Modelagem e Controle de Sistemas Fotovoltaicos

Aula 04 – P1: Modelagem e Controle de Conversor Boost

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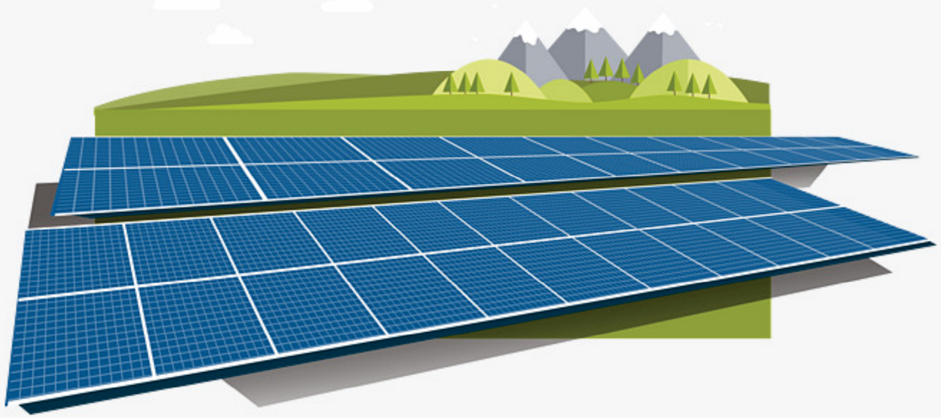
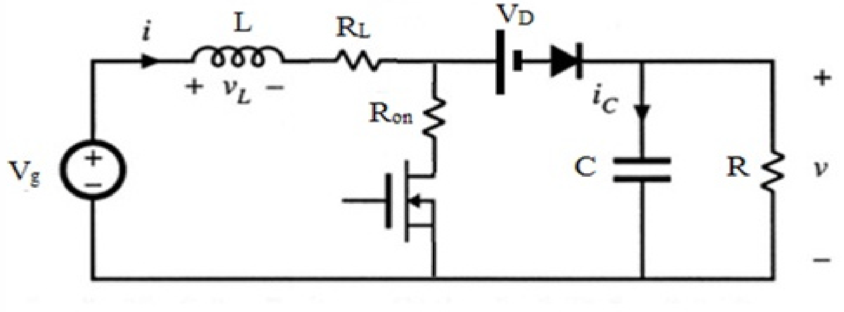
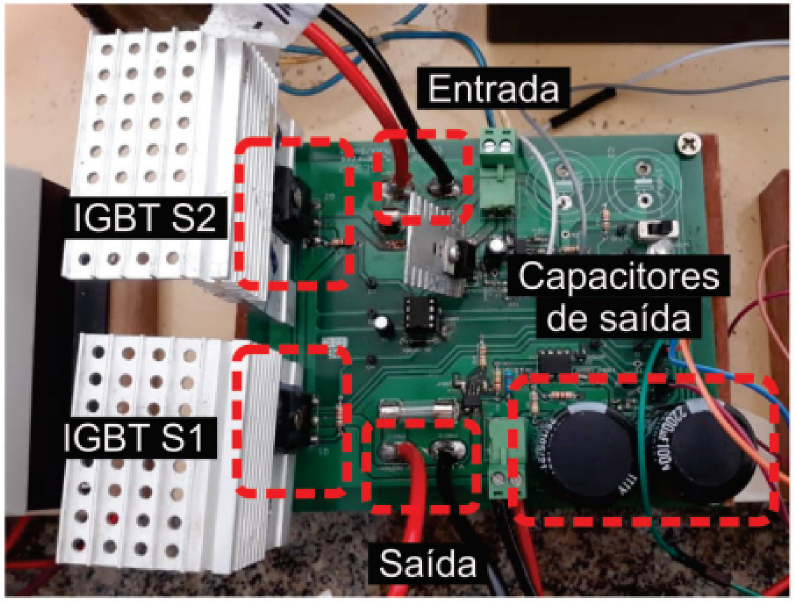


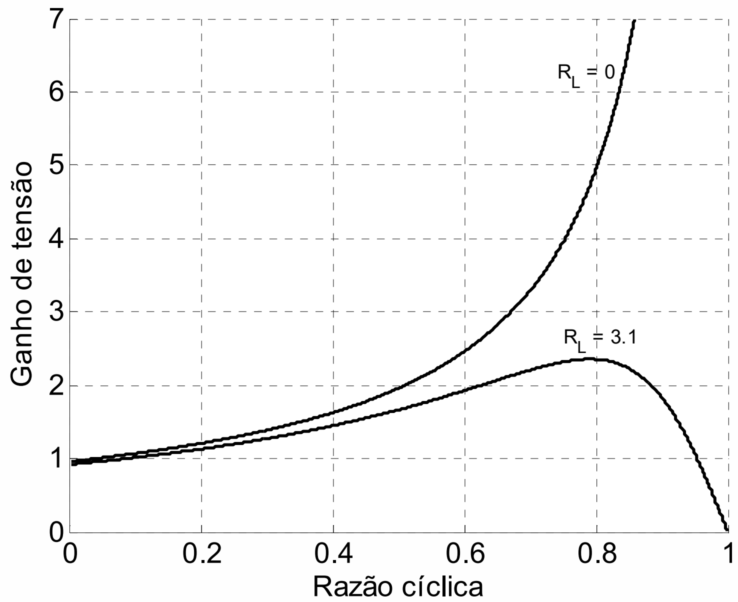
Considerações iniciais

- Conhecimento básico de circuitos elétricos
- Teoria de controle linear
- Transformada de Laplace
- Modelo médio *vs* modelo chaveado

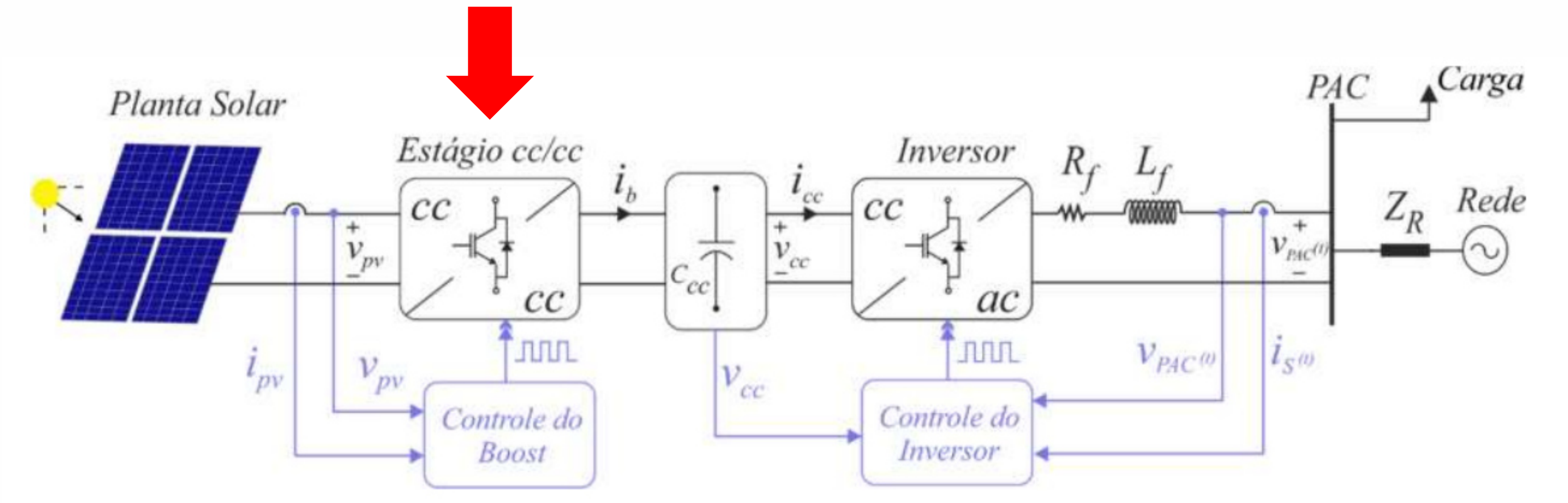
Conversor Boost – Controlador de carga





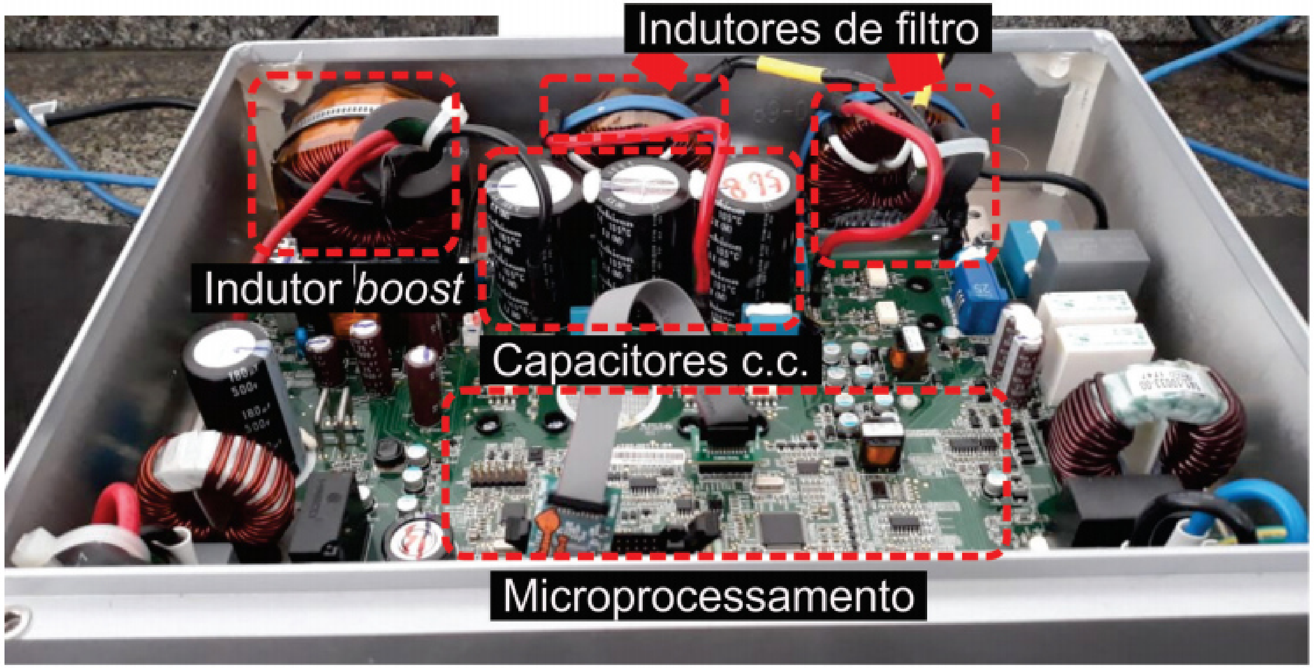


Estágio CC/CC elevador de tensão – Inversor Fotovoltaico

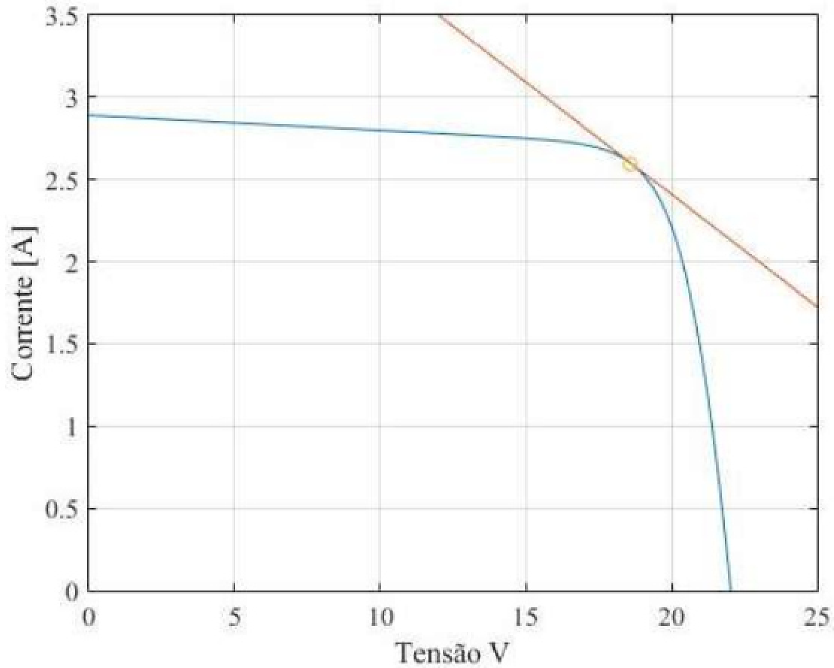


- ✓ Controlar a tensão de entrada do conversor.
- ✓ Fazer o módulo fotovoltaico operar no ponto de máxima potência.

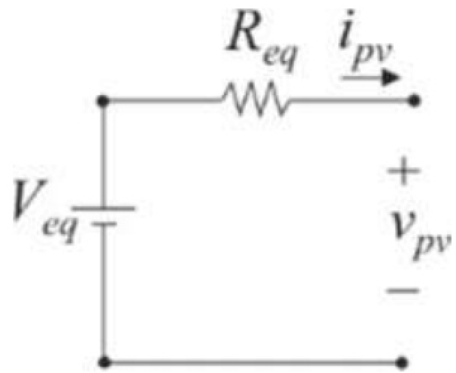
Estágio CC/CC elevador de tensão



Linearização do Módulo Fotovoltaico

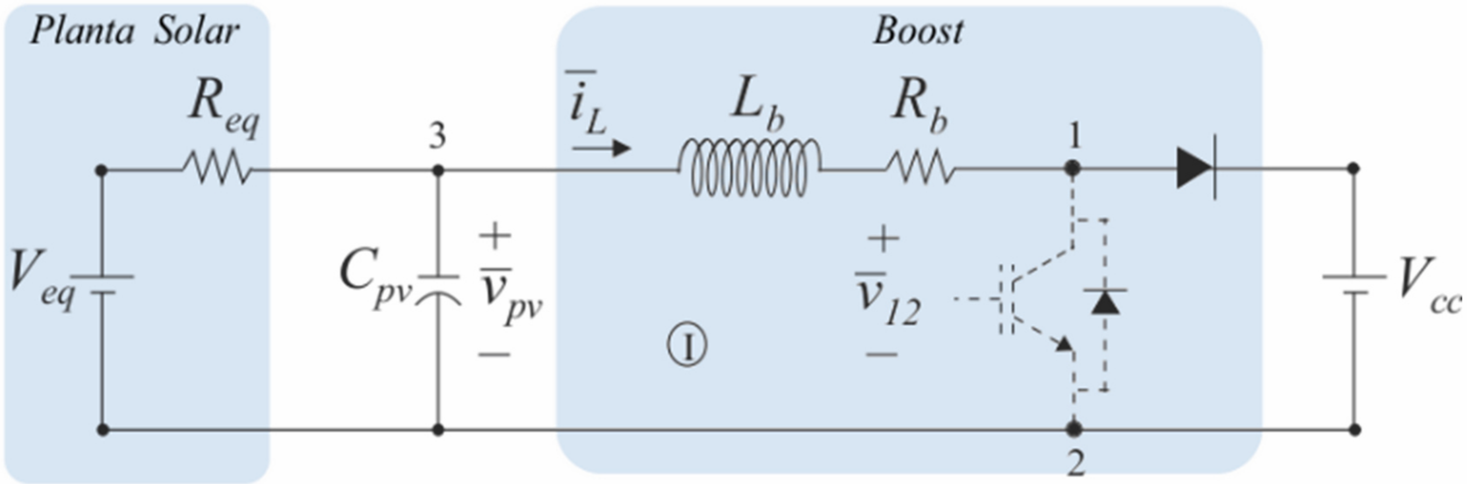


$$R_{eq} = \frac{V_{mpp}}{I_{mpp}} \qquad V_{eq} = 2V_{mpp}$$



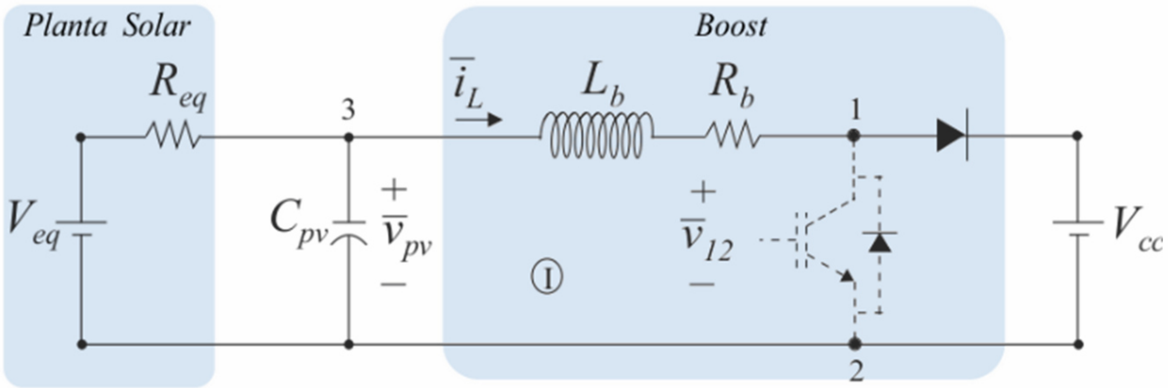
$$i_{pv} = I_{pv} - I_0\left(e^{\frac{v_{pv}+R_s i_{pv}}{V_t a}} - 1\right) - \frac{v_{pv} + R_s\, i_{pv}}{R_p}$$

Painel Solar + Conversor Boost



- ✓ Quando o transistor está ligado $\bar{v}_{12} = 0$
- ✓ Caso contrário $\bar{v}_{12} = V_{cc}$ de saída do conversor.
- ✓ Dessa forma, pode−se escrever a seguinte relação: $\bar{v}_{12} = (1 - d)V_{cc}$

Conversor Boost – Chave fechada ($v_{12} = 0$)

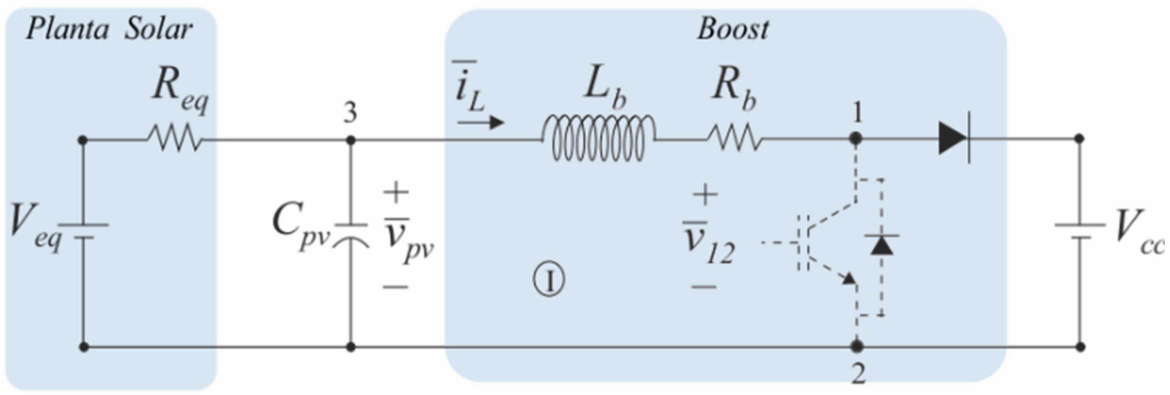


$$\begin{cases} \dfrac{V_{eq} - v_{pv}}{R_{eq}} = C_{pv}\dfrac{dv_{pv}}{dt} + i_L \\ v_{pv} - L_b\dfrac{di_L}{dt} - R_b i_L = 0 \end{cases}$$

$$\begin{bmatrix} \dfrac{dv_{pv}}{dt} \\ \dfrac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{C_{pv}R_{eq}} & -\dfrac{1}{C_{pv}} \\ \dfrac{1}{L_b} & -\dfrac{R_b}{L_b} \end{bmatrix} \cdot \begin{bmatrix} v_{pv} \\ i_L \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_{pv}R_{eq}} & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} V_{eq} \\ V_{CC} \end{bmatrix}$$

$$\dot{x} = A_1 x + B_1 u$$

Conversor Boost – Chave aberta $(v_{12} = V_{CC})$



$$\begin{cases} \dfrac{V_{eq} - v_{pv}}{R_{eq}} = C_{pv}\dfrac{dv_{pv}}{dt} + i_L \\ v_{pv} - L_b\dfrac{di_L}{dt} - R_b i_L - V_{CC} = 0 \end{cases}$$

$$\begin{bmatrix} \dfrac{dv_{pv}}{dt} \\ \dfrac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{C_{pv}R_{eq}} & -\dfrac{1}{C_{pv}} \\ \dfrac{1}{L_b} & -\dfrac{R_b}{L_b} \end{bmatrix} \cdot \begin{bmatrix} v_{pv} \\ i_L \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_{pv}R_{eq}} & 0 \\ 0 & -\dfrac{1}{L_b} \end{bmatrix} \cdot \begin{bmatrix} V_{eq} \\ V_{CC} \end{bmatrix}$$

$$\dot{x} = A_0 x + B_0 u$$

Linearização do conversor Boost

$$\dot{x} = Ax + Bu$$

A_0 A_1 B_0 B_1

A_1 B_1 → Chave ligada → Período do duty cycle = d

A_0 B_0 → Chave desligada → Período do duty cycle = (1-d)

Lembrando que d varia de 0-100%

$$\dot{X} = (dA_1 + (1-d)A_0) \cdot X + (dB_1 + (1-d)B_0) \cdot U$$

$$A = dA_1 + (1-d)A_0 \qquad B = dB_1 + (1-d)B_0$$

Linearização do conversor Boost

$$\dot{x} = Ax + Bu$$

$$\dot{x} = \begin{bmatrix} \dfrac{dv_{pv}}{dt} \\ \dfrac{di_L}{dt} \end{bmatrix}, \quad x = \begin{bmatrix} v_{pv} \\ i_L \end{bmatrix}, \quad u = \begin{bmatrix} V_{eq} \\ V_{CC} \end{bmatrix}$$

$$A = dA_1 + (1-d)A_0$$

$$B = dB_1 + (1-d)B_0$$

$$A_1 = \begin{bmatrix} -\dfrac{1}{C_{pv}R_{eq}} & -\dfrac{1}{C_{pv}} \\ \dfrac{1}{L_b} & -\dfrac{R_b}{L_b} \end{bmatrix} \qquad A_0 = \begin{bmatrix} -\dfrac{1}{C_{pv}R_{eq}} & -\dfrac{1}{C_{pv}} \\ \dfrac{1}{L_b} & -\dfrac{R_b}{L_b} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \dfrac{1}{C_{pv}R_{eq}} & 0 \\ 0 & 0 \end{bmatrix} \qquad B_0 = \begin{bmatrix} \dfrac{1}{C_{pv}R_{eq}} & 0 \\ 0 & -\dfrac{1}{L_b} \end{bmatrix}$$

Linearização do conversor Boost

$$\dot{x} = (dA_1 + (1-d)A_0) \cdot \mathrm{x} + (dB_1 + (1-d)B_0) \cdot \mathrm{u}$$

$$\dot{x} = (A_0 + (A_1 - A_0)d) \cdot \mathrm{x} + (B_0 + (B_1 - B_0)d) \cdot \mathrm{u}$$

$$\begin{cases} d = D + \hat{d} \\ x = X + \hat{x} \\ \mathrm{u} = U + \hat{u} \end{cases}$$

→ Análise de pequenos sinais

$$\dot{X} + \dot{\hat{x}} = \left(A_0 + (A_1 - A_0)(D + \hat{d})\right) \cdot (X + \hat{x}) + \left(B_0 + (B_1 - B_0)(D + \hat{d})\right) \cdot (U + \hat{u})$$

$$\dot{X} + \dot{\hat{x}} = A_0X + \mathrm{D}(A_1 - A_0)\mathrm{X} + B_0U + \mathrm{D}(B_1 - B_0)\mathrm{U} +$$
$$+ A_0\hat{x} + D\,(A_1 - A_0)\,\hat{x} + B_0\hat{u} + \mathrm{D}(B_1 - B_0)\hat{u} + \hat{d}(A_1 - A_0)\mathrm{X} + \hat{d}(B_1 - B_0)\mathrm{U} +$$
$$+ \hat{d}(A_1 - A_0)\hat{x} + \hat{d}(B_1 - B_0)\hat{u}$$

Linearização do conversor Boost

$$\dot{\hat{x}} = A_0\hat{x} + D\,(A_1 - A_0)\,\hat{x} + B_0\hat{u} + \mathrm{D}(B_1 - B_0)\hat{u} + \hat{d}(A_1 - A_0)\mathrm{X} + \hat{d}(B_1 - B_0)\mathrm{U}$$

$$\dot{\hat{x}} = A \cdot \hat{x} + B \cdot \hat{u} + [(A_1 - A_0) \cdot X + (B_1 - B_0) \cdot U] \cdot \hat{d}$$

$$\downarrow$$

$$M = [(A_1 - A_0) \cdot X + (B_1 - B_0) \cdot U]$$

$$\dot{\hat{x}} = A \cdot \hat{x} + B \cdot \hat{u} + M \cdot \hat{d}$$

$$\dot{\hat{x}} = A \cdot \hat{x} + [B \quad M].\begin{bmatrix} \hat{u} \\ \hat{d} \end{bmatrix} \Rightarrow \frac{d}{dt}(\hat{x}) = A \cdot \hat{x} + B_t \cdot \hat{u}_t$$

Transformada de Laplace

$$s \cdot \hat{x}(s) = A \cdot \hat{x}(s) + B_t \cdot \hat{u}_t(s) \Rightarrow \hat{x}(s) = (sI - A)^{-1} \cdot B_t\hat{u}_t(s)$$

Linearização do conversor Boost

$$\hat{x}(s) = (sI - A)^{-1} \cdot B_t \hat{u}_t(s) \qquad B_t = [B \quad M]$$

$$A = dA_1 + (1-d)A_0 = \begin{bmatrix} -\frac{1}{C_{pv}R_{eq}} & -\frac{1}{C_{pv}} \\ \frac{1}{L_b} & -\frac{R_b}{L_b} \end{bmatrix} \quad B = dB_1 + (1-d)B_0 = \begin{bmatrix} \frac{1}{C_{pv}R_{eq}} & 0 \\ 0 & \frac{-1+D}{L_b} \end{bmatrix}$$

$$M = [(A_1 - A_0) \cdot \mathrm{X} + (B_1 - B_0) \cdot U] = \begin{bmatrix} 0 \\ \frac{V_{CC}}{L_b} \end{bmatrix}$$

$$\begin{bmatrix} \hat{v}_{pv}(s) \\ \hat{\imath}_L(s) \end{bmatrix} = \left(\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} -\frac{1}{C_{pv}R_{eq}} & -\frac{1}{C_{pv}} \\ \frac{1}{L_b} & -\frac{R_b}{L_b} \end{bmatrix} \right)^{-1} \cdot \begin{bmatrix} \frac{1}{C_{pv}R_{eq}} & 0 & 0 \\ 0 & \frac{-1+D}{L_b} & \frac{V_{CC}}{L_b} \end{bmatrix} \begin{bmatrix} \widehat{V_{eq}} \\ \widehat{V_{cc}} \\ \hat{d} \end{bmatrix}$$

Linearização do conversor Boost

$$\begin{bmatrix}\hat{v}_{pv}(s)\\ \hat{\imath}_L(s)\end{bmatrix} = \mathrm{k}\begin{bmatrix}\left(s+\dfrac{R_b}{L_b}\right)\dfrac{1}{C_{pv}R_{eq}} & \dfrac{-1+D}{C_{pv}L_b} & -\dfrac{V_{CC}}{C_{pv}L_b}\\ \dfrac{1}{C_{pv}R_{eq}L_b} & \left(s+\dfrac{1}{C_{pv}R_{eq}}\right)\left(\dfrac{-1+D}{L_b}\right) & \left(s+\dfrac{1}{C_{pv}R_{eq}}\right)\dfrac{V_{CC}}{L_b}\end{bmatrix}\begin{bmatrix}\widehat{V_{eq}}\\ \widehat{V_{cc}}\\ \hat{d}\end{bmatrix}$$

$$\mathrm{k} = \frac{1}{s^2+\left(\dfrac{R_b}{L_b}+\dfrac{1}{C_{pv}R_{eq}}\right)s+\dfrac{R_b}{L_bC_{pv}R_{eq}}+\dfrac{1}{C_{pv}L_b}}$$

$$\frac{\hat{v}_{pv}}{\hat{d}} = -\mathrm{k}\frac{V_{CC}}{C_{pv}L_b}$$

$$\frac{\hat{\imath}_L}{\hat{d}} = \mathrm{k}\left(s+\frac{1}{C_{pv}R_{eq}}\right)\frac{V_{CC}}{L_b}$$

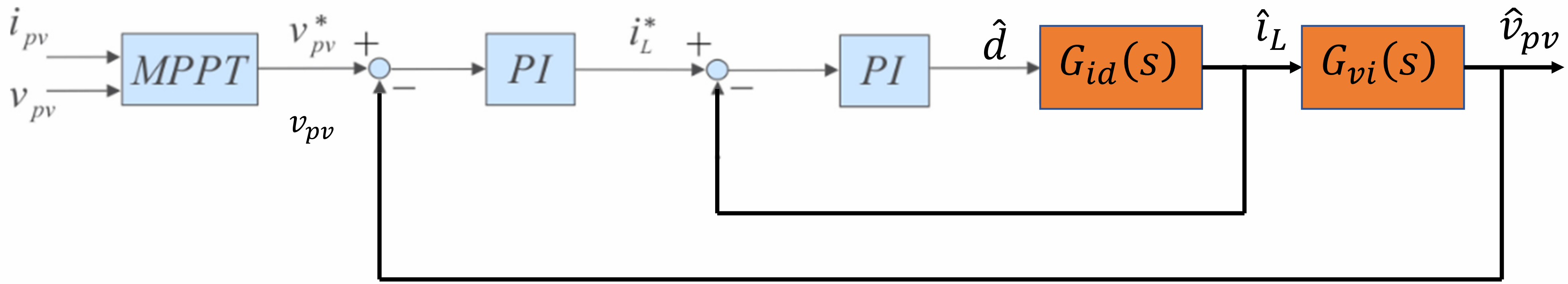
Linearização do conversor Boost

$$G_{vd}(s) = \frac{\hat{v}_{pv}(s)}{\hat{d}} = -\text{k}\frac{V_{CC}}{C_{pv}L_b}$$

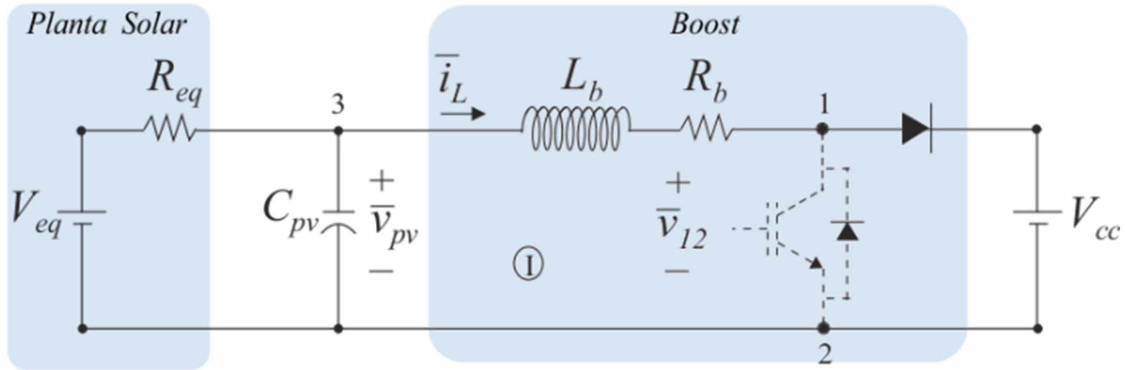
$$G_{vi}(s) = \frac{\hat{v}_{pv}(s)}{\hat{\iota}_L(s)} = -\frac{1}{C_{pv}s + \frac{1}{R_{eq}}}$$

$$G_{id}(s) = \frac{\hat{\iota}_L(s)}{\hat{d}} = \text{k}\left(s + \frac{1}{C_{pv}R_{eq}}\right)\frac{V_{CC}}{L_b}$$

Malha de controle da tensão de entrada do boost



Simplificando as funções de transferência



Considerando as variáveis de pequenos sinais:

$$\frac{V_{eq}}{R_{eq}} - \frac{V_{pv}}{R_{eq}} - \frac{\tilde{v}_{pv}}{R_{eq}} - C_{pv}\frac{d\tilde{v}_{pv}}{dt} - I_L - \tilde{\imath}_L = 0$$

Aplicando a transformada de Laplace e considerando somente os pequenos sinais:

$$-\frac{\tilde{v}_{pv}(s)}{R_{eq}} - C_{pv}s\tilde{v}_{pv}(s) - \tilde{\imath}_L(s) = 0$$

$$G_{vi}(s) = \frac{\tilde{v}_{pv}(s)}{\tilde{\imath}_L(s)} = -\frac{1}{C_{pv}s + \frac{1}{R_{eq}}}$$

Comparação das funções de transferência

Completo

$$G_{vi}(s) = \frac{\hat{v}_{pv}(s)}{\hat{i}_L(s)} = -\frac{1}{C_{pv}s + \frac{1}{R_{eq}}}$$

Simplificado

$$G_{vi}(s) = \frac{\tilde{v}_{pv}(s)}{\tilde{i}_L(s)} = -\frac{1}{C_{pv}s + \frac{1}{R_{eq}}}$$

Relação corrente no indutor x duty cycle

Considerando a tensão no capacitor de entrada do conversor *boost* controlada em V_{pv}, a equação das tensões médias na malha I é dada por:

$$V_{pv} - L_b \frac{d\bar{\imath}_L}{dt} - \bar{\imath}_L R_b - \bar{v}_{12} = 0$$

Considerando as variáveis de pequenos sinais:

$$V_{pv} - L_b \frac{d\tilde{\imath}_L}{dt} - I_L R_b - \tilde{\imath}_L R_b - V_{cc} + V_{cc} D + V_{cc}\tilde{d} = 0$$

Aplicando a transformada de Laplace e considerando somente os pequenos sinais:

$$-L_b s \tilde{\imath}_L(s) - \tilde{\imath}_L(s) R_b + V_{cc}\tilde{d}(s) = 0$$

$$G_{id}(s) = \frac{\tilde{\imath}_L(s)}{\tilde{d}(s)} = \frac{V_{cc}}{L_b s + R_b}$$

Comparação das funções de transferência

Completo

$$G_{id}(s) = \frac{\hat{\imath}_L(s)}{\hat{d}} = \mathrm{k}\left(s + \frac{1}{C_{pv}R_{eq}}\right)\frac{V_{CC}}{L_b}$$

$$\mathrm{k} = \frac{1}{s^2 + \left(\frac{R_b}{L_b} + \frac{1}{C_{pv}R_{eq}}\right)s + \frac{R_b}{L_b C_{pv} R_{eq}} + \frac{1}{C_{pv}L_b}}$$

Simplificado

$$G_{id}(s) = \frac{\tilde{\imath}_L(s)}{\tilde{d}(s)} = \frac{V_{cc}}{L_b s + R_b}$$

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Obrigado!

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