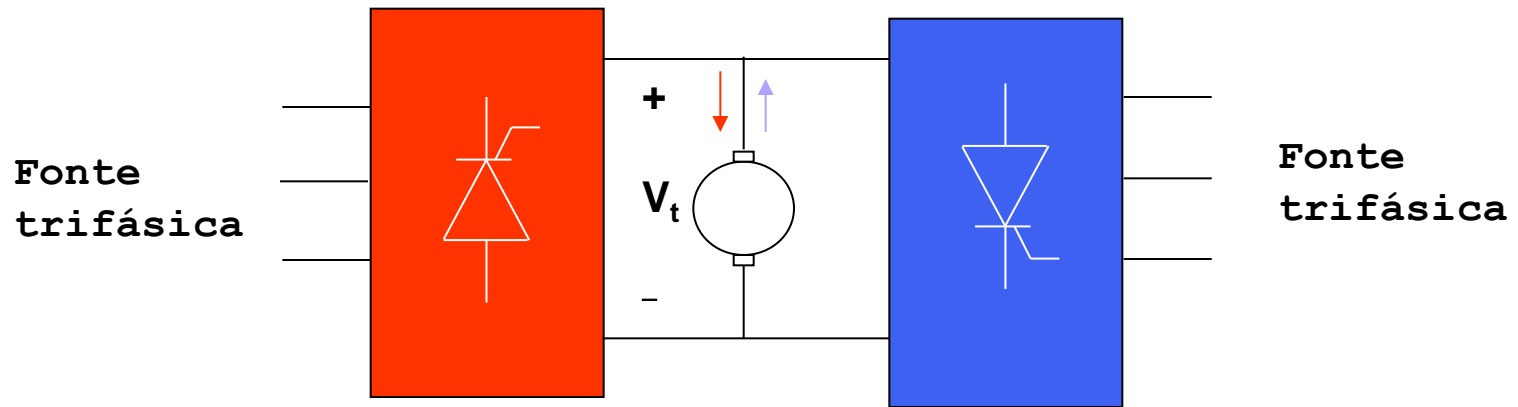


Acionadores CC

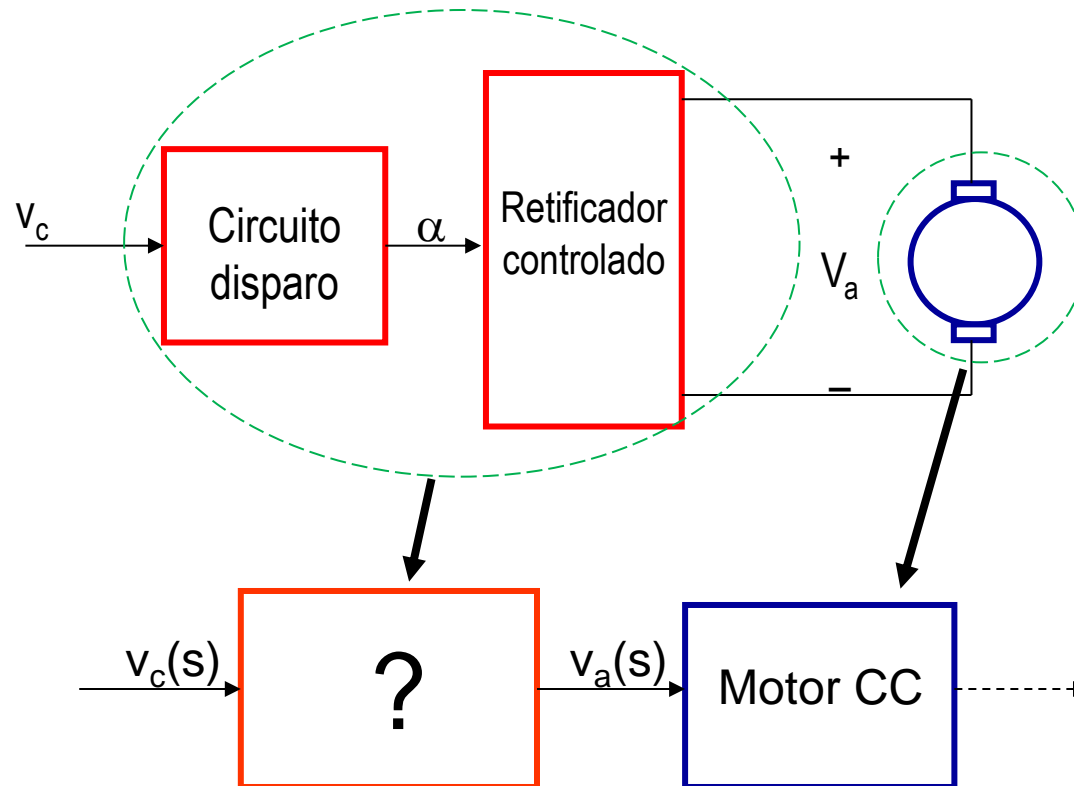


Operação no primeiro e quarto quadrante

Acionadores CC



Retificador Controlado

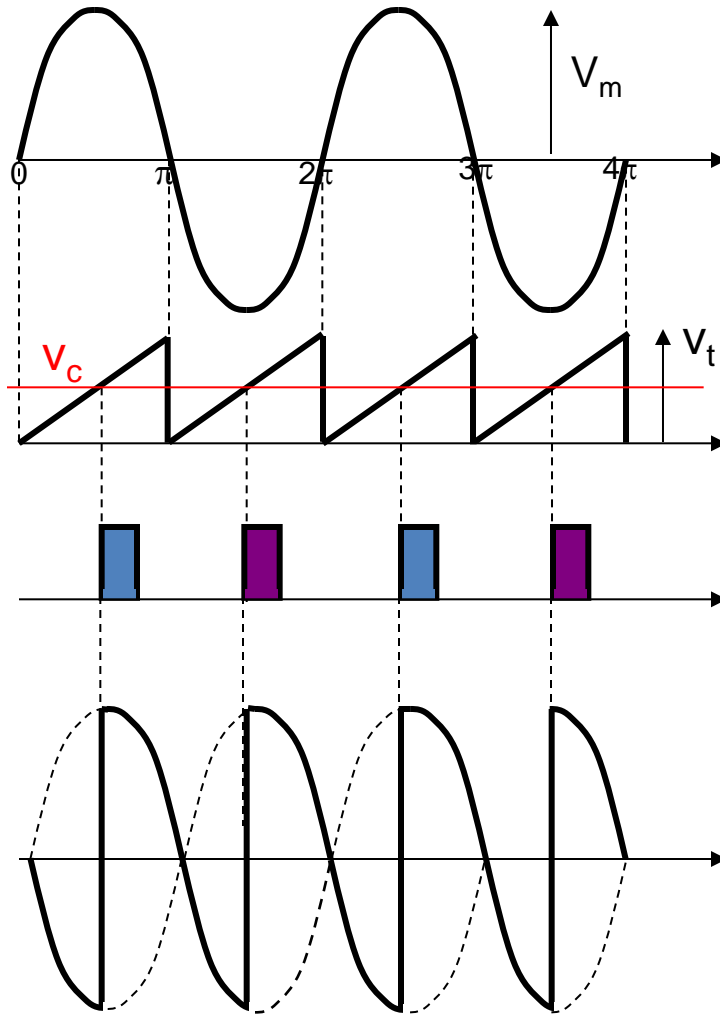


A relação entre v_c e v_a é determinado pelo circuito de disparo

É desejável uma relação linear entre v_c e v_a

Retificador Controlado

Controle linear do ângulo de disparo



Tensão de entrada

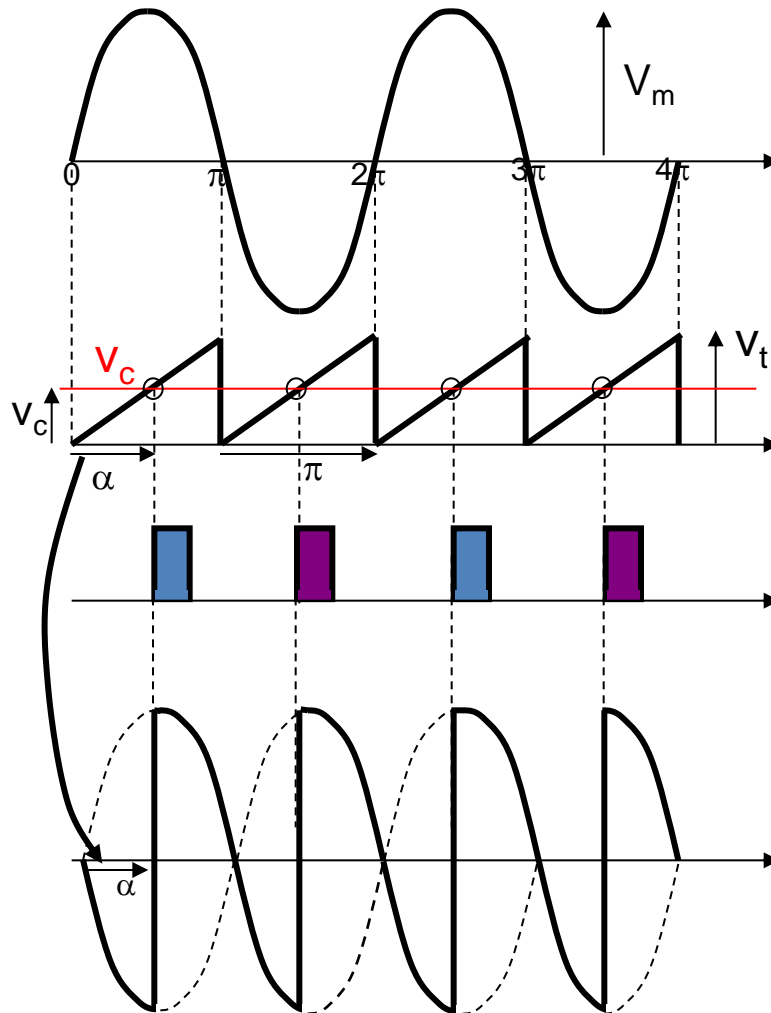
Sinal dente de serra e sinal de controle

Sinal de disparo

Tensão de saída

Retificador Controlado

Controle linear do ângulo de disparo



$$\frac{V_t}{\pi} = \frac{V_c}{\alpha}$$

$$\alpha = \frac{V_c}{V_t} \pi$$

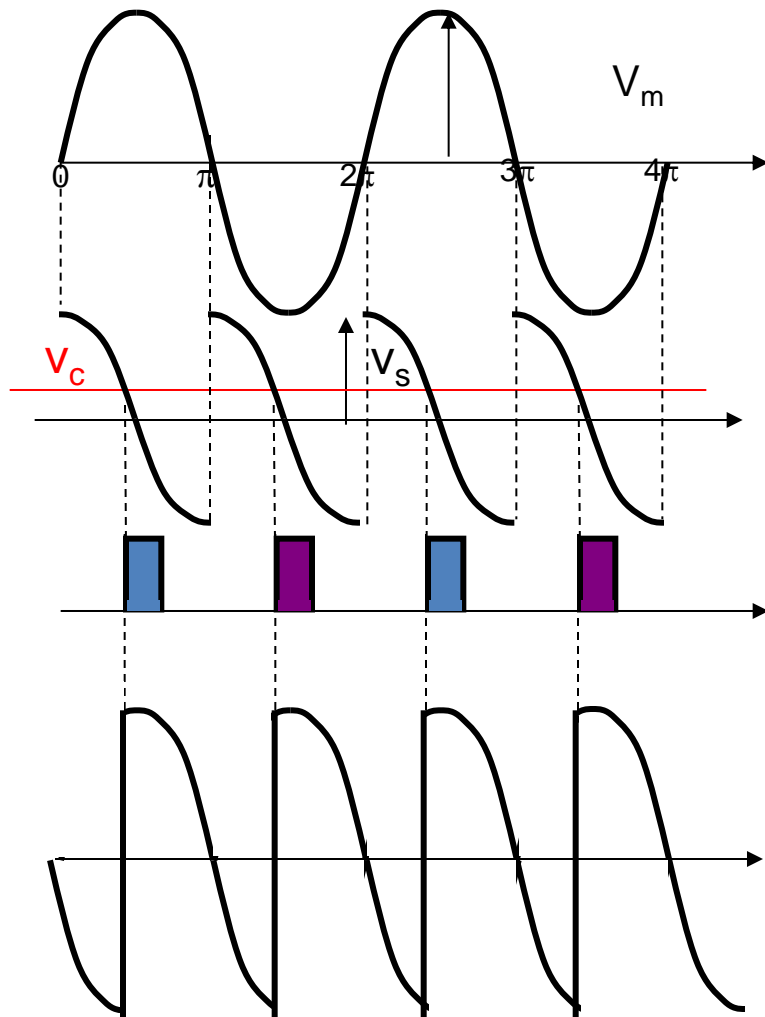
$$V_a = \frac{2V_m}{\pi} \cos(\alpha)$$

$$V_a = \frac{2V_m}{\pi} \cos\left(\frac{V_c}{V_t} \pi\right)$$

Relação não linear entre V_a e V_c

Retificador Controlado

Controle linear do ângulo de disparo



Tensão de entrada

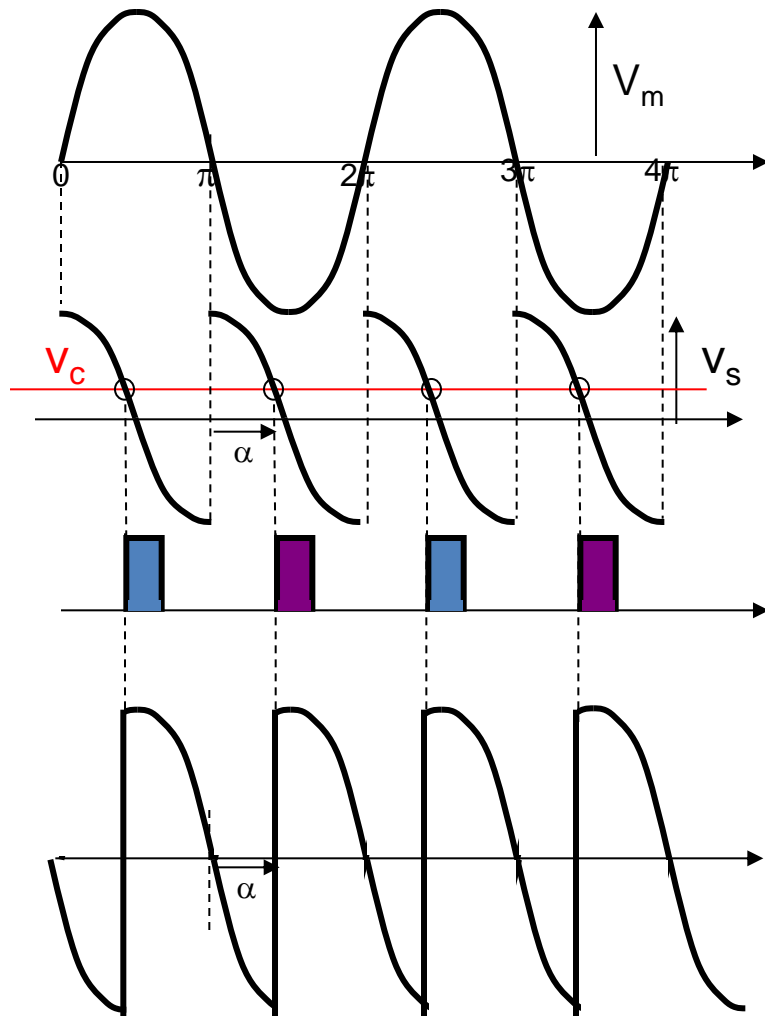
Sinal cossenoide comparada com v_c

Pulsos de disparo para os SCRs

Tensão de saída

Retificador Controlado

Controle linear do ângulo de disparo



$$V_s \cos(\omega t)$$

$$V_s \cos(\alpha) = v_c$$

$$\alpha = \cos^{-1}\left(\frac{v_c}{V_s}\right)$$

$$V_a = \frac{2V_m}{\pi} \cos(\alpha)$$

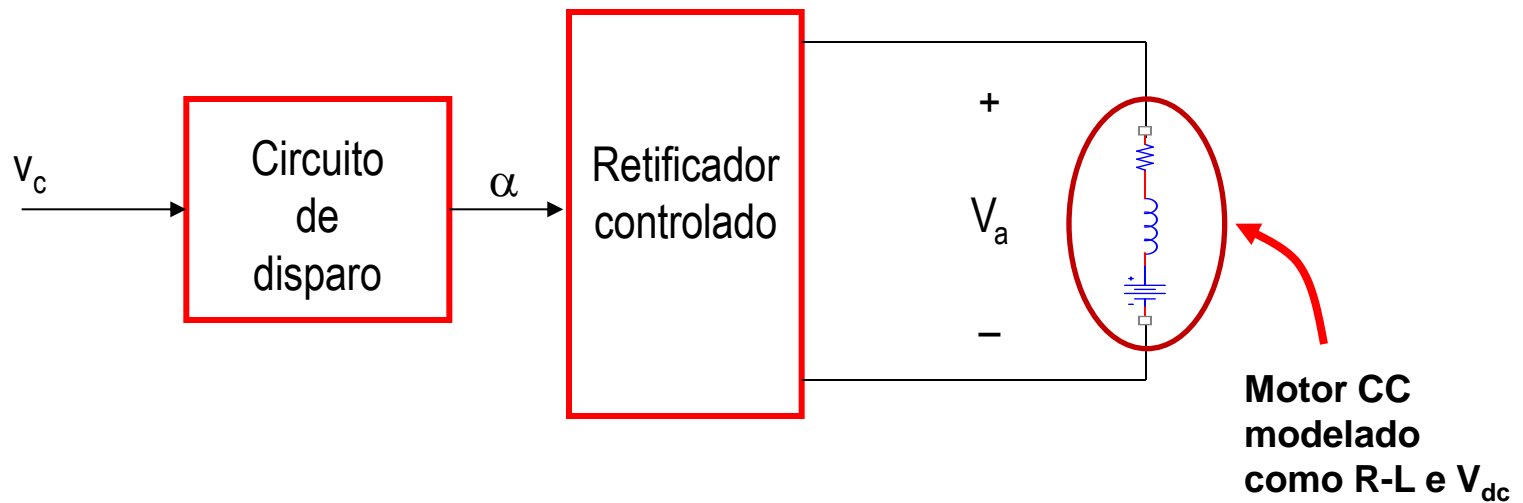
$$V_a = \frac{2V_m}{\pi} \cos\left(\cos^{-1}\left(\frac{v_c}{V_s}\right)\right)$$

$$V_a = \frac{2V_m}{\pi} \frac{v_c}{V_s}$$

Relação linear entre v_c e V_a

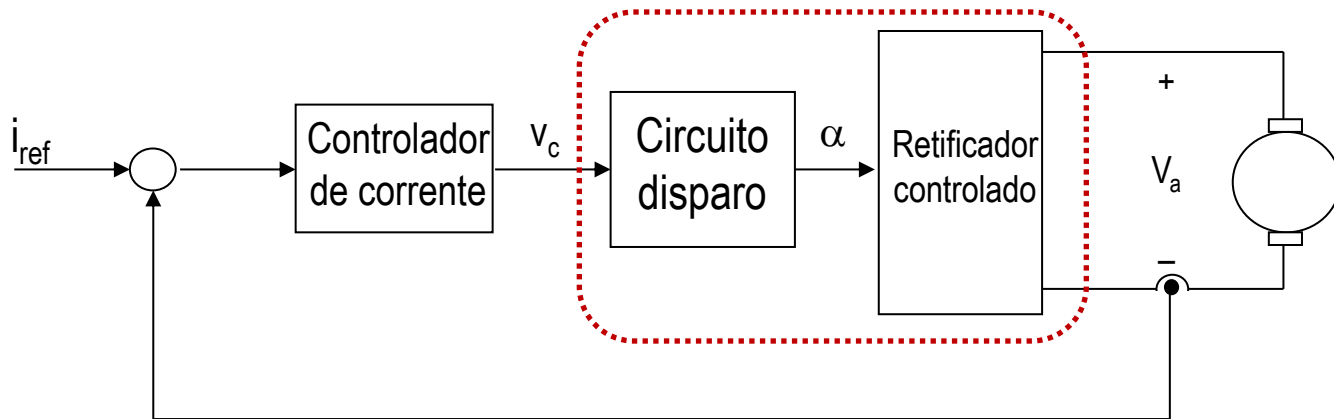
Retificador Controlado

Controle em Malha Aberta

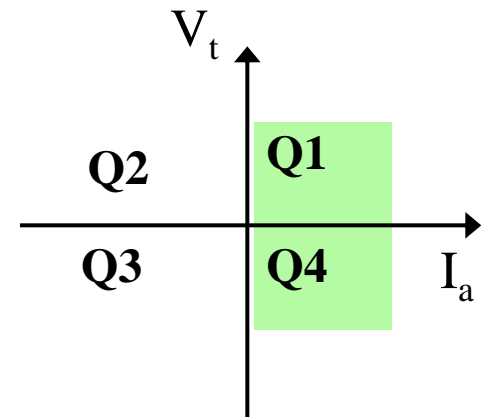


Retificador Controlado

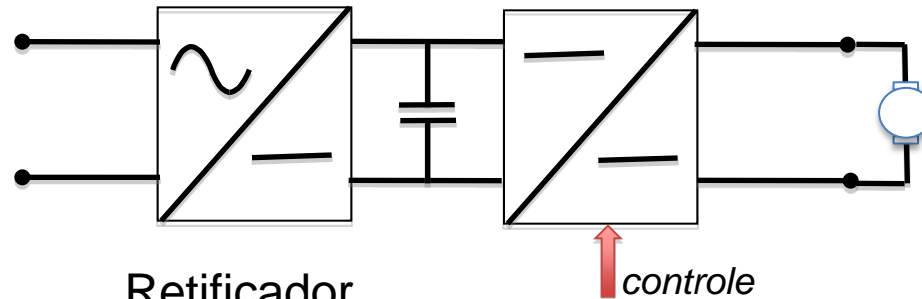
Controle em Malha Fechada



- O torque pode ser controlado
- Opera no Q1 e Q4



Acionadores CA/CC-CC/CC

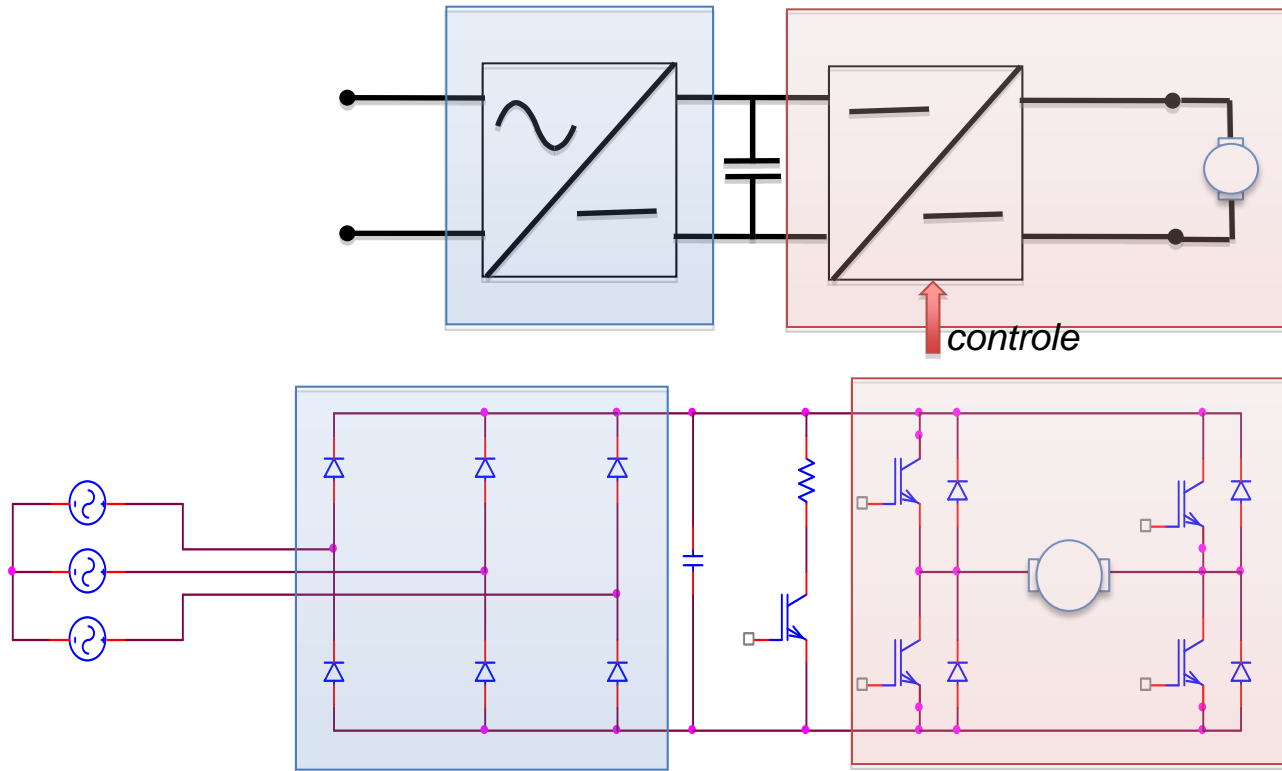


Retificador
não controlado

Conversor CC/CC
1-Quadrante
2-Quadrante
4-Quadrante

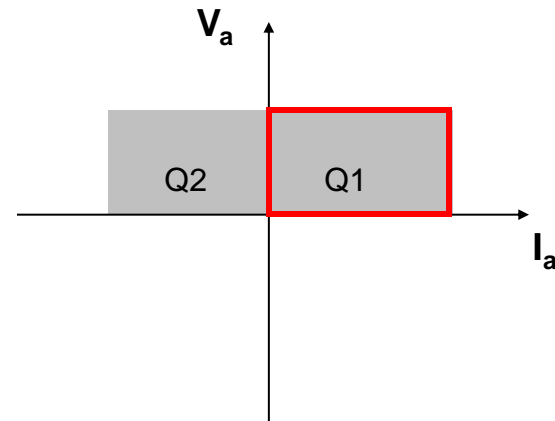
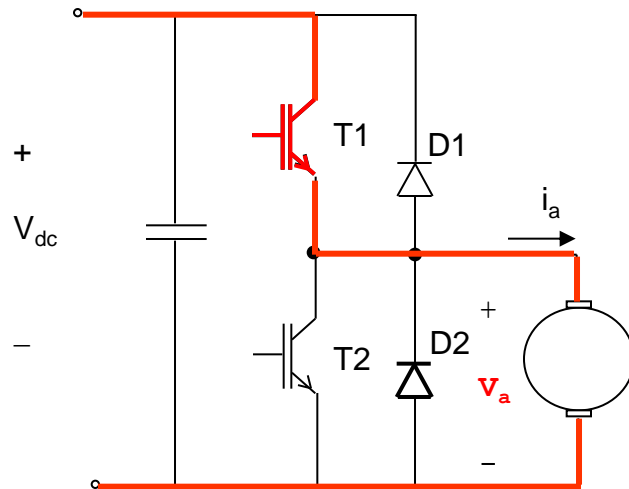
Acionadores CC

CA/CC - CC/CC



Acionamento CC

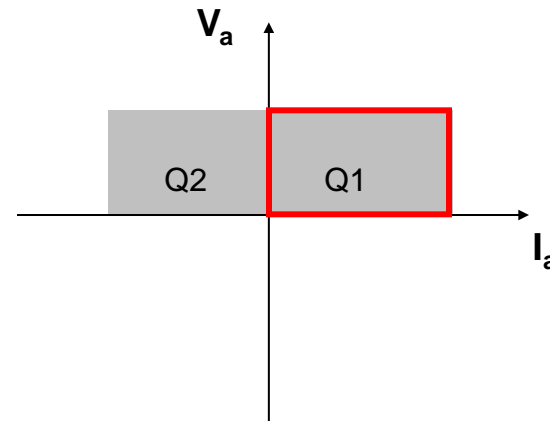
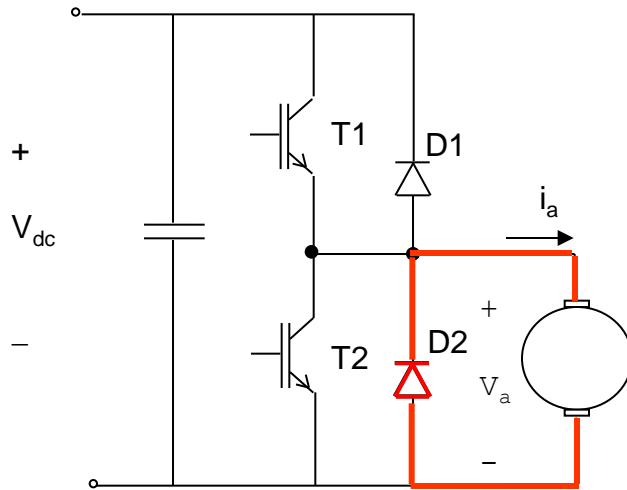
Conversor CC/CC (*Chopper*) de dois quadrantes



T1 conduz $\rightarrow v_a = V_{dc}$

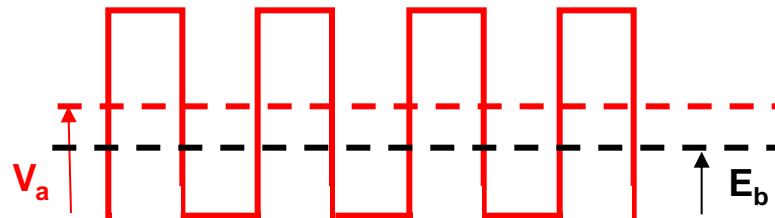
Acionamento CC

Conversor CC/CC de dois quadrantes



D2 conduz $\rightarrow v_a = 0$

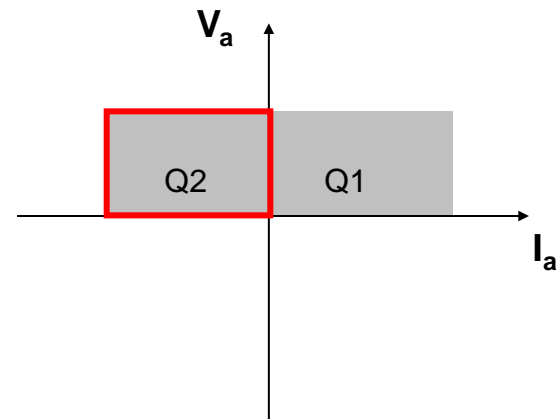
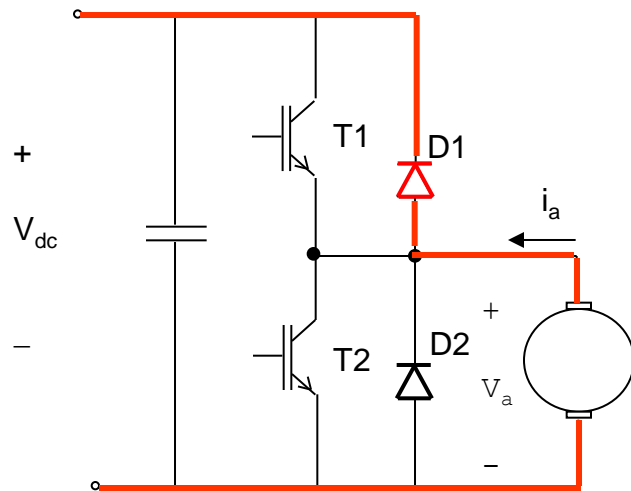
T1 conduz $\rightarrow v_a = V_{dc}$



Quadrante 1 A tensão média é maior que a fcm (E_b)

Acionamento CC

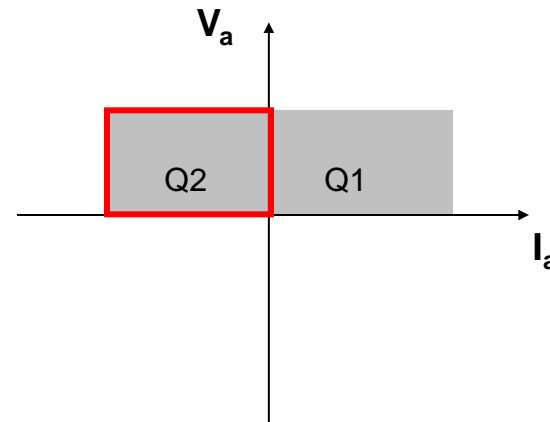
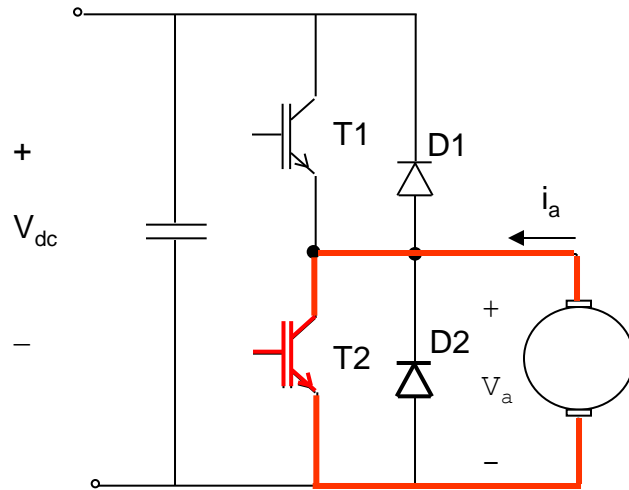
Conversor CC/CC de dois quadrantes



D1 conduz $\rightarrow v_a = V_{dc}$

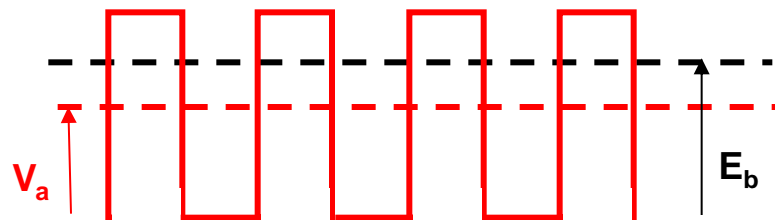
Acionamento CC

Conversor CC/CC de dois quadrantes



T2 conduz $\rightarrow v_a = 0$

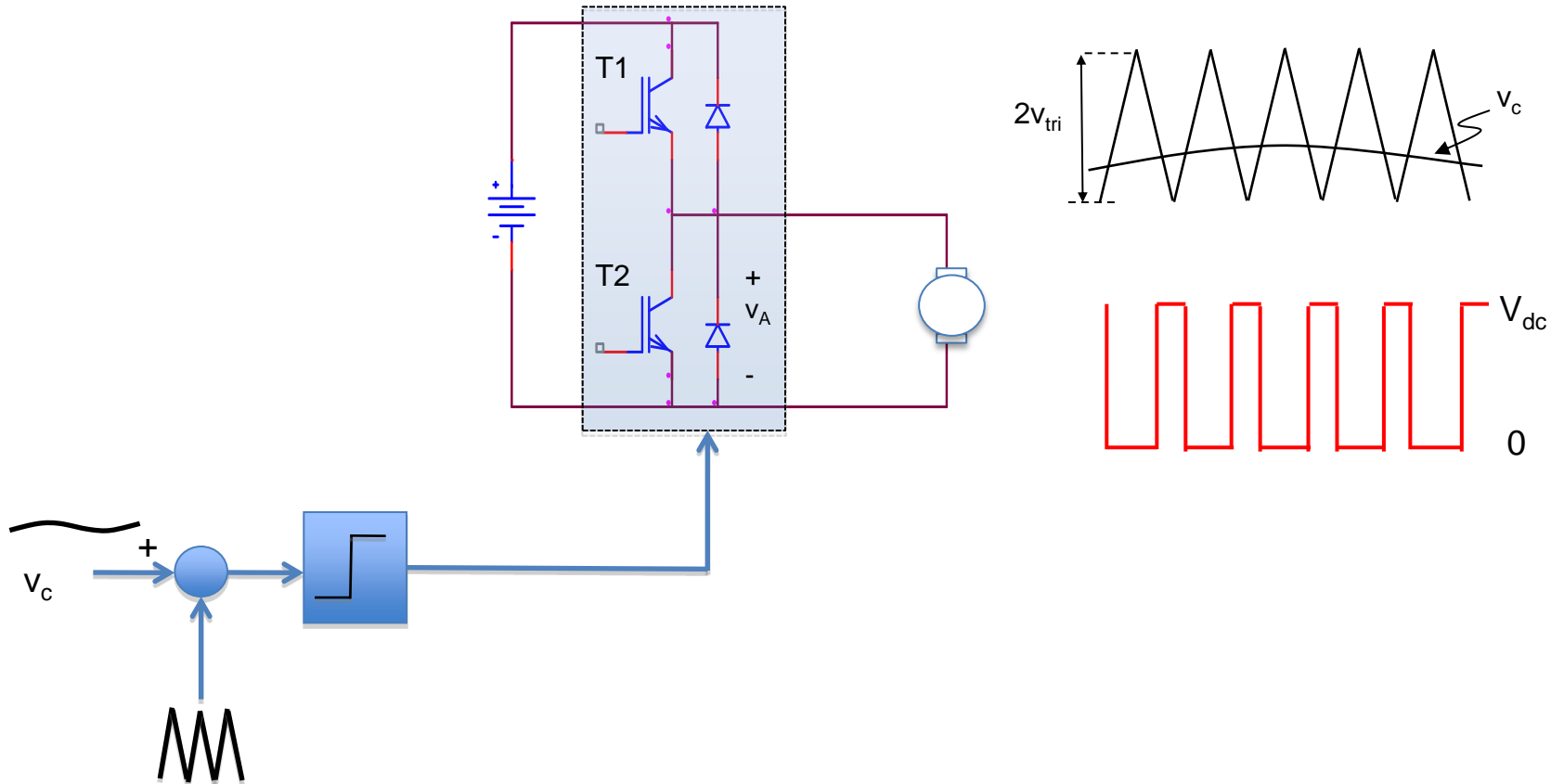
D1 conduz $\rightarrow v_a = V_{dc}$



Quadrante 2 A tensão média é menor que a fcm (E_b), forçando assim que a corrente circule no outro sentido.

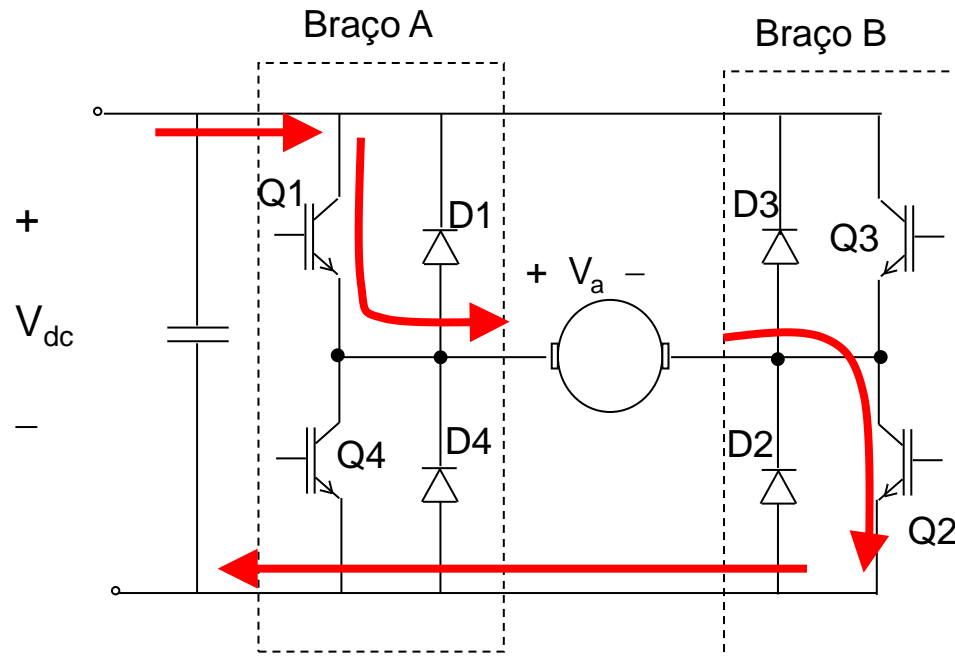
Acionadores CC

Conversor CC/CC de dois quadrantes *Modulação PWM*



Acionamento CC

Conversor CC/CC de quatro quadrantes

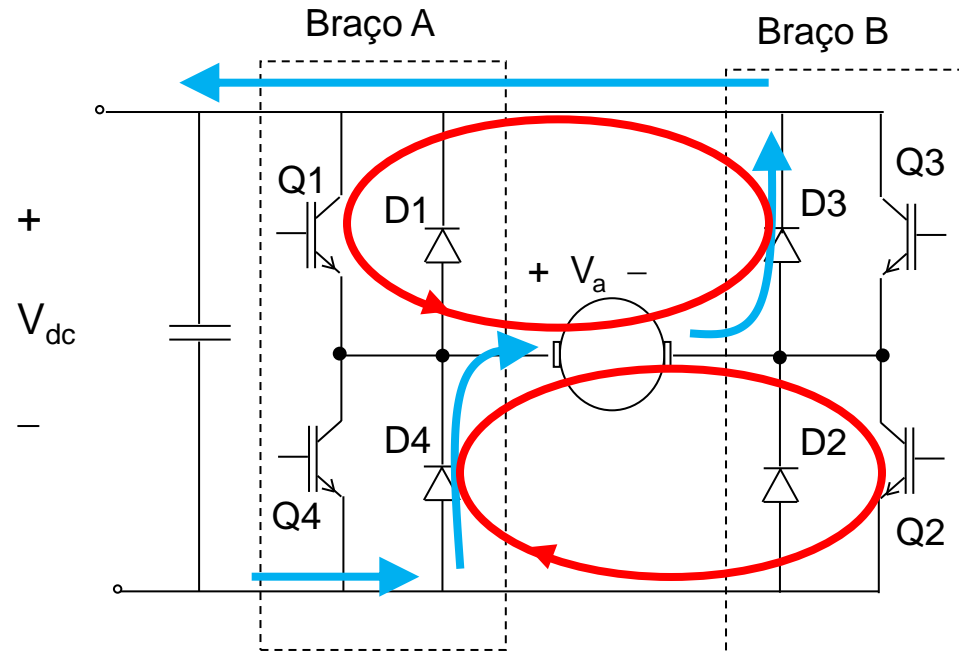


Corrente positiva

$v_a = V_{dc}$ **quando Q1 e Q2 conduzem**

Acionamento CC

Conversor CC/CC de quatro quadrantes



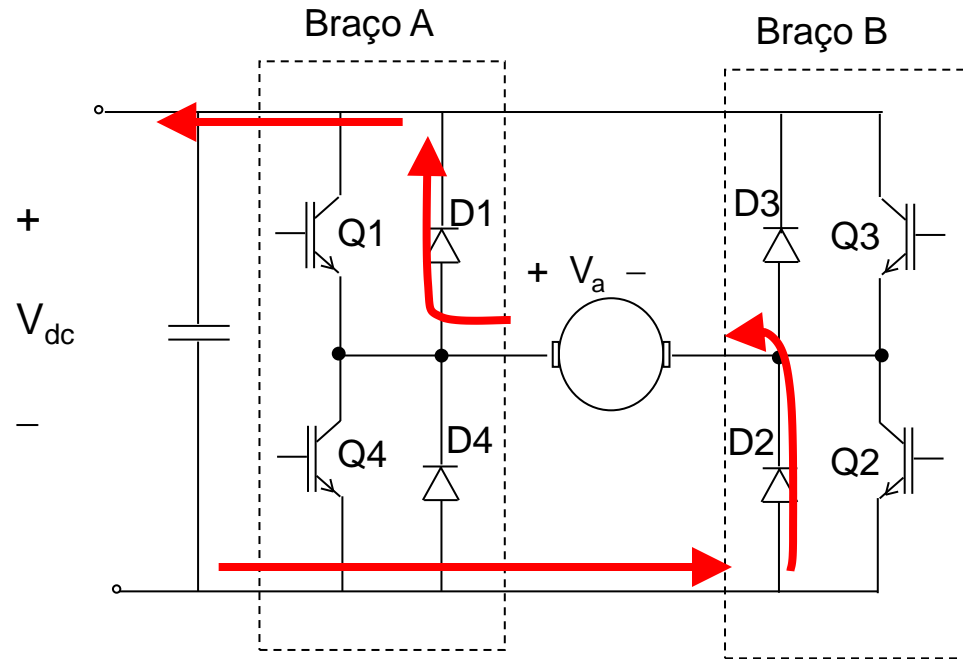
Corrente positiva

$v_a = -V_{dc}$ quando D3 e D4 conduzem

$v_a = 0$ A corrente circula livremente através de Q e D

Acionamento CC

Conversor CC/CC de quatro quadrantes

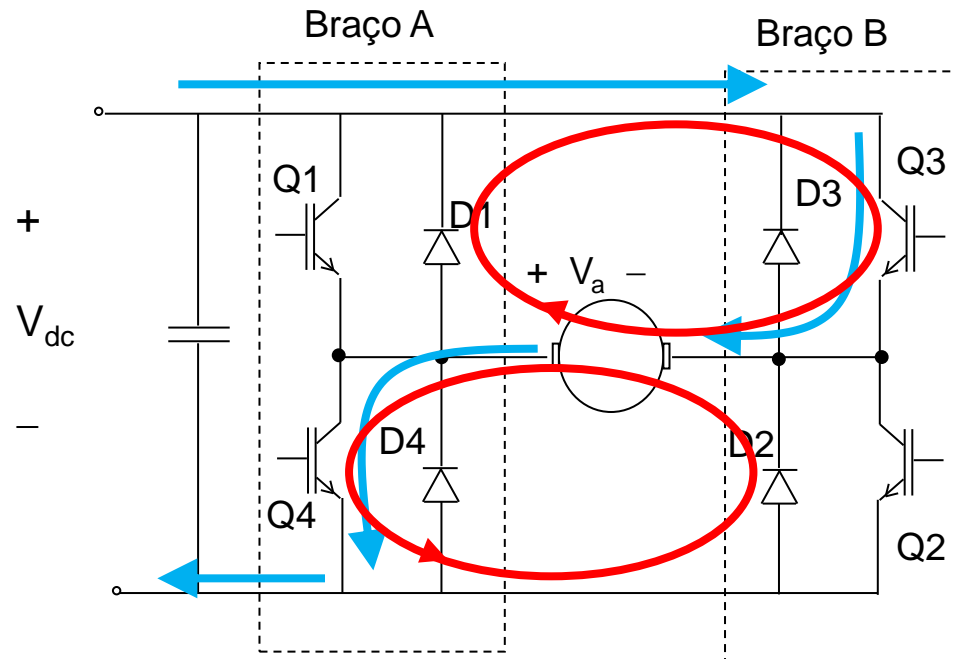


Corrente negativa

$v_a = V_{dc}$ **quando D1 e D2 conduzem**

Acionamento CC

Conversor CC/CC de quatro quadrantes



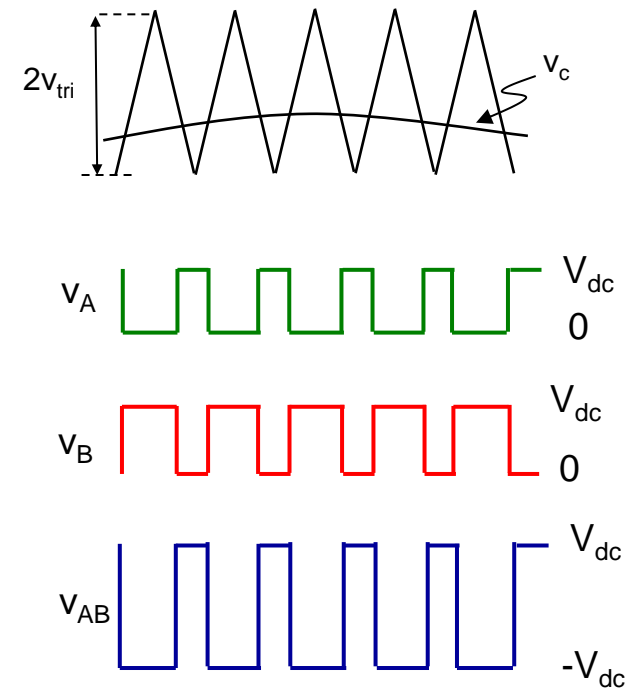
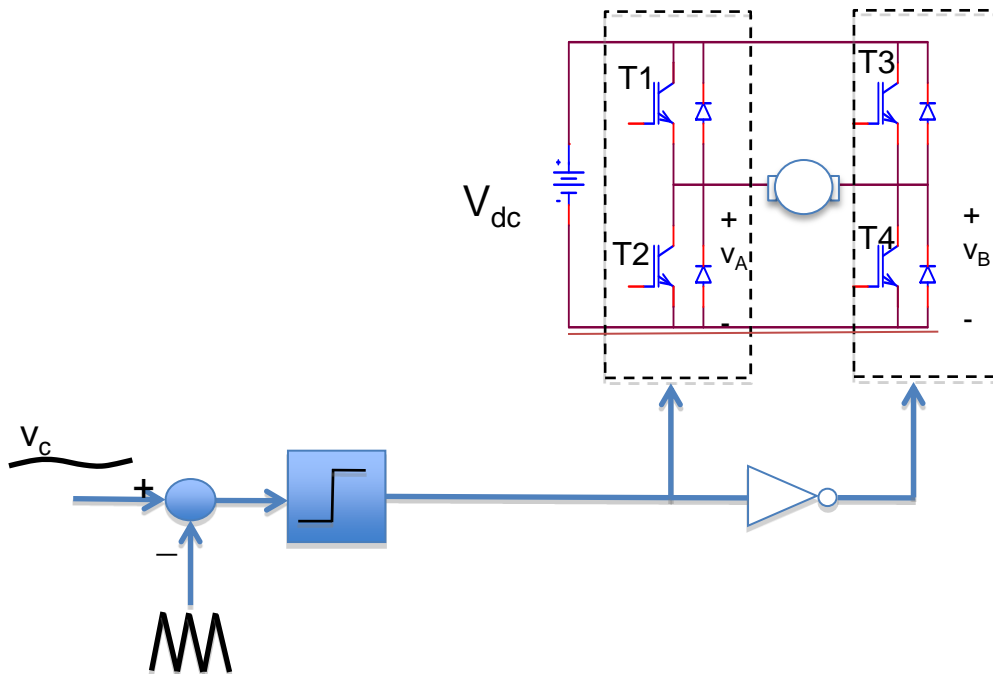
Corrente negativa

$v_a = -V_{dc}$ quando Q3 e Q4 conduzem

$v_a = 0$ A corrente circula livremente através de Q e D

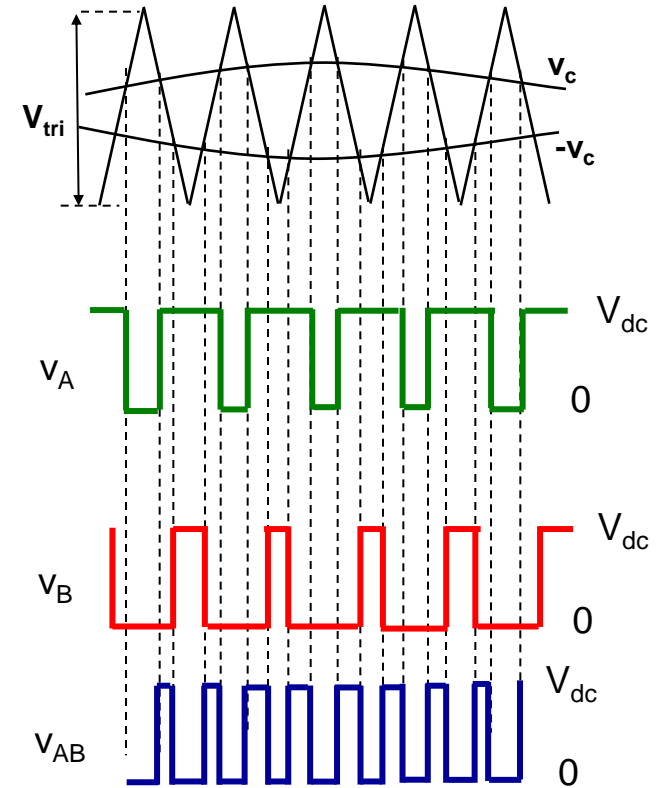
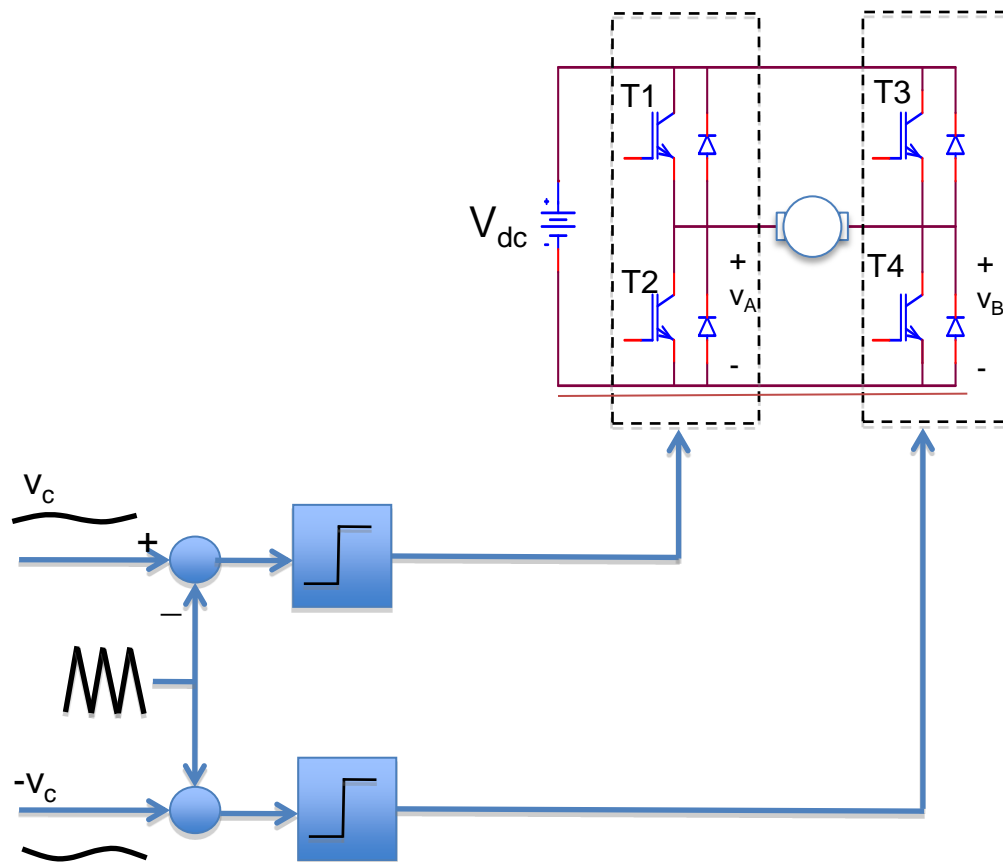
Acionadores CC

Estratégia de modulação *bipolar*
tensão de saída: V_{DC} e $-V_{DC}$



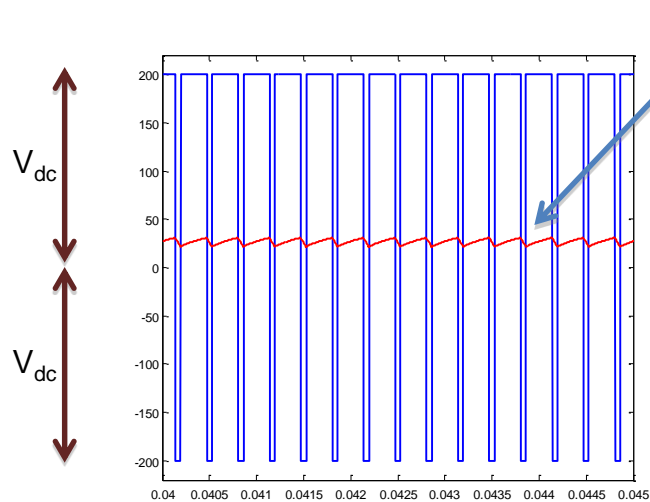
Acionadores CC

Estratégia de modulação *unipolar*
tensão de saída: V_{DC} e 0

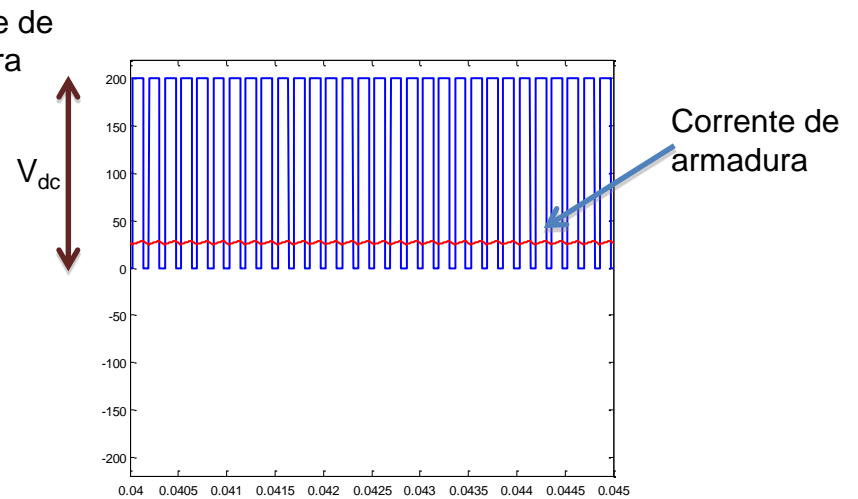


Acionadores CC

Conversor CC/CC de quatro quadrantes



Modulação bipolar

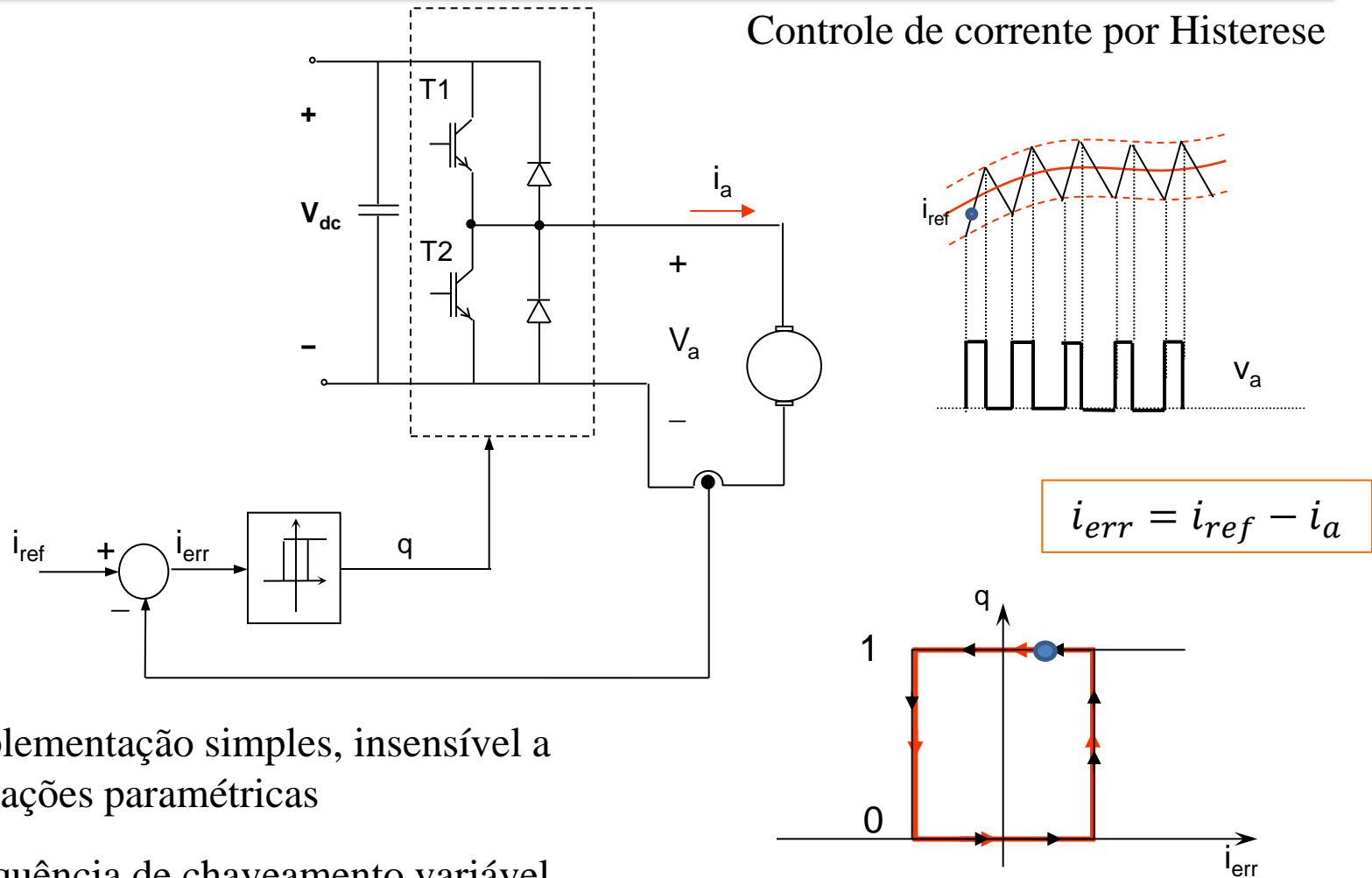


Modulação unipolar

- O *ripple* é menor
- A frequência de saída é efetivamente o dobro

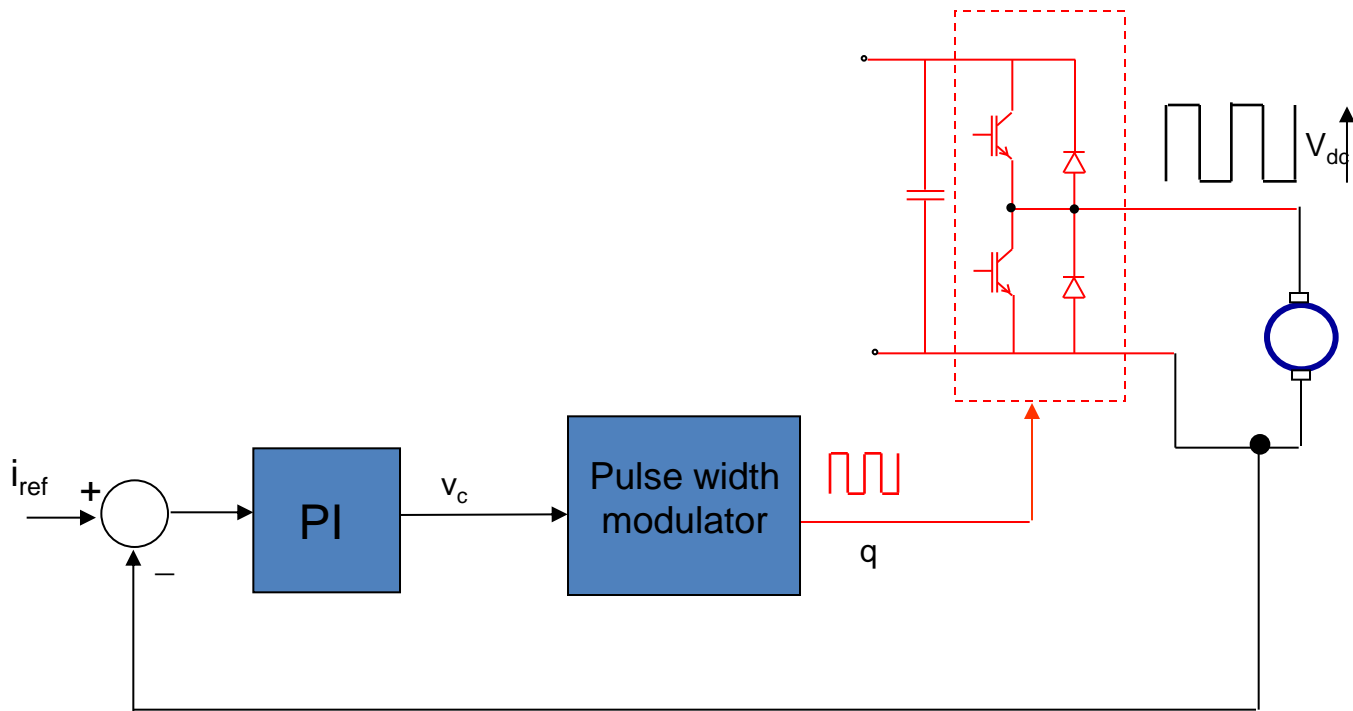
Controle de Corrente por histerese

Controle de corrente por Histerese



- Implementação simples, insensível a variações paramétricas
- Frequência de chaveamento variável

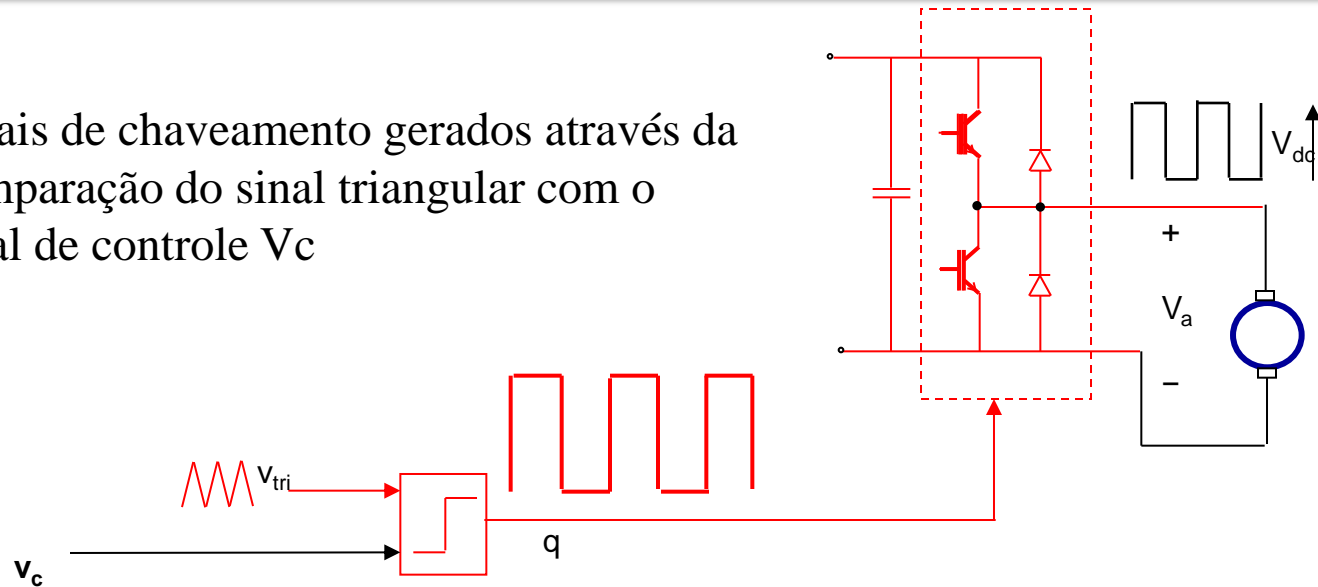
Controlador de Corrente PI



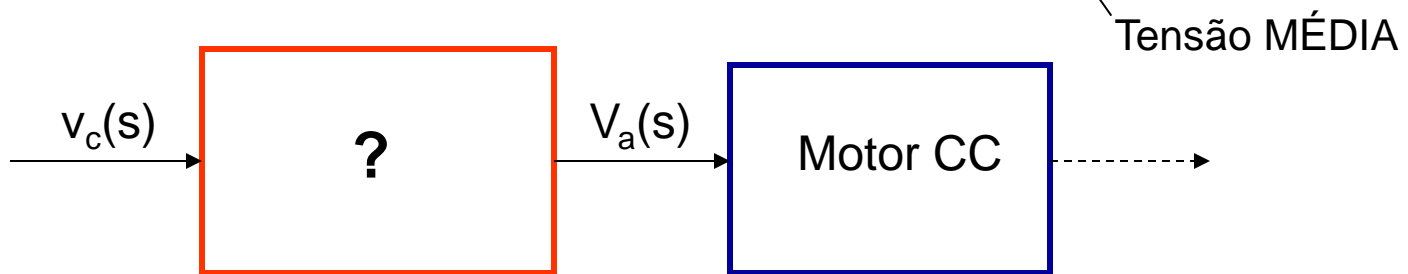
- Requer o modelo dos sistema para o projeto adequado do controlador PI
- Frequência de chaveamento constante

Modelo do Conversor CC (dois quadrantes)

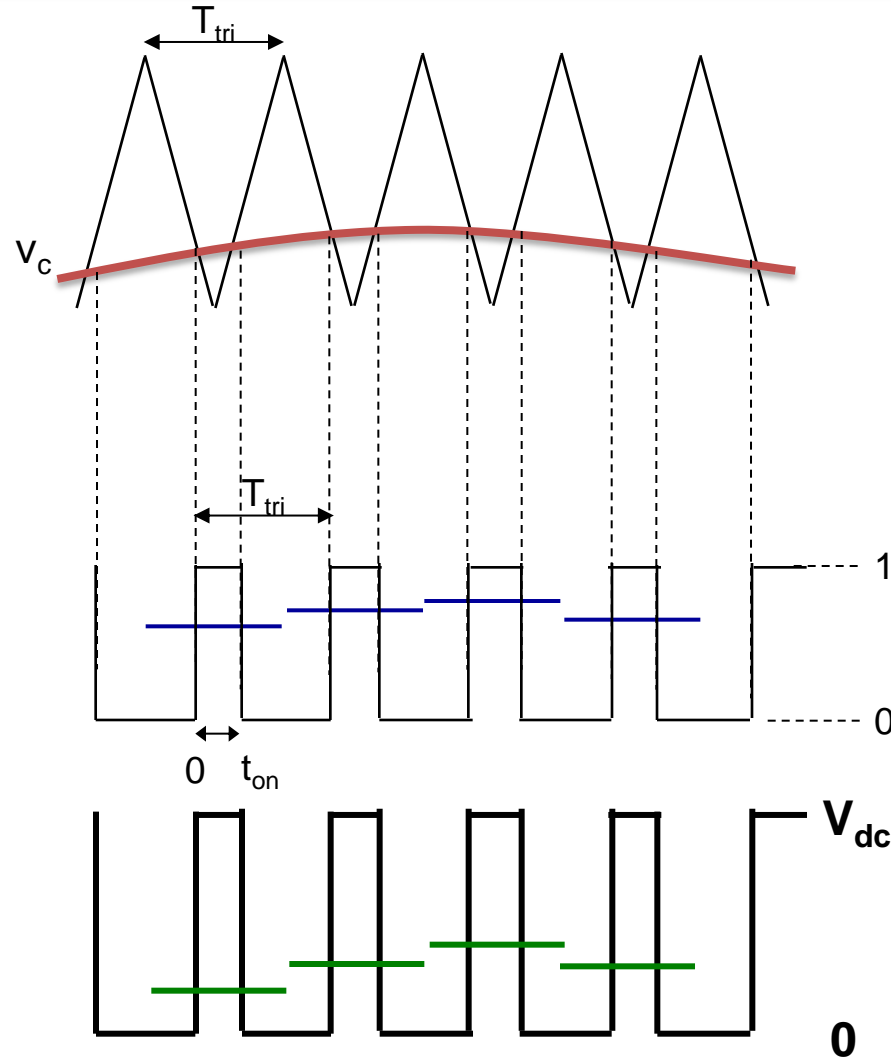
Sinais de chaveamento gerados através da comparação do sinal triangular com o sinal de controle v_c



Desejamos estabelecer a relação entre v_c e V_a



Modelo do Conversor CC (dois quadrantes)



Saída do comparador

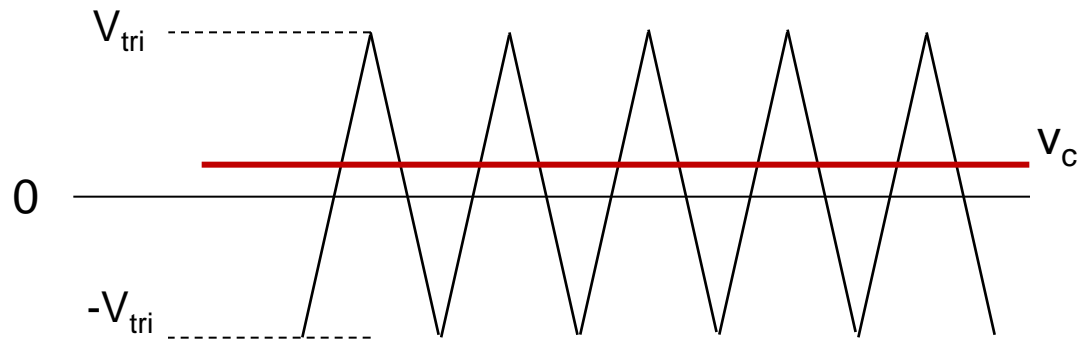
$$q = \begin{cases} 1 & V_c > V_{tri} \\ 0 & V_c < V_{tri} \end{cases}$$

$$d = \frac{1}{T_{tri}} \int_0^{t_{on}} q dt$$

$$d = \frac{t_{on}}{T_{tri}}$$

$$V_a = \frac{1}{T_{tri}} \int_0^{d T_{tri}} V_{dc} dt = d V_{dc}$$

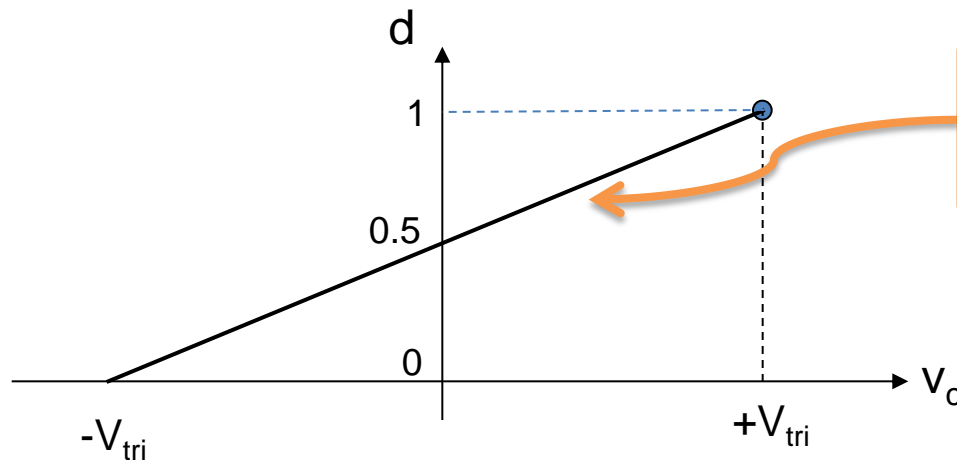
Modelo do Conversor CC (dois quadrantes)



Para $v_c = -V_{tri} \rightarrow d = 0$

Para $v_c = 0 \rightarrow d = 0.5$

Para $v_c = V_{tri} \rightarrow d = 1$



$$d = 0.5 + \frac{1}{2V_{tri}} v_c$$

Modelo do Conversor CC (dois quadrantes)

Assim a relação entre V_c e V_a é :

$$V_a = dV_{dc} \longrightarrow V_a = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} v_c$$

Introduzindo perturbações em V_c e V_a e separando as componentes CC e CA :

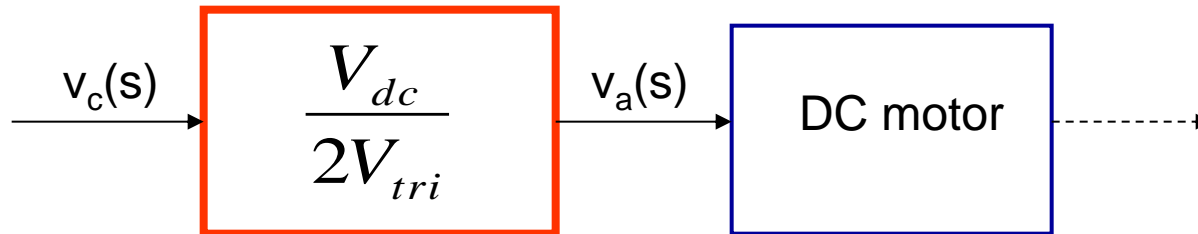
CC:
$$V_a = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} v_c$$

CA:
$$\tilde{v}_a = \frac{V_{dc}}{2V_{tri}} \tilde{v}_c$$

Modelo do Conversor CC (dois quadrantes)

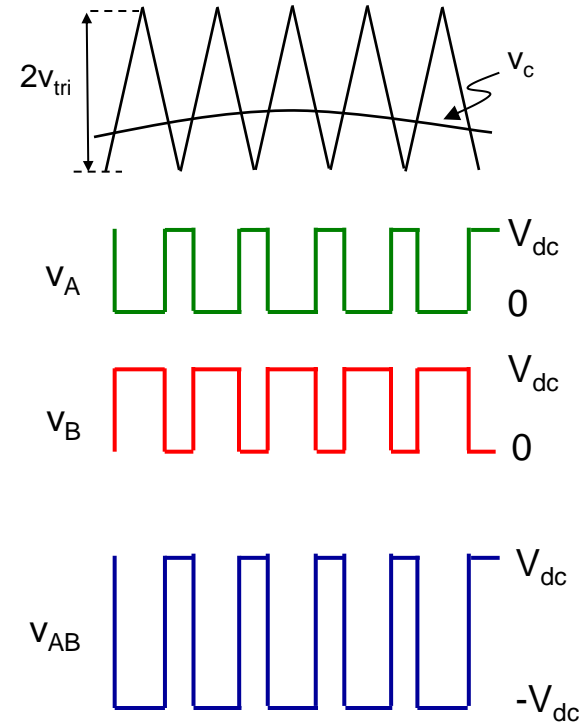
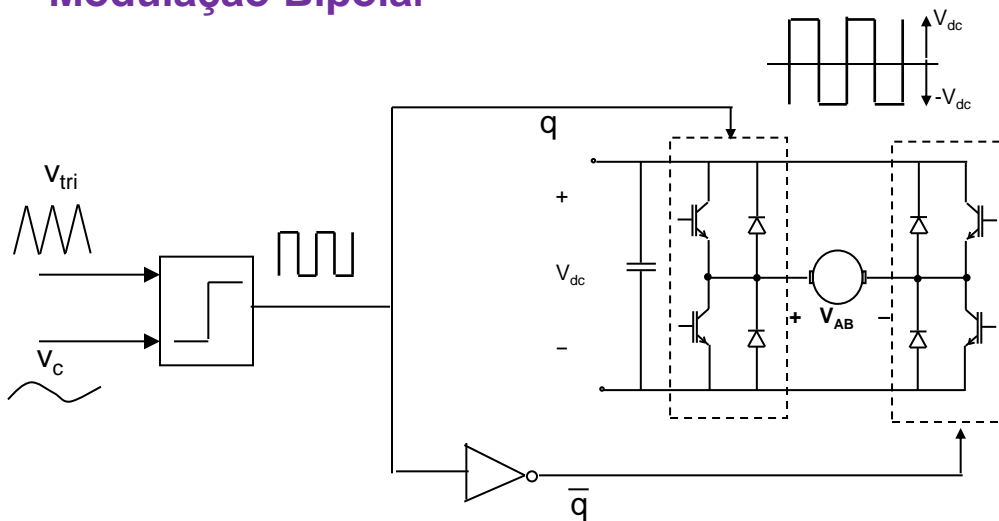
Aplicando a transformada de Laplace

$$\frac{v_a(s)}{v_c(s)} = \frac{V_{dc}}{2V_{tri}}$$



Modelo do Conversor CC (4 quadrantes)

Modulação Bipolar



$$d_A = 0.5 + \frac{V_c}{2V_{tri}}$$

$$d_B = 1 - d_A = 0.5 - \frac{V_c}{2V_{tri}}$$

$$V_A = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} V_c$$

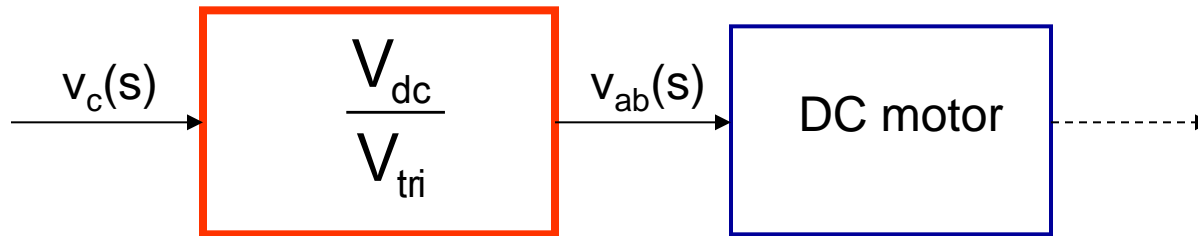
$$V_B = 0.5V_{dc} - \frac{V_{dc}}{2V_{tri}} V_c$$

$$V_A - V_B = V_{AB} = \frac{V_{dc}}{V_{tri}} V_c$$

Modelo do Conversor CC (4 quadrantes)

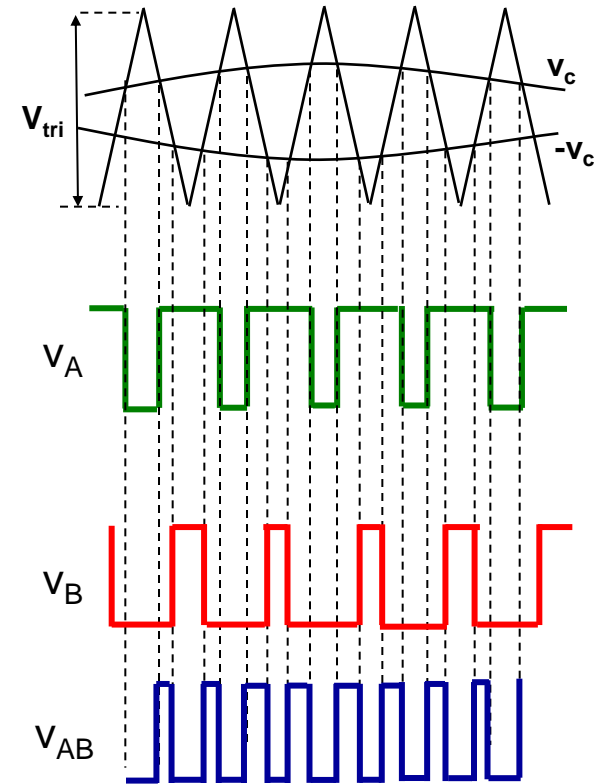
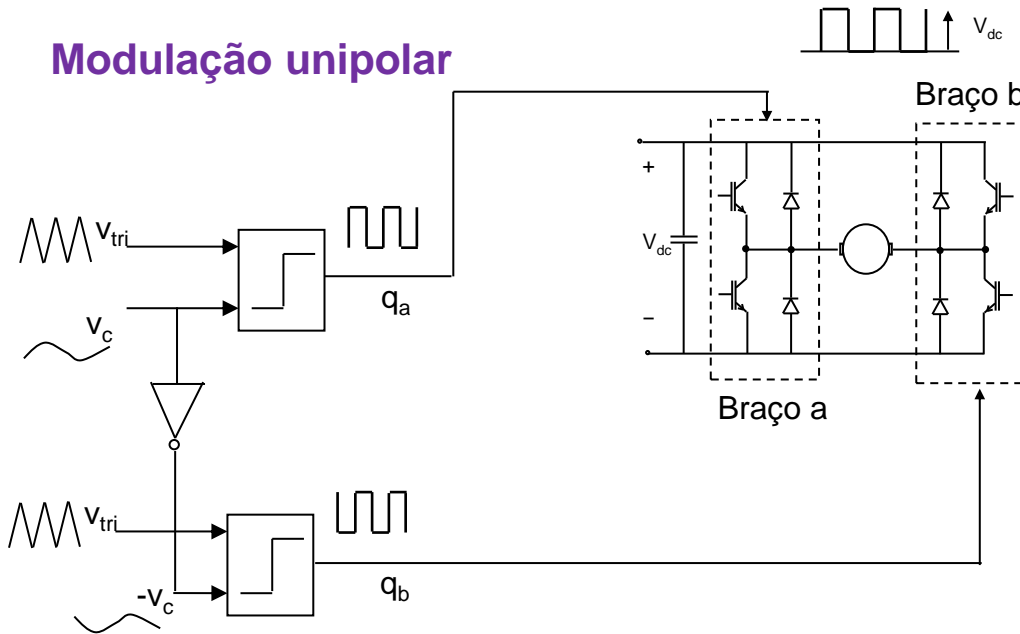
Modulação Bipolar

$$\frac{v_{ab}(s)}{v_c(s)} = \frac{V_{dc}}{V_{tri}}$$



Modelo do Conversor CC (4 quadrantes)

Modulação unipolar



$$d_A = 0.5 + \frac{V_c}{2V_{tri}}$$

$$d_B = 0.5 + \frac{-V_c}{2V_{tri}}$$

$$V_A = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} V_c$$

$$V_B = 0.5V_{dc} - \frac{V_{dc}}{2V_{tri}} V_c$$

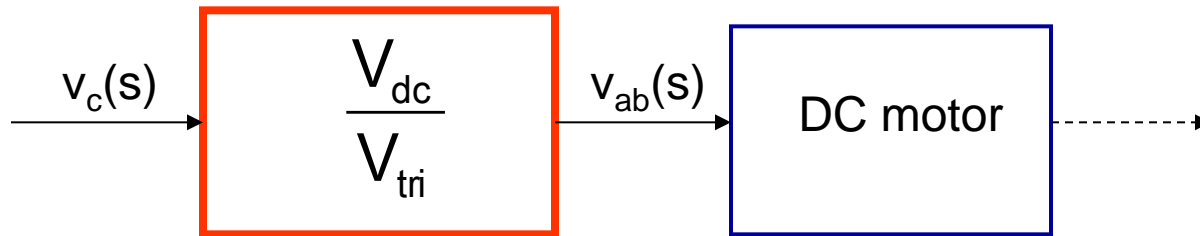
$$V_A - V_B = V_{AB} = \frac{V_{dc}}{V_{tri}} V_c$$

Igual ao caso anterior

Modelo do Conversor CC (4 quadrantes)

Modulação unipolar

$$\frac{v_{ab}(s)}{v_c(s)} = \frac{V_{dc}}{V_{tri}}$$



Motor CC com excitação separada

$$v_t = i_a R_a + L_a \frac{di_a}{dt} + e_a$$

$$T_e = T_L + B\omega + J \frac{d\omega}{dt}$$

$$T_e = k_t \phi i_a = k_E i_a$$

$$e_a = k_t \phi \omega = k_E \omega$$

Modelo para pequenos sinais, perturbar: V_t , i_a , e_a , T_e , T_L e ω

Componentes ca

$$\tilde{v}_t = \tilde{i}_a R_a + L_a \frac{d\tilde{i}_a}{dt} + \tilde{e}_a$$

$$\tilde{T}_e = k_E \tilde{i}_a$$

$$\tilde{e}_a = k_E \tilde{\omega}$$

$$\tilde{T}_e = \tilde{T}_L + B\tilde{\omega} + J \frac{d(\tilde{\omega})}{dt}$$

Componentes cc

$$V_t = I_a R_a + E_a$$

$$T_e = k_E I_a$$

$$E_a = k_E \omega$$

$$T_e = T_L + B\omega$$

Motor CC com excitação separada

Aplicando a transformada de Laplace

$$\tilde{v}_t = \tilde{i}_a R_a + L_a \frac{d\tilde{i}_a}{dt} + \tilde{e}_a \quad \longrightarrow \quad V_t(s) = I_a(s)R_a + L_a s I_a(s) + E_a(s)$$

$$\tilde{T}_e = k_E \tilde{i}_a \quad \longrightarrow \quad T_e(s) = k_E I_a(s)$$

$$\tilde{e}_a = k_E \tilde{\omega} \quad \longrightarrow \quad E_a(s) = k_E \omega(s)$$

$$\tilde{T}_e = \tilde{T}_L + B\tilde{\omega} + J \frac{d(\tilde{\omega})}{dt} \quad \longrightarrow \quad T_e(s) = T_L(s) + B\omega(s) + sJ\omega(s)$$

Motor CC com excitação separada

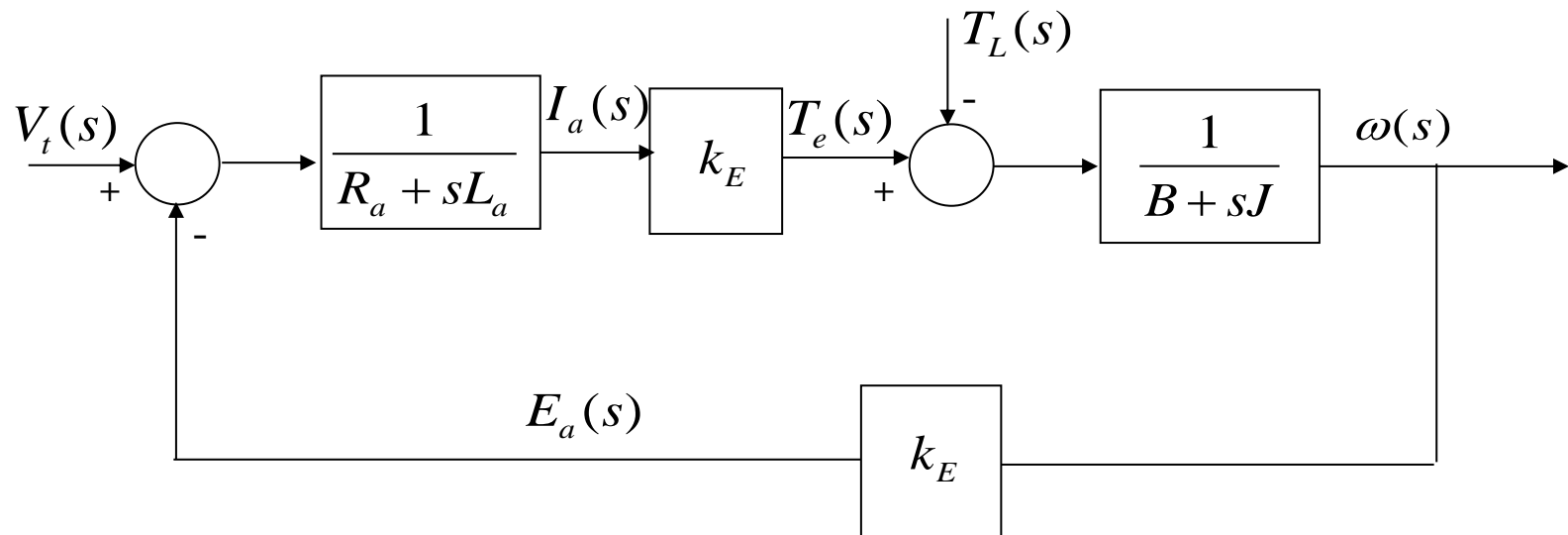
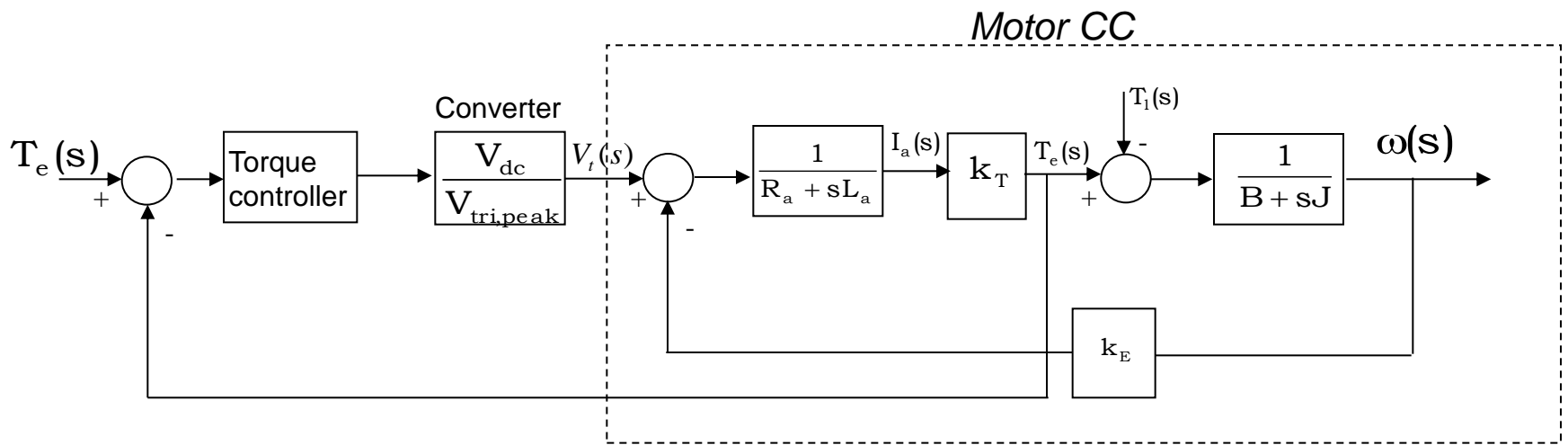
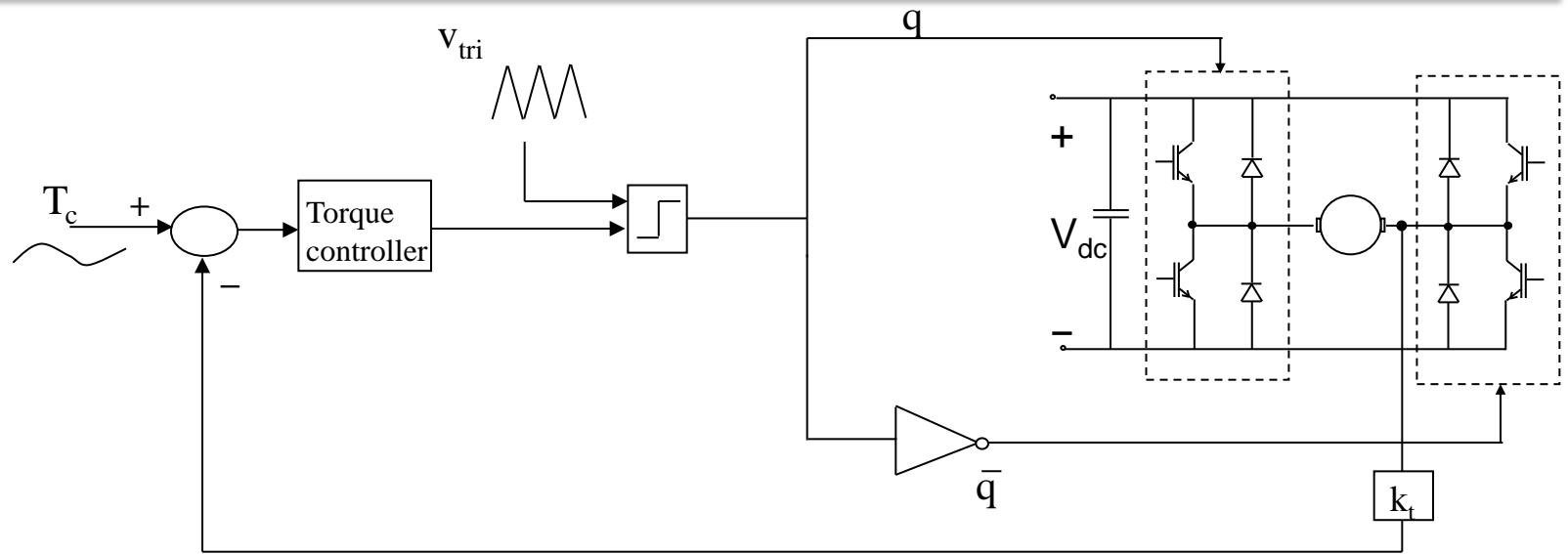


Diagrama de Blocos do motor CC com excitação separada

Controle do Torque em Malha fechada



Controle da Velocidade em Malha Fechada

Projeto do controlador

- Começar pela malha interna (controle de corrente ou torque), **a mais rápida** – **maior largura de banda**
- Malha externa (posição ou velocidade), **a mais lenta** – **menor largura de banda**
- O projeto começa pela malha mais interna

Controle da Velocidade em Malha Fechada

OBJETIVOS:

- Resposta rápida – maior largura de banda
- Overshoot menor
boa margem de fase ($>65^\circ$)
- Erro em regime pequeno – ganho CC alto

Diagrama BODE

MÉTODO

- Obter o modelo para pequenos sinais
- Projetar os controladores baseado neste modelo
- Realizar a simulação

Controle em Malha Fechada

Exemplo

$$R_a = 2 \Omega$$

$$L_a = 5.2 \text{ mH}$$

$$B = 1 \times 10^{-4} \text{ kg.m}^2/\text{sec}$$

$$J = 152 \times 10^{-6} \text{ kg.m}^2$$

$$k_e = 0.1 \text{ V}/(\text{rad/s})$$

$$k_t = 0.1 \text{ Nm/A}$$

$$V_{dc} = 60 \text{ V}$$

$$V_{tri} = 5 \text{ V}$$

$$f_s = 33 \text{ kHz}$$

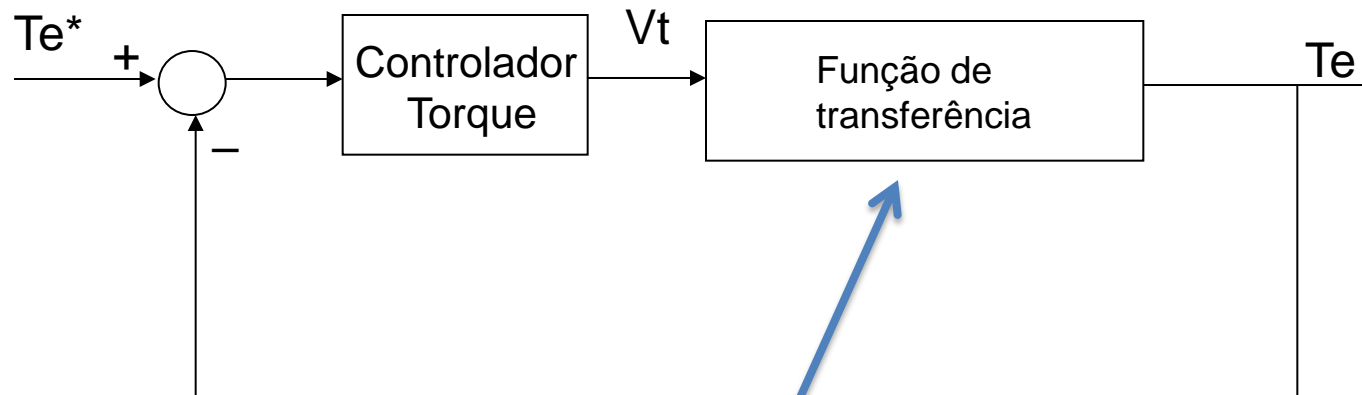
- Sinais de chaveamento obtidas da comparação de v_c e a onda triangular.
- Utilizar controladores PI

$B \rightarrow$ Coeficiente de atrito viscoso

$J \rightarrow$ Momento de inércia

Controlador de Torque

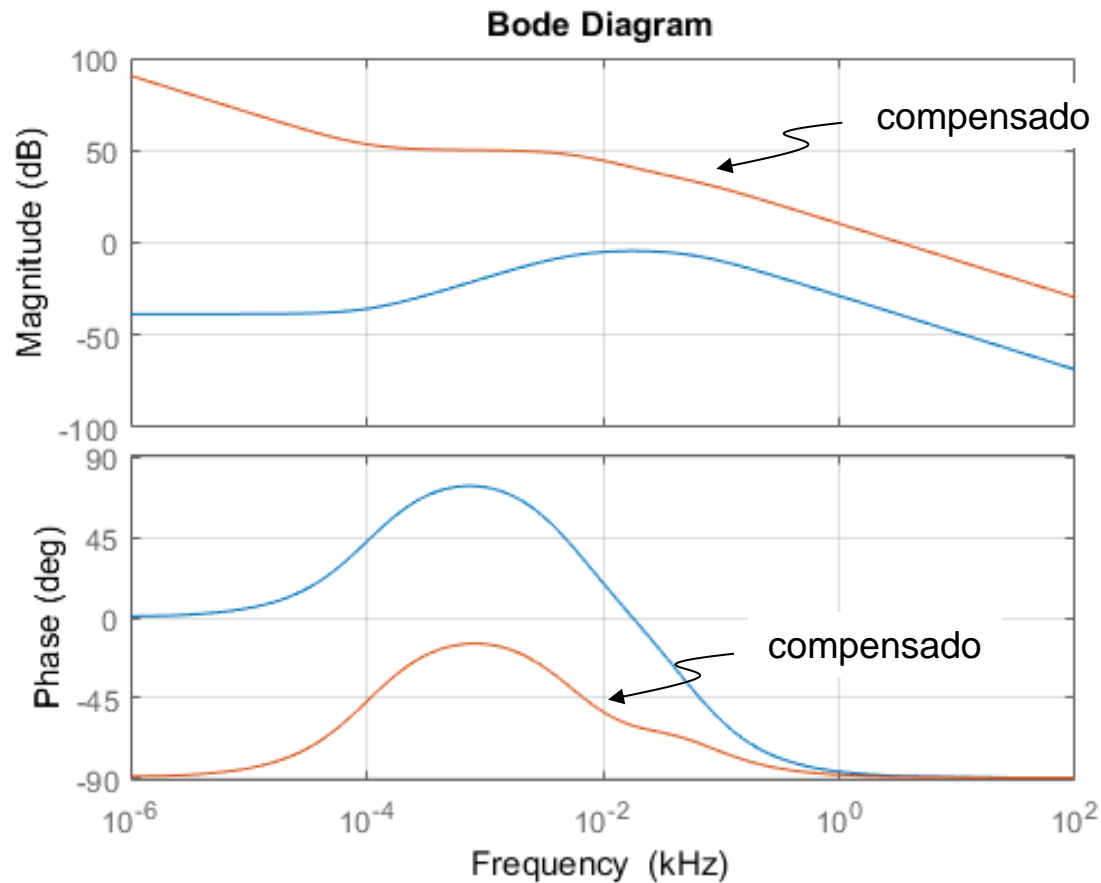
Projeto do controlador de torque



$$\frac{T_e}{V_t} = \frac{\frac{k_t}{R_a + sL_a}}{1 + \frac{k_e k_t}{(B + sJ)(R_a + sL_a)}} \quad (T_L=0)$$

Controlador de Torque

Projeto do controlador de torque
Ganho em malha aberta

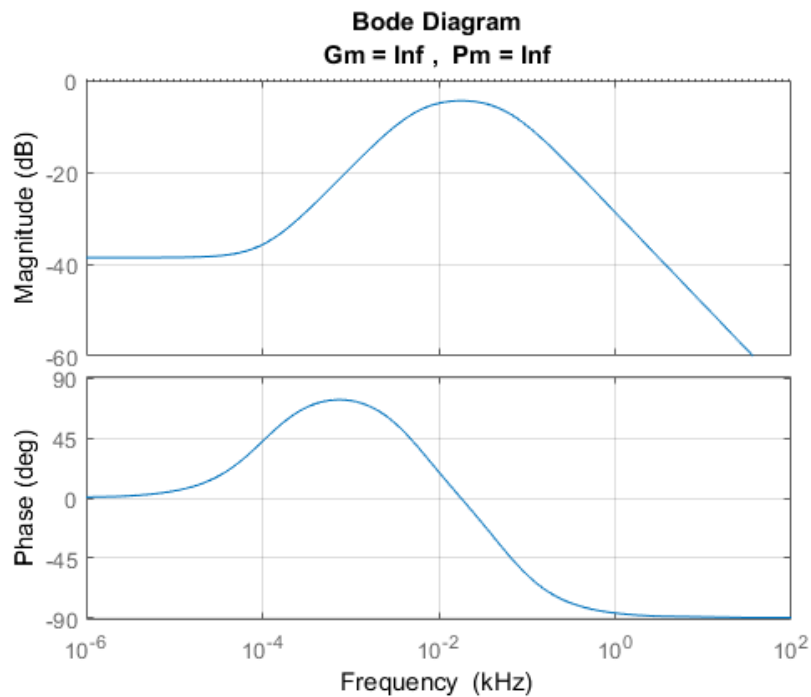


$$k_{pT} = 90$$

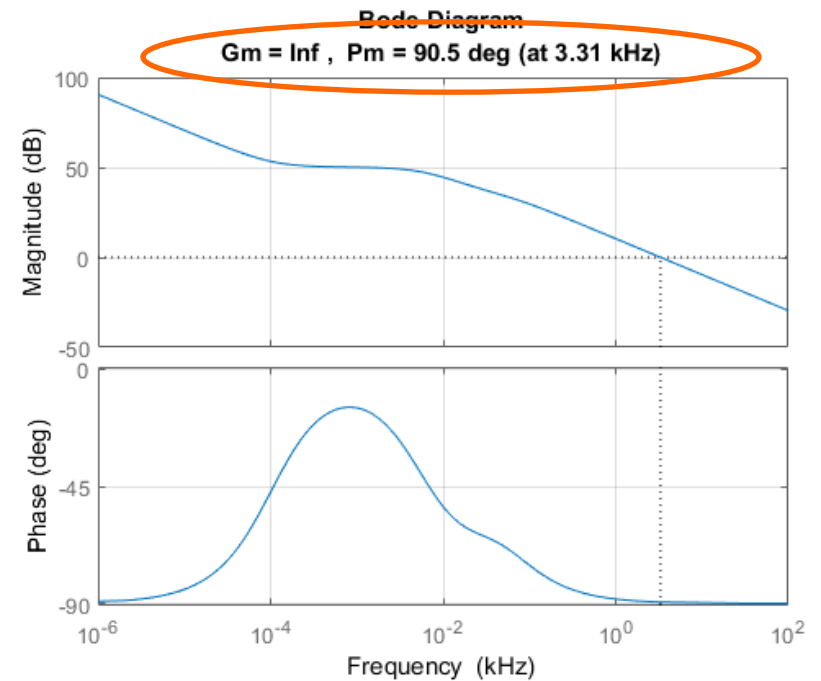
$$k_{iT} = 18000$$

Controlador de Torque

Margem de fase



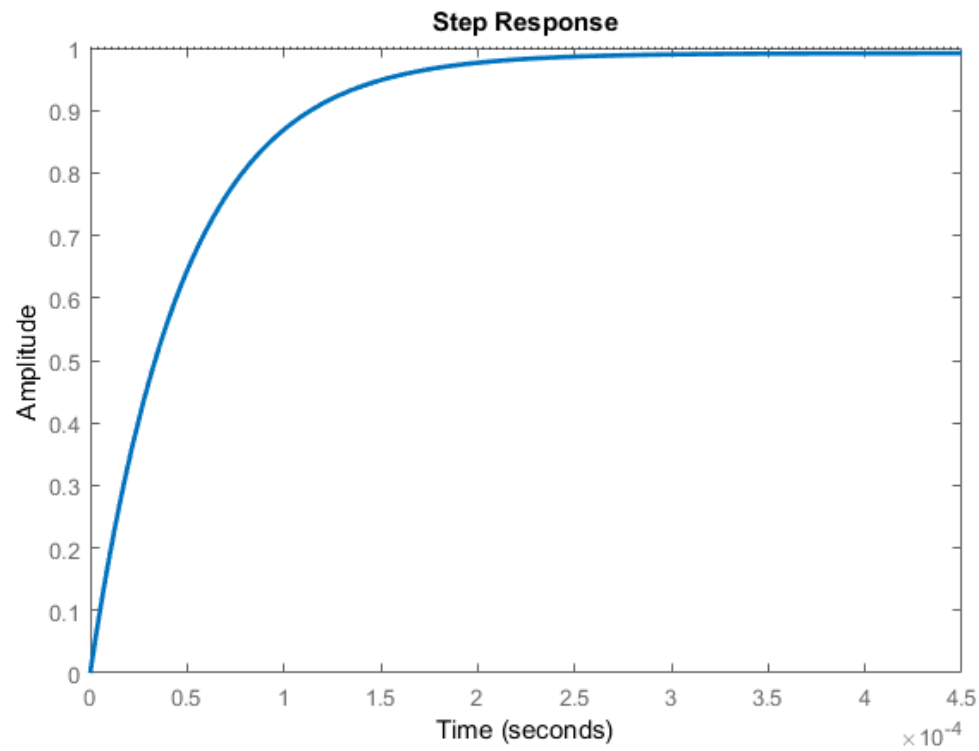
Sem compensar



Compensado

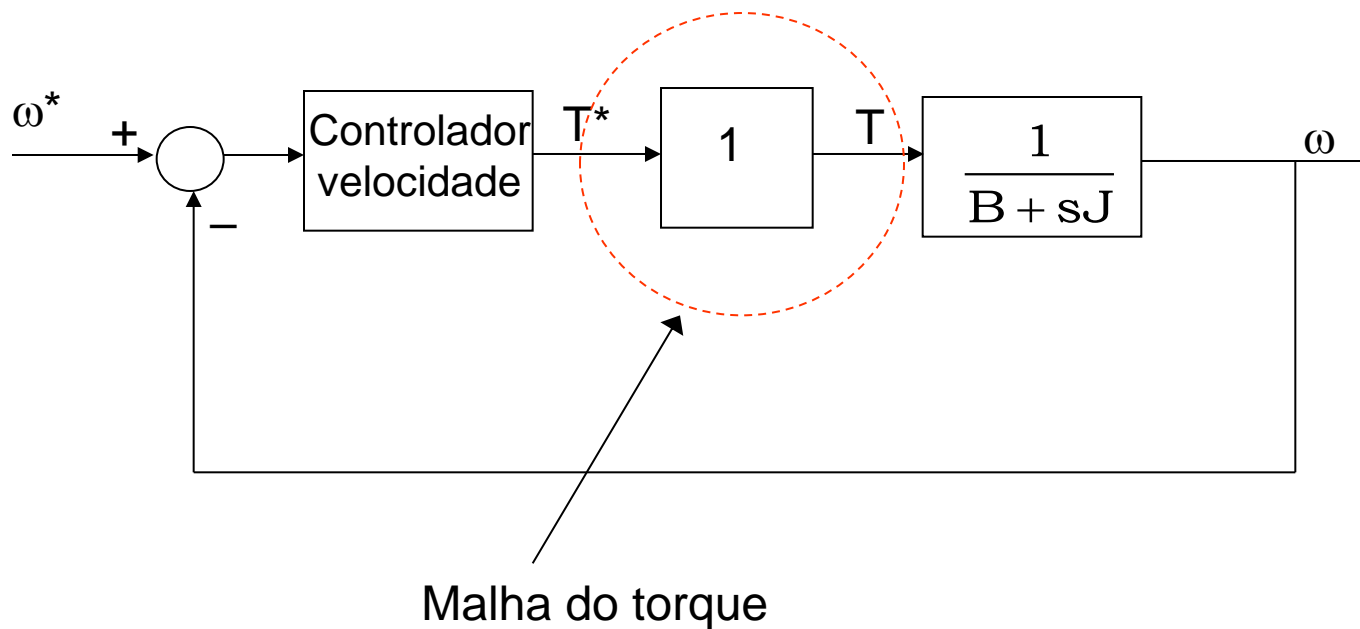
Controlador de Torque

Resposta ao degrau
Malha fechada



Controlador de Velocidade

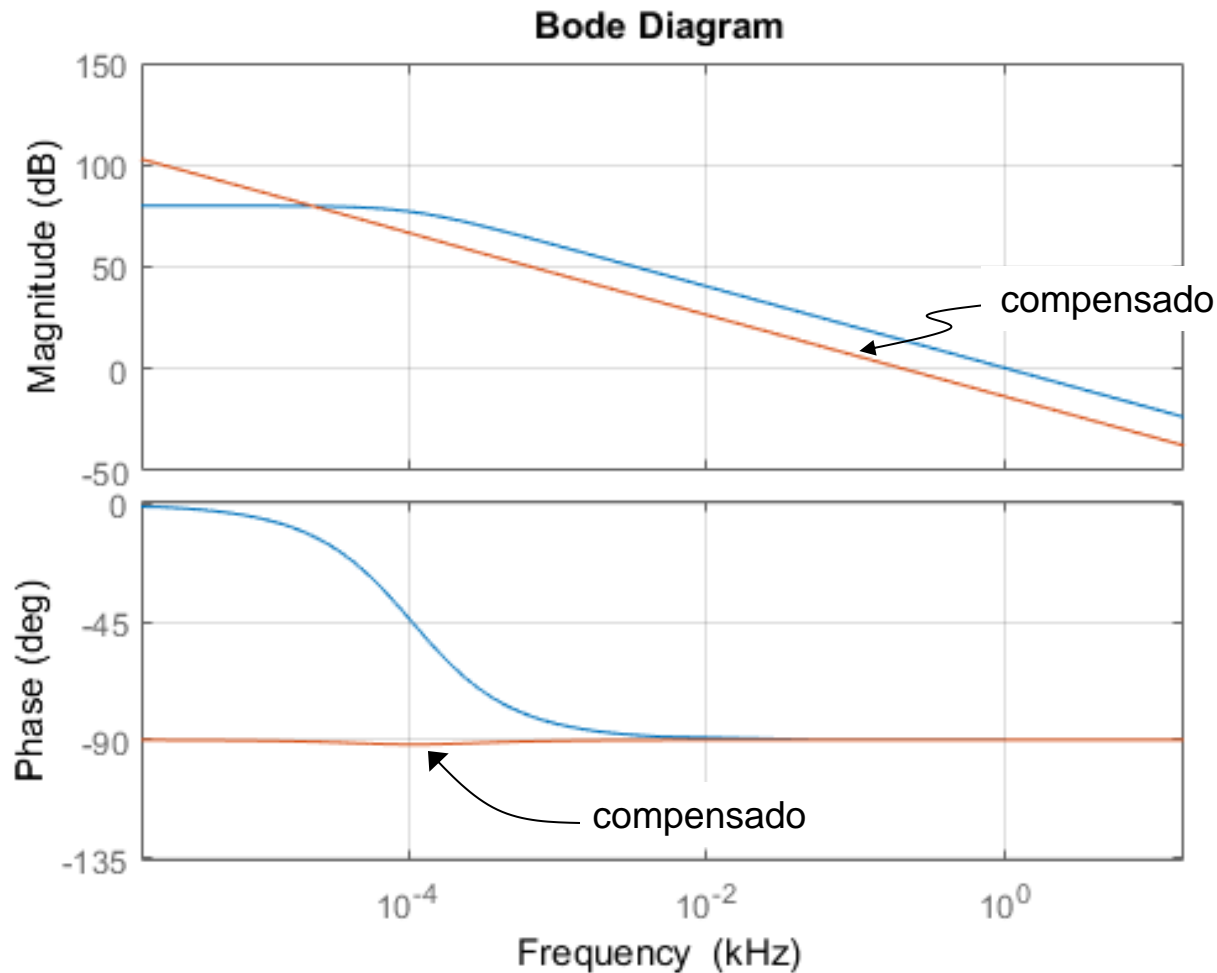
Projeto do controlador de velocidade



Controlador de Velocidade

Projeto do controlador de velocidade

Ganho em malha aberta

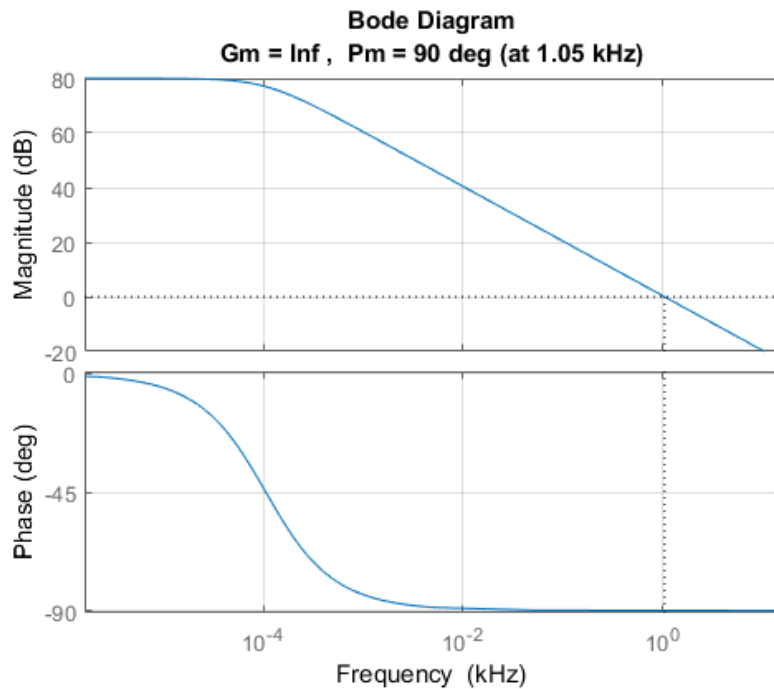


$$k_{ps} = 0.2$$

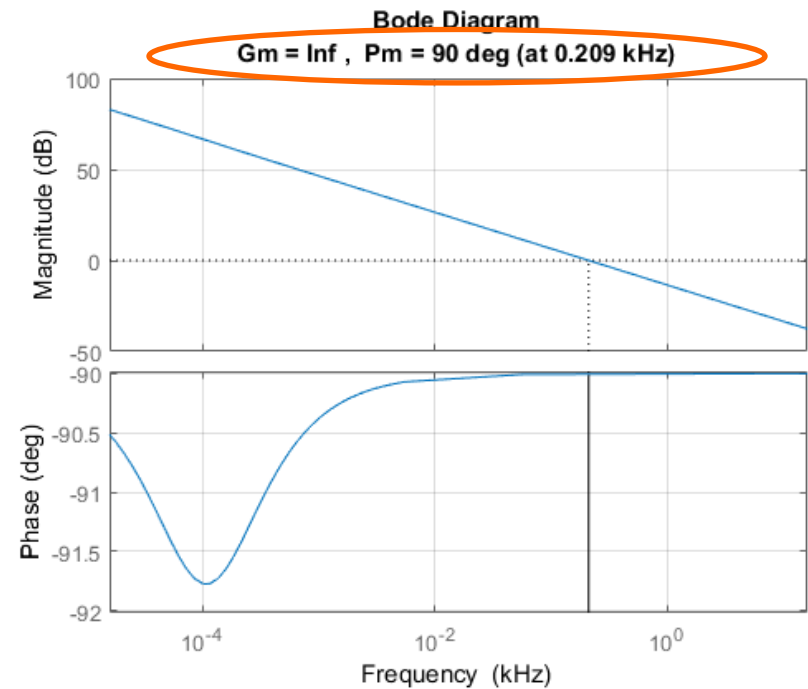
$$k_{is} = 0.14$$

Controlador de Velocidade

Margem de fase



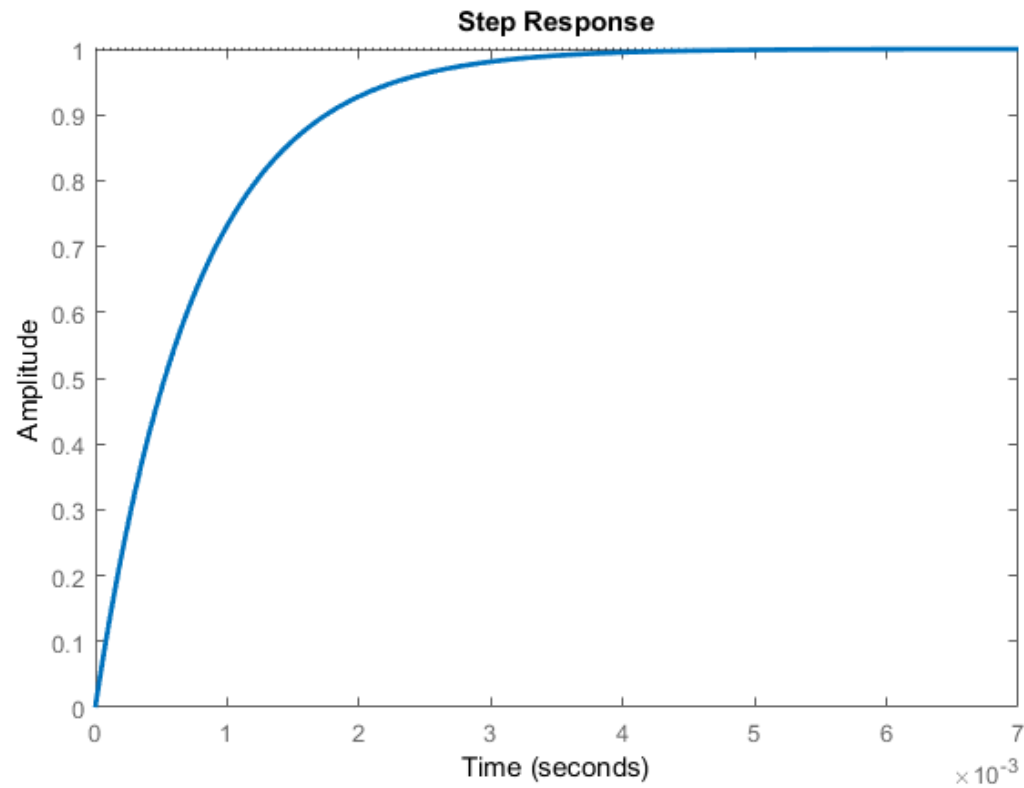
Sem compensar



Compensado

Controlador de Velocidade

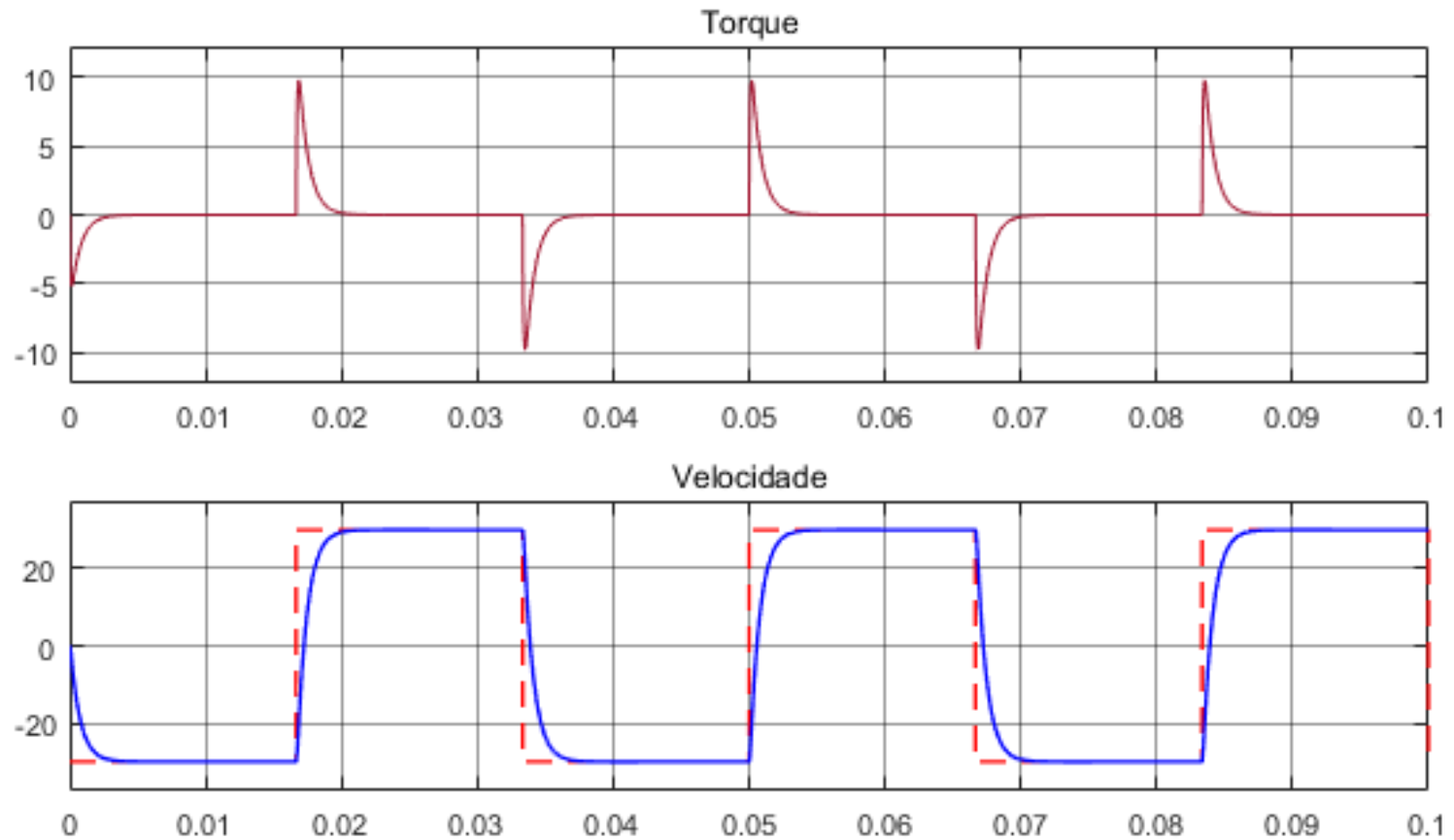
Resposta ao degrau
Malha fechada



Resultados

Resultados de simulação

Reversão de velocidade sem carga



Trabalho de simulação 1

Projetar um compensador (PI, avanço, atraso, etc.) com o objetivo de controlar a velocidade de um motor de corrente contínua (reversão de velocidade em degrau e trapezoidal considerando carga nominal).

- + Escolha os parâmetros e valores nominais de um MCC
- + Simular o sistema utilizando os modelos tanto do conversor como da máquina.
- + Faça um relatório de no **máximo 6 páginas**, fonte Times New Roman, tamanho 12, espaçamento 1,5.
- + O trabalho (relatório (pdf) + arquivo de *Simulink/Matlab r2015b*) deverá ser encaminhado para o e-mail: jose.azcue@ufabc.edu.br, com o assunto “Trabalho de Simulação 01 EEL101 2Q2019” (sem as aspas), até às 23h do dia 03-07-2019.

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