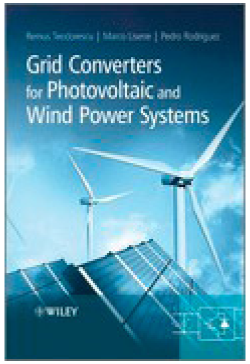

Grid Converters for Photovoltaic and Wind Power Systems

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Chapter 8

Grid Synchronization in Three-Phase Power Converters

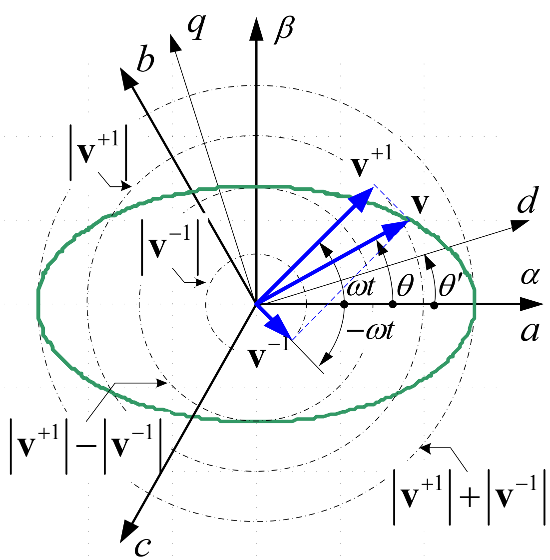
Outline

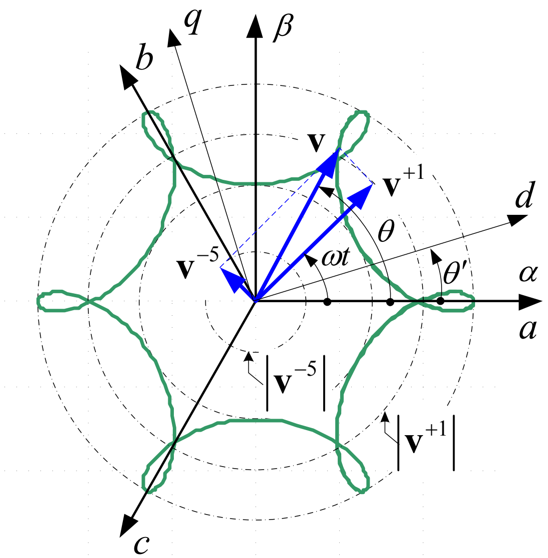
- Introduction
- Three-phase voltage vector under grid faults
- Types of voltage sags
- Synchronous Reference Frame PLL (SRF-PLL)
- Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL)
- Double Second Order Generalized Integrator FLL (DSOGI-FLL)
- Conclusions

Introduction

- One of the most important aspects to consider in the control of power converters connected to electrical grids is the proper synchronization with the three-phase utility voltages
- The three-phase voltage should be understood as a vector consisting of three voltage components
- The module and the rotation speed of the three-phase grid voltage vector keep constant when balanced sinusoidal waveforms are present in the three phases of the system –with equal amplitude, frequency and relative phase shifting
- The three-phase grid voltage vector consists of two sequence components (positive and negative) during grid faults, which result in oscillations in the module and the rotation speed
- The real-time detection of the sequence-components of the voltage vector during grid faults is an essential issue in the control of distributed generation systems

Three-phase voltage vector under grid faults





- Positive-sequence voltage vector at the fundamental frequency interacting with an either positive- or negative-sequence n^{th} order component :

$$\mathbf{v}_{abc} = \mathbf{v}_{abc}^{+1} + \mathbf{v}_{abc}^{n} = V^{+1}\begin{bmatrix}\cos(\omega t)\\ \cos(\omega t - \frac{2\pi}{3})\\ \cos(\omega t + \frac{2\pi}{3})\end{bmatrix} + V^{n}\begin{bmatrix}\cos(n\omega t)\\ \cos(n\omega t - \frac{2\pi}{3})\\ \cos(n\omega t + \frac{2\pi}{3})\end{bmatrix}$$

- Voltage vector on the d-q reference frame:

$$\mathbf{v}_{dq} = \sqrt{\frac{3}{2}}V^{+1}\begin{bmatrix}1\\0\end{bmatrix} + \sqrt{\frac{3}{2}}V^{n}\begin{bmatrix}\cos\left(\left(n-1\right)\omega t\right)\\ \sin\left(\left(n-1\right)\omega t\right)\end{bmatrix}$$

- Amplitude and phase-angle:

$$|\mathbf{v}| = \sqrt{v_\alpha^2 + v_\beta^2} = \sqrt{\frac{3}{2}\left[\left(V^{+1}\right)^2 + \left(V^{n}\right)^2 + 2V^{+1}V^{n}\cos\left(\left(n-1\right)\omega t\right)\right]}$$

$$\theta = \tan^{-1}\frac{v_\beta}{v_\alpha} = \omega t + \tan^{-1}\left[\frac{V^{n}\sin\left(\left(n-1\right)\omega t\right)}{V^{+1} + V^{n}\cos\left(\left(n-1\right)\omega t\right)}\right]$$

Three-phase voltage vector under grid faults

- Example:

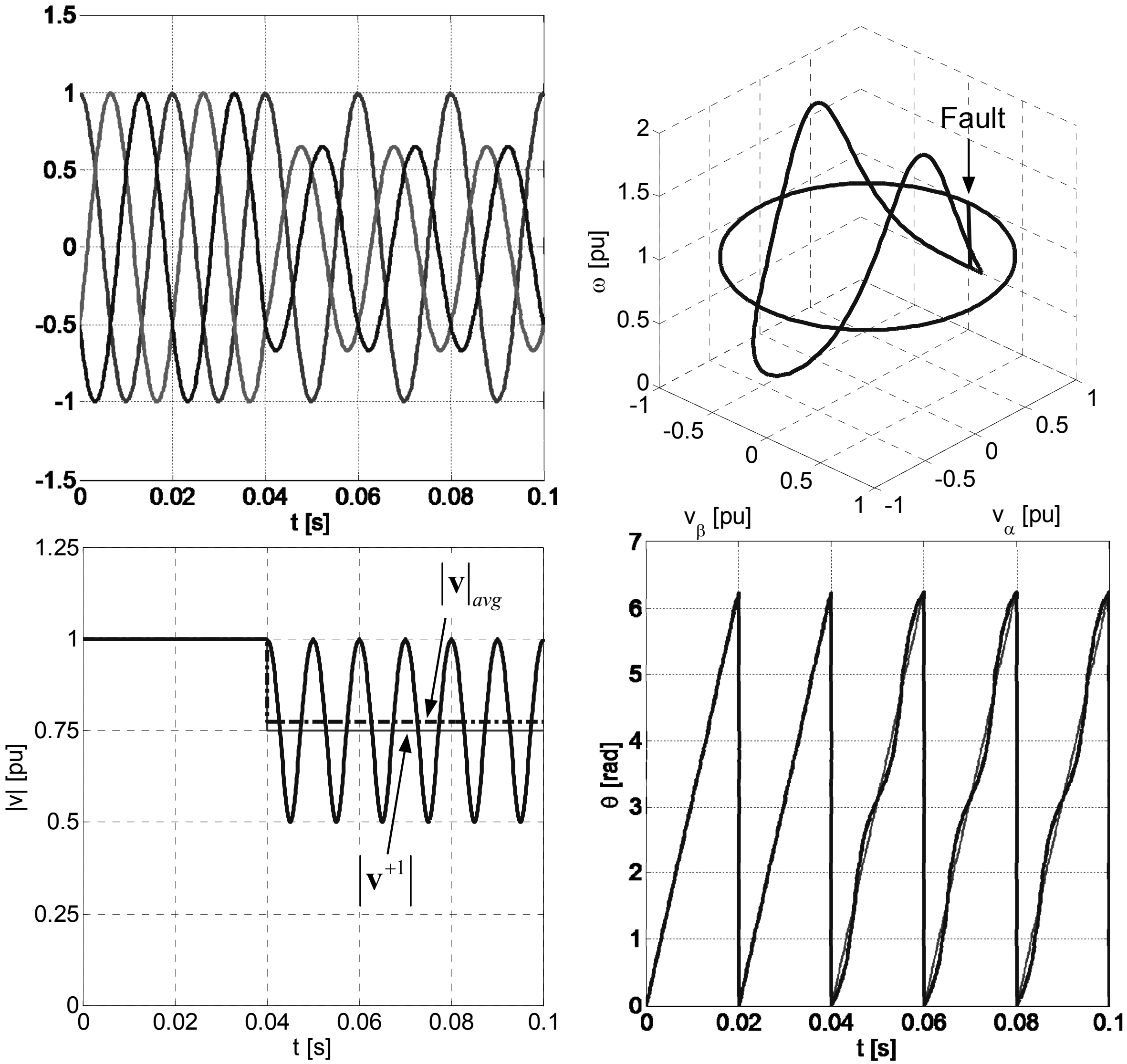
Positive- and negative-sequence components are considered, being:

$$v^{+1} = 0.75 \text{ p.u.}$$

$$v^{-1} = 0.25 \text{ p.u.}$$

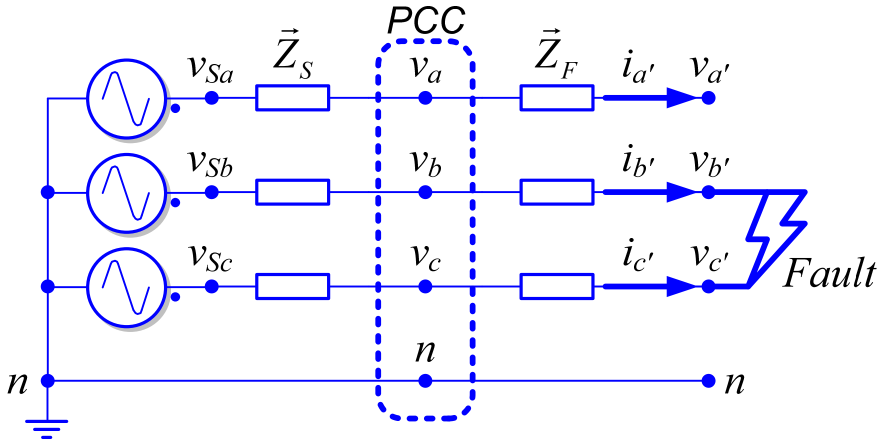
(it is assumed here that the pre-fault voltage amplitude is equal to 1 p.u.)

Amplitude and phase-angle present oscillations at twice the fundamental frequency during grid faults.



Unbalanced grid voltages during a grid fault

- Line-to-line fault



$$v_{b'} = v_{c'}\,;\, i_{b'} = -i_{c'}\,;\;\; i_{a'} = 0$$

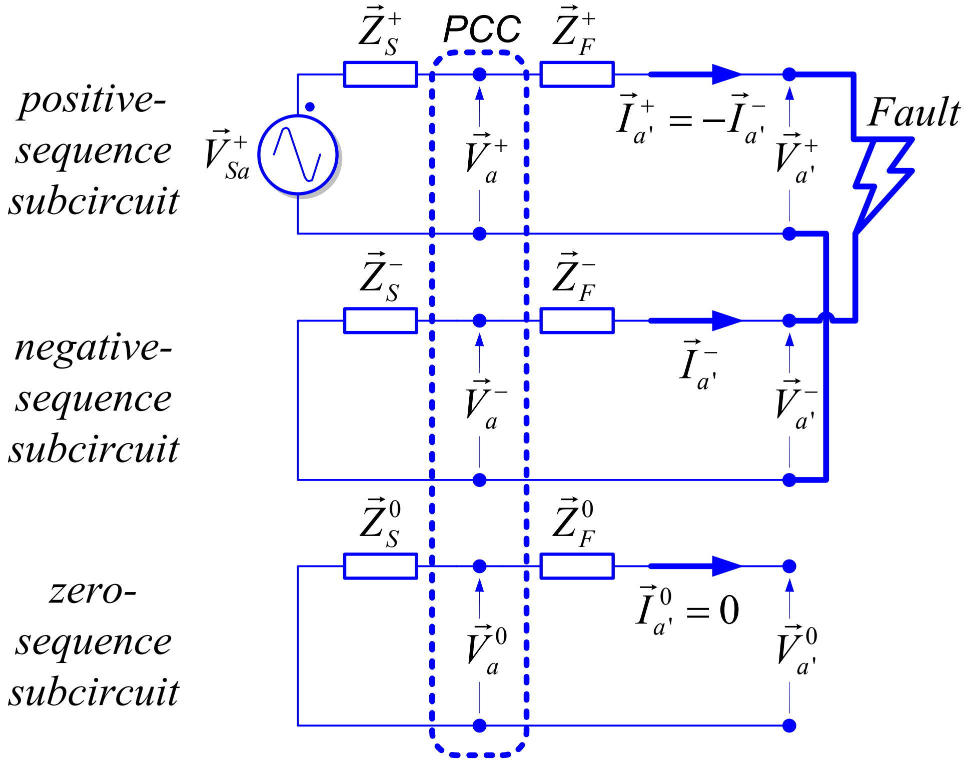
Symmetrical components

$$\mathbf{V}_{+-0(a')} = \begin{bmatrix} \vec{V}_{a'}^{+} \\ \vec{V}_{a'}^{-} \\ \vec{V}_{a'}^{0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \vec{V}_{a'} \\ \vec{V}_{b'} \\ \vec{V}_{c'} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} \vec{V}_{a'} - \vec{V}_{b'} \\ \vec{V}_{a'} - \vec{V}_{b'} \\ \vec{V}_{a'} + 2\vec{V}_{b'} \end{bmatrix}$$

$$\mathbf{I}_{+-0(a')} = \begin{bmatrix} \vec{I}_{a'}^{+} \\ \vec{I}_{a'}^{-} \\ \vec{I}_{a'}^{0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \vec{I}_{a'} \\ \vec{I}_{b'} \\ \vec{I}_{c'} \end{bmatrix} = \frac{1}{\sqrt{3}}\begin{bmatrix} j\vec{I}_{b'} \\ -j\vec{I}_{b'} \\ 0 \end{bmatrix}$$

Unbalanced grid voltages during a grid fault

- Line-to-line fault



Unbalanced voltage at the PCC

$$\vec{V}_a^+ = \frac{\vec{Z}_S + \left(\vec{Z}_F^+ + \vec{Z}_F^-\right)}{2\vec{Z}_S + \left(\vec{Z}_F^+ + \vec{Z}_F^-\right)} \vec{V}_{Sa}^+ \qquad \vec{V}_a^- = \frac{\vec{Z}_S}{2\vec{Z}_S + \left(\vec{Z}_F^+ + \vec{Z}_F^-\right)} \vec{V}_{Sa}^+ \qquad \vec{V}_a^0 = 0$$

Unbalanced grid voltages during a grid fault

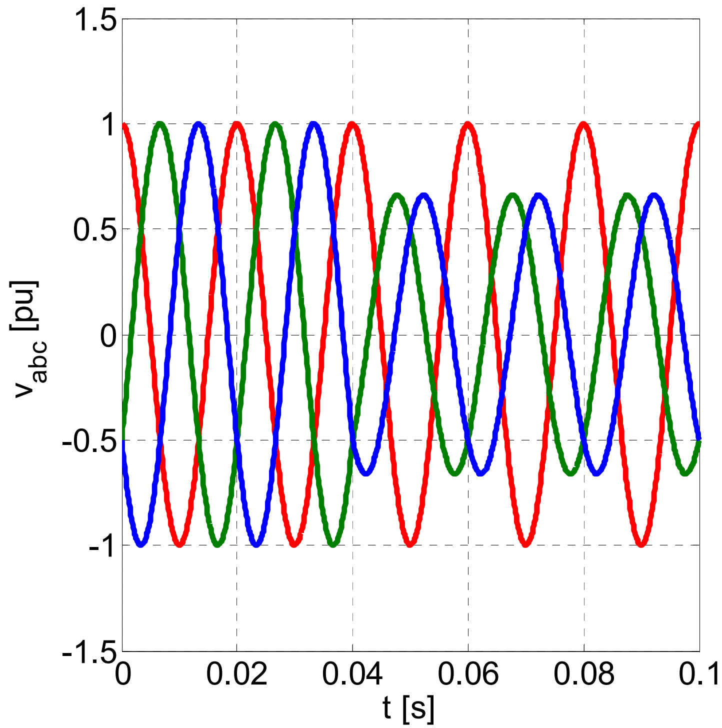
- Dip (Sag) parameter

$$\vec{D} = D\angle\rho_D = \frac{\left(\vec{Z}_F^+ + \vec{Z}_F^-\right)}{2\vec{Z}_S + \left(\vec{Z}_F^+ + \vec{Z}_F^-\right)}$$

  - Unbalanced voltage at the PCC

$$\mathbf{V}_{+-0(pcc)} = \begin{bmatrix} \vec{V}_a^+ \\ \vec{V}_a^- \\ \vec{V}_a^0 \end{bmatrix} = \frac{1}{2}\vec{V}_{Sa}^+ \begin{bmatrix} 1+\vec{D} \\ 1-\vec{D} \\ 0 \end{bmatrix}$$

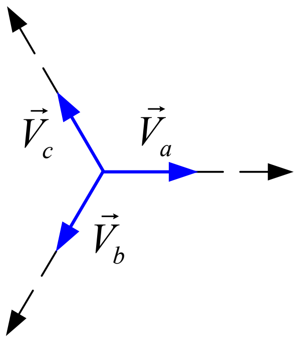
$$\mathbf{V}_{abc(pcc)} = \begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} \vec{V}_a^+ \\ \vec{V}_a^- \\ \vec{V}_a^0 \end{bmatrix} = \vec{V}_{Sa}^+ \begin{bmatrix} 1 \\ -\frac{1}{2} - \frac{\sqrt{3}}{2}\vec{D} \\ -\frac{1}{2} + \frac{\sqrt{3}}{2}\vec{D} \end{bmatrix}$$

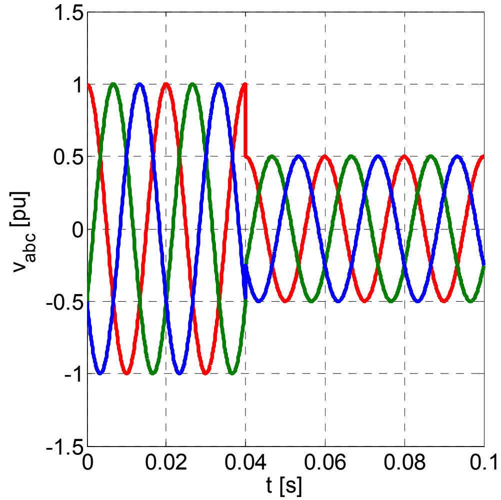


Types of voltage sags

Sag A

Three-phase fault





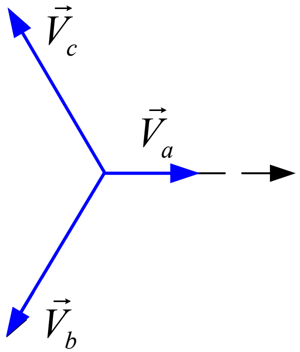
$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix}=\begin{bmatrix}1\\ -\frac{1}{2}-j\frac{\sqrt{3}}{2}\\ -\frac{1}{2}+j\frac{\sqrt{3}}{2}\end{bmatrix}\vec{D}\vec{V}_{Sa}^{+},$$

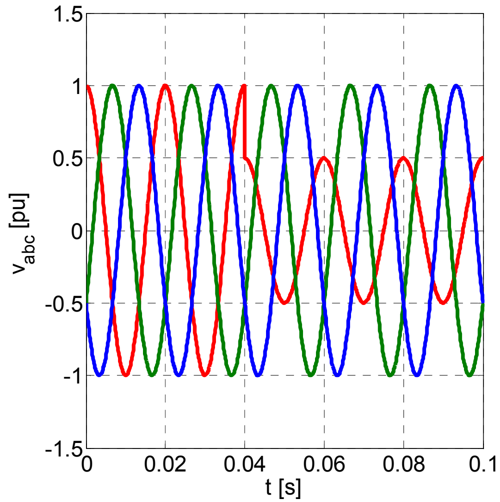
$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix}=\begin{bmatrix}1\\ 0\\ 0\end{bmatrix}\vec{D}\vec{V}_{Sa}^{+},$$

$$\vec{D}=\frac{\vec{Z}_F^{+}}{\vec{Z}_S+\vec{Z}_F^{+}}$$

Sag B

Single-phase to ground fault





$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix}=\begin{bmatrix}\vec{D}\\ -\frac{1}{2}-j\frac{\sqrt{3}}{2}\\ -\frac{1}{2}+j\frac{\sqrt{3}}{2}\end{bmatrix}\vec{V}_{Sa}^{+},$$

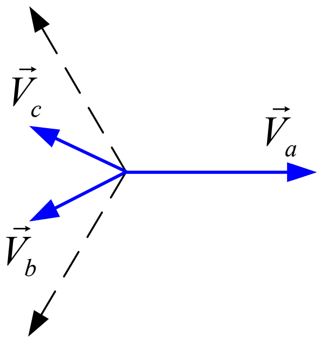
$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix}=\begin{bmatrix}\frac{1}{3}\left(2+\vec{D}\right)\\ \frac{-1}{3}\left(1-\vec{D}\right)\\ \frac{-1}{3}\left(1-\vec{D}\right)\end{bmatrix}\vec{V}_{Sa}^{+},$$

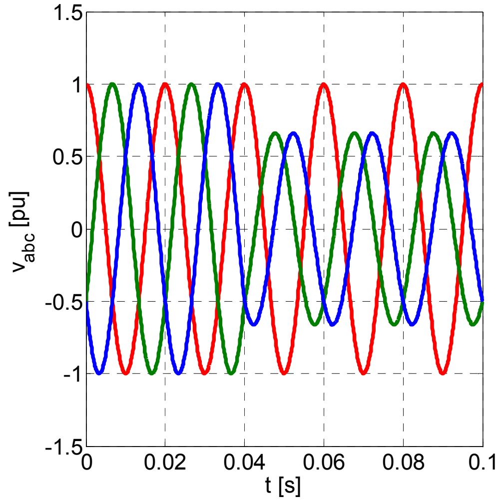
$$\vec{D}=\frac{\vec{Z}_F^{+}+\vec{Z}_F^{-}+\vec{Z}_F^{0}}{3\vec{Z}_S+\vec{Z}_F^{+}+\vec{Z}_F^{-}+\vec{Z}_F^{0}}$$

Types of voltage sags

Sag C

Phase-to-phase fault





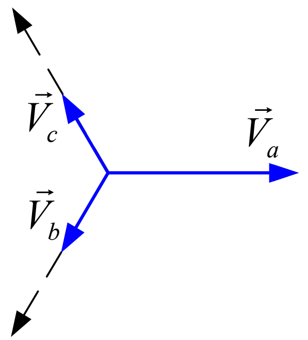
$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix}=\begin{bmatrix}1\\ -\frac{1}{2}-j\frac{\sqrt{3}}{2}\vec{D}\\ -\frac{1}{2}+j\frac{\sqrt{3}}{2}\vec{D}\end{bmatrix}\vec{V}_{Sa}^{+},$$

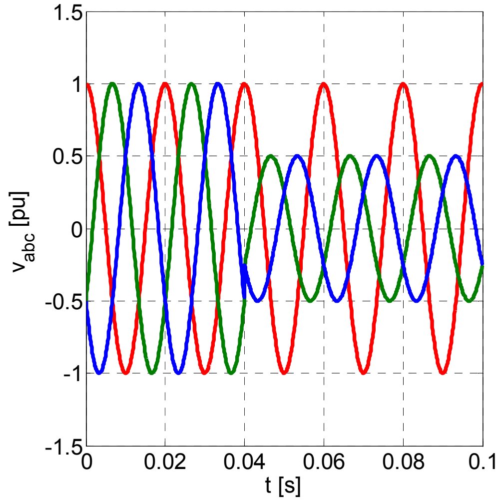
$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix}=\begin{bmatrix}\frac{1}{2}\left(1+\vec{D}\right)\\ \frac{1}{2}\left(1-\vec{D}\right)\\ 0\end{bmatrix}\vec{V}_{Sa}^{+},$$

$$\vec{D}=\frac{\vec{Z}_F^{+}+\vec{Z}_F^{-}}{2\vec{Z}_S+\vec{Z}_F^{+}+\vec{Z}_F^{-}}$$

Sag E

Single-phase to ground fault



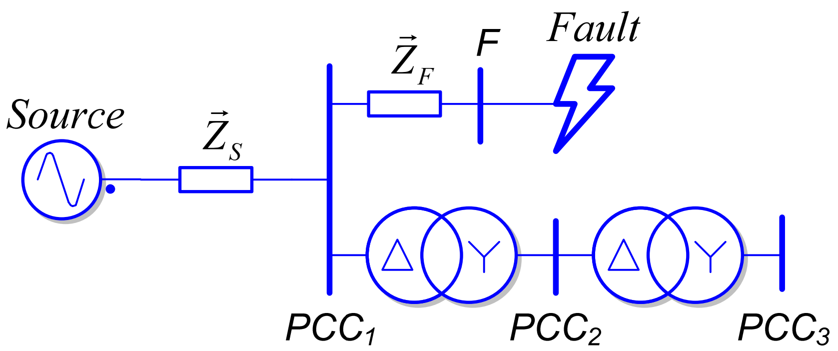


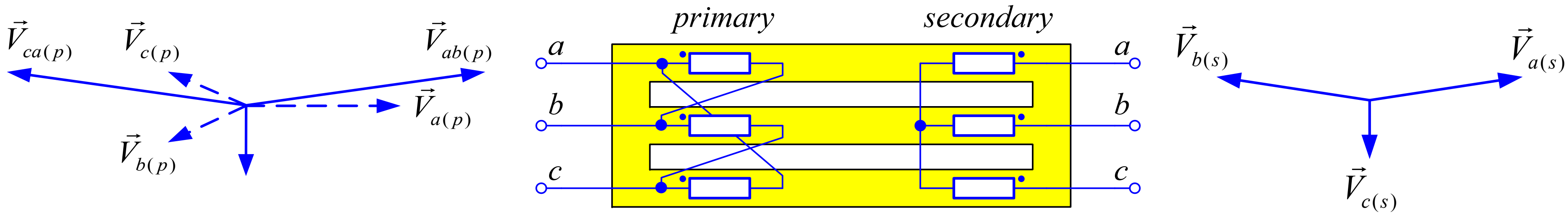
$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix}=\begin{bmatrix}1\\ -\frac{1}{2}\vec{D}-j\frac{\sqrt{3}}{2}\vec{D}\\ -\frac{1}{2}\vec{D}+j\frac{\sqrt{3}}{2}\vec{D}\end{bmatrix}\vec{V}_{Sa}^{+},$$

$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix}=\begin{bmatrix}\frac{1}{3}\left(1+2\vec{D}\right)\\ \frac{1}{3}\left(1-\vec{D}\right)\\ \frac{1}{3}\left(1-\vec{D}\right)\end{bmatrix}\vec{V}_{Sa}^{+},$$

$$\vec{D}=\frac{\vec{Z}_F}{\vec{Z}_S+\vec{Z}_F}$$

Propagation of voltage sags



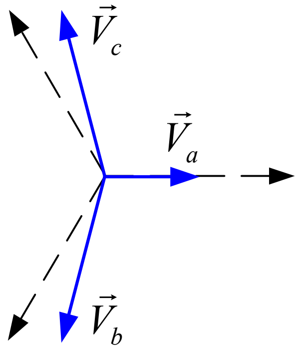


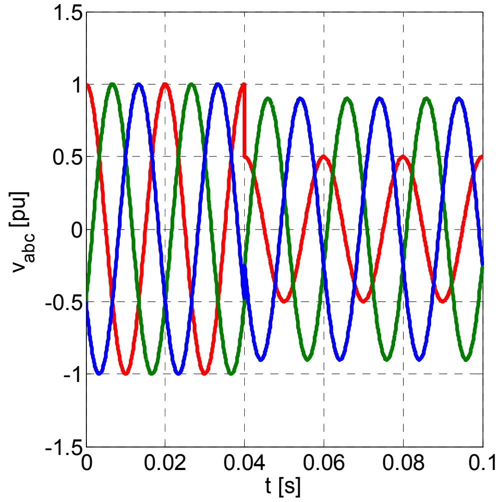
Fault type	Point of common coupling		
	PCC1	PCC_2	PCC_3
Three-phase / Three-phase to ground	A	A	A
Single-phase to ground	B	C	D
Two-phase	C	D	C
Two-phase to ground	E	F	G

Propagation of voltage sags

Sag D

Propagation of a sag type C



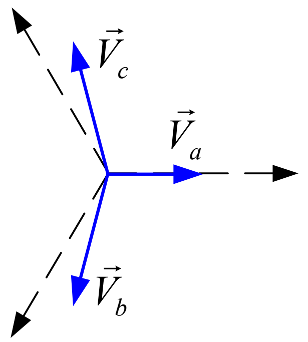


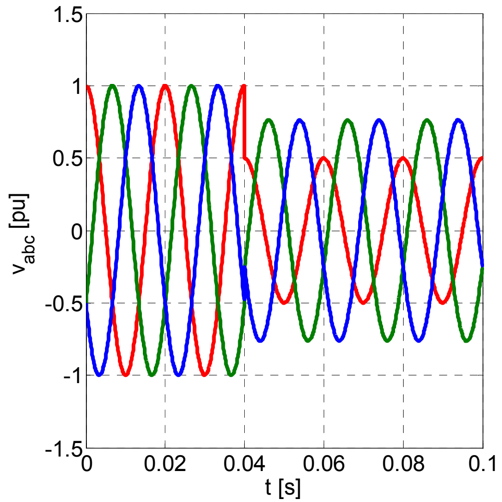
$$\begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} \vec{D} \\ -\frac{1}{2}\vec{D} - j\frac{\sqrt{3}}{2} \\ -\frac{1}{2}\vec{D} + j\frac{\sqrt{3}}{2} \end{bmatrix} \vec{V}_{Sa}^{+},$$

$$\begin{bmatrix} \vec{V}_a^{+} \\ \vec{V}_a^{-} \\ \vec{V}_a^{0} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(1+\vec{D}\right) \\ -\frac{1}{2}\left(1-\vec{D}\right) \\ 0 \end{bmatrix} \vec{V}_{Sa}^{+}$$

Sag E

Propagation of a sag type E

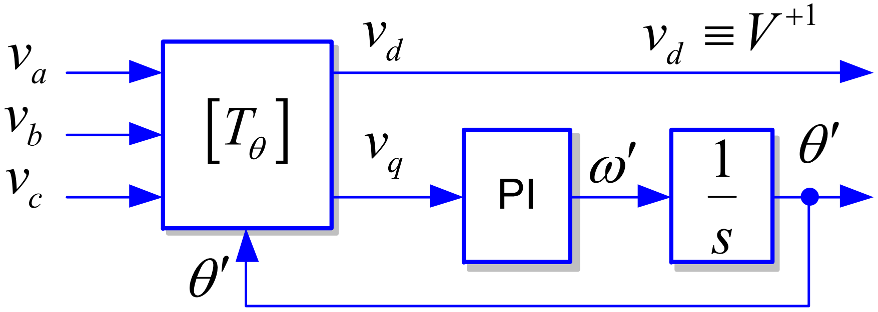


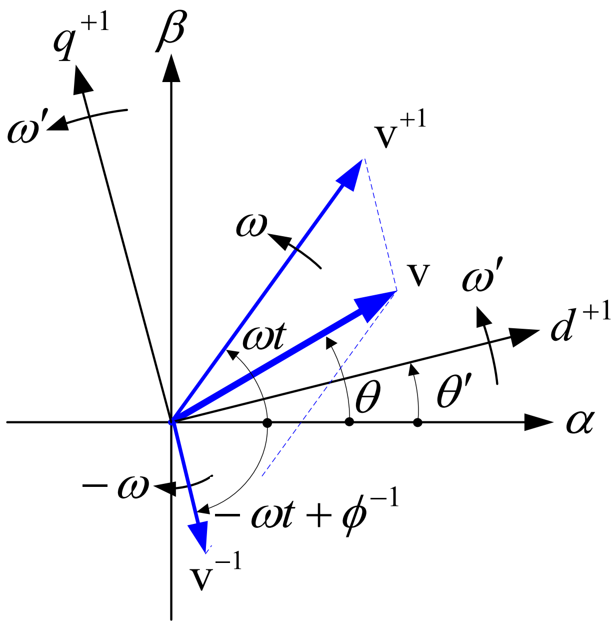


$$\begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} \vec{D} \\ -\frac{1}{2}\vec{D} - j\left(\frac{2+\vec{D}}{\sqrt{12}}\right) \\ -\frac{1}{2}\vec{D} + j\left(\frac{2+\vec{D}}{\sqrt{12}}\right) \end{bmatrix} \vec{V}_{Sa}^{+},$$

$$\begin{bmatrix} \vec{V}_a^{+} \\ \vec{V}_a^{-} \\ \vec{V}_a^{0} \end{bmatrix} = \begin{bmatrix} \frac{1}{3}\left(1+2\vec{D}\right) \\ \frac{-1}{3}\left(1-\vec{D}\right) \\ 0 \end{bmatrix} \vec{V}_{Sa}^{+}$$

Synchronous Reference Frame PLL (SRF-PLL)

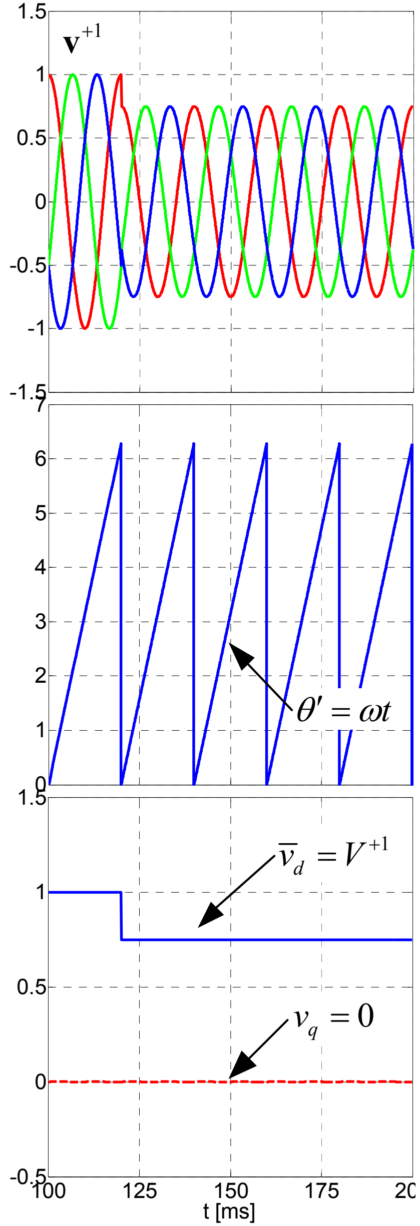




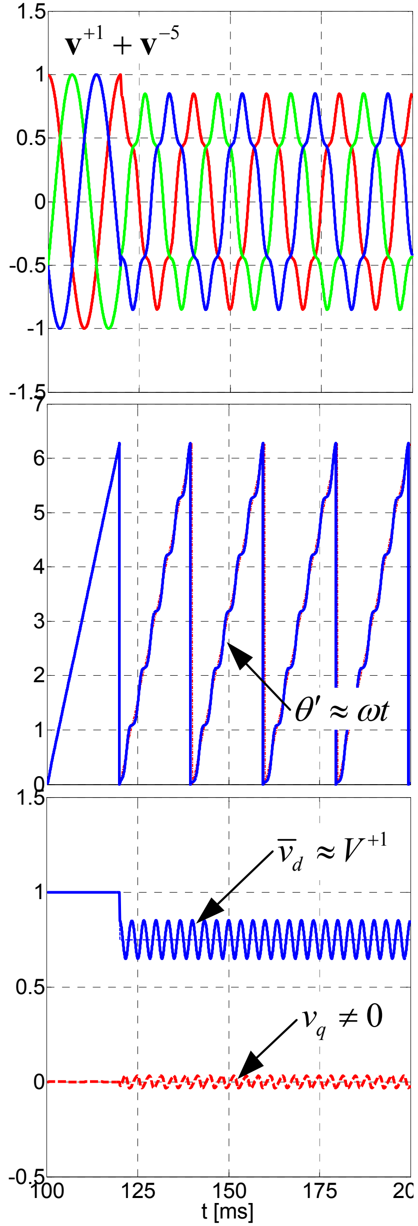
$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = [T_\theta] \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad , \quad [T_\theta] = \frac{2}{3} \begin{bmatrix} \cos(\theta') & \cos(\theta' - \frac{2\pi}{3}) & \cos(\theta' + \frac{2\pi}{3}) \\ -\sin(\theta') & -\sin(\theta' - \frac{2\pi}{3}) & -\sin(\theta' + \frac{2\pi}{3}) \end{bmatrix}$$

SRF-PLL under unbalanced and distorted grid

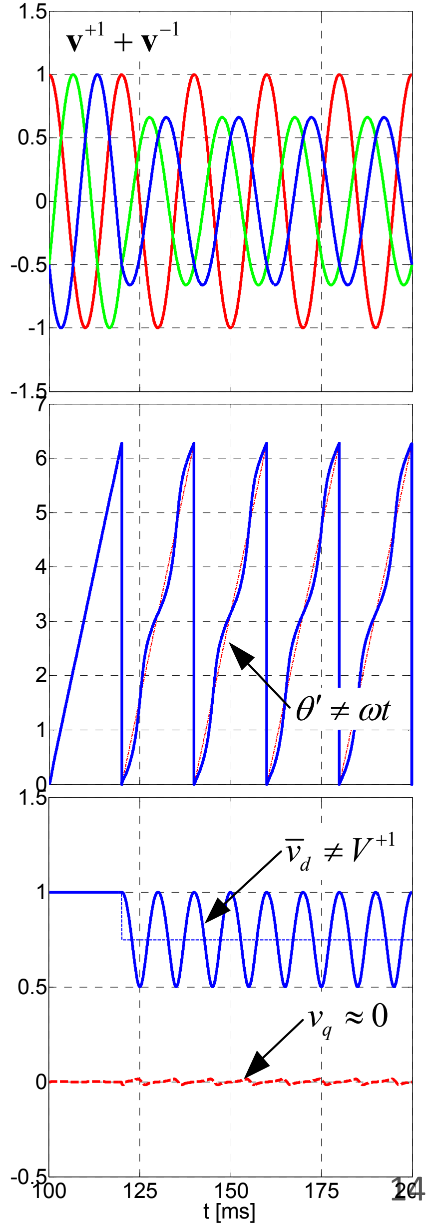
- Balanced grid fault



- Balanced and distorted grid fault

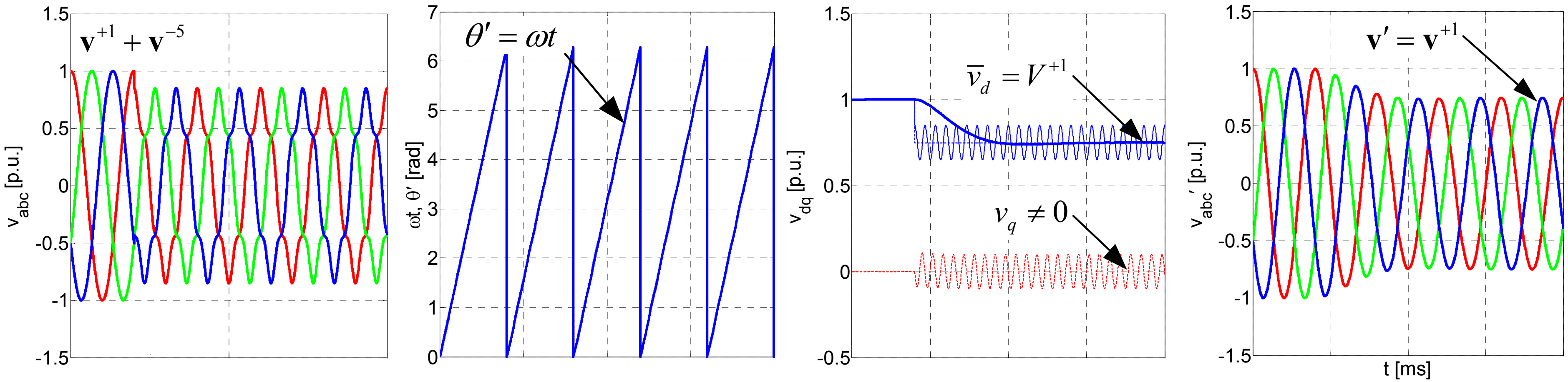


- Unbalanced grid fault

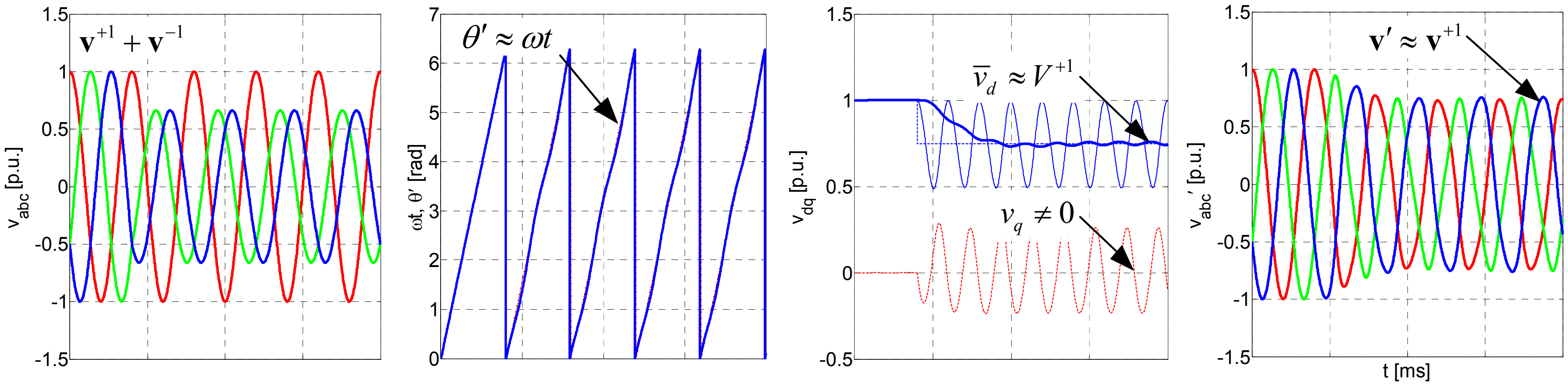


SRF-PLL under unbalanced and distorted grid

- Reduction of the PLL bandwidth plus filtering can help to attenuate the effect of high-order harmonics on the SRF-PLL output signals



- Limitation of the PLL bandwidth plus filtering is not the most effective solution to extract the positive-sequence component from unbalanced three-phase voltages



Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL)

- The double synchronous reference frame (DSRF)

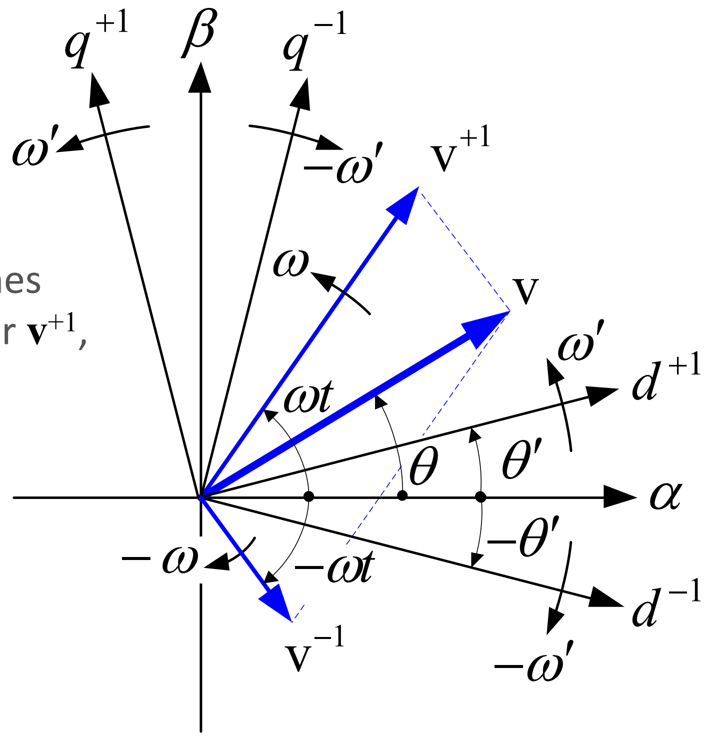
Unbalanced grid voltage $\mathbf{v}$ on the α–β reference frame:

$$\mathbf{v}_{\alpha\beta} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = V^{+1}\begin{bmatrix} \cos(\omega t) \\ \sin(\omega t) \end{bmatrix} + V^{-1}\begin{bmatrix} \cos(-\omega t) \\ \sin(-\omega t) \end{bmatrix}$$

Unbalanced input voltage vector $\mathbf{v}$ on the DSRF when the angular position of the positive reference frame dq^{+1} matches the angular position of the positive-sequence voltage vector $\mathbf{v}^{+1}$, that is, $\theta' = \omega t$.

$$\mathbf{v}_{dq^{+1}} = \begin{bmatrix} v_{d^{+1}} \\ v_{q^{+1}} \end{bmatrix} = \left[T_{dq^{+1}}\right]\cdot \mathbf{v}_{\alpha\beta} = V^{+1}\begin{bmatrix} 1 \\ 0 \end{bmatrix} + V^{-1}\begin{bmatrix} \cos(-2\omega t) \\ \sin(-2\omega t) \end{bmatrix}$$

$$\mathbf{v}_{dq^{-1}} = \begin{bmatrix} v_{d^{-1}} \\ v_{q^{-1}} \end{bmatrix} = \left[T_{dq^{-1}}\right]\cdot \mathbf{v}_{\alpha\beta} = V^{+1}\begin{bmatrix} \cos(2\omega t) \\ \sin(2\omega t) \end{bmatrix} + V^{-1}\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$



The dc values on the dq^{+1} and the dq^{-1} frames correspond to the amplitude the sinusoidal signals of $\mathbf{v}^{+1}$ and $\mathbf{v}^{-1}$, while the oscillations at 2ω correspond to the coupling between axes appearing as a consequence of the voltage vectors rotating in opposite direction

Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL)

- The decoupling network

Generic input voltage vector $\mathbf{v}$:

$$\mathbf{v}_{\alpha\beta} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \mathbf{v}_{\alpha\beta}^{n} + \mathbf{v}_{\alpha\beta}^{m} = V^n \begin{bmatrix} \cos(n\omega t + \phi^n) \\ \sin(n\omega t + \phi^n) \end{bmatrix} + V^m \begin{bmatrix} \cos(m\omega t + \phi^m) \\ \sin(m\omega t + \phi^m) \end{bmatrix}$$

If a perfect synchronization of the PLL is possible, with $\theta' = \omega t$, the voltage vector $\mathbf{v}$ can be expressed on generic dq^n and dq^m reference frames as follows:

$$\mathbf{v}_{dq^n} = \begin{bmatrix} v_{d^n} \\ v_{q^n} \end{bmatrix} = \begin{bmatrix} \overline{v}_{d^n} \\ \overline{v}_{q^n} \end{bmatrix} + \begin{bmatrix} \tilde{v}_{d^n} \\ \tilde{v}_{q^n} \end{bmatrix} = \underbrace{V^n \begin{bmatrix} \cos(\phi^n) \\ \sin(\phi^n) \end{bmatrix}}_{dc\ terms} + \underbrace{V^m \cos(\phi^m) \begin{bmatrix} \cos((n-m)\omega t) \\ -\sin((n-m)\omega t) \end{bmatrix} + V^m \sin(\phi^m) \begin{bmatrix} \sin((n-m)\omega t) \\ \cos((n-m)\omega t) \end{bmatrix}}_{ac\ terms}$$

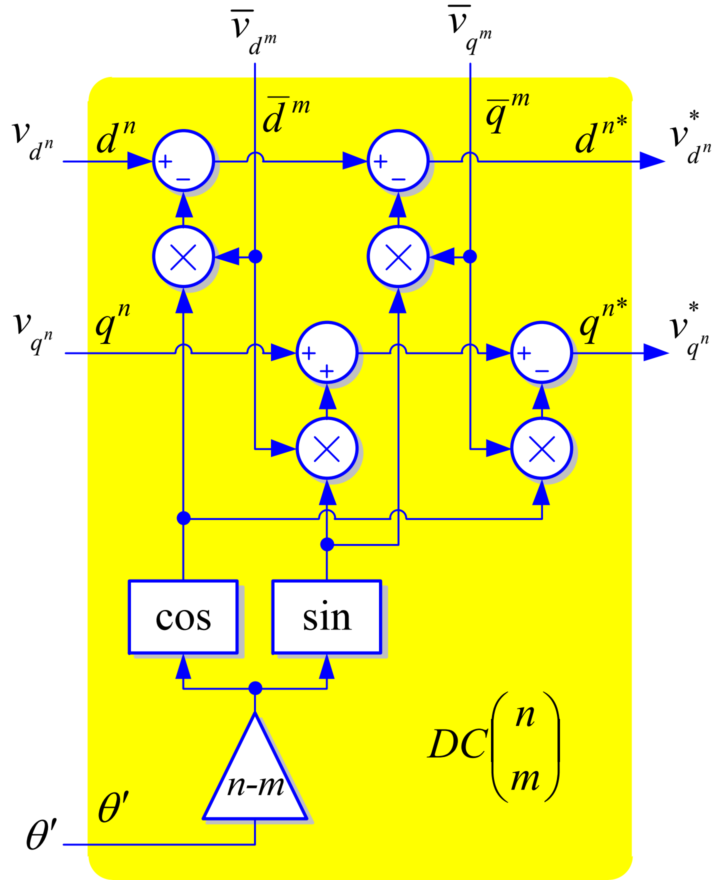
$$\mathbf{v}_{dq^m} = \begin{bmatrix} v_{d^m} \\ v_{q^m} \end{bmatrix} = \begin{bmatrix} \overline{v}_{d^m} \\ \overline{v}_{q^m} \end{bmatrix} + \begin{bmatrix} \tilde{v}_{d^m} \\ \tilde{v}_{q^m} \end{bmatrix} = \underbrace{V^m \begin{bmatrix} \cos(\phi^m) \\ \sin(\phi^m) \end{bmatrix}}_{dc\ terms} + \underbrace{V^n \cos(\phi^n) \begin{bmatrix} \cos((n-m)\omega t) \\ \sin((n-m)\omega t) \end{bmatrix} + V^n \sin(\phi^n) \begin{bmatrix} -\sin((n-m)\omega t) \\ \cos((n-m)\omega t) \end{bmatrix}}_{ac\ terms}$$

The amplitude of the ac terms in the dp^n axes depends on the dc terms of the signals on the dq^m axes, and vice versa.

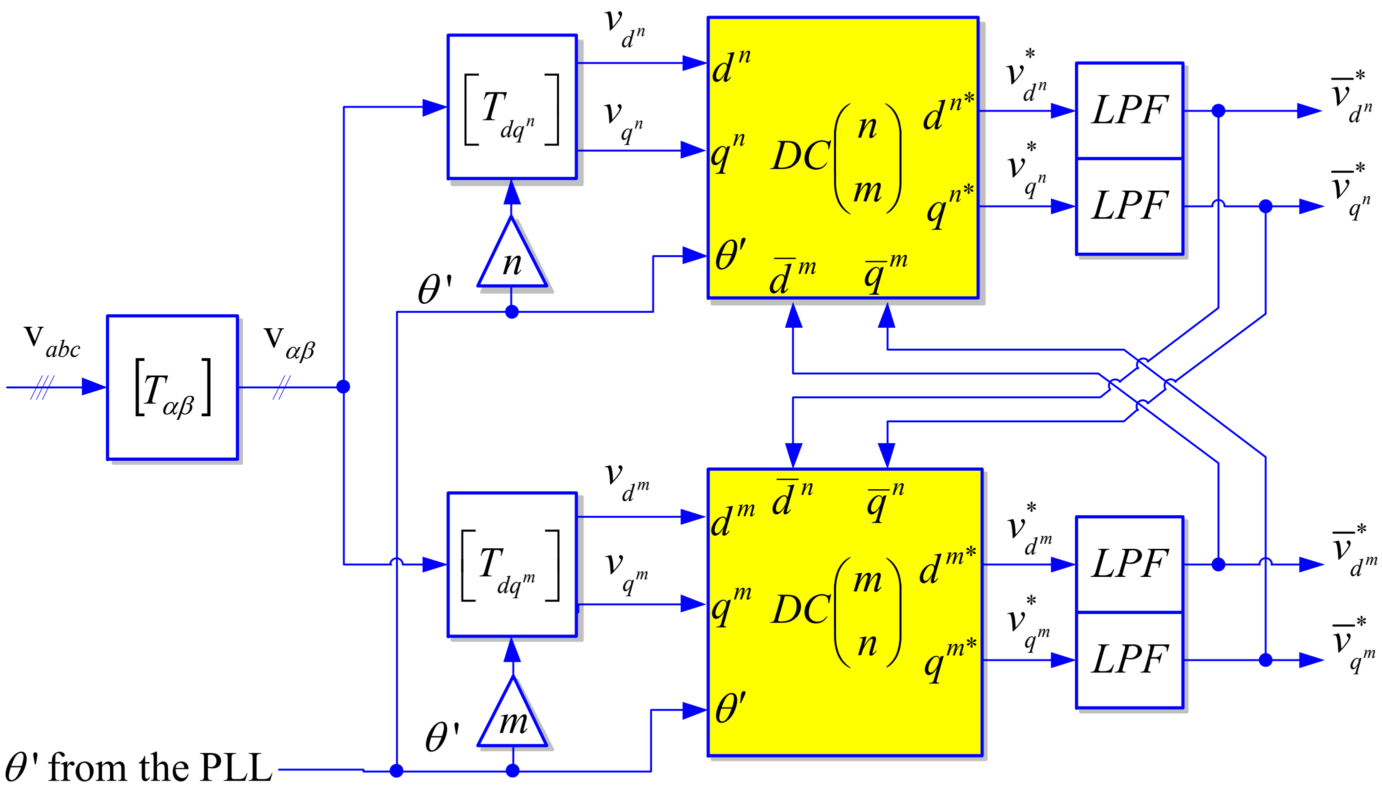
Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL)

- The decoupling network

The decoupling cell cancels out the oscillations generated by the voltage vector $\mathbf{v}^m$ on the dq^n axes signals. For cancelling out the oscillations in the dq^m axes signals, the same structure may be used but swapping the m and n indexes in it.



Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL)



A cross-feedback decoupling network is used to estimate the value of the dc terms on the positive- and negative-reference frames. The LPF block is a low-pass filter such as:

$$LPF(s) = \frac{\omega_f}{s + \omega_f}$$

Analysis of the DDSRF-PLL

Unbalanced input voltage vector $\mathbf{v}$:

$$\mathbf{v}_{\alpha\beta} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \mathbf{v}_{\alpha\beta}^{+1} + \mathbf{v}_{\alpha\beta}^{-1} = V^{+1}\begin{bmatrix} \cos(\omega t + \phi^{+1}) \\ \sin(\omega t + \phi^{+1}) \end{bmatrix} + V^{-1}\begin{bmatrix} \cos(-\omega t + \phi^{-1}) \\ \sin(-\omega t + \phi^{-1}) \end{bmatrix}$$

d-*q* signals on the positive- and negative-reference frames:

$$\mathbf{v}_{dq^{+1}} = \begin{bmatrix} v_{d^{+1}} \\ v_{q^{+1}} \end{bmatrix} = V^{+1}\begin{bmatrix} \cos(\phi^{+1}) \\ \sin(\phi^{+1}) \end{bmatrix} + V^{-1}\begin{bmatrix} \cos(2\omega t) & \sin(2\omega t) \\ -\sin(2\omega t) & \cos(2\omega t) \end{bmatrix}\begin{bmatrix} \cos(\phi^{-1}) \\ \sin(\phi^{-1}) \end{bmatrix}$$

$$\mathbf{v}_{dq^{-1}} = \begin{bmatrix} v_{d^{-1}} \\ v_{q^{-1}} \end{bmatrix} = V^{-1}\begin{bmatrix} \cos(\phi^{-1}) \\ \sin(\phi^{-1}) \end{bmatrix} + V^{+1}\begin{bmatrix} \cos(2\omega t) & -\sin(2\omega t) \\ \sin(2\omega t) & \cos(2\omega t) \end{bmatrix}\begin{bmatrix} \cos(\phi^{+1}) \\ \sin(\phi^{+1}) \end{bmatrix}$$

Arranging terms:

$$\mathbf{v}_{dq^{+1}} = \begin{bmatrix} v_{d^{+1}} \\ v_{q^{+1}} \end{bmatrix} = \overline{\mathbf{v}}_{dq^{+1}} + \left[T_{dq^{+2}}\right]\overline{\mathbf{v}}_{dq^{-1}}$$

$$\mathbf{v}_{dq^{-1}} = \begin{bmatrix} v_{d^{-1}} \\ v_{q^{-1}} \end{bmatrix} = \overline{\mathbf{v}}_{dq^{-1}} + \left[T_{dq^{-2}}\right]\overline{\mathbf{v}}_{dq^{+1}}$$

$$\begin{cases} \left[T_{dq^{+2}}\right] = \left[T_{dq^{-2}}\right]^T = \begin{bmatrix} \cos(2\omega t) & \sin(2\omega t) \\ -\sin(2\omega t) & \cos(2\omega t) \end{bmatrix} \\ \overline{\mathbf{v}}_{dq^{+1}} = \begin{bmatrix} \overline{v}_{d^{+1}} \\ \overline{v}_{q^{+1}} \end{bmatrix} = V^{+1}\begin{bmatrix} \cos(\phi^{+1}) \\ \sin(\phi^{+1}) \end{bmatrix} \\ \overline{\mathbf{v}}_{dq^{-1}} = \begin{bmatrix} \overline{v}_{d^{-1}} \\ \overline{v}_{q^{-1}} \end{bmatrix} = V^{-1}\begin{bmatrix} \cos(\phi^{-1}) \\ \sin(\phi^{-1}) \end{bmatrix} \end{cases}$$

Analysis of the DDSRF-PLL

The relationship between the signals on the positive- and negative-reference frame is given by:

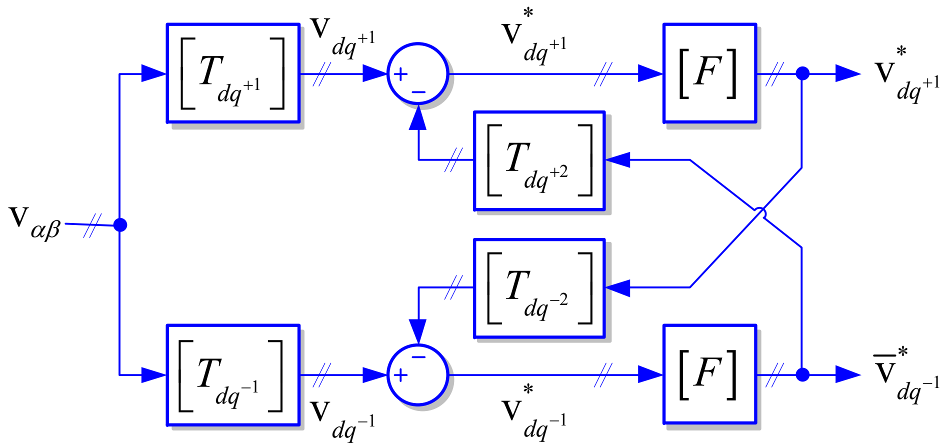
$$\mathbf{v}_{dq^{+1}} = \left[T_{dq^{+2}}\right]\mathbf{v}_{dq^{-1}} \quad \text{and} \quad \mathbf{v}_{dq^{-1}} = \left[T_{dq^{-2}}\right]\mathbf{v}_{dq^{+1}}$$

The estimated values at the output of the DDSRF can be written as:

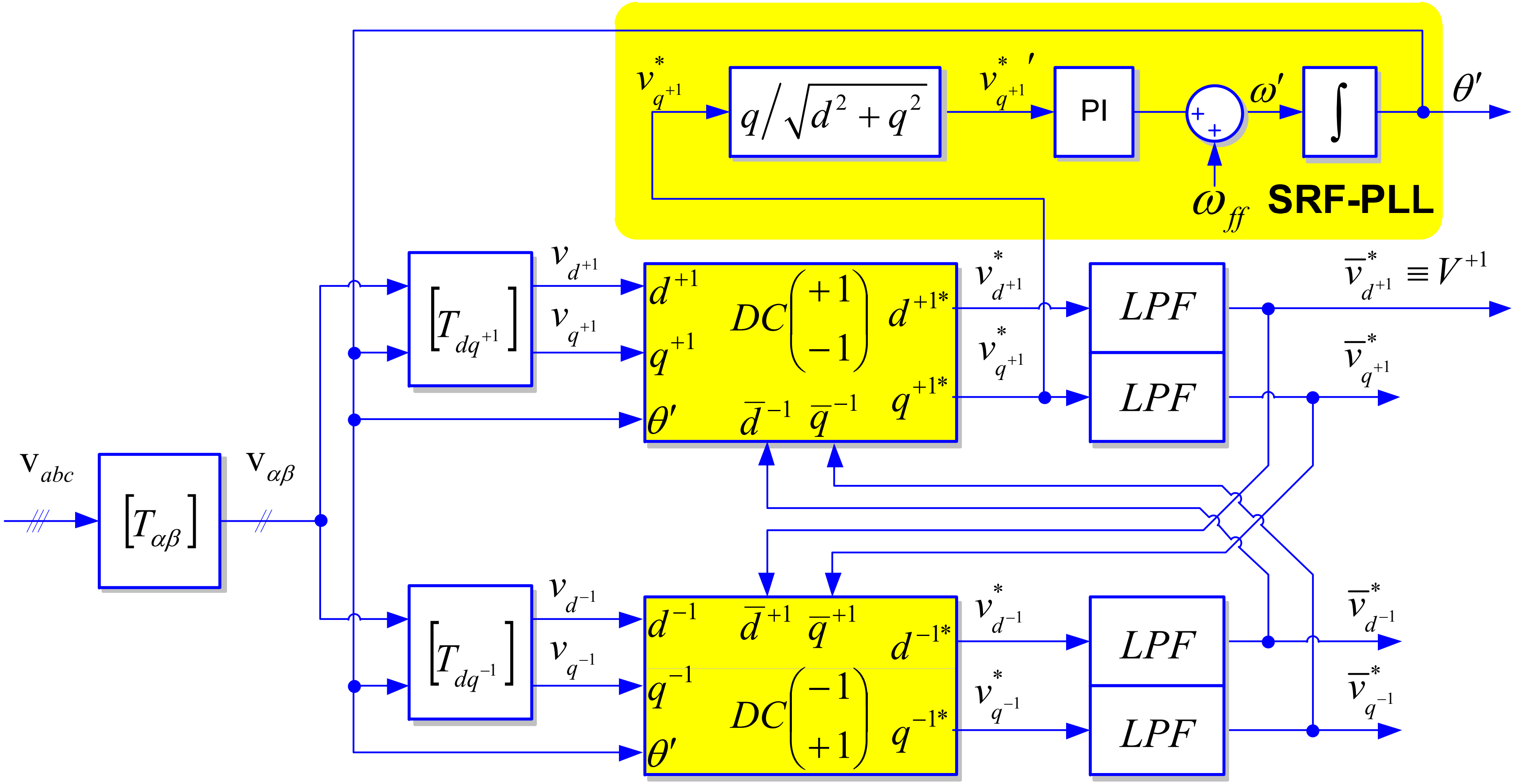
$$\overline{\mathbf{v}}^*_{dq^{+1}} = \begin{bmatrix} \overline{v}^*_{d^{+1}} \\ \overline{v}^*_{q^{+1}} \end{bmatrix} = [F]\left\{\mathbf{v}_{dq^{+1}} - \left[T_{dq^{+2}}\right]\overline{\mathbf{v}}^*_{dq^{-1}}\right\}$$

$$\overline{\mathbf{v}}^*_{dq^{-1}} = \begin{bmatrix} \overline{v}^*_{d^{-1}} \\ \overline{v}^*_{q^{-1}} \end{bmatrix} = [F]\left\{\mathbf{v}_{dq^{-1}} - \left[T_{dq^{-2}}\right]\overline{\mathbf{v}}^*_{dq^{+1}}\right\}$$

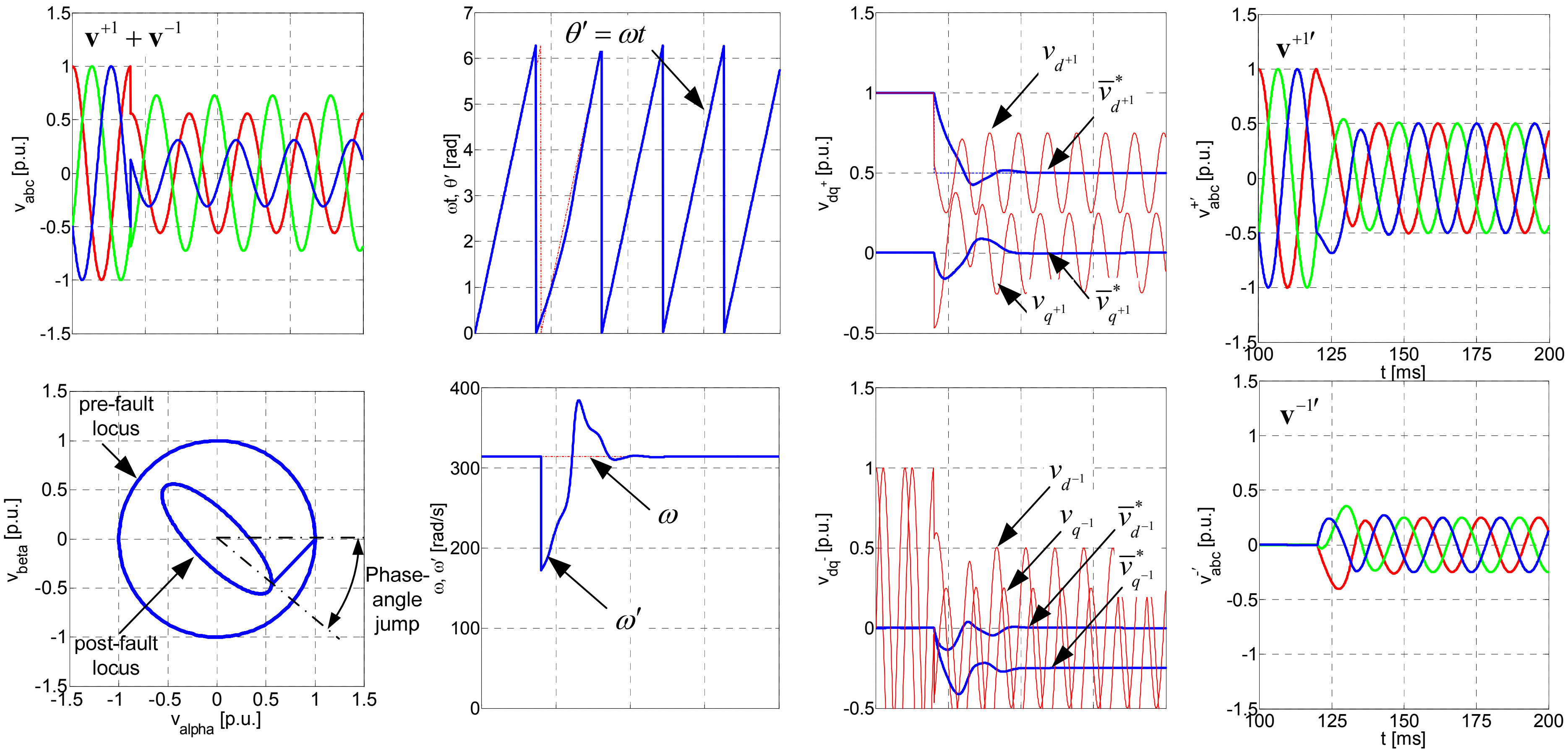
$$[F] = \begin{bmatrix} LPF(s) & 0 \\ 0 & LPF(s) \end{bmatrix}$$



Structure of the DDSRF-PLL

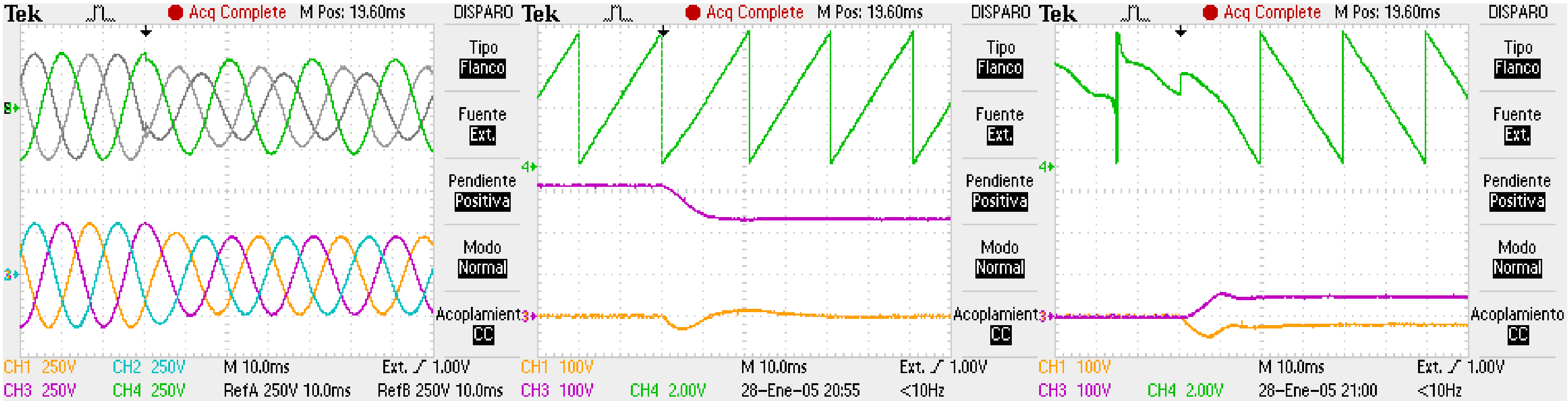


Response of the DDSRF-PLL

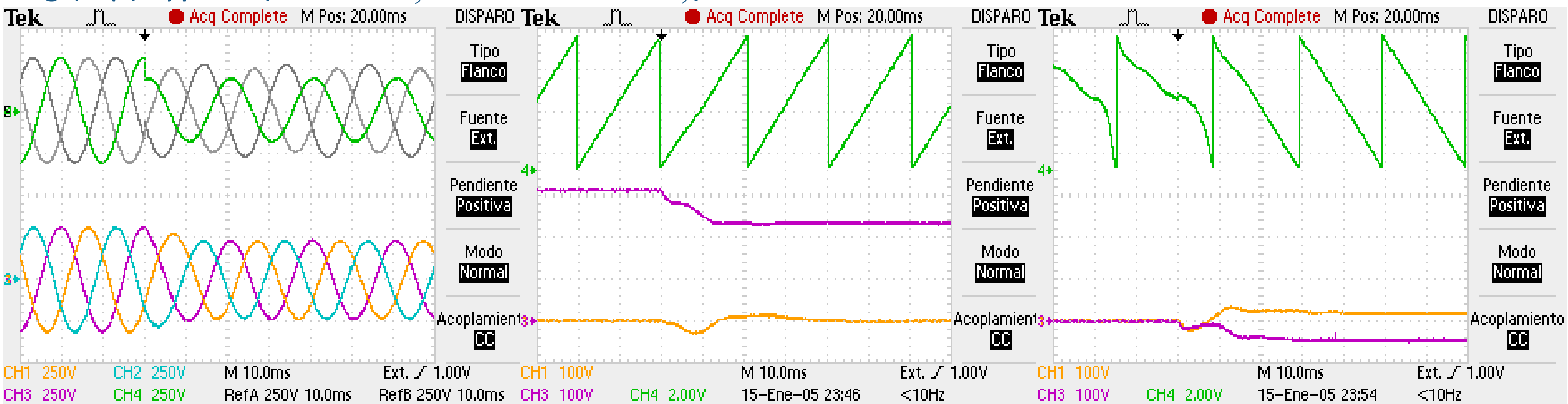


Response of the DDSRF-PLL

Sag (dip) type C ($\vec{V} = 0,6\angle -20^o$ $\vec{F} = 0,9\angle -10^o$



Sag (dip) type D ($\vec{V} = 0,6\angle -20^o$ $\vec{F} = 0,9\angle -10^o$



Double Second Order Generalized Integrator FLL (DSOGI-FLL)

- Instantaneous symmetrical components

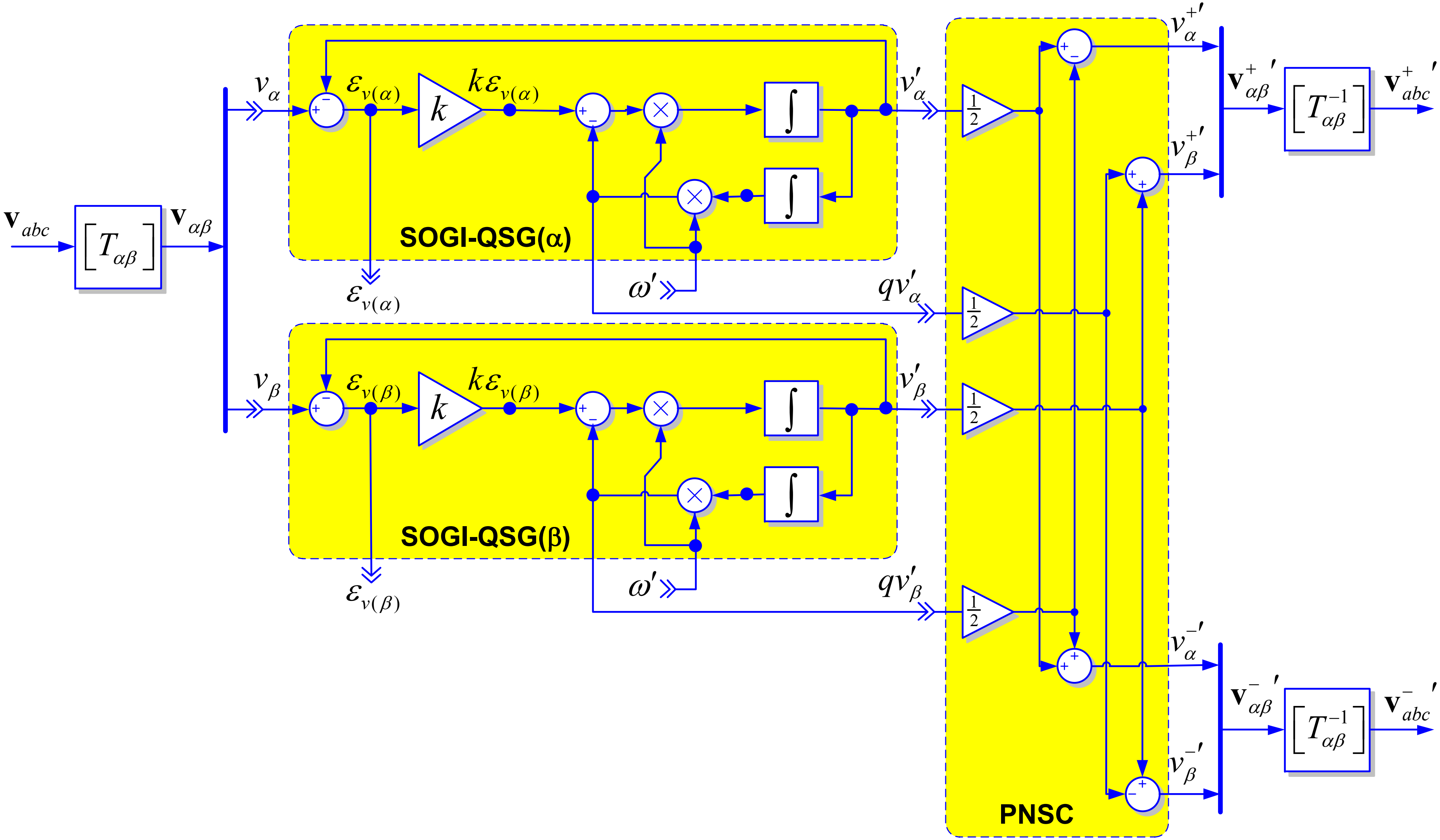
$$\mathbf{v}_{abc} = \mathbf{v}^{+}_{abc} + \mathbf{v}^{-}_{abc} + \mathbf{v}^{0}_{abc} \begin{cases} \mathbf{v}^{+}_{abc} = \left[T_{+}\right]\mathbf{v}_{abc} \quad ; \quad \begin{bmatrix} v_a^{+} \\ v_b^{+} \\ v_c^{+} \end{bmatrix} = \dfrac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \\ \mathbf{v}^{-}_{abc} = \left[T_{-}\right]\mathbf{v}_{abc} \quad ; \quad \begin{bmatrix} v_a^{-} \\ v_b^{-} \\ v_c^{-} \end{bmatrix} = \dfrac{1}{3}\begin{bmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \\ \mathbf{v}^{0}_{abc} = \left[T_{0}\right]\mathbf{v}_{abc} \quad ; \quad \begin{bmatrix} v_a^{0} \\ v_b^{0} \\ v_c^{0} \end{bmatrix} = \dfrac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \end{cases}$$

$$\mathbf{v}^{+}_{\alpha\beta} = \left[T_{\alpha\beta}\right]\left[T_{+}\right]\left[T_{\alpha\beta}\right]^{-1}\mathbf{v}_{\alpha\beta} = \left[T_{\alpha\beta^{+}}\right]\mathbf{v}_{\alpha\beta} \quad ; \quad \left[T_{\alpha\beta^{+}}\right] = \frac{1}{2}\begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix}$$

$$q = e^{-j\frac{\pi}{2}}$$

$$\mathbf{v}^{-}_{\alpha\beta} = \left[T_{\alpha\beta}\right]\left[T_{-}\right]\left[T_{\alpha\beta}\right]^{-1}\mathbf{v}_{\alpha\beta} = \left[T_{\alpha\beta^{-}}\right]\mathbf{v}_{\alpha\beta} \quad ; \quad \left[T_{\alpha\beta^{-}}\right] = \frac{1}{2}\begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix}$$

Structure of the DSOGI



Response of the DSOGI

- DSOGI transfer function

Complex frequency (s=σ+$j\omega$)

$$\mathbf{v}_{\alpha\beta}^{+} = \left[T_{\alpha\beta^{+}}\right]\mathbf{v}_{\alpha\beta} = \frac{1}{2}\begin{bmatrix} D(s) & -Q(s) \\ Q(s) & D(s) \end{bmatrix}\mathbf{v}_{\alpha\beta} = \frac{1}{2}\frac{k\omega'}{s^2 + k\omega' s + \omega'^2}\begin{bmatrix} s & -\omega' \\ \omega' & s \end{bmatrix}\mathbf{v}_{\alpha\beta}$$

Harmonic frequency (s=$j\omega$)

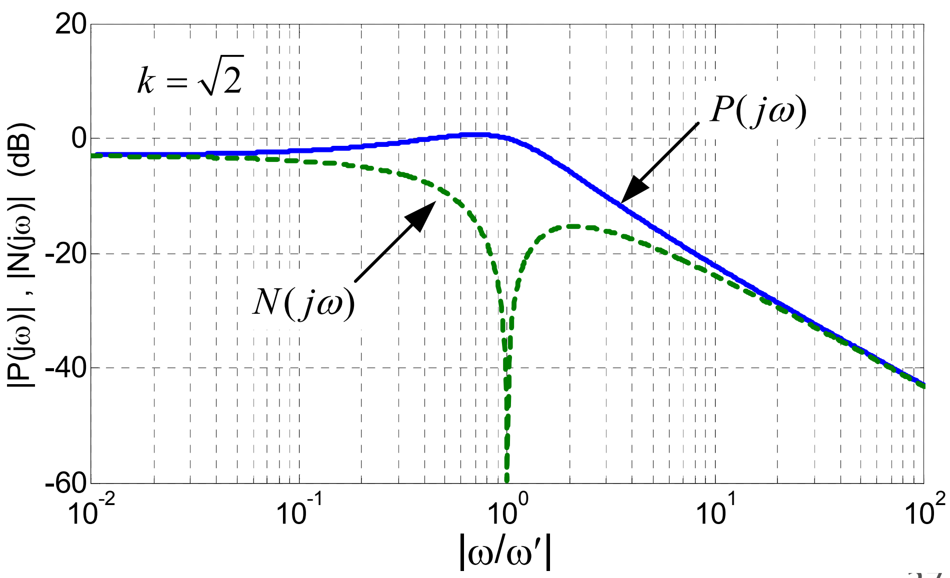
$$\begin{bmatrix} v_{\alpha}^{+} \\ v_{\beta}^{+} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} D(j\omega) & -Q(j\omega) \\ Q(j\omega) & D(j\omega) \end{bmatrix}\begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix} = \frac{1}{2}\frac{k\omega'}{\left(\omega'^2 - \omega^2\right) + jk\omega'\omega}\begin{bmatrix} j\omega & -\omega' \\ -\omega & j\omega \end{bmatrix}\begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix}$$

$$v_{\beta}(j\omega) = -jv_{\alpha}(j\omega)$$

$$\begin{bmatrix} v_{\alpha}^{+} \\ v_{\beta}^{+} \end{bmatrix} = \frac{1}{2}\frac{k\omega'\left(\omega + \omega'\right)}{k\omega'\omega + j\left(\omega^2 - \omega'^2\right)}\begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix}$$

$$P(j\omega) = \left|\mathbf{v}_{\alpha\beta}^{+}{}'\right| \Big/ \left|\mathbf{v}_{\alpha\beta}^{+}\right|$$

$$N(j\omega) = \left|\mathbf{v}_{\alpha\beta}^{+}{}'\right| \Big/ \left|\mathbf{v}_{\alpha\beta}^{-}\right|$$

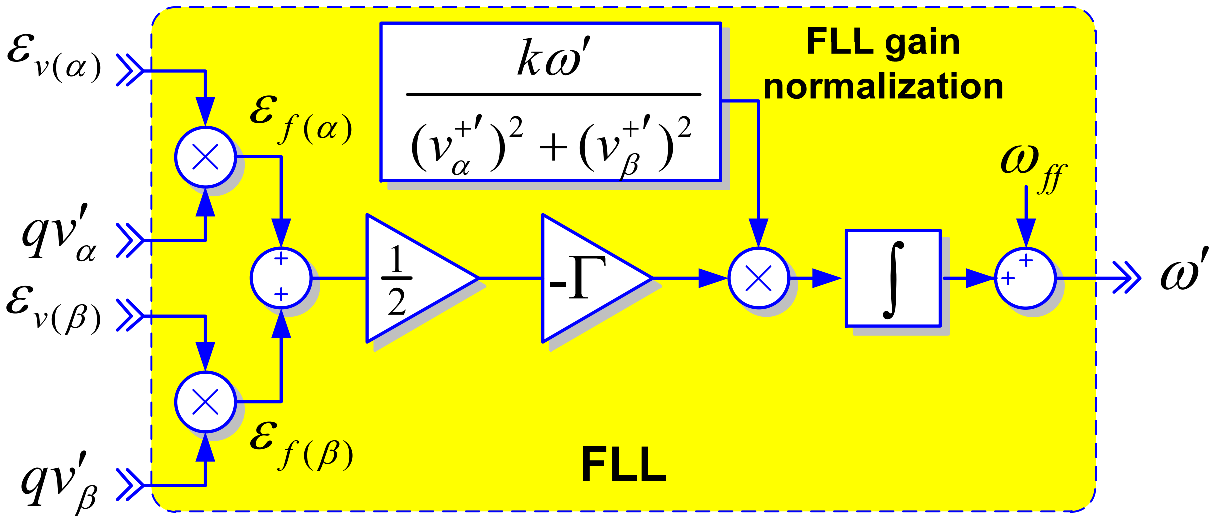


Structure of the FLL for the DSOGI

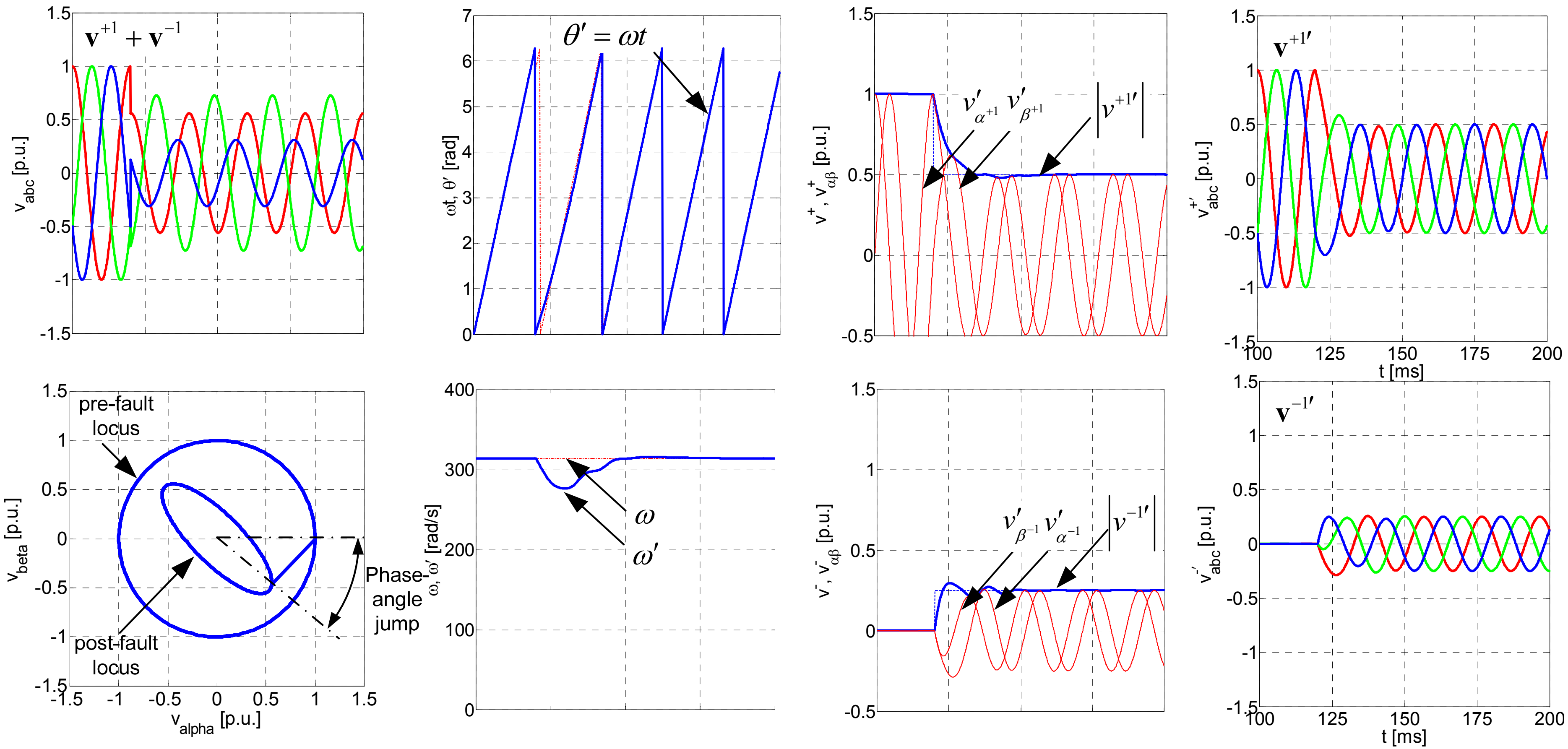
- The use of two independent FLLs in the DSOGI-FLL might seem conceptually odd since its two input signals, v_α and v_β, have the same frequency

- The DSOGI uses a single FLL in which the frequency error signals generated by the QSGs of the α and β signals have been combined by calculating a average error signal.

$$\varepsilon_f = \frac{\varepsilon_{f(\alpha)} + \varepsilon_{f(\beta)}}{2} = \frac{1}{2}\left(\varepsilon_\alpha q v'_\alpha + \varepsilon_\beta q v'_\beta\right)$$

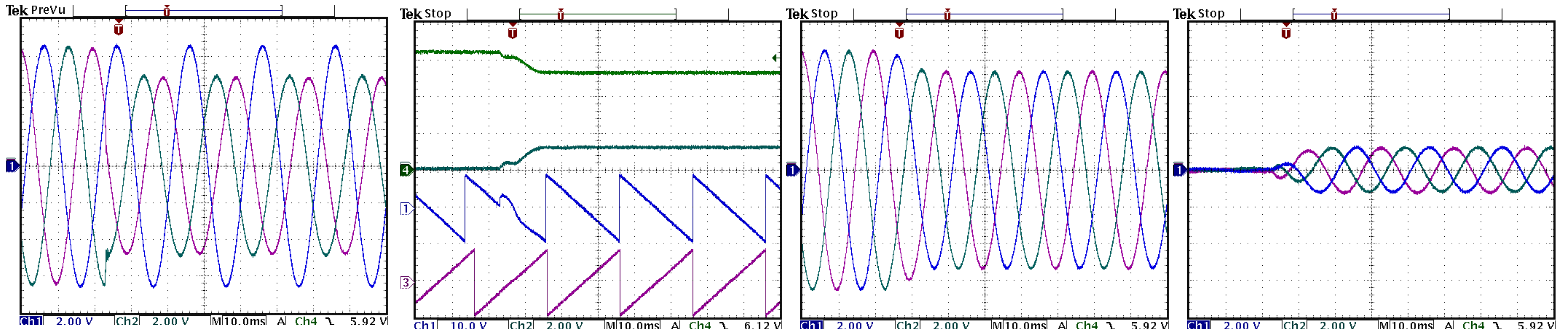


Response of the DSOGI

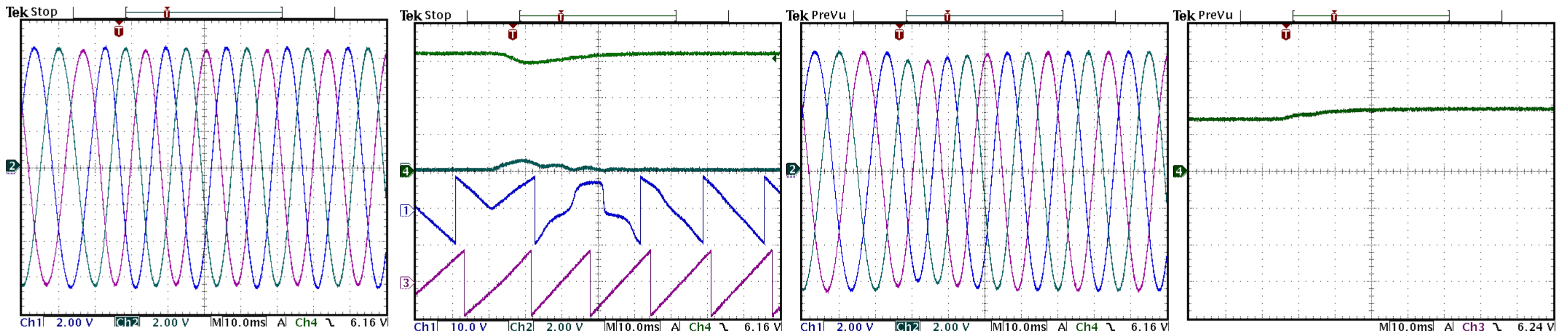


Response of the DSOGI

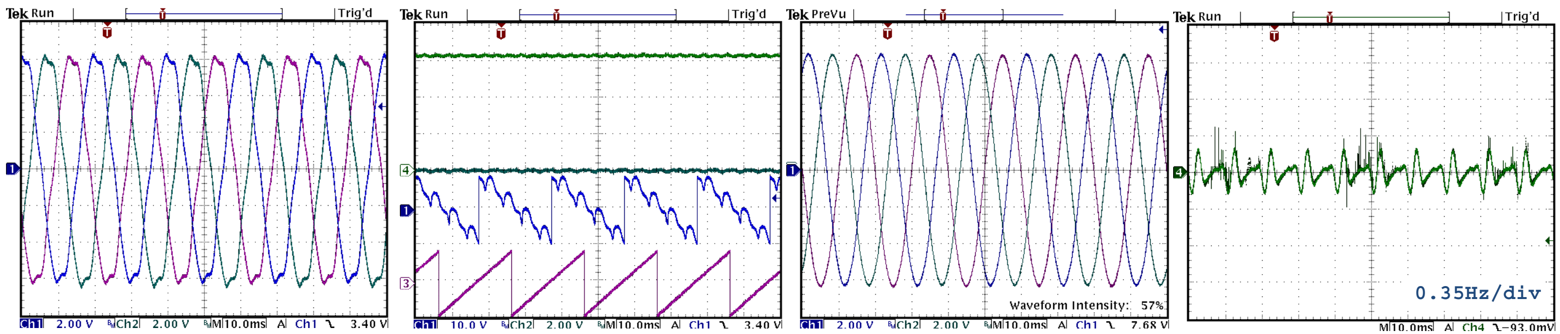
Voltage sag



Frequency variation



Voltage distortion



Conclusion

- Grid synchronization of three-phase power converter is an essential issue to control the delivered active/reactive power and the grid support services
- Conventional SRF-PLL is not the most suitable technique for synchronizing with unbalanced grid voltages during grid faults
- Specific synchronization techniques should be used to estimate the instantaneous positive and negative sequence components of the unbalanced grid voltage during faults
- The DDSRF-PLL makes possible a good synchronization during unbalanced conditions by decoupling axis signals on the positive- and negative-reference frames
- The DSOGI-FLL is a very effective solution, based on adaptive filtering, for grid monitoring and synchronization under generic grid operating conditions