



Sincronización de sistemas

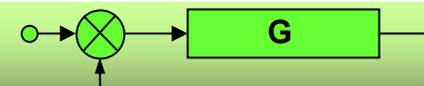
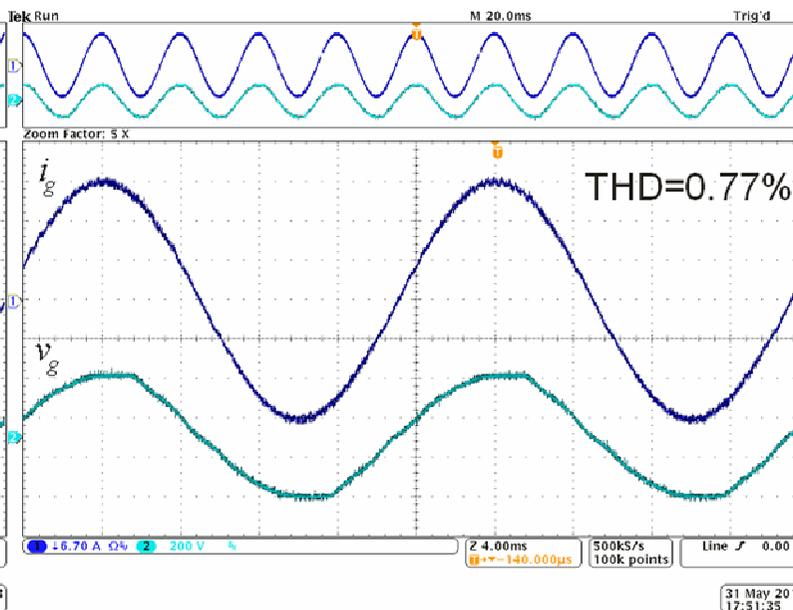
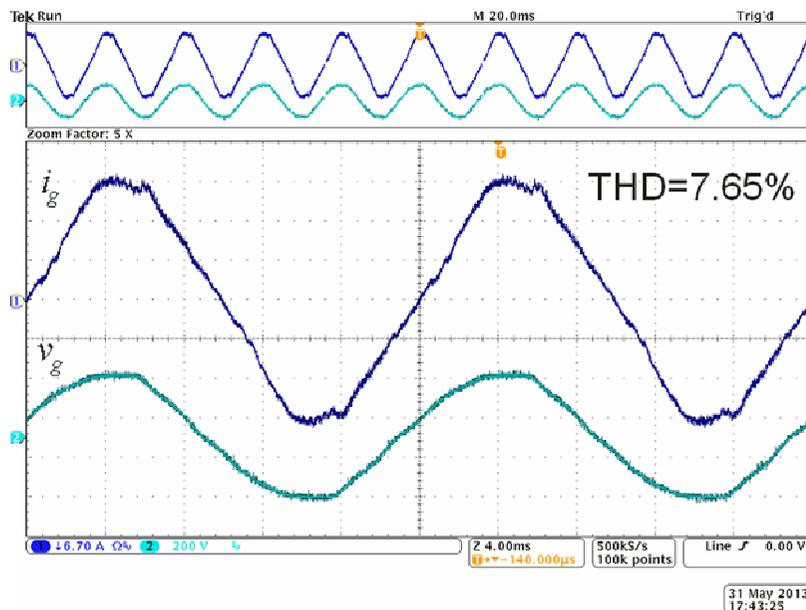
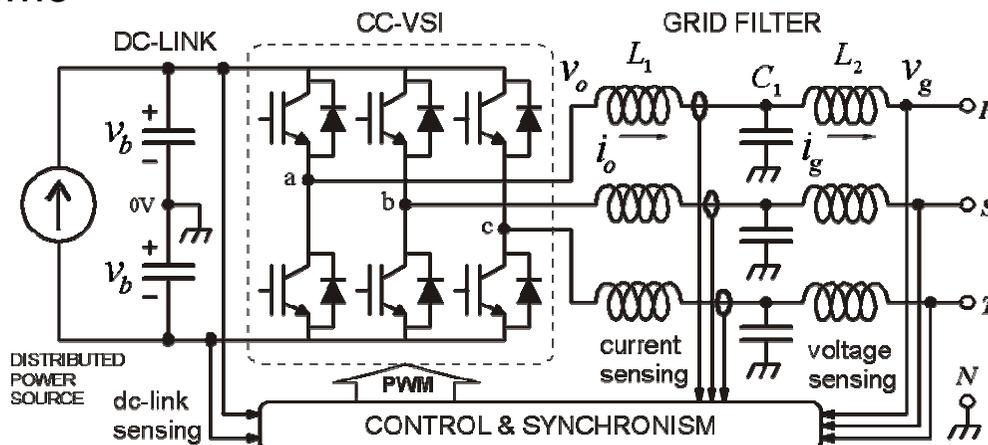
Lazo de enganche de fase (PLL), sistemas digitales y enfoques monofásico / trifásico





El problema del sincronismo

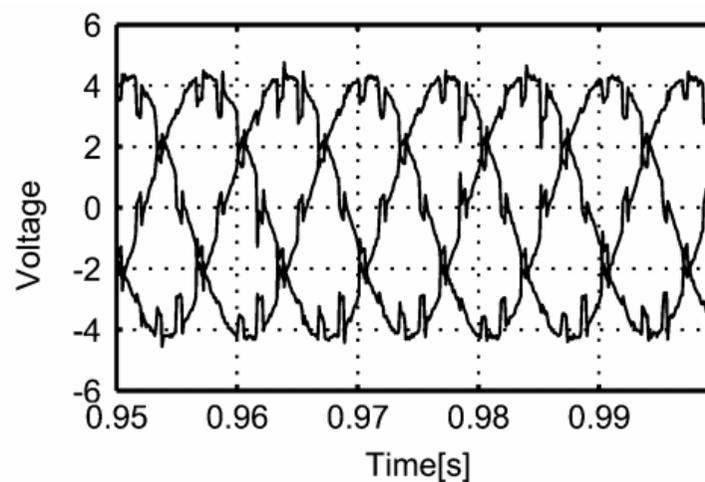
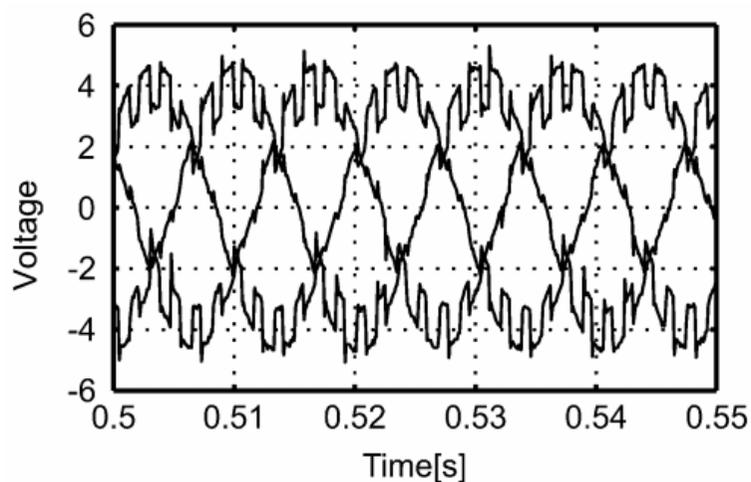
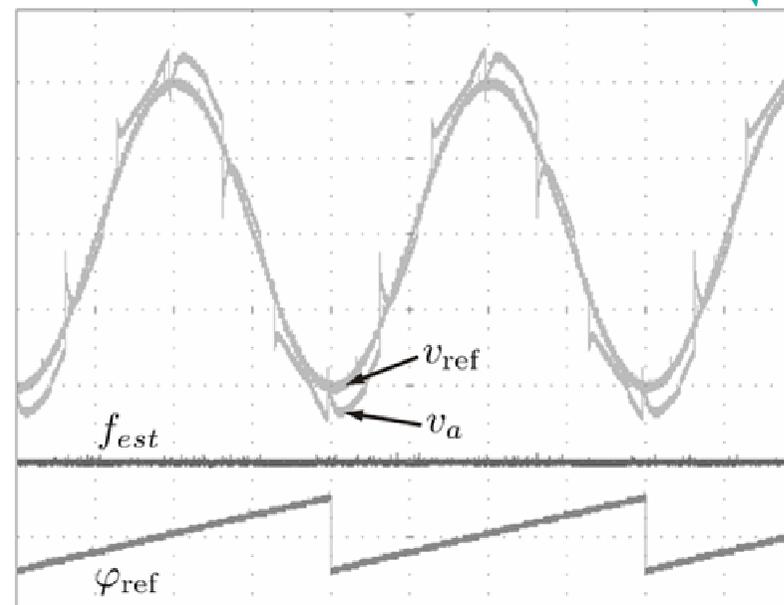
- Inyección de energía a la red
- Control de convertidores AC/DC
- Medición de parámetros de calidad de la energía





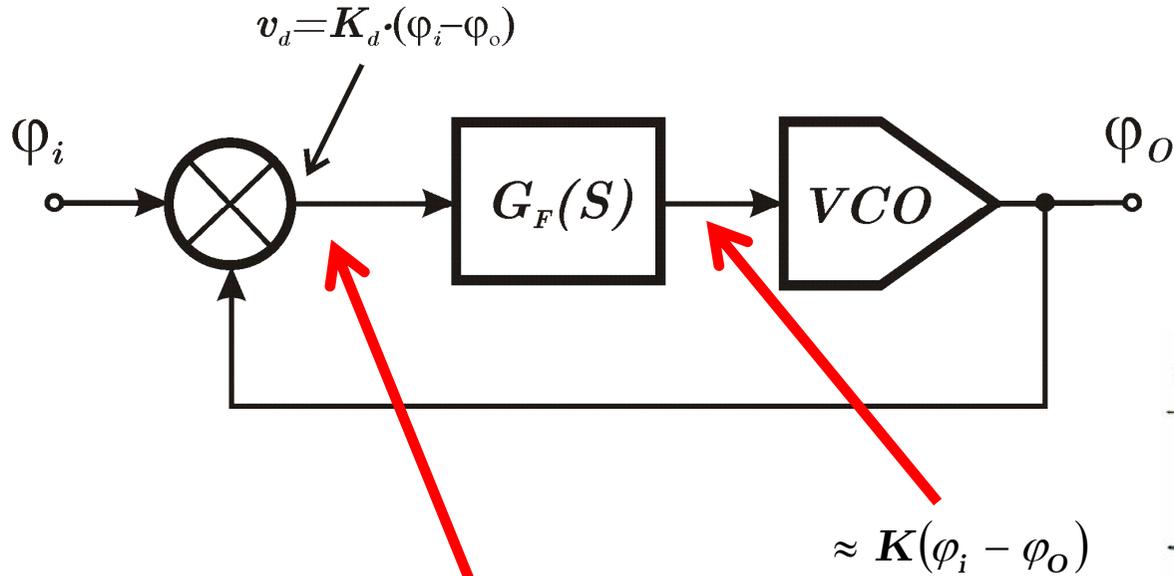
El problema del sincronismo

- Inyección de energía a la red
- Control de convertidores AC/DC
- Medición de parámetros de calidad de la energía





Consideraciones generales sobre el PLL

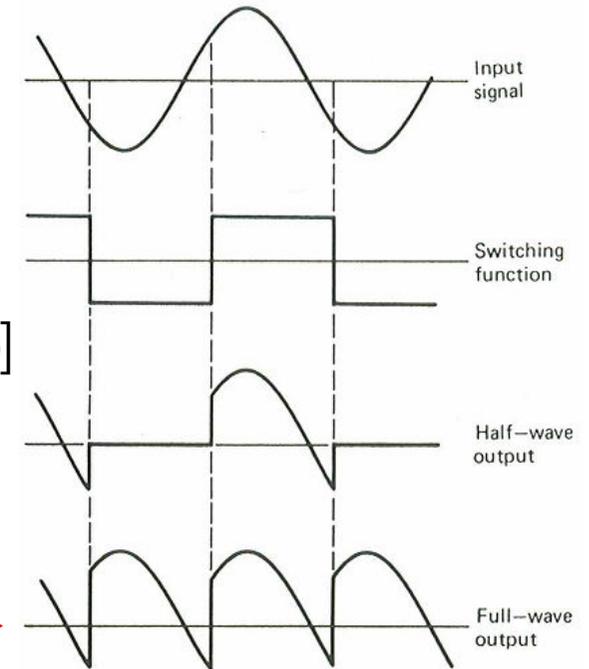


$$\approx K(\phi_i - \phi_o)$$

$$\cos(\omega t + \phi_i) \cdot \text{sen}(\omega t + \phi_o) = \frac{1}{2} [\text{sen}(2\omega t + \phi_i + \phi_o) - \text{sen}(\phi_i - \phi_o)]$$

¿Qué pasa si la forma de onda a la salida del VCO es de tipo cuadrada?

$$\langle v_d \rangle = \frac{2\hat{V}}{\pi} \text{sen}(\phi_i - \phi_o) \rightarrow$$

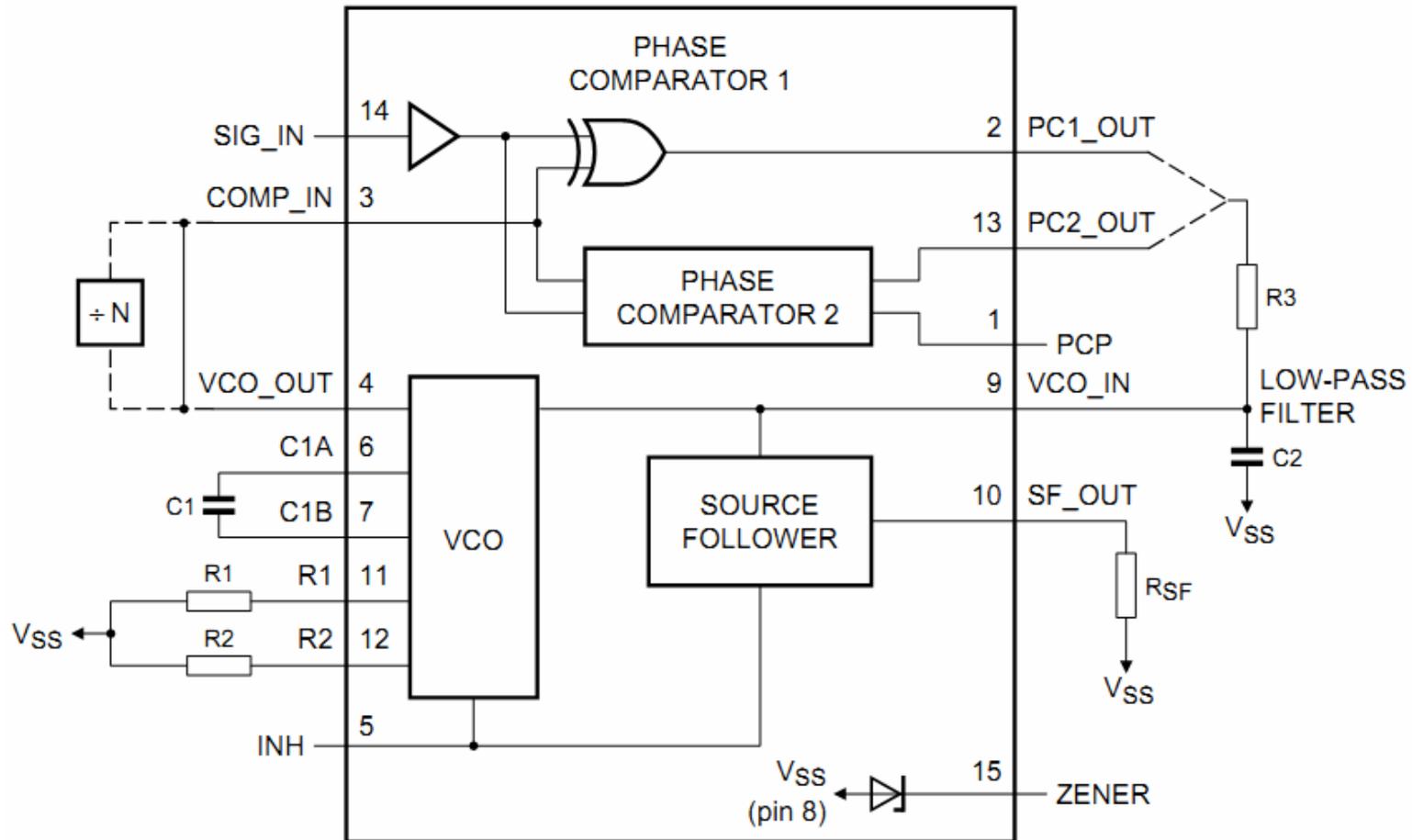


Phaselock Techniques, Floyd M. Gardner



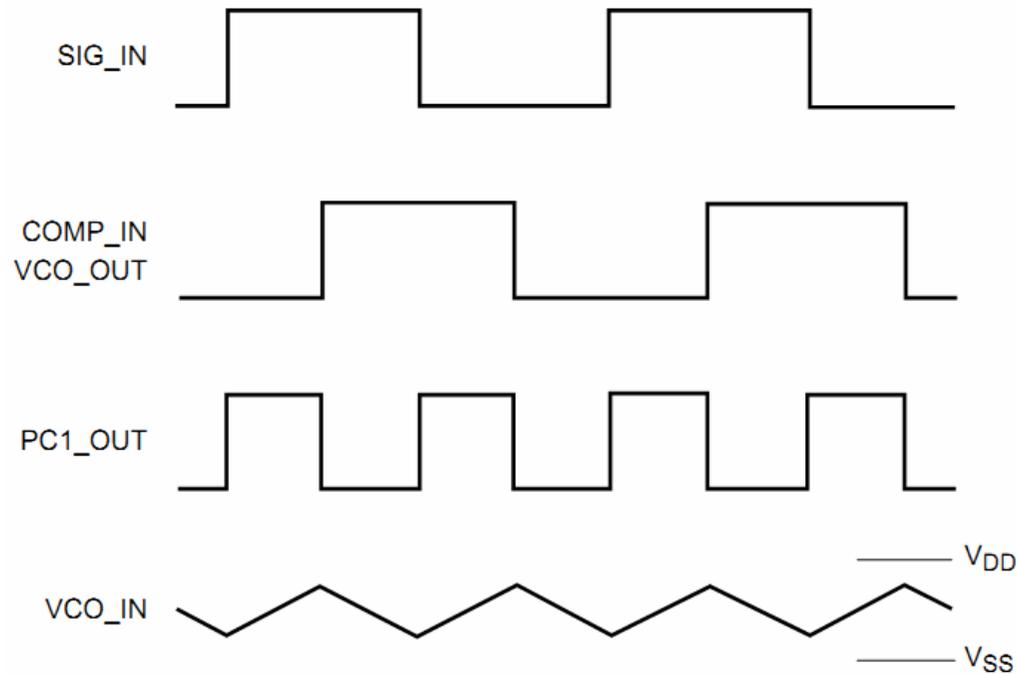


Detectores de fase digitales: el circuito integrado 4046





Comparador de fase tipo I



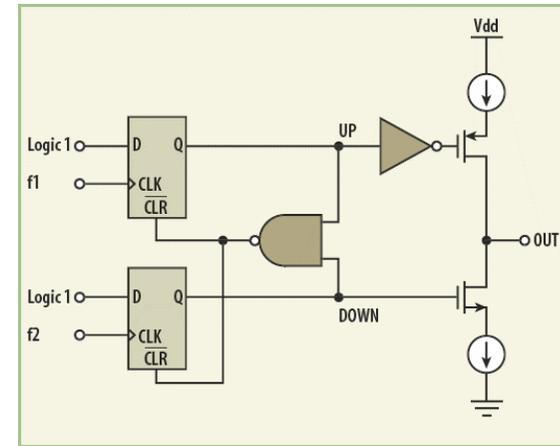
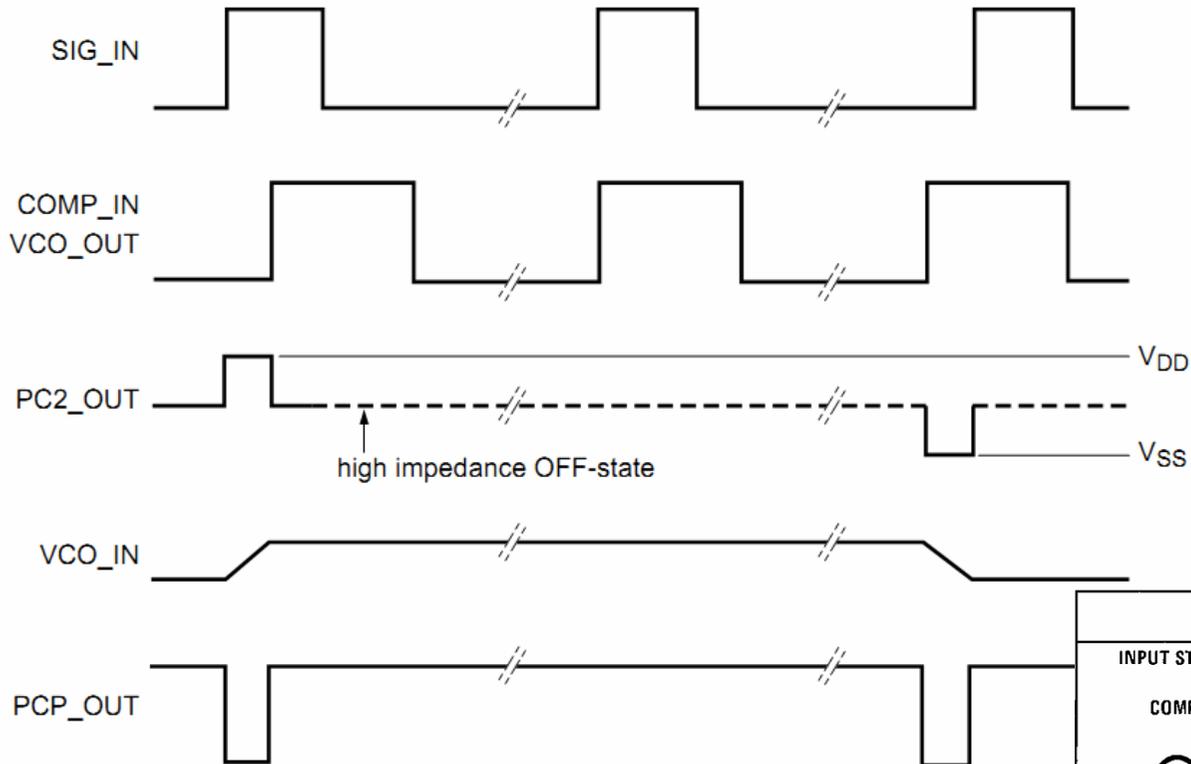
SIG_IN	COMP_IN	PC1_OUT
0	0	0
0	1	1
1	0	1
1	1	0

$$\frac{\langle PC1_{OUT} \rangle}{\Delta\varphi} = \frac{V_{CC}}{\pi}$$

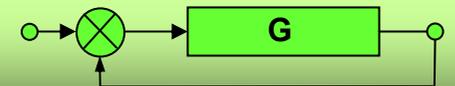




Comparador de fase tipo II



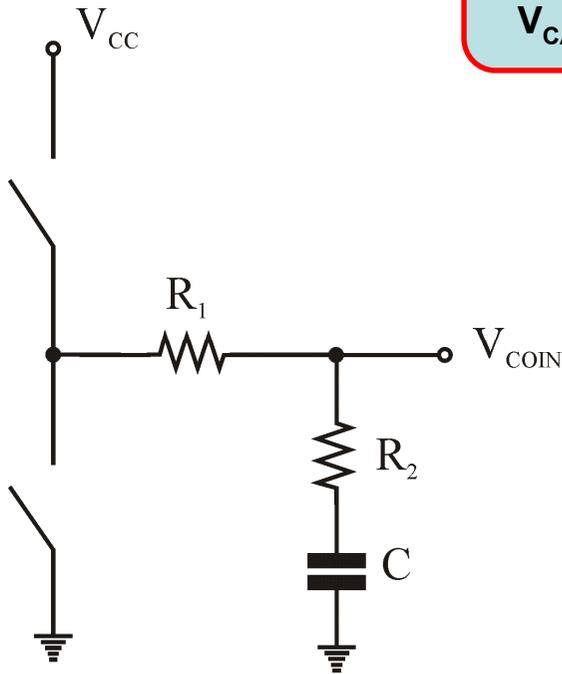
PHASE COMPARATOR II			
INPUT STATE			
COMPARATOR IN			
PHASE COMP II OUT	0	3-STATE	1
PHASE PULSES	0	1	0





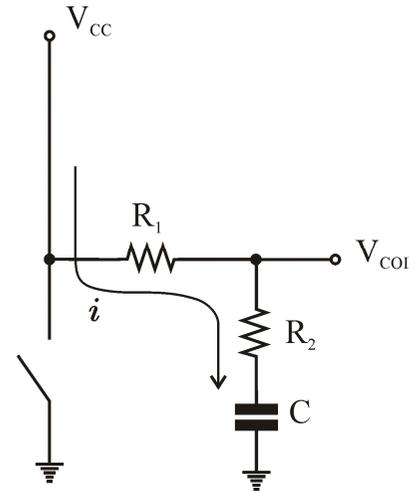
Comparador de fase tipo II

Punto de operación
 $V_{CAP} = V_{CC}/2$



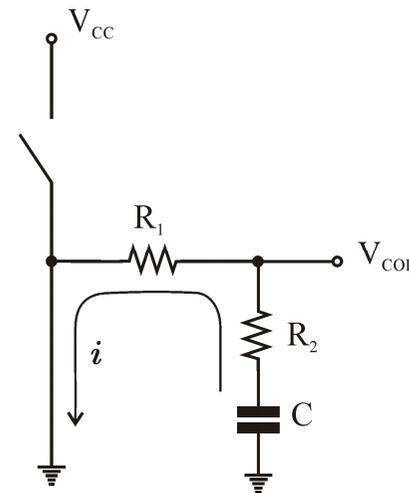
Lazo enganchado
(alta impedancia)

$$\varphi_i = \varphi_o$$



$$i = \frac{V_{CC}}{2(R_1 + R_2)}$$

$$\varphi_i > \varphi_o$$



$$i = \frac{-V_{CC}}{2(R_1 + R_2)}$$

$$\varphi_i < \varphi_o$$



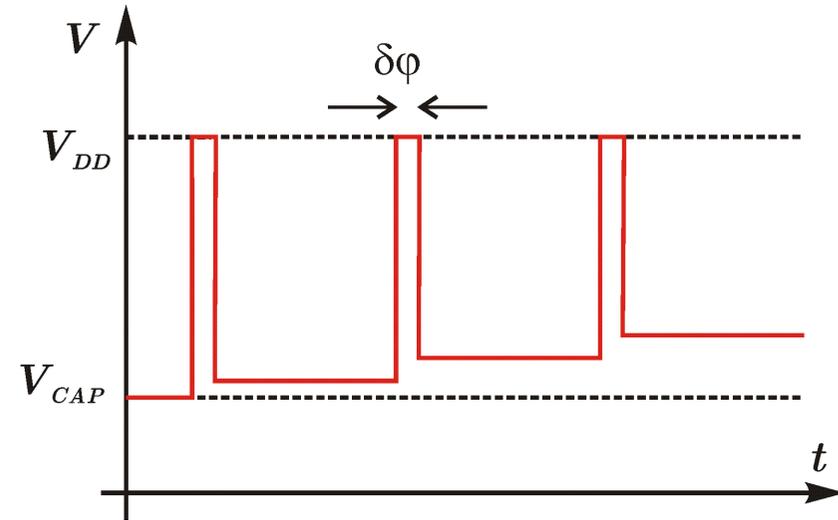
Comparador de fase tipo II

$$i = \frac{V_{CC}}{2(R_1 + R_2)}$$

$$\langle i \rangle = \frac{V_{CC}}{2(R_1 + R_2)} \cdot \frac{\Delta\phi}{2\pi}$$

$$V_{COIN} = \langle i \rangle \cdot Z = \langle i \rangle \cdot \frac{(SCR_2 + 1)}{SC}$$

$$\frac{V_{COIN}}{\Delta\phi} = \frac{V_{CC}}{4\pi} \cdot \frac{(SCR_2 + 1)}{SC(R_1 + R_2)}$$

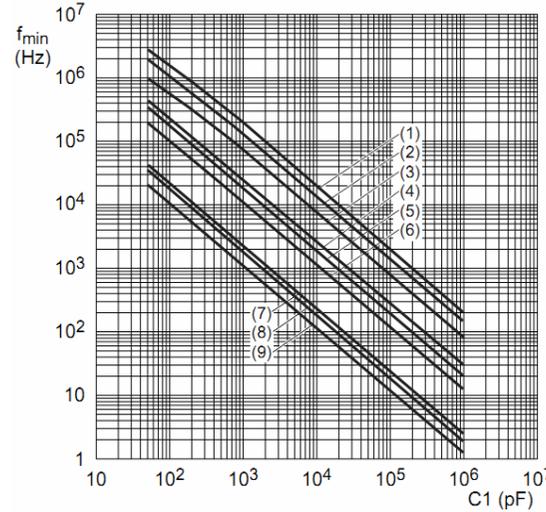
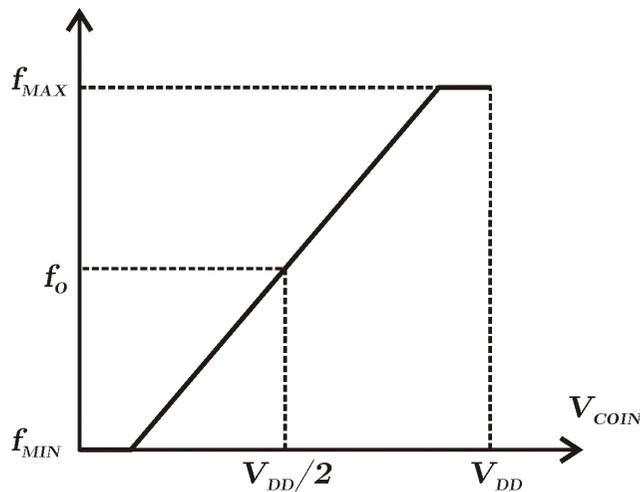
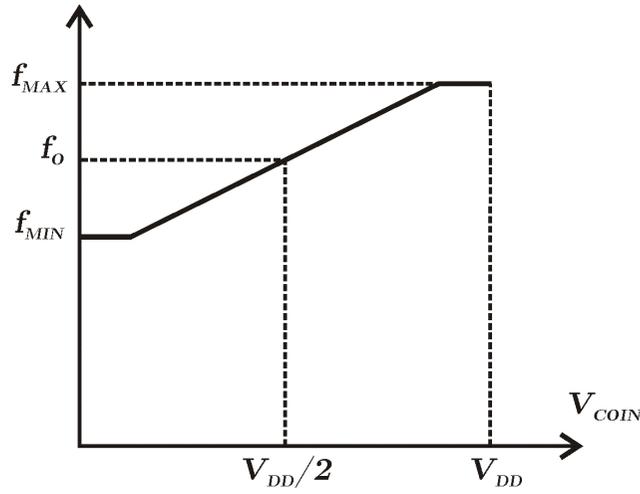


¿Qué pasa si la fuente de alimentación del PLL es $\pm V_{CC}$ o el punto de operación es $\neq V_{CC}/2$?

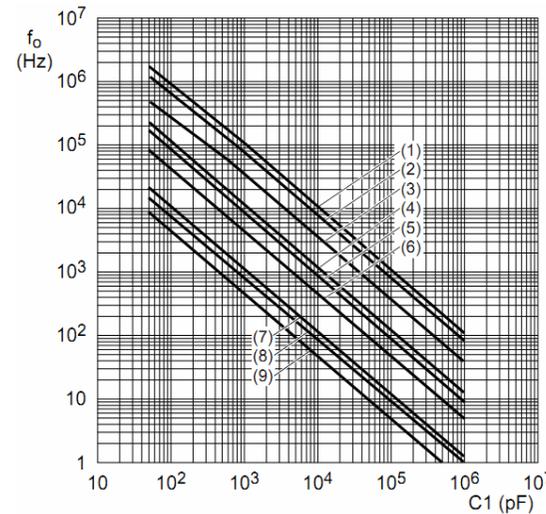




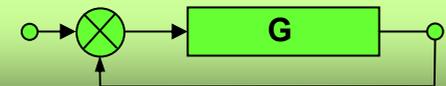
Oscilador controlado por tensión (VCO)



$T_{amb} = 25\text{ }^\circ\text{C}$; V_{CO_IN} at $0.5V_{DD}$;
 INH_IN at V_{SS} ; $R2 = \infty$.
Lines (1), (4), and (7): $V_{DD} = 15\text{ V}$;
Lines (2), (5), and (8): $V_{DD} = 10\text{ V}$;
Lines (3), (6), and (9): $V_{DD} = 5\text{ V}$;
Lines (1), (2), and (3): $R1 = 10\text{ k}\Omega$;
Lines (4), (5), and (6): $R1 = 100\text{ k}\Omega$;
Lines (7), (8), and (9): $R1 = 1\text{ M}\Omega$.



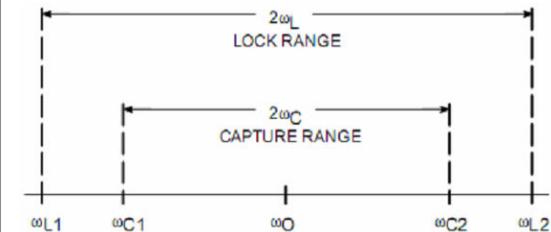
$T_{amb} = 25\text{ }^\circ\text{C}$; V_{CO_IN} at V_{SS} ; INH_IN at V_{SS} ; $R1 = \infty$.
Lines (1), (4), and (7): $V_{DD} = 15\text{ V}$;
Lines (2), (5), and (8): $V_{DD} = 10\text{ V}$;
Lines (3), (6), and (9): $V_{DD} = 5\text{ V}$;
Lines (1), (2), and (3): $R2 = 10\text{ k}\Omega$;
Lines (4), (5), and (6): $R2 = 100\text{ k}\Omega$;
Lines (7), (8), and (9): $R2 = 1\text{ M}\Omega$.





Comparador de fase + VCO

Characteristics	Using Phase Comparator I		Using Phase Comparator II	
	VCO Without Offset $R2 = \infty$	VCO With Offset	VCO Without Offset $R2 = \infty$	VCO With Offset
VCO Frequency				
For No Signal Input	VCO in PLL system will adjust to center frequency, f_0		VCO in PLL system will adjust to lowest operating frequency, f_{min}	
Frequency Lock Range, $2f_L$	$2f_L = \text{full VCO frequency range}$ $2f_L = f_{max} - f_{min}$			
Frequency Capture Range, $2f_C$		$2f_C \approx \frac{1}{\pi} \sqrt{\frac{2\pi f_L}{\tau_1}}$		
Loop Filter Component Selection		For $2f_C$, see Ref.	$f_C = f_L$	
Phase Angle Between Single and Comparator	90° at center frequency (f_0), approximating 0° and 180° at ends of lock range ($2f_L$)		Always 0° in lock	
Locks on Harmonics of Center Frequency	Yes		No	
Signal Input Noise Rejection	High		Low	



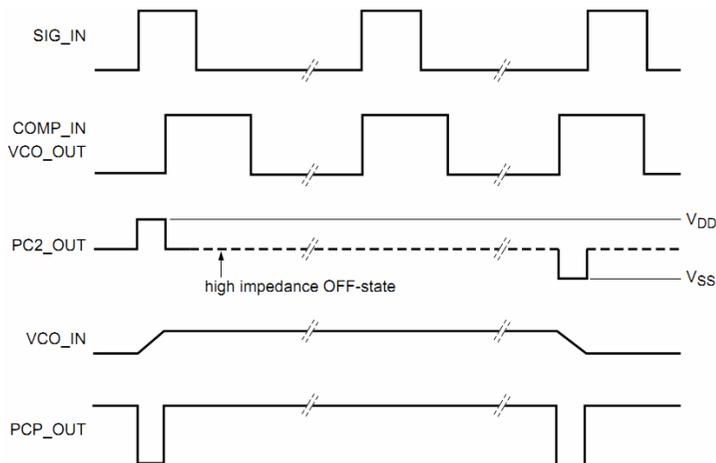
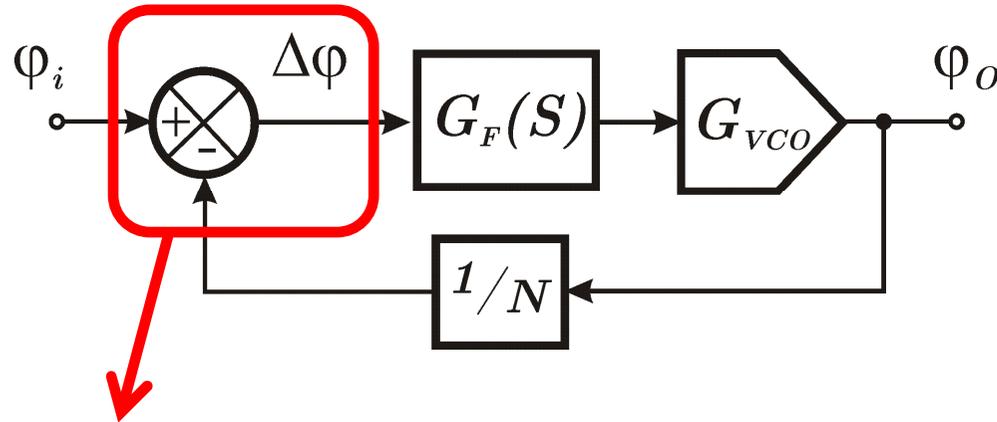
Rango de captura (capture range)
Rango de frecuencias dentro de las cuales el PLL se engancha estando inicialmente desenganchado.

Rango de enganche (lock range)
Rango de frecuencias que el PLL puede seguir una vez enganchado



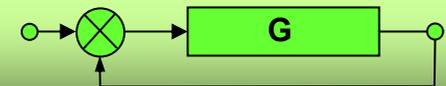


Modelo del PLL basado en el comparador de fase tipo II



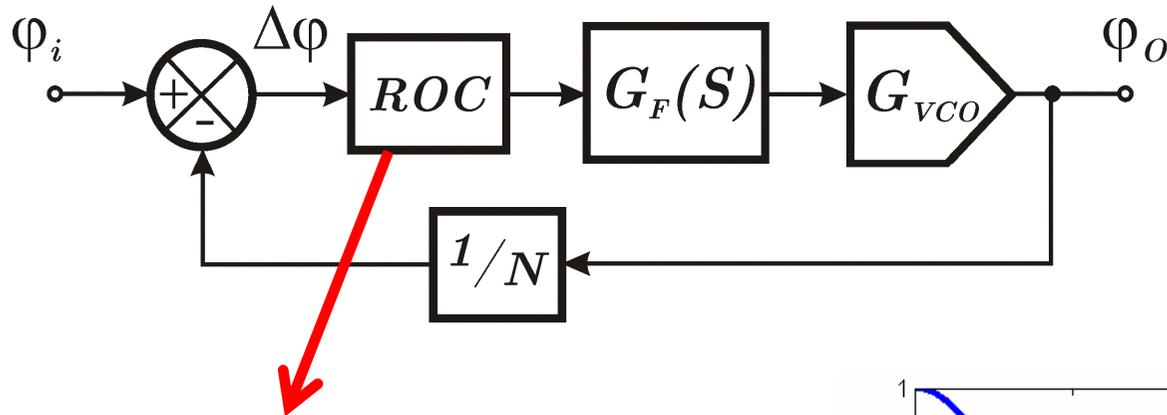
$$G_F(S) = \frac{V_{COIN}}{\Delta\phi} = \frac{V_{CC}}{4\pi} \cdot \frac{(SCR_2 + 1)}{SC(R_1 + R_2)}$$

$$G_{VCO}(S) = \frac{\phi_o}{V_{COIN}} = \frac{2\pi \cdot f_{MX}}{V_{CC}} \cdot \frac{1}{S}$$





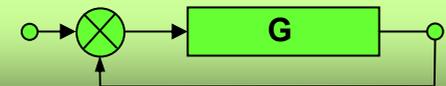
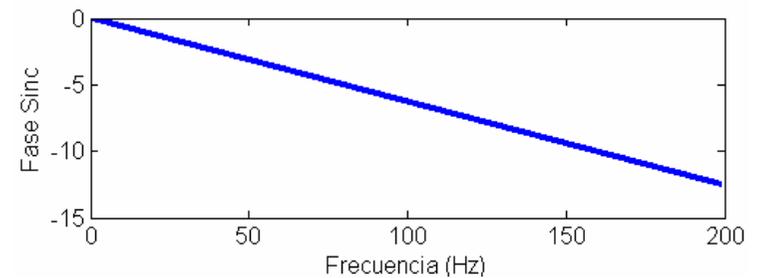
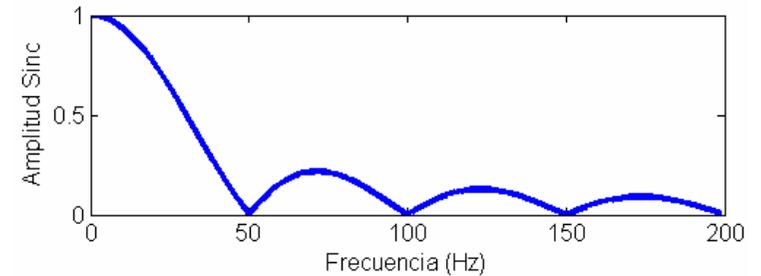
Modelo del PLL basado en el comparador de fase tipo II



$$ROC = \frac{1 - e^{-ST}}{ST}$$

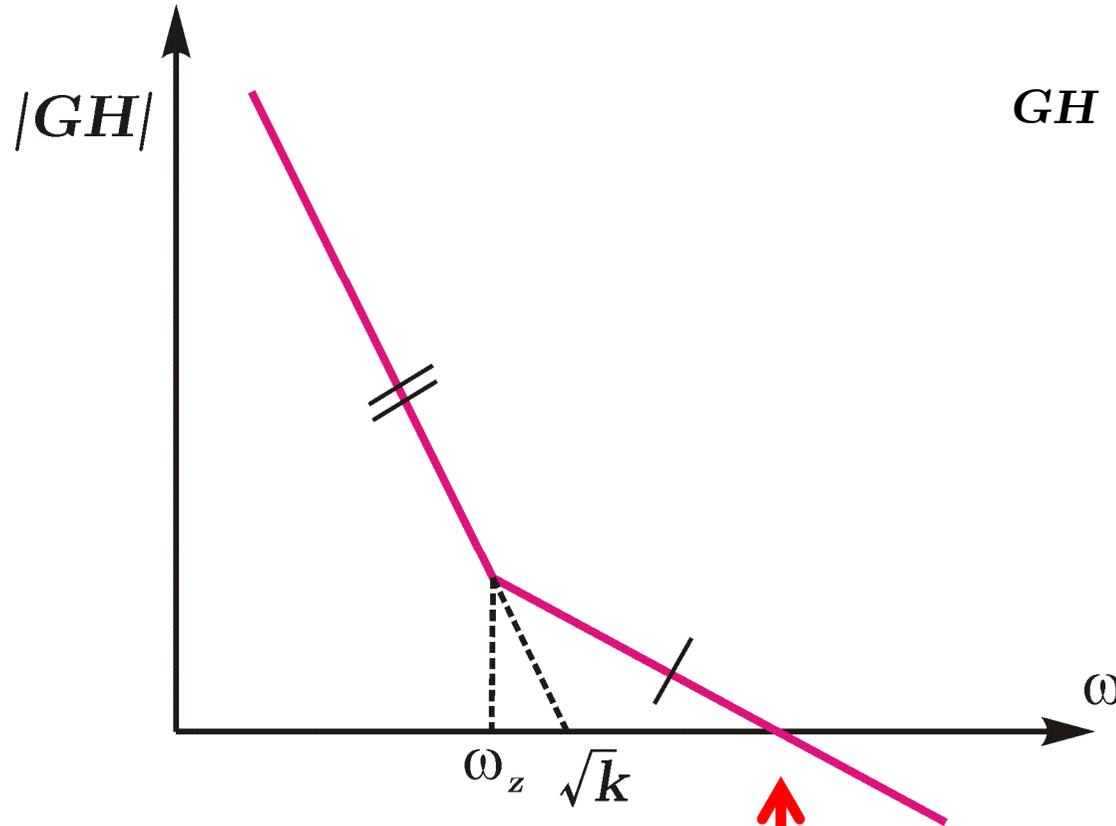
$$ROC(j\omega) = \frac{1 - e^{-j\omega T}}{j\omega T} = \frac{e^{-j\omega T/2}}{2} \cdot \frac{e^{j\omega T/2} - e^{-j\omega T/2}}{j\omega T/2}$$

$$ROC(j\omega) = e^{-j\omega T/2} \cdot \frac{\text{sen}\left(\frac{\omega T}{2}\right)}{\frac{\omega T}{2}} = e^{-j\omega T/2} \cdot \text{sinc}\left[\frac{\omega T}{2}\right]$$





Modelo del PLL basado en el comparador de fase tipo II



$$GH = \frac{f_o}{CN(R_1 + R_2)} \cdot \frac{(SCR_2 + 1)}{S^2}$$

$$GH = \frac{k \cdot \left(\frac{S}{\omega_z} + 1 \right)}{S^2}$$

¿Cómo se puede considerar el efecto del ROC?

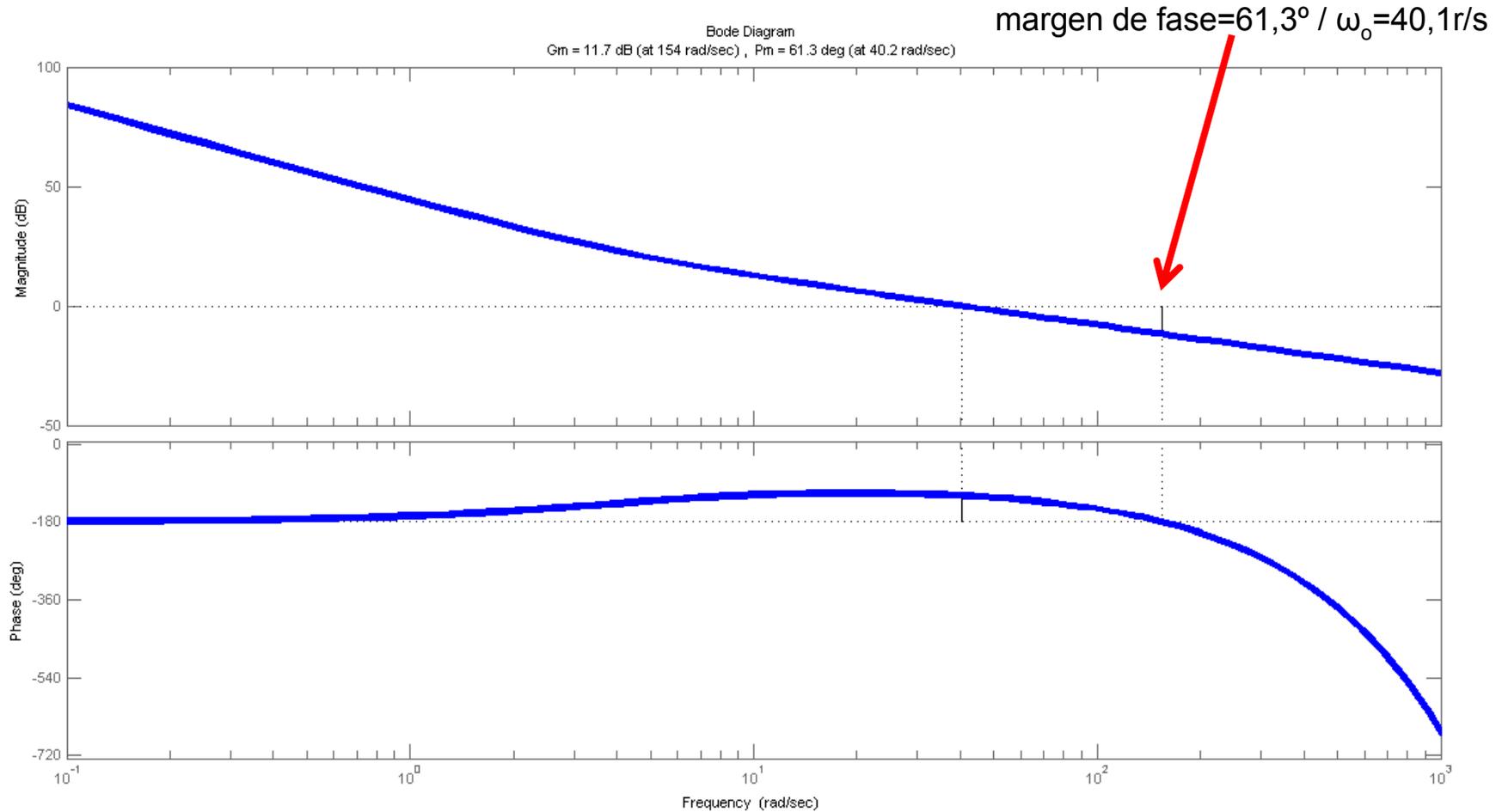
¿Margen de fase?





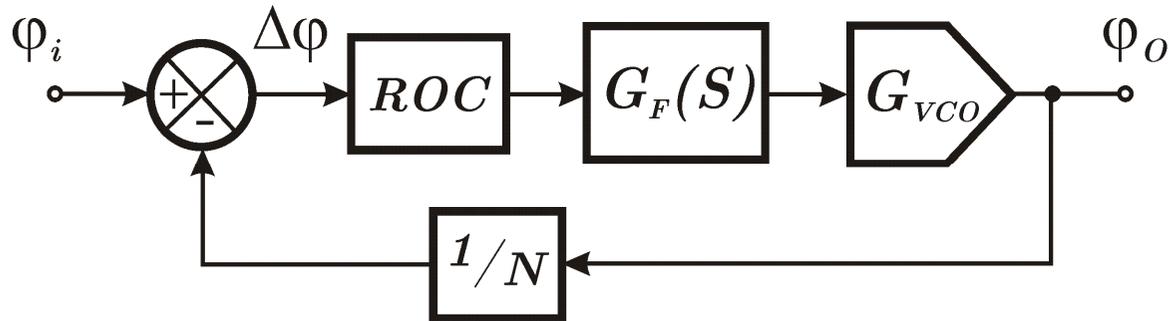
Modelo del PLL basado en el comparador de fase tipo II

$C=1\mu\text{F}$ / $R1=62,5\text{k}\Omega$ / $R2=250\text{k}\Omega$ / margen de fase aprox. $=67^\circ$ / $\omega_o=40\text{r/s}$





Problema sugerido



La frecuencia de la señal de entrada puede variar en un rango determinado:

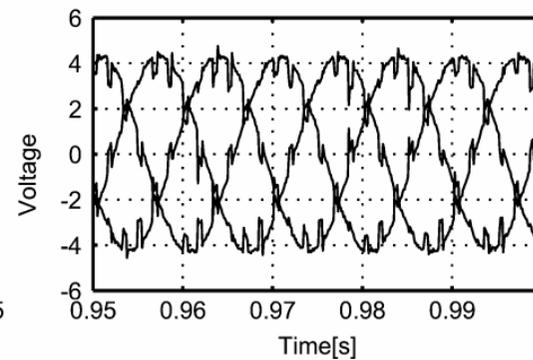
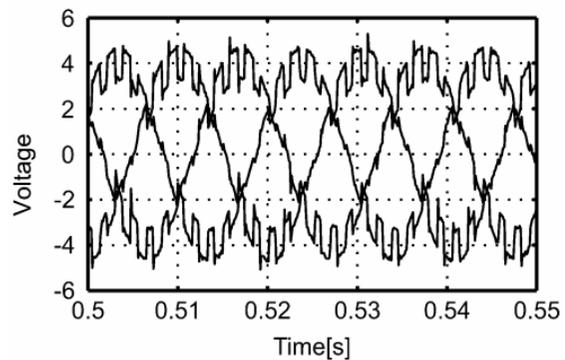
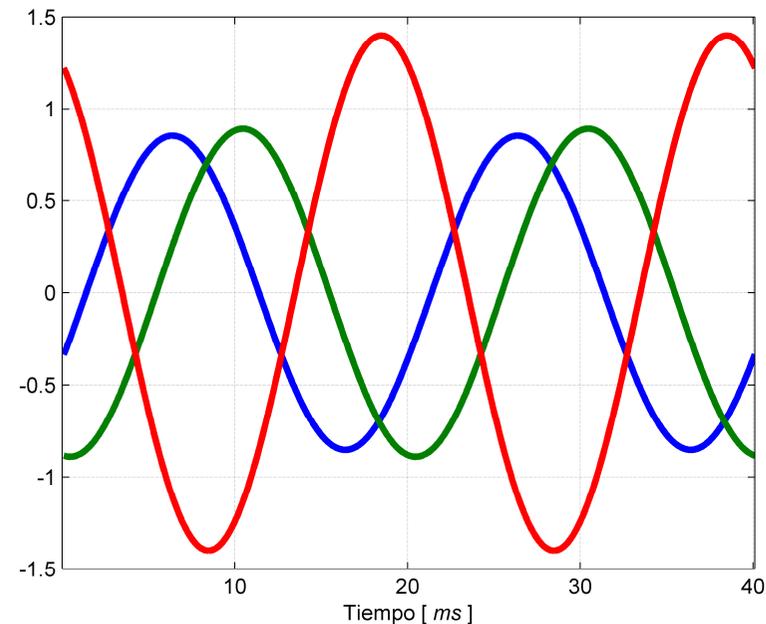
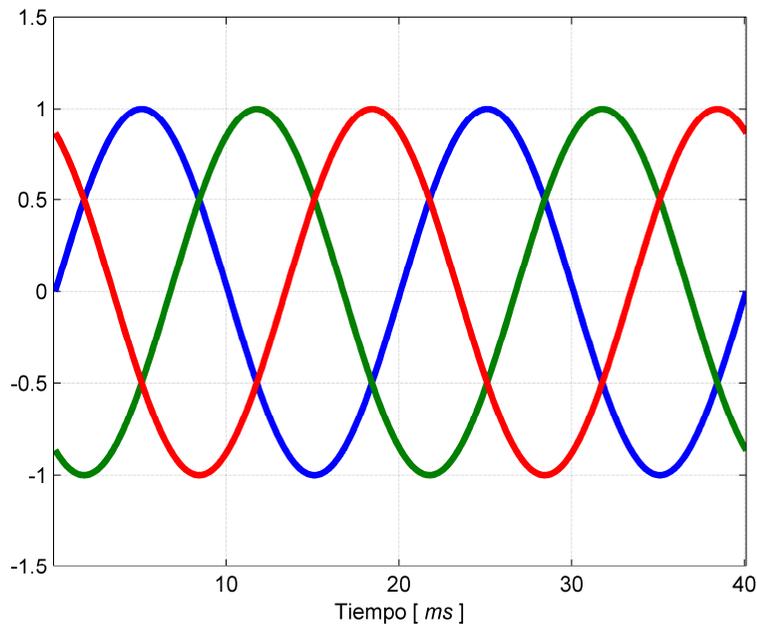
$$f_{min} < f_i < f_{max}$$

Ajustar los valores de $G_F(s)$ y G_{VCO} para obtener el máximo ancho de banda del lazo, garantizando la estabilidad para todos los puntos de operación





El problema del sincronismo en sistemas trifásicos



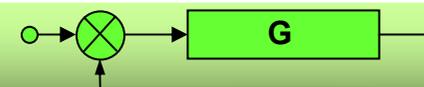
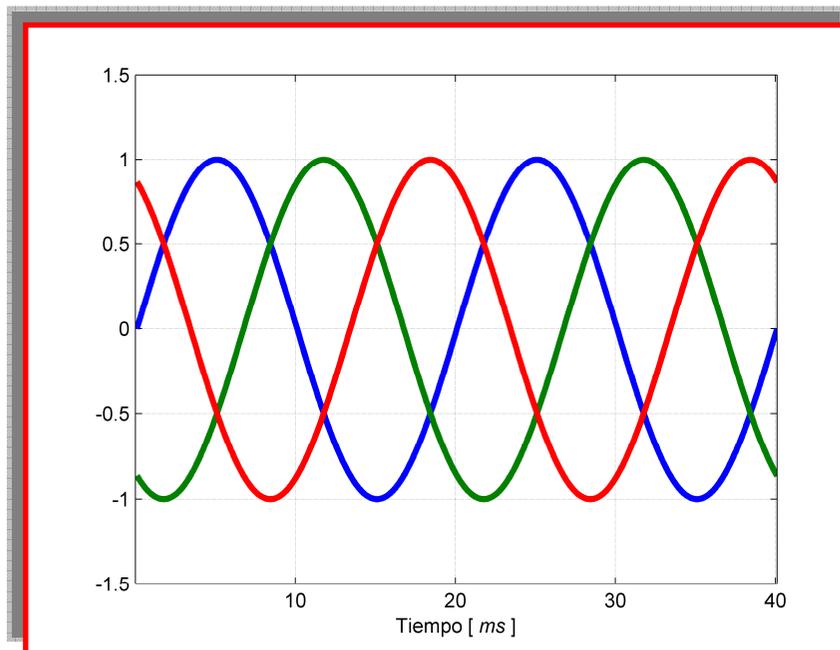
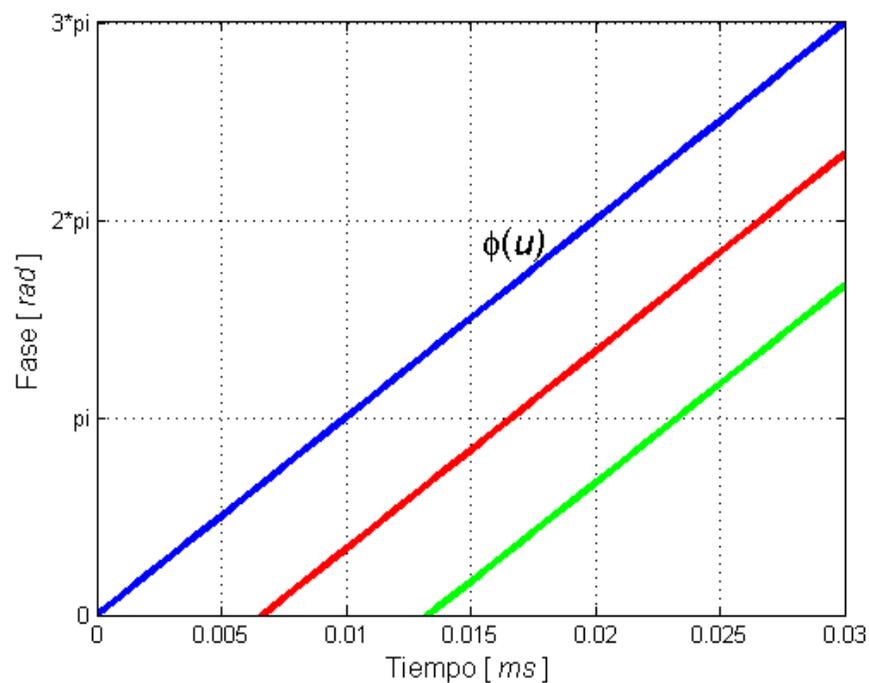
Simulaciones
en Matlab



Representación de sistemas trifásicos balanceados

Sistema trifásico balanceado

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = V_{+1} \begin{bmatrix} \cos(\varphi_u(t)) \\ \cos(\varphi_u(t) - 2\pi/3) \\ \cos(\varphi_u(t) - 4\pi/3) \end{bmatrix}$$





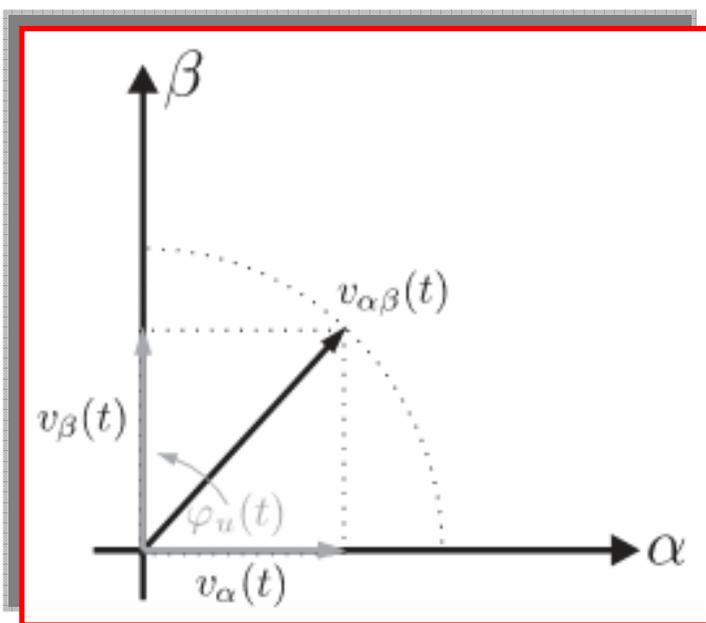
Representación del sistema trifásico en otros marcos de referencia

Estacionario

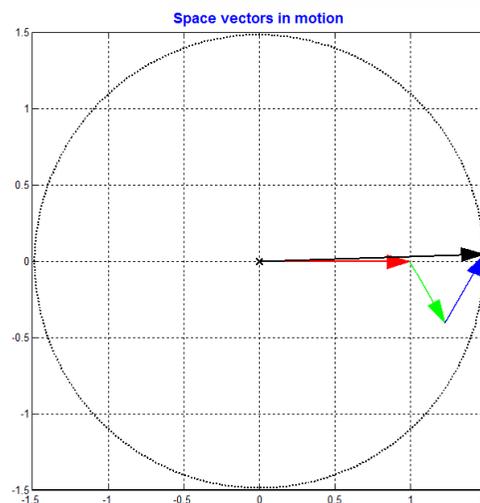
$$v_{\alpha\beta}(t) = \frac{2}{3} \left[v_a(t) + v_b(t)e^{j2\pi/3} + v_c(t)e^{j4\pi/3} \right]$$

$$v_{\alpha\beta}(t) = V_1 e^{j\varphi_u(t)} = v_\alpha(t) + jv_\beta(t)$$

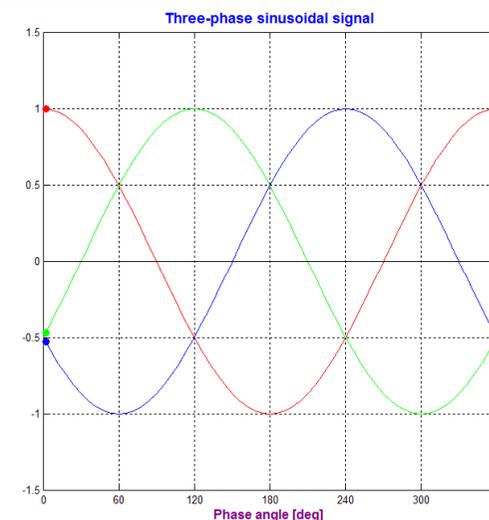
$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = V_1 \begin{bmatrix} \cos(\varphi_u(t)) \\ \sin(\varphi_u(t)) \end{bmatrix}$$



Vector espacial

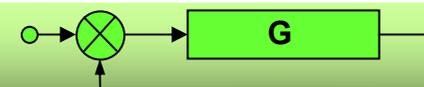


Phase A Phase B Phase C
Resultant rotating space vector



<http://www.ece.umn.edu/users/riaz/animations/spacevecmovie.html>

www3.fi.mdp.edu.ar/control403
www3.fi.mdp.edu.ar/electronica/catedraswrapper/4c8-sistemas-de-control

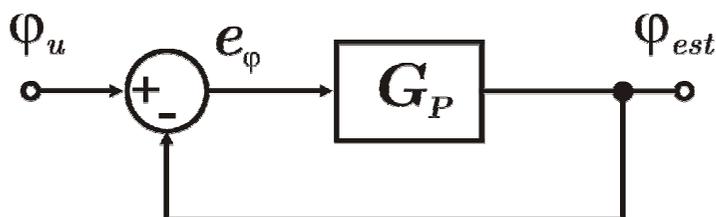


SISTEMAS DE CONTROL



Representación del sistema trifásico en otros marcos de referencia

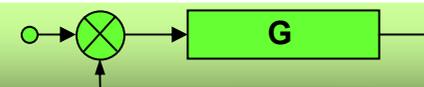
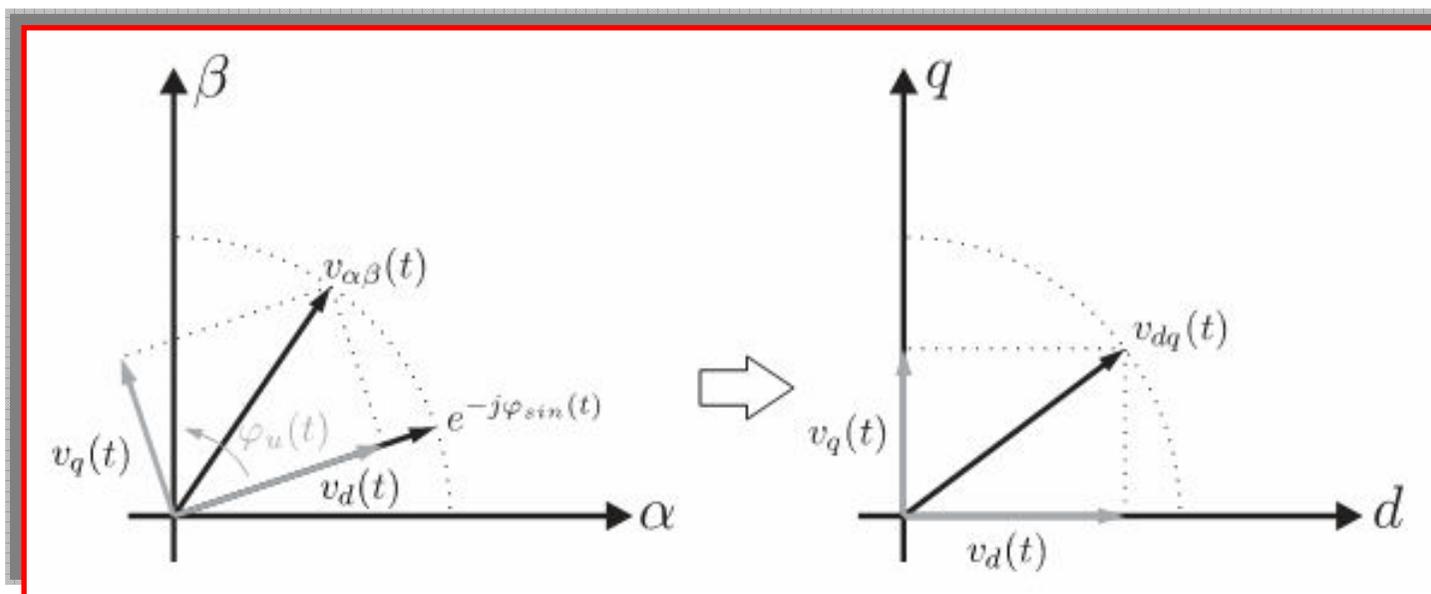
Sincrónico



$$v_{dq}(t) = v_{\alpha\beta}(t)e^{-j\varphi_{sin}(t)}$$

$$v_{dq}(t) = V_1 e^{j(\varphi_u(t) - \varphi_{sin}(t))}$$

$$\begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = V_1 \begin{bmatrix} \cos(\varphi_u(t) - \varphi_{sin}(t)) \\ \sin(\varphi_u(t) - \varphi_{sin}(t)) \end{bmatrix}$$





Implementación de los marcos de referencia en el dominio temporal

Estacionario

$$v_{\alpha\beta}(t) = \frac{2}{3} [v_a(t) + v_b(t)e^{j2\pi/3} + v_c(t)e^{j4\pi/3}]$$

$$\vec{v}_{\alpha\beta}(t) = T_{\alpha\beta} \vec{v}_{abc}(t) \Leftrightarrow \begin{bmatrix} v_{\alpha}(t) \\ v_{\beta}(t) \end{bmatrix} = T_{\alpha\beta} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix}$$

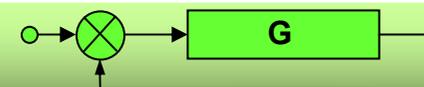
$$T_{\alpha\beta} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

Sincrónico

$$v_{dq}(t) = v_{\alpha\beta}(t)e^{-j\varphi_{sin}(t)}$$

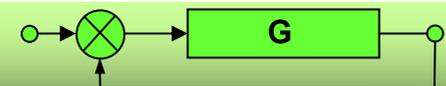
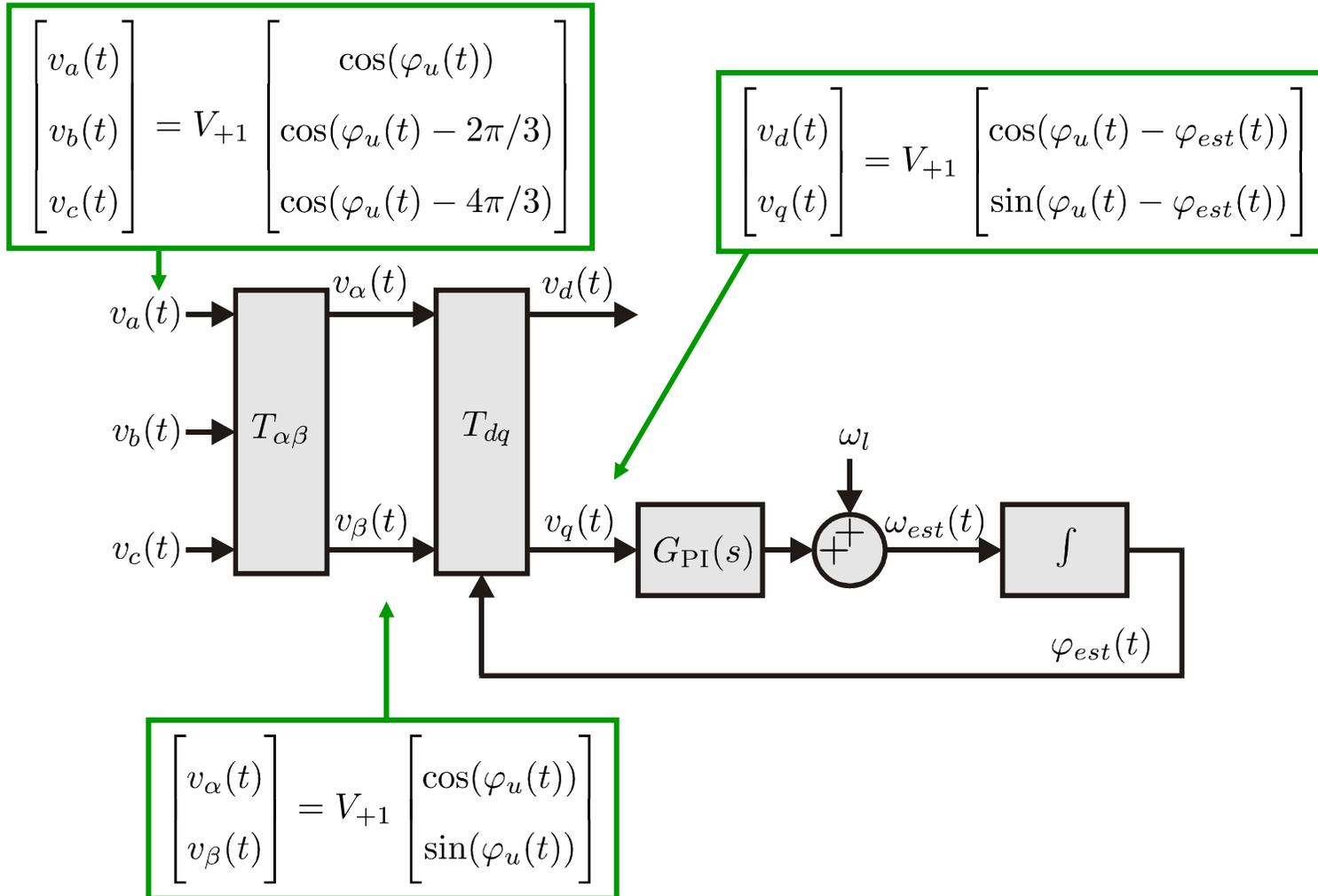
$$\vec{v}_{dq}(t) = T_{dq} \vec{v}_{\alpha\beta}(t) \Leftrightarrow \begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = T_{dq} \begin{bmatrix} v_{\alpha}(t) \\ v_{\beta}(t) \end{bmatrix}$$

$$T_{dq} = \begin{bmatrix} \cos(\varphi_{sin}(t)) & \sin(\varphi_{sin}(t)) \\ -\sin(\varphi_{sin}(t)) & \cos(\varphi_{sin}(t)) \end{bmatrix}$$



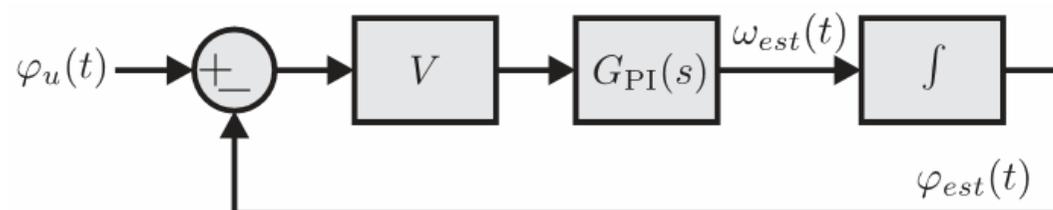


Synchronous Reference Frame (SRF-PLL) – Kaura, 1996





Modelo matemático del SRF-PLL



$$v_q(t) \approx V_1(\varphi_u(t) - \varphi_{est}(t))$$

$$G_{PI}(s) = K \left(\frac{1 + s\tau}{s\tau} \right)$$



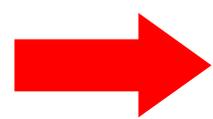
$$GH = KV \cdot \frac{(1 + s\tau)}{s^2\tau}$$

Transferencia de lazo cerrado y ecuaciones de diseño en función del amortiguamiento y el ancho de banda

$$TLC(s) = \frac{s\tau KV + KV}{s^2\tau + s\tau KV + KV}$$

$$K = \frac{2\zeta\omega_n}{V}$$

$$\tau = \frac{2\zeta}{\omega_n}$$



Ver Matlab

$$TLC(s) = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$\omega_n = \sqrt{\frac{KV}{\tau}}$$

$$\zeta = \frac{\sqrt{KV\tau}}{2}$$

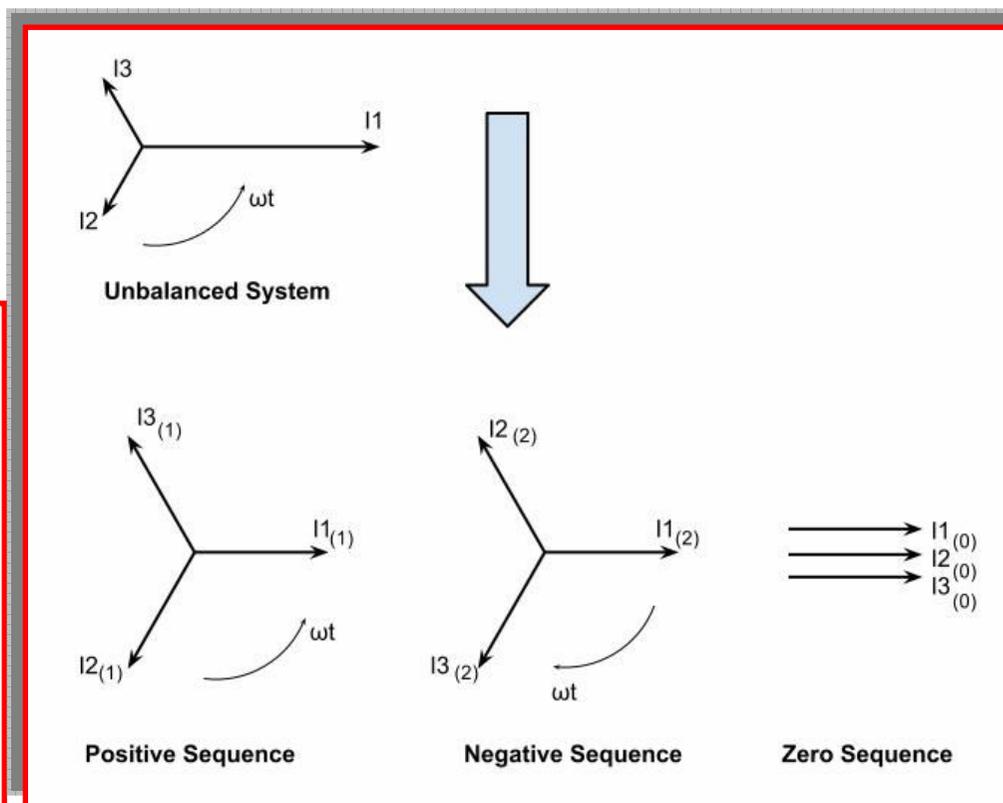
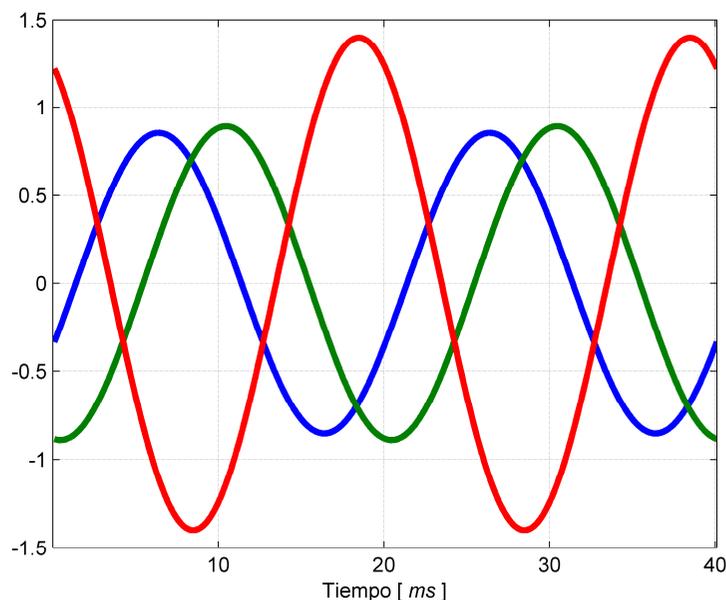




Representación de sistemas trifásicos desbalanceados

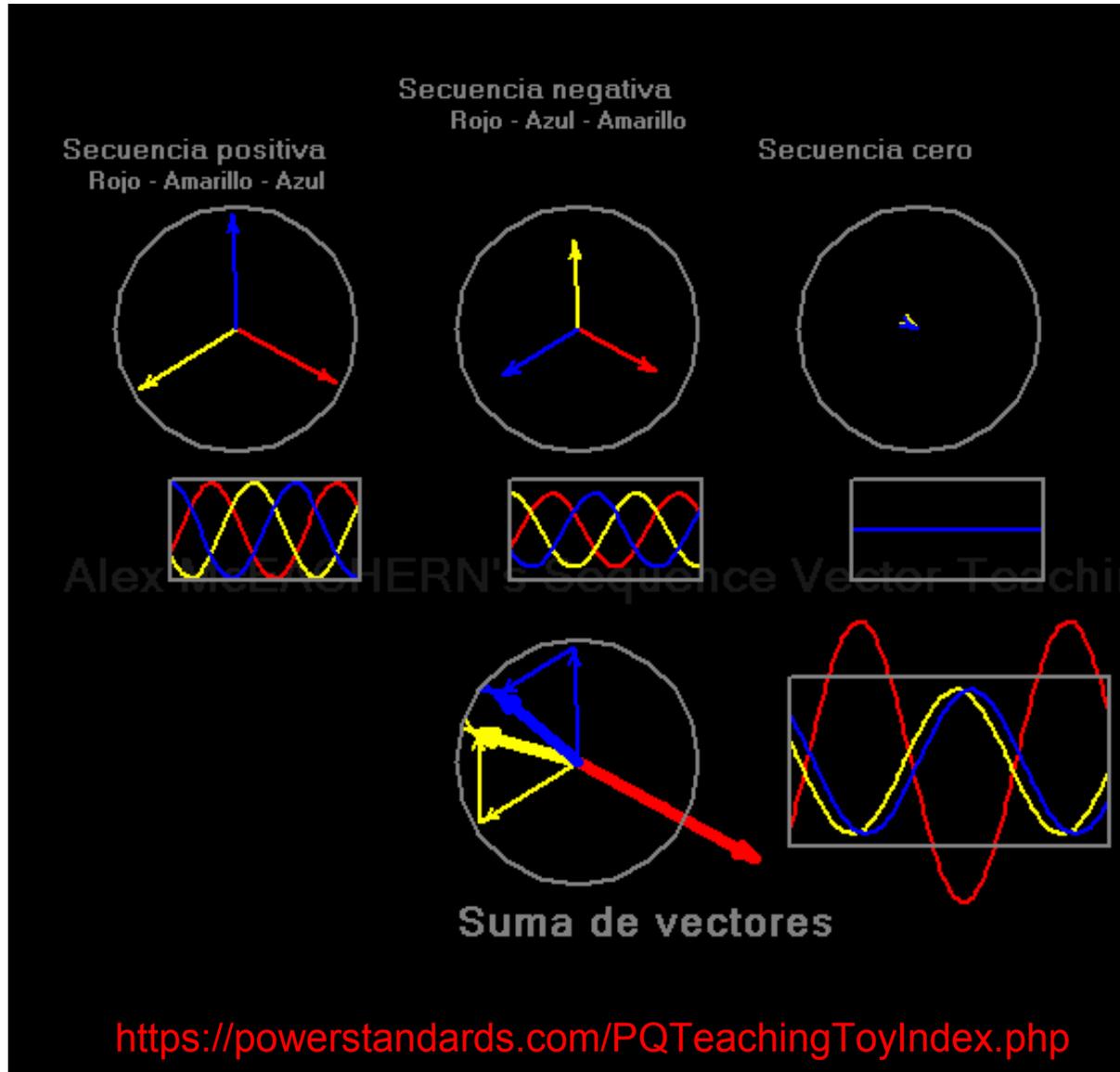
Componentes simétricas (Marco de referencia natural)

Un sistema polifásico desbalanceado, con n fases, se puede representar como la suma de n sistemas equilibrados (Teorema de Fortescue)



40% secuencia negativa
20% secuencia cero

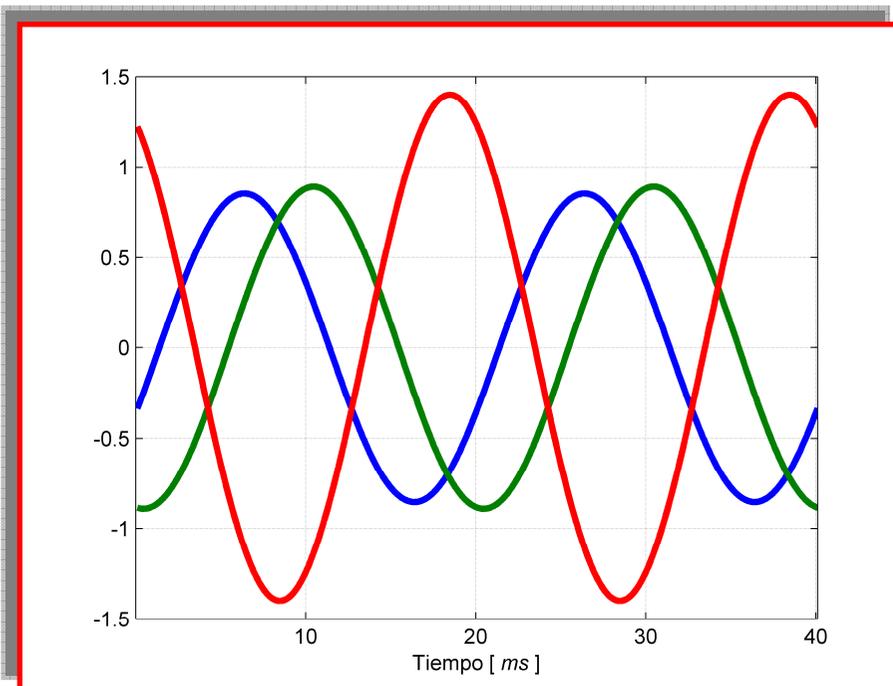




Software PSL



Representación de sistemas trifásicos desbalanceados



$$T_+ = \frac{1}{3} \begin{bmatrix} 1 & g & g^2 \\ g^2 & 1 & g \\ g & g^2 & 1 \end{bmatrix}$$

$$T_- = \frac{1}{3} \begin{bmatrix} 1 & g^2 & g \\ g & 1 & g^2 \\ g^2 & g & 1 \end{bmatrix}$$

$$g = e^{j2\pi/3}$$

Operador de Fortescue

(120°)

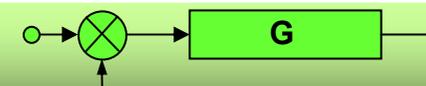
$$T_h = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

40% secuencia negativa

20% secuencia cero

Sistema trifásico desbalanceado

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = V_+ \begin{bmatrix} \cos(\varphi_u(t)) \\ \cos(\varphi_u(t) - 2\pi/3) \\ \cos(\varphi_u(t) - 4\pi/3) \end{bmatrix} + V_- \begin{bmatrix} \cos(-\varphi_u(t) + \varphi_-) \\ \cos(-\varphi_u(t) - 2\pi/3 + \varphi_-) \\ \cos(-\varphi_u(t) - 4\pi/3 + \varphi_-) \end{bmatrix} + V_h \begin{bmatrix} \cos(\varphi_u(t) + \varphi_h) \\ \cos(\varphi_u(t) + \varphi_h) \\ \cos(\varphi_u(t) + \varphi_h) \end{bmatrix}$$





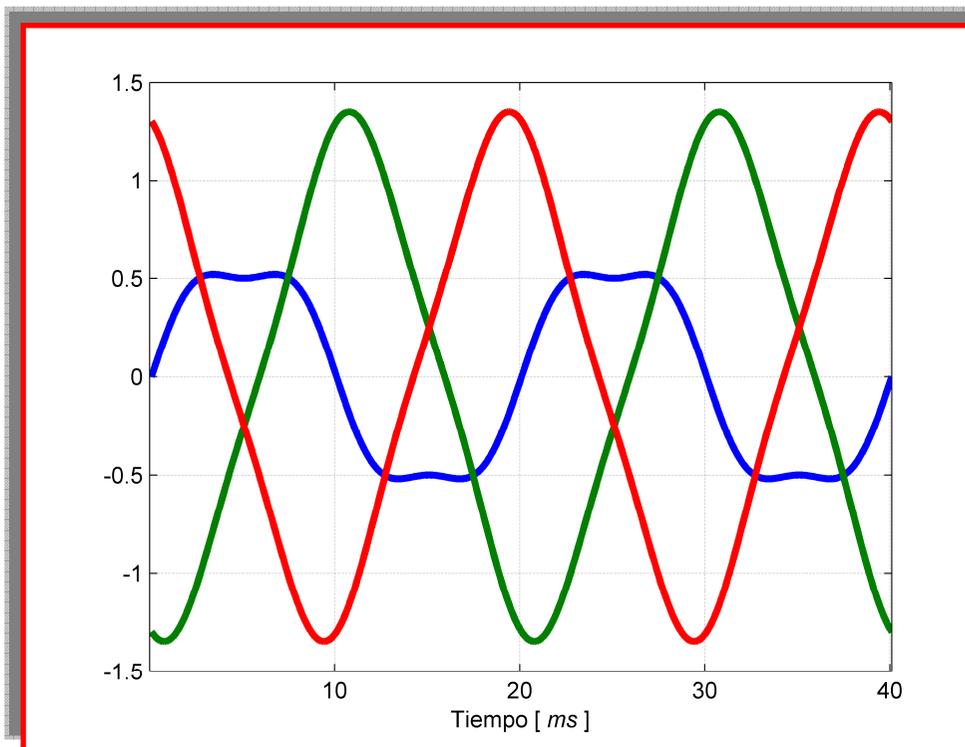
Representación de sistemas trifásicos desbalanceados y con distorsión armónica

Sistema trifásico desbalanceado con componentes armónicas

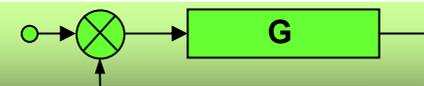
40% secuencia negativa

10% de 3° armónico de secuencia positiva

Simulación en
Matlab

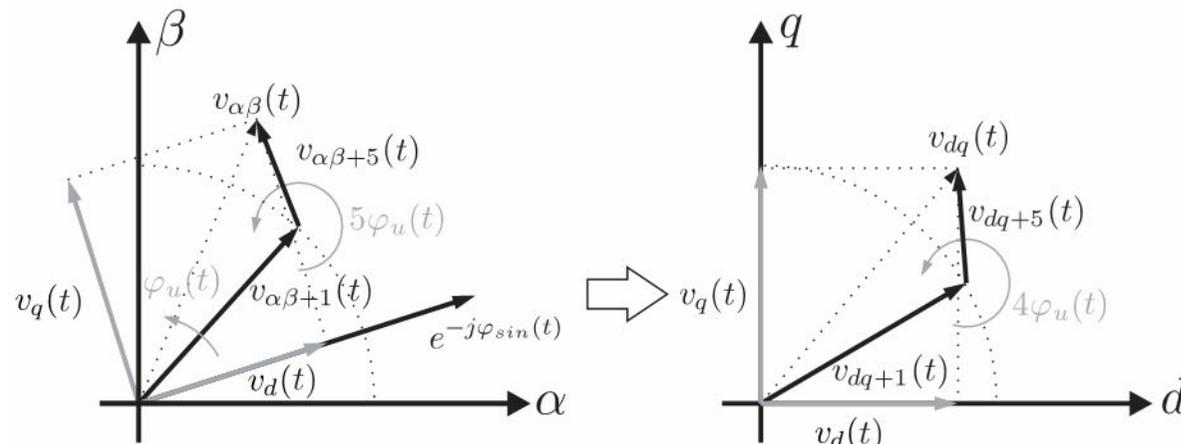


$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = V_{+1} \begin{bmatrix} \cos(\varphi_u(t)) \\ \cos(\varphi_u(t) - 2\pi/3) \\ \cos(\varphi_u(t) - 4\pi/3) \end{bmatrix} + \sum_{\substack{n=-\infty \\ n \neq 0,1}}^{\infty} V_n \begin{bmatrix} \cos(n\varphi_u(t) + \varphi_n) \\ \cos(n\varphi_u(t) - 2\pi/3 + \varphi_n) \\ \cos(n\varphi_u(t) - 4\pi/3 + \varphi_n) \end{bmatrix} + \sum_{h=1}^{\infty} V_h \begin{bmatrix} \cos(h\varphi_u(t) + \varphi_h) \\ \cos(h\varphi_u(t) + \varphi_h) \\ \cos(h\varphi_u(t) + \varphi_h) \end{bmatrix}$$

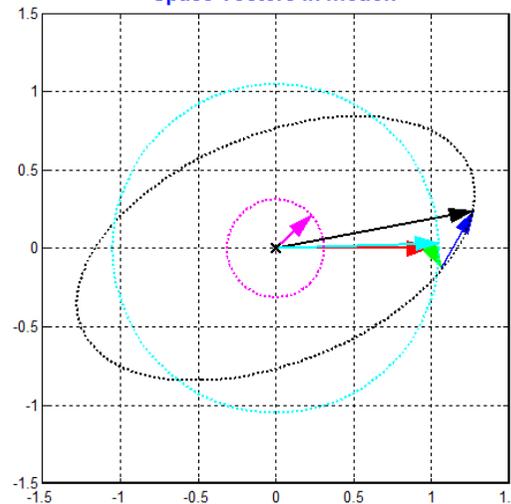




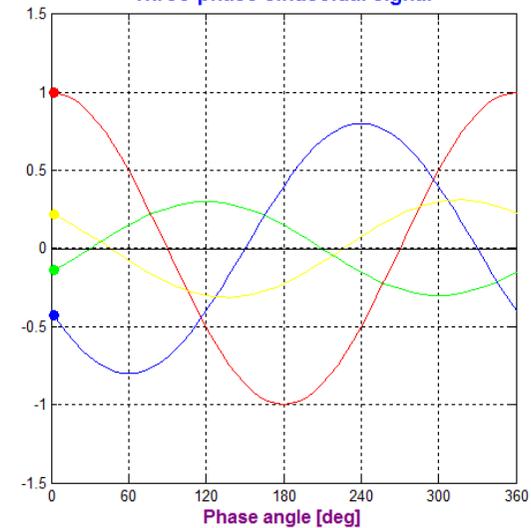
Error en los marcos de referencia debido a la presencia de componentes armónicas



Space vectors in motion



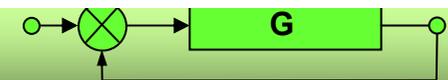
Three-phase sinusoidal signal



Phase A Phase B Phase C Resultant
Positive sequence Negative sequence Zero sequence

<http://www.ece.umn.edu/users/riaz/animations/spacevecunbalanced.html>

www3.fi.mdp.edu.ar/control403
www3.fi.mdp.edu.ar/electronica/catedraswrapper/4c8-sistemas-de-control



SISTEMAS DE CONTROL