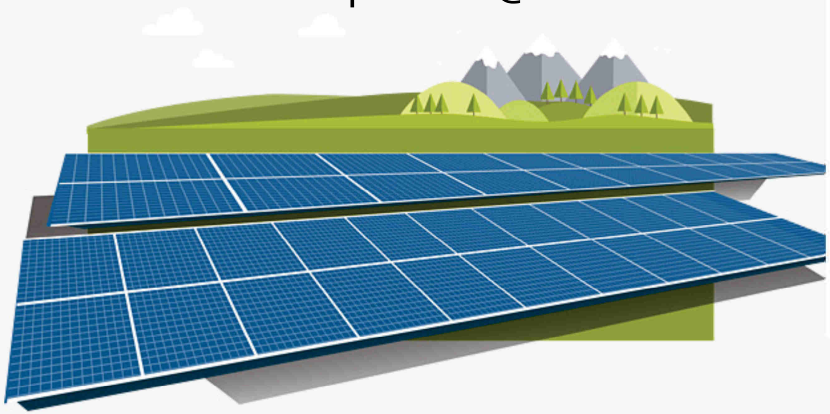
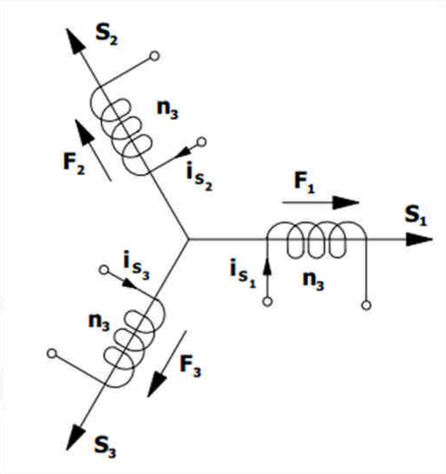
Modelagem e Controle de Sistemas Fotovoltaicos

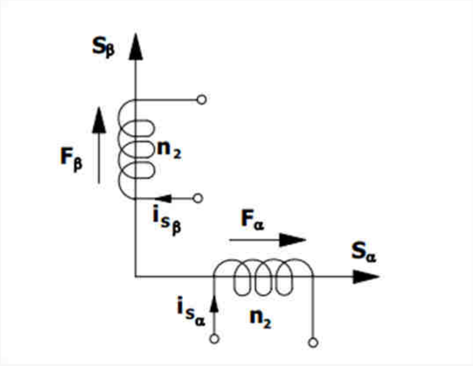
Aula 06 – P1: Transformações de Clarke e de Park

Prof. Heverton Augusto Pereira

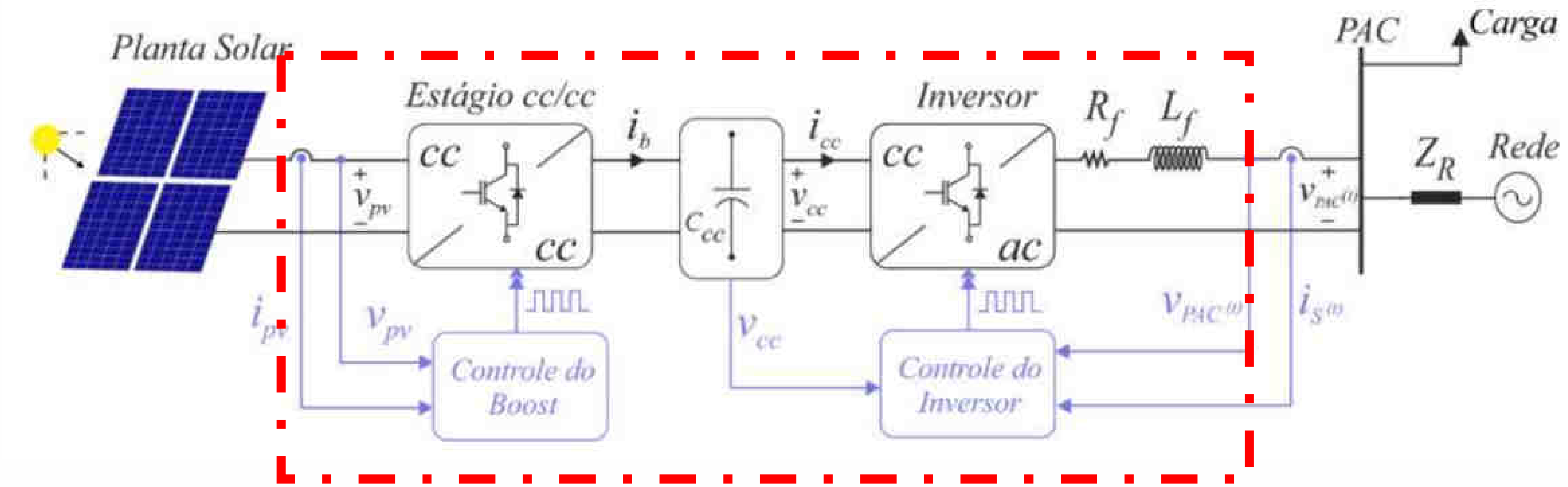
heverton.pereira@ufv.br



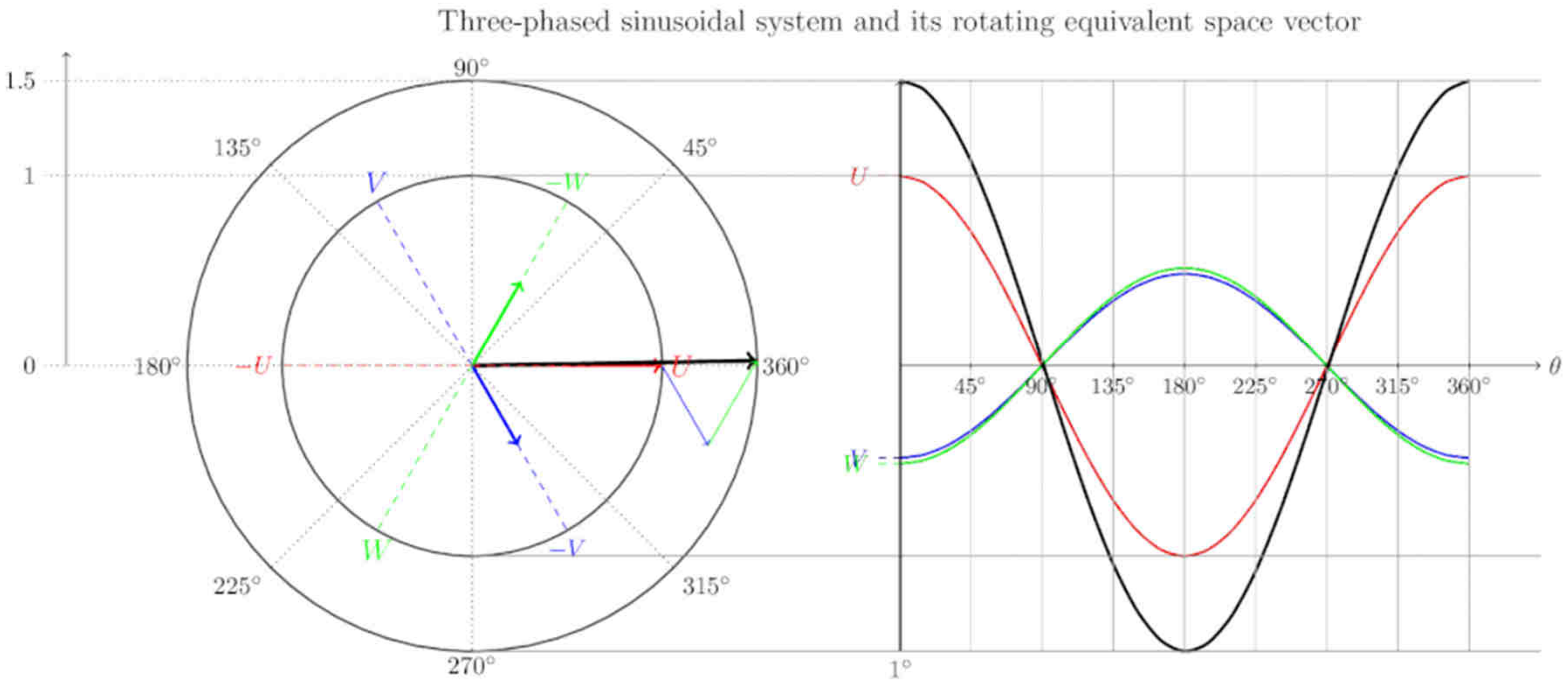




Inversor Fotovoltaico



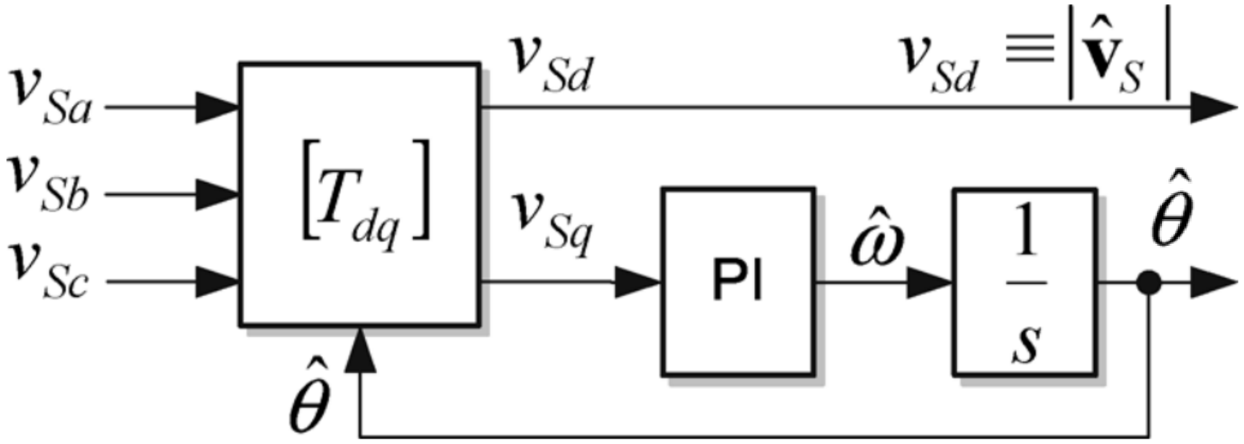
- ✓ Sincronismo com a rede
- ✓ Controlar a injeção de potência ativa e reativa na rede elétrica;
- ✓ Realiza a proteção do sistema fotovoltaico quando existem problemas na rede elétrica;



https://www.switchcraft.org/learning/2017/3/15/space-vector-pwm-intro

Sistema de Sincronismo

- PLL: *Phase Locked Loop*
- Medição do ângulo de fase e a frequência da rede
- Controlar a injeção de potência ativa e reativa na rede elétrica
- Realiza a proteção do sistema fotovoltaico quando existem problemas na rede elétrica

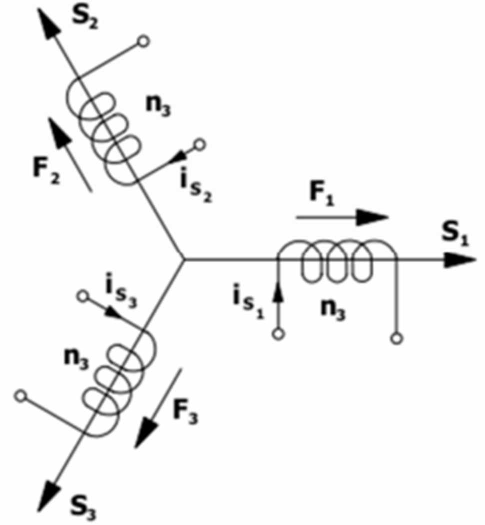


Fonte: P. Rodriguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, "Decoupled double synchronous reference frame PLL for power converters control,"IEEE Trans. Power Electron., vol. 22, no. 2, pp. 584–592, Mar. 2007.

Fasor Espacial de um Sistema Trifásico

$$\begin{cases} i_a(t) = \hat{I}\ cos(\omega_n\, t + \ \theta_0) \\ i_b(t) = \hat{I}\ cos\left(\omega_n\, t + \ \theta_0 - \dfrac{2\pi}{3}\right) \\ i_c(t) = \hat{I}\ cos\left(\omega_n\, t + \ \theta_0 - \dfrac{4\pi}{3}\right). \end{cases}$$

$$\begin{cases} |F_a(t)| = N_a\ |i_a(t)| \\ |F_b(t)| = N_b\ |i_b(t)| \\ |F_c(t)| = N_c\ |i_c(t)| \end{cases}$$



$$\overrightarrow{F_R} = \overrightarrow{F_a} + \overrightarrow{F_b} + \overrightarrow{F_c}.$$

$$\overrightarrow{F_R} = N_a i_a(t)\ e^{j0} + N_b i_b(t) e^{j\frac{2\pi}{3}} + N_c i_c(t) e^{j\frac{4\pi}{3}}$$

$$N = N_a = N_b = N_c$$

$$\overrightarrow{F_R} = N\ \left(i_a(t)\ e^{j0} + \ i_b(t) e^{j\frac{2\pi}{3}} + \ i_c(t) e^{j\frac{4\pi}{3}}\right) = N\,\vec{i}$$

Fasor Espacial de um Sistema Trifásico

$$\overrightarrow{F_R} = N\left(i_a(t)\,e^{j0} + i_b(t)e^{j\frac{2\pi}{3}} + i_c(t)e^{j\frac{4\pi}{3}}\right) = N\,\vec{\imath}$$

$$e^{j\theta} = \cos\theta + j\,sen\,\theta$$

$$\vec{\imath} = \frac{3}{2}\,\hat{I}\,e^{j\,(\omega_n t + \theta_0)}$$ → Fasor Espacial

$$\vec{\imath} = \frac{2}{3}\left(i_a(t)\,e^{j0} + i_b(t)e^{j\frac{2\pi}{3}} + i_c(t)e^{j\frac{4\pi}{3}}\right)$$

Invariância em amplitude da transformação.

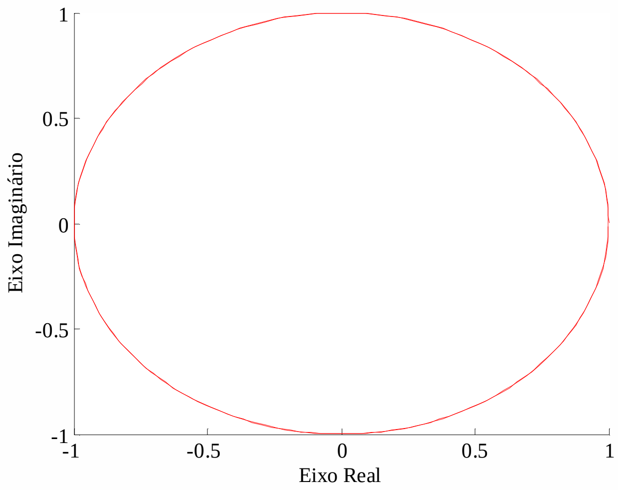
$$\vec{v} = \frac{2}{3}\left(v_a(t)\,e^{j0} + v_b(t)e^{j\frac{2\pi}{3}} + v_c(t)e^{j\frac{4\pi}{3}}\right)$$

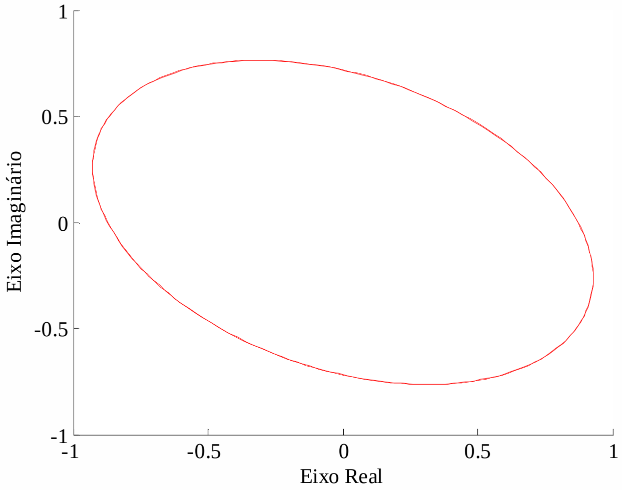
Fasor Espacial de um Sistema Trifásico

$$\begin{cases} i_a(t) = \widehat{I_a}\ cos(377\,t) \\ i_b(t) = \widehat{I_b}\ cos\left(377\,t - \dfrac{2\pi}{3}\right) \\ i_c(t) = \widehat{I_c}\ cos\left(377\,t - \dfrac{4\pi}{3}\right). \end{cases}$$

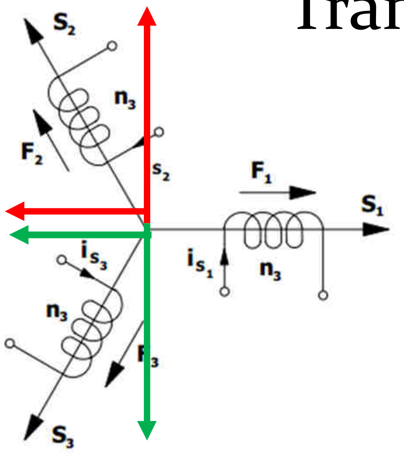
a) $I_a = I_b = I_c = 1\,p.u.$

b) $I_a = I_b = 1\,p.u.\ e\ = I_c = 0{,}5\,p.u.$





Transformação de Clarke



$$\begin{bmatrix} F_\alpha \\ F_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix}.$$

$$F_\alpha = \; F_a + F_b \cos\frac{2\pi}{3} + F_c \cos\frac{4\pi}{3}$$

$$F_\beta = \; 0 + \; F_b \, sen\frac{2\pi}{3} + F_c \, sen\frac{4\pi}{3}$$

Transformação de Clarke

$$\begin{bmatrix} F_\alpha \\ F_\beta \end{bmatrix} = N_2 \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \; e \; \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} = N_3 \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{N_3}{N_2} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

- ✓ Para que a transformação seja invertível, a matriz de transformação deve ser quadrada.
- ✓ Assim, define-se a corrente i_0 dada por:

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = [T_{\alpha\beta}] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$T_{0\alpha\beta} = \frac{N_3}{N_2} \begin{bmatrix} k & k & k \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}.$$

Transformação de Clarke

$$[T_{0\alpha\beta}][T_{0\alpha\beta}]^{-1} = [T_{0\alpha\beta}][T_{0\alpha\beta}]^{T} = I \qquad I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

$$\left(\frac{N_3}{N_2}\right)^2 \begin{bmatrix} k & k & k \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} k & 1 & 0 \\ k & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ k & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

$$\begin{cases} 3\left(\frac{N_3}{N_2}\right)^2 k^2 = 1 \\ \frac{3}{2}\left(\frac{N_3}{N_2}\right)^2 = 1 \end{cases} \qquad \begin{cases} k = \frac{1}{\sqrt{2}} \\ \frac{N_3}{N_2} = \sqrt{\frac{2}{3}}\,. \end{cases}$$

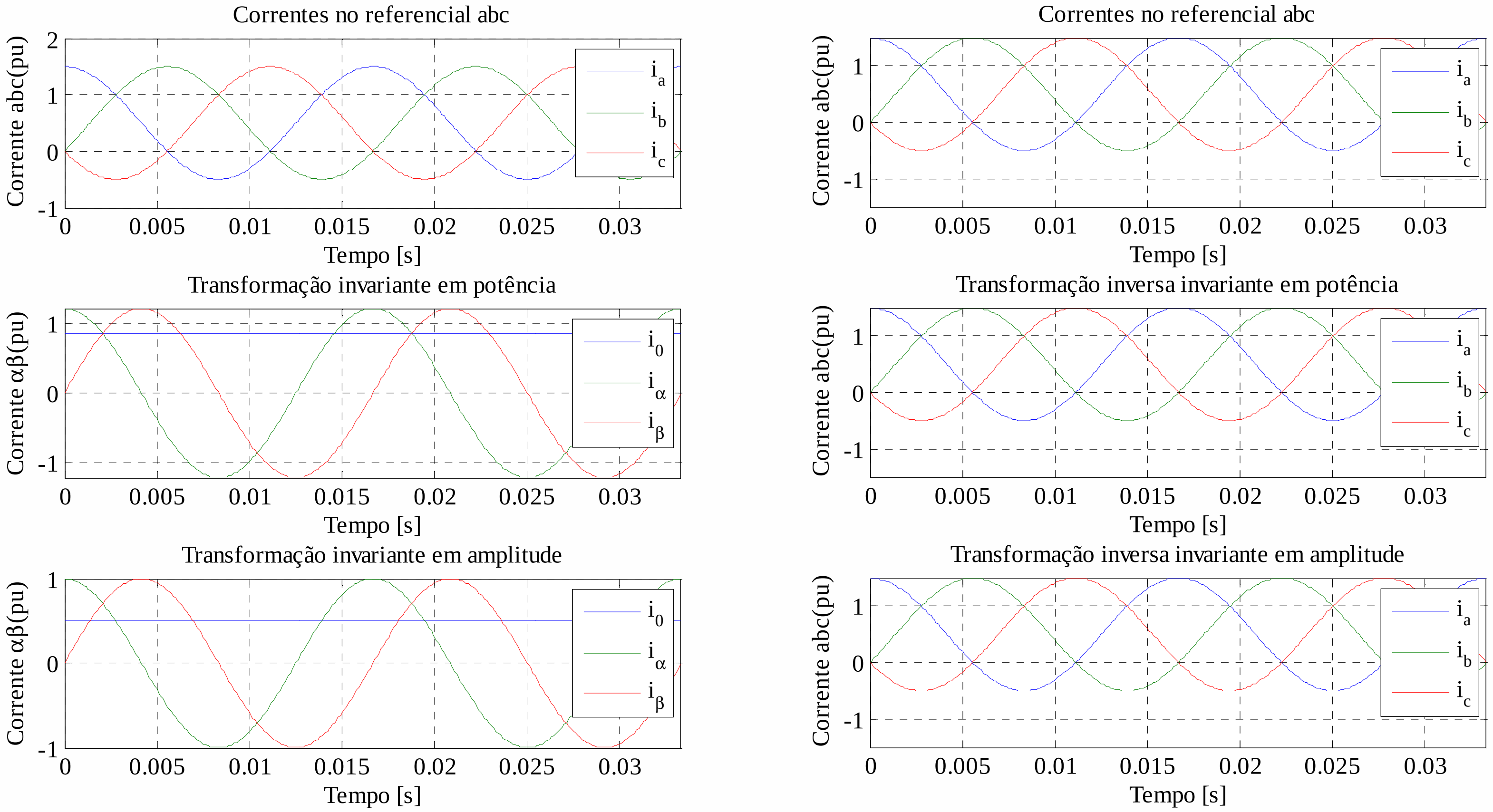
Transformação de Clarke

Esta transformação de coordenadas é conhecida como transformação de Clarke

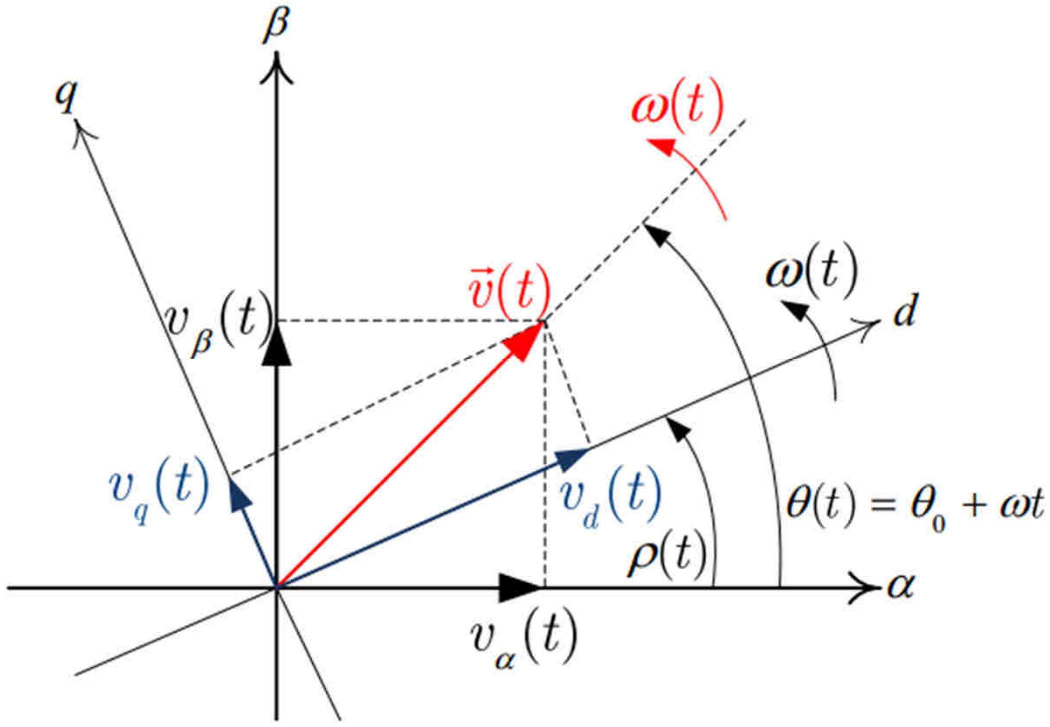
$$[T_{0\alpha\beta}] = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}.$$

$$[T_{0\alpha\beta}]^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}.$$

Transformação de Clarke



Transformação de Park



$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\rho & \operatorname{sen}\rho \\ -\operatorname{sen}\rho & \cos\rho \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

Transformação de Park

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\rho & \operatorname{sen}\rho \\ 0 & -\operatorname{sen}\rho & \cos\rho \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix}$$

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\rho & \operatorname{sen}\rho \\ 0 & -\operatorname{sen}\rho & \cos\rho \end{bmatrix} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}.$$

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \cos\rho & -\frac{1}{2}\cos\rho + \frac{\sqrt{3}}{2}\operatorname{sen}\rho & -\frac{1}{2}\cos\rho - \frac{\sqrt{3}}{2}\operatorname{sen}\rho \\ -\operatorname{sen}\rho & \frac{1}{2}\cos\rho + \frac{\sqrt{3}}{2}\operatorname{sen}\rho & \frac{1}{2}\cos\rho - \frac{\sqrt{3}}{2}\operatorname{sen}\rho \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}.$$

Transformação de Park

$$\begin{cases} v_a(t) = \hat{V}\ \cos(\omega t + \ \theta_0) \\ v_b(t) = \hat{V}\ \cos\left(\omega t + \ \theta_0 - \dfrac{2\pi}{3}\right) \\ v_c(t) = \hat{V}\ \cos\left(\omega t + \ \theta_0 - \dfrac{4\pi}{3}\right) \end{cases}.$$

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \dfrac{1}{2} & \dfrac{1}{2} & \dfrac{1}{2} \\ \cos\rho & \cos\left(\rho - \dfrac{2\pi}{3}\right) & \cos\left(\rho - \dfrac{4\pi}{3}\right) \\ -\operatorname{sen}\rho & -\operatorname{sen}\left(\rho - \dfrac{2\pi}{3}\right) & -\operatorname{sen}\left(\rho - \dfrac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} \hat{V}\ \cos(\omega t + \ \theta_0) \\ \hat{V}\ \cos\left(\omega t + \ \theta_0 - \dfrac{2\pi}{3}\right) \\ \hat{V}\ \cos\left(\omega t + \ \theta_0 - \dfrac{4\pi}{3}\right) \end{bmatrix}.$$

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 0 \\ \hat{V}\ \cos\ (\omega t + \ \theta_0 - \ \rho) \\ \hat{V}\ \operatorname{sen}\ (\omega t + \ \theta_0 - \ \rho) \end{bmatrix}$$

Transformação de Park

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 0 \\ \hat{\mathrm{V}} \cos\,(\omega t + \theta_0 - \rho) \\ \hat{\mathrm{V}} \,\mathrm{sen}\,(\omega t + \theta_0 - \rho) \end{bmatrix}$$

$$\vec{v}_{dq} = \vec{v}\, e^{-j\,\rho(t)} = \hat{\mathrm{V}}\, e^{-j\,(\{\omega t - \rho(t)\} + \theta_0)}$$

$$\rho(t) = \omega t$$

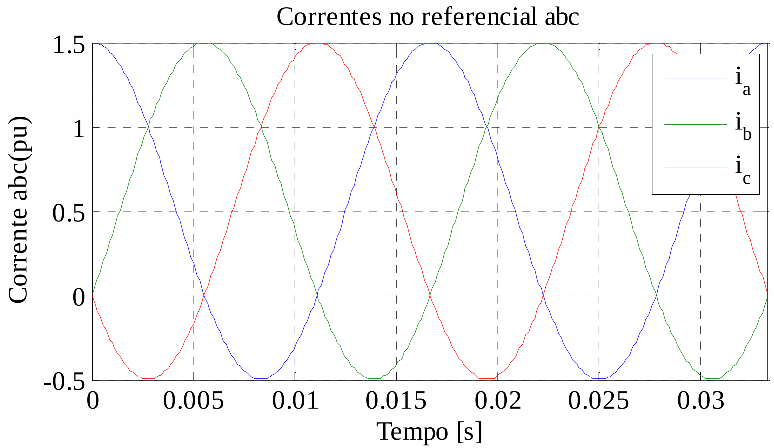
$$\vec{v}_{dq} = \hat{\mathrm{V}}\, e^{-j\,(\{\omega t - \omega t\} + \theta_0)} \Longrightarrow \boxed{\vec{v}_{dq} = \hat{\mathrm{V}}\, e^{-j\,\theta_0}}.$$

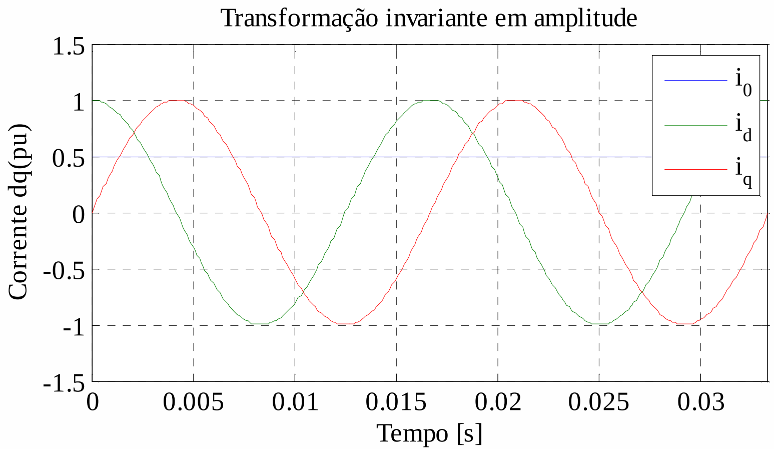
$$\vec{v}_{dq} = v_d + j\, v_q. \qquad \begin{cases} v_d = \hat{\mathrm{V}} \cos(\theta_0) \\ v_q = \hat{\mathrm{V}}\, \mathrm{sen}(\theta_0) \end{cases}.$$

Transformação de Park

$$\begin{cases} i_a(t) = \cos(377\,t + \theta) \\ i_b(t) = \cos\left(377\,t - \dfrac{2\pi}{3} + \theta\right) \\ i_c(t) = \cos\left(377\,t - \dfrac{4\pi}{3} + \theta\right) \end{cases}$$

a) $\rho = 0\ e\ \theta = 0°$. Qual a amplitude das componentes obtidas? Qual a frequência das formas de onda obtidas?

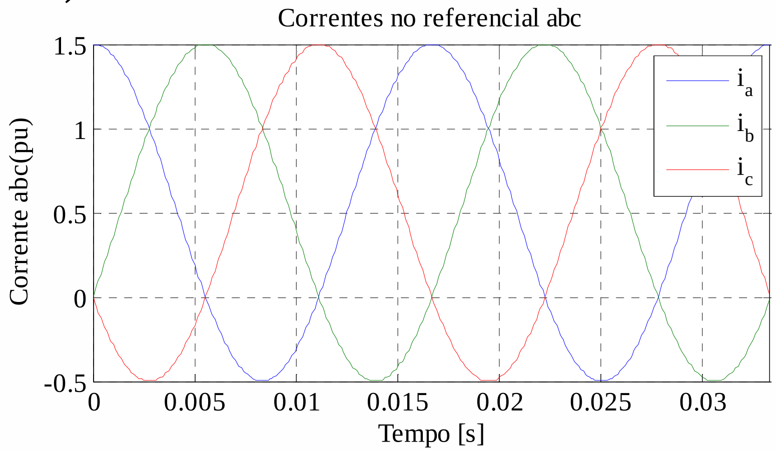


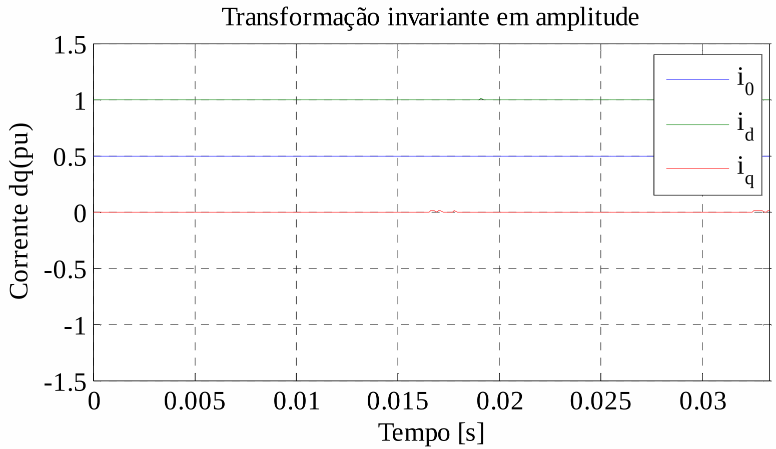


Transformação de Park

$$\begin{cases} i_a(t) = \cos(377\,t + \theta) \\ i_b(t) = \cos\left(377\,t - \dfrac{2\pi}{3} + \theta\right) \\ i_c(t) = \cos\left(377\,t - \dfrac{4\pi}{3} + \theta\right) \end{cases}$$

b) $\rho = 377t \; e \; \theta = 0°$. Qual a amplitude das componentes obtidas? Qual a frequência das formas de onda obtidas?

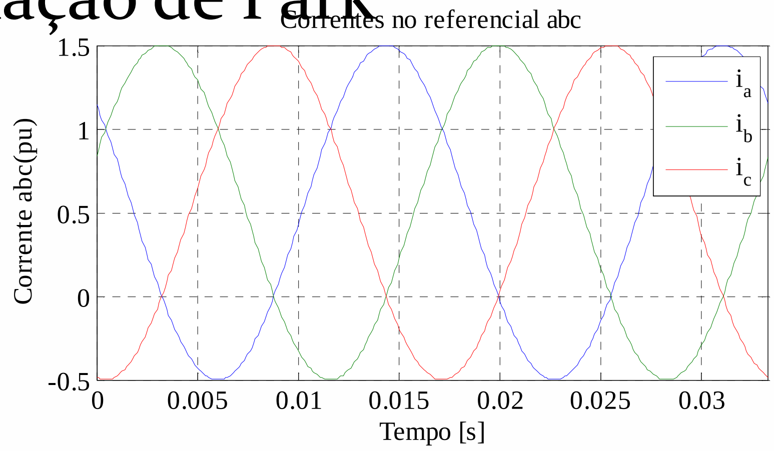


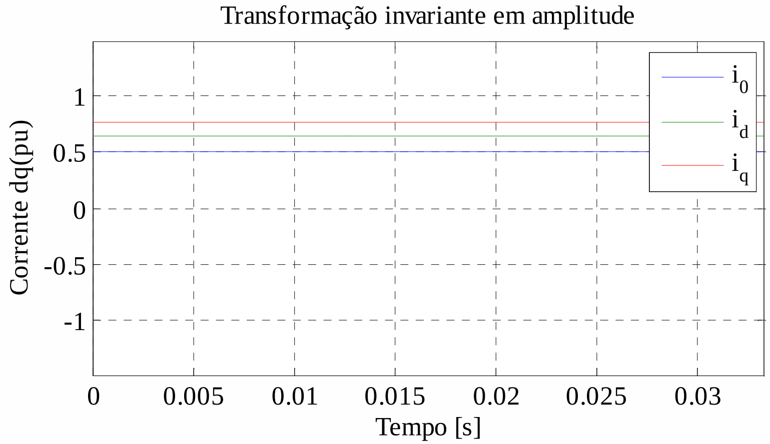


Transformação de Park

$$\begin{cases} i_a(t) = cos(377\,t + \theta) \\ i_b(t) = cos\left(377\,t - \frac{2\pi}{3} + \theta\right) \\ i_c(t) = cos\left(377\,t - \frac{4\pi}{3} + \theta\right) \end{cases}$$

c) $\rho = 377t\ e\ \theta = 50°$. Qual a amplitude das componentes obtidas? Qual a frequência das formas de onda obtidas?Conclua.

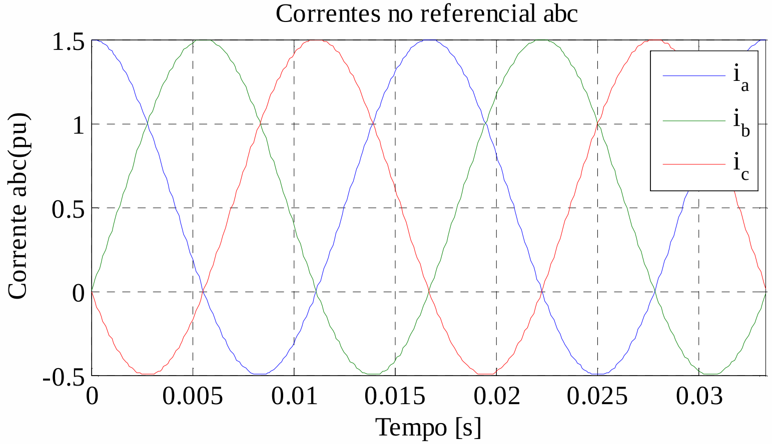


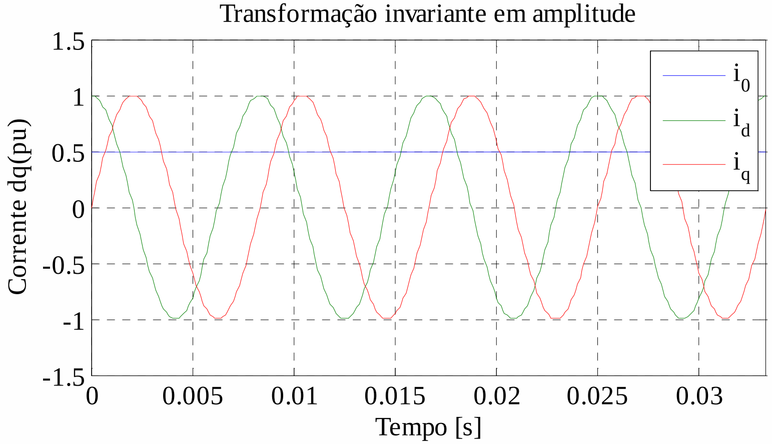


Transformação de Park

$$\begin{cases} i_a(t) = \cos(377\,t + \theta) \\ i_b(t) = \cos\left(377\,t - \dfrac{2\pi}{3} + \theta\right) \\ i_c(t) = \cos\left(377\,t - \dfrac{4\pi}{3} + \theta\right) \end{cases}$$

d) $\rho = -377t\ e\ \theta = 0°$. Qual a amplitude das componentes obtidas? Qual a frequência das formas de onda obtidas?Conclua.





www.gesep.ufv.br

Gesep

gesep_vicosa

Gesep UFV

EStimate - Sistemas Fotovoltaicos

Google Play

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

Obrigado!

Heverton Augusto Pereira
Prof. Departamento de Engenheira Eletrica | UFV
Coordenador da Gerência de Especialistas em Sistemas Elétricos de Potência |Gesep
Membro do Programa de Pós-Graduaçao em Engenharia Elétrica | PPGEL/CEFET-MG
E-mail: heverton.pereira@ufv.br