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

Conversores CC-CC

Prof. Clovis Antonio Petry.

Florianópolis, agosto 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-cc:
   - Aplicações;
   - Introdução;
   - Modulação PWM;
   - Princípio de funcionamento.
2. Conversores cc-cc não-isolados:
   - Conversor Buck;
   - Conversor Boost;
   - Conversor Buck-Boost.
3. Conversores cc-cc isolados:
   - Principais topologias;
   - Conversor Flyback.

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Motivação

As aplicações de conversores cc-cc são diversas, desde fontes de alimentação, acionamento de cargas, co-geração de energia, etc.

https://www.amazon.com/Regulator-Converter%C2%A3%C2%ACDC-DC-Positive-Boost-Buck-Converter/dp/B07T6XDPMK

Aplicações de Conversores CC-CC

Algumas aplicações:

- Controle de velocidade de motores CC;
- Fontes chaveadas;
- Energias alternativas;
- Correção de fator de potência;
- Carregadores de bateria;
- Aplicações veiculares;
- Adaptação de tensão contínua;
- Entre outras.

https://www.filipeflop.com/

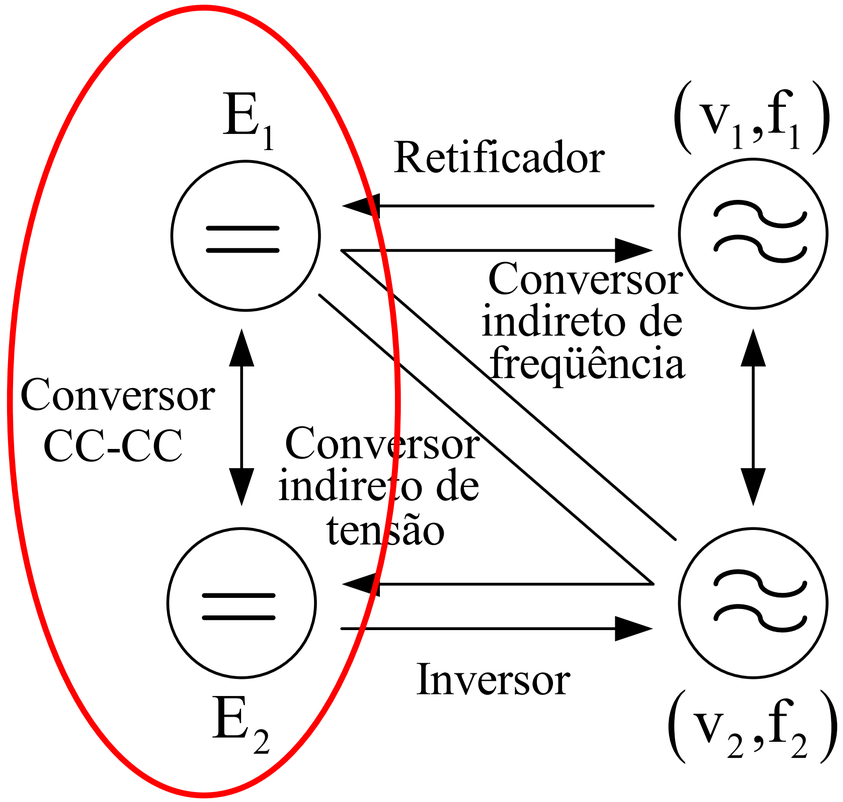
https://www.filipeflop.com/

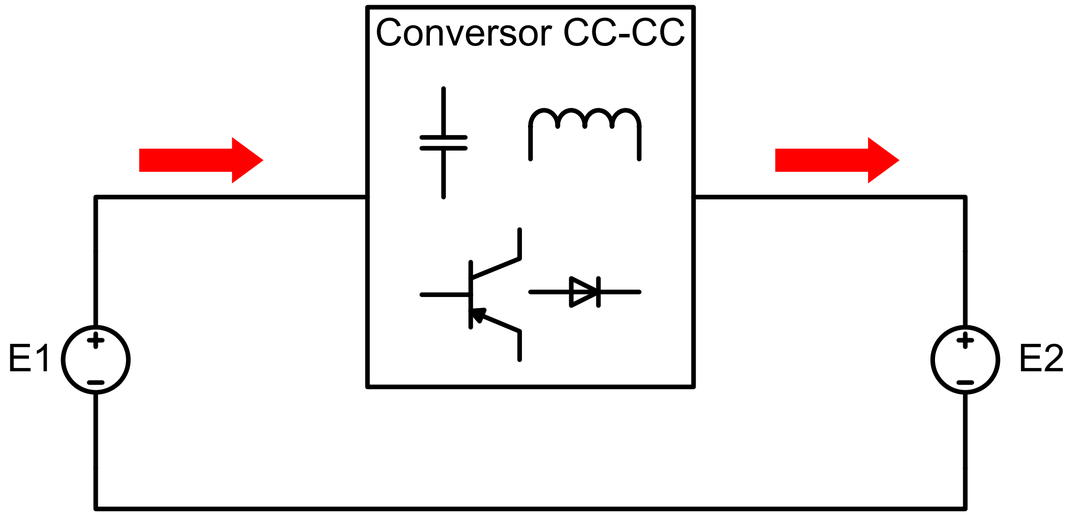
https://www.geesysindia.com

Conversores CC-CC

Princípio geral:

- Controlar o fluxo de potência entre duas fontes de tensão contínua.





https://ivobarbi.com.br/

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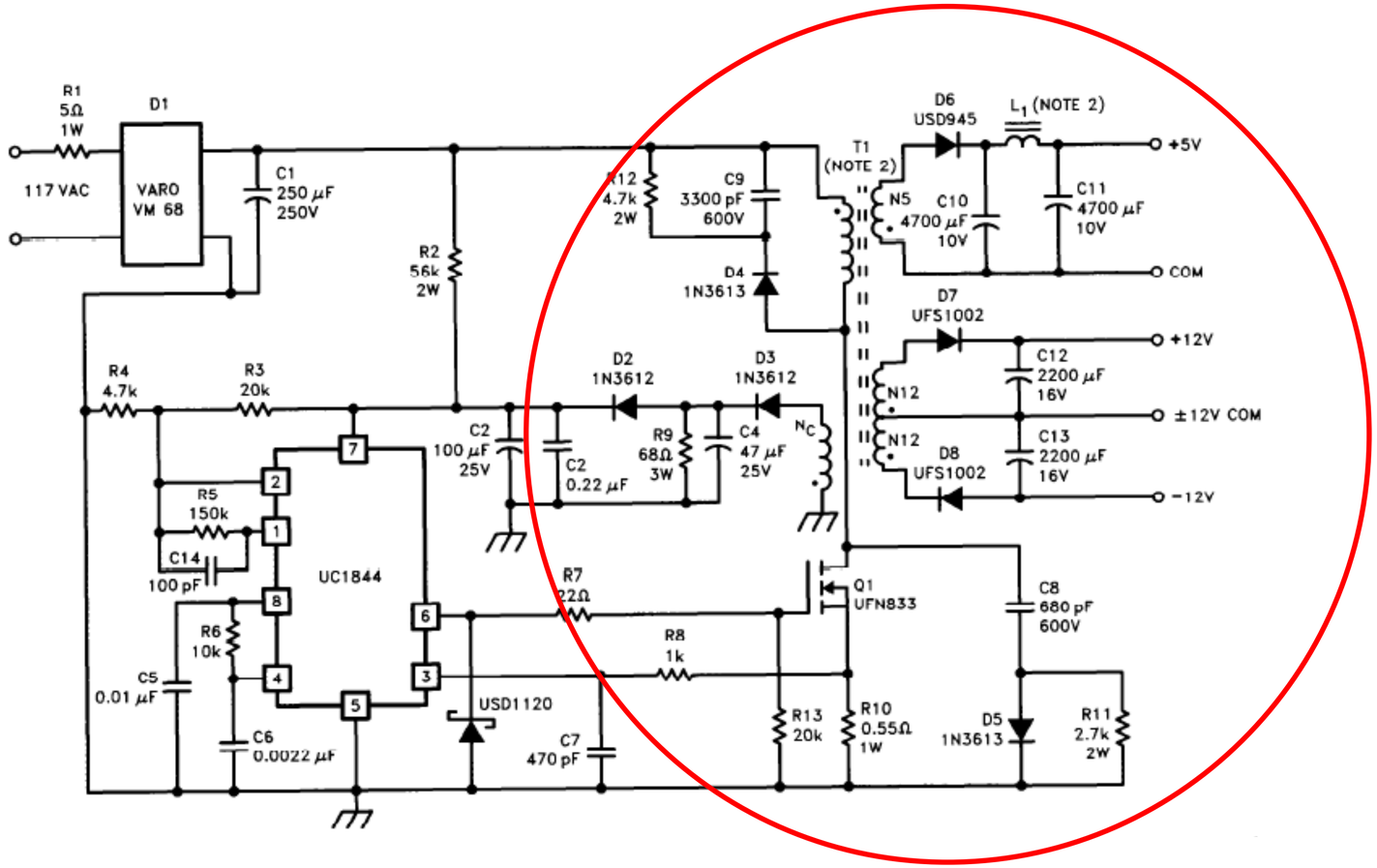
Conversores CC-CC

Estágio de conversão CC-CC de uma fonte chaveada:

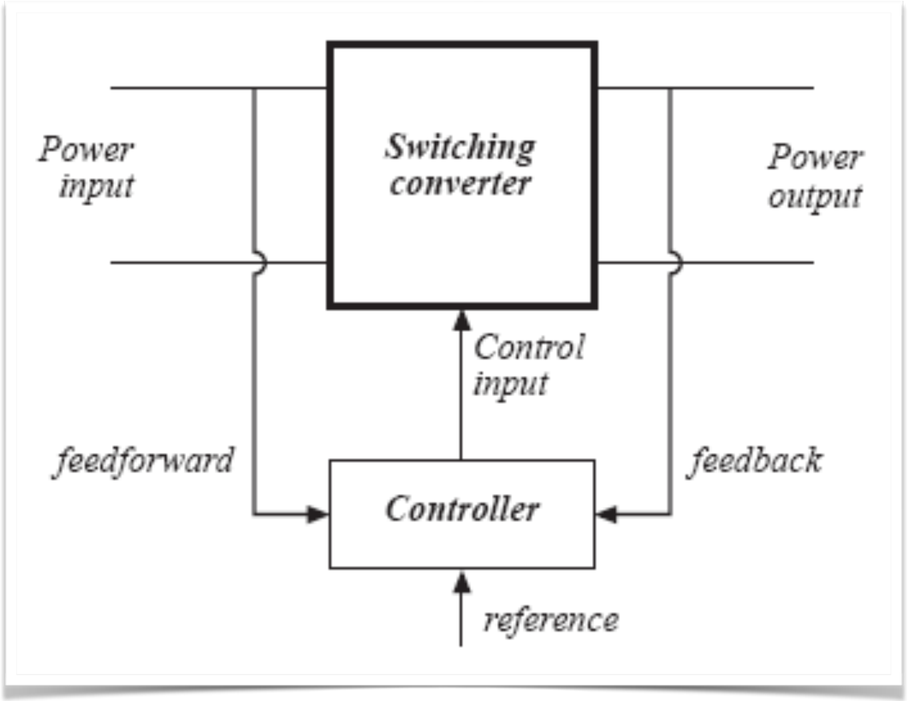


https://www.ti.com/

Conversores CC-CC

Princípio:

Os circuitos em eletrônica de potência são denominados não-lineares, pois utilizam os semicondutores como chaves, ligadas ou desligadas.

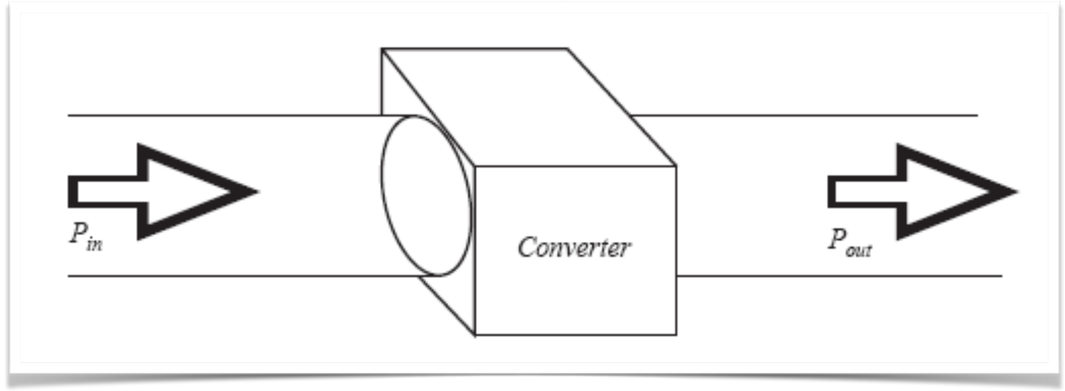


https://ecee.colorado.edu/~rwe/textbook.html

Conversores CC-CC

Objetivo maior:

Busca da máxima eficiência.



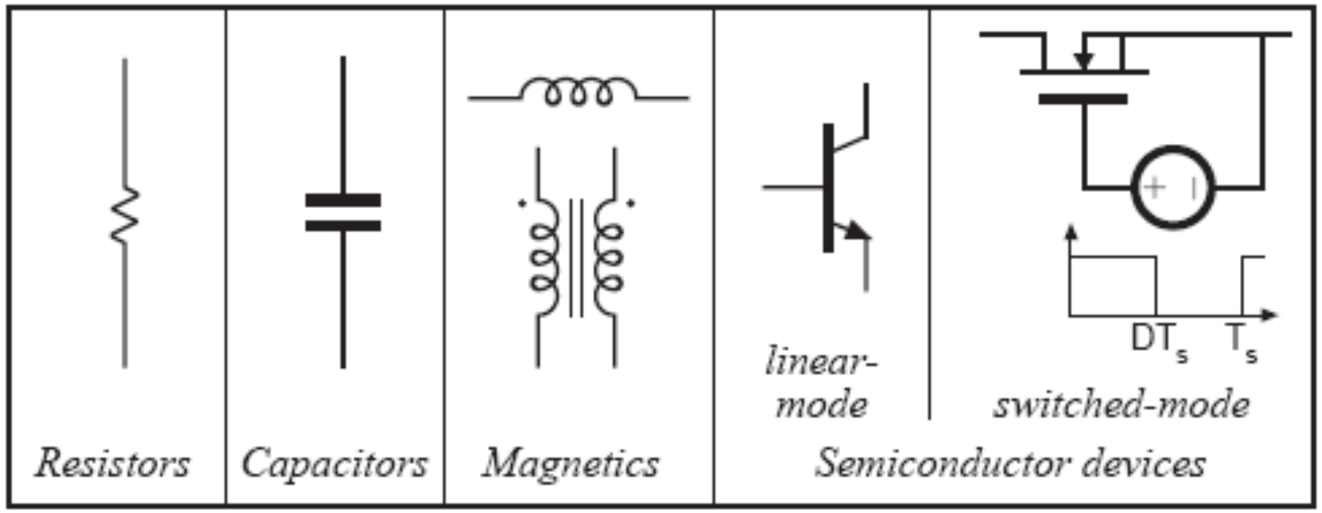
$$\eta = \frac{P_{out}}{P_{in}}$$

https://ecee.colorado.edu/~rwe/textbook.html

Conversores CC-CC

Objetivo maior:

Busca da máxima eficiência.



Evitar Perdas

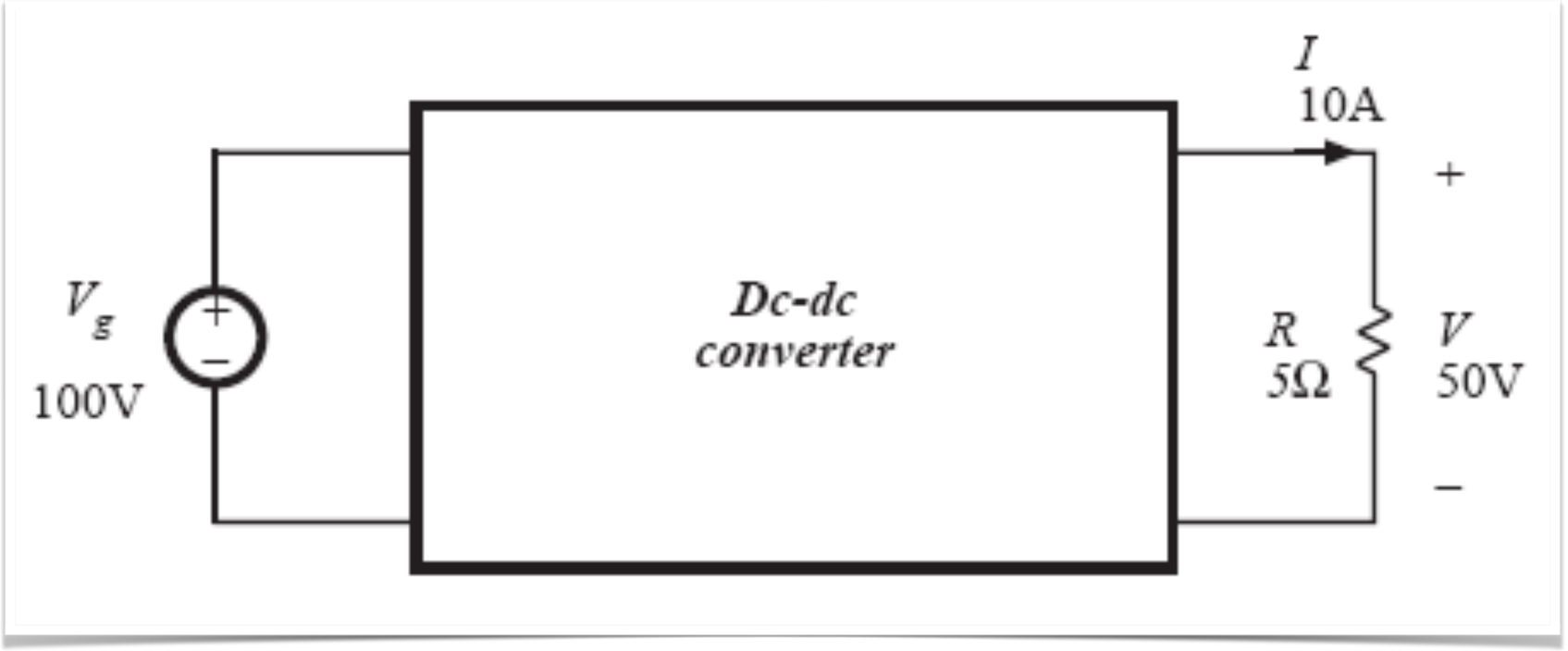
Evitar Interferências

Evitar Perdas

https://ecee.colorado.edu/~rwe/textbook.html

Conversores CC-CC

Exemplo: Como realizar esta conversão?

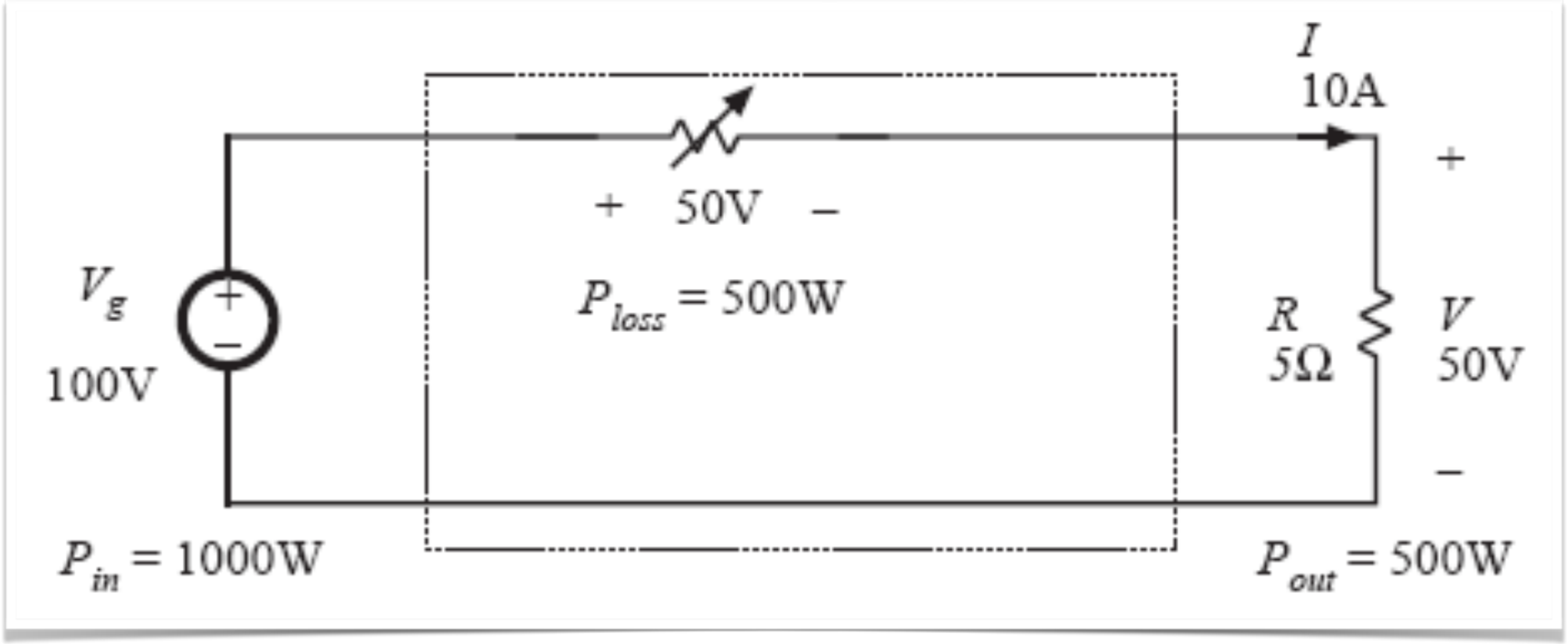


https://ecee.colorado.edu/~rwe/textbook.html

Conversores CC-CC

Exemplo: Como realizar esta conversão?

Usando resistores.

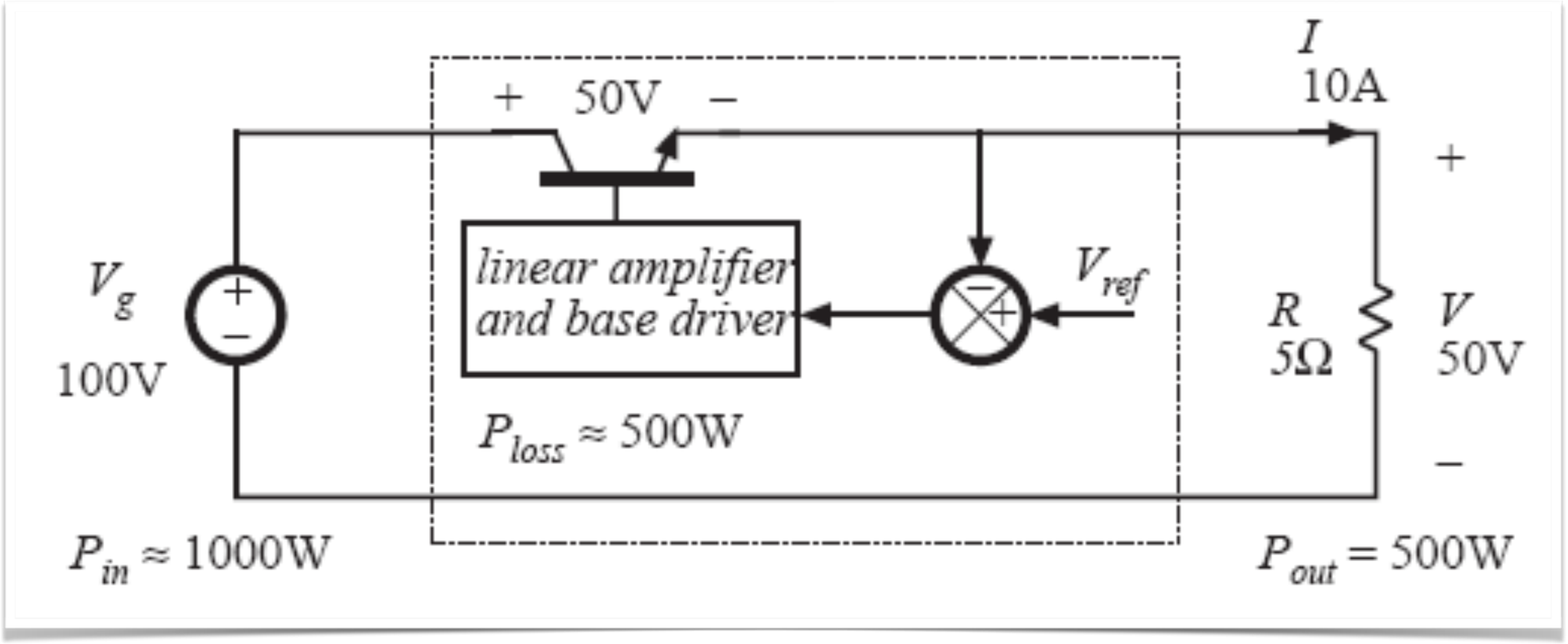


https://ecee.colorado.edu/~rwe/textbook.html

Conversores CC-CC

Exemplo: Como realizar esta conversão?

Usando reguladores lineares.

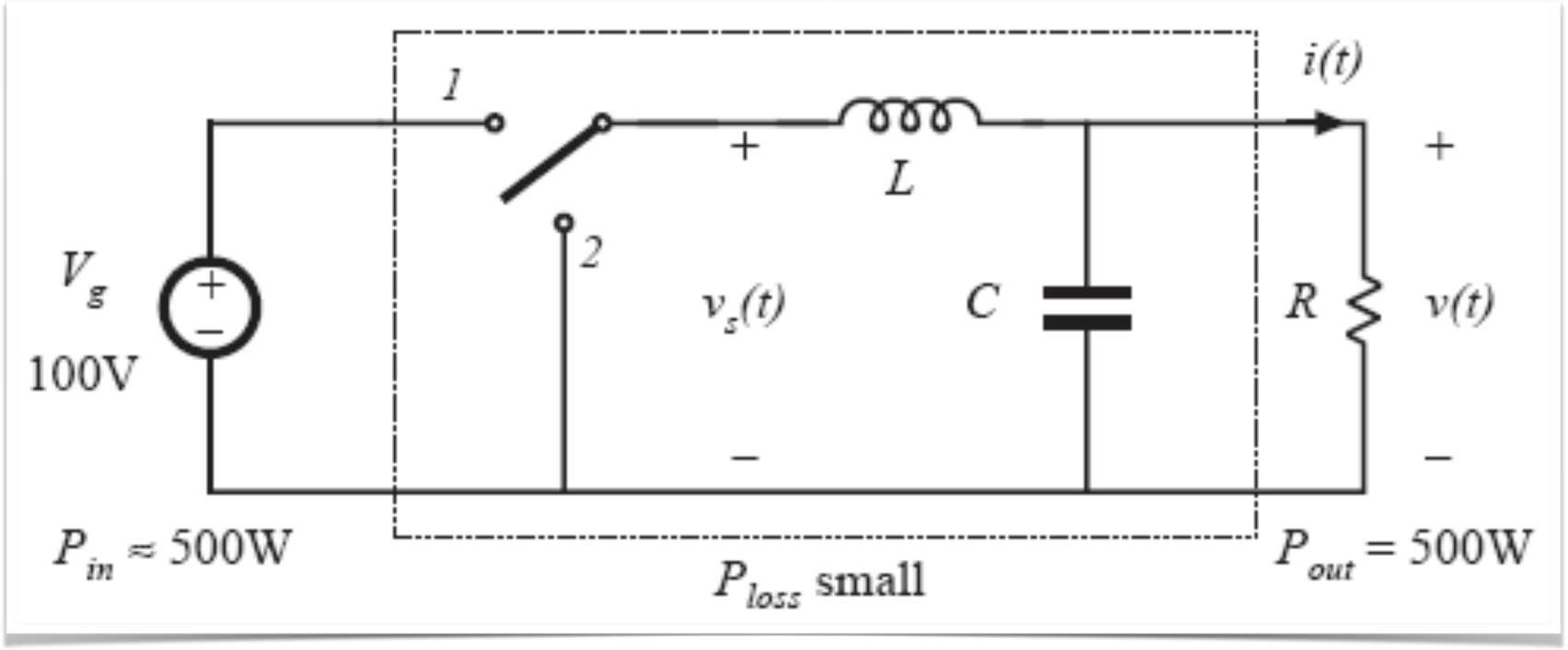


https://ecee.colorado.edu/~rwe/textbook.html

Conversores CC-CC

Exemplo: Como realizar esta conversão?

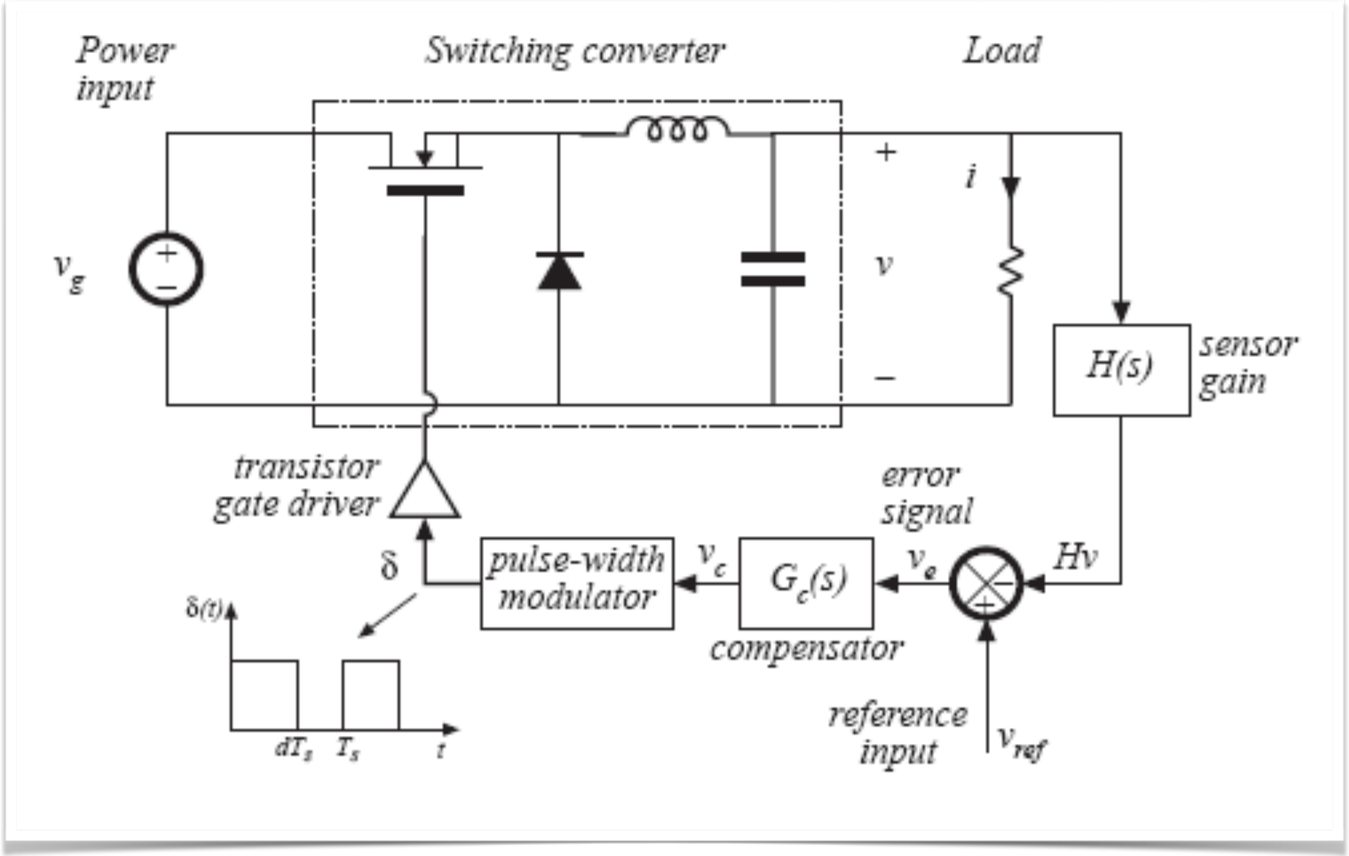
Usando comutação em alta frequência.



https://ecee.colorado.edu/~rwe/textbook.html

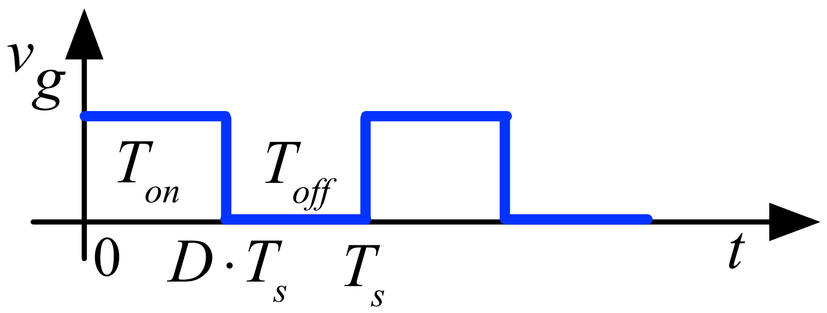
Conversores CC-CC

Diagrama de blocos completo:



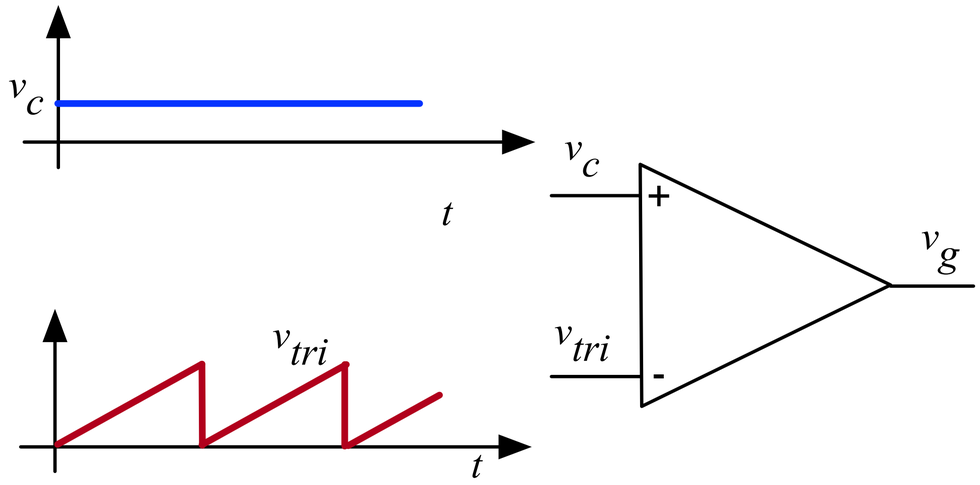
https://ecee.colorado.edu/~rwe/textbook.html

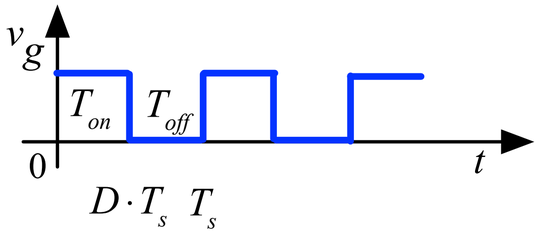
Modulação PWM



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

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

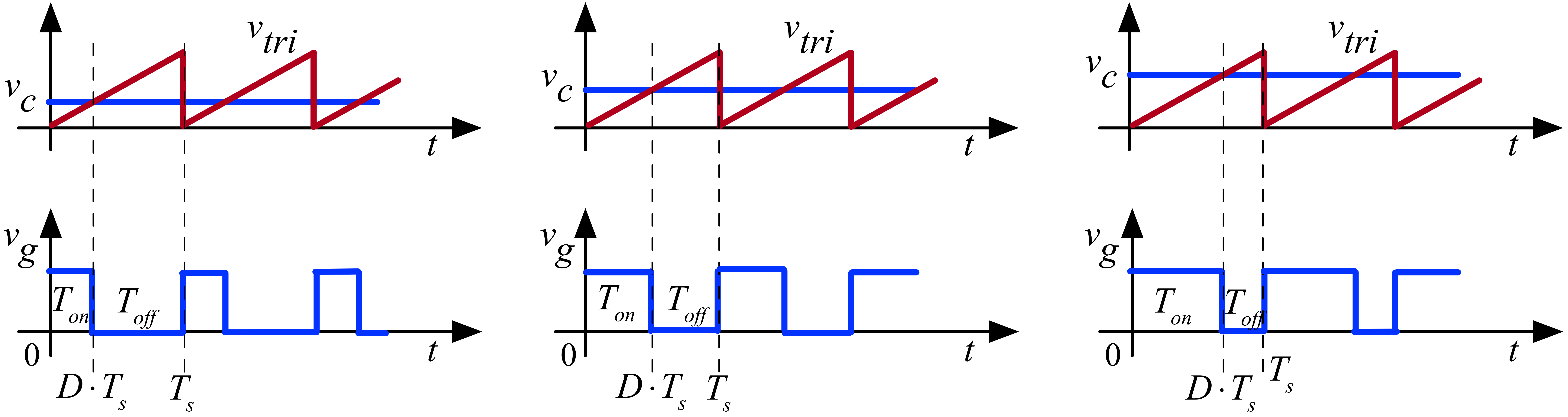




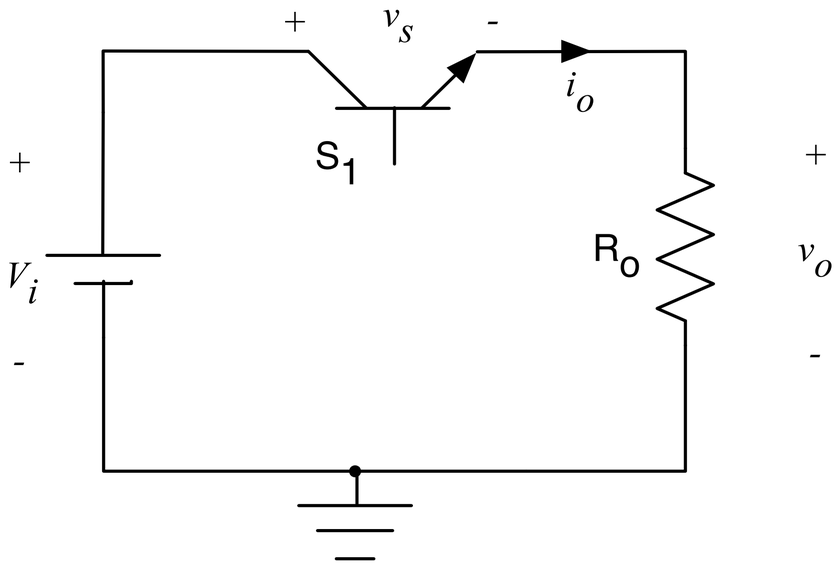
$$D = \frac{T_{on}}{T_s}$$

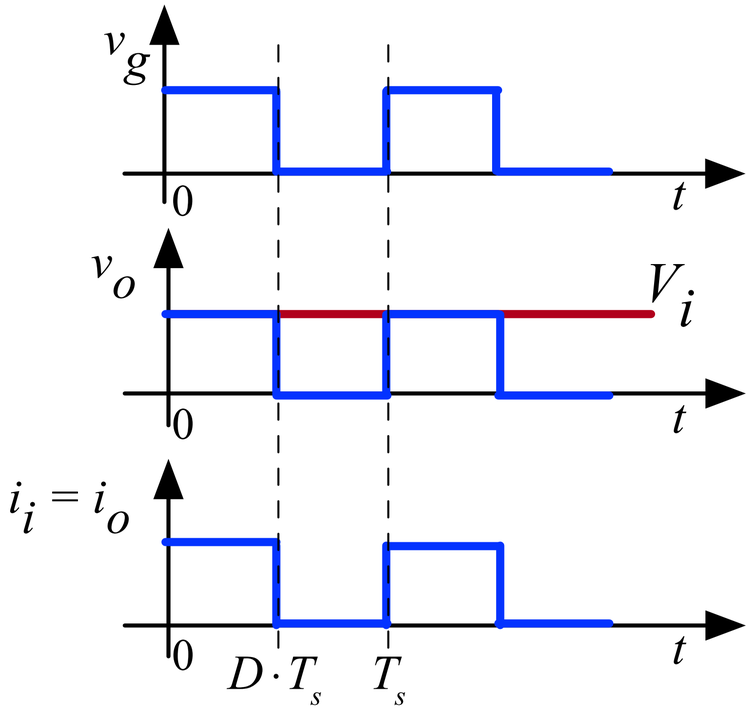
$$D = \frac{V_c}{V_{tri}}$$

Modulação PWM



Princípio de funcionamento





$$V_i = \text{definido}$$

$$V_{o(\max)} = V_i$$

$$D = \frac{V_o}{V_i}$$

$$V_o = \frac{1}{T_s} \cdot V_i \cdot D \cdot T_s \rightarrow V_o = D \cdot V_i$$

$$P_o = V_o \cdot I_o$$

$$P_i = P_o \rightarrow \eta = 1$$

$$I_{o(\max)} = \frac{V_{o(\max)}}{R_o}$$

$$I_o = \frac{V_o}{R_o}$$

$$I_i = I_o$$

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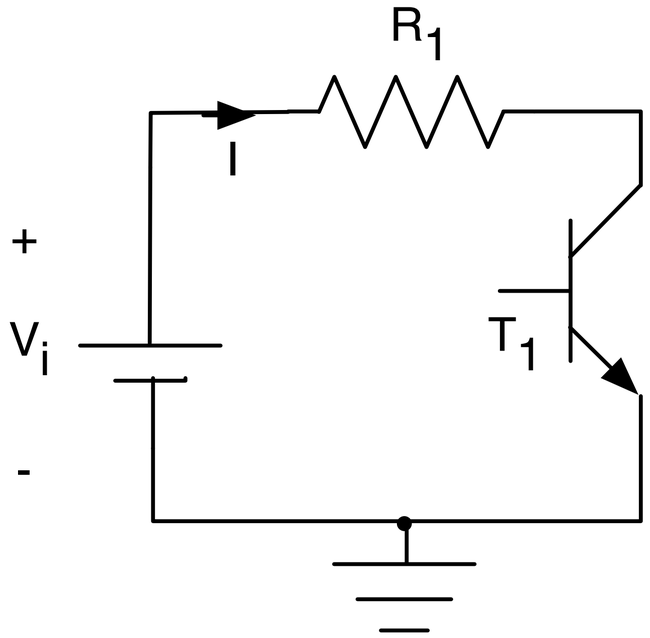
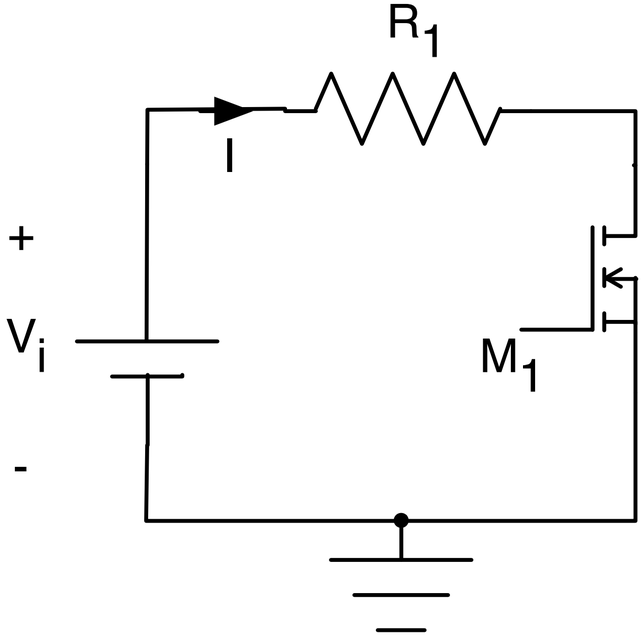
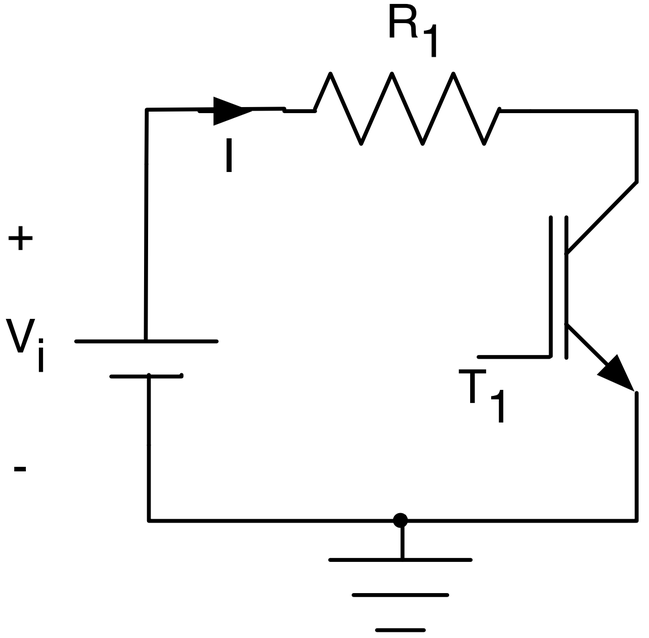
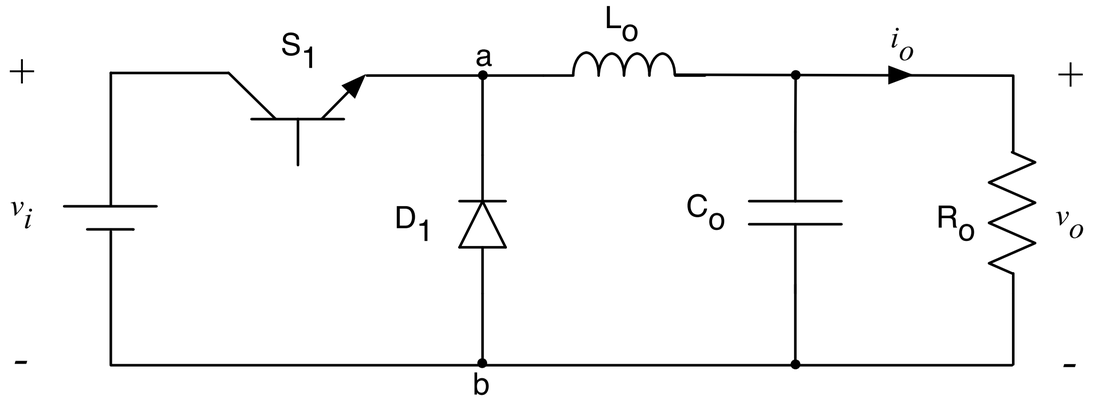
Princípio de funcionamento



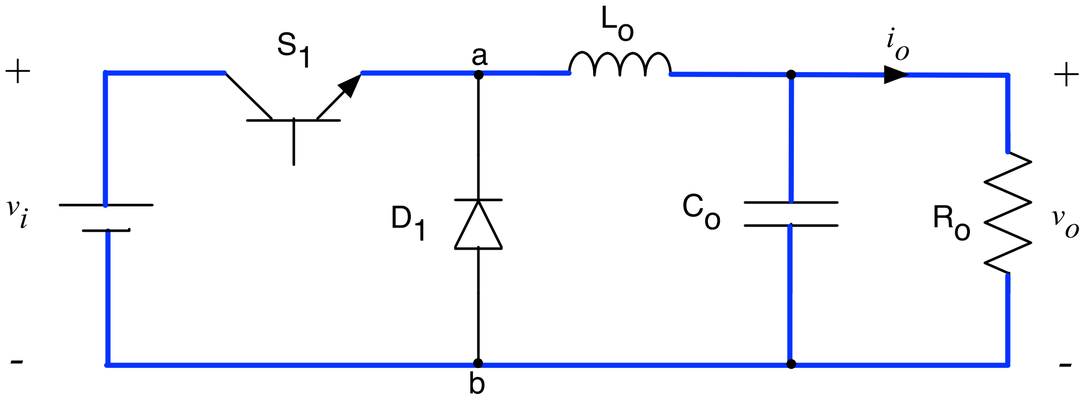




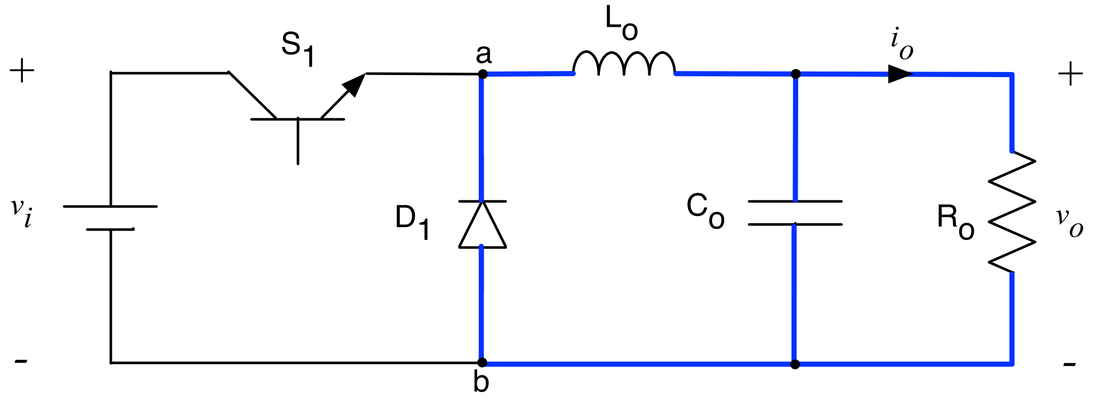
Conversor Buck



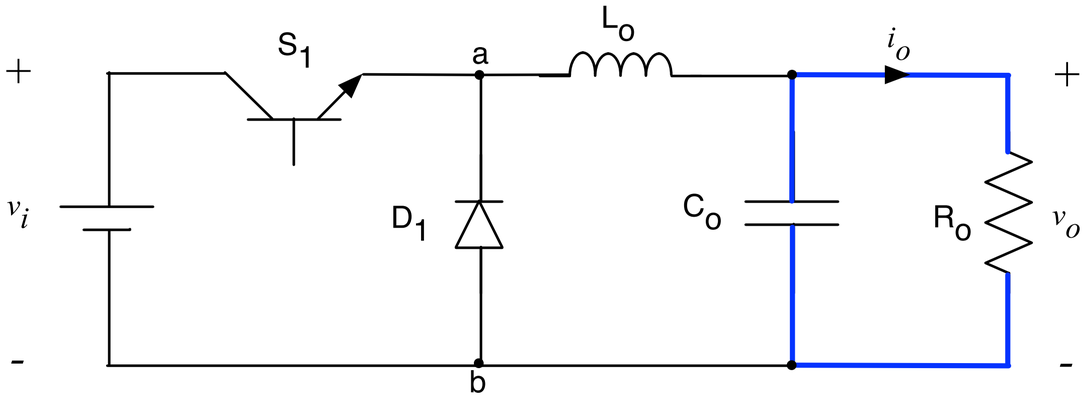
Conversor Buck



Primeira etapa

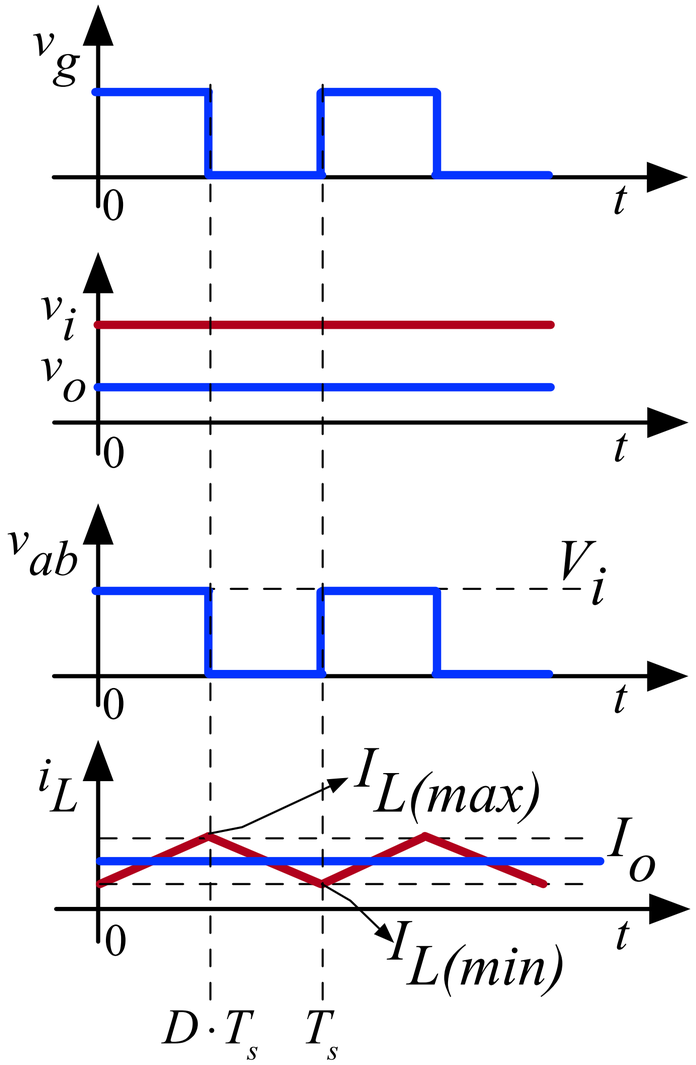


Segunda etapa

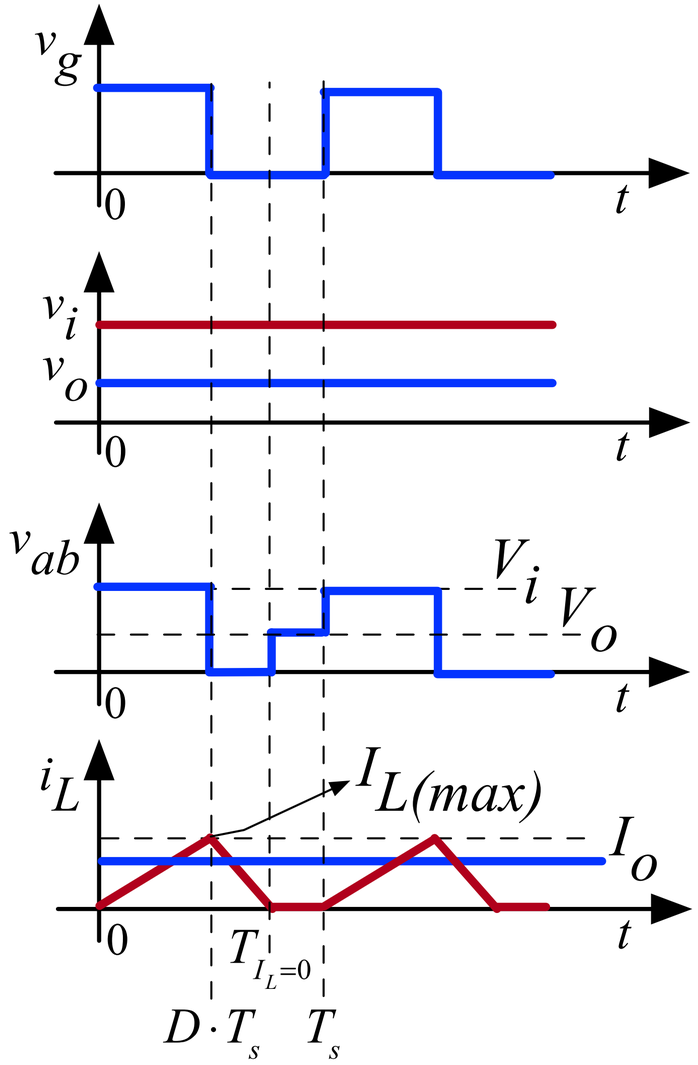


Terceira etapa

Conversor Buck



Condução contínua

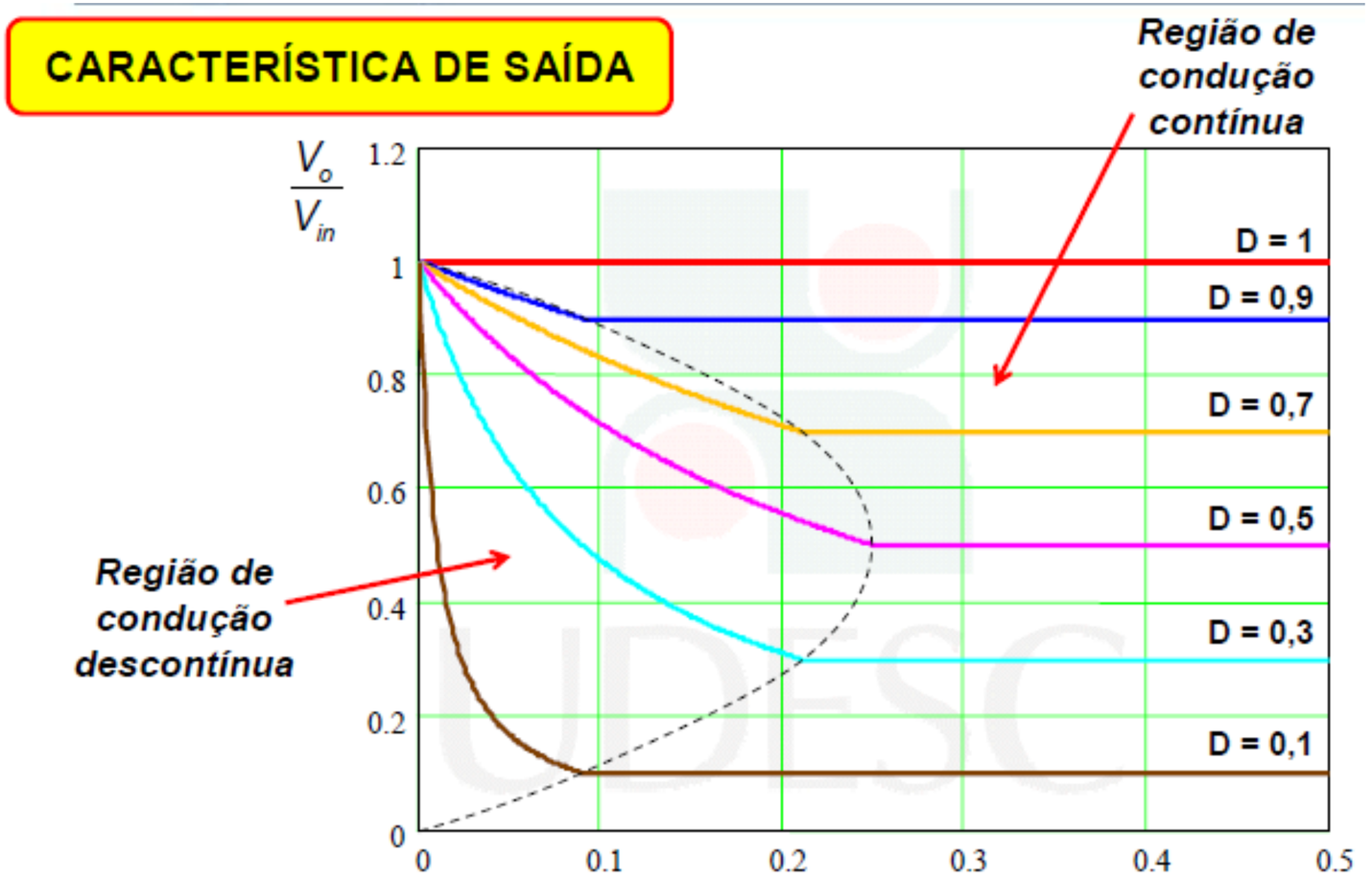


Condução descontínua

Conversor Buck

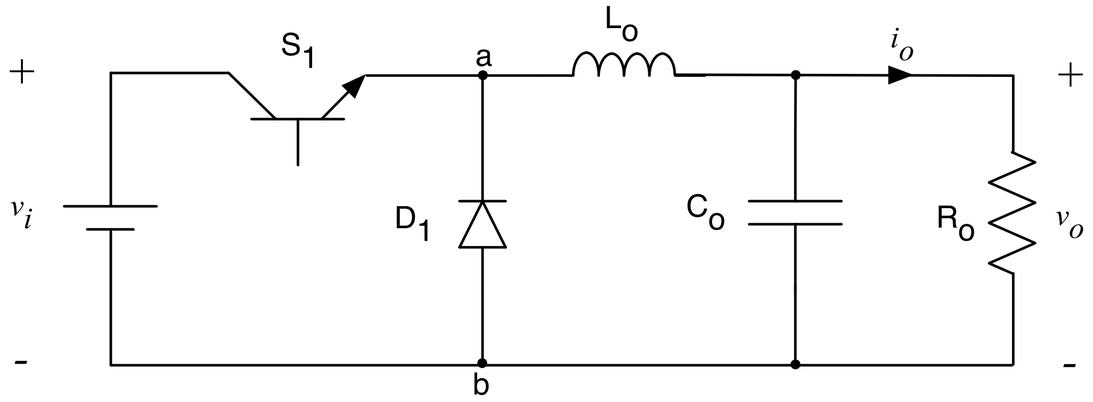
Condução contínua versus condução descontínua:

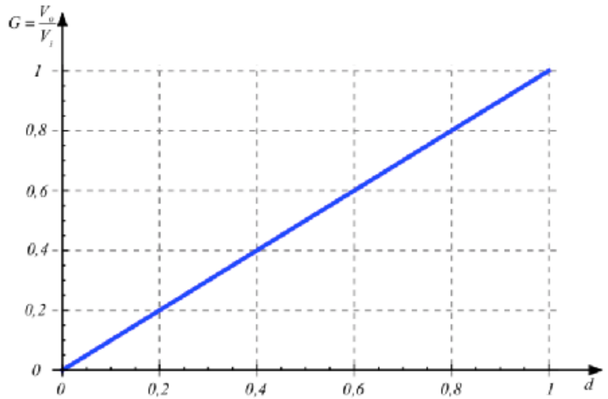
$$\gamma = \frac{2 \cdot L_o \cdot I_o}{V_i \cdot T_s}$$



https://www.udesc.br/cct/npee/estrutura/lepo

Conversor Buck





$V_i = \text{definido}$

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

$$V_{Lo} = 0 \rightarrow V_{ab} = V_o$$

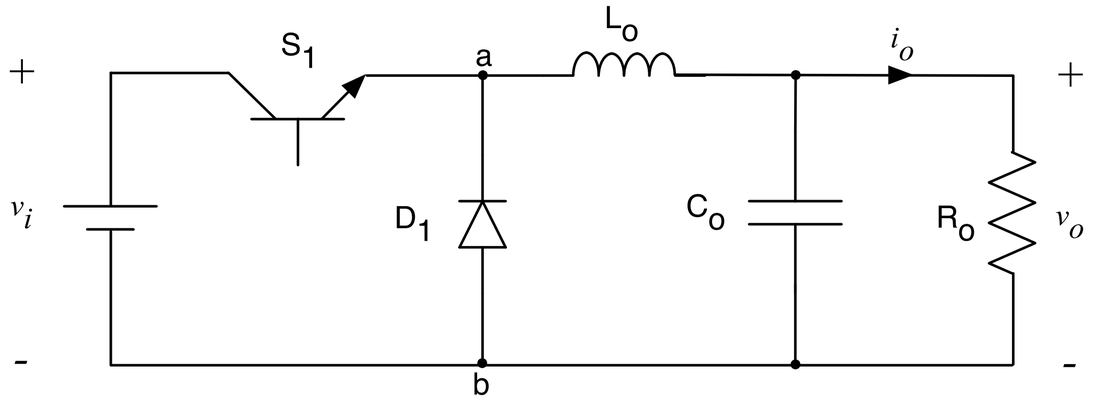
$$V_o = D \cdot V_i$$

Condução contínua

$$V_o = \frac{2 \cdot V_i}{1 + \sqrt{1 + \frac{8 \cdot L_o \cdot F_s}{R_o \cdot D^2}}}$$

Condução descontínua

Conversor Buck



$$\Delta i = \% \cdot I_o \left[A \right]$$

$$L_o = \frac{V_i}{\Delta i \cdot F_s} \cdot D \cdot \left(1 - D\right)$$

$$\Delta v = \% \cdot V_o \left[V \right]$$

$$C_o = \frac{V_i}{31 \cdot \Delta v \cdot L_o \cdot F_s^2}$$

$$I_o = \frac{V_o}{R_o}$$

$$I_{Lo} = I_o$$

$$I_i = I_{S1} = D \cdot I_o$$

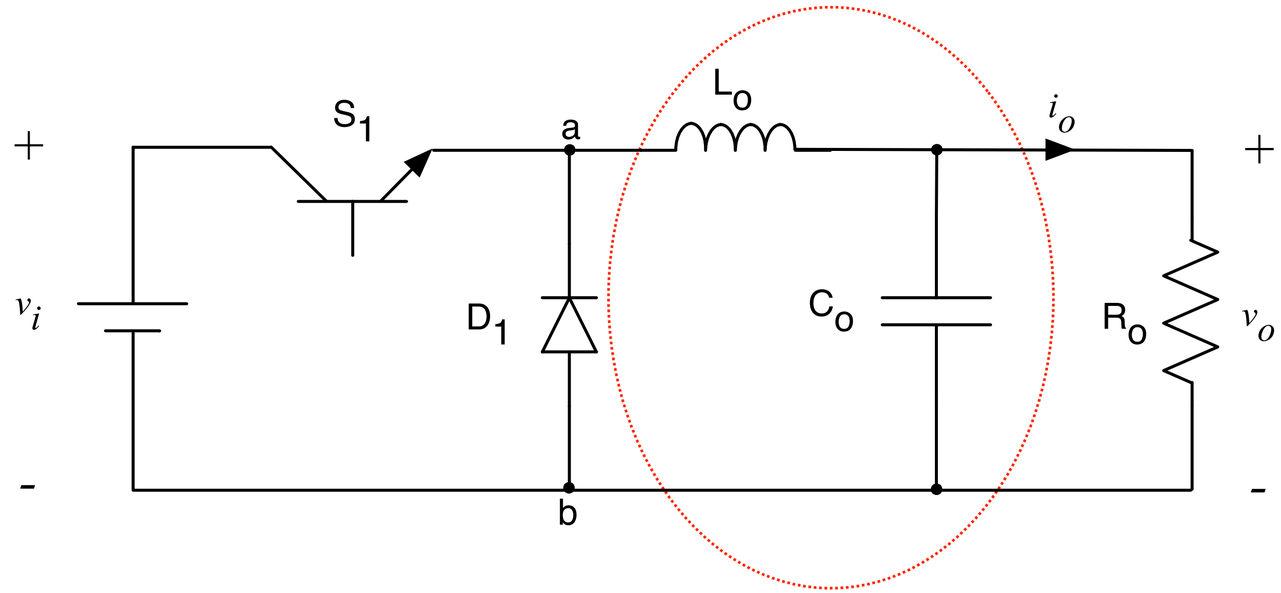
$$I_{D1} = \left(1 - D\right) \cdot I_o$$

$$I_{Lo(\max)} = I_{S1(\max)} = I_{D1(\max)} = I_o + \frac{\Delta i}{2}$$

$$V_{S1(\max)} = V_{D1(\max)} = V_i$$

Conversor Buck

Filtro de saída (frequência de ressonância):



$$F_o = \frac{1}{2\pi \cdot \sqrt{L_o \cdot C_o}}$$

$$F_o \leq \frac{F_s}{10}$$

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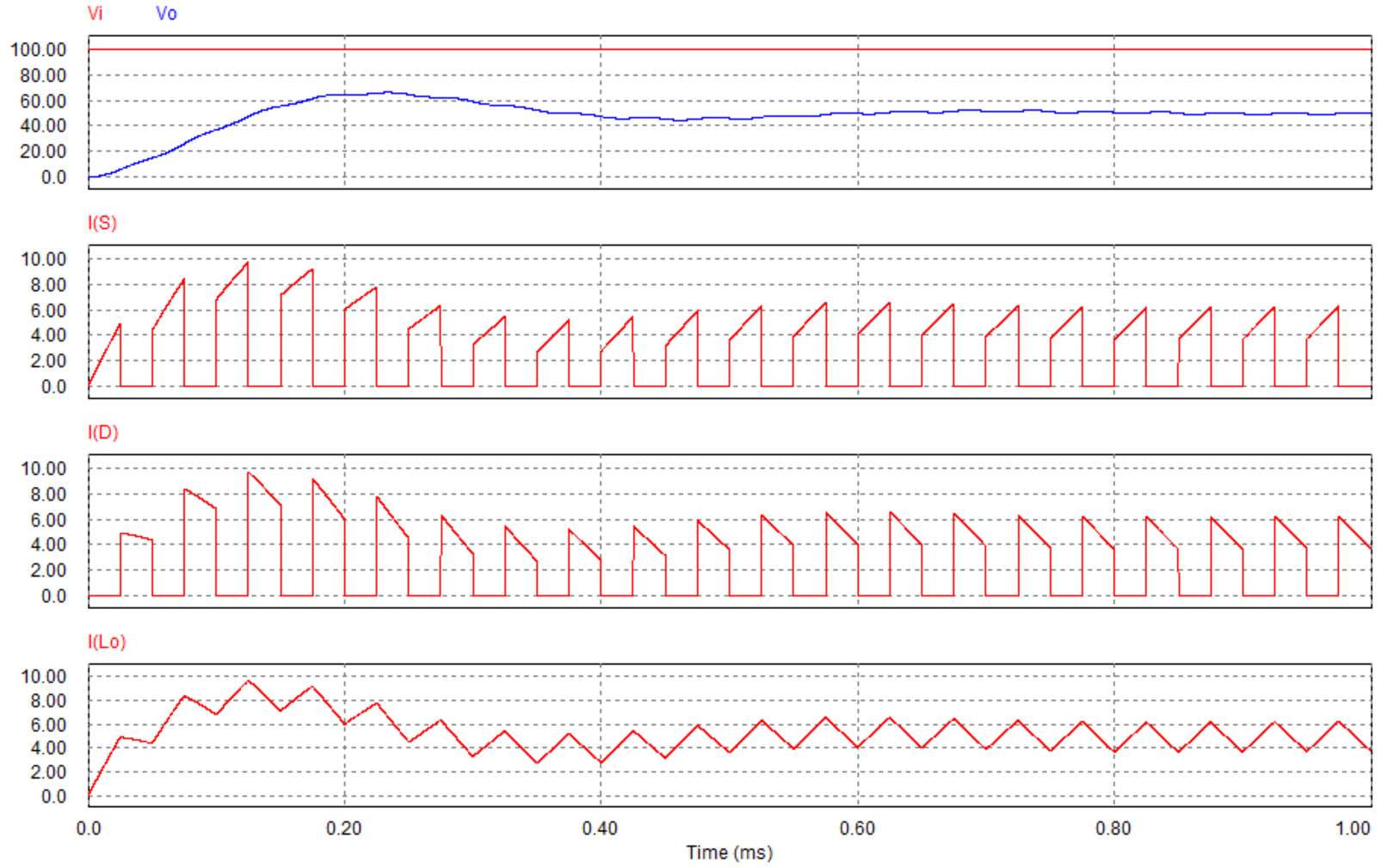
Conversor Buck

Principais formas de onda durante o transitório de partida:



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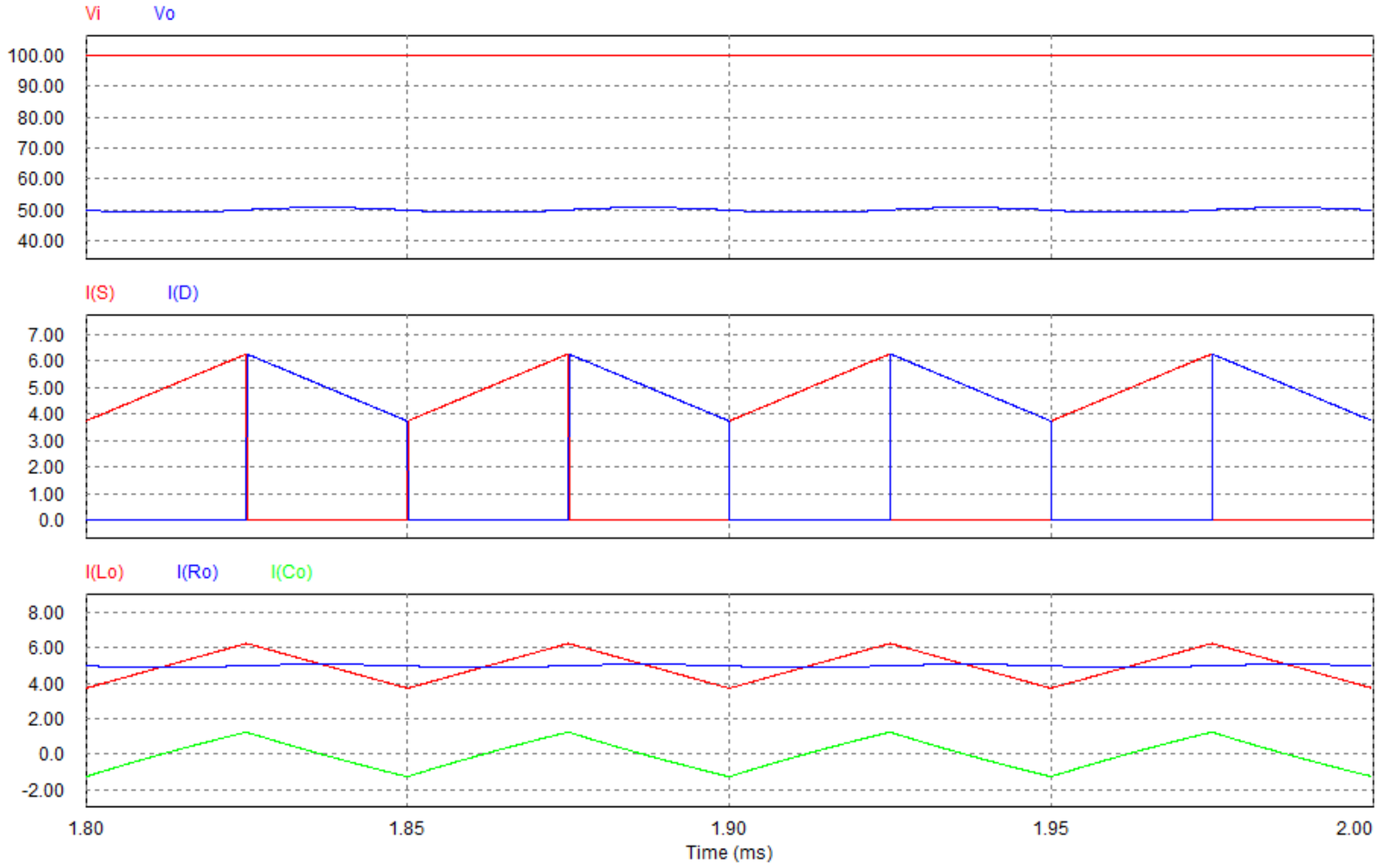
Conversor Buck

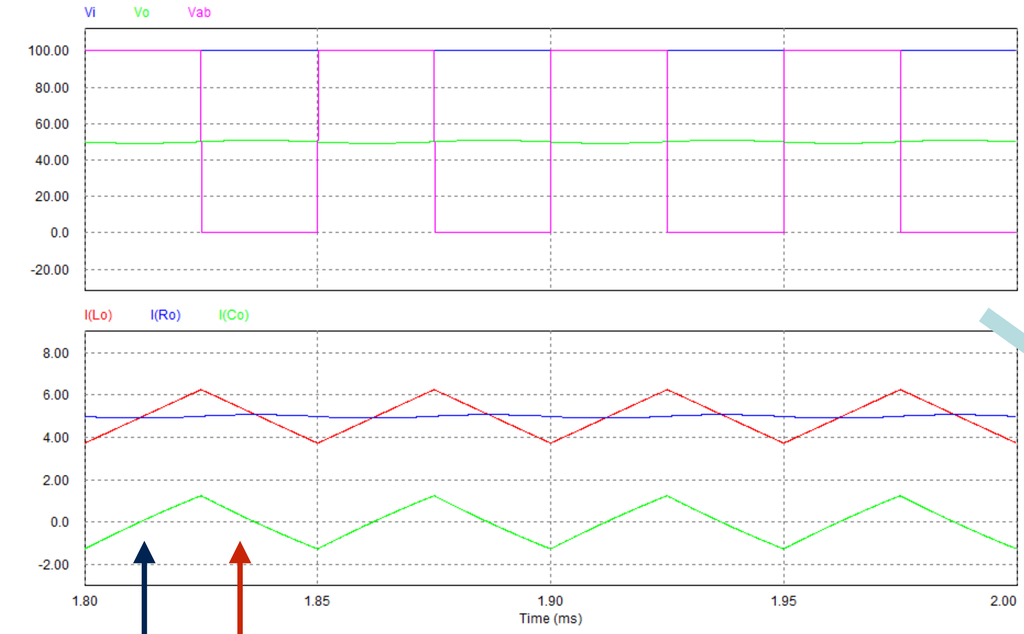
Principais formas de onda durante operação em regime permanente:



Conversor Buck

Principais formas de onda para CCM e DCM:

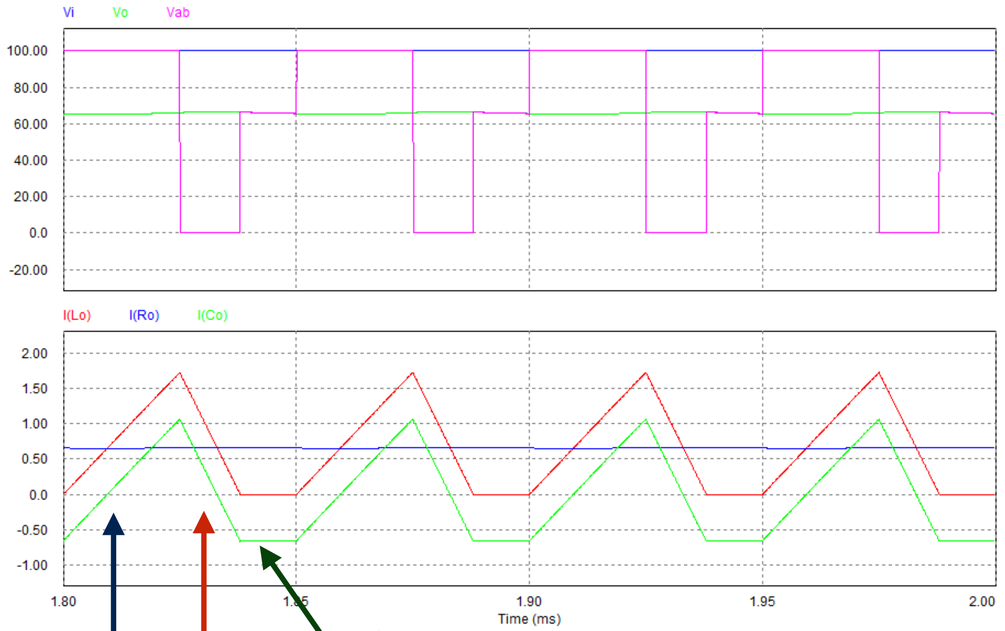
- Diminuição da carga;
- Indutor do filtro de saída muito baixo;
- Alteração da freqüência de comutação;
- Alteração da tensão de entrada.



Condução contínua - 2 etapas

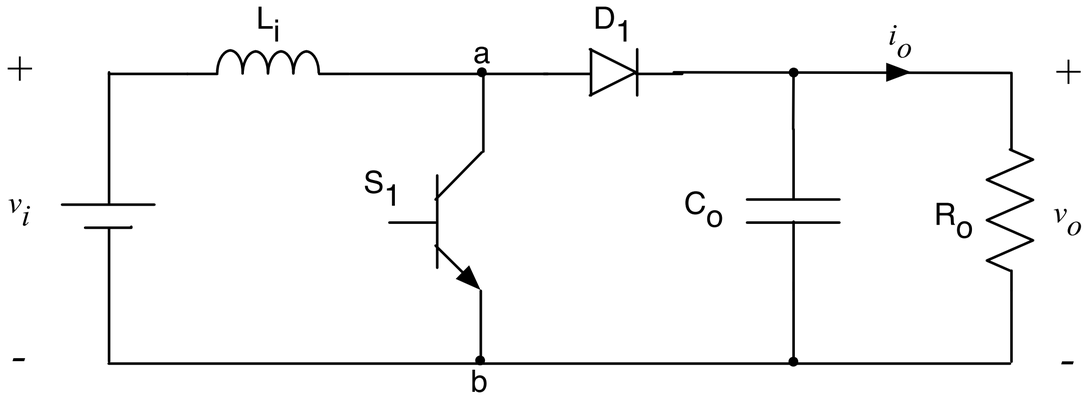
1ª etapa 2ª etapa

Condução descontínua - 3 etapas

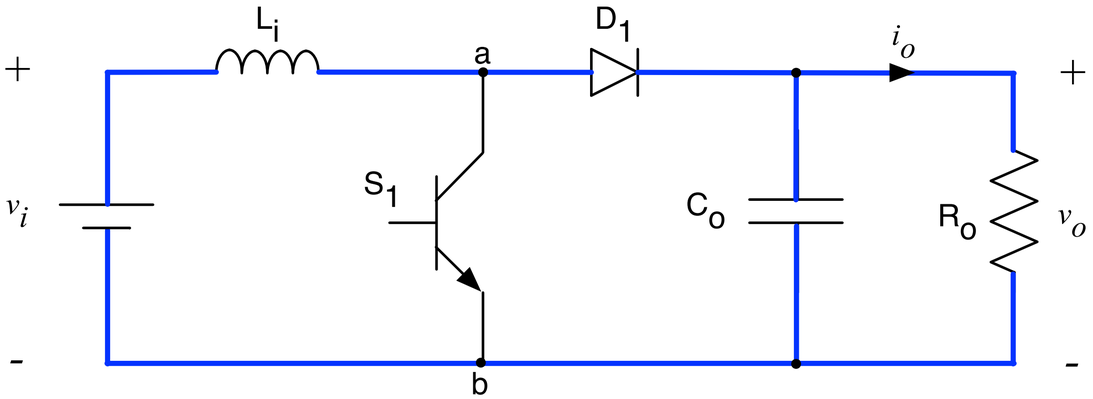


1ª etapa 2ª etapa 3ª etapa

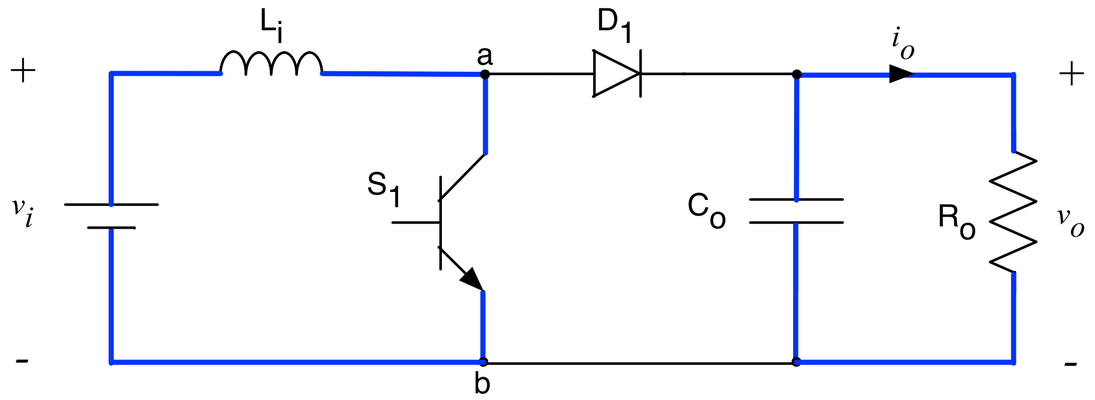
Conversor Boost



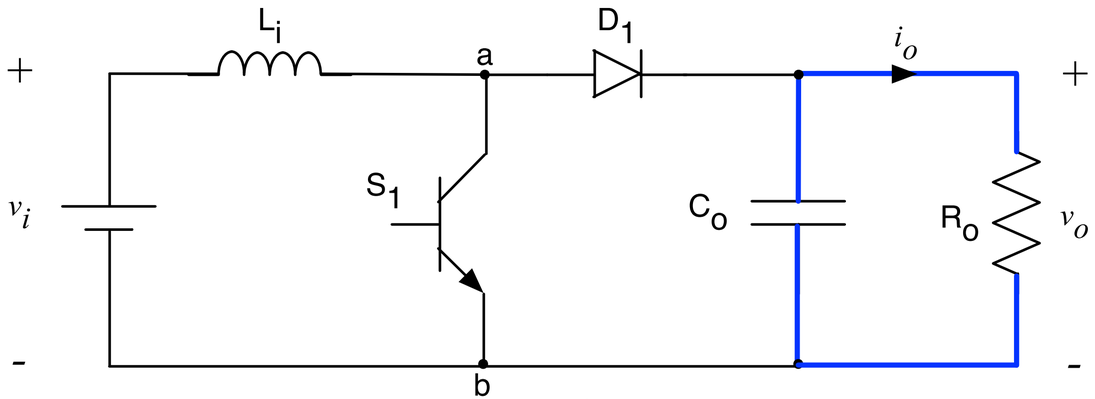
Conversor Boost



Segunda etapa

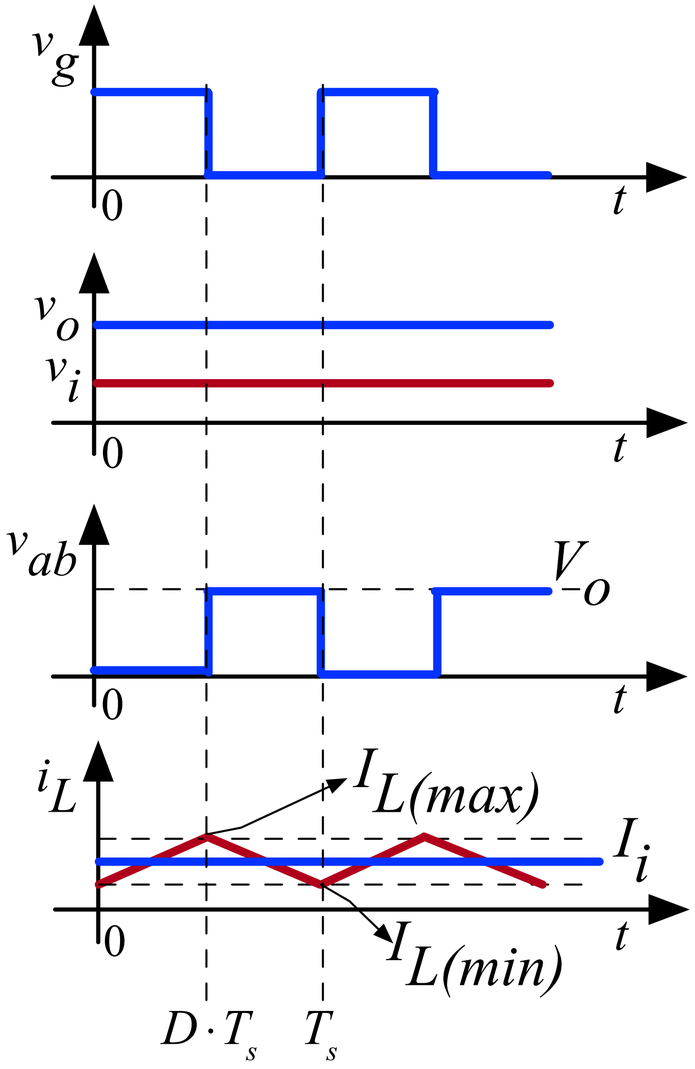


Primeira etapa

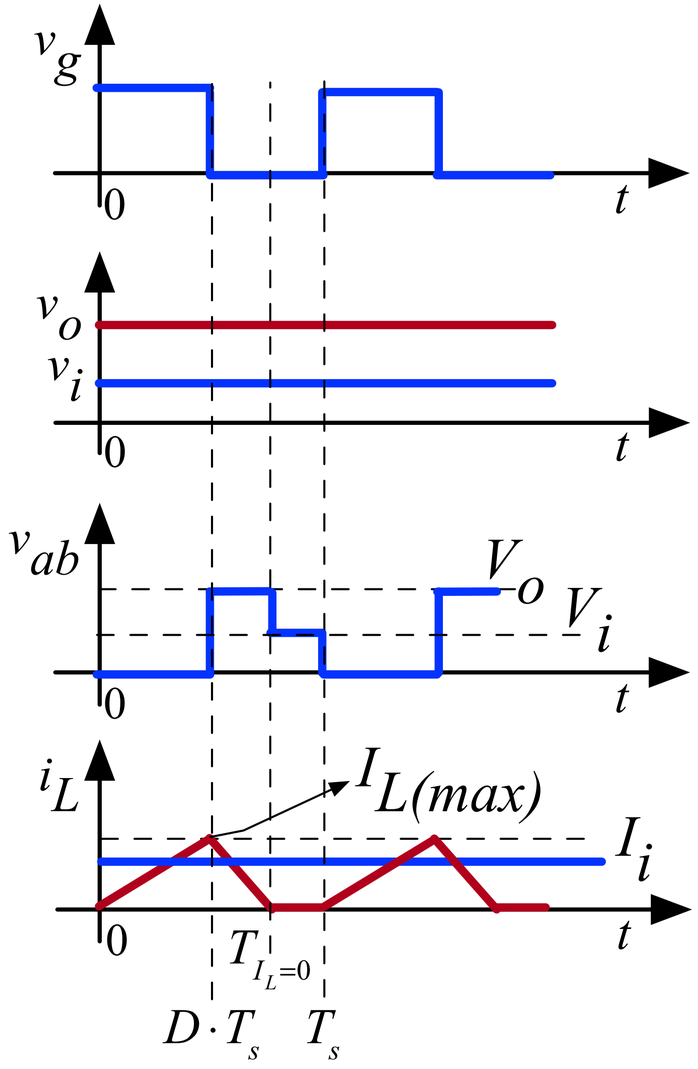


Terceira etapa

Conversor Boost

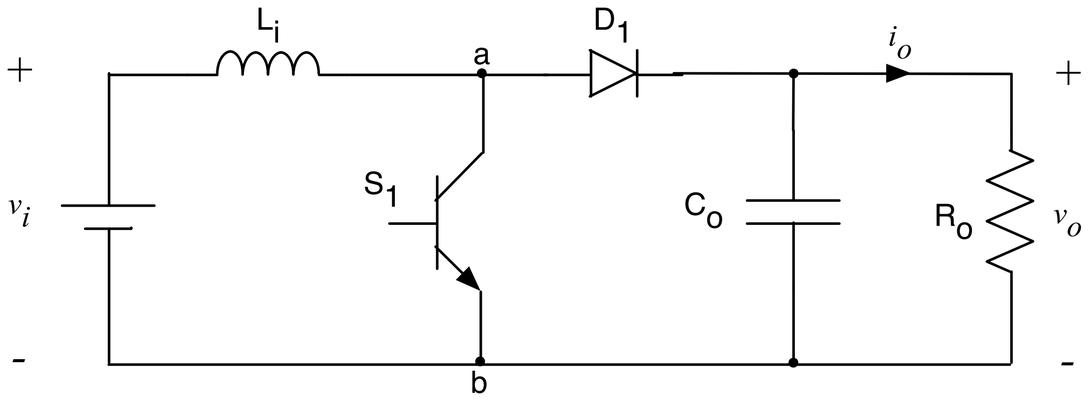


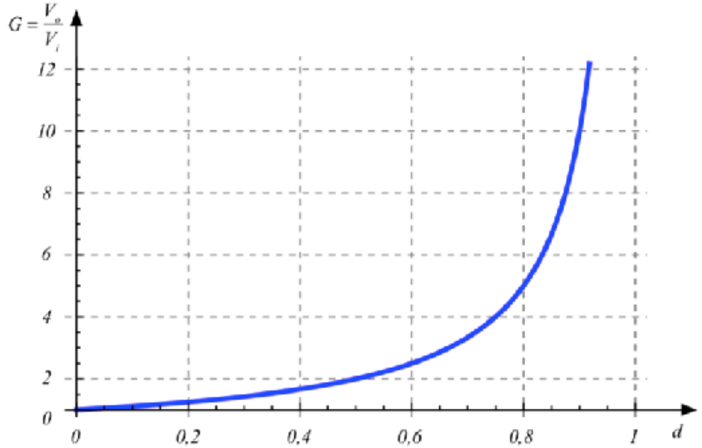
Condução contínua



Condução descontínua

Conversor Boost





$$V_i = \text{definido}$$

$$V_{ab} = \frac{1}{T_s} \cdot V_o \cdot \left(T_s - D \cdot T_s\right) \rightarrow V_{ab} = V_o \cdot \left(1 - D\right)$$

$$V_{Lo} = 0 \rightarrow V_{ab} = V_i$$

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

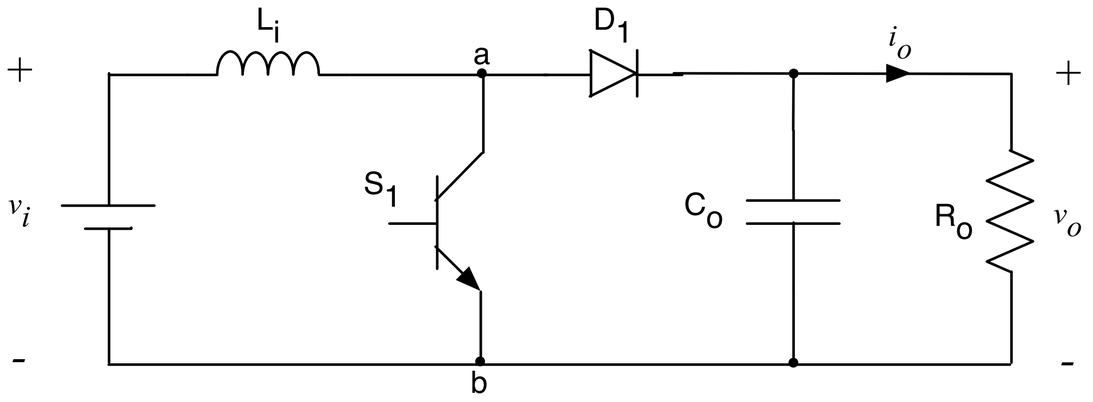
$$V_o = \frac{V_i}{\left(1 - D\right)}$$

Condução contínua

$$V_o = V_i \cdot \left(1 + \frac{V_i \cdot D^2}{2 \cdot F_s \cdot L_i \cdot I_o}\right)$$

Condução descontínua

Conversor Boost



$$\Delta i = \% \cdot I_i \left[A \right]$$

$$L_i = \frac{V_i}{\Delta i \cdot F_s} \cdot D$$

$$\Delta v = \% \cdot V_o \left[V \right]$$

$$C_o = \frac{I_o}{\Delta v \cdot F_s} \cdot \frac{V_o - V_i}{V_o}$$

$$I_o = \frac{V_o}{R_o}$$

$$I_{Li} = I_i = \frac{P_i}{V_i} \rightarrow P_i = P_o \rightarrow \eta = 1$$

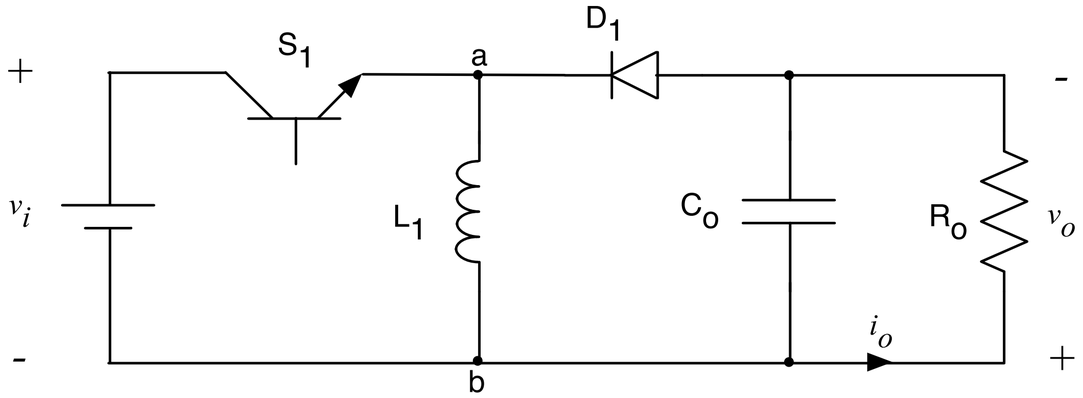
$$I_{Li(\max)} = I_{S1(\max)} = I_{D1(\max)} = I_i + \frac{\Delta i}{2}$$

$$I_{S1} = D \cdot I_i$$

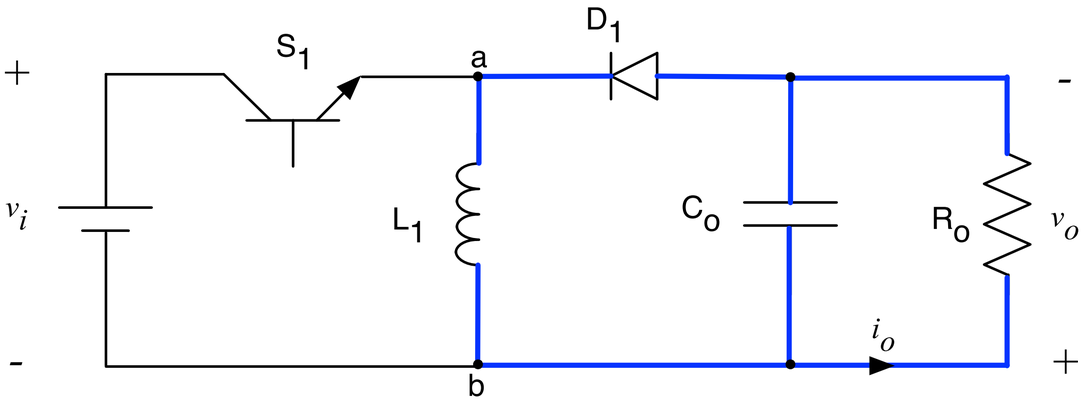
$$I_{D1} = \left(1 - D\right) \cdot I_i$$

$$V_{S1(\max)} = V_{D1(\max)} = V_o$$

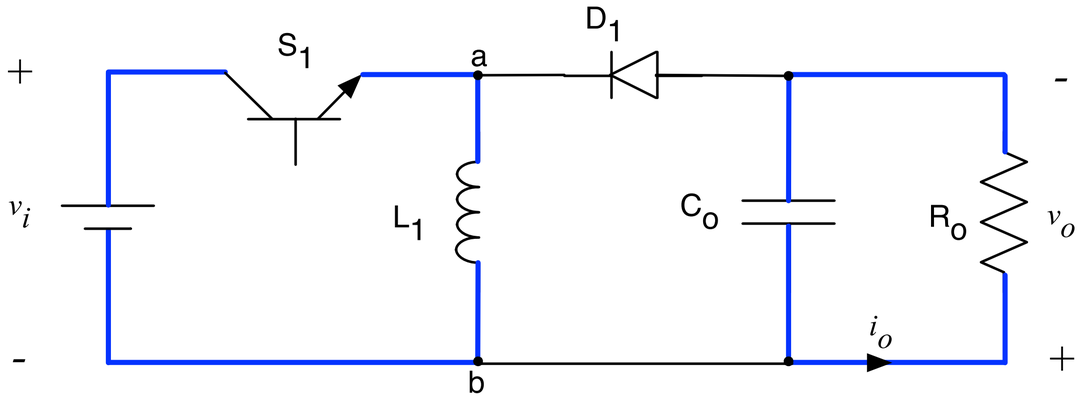
Conversor Buck-Boost



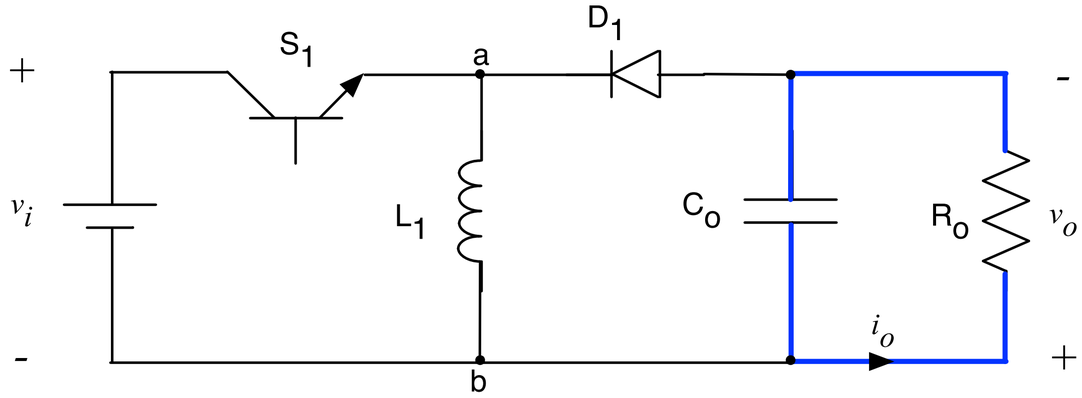
Conversor Buck-Boost



Segunda etapa

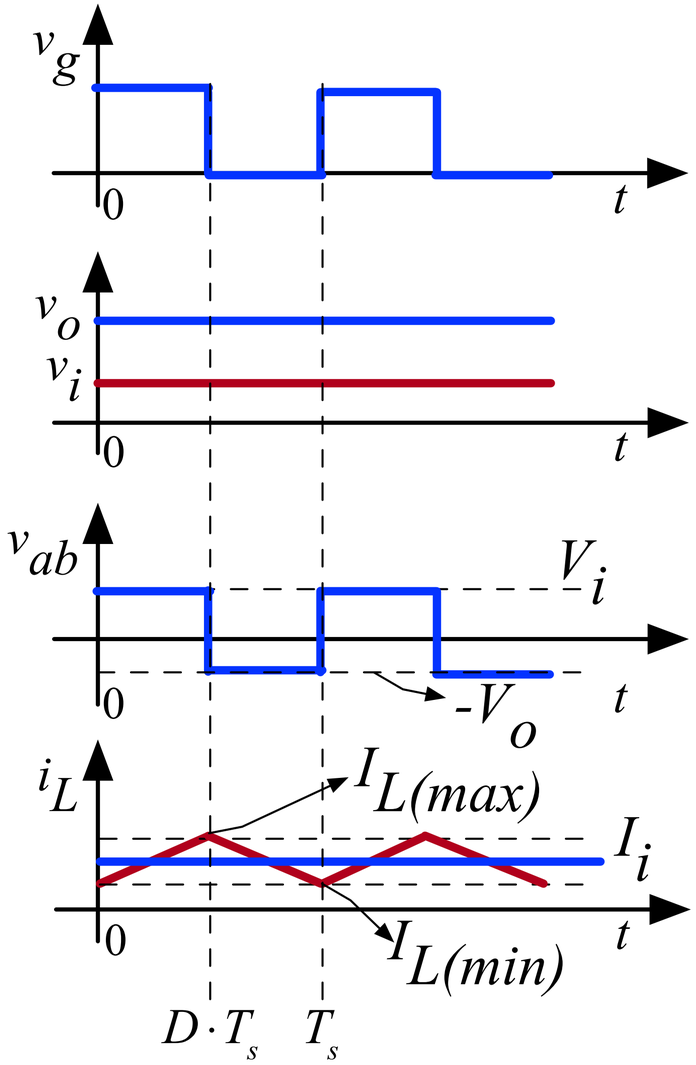


Primeira etapa

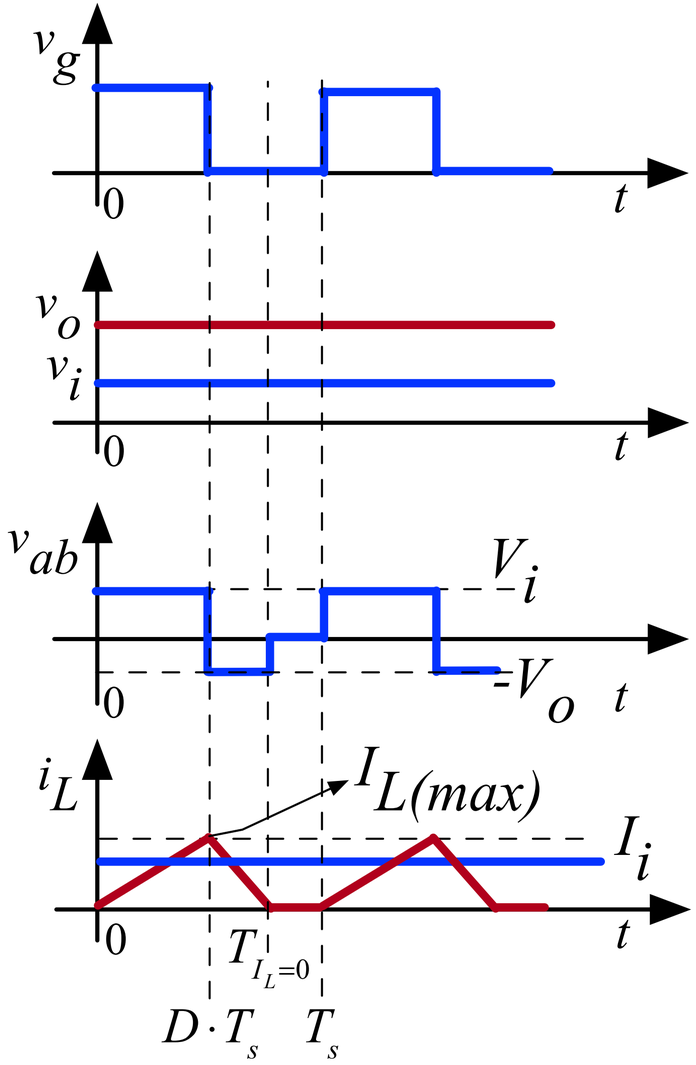


Terceira etapa

Conversor Buck-Boost

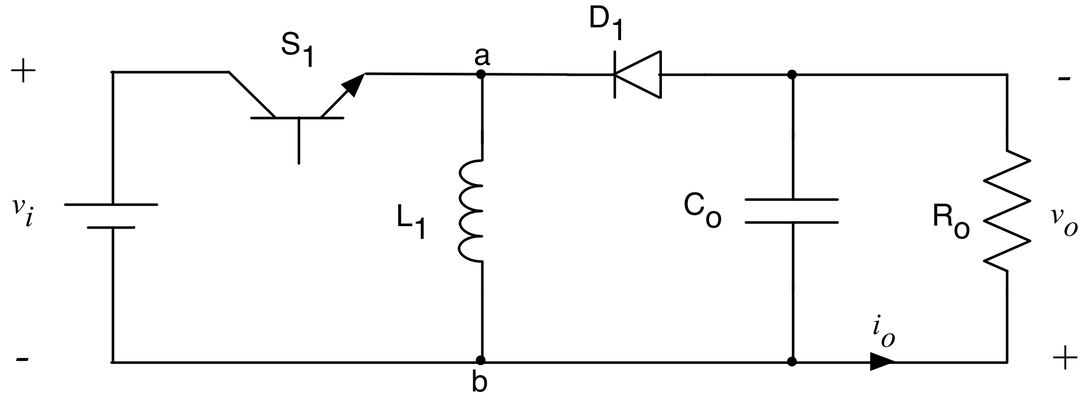


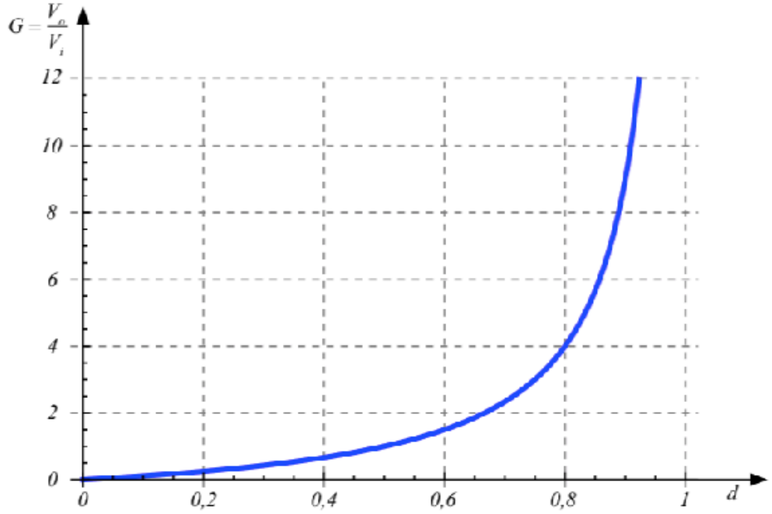
Condução contínua



Condução descontínua

Conversor Buck-Boost





$V_i = \text{definido}$

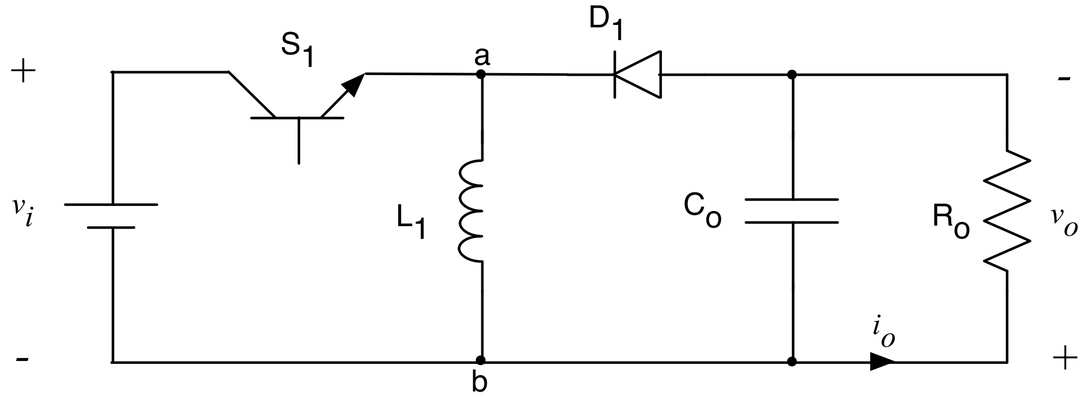
$$V_{ab} = \frac{1}{T_s} \cdot \left[\left(V_i \cdot D \cdot T_s \right) + \left(-V_o \cdot \left(T_s - D \cdot T_s \right) \right) \right] \rightarrow V_{ab} = V_i \cdot D - V_o \cdot \left(1 - D \right)$$

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

$$V_o = V_i \cdot \frac{D}{1 - D}$$ Condução contínua

$$V_o = V_i \cdot D \cdot \sqrt{\frac{R_o}{2 \cdot F_s \cdot L_i}}$$ Condução descontínua

Conversor Buck-Boost



$$\Delta i = \% \cdot I_i\left[A\right] \rightarrow \Delta i = \% \cdot I_o\left[A\right]$$

$$L_1 = \frac{V_o}{\Delta i \cdot F_s} \cdot \left(1 - D\right)$$

$$\Delta v = \% \cdot V_o\left[V\right]$$

$$C_o = \frac{D \cdot I_o}{\Delta v \cdot F_s}$$

$$I_o = \frac{V_o}{R_o}$$

$$I_{D1} = I_o$$

$$I_{S1} = I_i = \frac{P_i}{V_i} \rightarrow P_i = P_o \rightarrow \eta = 1$$

$$I_{L1} = I_i + I_o$$

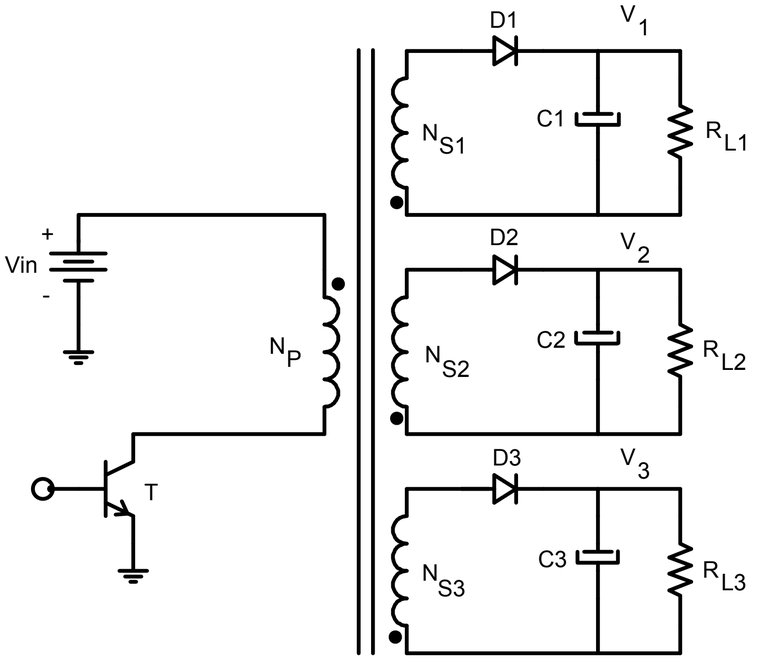
$$I_{L1(\max)} = I_{S1(\max)} = I_{D1(\max)} = I_{L1} + \frac{\Delta i}{2}$$

$$V_{S1(\max)} = V_{D1(\max)} = V_i + V_o$$

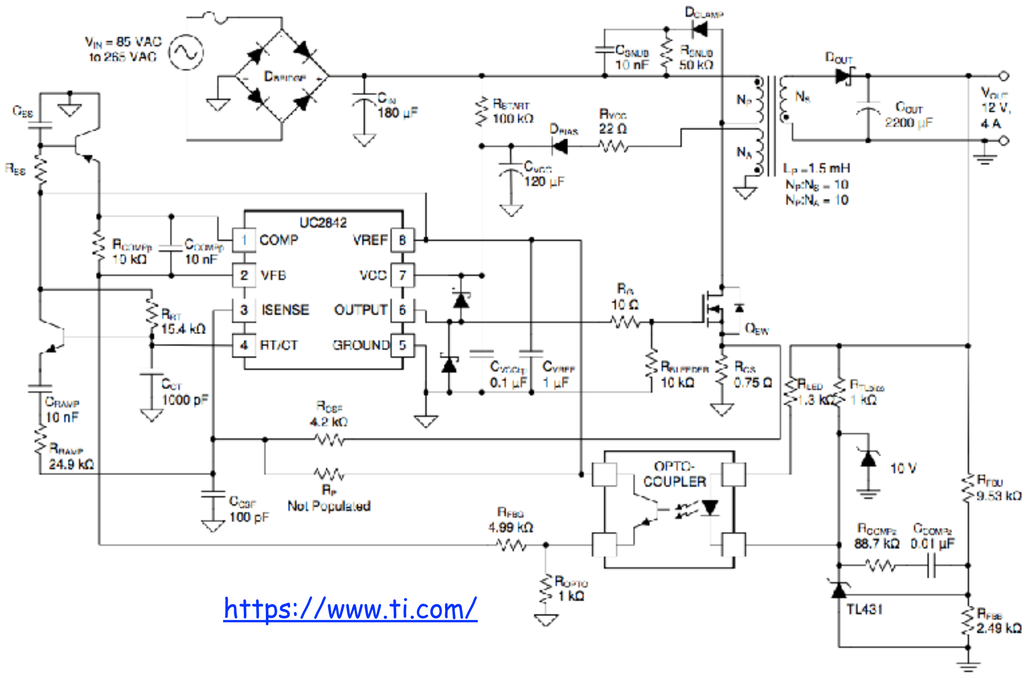
Conversores CC-CC Isolados

Características dos conversores isolados:

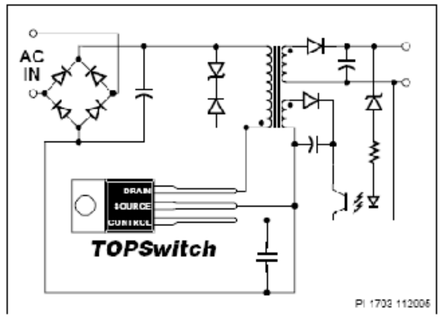
- Isolamento;
- Número de saídas;
- Regulação da tensão de saída;
- Tendência de simplificação dos circuitos.



https://ivobarbi.com.br/



https://www.ti.com/

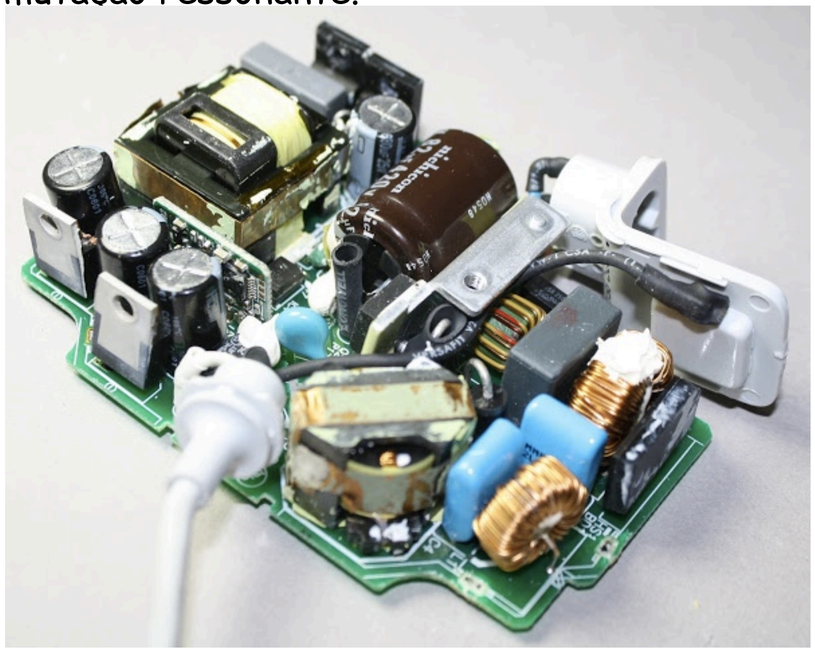


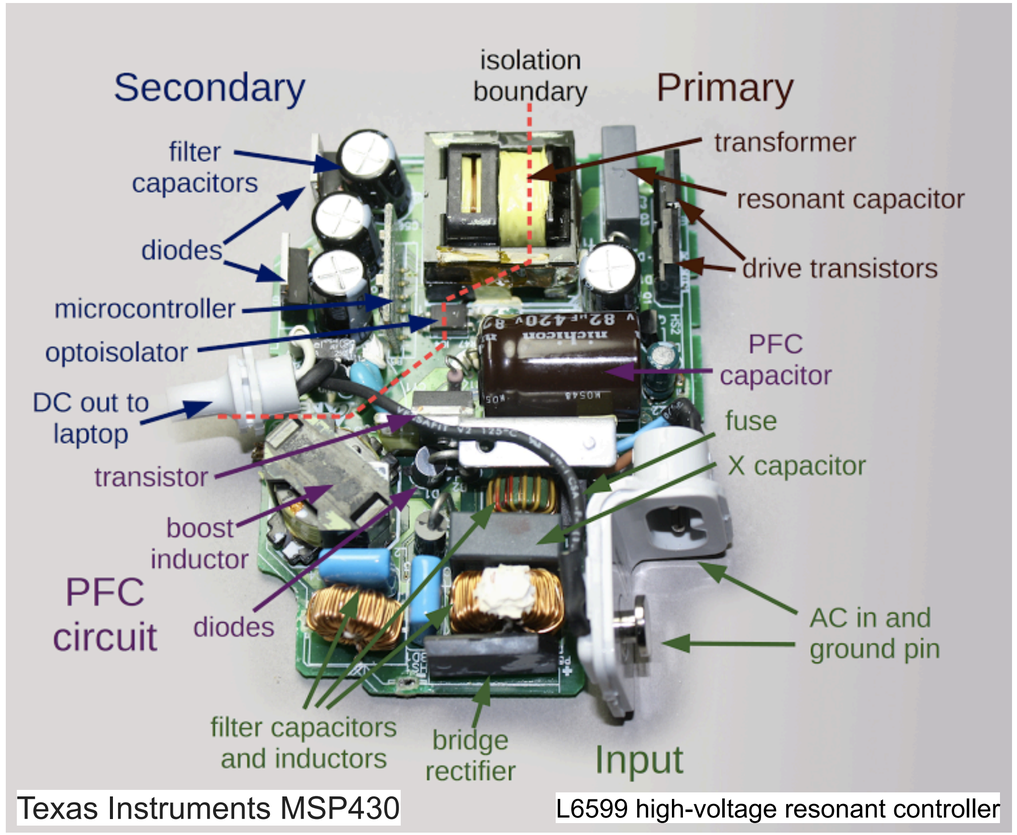
https://www.power.com/

Conversores CC-CC Isolados

Elementos de uma fonte chaveada completa:

- Filtro de entrada;
- Proteção;
- Comunicação;
- Correção de fator de potência;
- Comutacão ressonante.



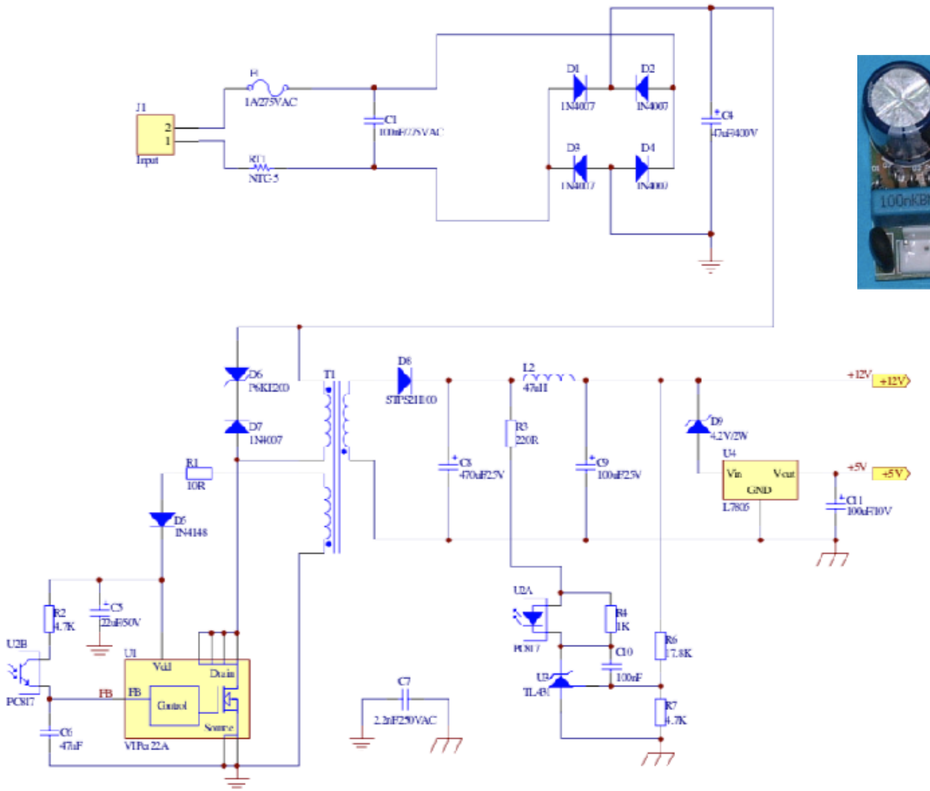


Texas Instruments MSP430

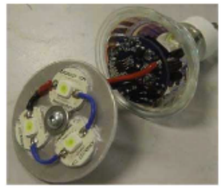
L6599 high-voltage resonant controller

http://www.righto.com/2015/11/macbook-charger-teardown-surprising.html

Conversores CC-CC Isolados



Conversor isolado
10 W SMPS com Viper22A
para condicionadores de ar

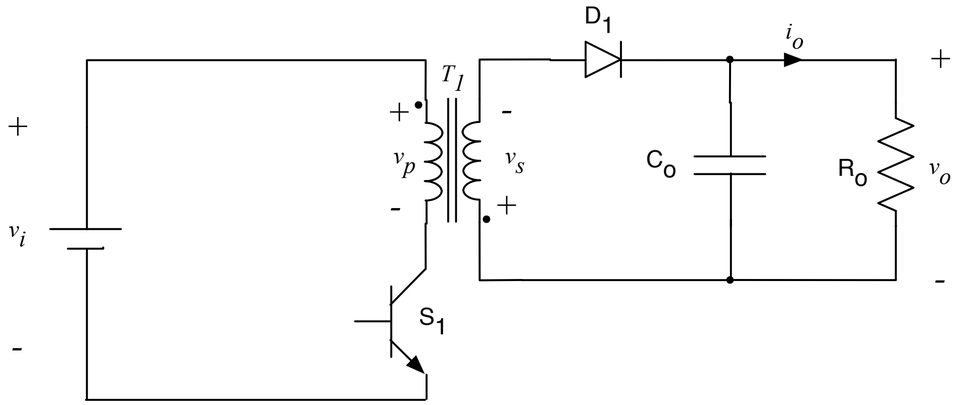


Conversor não-isolado
3 W LED driver com Viper22A

https://www.st.com/resource/en/application_note/cd00047746-vipower-10w-power-smps-using-viper22a-for-air-conditioner-application-stmicroelectronics.pdf

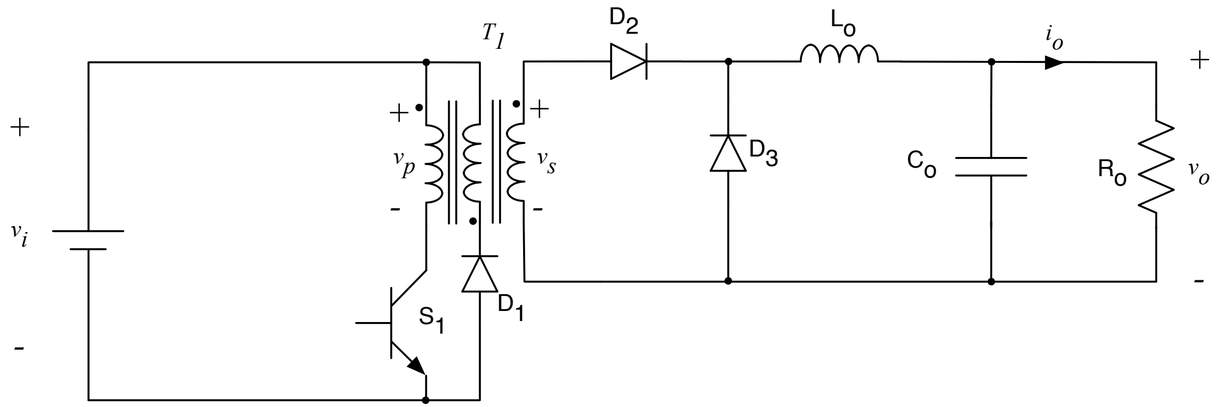
https://www.st.com/resource/en/application_note/cd00229993-stevalill026v1-nonisolated-3-w-offline-led-driver-based-on-the-viper22ae-stmicroelectronics.pdf

Conversores CC-CC Isolados



Conversor Flyback

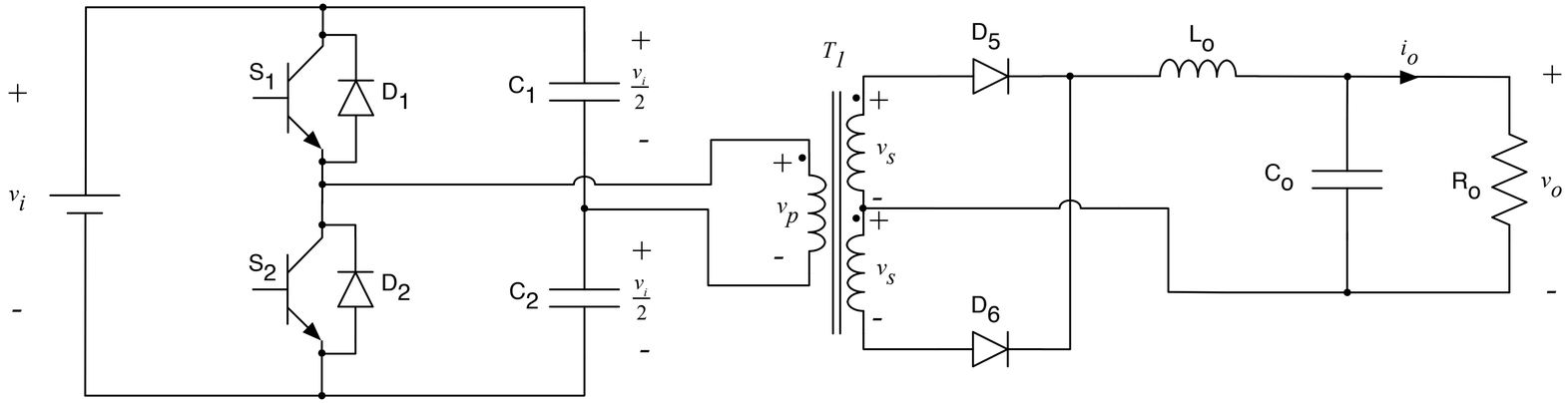
$$\frac{V_o}{V_i} = \frac{D}{n \cdot (1 - D)} \rightarrow n = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$



Conversor Forward

$$\frac{V_o}{V_i} = \frac{D}{n} \rightarrow n = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

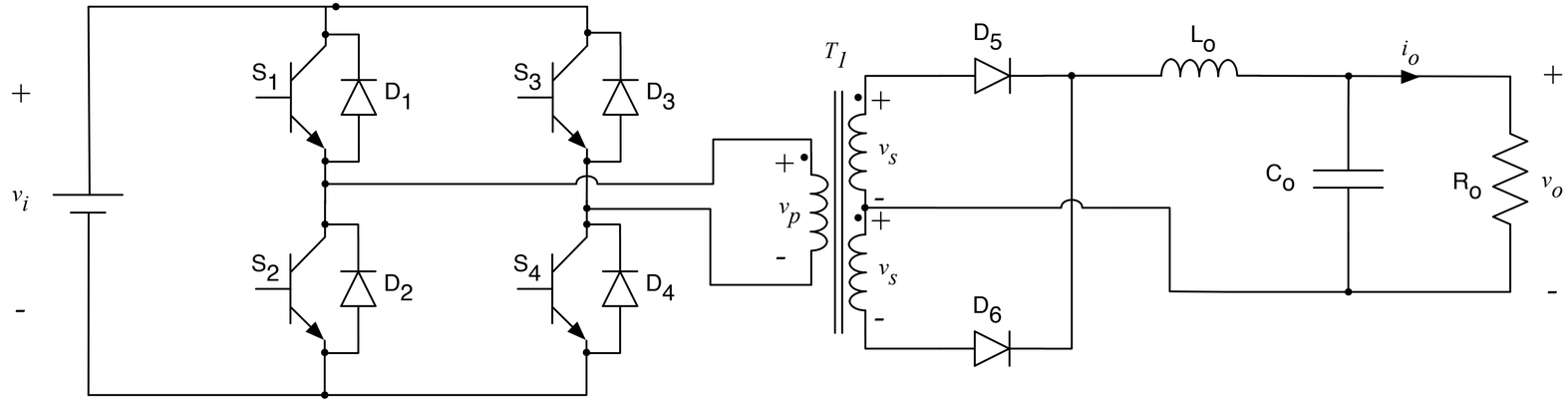
Conversores CC-CC Isolados



Conversor Meia Ponte (HB)

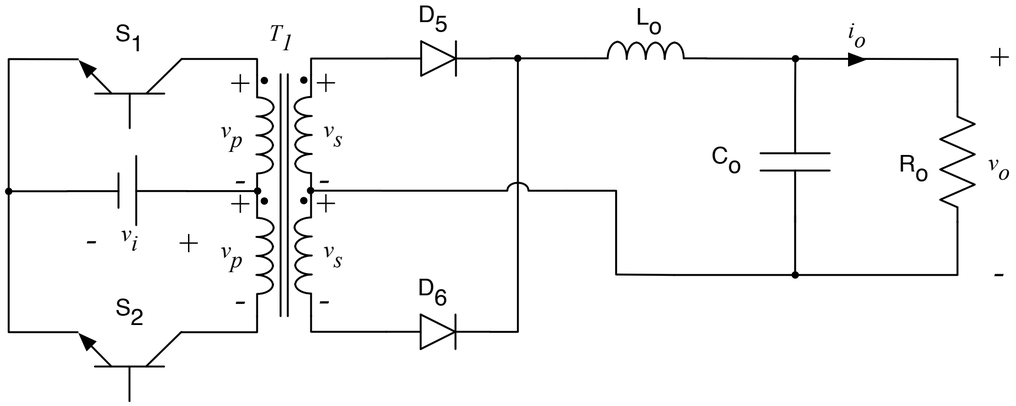
$$\frac{V_o}{V_i} = \frac{D}{2n} \rightarrow n = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Conversor Ponte Completa (FB)

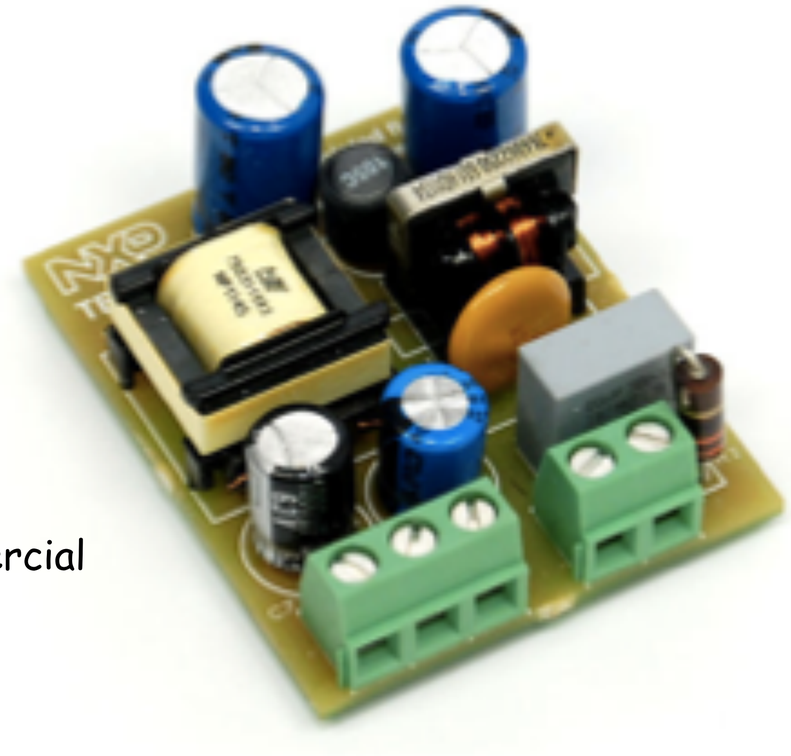


$$\frac{V_o}{V_i} = \frac{D}{n} \rightarrow n = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Conversores CC-CC Isolados



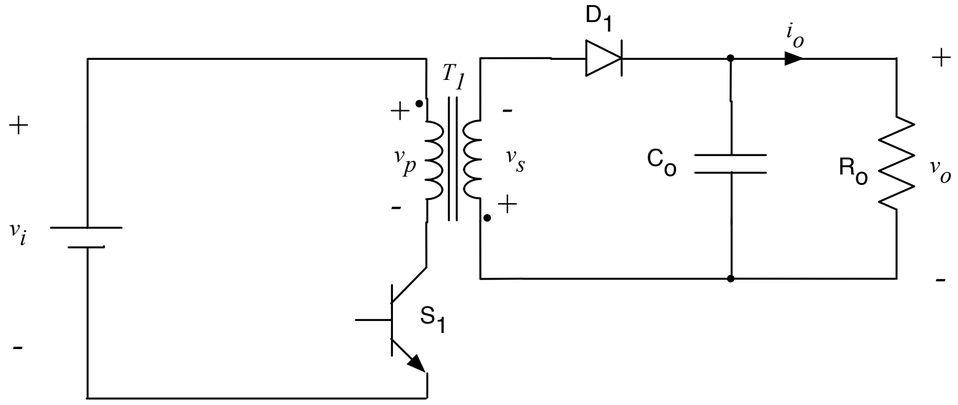
Conversor Push-Pull



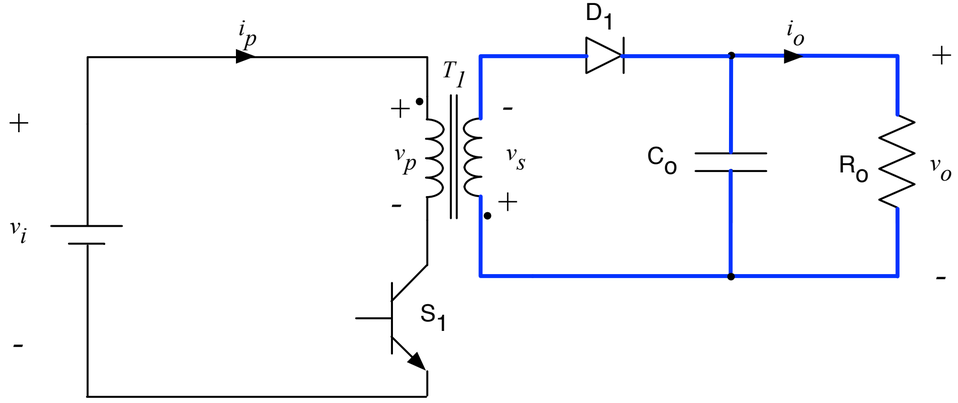
Conversor Flyback comercial

www.nxp.com

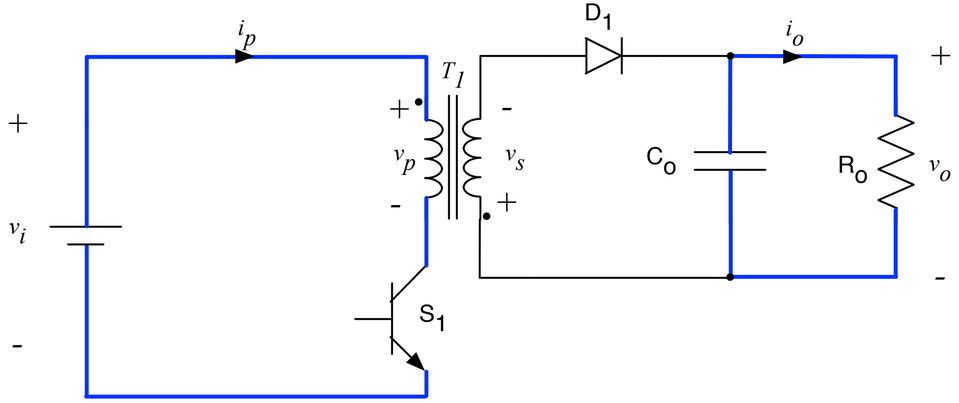
Conversor Flyback



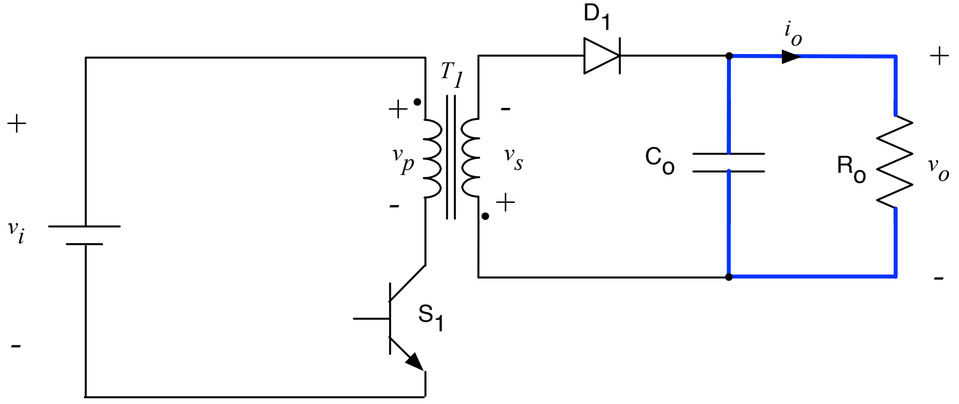
Conversor Flyback



Segunda etapa

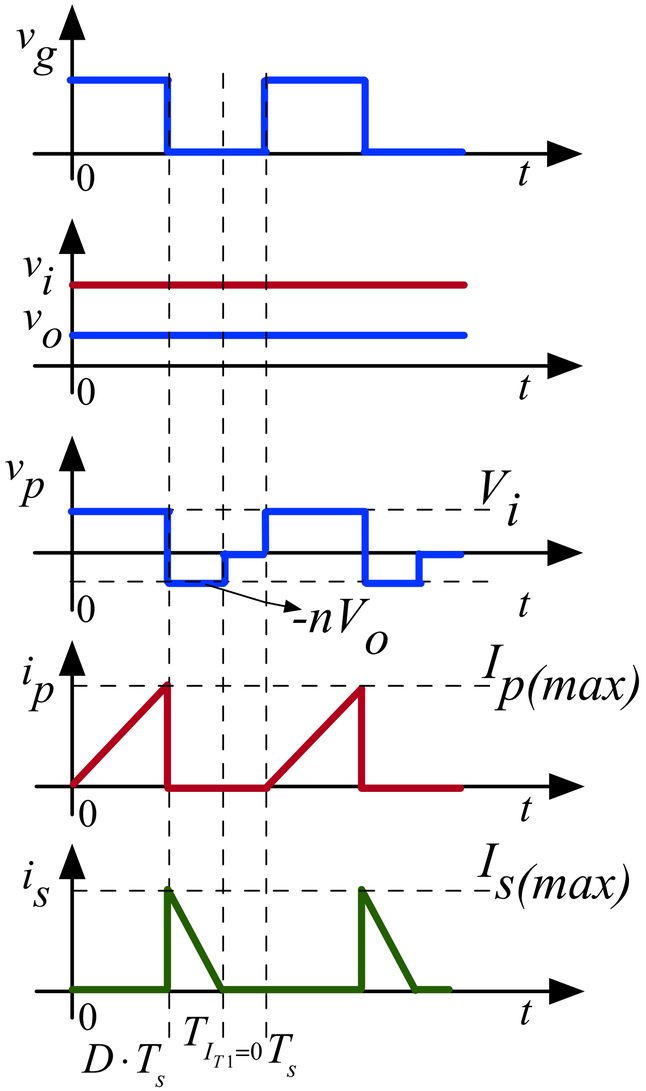


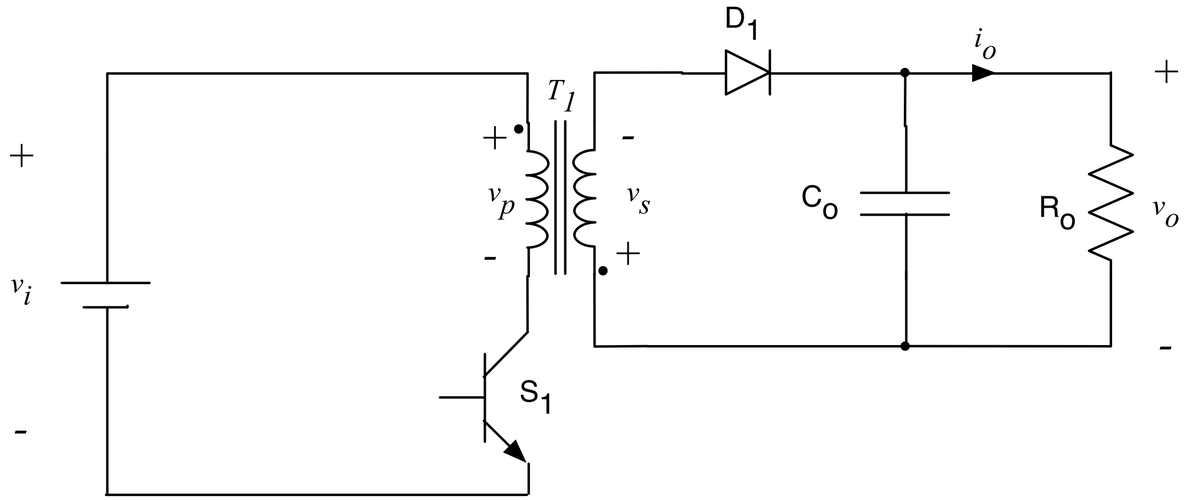
Primeira etapa



Terceira etapa

Conversor Flyback



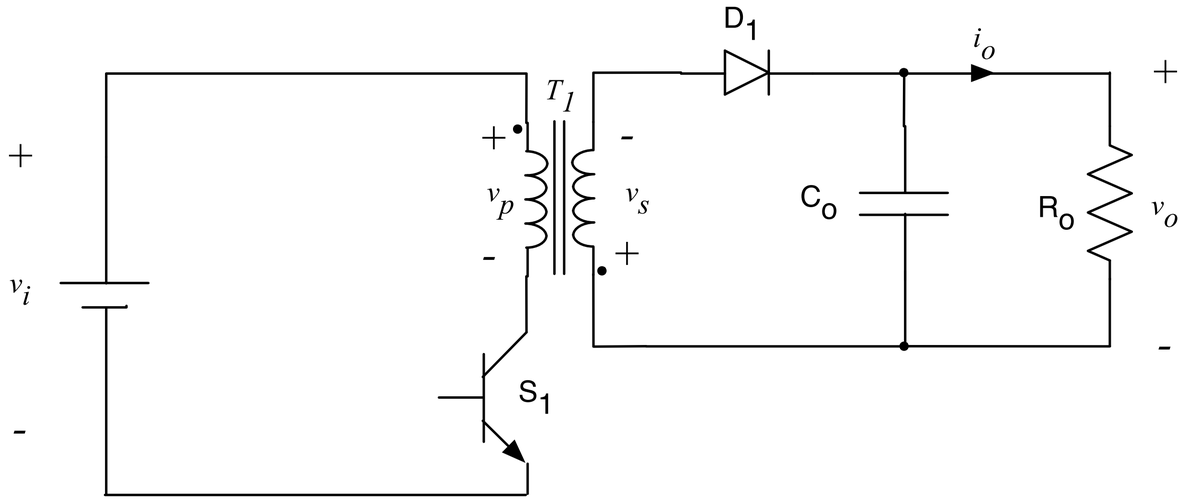


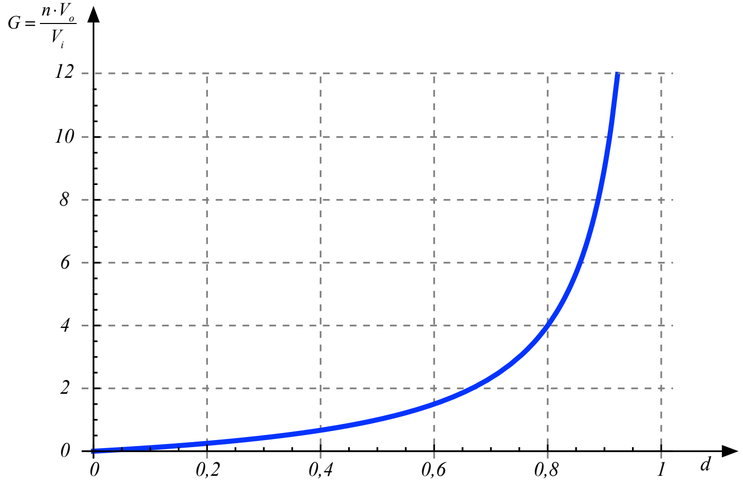
$$V_i = \text{definido}$$

$$V_p = \frac{1}{T_s} \cdot \left[\left(V_i \cdot D \cdot T_s \right) + \left(-n \cdot V_o \cdot \left(T_s - D \cdot T_s \right) \right) \right] \rightarrow n = \frac{V_p}{V_s} \rightarrow \frac{n \cdot V_o}{V_i} = \frac{D}{1-D}$$

$$V_o' = n \cdot V_o \rightarrow V_o' = V_i \cdot \frac{D}{1-D}$$

Conversor Flyback





$$V_{S1(\max)} = V_i + n \cdot V_o$$

$$V_{D1(\max)} = V_o + \frac{V_i}{n}$$

$$I_o = \frac{V_o}{R_o}$$

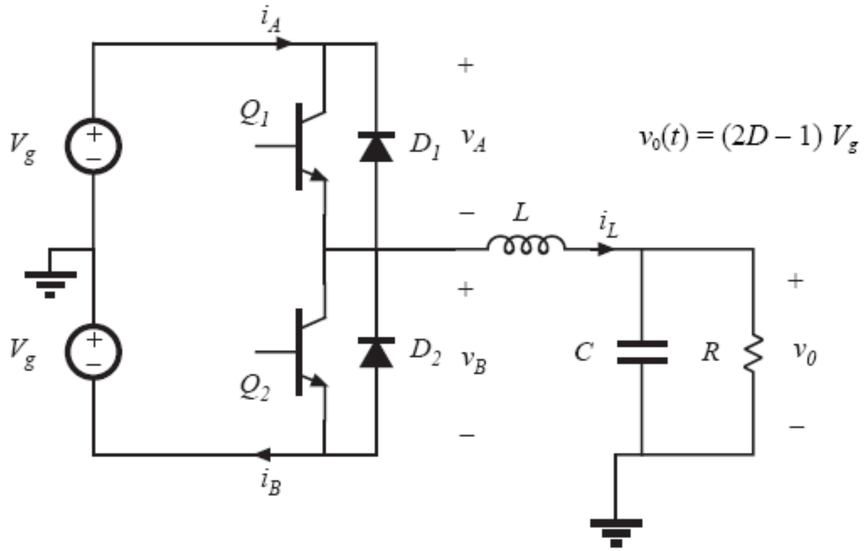
$$I_{D1} = I_o$$

$$I_{p(\max)} = I_{S1(\max)} = \frac{V_i \cdot D}{L_1 \cdot F_s}$$

$$I_{S1} = I_i = \frac{P_i}{V_i} \rightarrow P_i = P_o \rightarrow \eta = 1$$

Próxima Aula

Conversores cc-ca



$$v_0(t) = (2D - 1)\, V_g$$