Instituto Federal de Educação, Ciência e Tecnologia de Santa Catarina
Departamento Acadêmico de Eletrônica
Processamento Eletrônico de Energia

Conversores CC-CA

Prof. Clovis Antonio Petry.

Florianópolis, setembro de 2020.

Curso Básico de Processamento Eletrônico de Energia

O material do curso está disponível em:

1. Moodle para os alunos matriculados na disciplina.
2. Página do professor.
3. Canal no youtube do professor.

https://moodle.ifsc.edu.br

www.ProfessorPetry.com.br

https://www.youtube.com

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Agenda

Esta aula está organizada em:

1. Introdução aos conversores cc-ca:
   - Introdução;
   - Quadrantes de operação;
   - Modulação PWM senoidal;
   - Princípio de funcionamento.
2. Conversor meia ponte:
   - Onda quadrada;
   - PWM senoidal.
3. Conversor ponte completa:
   - Onda quadrada;
   - PWM senoidal.
4. Aplicações em destaque.

Motivação

Os conversores cc-ca tem ampla utilização na indústria, por exemplo no acionamento de motores.

https://www.weg.net/

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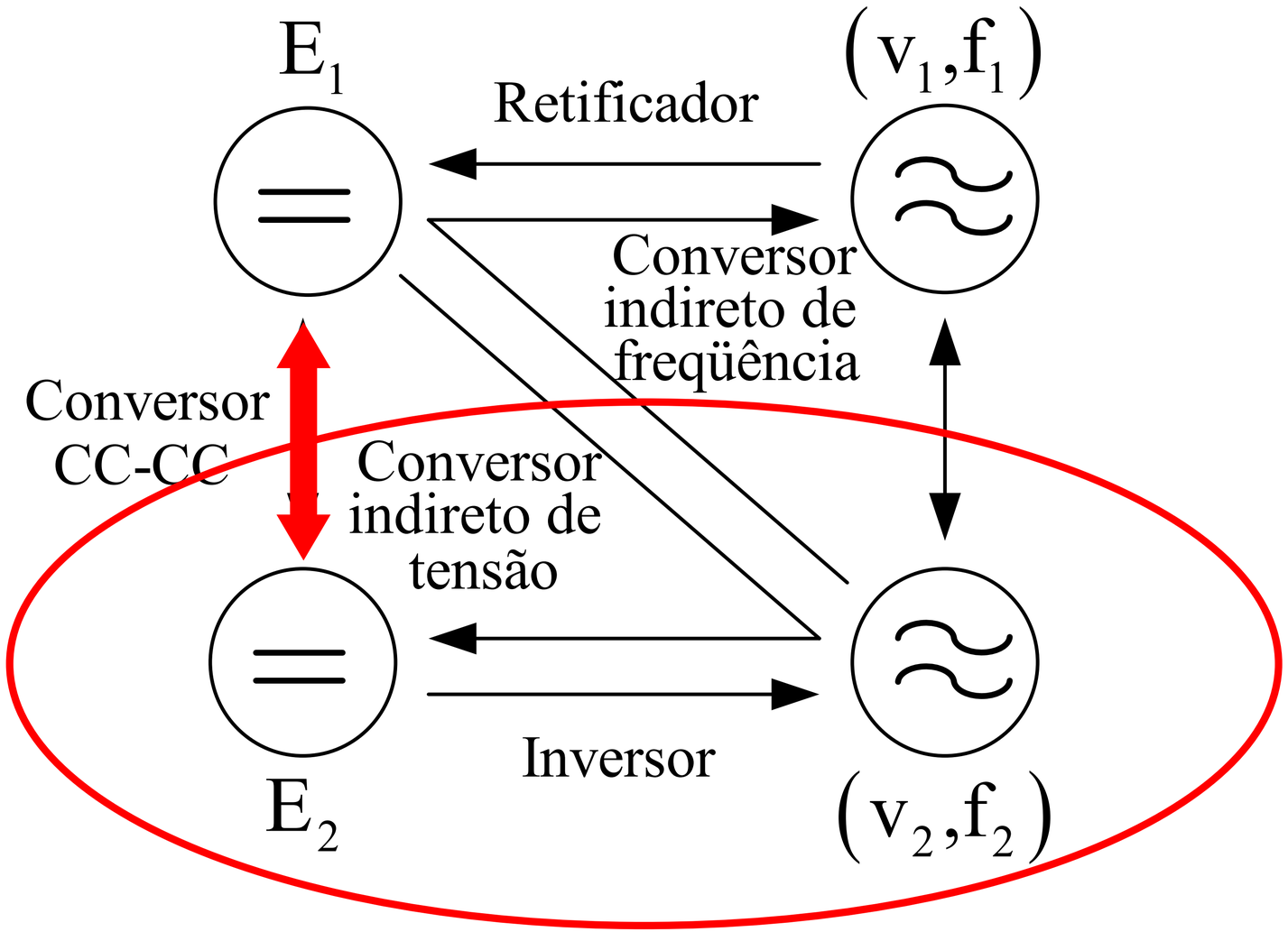
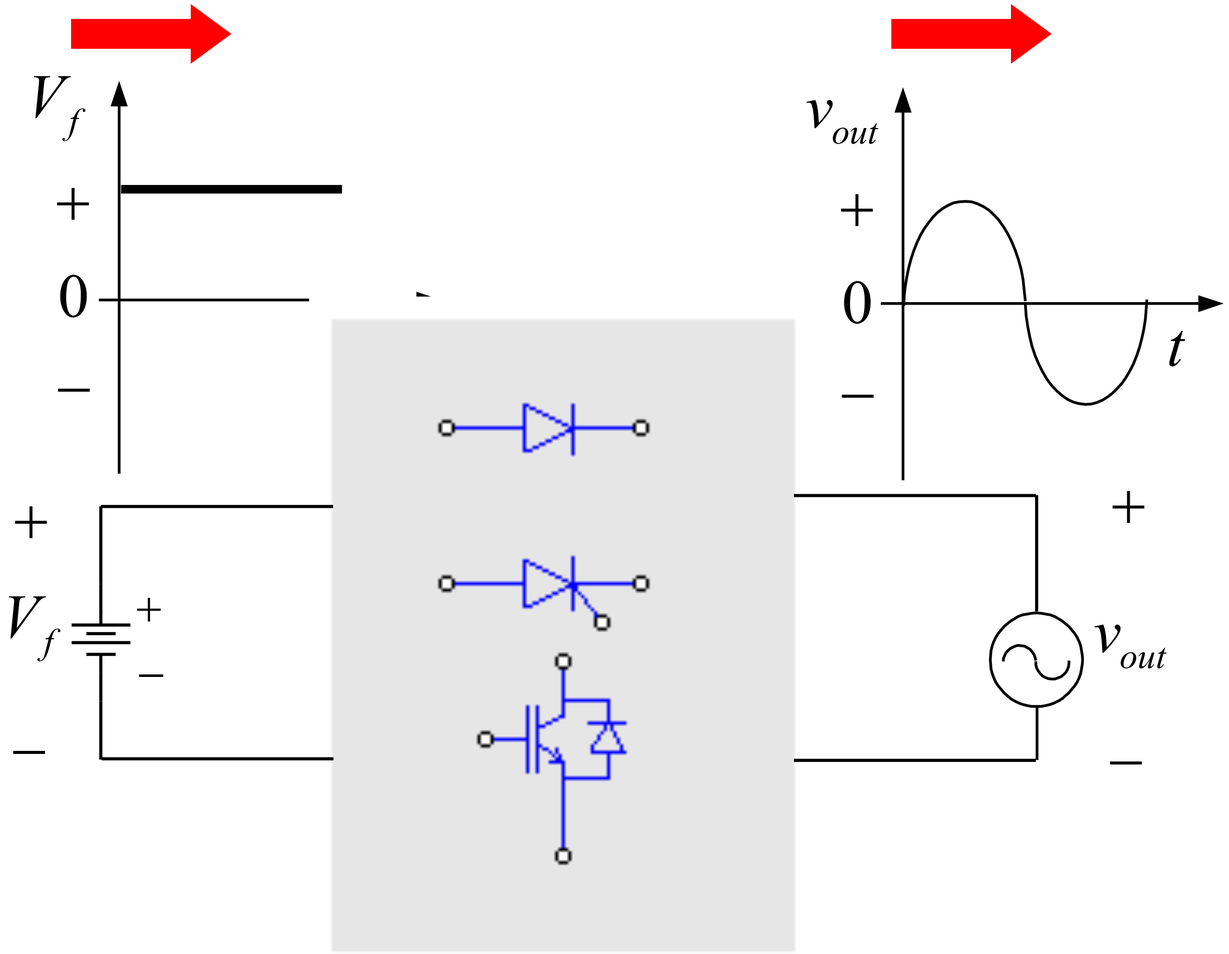
Conversores CC-CA



Conversores CC-CA

Princípio geral:

- Controla o fluxo de potência entre uma fonte de tensão contínua e outra alternada.



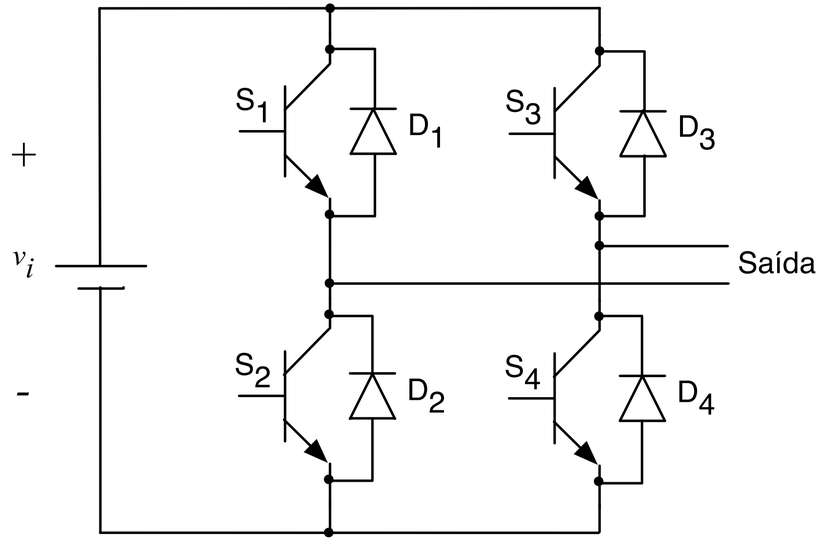
Conversores CC-CA

Algumas características:

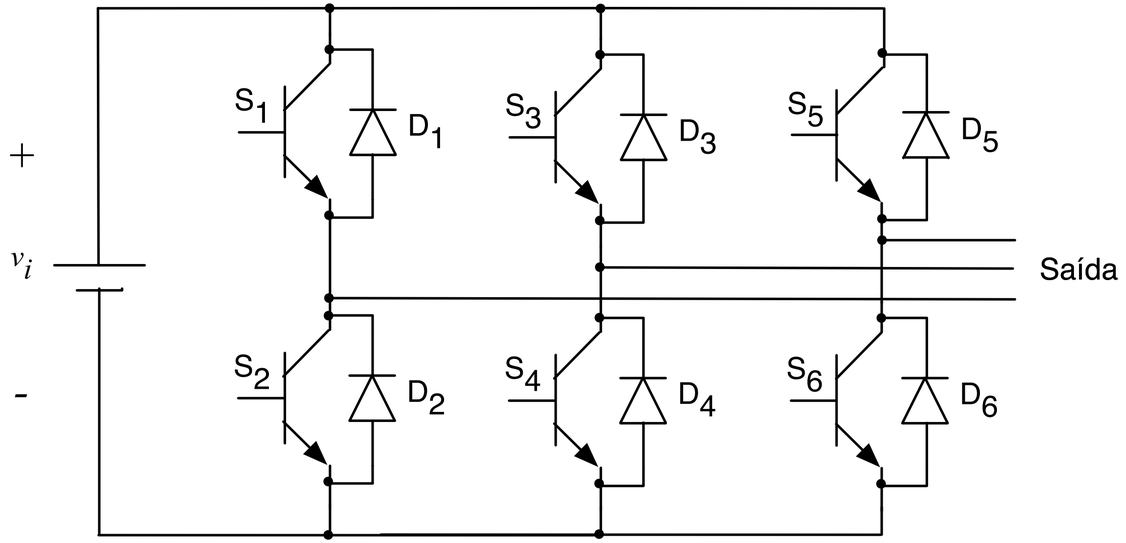
- Denominados de inversores: convertem tensão contínua em tensões alternadas;
- Podem ser monofásicos, trifásicos ou n-fásicos;
- Unidirecionais ou bidirecionais;
- Comandados em alta freqüência
- Modulação simples ou complexa;
- Dois níveis ou multiníveis;
- Podem ser isolados ou não-isolados;
- Podem operar em condução contínua ou descontínua;
- Controlados no modo tensão ou corrente;
- Comutação normal ou suave;
- Inversores de tensão ou corrente;
- Aplicações dos conversores CC-CA.

Conversores CC-CA

Número de fases:



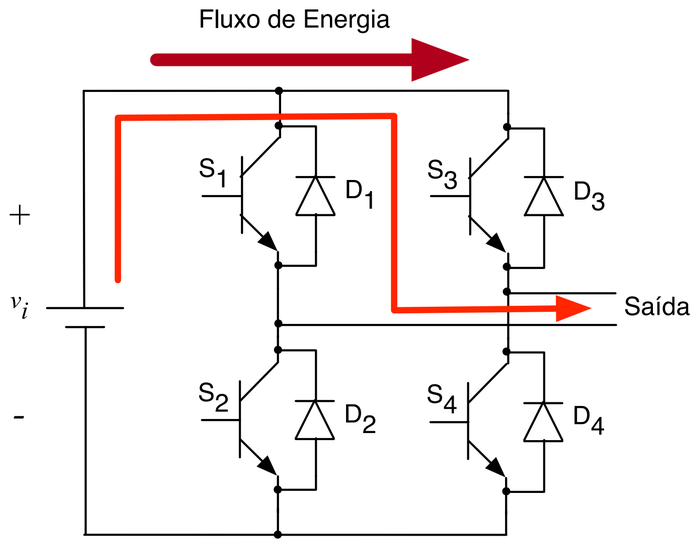
Conversor monofásico



Conversor trifásico

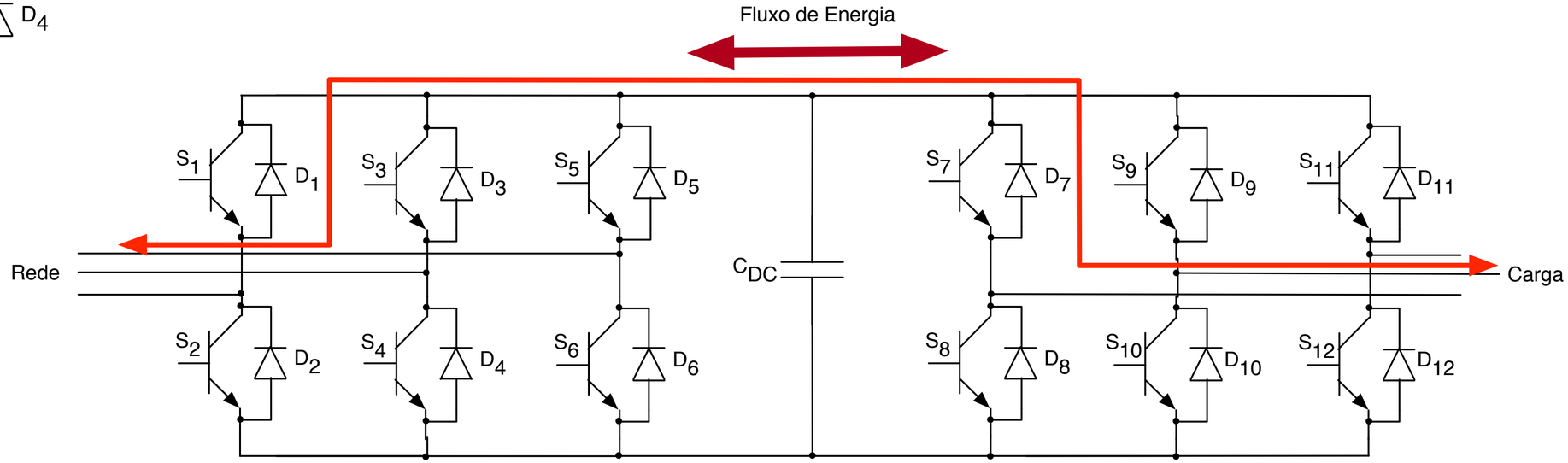
Conversores CC-CA

Fluxo de energia:



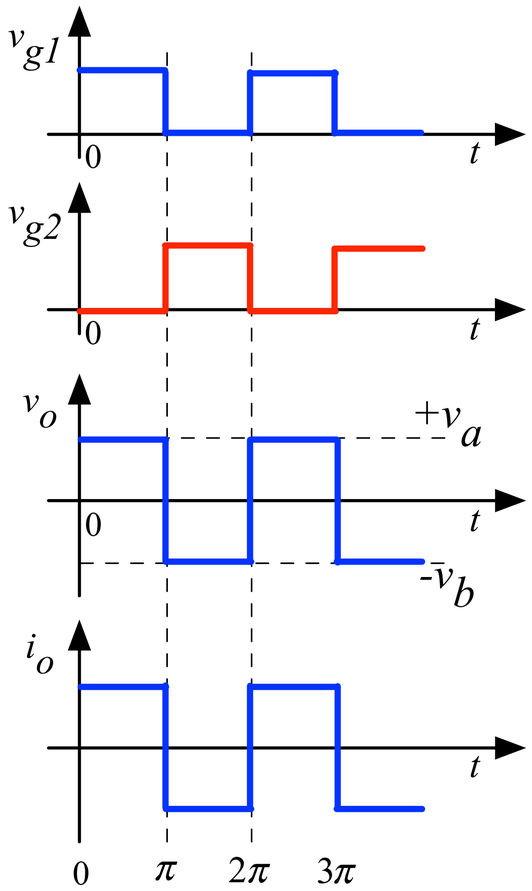
Conversor unidirecional

Conversor bidirecional

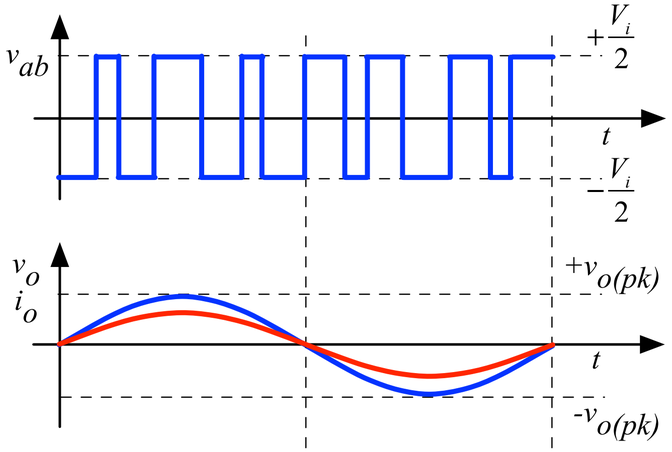


Conversores CC-CA

Modulação:



Onda quadrada



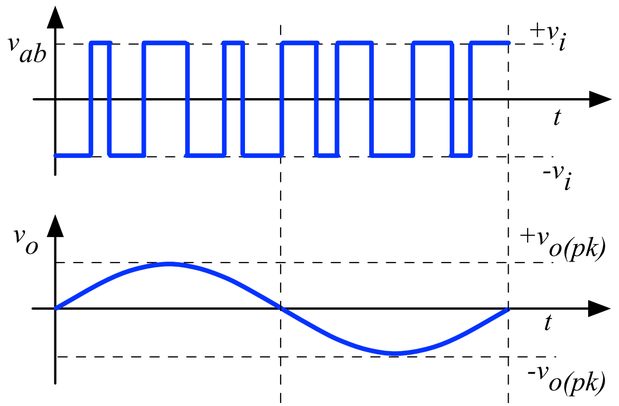
PWM Senoidal

Vetorial

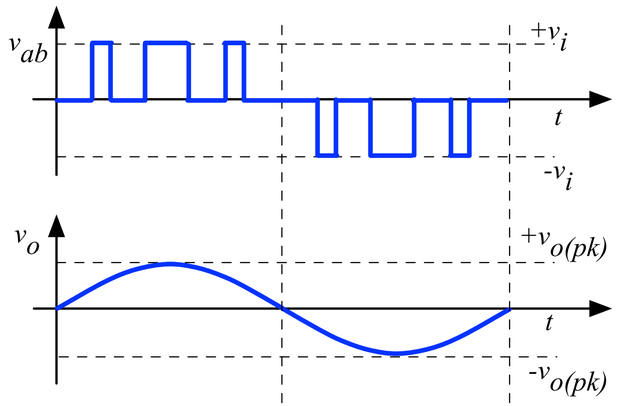
Fonte: TOMASELLI, Luis C. Estudo de Acionamentos à Velocidade Variável para Motores de Indução Monofásicos com Capacitor Permanente para Aplicações em Ventiladores. Florianópolis, SC – Brasil, 2004. Tese (Doutorado em Engenharia Elétrica) – Centro Tecnológico, Universidade Federal de Santa Catarina.

Conversores CC-CA

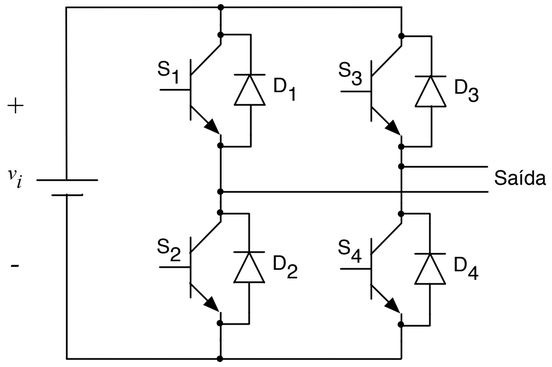
Número de níveis:



2 níveis



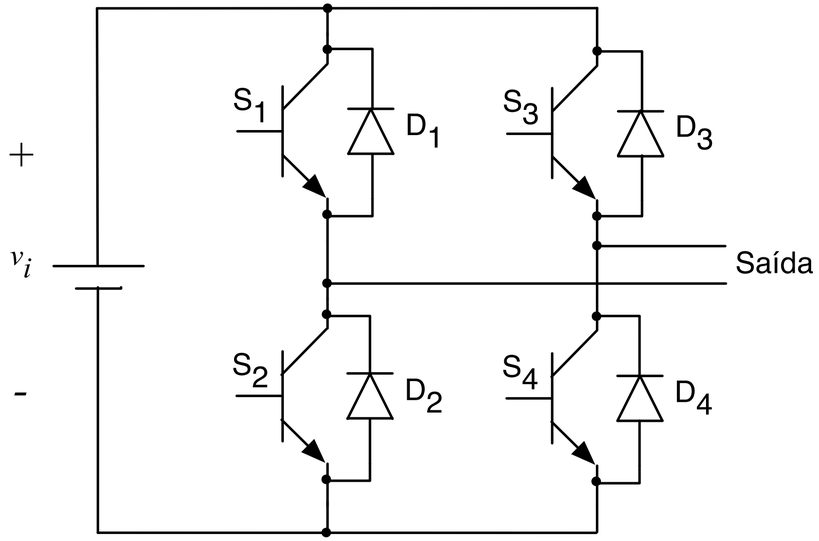
3 níveis



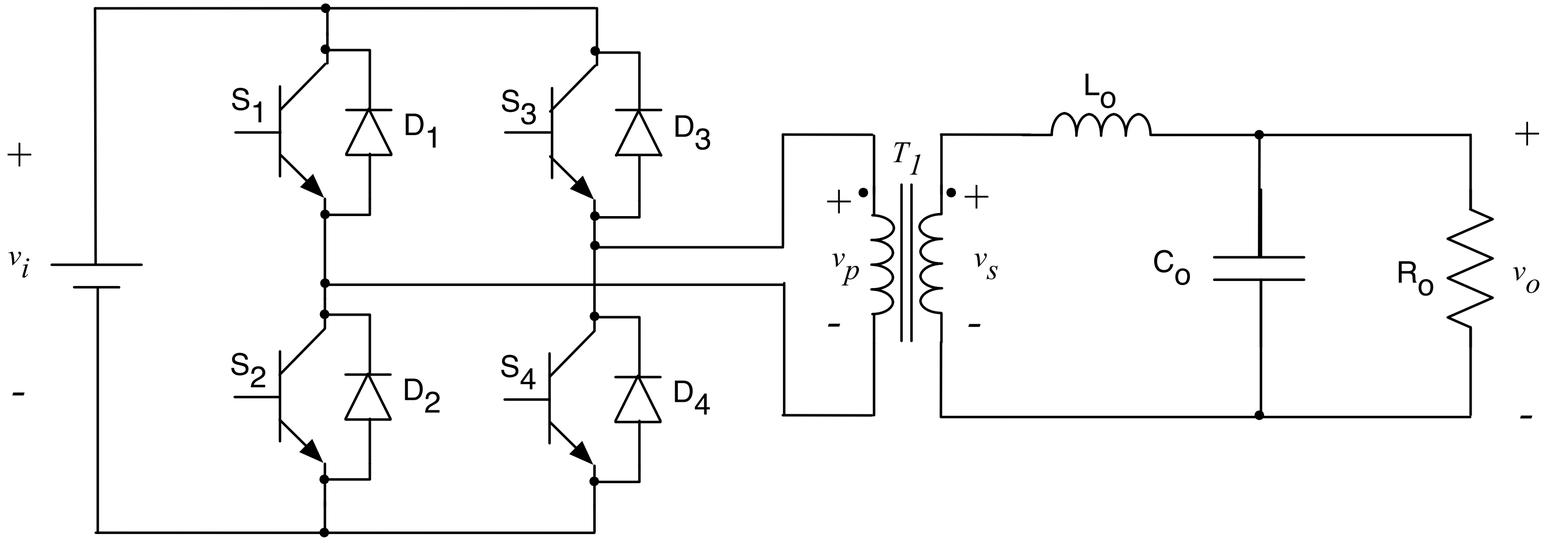
5 níveis

Conversores CC-CA

Isolamento:



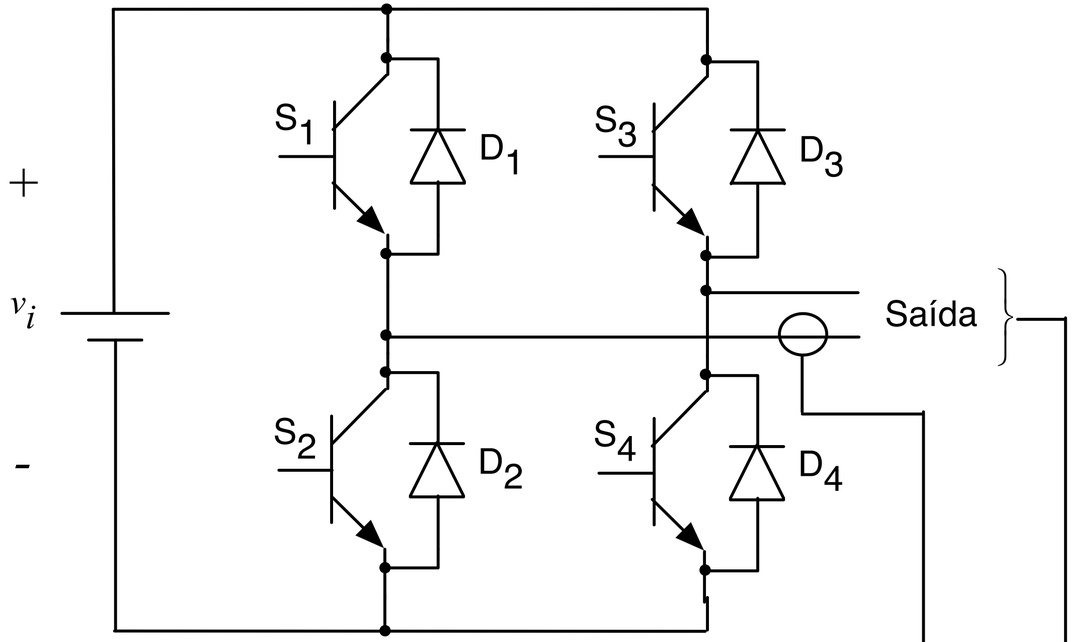
Conversor não-isolado



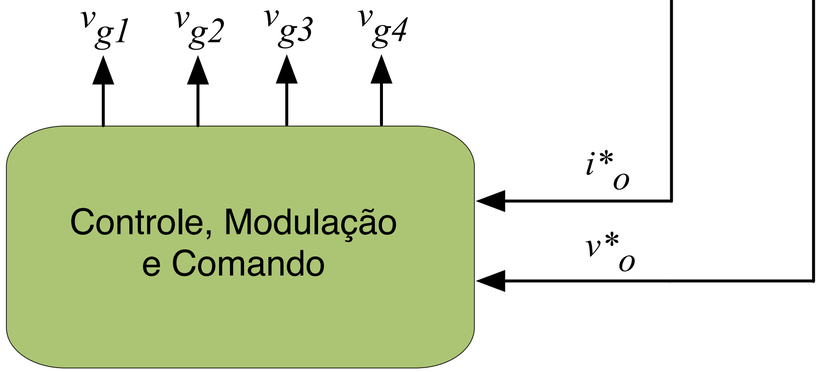
Conversor isolado

Conversores CC-CA

Controle:

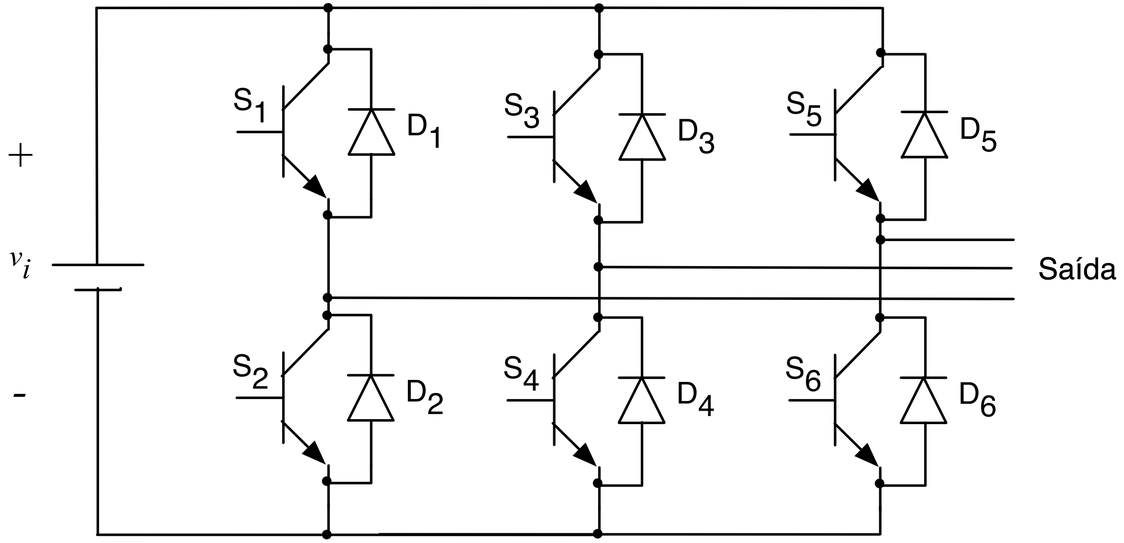


Controle multimalhas

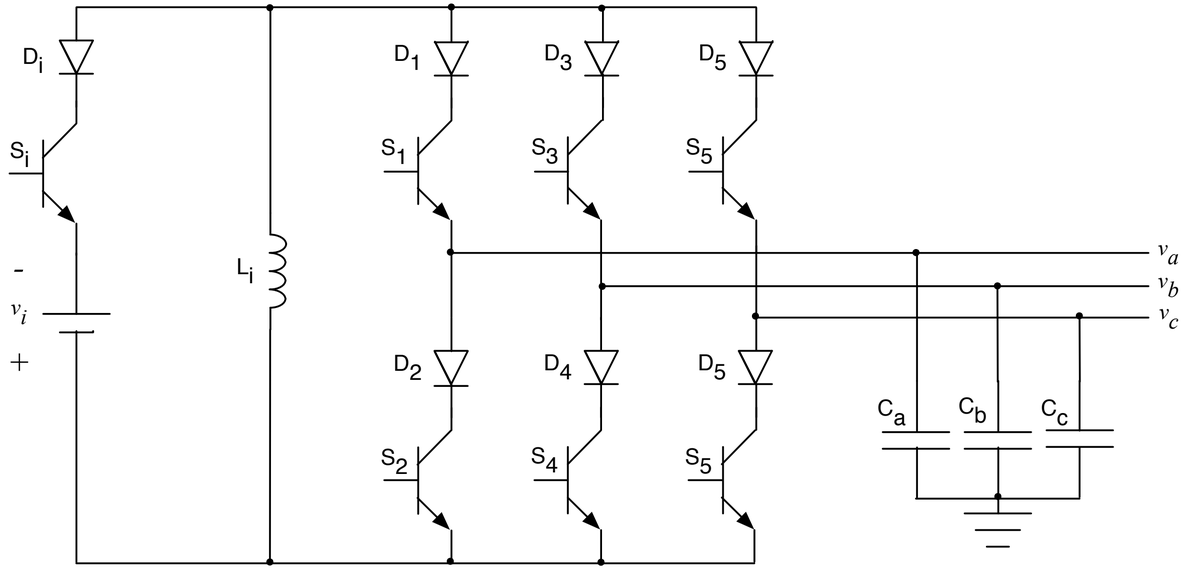


Conversores CC-CA

Tipo de conversão:



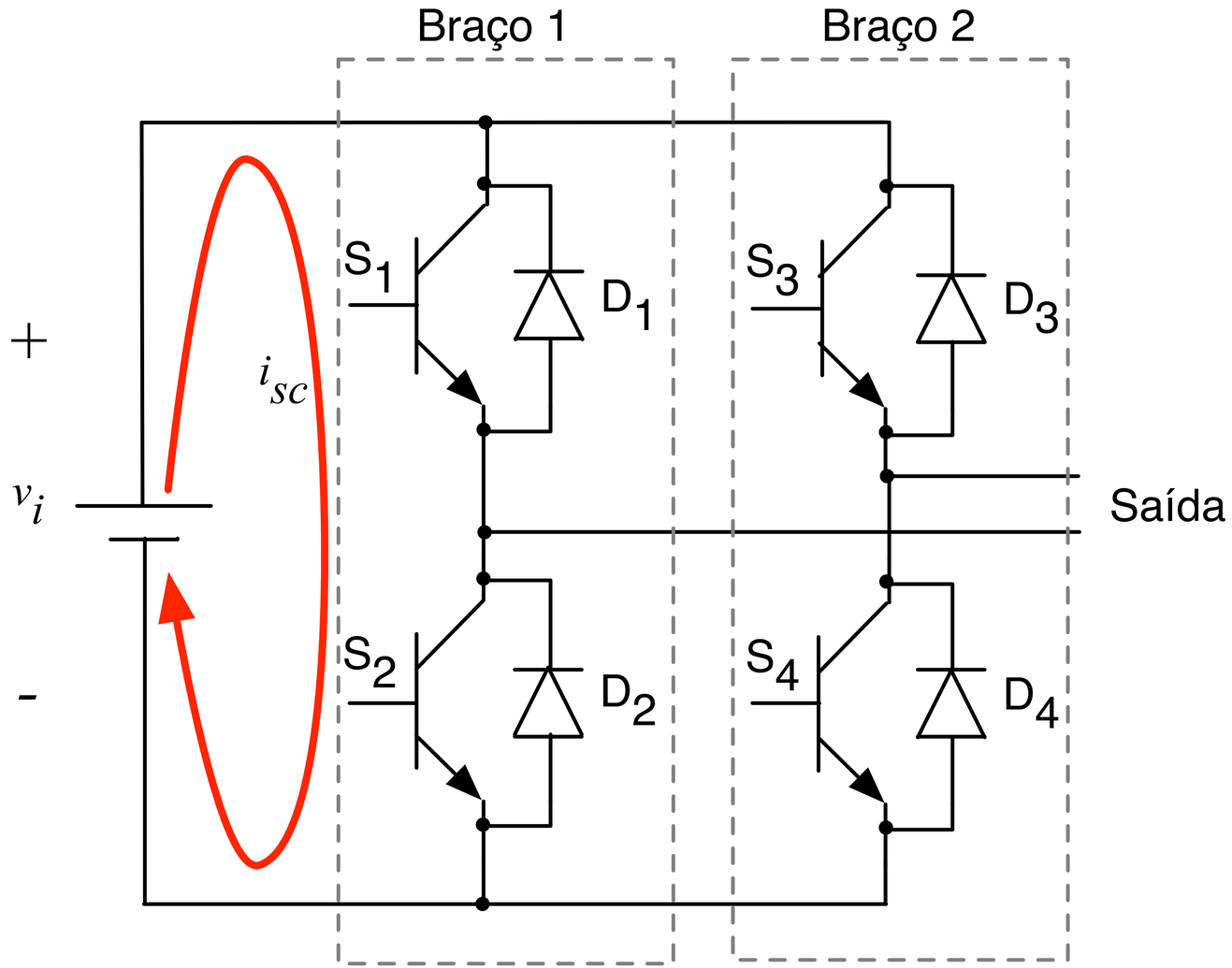
Inversor de tensão



Inversor de corrente

Conversores CC-CA

Comutação:



Curto de braço

Aplicações de Conversores CC-CA

Algumas aplicações:

- Acionamento de motores de corrente contínua;
- Acionamento de motores de corrente alternada;
- Energias alternativas;
- Isolamento em alta freqüência;
- Filtros ativos;
- Estabilizadores de tensão;
- UPS;
- Aplicações espaciais, aeronáuticas e veiculares
- Entre outras.

http://www.vonder.com.br/

https://www.energiasolarphb.com.br/

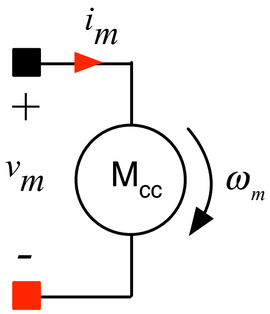
https://www.weg.net/

https://www.weg.net/

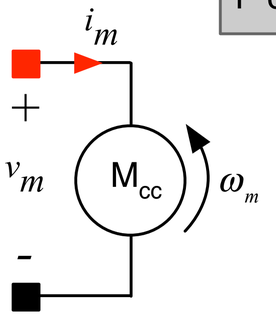
Quadrantes de Operação

2º quadrante

$$\begin{cases} v_m < 0 \\ i_m > 0 \end{cases} \rightarrow P_m < 0 \rightarrow \text{Modo gerador}$$



1º quadrante



$$\begin{cases} v_m > 0 \\ i_m > 0 \end{cases} \rightarrow P_m > 0 \rightarrow \text{Modo motor}$$

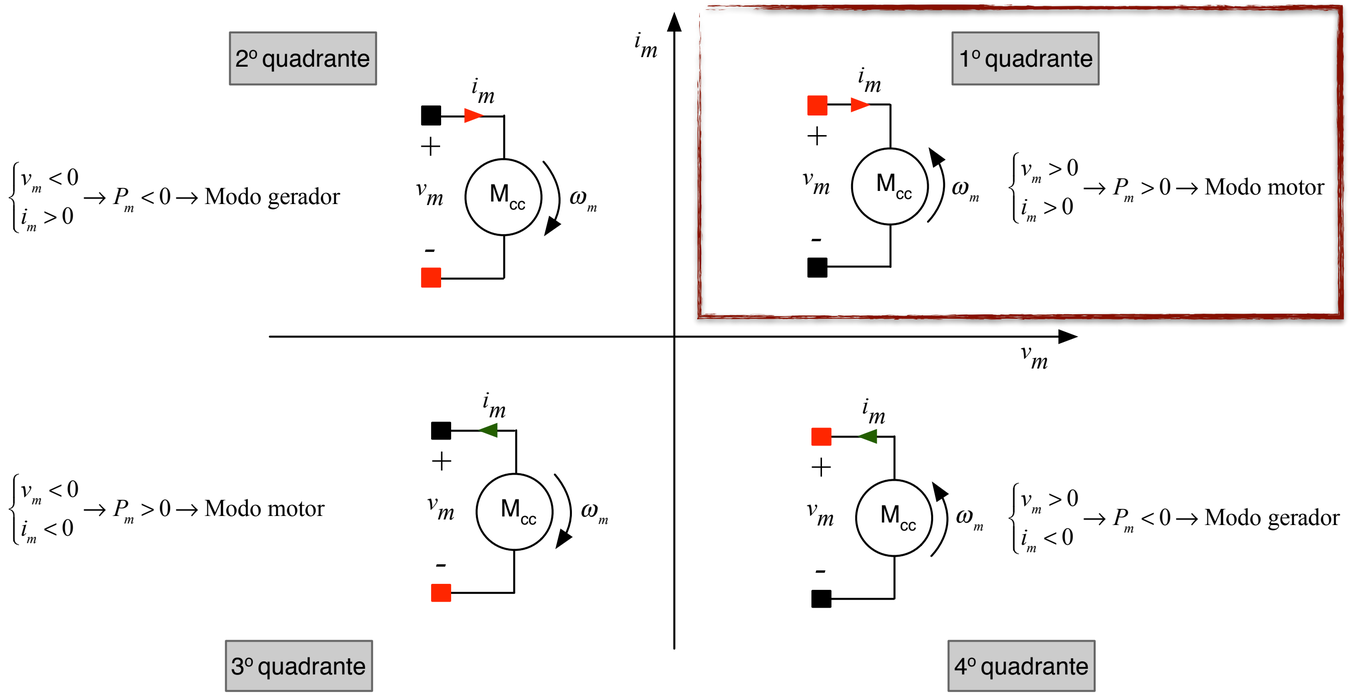
$$\begin{cases} v_m < 0 \\ i_m < 0 \end{cases} \rightarrow P_m > 0 \rightarrow \text{Modo motor}$$

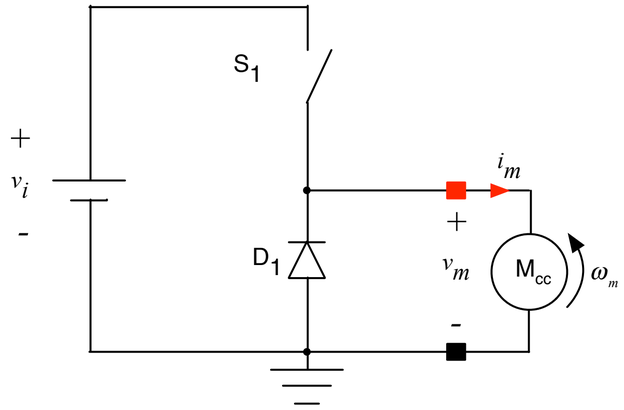
3º quadrante

$$\begin{cases} v_m > 0 \\ i_m < 0 \end{cases} \rightarrow P_m < 0 \rightarrow \text{Modo gerador}$$

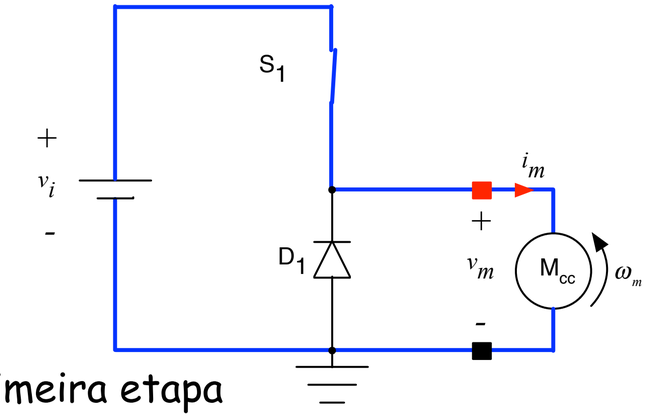
4º quadrante

Quadrantes de Operação

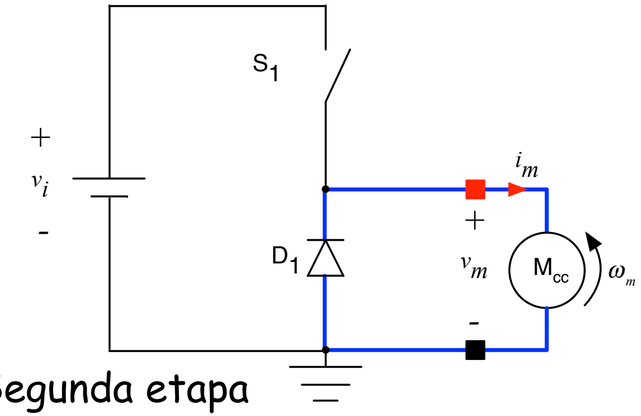




Conversor simples com chave

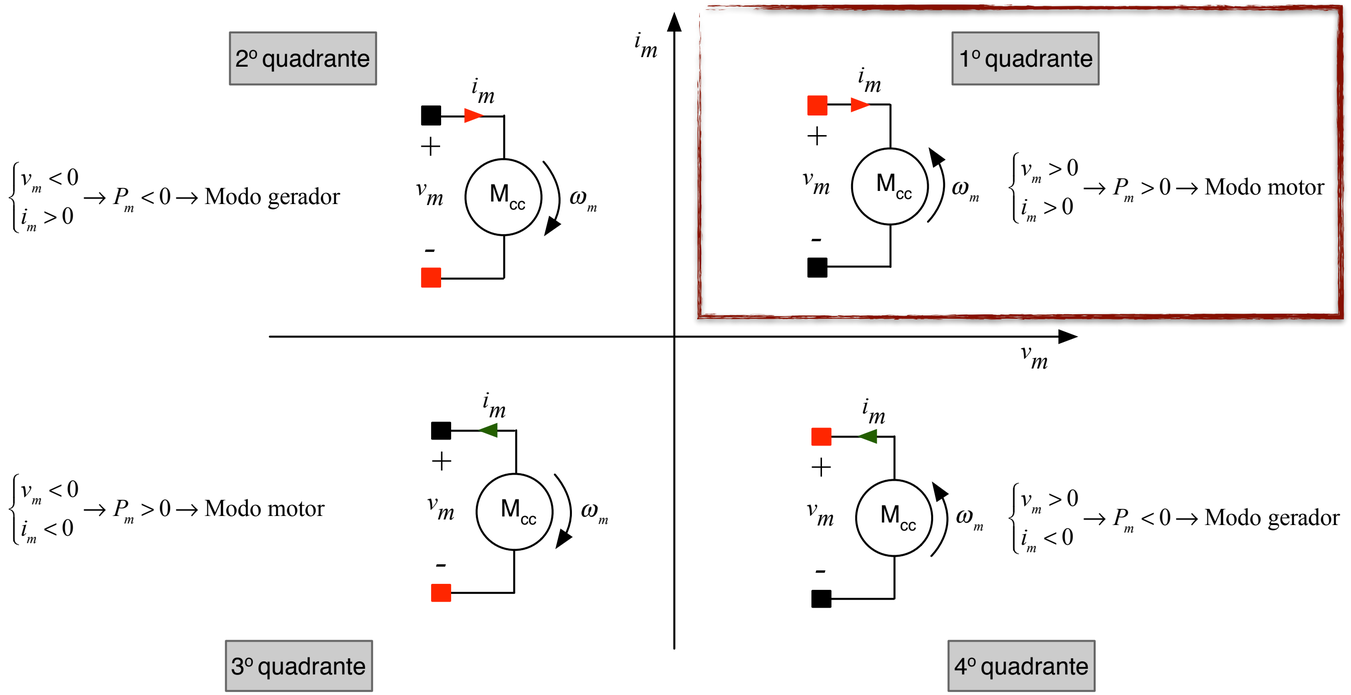


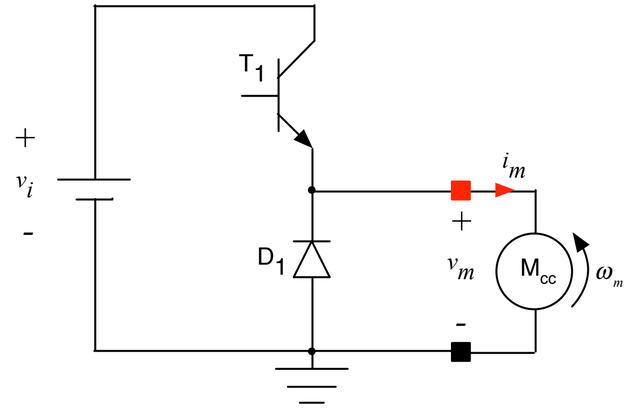
Primeira etapa



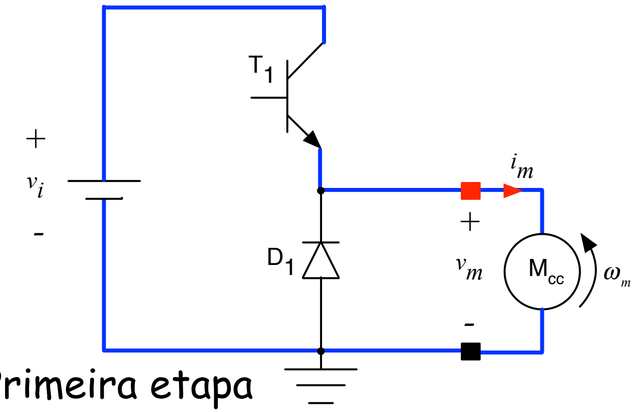
Segunda etapa

Quadrantes de Operação

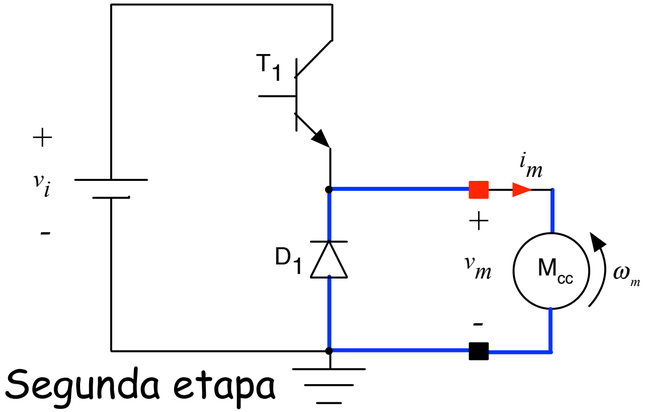




Conversor simples com transistor

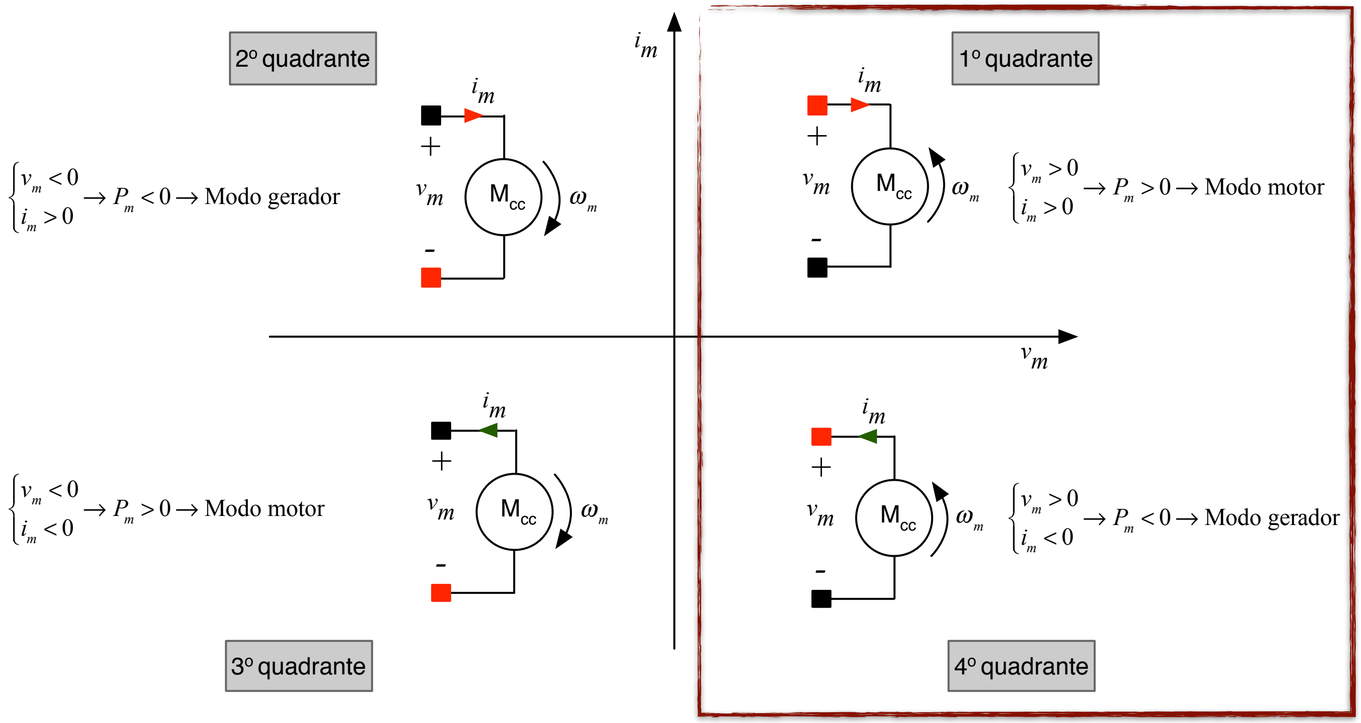


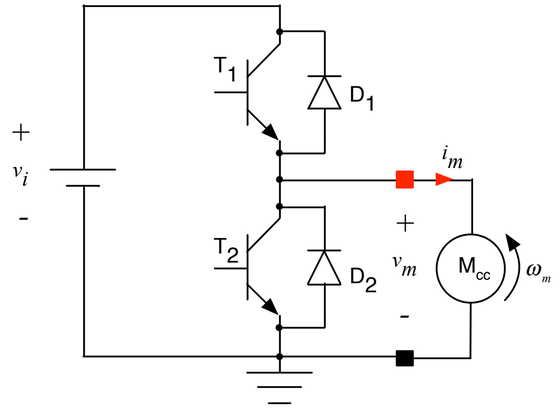
Primeira etapa



Segunda etapa

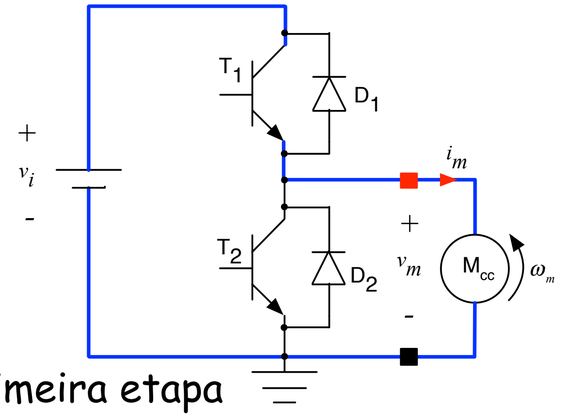
Quadrantes de Operação



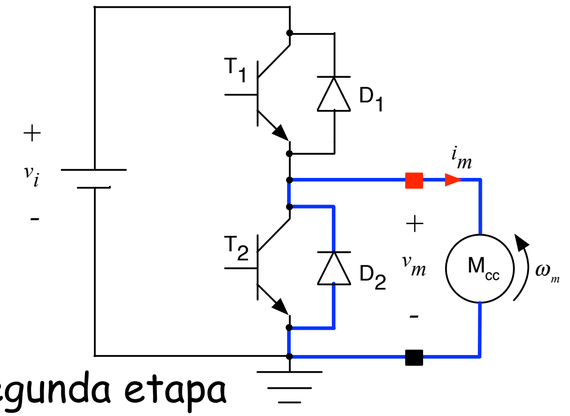


Conversor meia ponte

Modo motor



Primeira etapa



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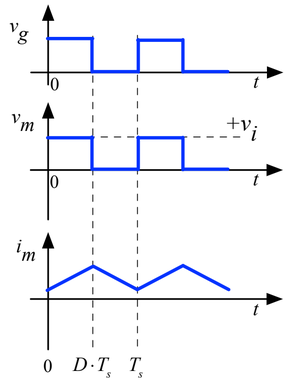
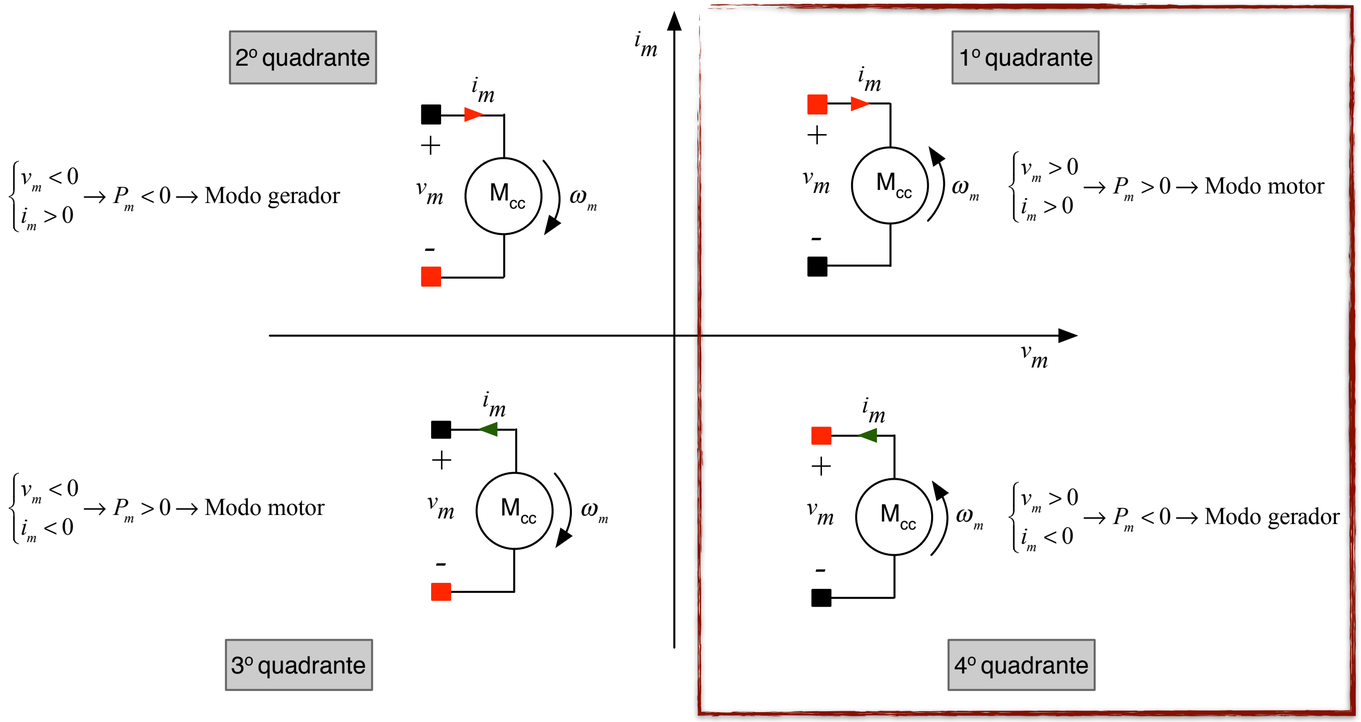
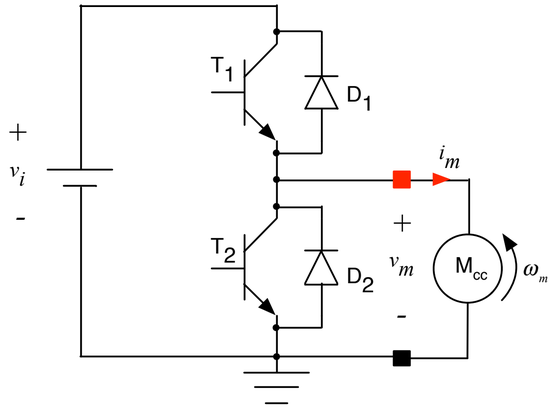


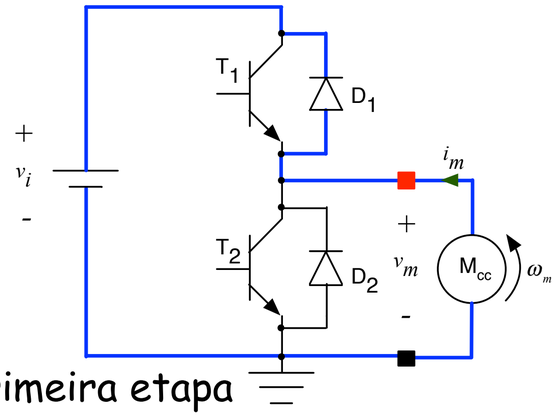
Quadrantes de Operação



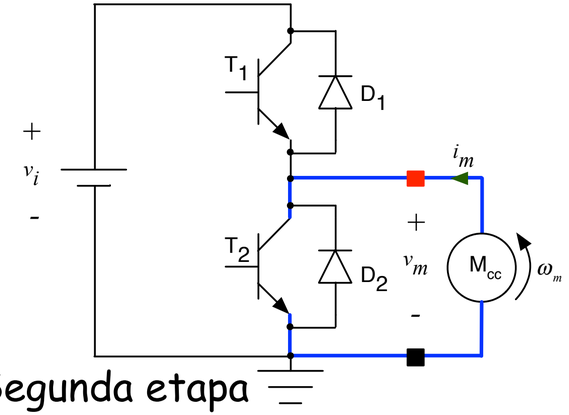


Conversor meia ponte

Modo gerador



Primeira etapa



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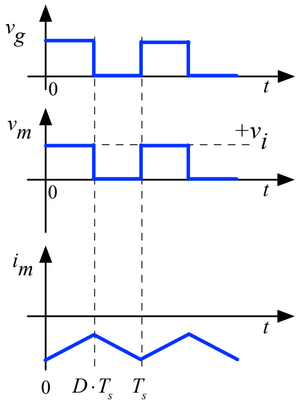

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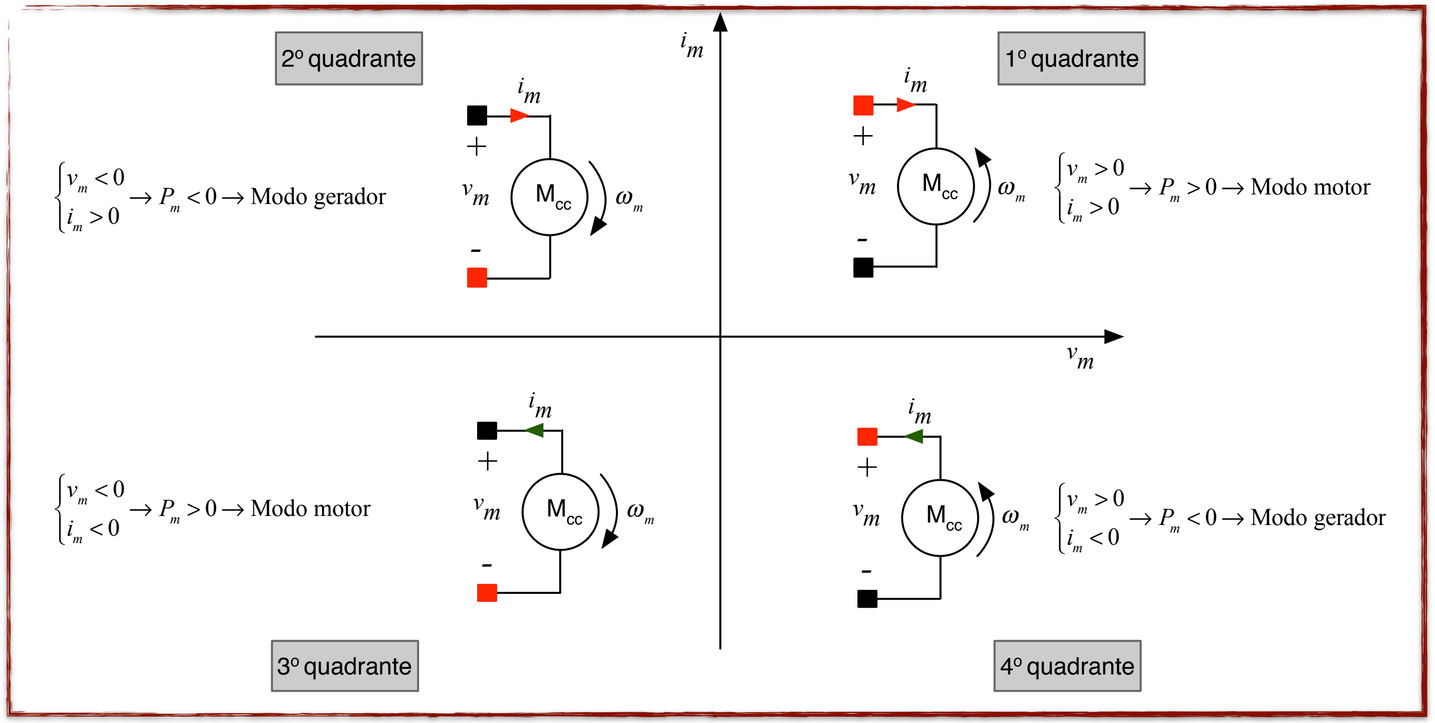
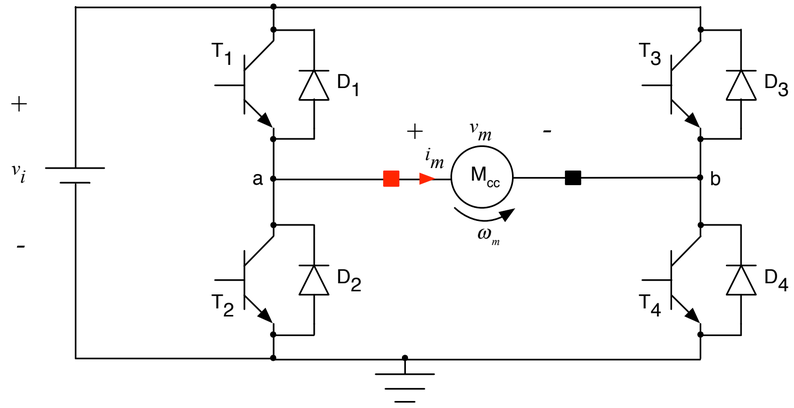
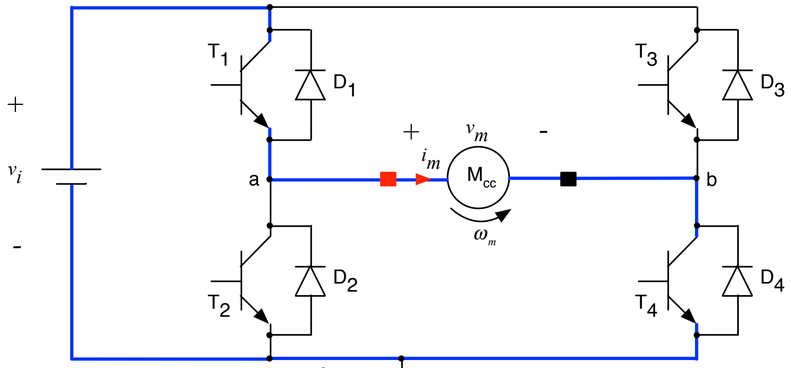


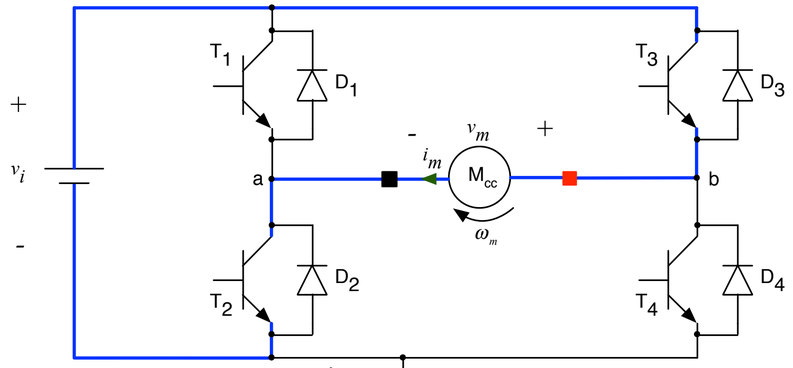


Conversor ponte completa

Modo motor

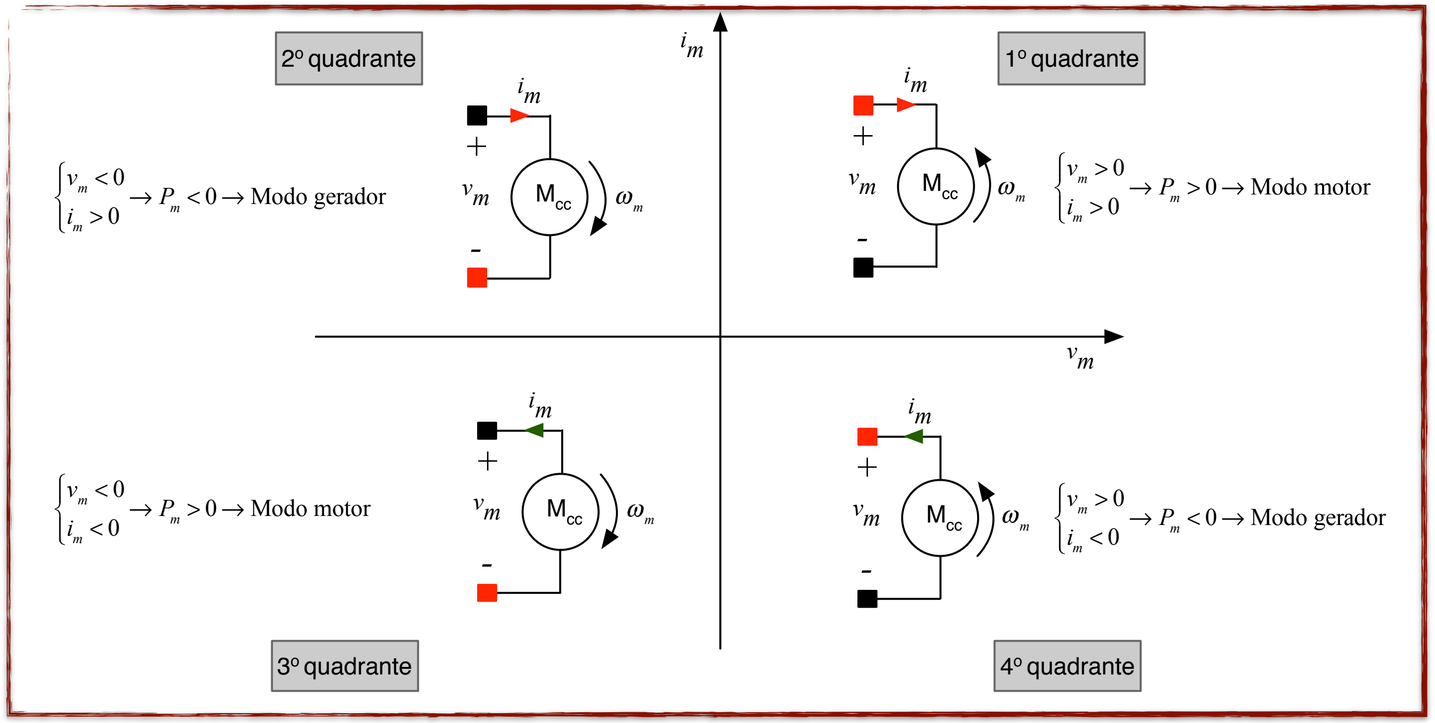


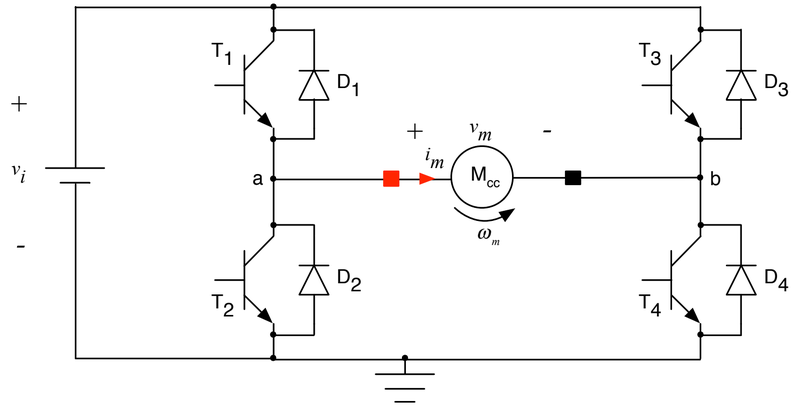
Rotação um sentido



Rotação em outro sentido

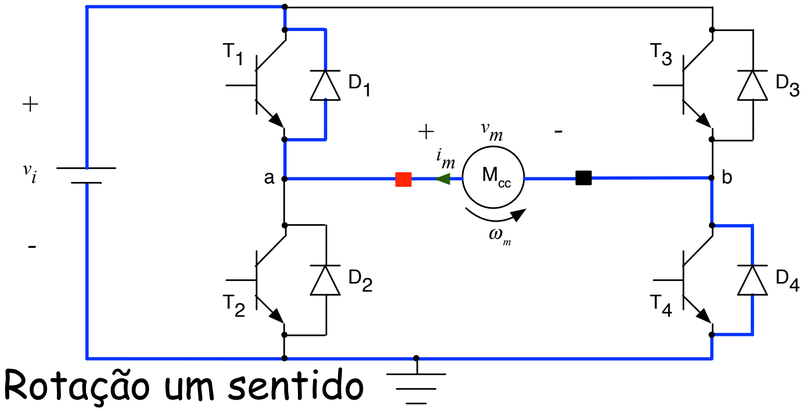
Quadrantes de Operação



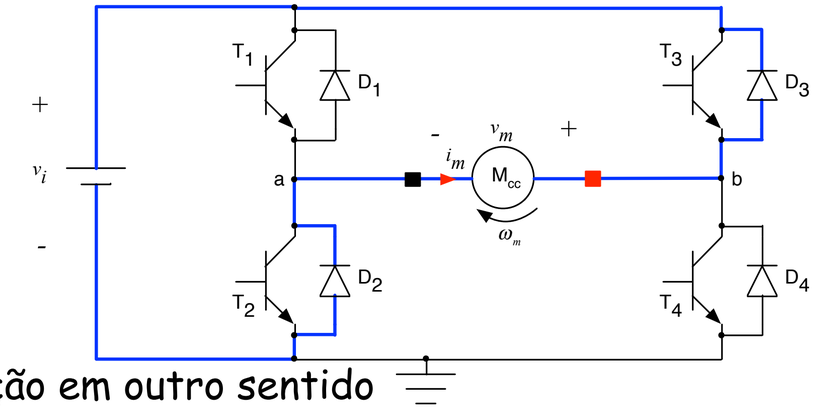


Conversor ponte completa

Modo gerador

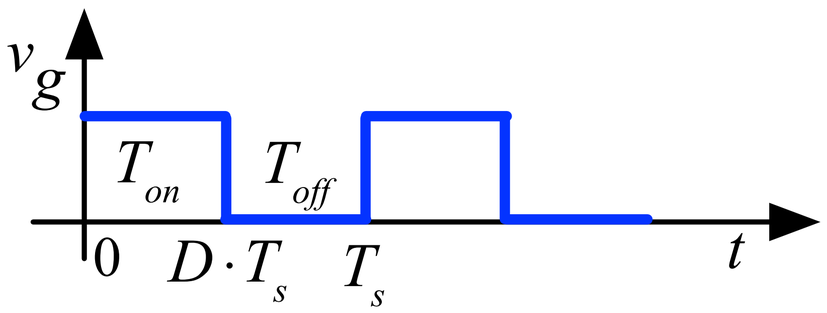


Rotação um sentido



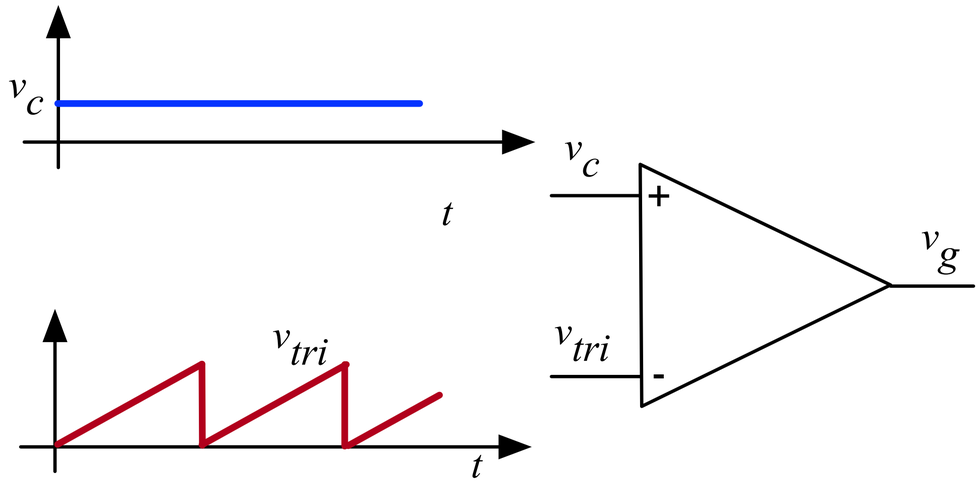
Rotação em outro sentido

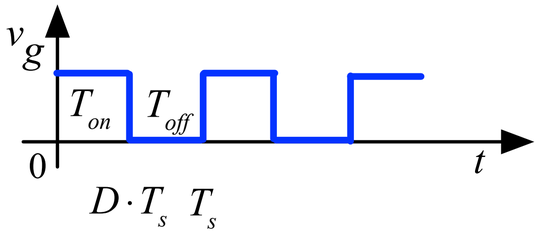
Modulação PWM



$$T_s = \frac{1}{F_s} \qquad T_{on} = D \cdot T_s$$

$$T_{of} = T_s - T_{on} = T_s - D \cdot T_s = \left(1 - D\right) \cdot T_s$$





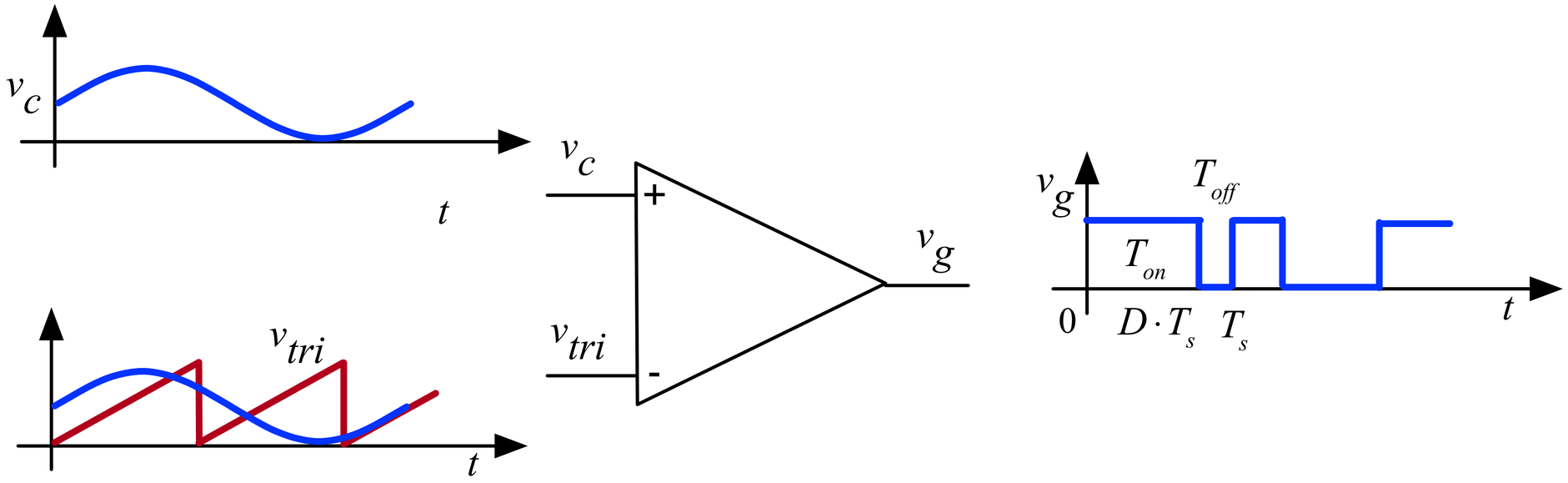
$$D = \frac{T_{on}}{T_s}$$

$$D = \frac{V_c}{V_{tri}}$$

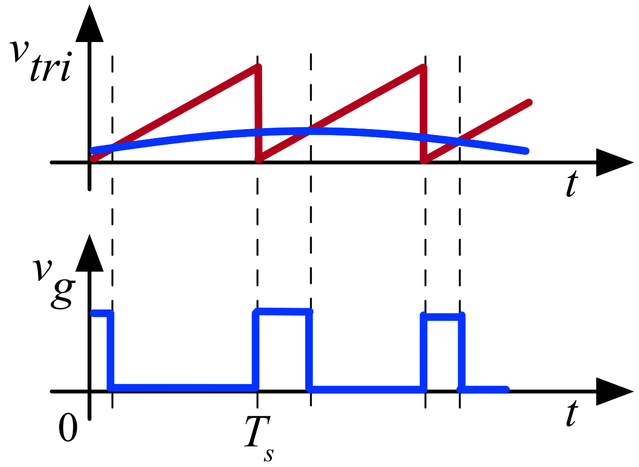
Modulação PWM Senoidal

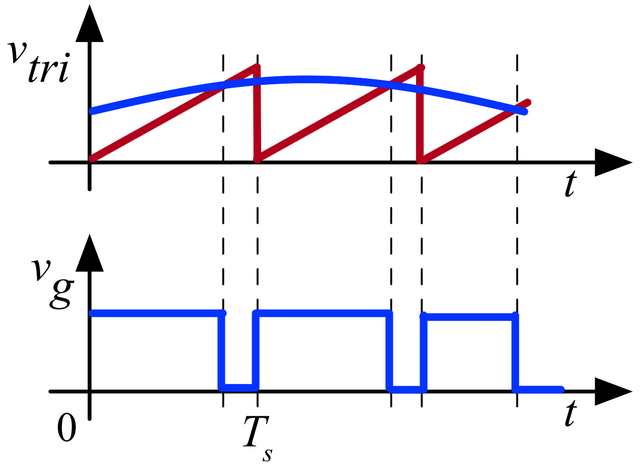
$$d(t) = \frac{v_c(t)}{v_{tri}(t)} = \frac{V_c \cdot seno(t)}{V_{tri}} = \frac{V_c}{V_{tri}} \cdot seno(t)$$

$$IM = \frac{V_c}{V_{tri}} \rightarrow d(t) = IM \cdot seno(t)$$

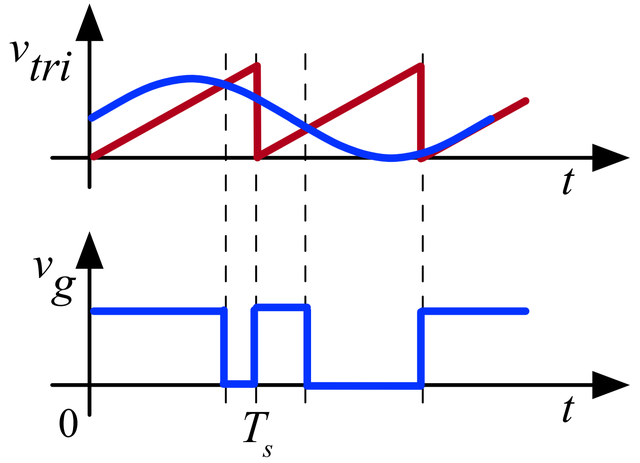


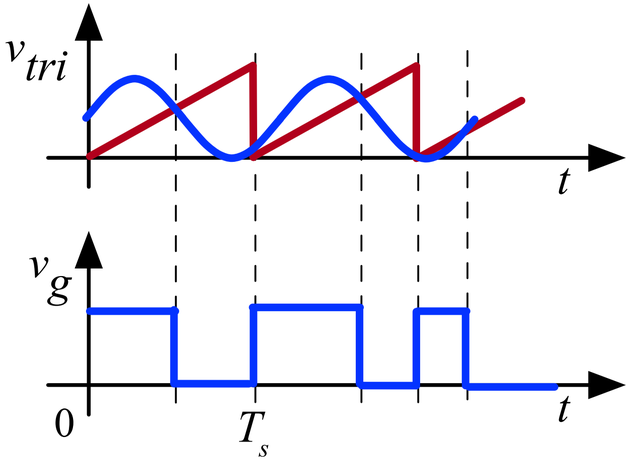
Modulação PWM Senoidal





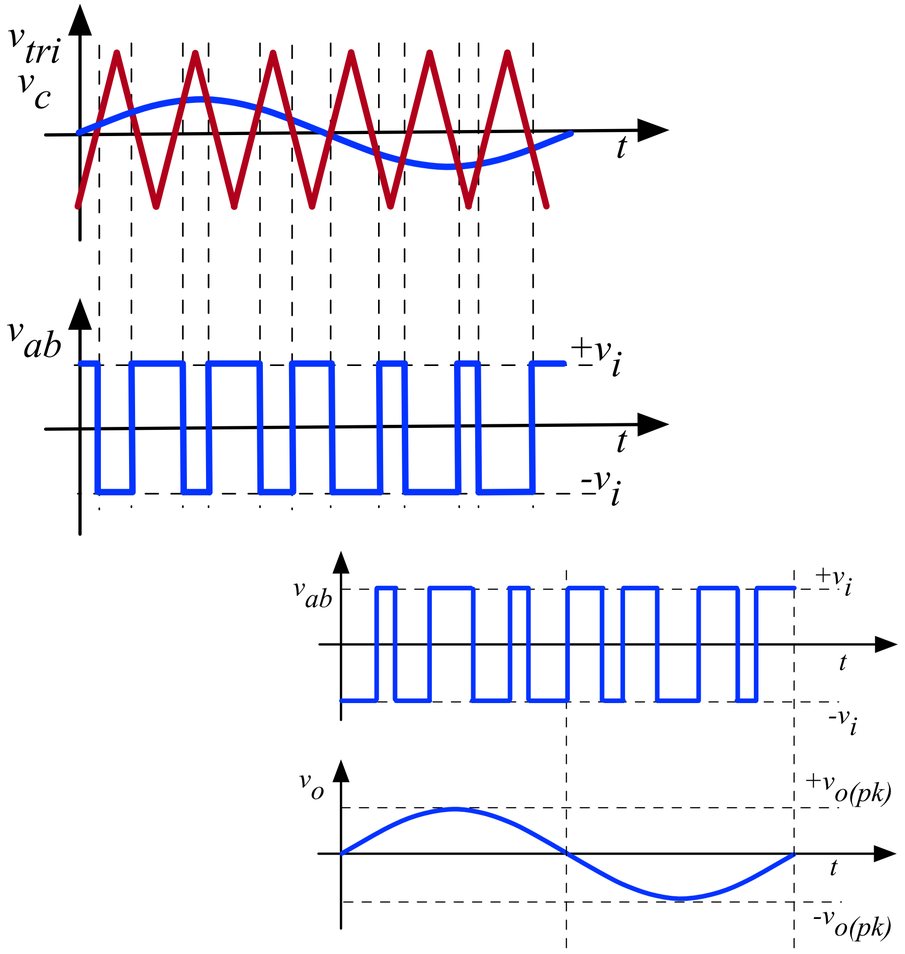
Modificação na amplitude da modulante



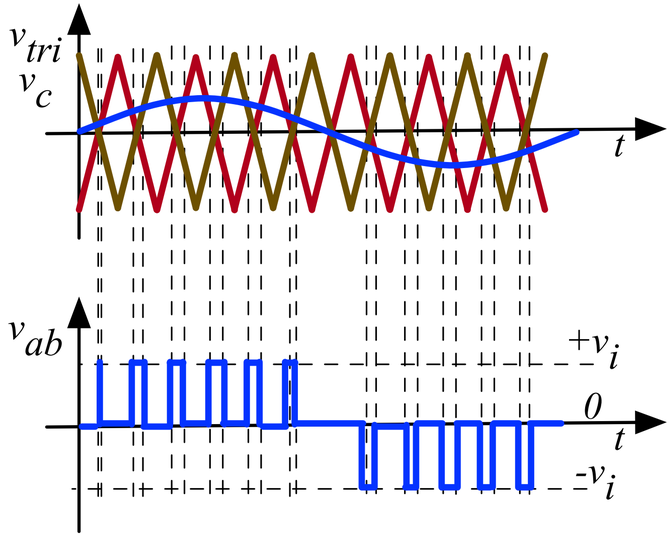


Modificação na frequência da modulante

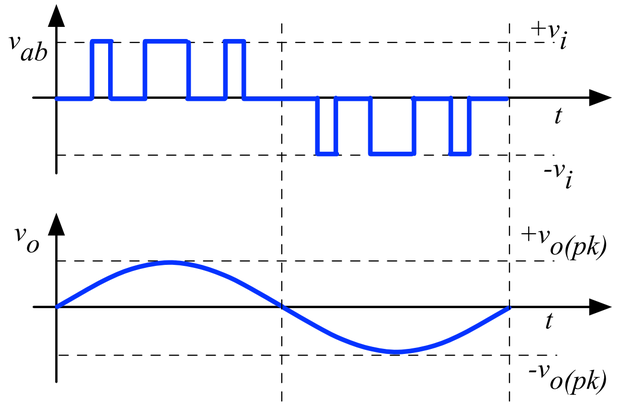
Modulação PWM Senoidal



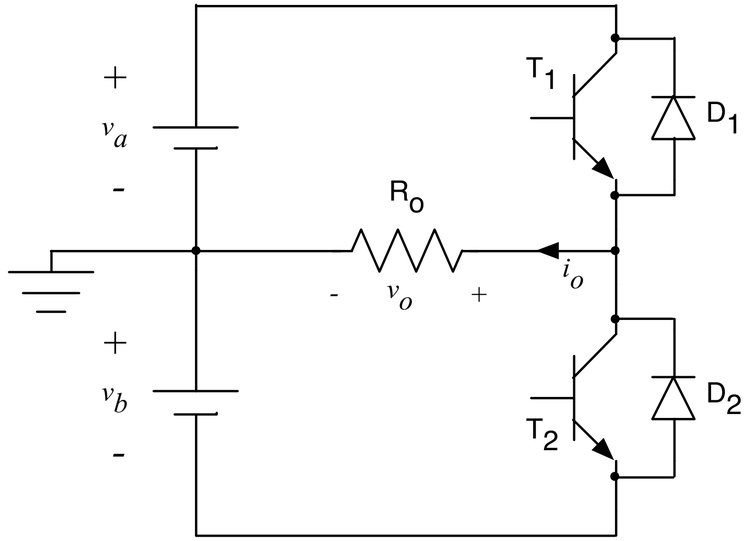
Modulação 2 níveis (bipolar)



Modulação 3 níveis (unipolar)



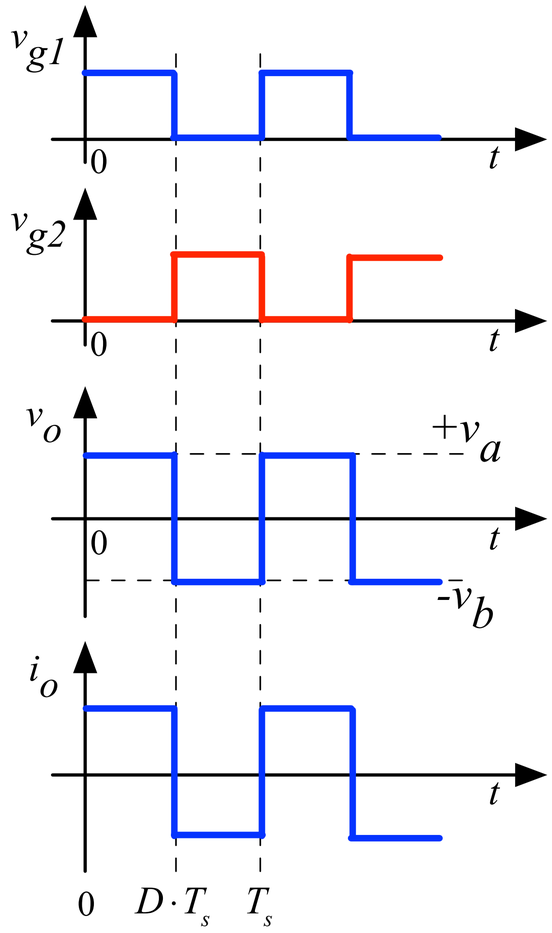
Princípio de funcionamento



$$\begin{cases} v_a = V_a \\ v_b = V_b \end{cases} \rightarrow \text{definidas} \qquad \begin{aligned} +V_{o(\max)} &= V_{a(\max)} \\ -V_{o(\max)} &= V_{b(\max)} \end{aligned}$$

$$V_a = V_b = \frac{V_i}{2} \qquad V_o = \frac{1}{T_s} \cdot V_a \cdot D \cdot T_s + \frac{1}{T_s} \cdot \left(-V_b\right) \cdot \left(1 - D\right) \cdot T_s$$

$$V_o = V_a \cdot D - V_b \cdot \left(1 - D\right)$$

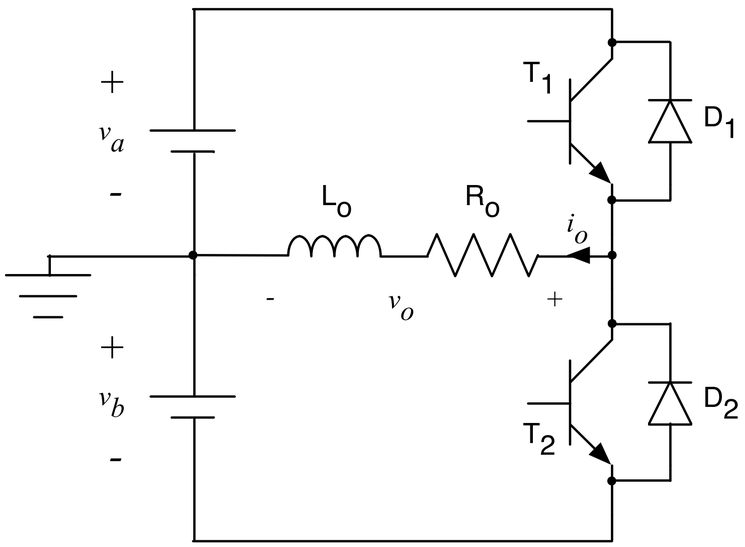


$$V_o = \frac{V_i}{2} \cdot \left(2 \cdot D - 1\right)$$

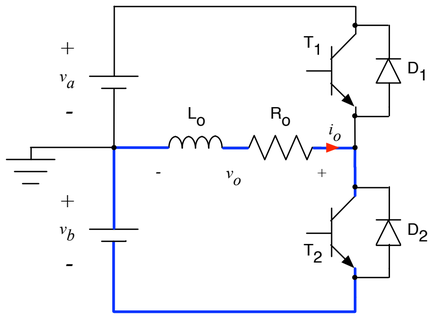
$$V_o = \begin{cases} D = 0 \rightarrow -\frac{V_i}{2} \\ D = 0{,}5 \rightarrow 0 \\ D = 1 \rightarrow +\frac{V_i}{2} \end{cases}$$

$$D = \frac{1}{2} + \frac{V_o}{V_i}$$

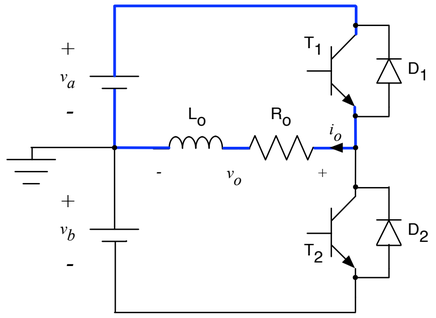
Princípio de funcionamento



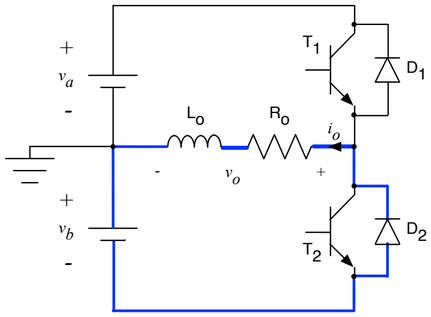
Tempo morto



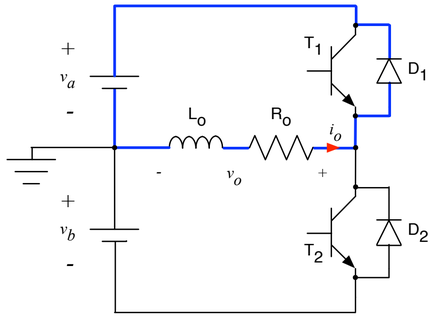
Terceira etapa



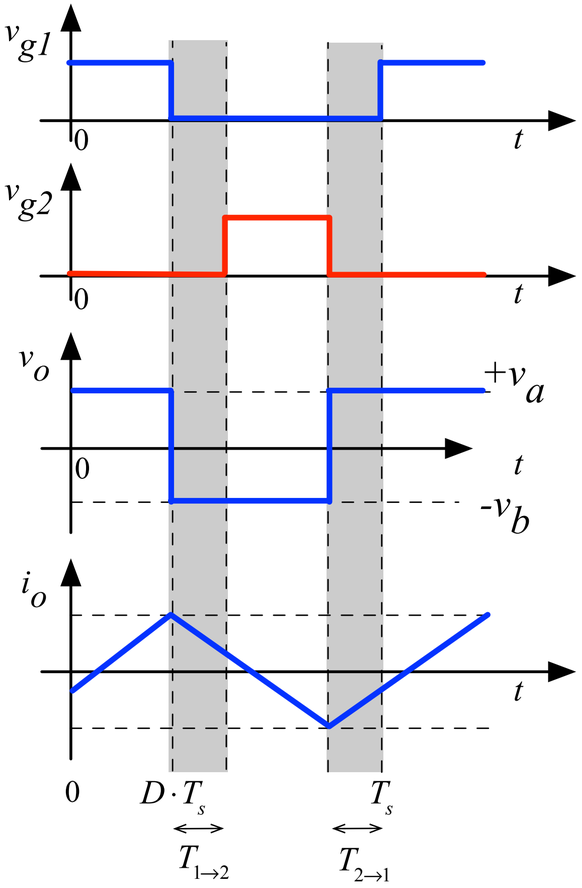
Primeira etapa



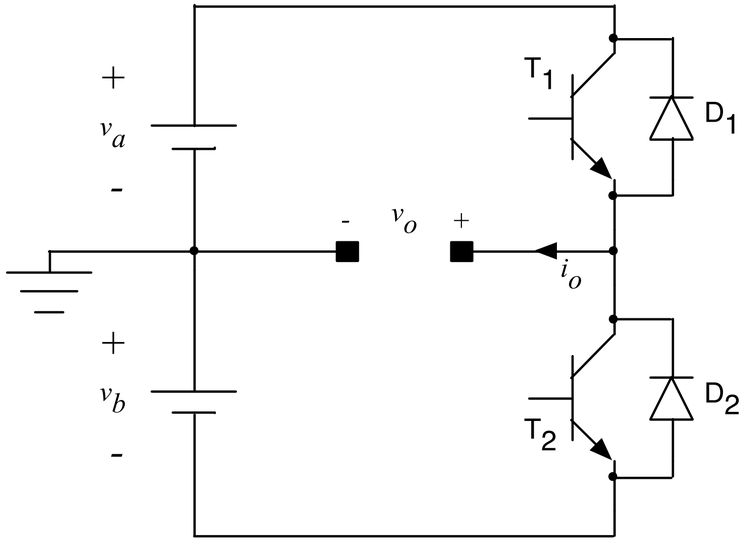
Segunda etapa



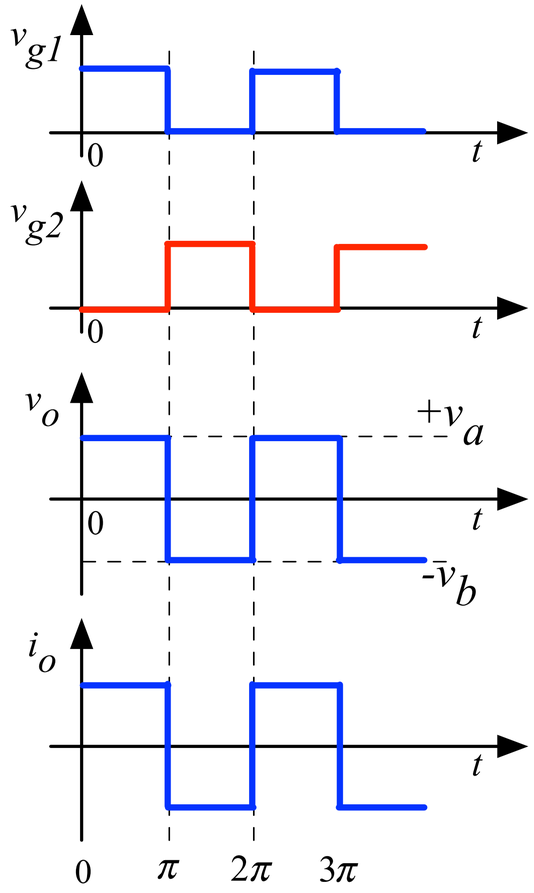
Quarta etapa



Conversor Meia Ponte

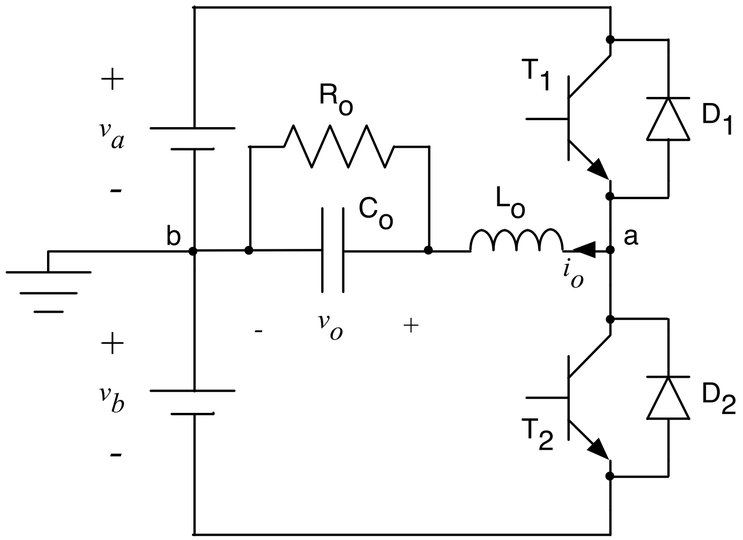


Onda Quadrada

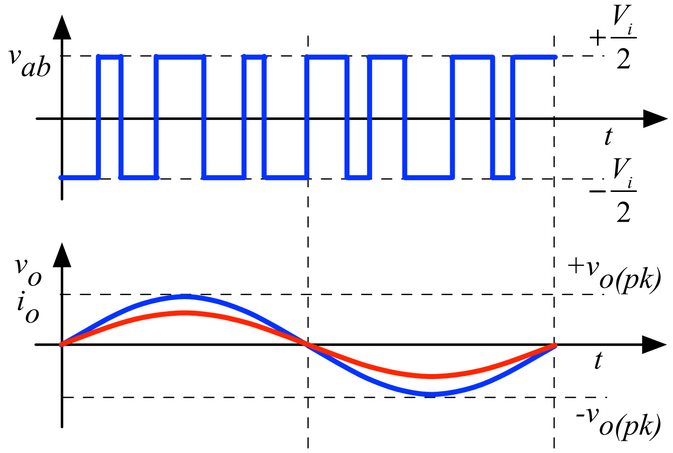


$$V_{o(ef)} = \frac{V_i}{2} \rightarrow V_a = V_b = \frac{V_i}{2}$$

Conversor Meia Ponte



PWM Senoidal



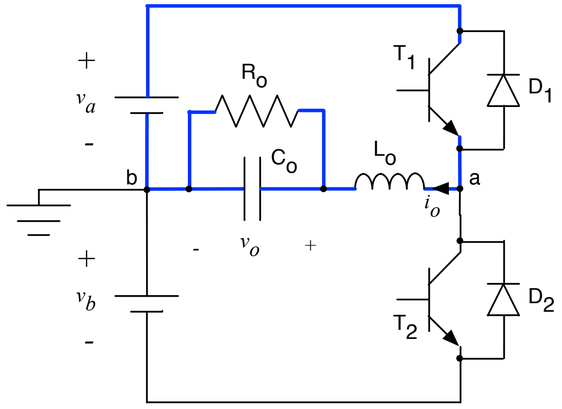
$$V_a = V_b = \frac{V_i}{2}$$

$$V_{Lo} = 0 \rightarrow V_o = V_{ab} \rightarrow V_o = \frac{V_i}{2} \cdot \left(2 \cdot D - 1\right)$$

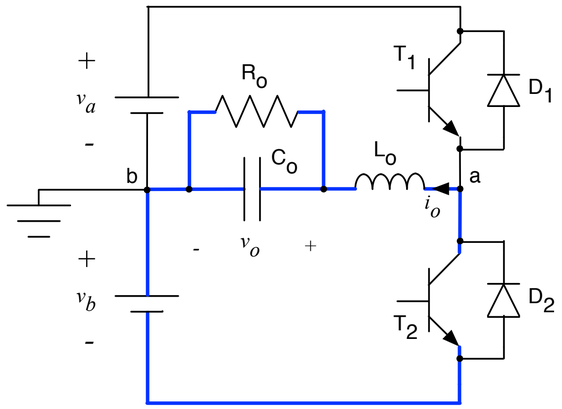
$$v_o\left(t\right) = V_{o(pk)} \cdot seno(t)$$

$$d\left(t\right) = \frac{1}{2} + \frac{V_{o(pk)} \cdot seno\left(t\right)}{V_i} \rightarrow d\left(t\right) = \frac{1}{2} + \frac{V_{o(pk)}}{V_i} \cdot seno\left(t\right)$$

$$IM = \frac{V_{o(pk)}}{V_i} \rightarrow d\left(t\right) = \frac{1}{2} + IM \cdot seno\left(t\right)$$

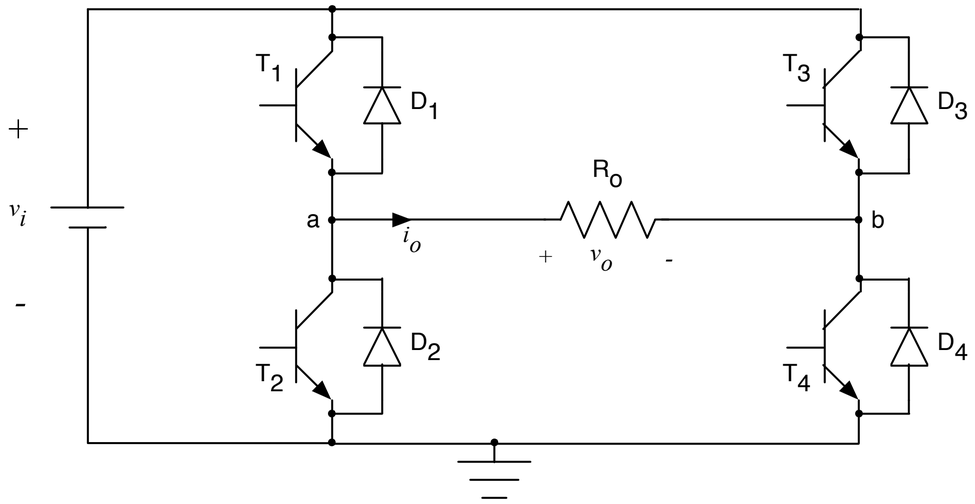


Primeira etapa



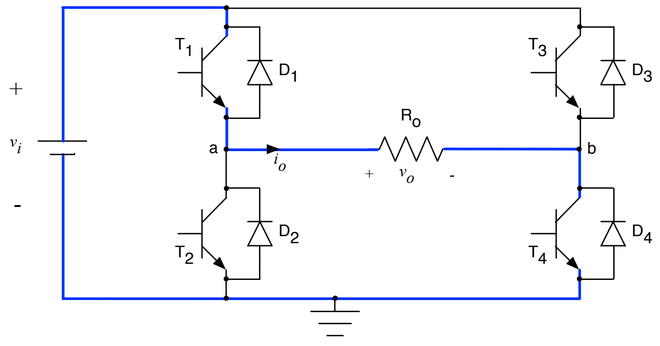
Segunda etapa

Conversor Ponte Completa

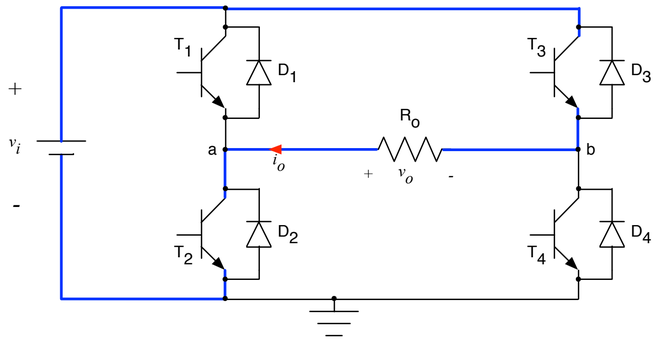


Onda Quadrada

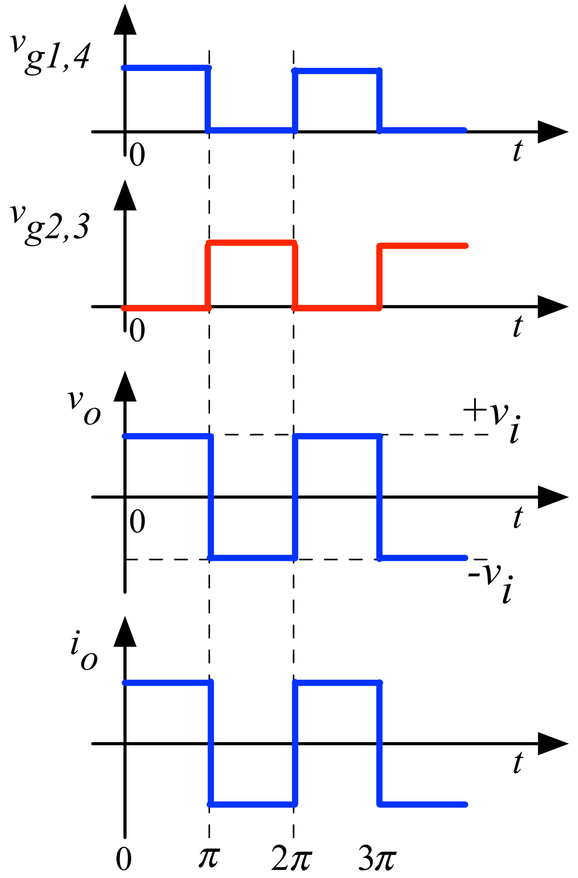
$$V_{o(ef)} = V_i$$



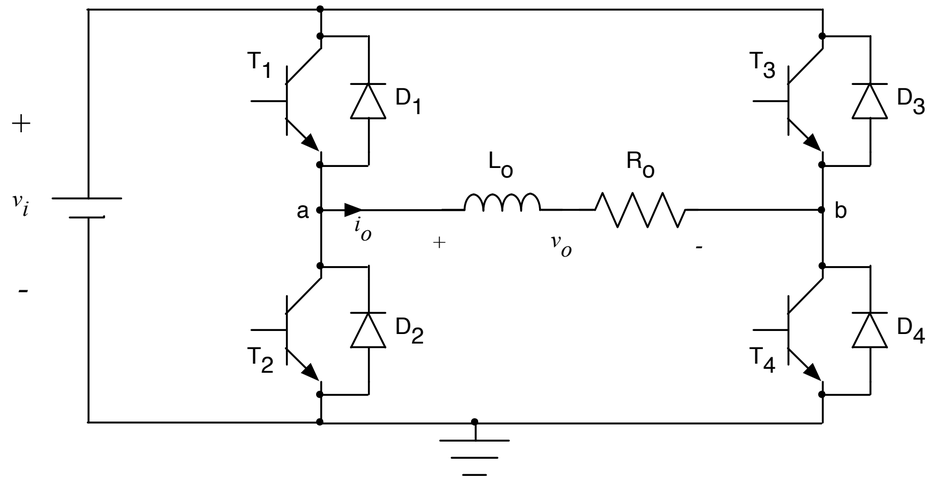
Primeira etapa



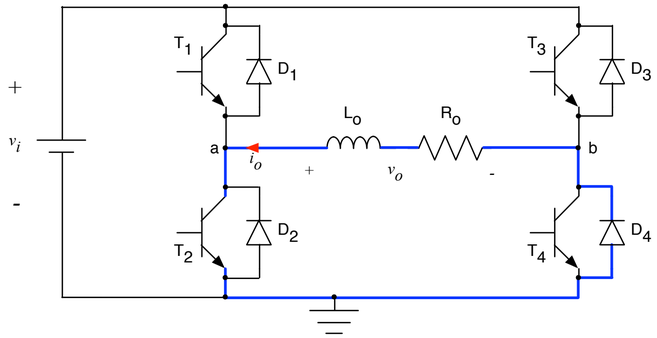
Segunda etapa

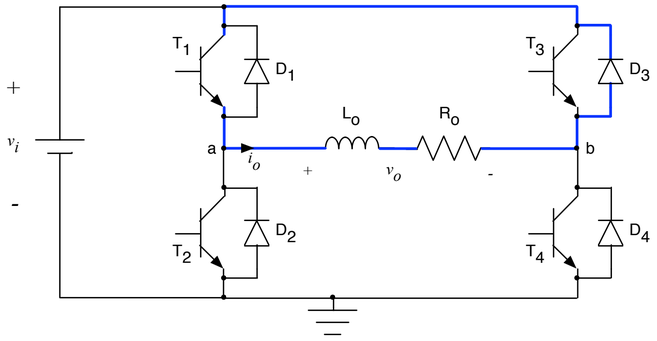


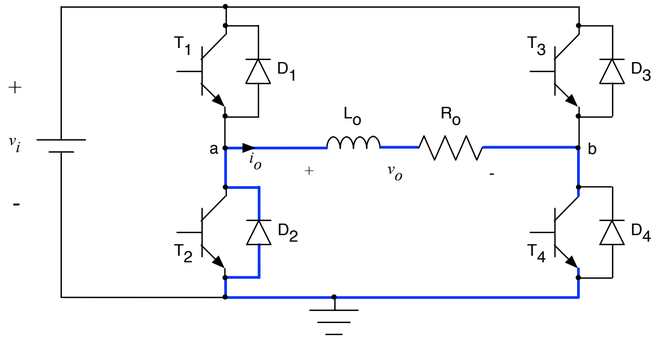
Conversor Ponte Completa



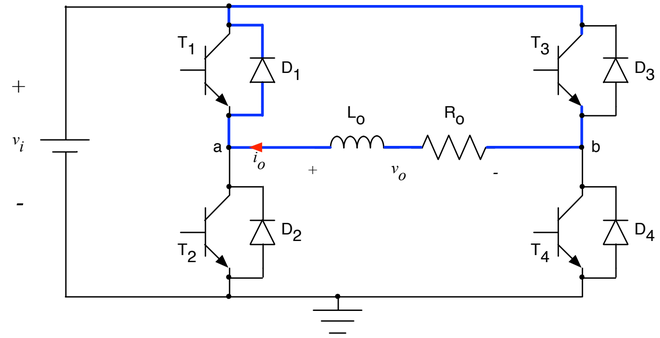
Três níveis







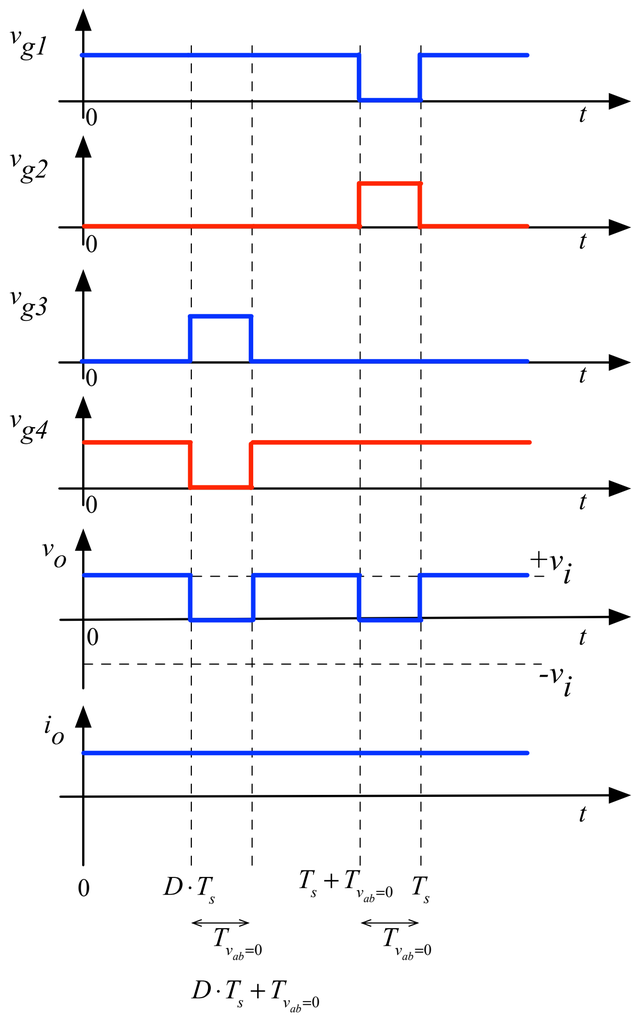
Semiciclo positivo



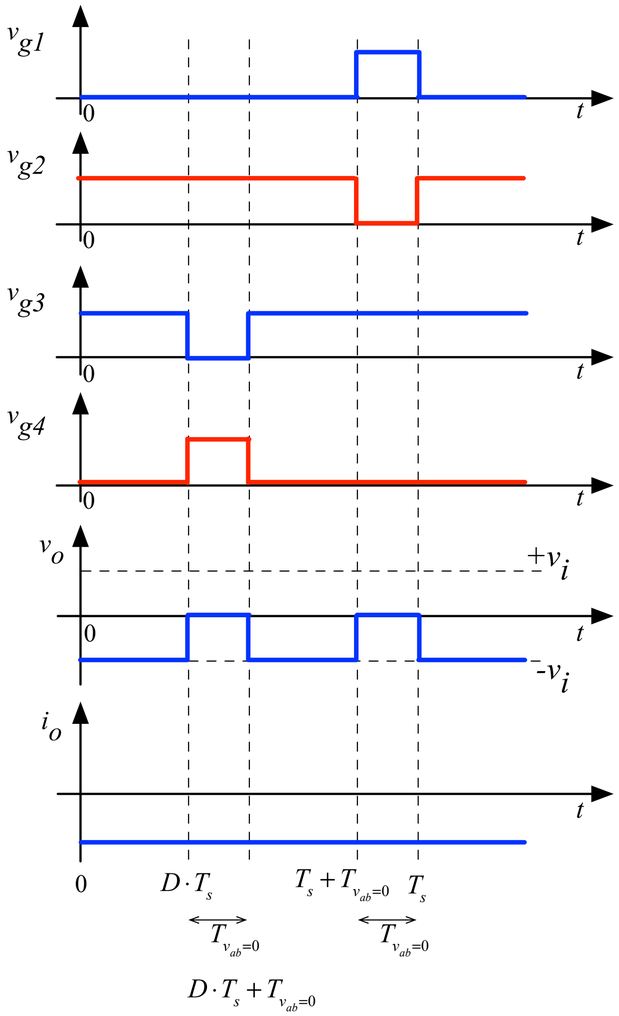
Semiciclo negativo

Conversor Ponte Completa

Três níveis

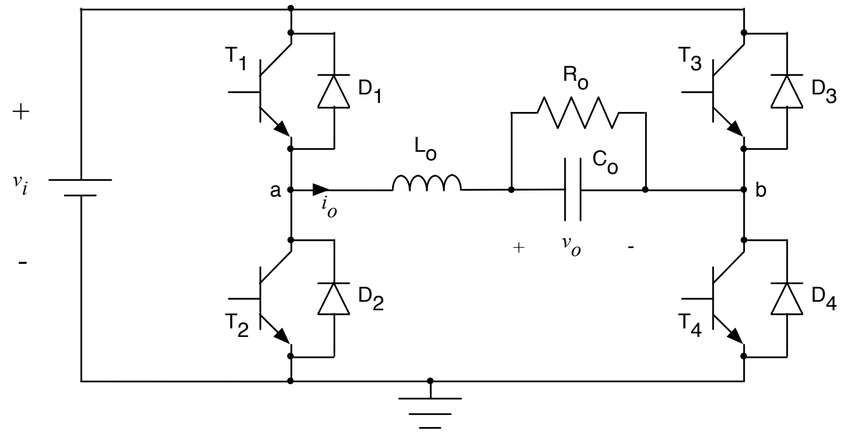


Semiciclo positivo

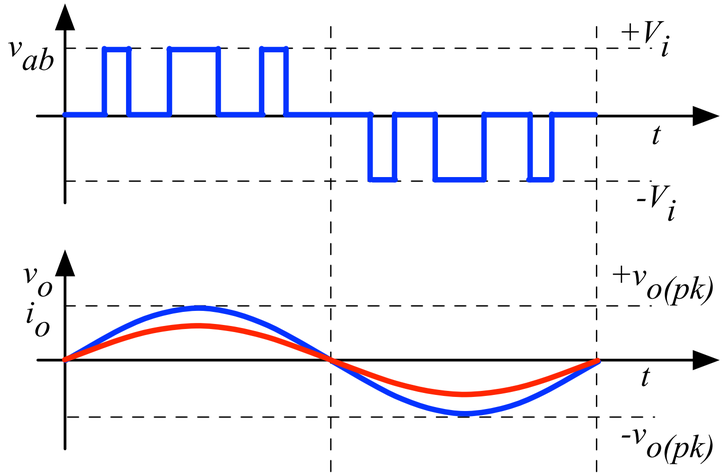


Semiciclo negativo

Conversor Ponte Completa



PWM Senoidal



$$V_i = \text{definida}$$

$$V_{ab} = \frac{1}{T_s} \cdot V_i \cdot D \cdot T_s$$

$$V_{ab} = V_i \cdot D$$

$$V_{Lo} = 0 \rightarrow V_o = V_{ab} \rightarrow V_o = V_i \cdot D$$

$$V_{o(ef)} = \frac{V_{o(pk)}}{\sqrt{2}}$$

$$v_o(t) = V_{o(pk)} \cdot seno(t)$$

$$V_{o(pk)} \cdot seno(t) = V_i \cdot d(t)$$

$$d(t) = \frac{V_{o(pk)} \cdot seno(t)}{V_i} \rightarrow d(t) = \frac{V_{o(pk)}}{V_i} \cdot seno(t)$$

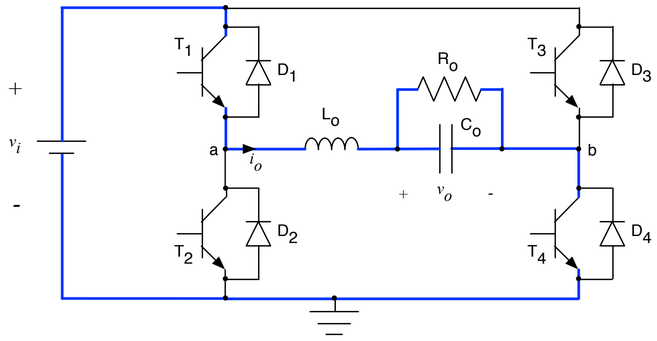
$$IM = \frac{V_{o(pk)}}{V_i} \rightarrow d(t) = IM \cdot seno(t)$$

$$\Delta i = \% \cdot I_o[A] \qquad \Delta v = \% \cdot V_o[V]$$

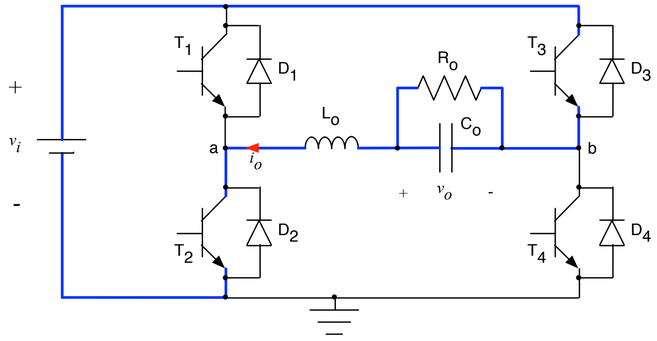
$$L_o = \frac{V_i}{2 \cdot \Delta_i \cdot F_s} \cdot D \cdot (1 - D) \qquad C_o = \frac{V_i}{4 \cdot \pi^3 \cdot \Delta v \cdot L_o \cdot F_s^2}$$

Conversor Ponte Completa

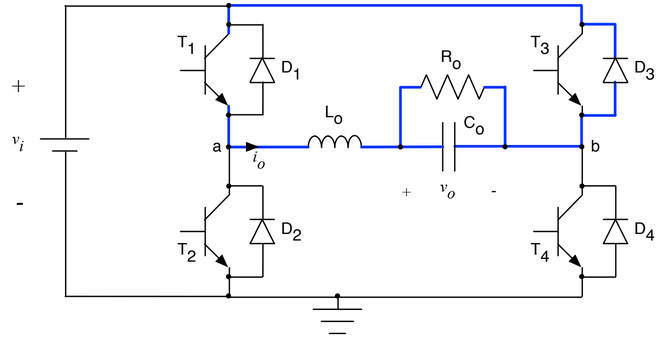
PWM Senoidal



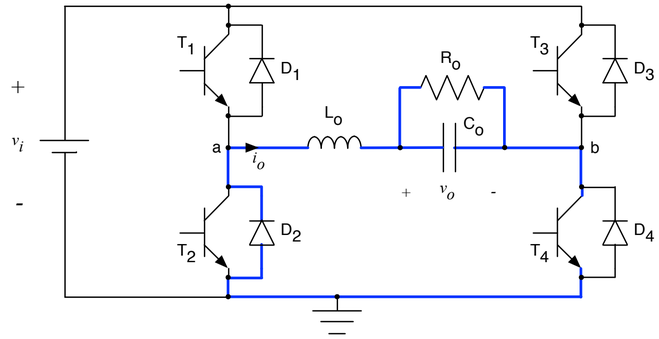
$v_{ab} = +V_i$ e $i_o > 0$



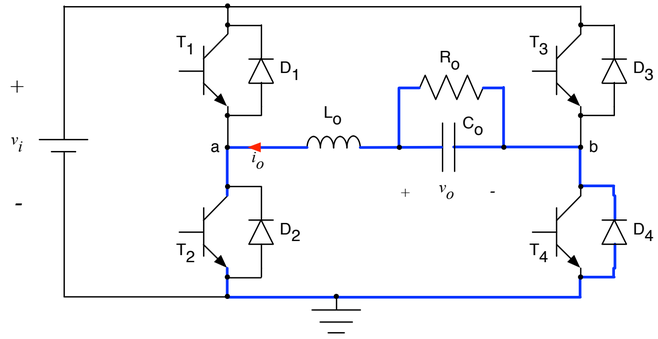
$v_{ab} = -V_i$ e $i_o < 0$



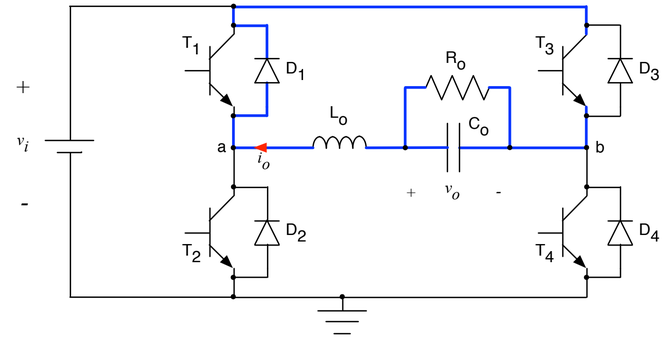
$v_{ab} = 0$ e $i_o > 0$



$v_{ab} = 0$ e $i_o > 0$



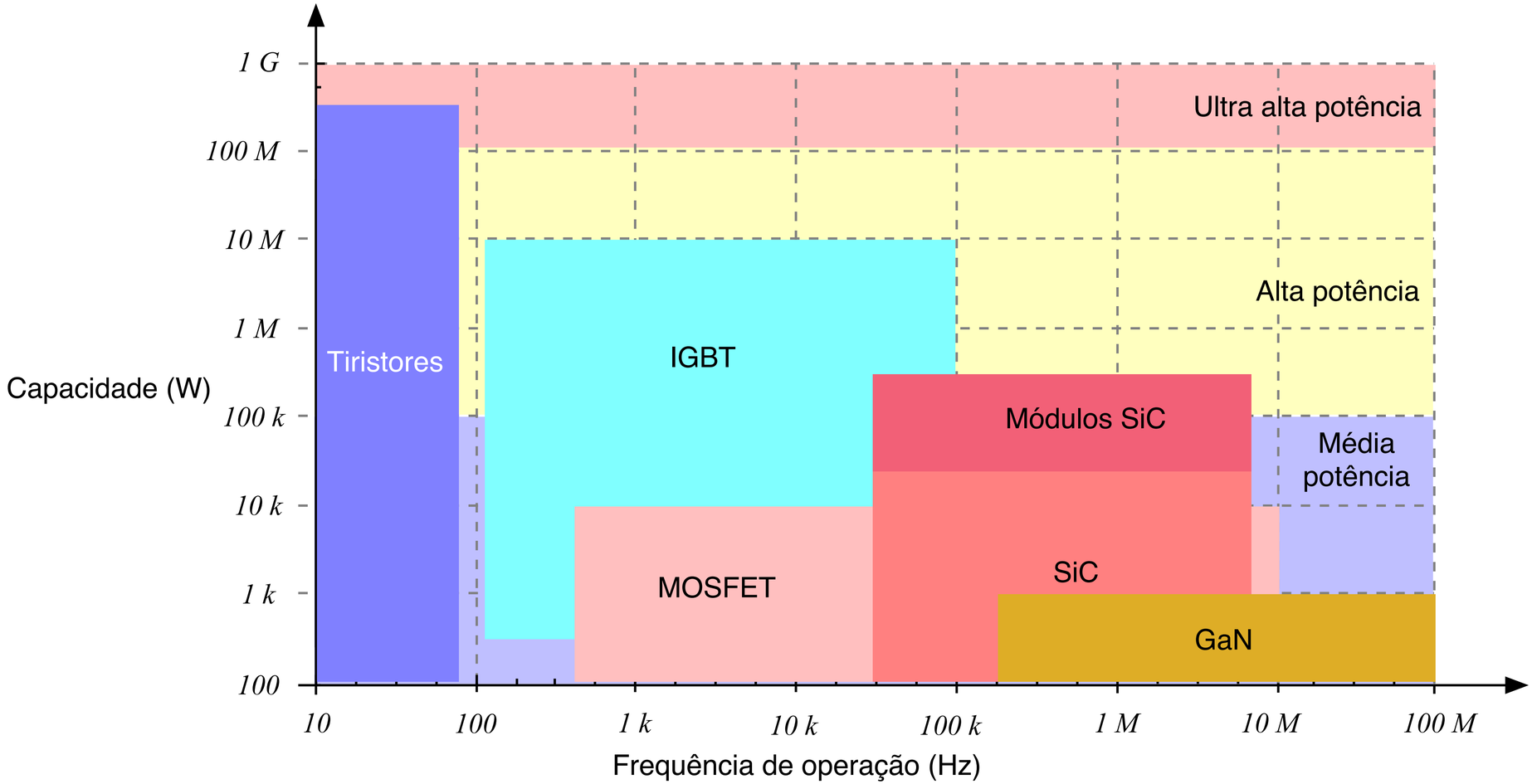
$v_{ab} = 0$ e $i_o < 0$



$v_{ab} = 0$ e $i_o < 0$

Aplicações Recentes

Cenário de semicondutores:



https://entrepreneurialenergy.files.wordpress.com/2011/06/infineon_power_semiconductor_devices_chart.png

Aplicações Recentes

Redes Inteligentes (Smart Grid):

www.smartgrid.epri.com

Aplicações Recentes

Redes Inteligentes (Smart Grid):

- Sendai, Japão;
- Fotovoltaica;
- Hidrogênio (Fuel Cell);
- Geração à gás;
- Banco de baterias;
- 950 kW.

http://microgridprojects.com/microgrid/sendai-microgrid/

Aplicações Recentes

Geração de energia e veículos elétricos:

http://fotovoltaica.ufsc.br/

Aplicações Recentes

Geração de energia e veículos elétricos:

Usina Solar Cidade Azul, Tubarão - SC:

- Potência de 3 MWp em 3 x 1 MWp;
- Silício amorfo/microcristalino (a-Si/μc-Si);
- Silício multicristalino/policristalino (p-Si);
- Disseleneto de cobre, índio e gálio (CIGS);
- Nome atual: Usina Fotovoltaica Nova Aurora.

https://www.engie.com.br/complexo-gerador/usinas/usina-fotovoltaica-nova-aurora/

Central Eólica Tubarão, Tubarão - SC:

- Potência de 2,1 MW;
- Torre de 120 metros;
- Rotor com diâmetro de 110 metros;
- Tecnologia nacional.

https://www.engie.com.br/complexo-gerador/usinas/central-eolica-tubarao/

http://fotovoltaica.ufsc.br/sistemas/fotov/blog/2018/02/28/usina-solar-cidade-azul-usca/

Aplicações Recentes

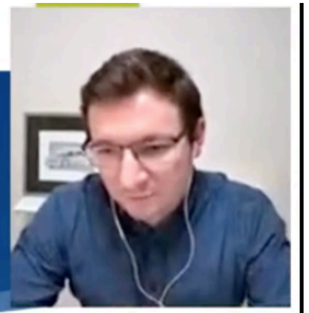
Veículos elétricos:

https://coppe.ufrj.br/

Aplicações Recentes

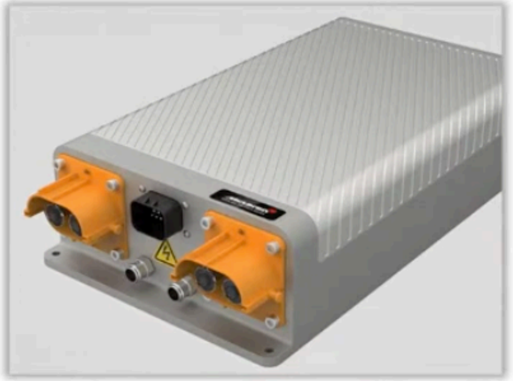
Veículos elétricos:

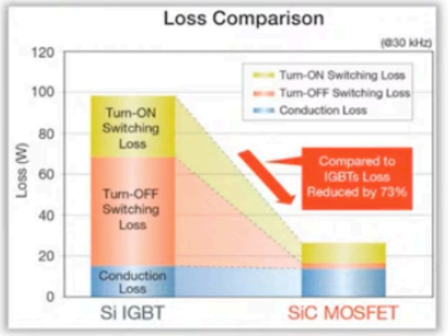
McLaren Speedtail



Inversores para Veículos Elétricos

- Inovações para Industria Automotivas/Motorsport





Inversor Trifasico SiC: 200kW ⇨ 4Kg
Versão SiC Hexafasica: 400kW

Propulsão Integrada
e-axle ⇨ 4.4kW/kg

https://www.mclaren.com/applied/innovation/automotive/#!#vehicle-electrification

https://www.youtube.com/watch?v=3XRnbYZaGUw

Próxima Aula

Conversores ca-ca

https://www.apc.com/

https://www.sms.com.br/

http://upsai.com.br/

https://www.zael.com.br/