# Grid Synchronization in Power Converters

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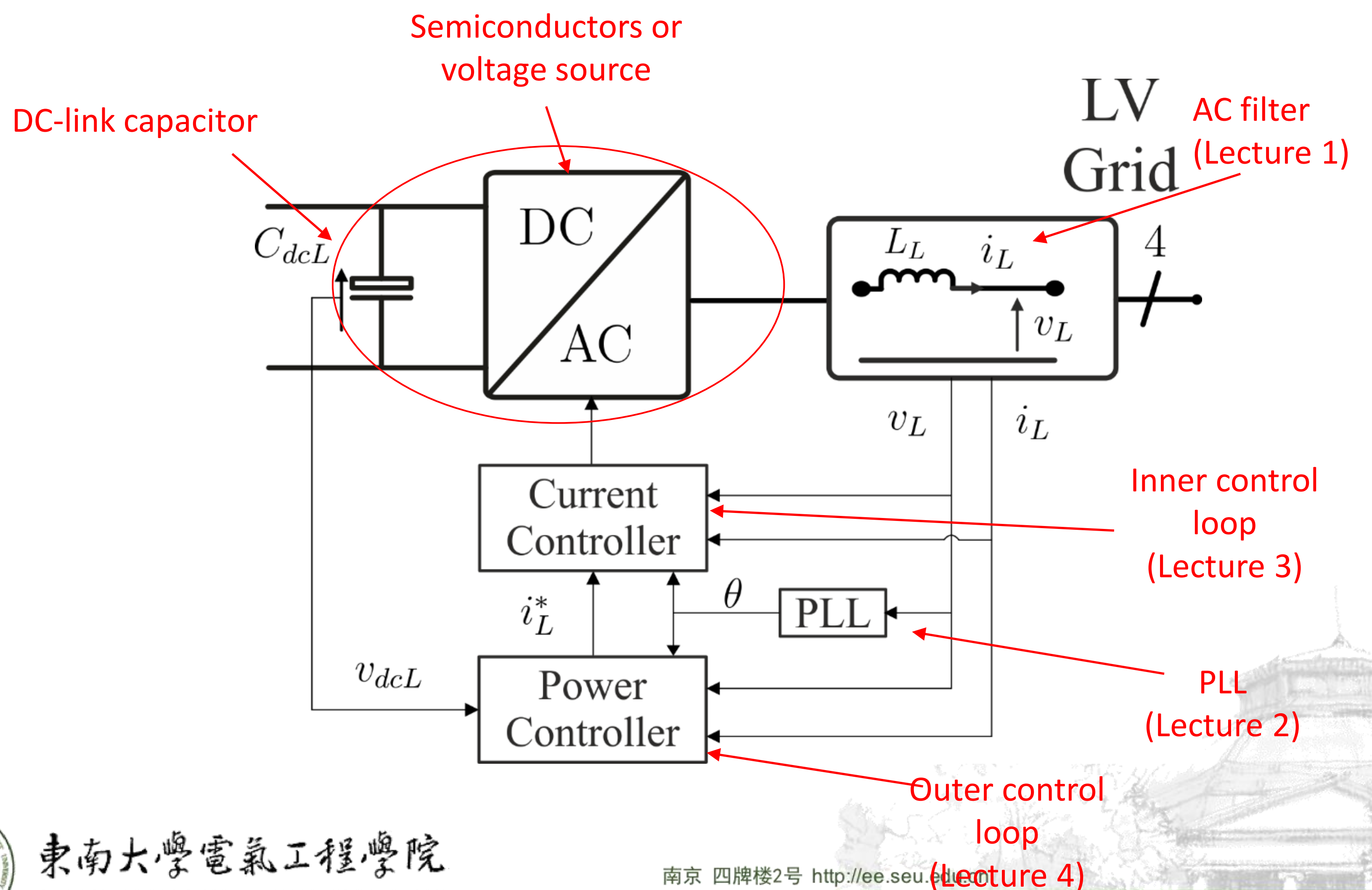
# Key Components of Grid Converters



# Grid Synchronization in Power Converters

- PLL basics and single-phase PLL
- Grid synchronization in three-phase power converters
- PLL-less converter: an introduction

# Grid Synchronization in Power Converters

- PLL basics and single-phase PLL
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# Outline

- PLL Basics
- PLL analysis
- Single-phase PLLs using quadrature signals
- PLLs using adaptive filters
- Conclusions

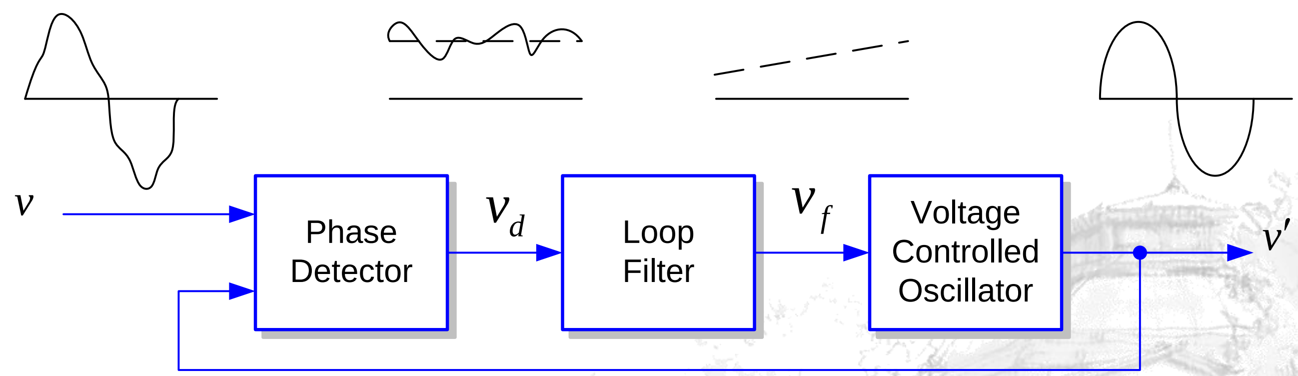
# PLL Basics

Basic blocks:

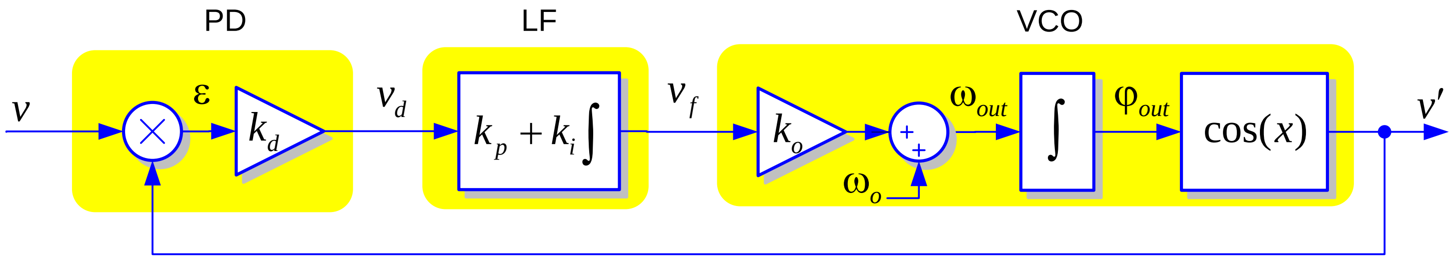
- Phase Detector (PD). This block generates an output signal proportional to the phase difference between its two input signals. Depending on the type of PD, high frequency ac components appear together the dc phase difference signal

- Loop Filter (LF). This block exhibits low pass characteristic and filters out the high frequency ac components from the PD output. Typically this is a 1-st order LPF or PI controller

- Voltage Controlled Oscillator (VCO). This block generates at its output an ac signal whose frequency varies respect a central frequency as a function of the input voltage



# PLL Basics




Phase Detector:

Input signal: $v = A\sin\left(\omega_{in} t + \theta_{in}\right)$

VCO output: $v' = \cos\left(\omega_{out} t + \theta_{out}\right)$

Multiplier PD output:

$$v_d = Ak_d \sin\left(\omega_{in} t + \theta_{in}\right)\cos\left(\omega_{out} t + \theta_{out}\right)$$

$$v_d = \frac{Ak_d}{2}\left[\sin\left(\left(\omega_{in} - \omega_{out}\right)t + \left(\theta_{in} - \theta_{out}\right)\right) + \sin\left(\left(\omega_{in} + \omega_{out}\right)t + \left(\theta_{in} + \theta_{out}\right)\right)\right]$$

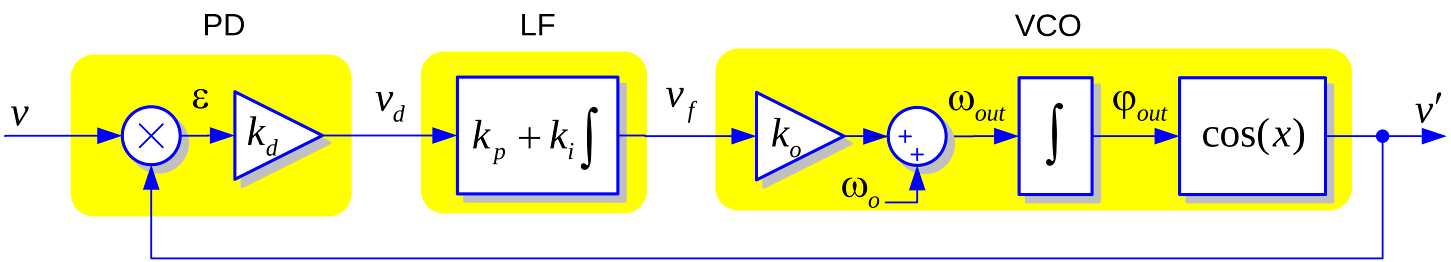
We are only interested in the ‘dc’ term between, whereas the term at twice the center frequency should be canceled out by the LF

$$\bar{v}_d = \frac{Ak_d}{2}\sin\left(\left(\omega_{in} - \omega_{out}\right)t + \left(\theta_{in} - \theta_{out}\right)\right)$$

Let the VCO is tuned with the input frequency, that is $\omega_{in} \approx \omega_{out}$

$$\bar{v}_d = \frac{Ak_d}{2}\sin\left(\theta_{in} - \theta_{out}\right)$$

# PLL Basics




Small signal linearized PD response:

The multiplier PD produces a non-linear phase detection because the sinusoidal function

$$\bar{v}_d = \frac{Ak_d}{2}\sin\left(\theta_{in} - \theta_{out}\right)$$

Let $\theta_{\mathrm{in}} \approx \theta_{out}$ , so: $$\sin\left(\theta_{in} - \theta_{out}\right) \approx \left(\theta_{in} - \theta_{out}\right)$$

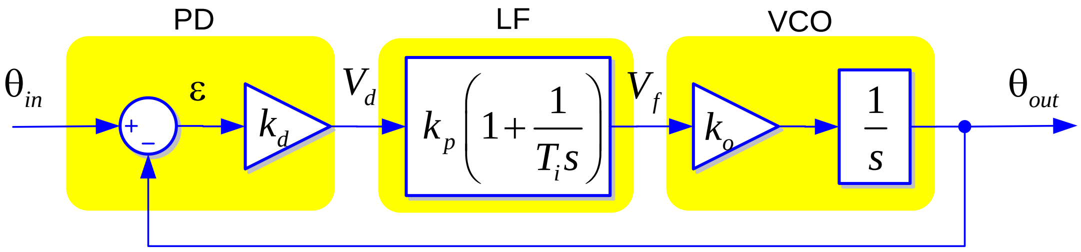
Therefore : $$\bar{v}_d \approx \frac{Ak_d}{2}\left(\theta_{in} - \theta_{out}\right)$$

This equation represents the small signal linearized model of the multiplier PD. Therefore, in the locked state, the multiplier PD represents a zero-order block with gain which is dependent on the input signal amplitude

Small signal model of the VCO: $$\bar{\omega}_{out} = \left(\omega_o + \Delta\bar{\omega}_{out}\right) = \left(\omega_o + k_o \bar{v}_f\right) = \omega_{in} \quad ; \quad \tilde{\omega}_{out} = k_o \tilde{v}_f$$

$$\tilde{\theta}_{out}(t) = \int \tilde{\omega}_{out} dt = \int k_o \tilde{v}_f dt$$

# Linearized Small Signal PLL Model




It will be assumed further that $K_d=K_o=1$ (typically)

$$V_d(s)=\frac{A}{2}\left(\Theta_{in}(s)-\Theta_{out}(s)\right) \qquad V_f(s)=k_p\left(1+\frac{1}{T_i s}\right)V_d(s) \qquad \Theta_{out}(s)=\frac{1}{s}V_f(s)$$

Transfer functions:

Open Loop Phase Transfer Function:

$$F_{OL}(s)=\frac{LF(s)}{s}=\frac{K_p\left(1+\frac{1}{T_i s}\right)}{s}=\frac{k_p s+\frac{k_p}{T_i}}{s^2}$$

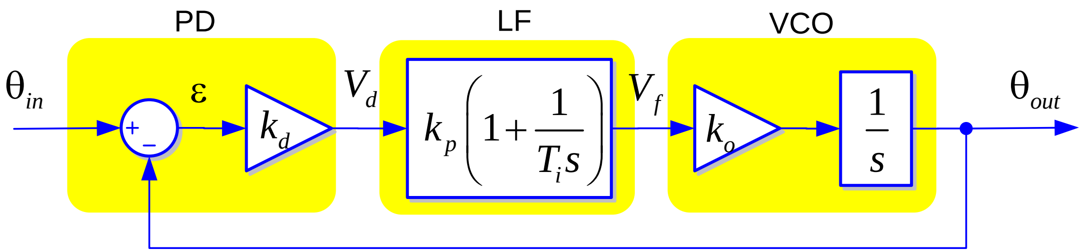
Closed Loop Phase Transfer Function: (low-pass)

$$H_\theta(s)=\frac{\Theta_{out}(s)}{\Theta_{in}(s)}=\frac{LF(s)}{s+LF(s)}=\frac{K_p s+\frac{K_p}{T_i}}{s^2+K_p s+\frac{K_p}{T_i}}$$

Closed Loop Error Transfer Function: (high-pass)

$$E_\theta(s)=\frac{V_d(s)}{\Theta_{in}(s)}=1-H_\theta(s)=\frac{s}{s+LP(s)}=\frac{s^2}{s^2+K_p s+\frac{K_p}{T_i}}$$

# Linearized Small Signal PLL Model

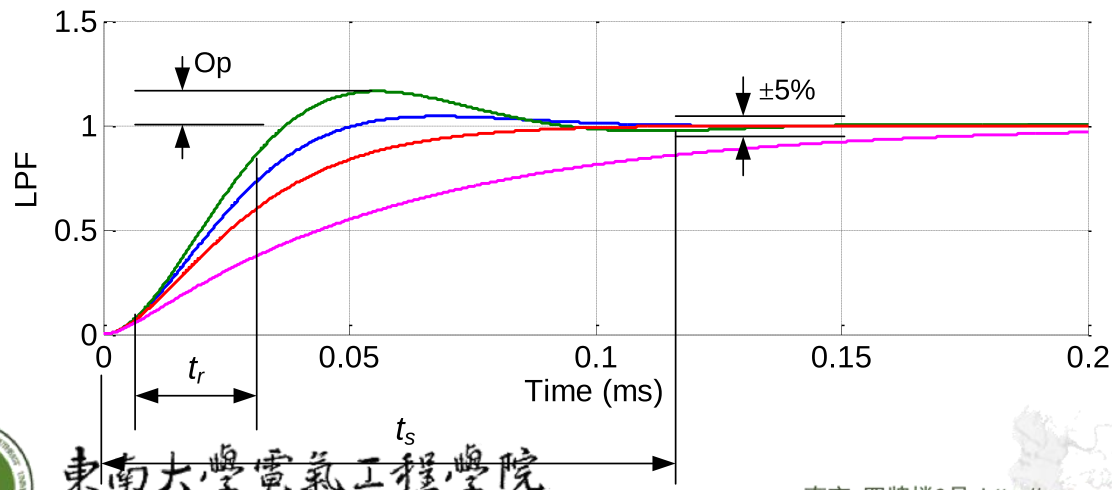



Tuning:

General form of second order transfer functions:

$$H_{\theta}(s)=\frac{2\zeta\omega_n s+\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad E_{\theta}(s)=\frac{s^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad \omega_n=\sqrt{\frac{K_p}{T_i}};\quad \xi=\frac{\sqrt{K_pT_i}}{2}$$

Standard specifications for second order systems without zeros as a rough approximation that should give a 5% overshoot at step response



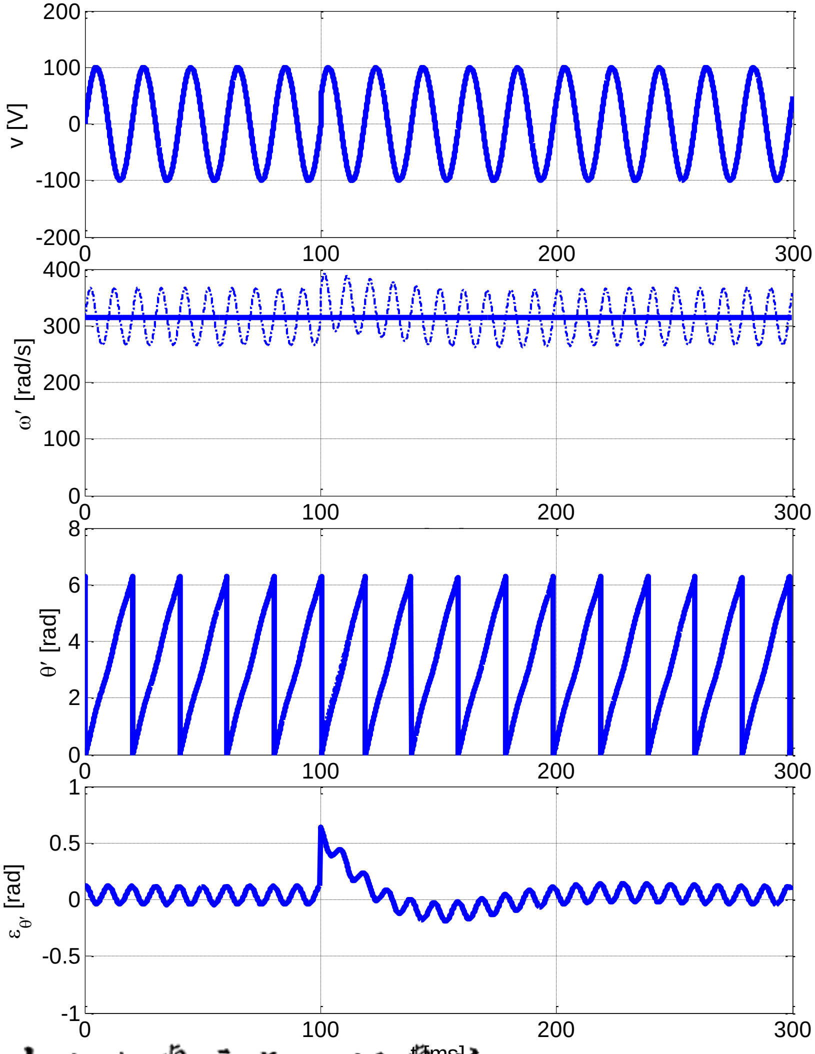

$$\xi=\frac{1}{\sqrt{2}}$$

$$t_s=\frac{4.6}{\xi\omega_n}\quad;\quad t_r=\frac{1.8}{\omega_n}$$

$$K_p=2\xi\omega_n\ ;\quad T_i=\frac{2\xi}{\omega_n}$$

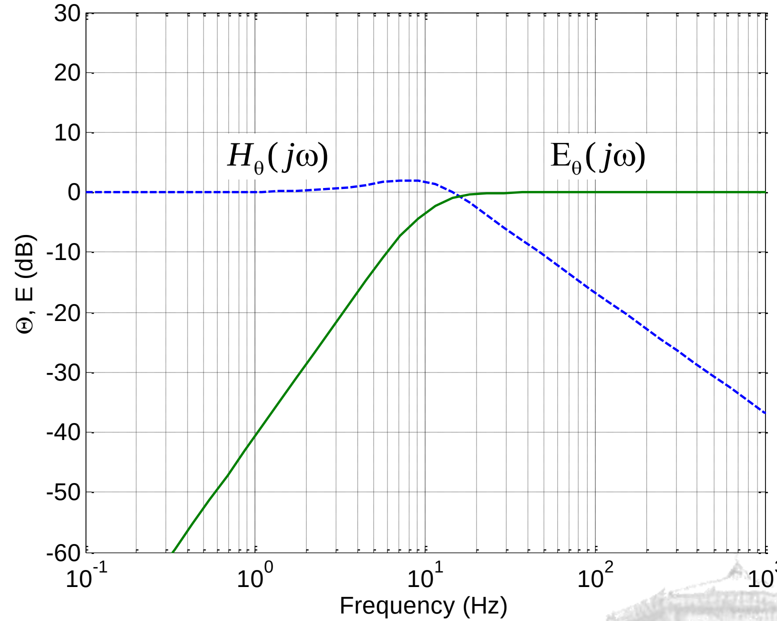
$$K_p=\frac{9.2}{t_s}\quad;\quad T_i=\frac{t_s\xi^2}{2.3}$$

# Basic PLL Model Response




$$\xi = \frac{1}{\sqrt{2}} \quad ; \quad t_s = 100ms$$

$$\xi = \frac{1}{\sqrt{2}} \quad ; \quad \omega_n = 10.34Hz$$




$$\omega_{3dB} = \omega_n \left[ 1 + 2\xi^2 + \sqrt{(1+2\xi)^2 + 1} \right]^{1/2}$$

$$\xi = \frac{1}{\sqrt{2}} \quad ; \quad \omega_{3dB} = 2.06\omega_n$$

# Key Parameters of PLL

- The hold range $\Delta\omega_H$ is the frequency range at which a PLL is able to maintain lock statically

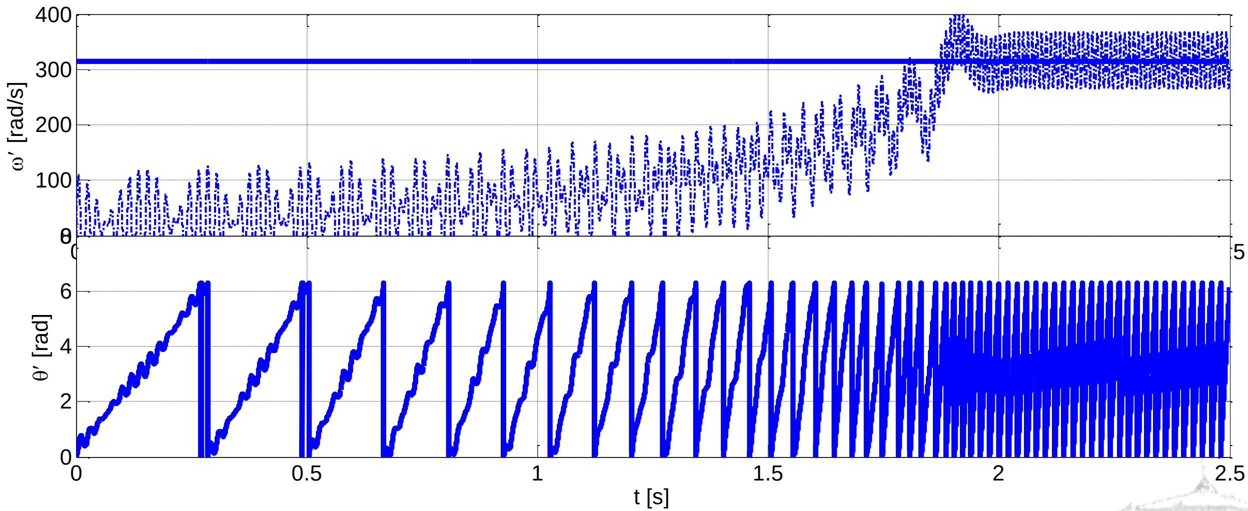
$$\Delta\omega_H = K_o K_d LF(0)$$

For the PI, *LF(0)*=∞ and the hold range is only limited by the frequency range of the VCO

- The pull-in range $\Delta\omega_P$ is the frequency range at which a PLL will always became locked, but the process can become rather slow. For the PI loop filter this range trends to infinite

Pull-in time:

$$T_P \approx \frac{\pi^2}{16}\frac{\Delta\omega_{in}^2}{\xi\omega_n^3}$$




- The lock range $\Delta\omega_L$ is the frequency range within which a PLL locks within one-single beat note between the reference frequency and the output frequency

$$\Delta\omega_L \approx 2\xi\omega_n \approx 2\xi\sqrt{\frac{k_p}{T_i}}$$

Lock-in time: $T_L \approx \dfrac{2\pi}{\omega_n}$

# PLL with Orthogonal Input Signal

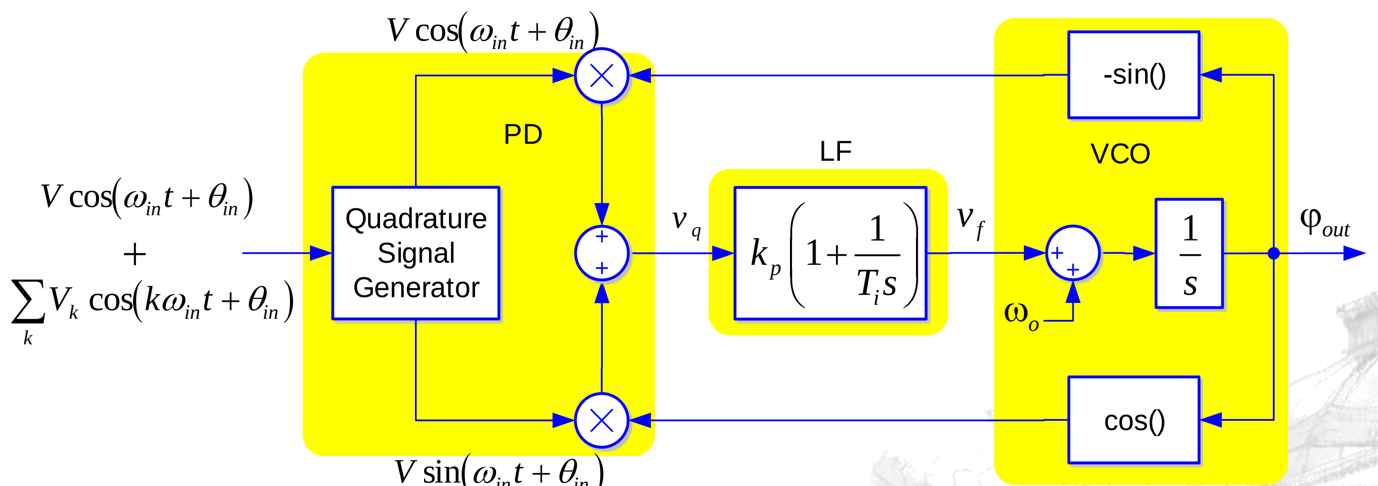
Even though input frequency is locked, multiplier PD gives rise to oscillations in the detected phase-angle error signal at twice the input frequency

LF bandwidth should be limited in order to attenuate oscillations at $\omega_{in}+\omega_{out}$ in the detected phase-angle error signal

From orthogonal sinusoidal signals we have:

$$V sin(\omega_{in}t+\theta_{in})cos(\omega_{out}t+\theta_{out})-V cos(\omega_{in}t+\theta_{in})sin(\omega_{out}t+\theta_{out})=V sin\big((\omega_{in}-\omega_{out})t+(\theta_{in}-\theta_{out})\big)$$

Assuming operation in the lock rang, i.e., $\omega_{in}=\omega_{out}$: $v_q=V sin(\theta_{in}-\theta_{out})$



# Park Transformation in PD

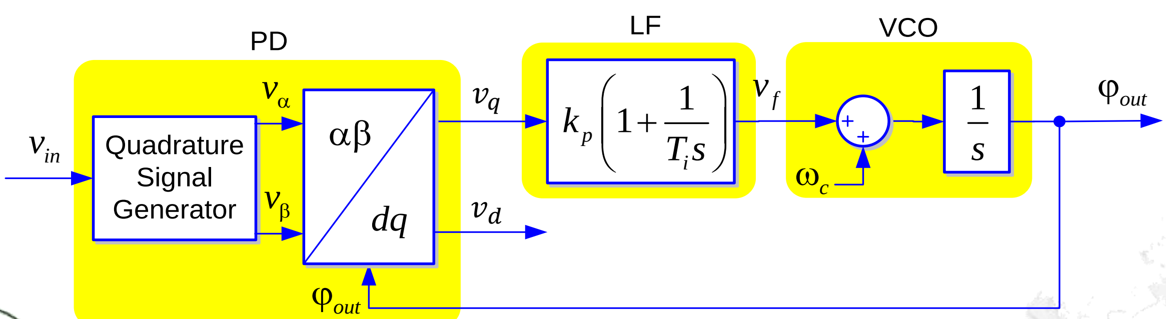
Park transformation:

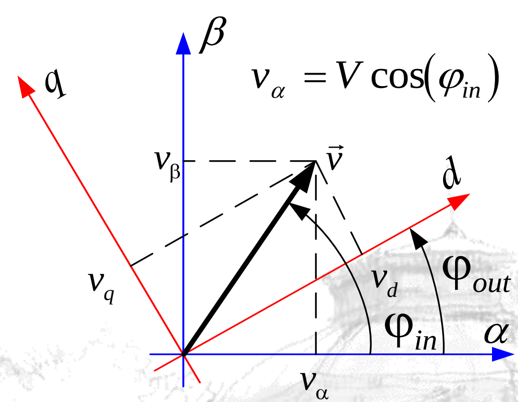
$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = V \begin{bmatrix} cos(\varphi_{out}) + sin(\varphi_{out}) \\ -sin(\varphi_{out}) + cos(\varphi_{out}) \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \qquad \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = V \begin{bmatrix} cos(\varphi_{in}) \\ sin(\varphi_{in}) \end{bmatrix}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = V \begin{bmatrix} cos(\varphi_{out})cos(\varphi_{in}) + sin(\varphi_{out})sin(\varphi_{in}) \\ -sin(\varphi_{out})cos(\varphi_{in}) + cos(\varphi_{out})sin(\varphi_{in}) \end{bmatrix} = V \begin{bmatrix} cos(\varphi_{in} - \varphi_{out}) \\ sin(\varphi_{in} - \varphi_{out}) \end{bmatrix}$$

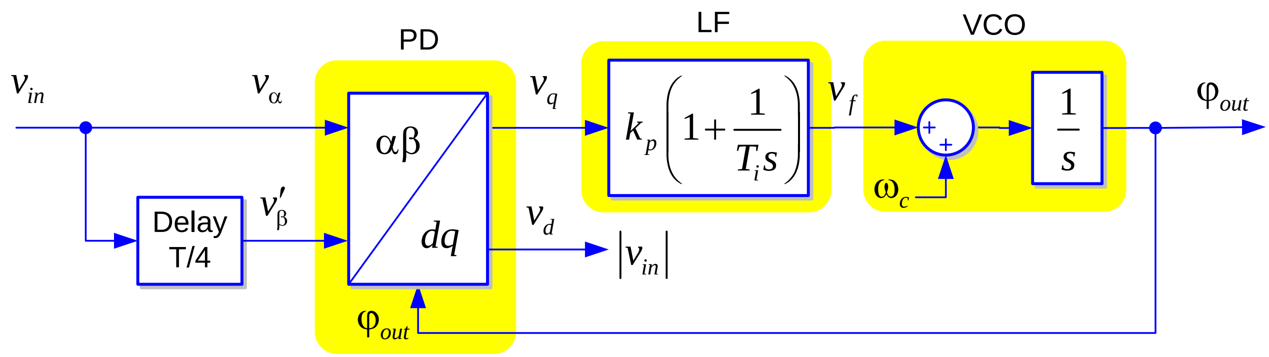
Assuming $\omega_{in}=\omega_{out}$ :

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = V \begin{bmatrix} cos(\theta_{in} - \theta_{out}) \\ sin(\theta_{in} - \theta_{out}) \end{bmatrix}$$



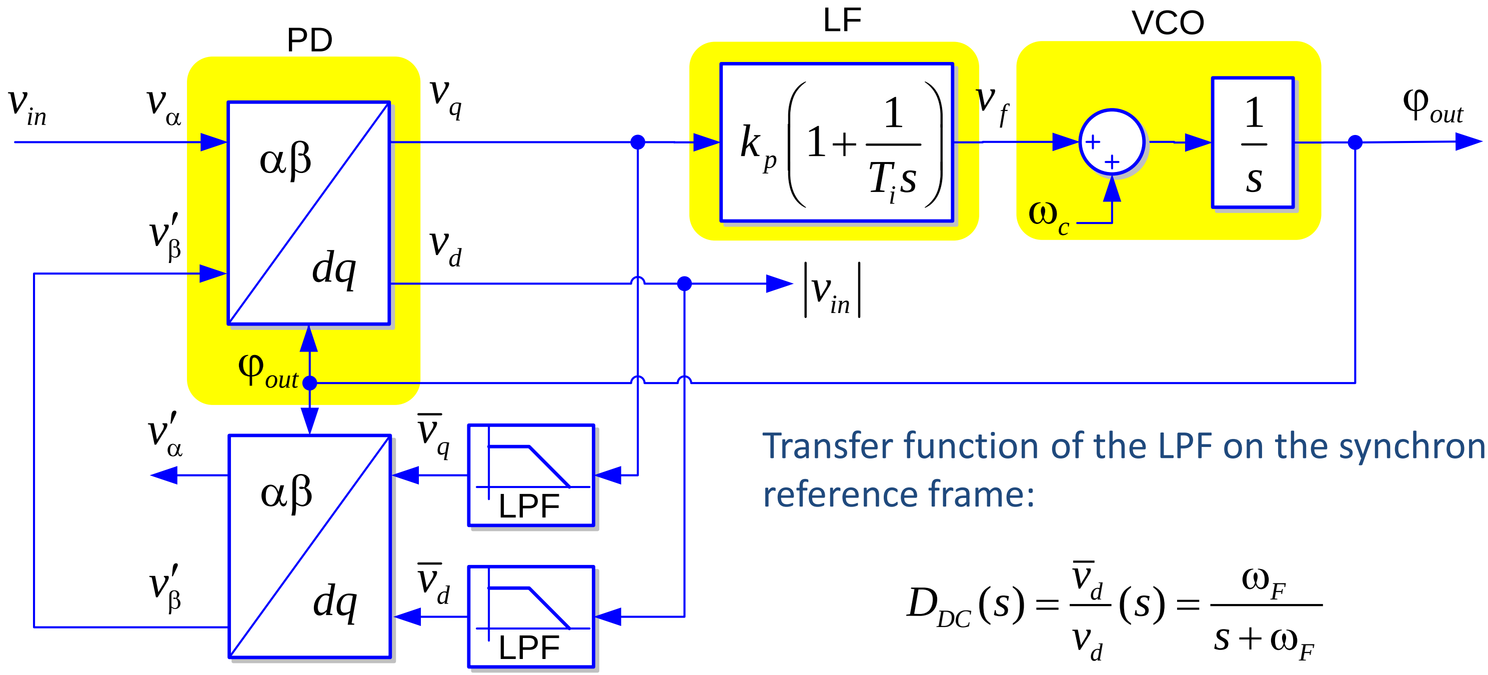



# QSG Based on Transport Delay




- The transport delay block is easily implemented through the use of a first-in-first-out (FIFO) buffer, with size set to one fourth the number of samples contained in one cycle of the fundamental frequency
- This method works fine for fixed grid frequency. If the grid frequency is changing with for ex +/-1 Hz, then the PLL will produce an error
- If input voltage consists of several frequency components, orthogonal signals generation will produce errors because each of the components should be delayed one fourth of its fundamental period

# QSG Based on Inverse Park Transformation




Transfer function of the LPF on the synchronous reference frame:

$$D_{DC}(s)=\frac{\bar{v}_d}{v_d}(s)=\frac{\omega_F}{s+\omega_F}$$

Transfer function of the LPF on the stationary reference frame:

$$B_{AC}(s)=\frac{V_\beta{}'}{V_\alpha}(s)=\frac{k\omega_o^2}{s^2+sk\omega_o+\omega_o^2}\quad ;\quad k=\frac{\omega_f}{\omega_o}$$

$$A_{AC}(s)=\frac{V_\alpha{}'}{V_\alpha}(s)=\frac{sk\omega_o}{s^2+sk\omega_o+\omega_o^2}\quad ;\quad k=\frac{\omega_f}{\omega_o}$$

$$\left.\begin{aligned} v'_\alpha &= \bar{v}_d\cos(\omega' t)-\bar{v}_q\sin(\omega' t)\\ v'_\beta &= \bar{v}_d\sin(\omega' t)+\bar{v}_q\cos(\omega' t)\end{aligned}\right\} V_\alpha{}'(s)=\frac{s}{\omega_o}V_\beta{}'(s)$$

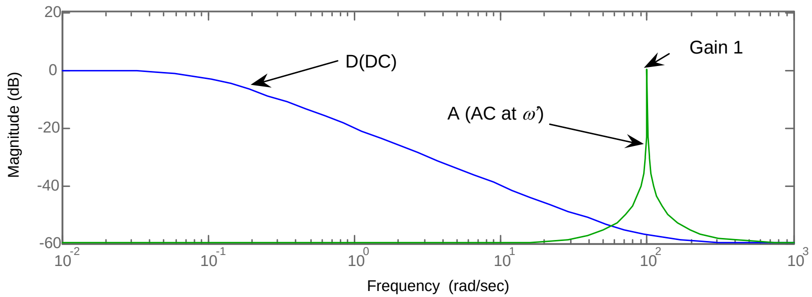
# F(s) From Stationary to Synchronous Frame

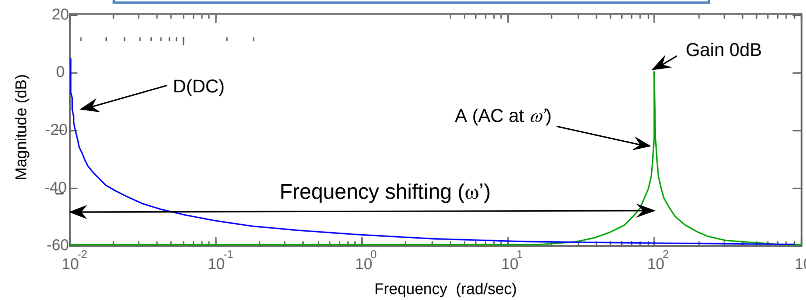
synchronous reference frame

$$D_{DC}(s)=\frac{\bar{v}_d}{v_d}(s)=\frac{\omega_F}{s+\omega_F}$$

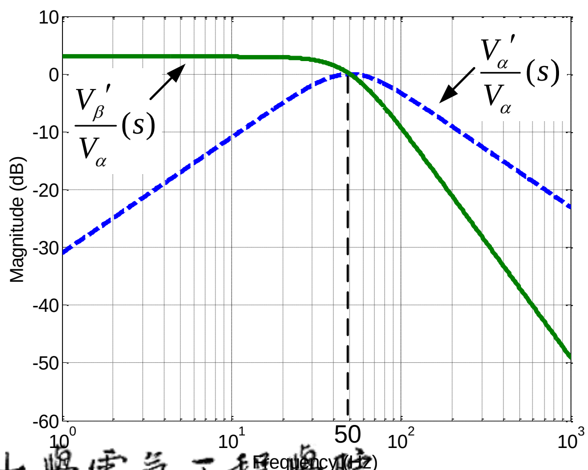
stationary reference frame

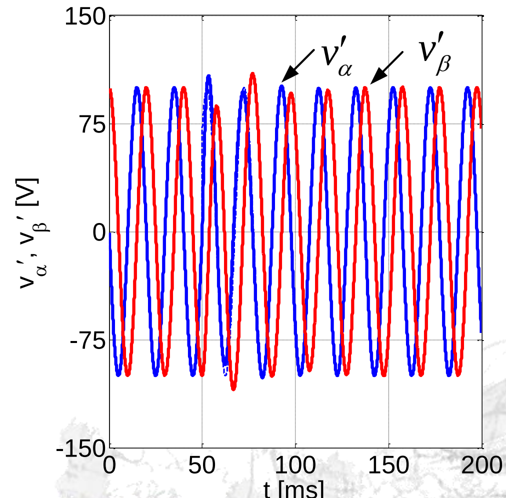
$$A_{AC}(s)=\frac{V_\alpha'}{V_\alpha}(s)=\frac{sk\omega_o}{s^2+sk\omega_o+\omega_o^2}$$




Frequency and time response:



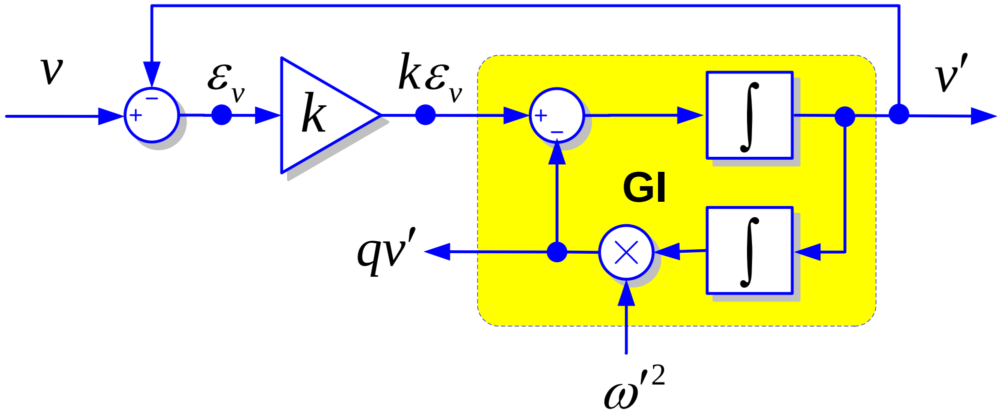
# The Generalized Integrator

The GI is a mathematical concept that stems from the principle that the time-domain convolution product of a function by itself gives rise to the original function multiplied by the time variable.

$$GI(s) = \frac{s}{s^2 + \omega'^2}$$

This transfer function will act as an 'amplitude integrator' for any sinusoid with frequency ω' applied to its input

Resulting adaptive filter:




$$\boxed{D(s) = \frac{v'}{v}(s) = \frac{ks}{s^2 + ks + \omega'^2}}$$

$$\boxed{Q(s) = \frac{qv'}{v}(s) = \frac{k\omega'^2}{s^2 + ks + \omega'^2}}$$

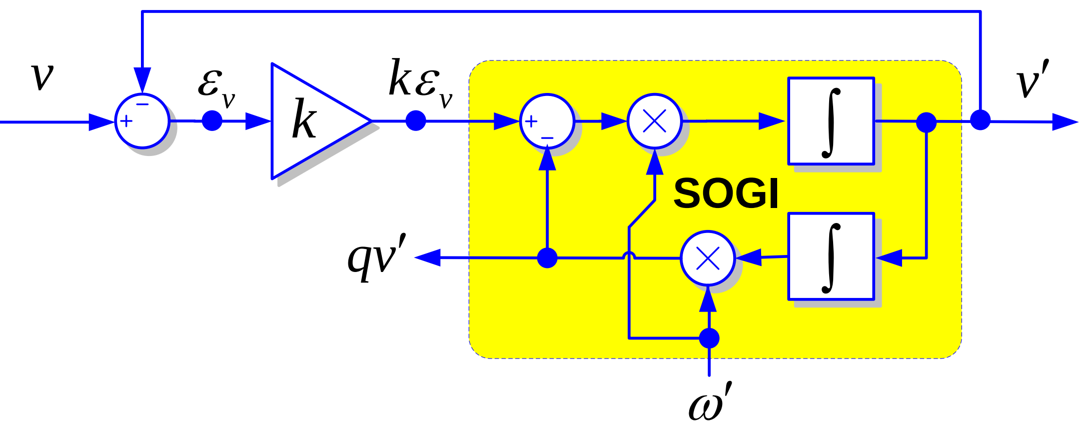
v' and qv' signals are in-quadrature. However, the GI is not the most suitable choice to implement a frequency-variable adaptive filter, since both the bandwidth and the static gain of D(s) and Q(s) are not only a function of the gain k, but they also depend on the center frequency of the filter.

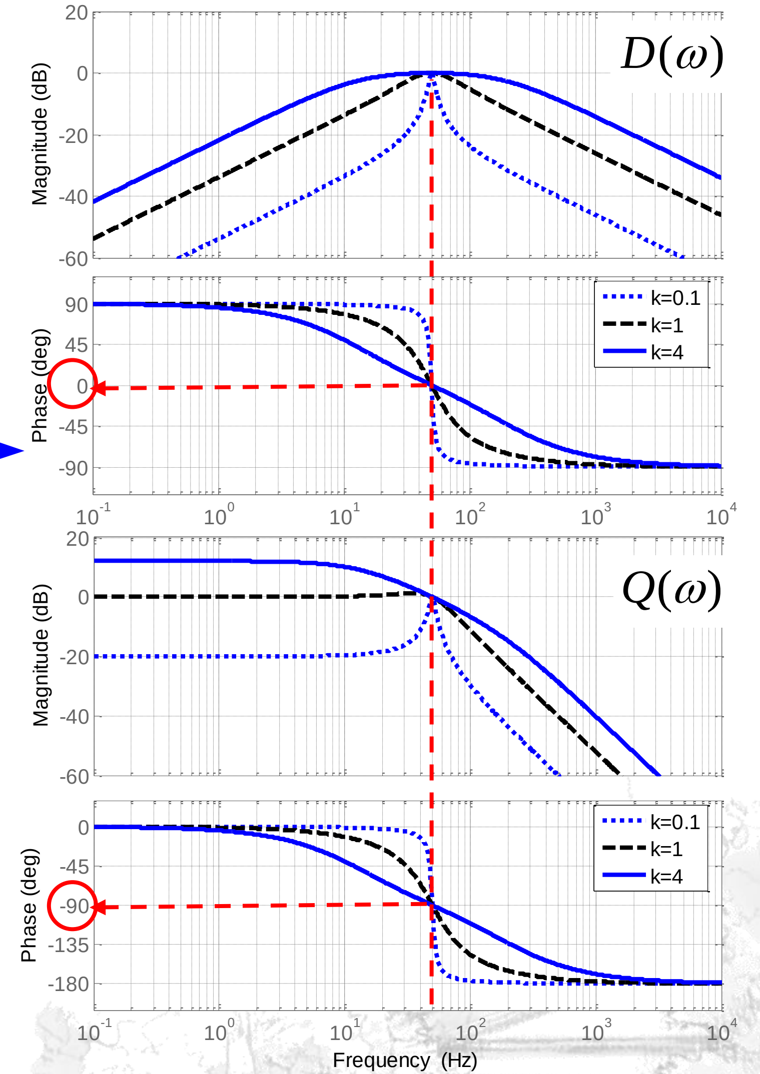
# Second Order Generalized Integrator (SOGI)

The SOGI, an alternative generalized integrator is proposed to achieve the following transfer function:

$$SOGI(s) = \frac{\omega' s}{s^2 + \omega'^2}$$

Resulting adaptive filter:



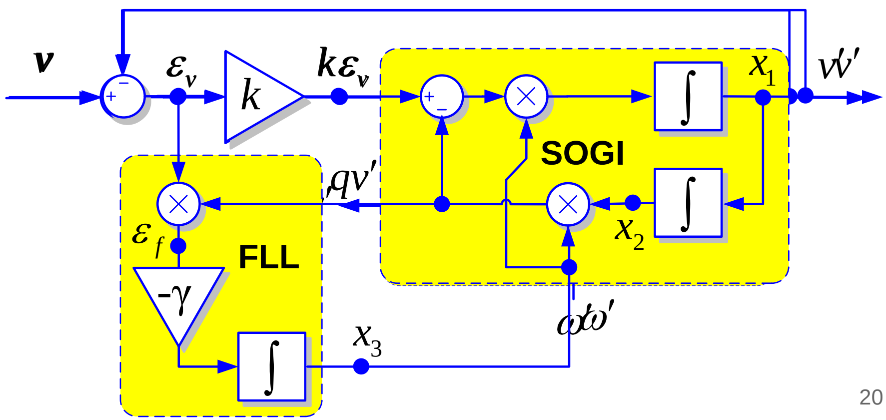

$$D(s) = \frac{v'}{v}(s) = \frac{k\omega' s}{s^2 + k\omega' s + \omega'^2}$$

$$Q(s) = \frac{qv'}{v}(s) = \frac{k\omega'^2}{s^2 + k\omega' s + \omega'^2}$$

$$t_{s(AF)} = \frac{10}{k\omega'}$$

$$\xi = \frac{1}{\sqrt{2}}$$

# The Frequency Locked Loop (FLL)



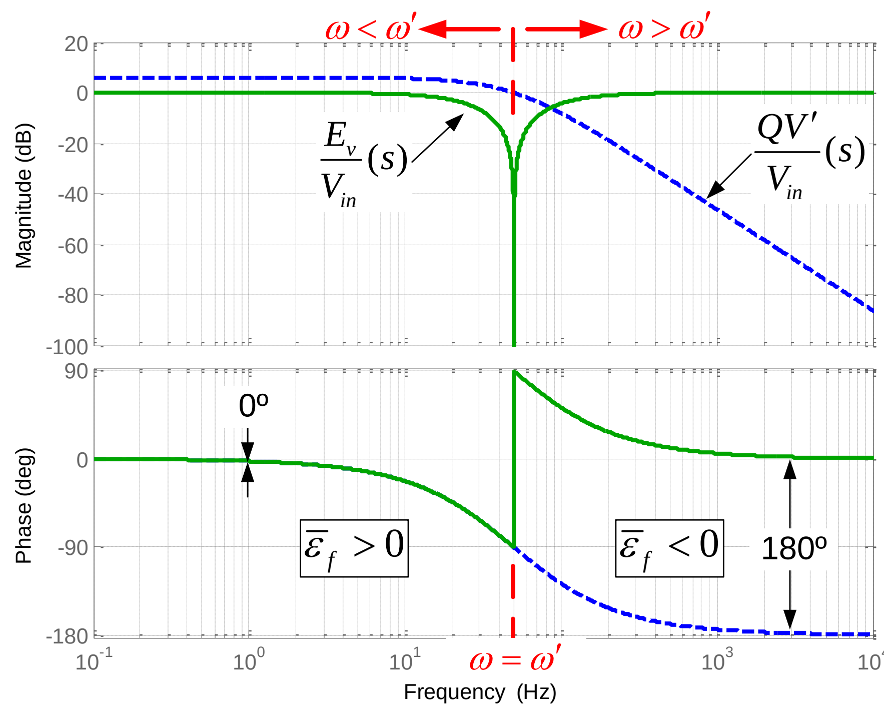

$$D(s)=\frac{v'}{v}(s)=\frac{k\omega' s}{s^2+k\omega' s+\omega'^2}$$

$$Q(s)=\frac{qv'}{v}(s)=\frac{k\omega'^2}{s^2+k\omega' s+\omega'^2}$$

$$E(s)=\frac{\varepsilon_v}{v}(s)=\frac{s^2+\omega'^2}{s^2+k\omega' s+\omega'^2}$$

- If a frequency error variable $e_f$ is defined as the product of qv' by $\varepsilon_v$, the average value of $\varepsilon_f$ will be positive when $\omega<\omega'$, zero when $\omega=\omega'$ and negative when $\omega>\omega'$

- An integral controller with a negative gain -γ, can be used to make zero the dc component of $\varepsilon_f$ by shifting the AF resonance frequency $\omega'$ until matching the input frequency $\omega$



# Conclusions

- Grid monitoring is performed by grid-converters to determine connection conditions and to support grid services
- Grid synchronization allows a right instantaneous interaction between the power converter and the grid
- PLL is a very useful method that enable the grid inverters to:
  - Create a "clean" current reference synchronized with the grid
  - Comply with the grid monitoring standards
- The PLL generate is able to track the frequency and phase of the input signal in a designed settling time
- By setting a higher settling time a "filtering" effect can be achieved in order to obtain a "clean" reference even with a polluted grid
- Some PLLs need two signals in quadrature at the input
- For single-phase systems as there is only one signal available, the orthogonal signal needs to be created artificially
- Transport Delay, Inverse Park Transformation, or Second Order Generalized Integrators are some the methods used for quadrature signal generation
- FLL based on a SOGI is a very effective method for single phase synchronization

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# Outline

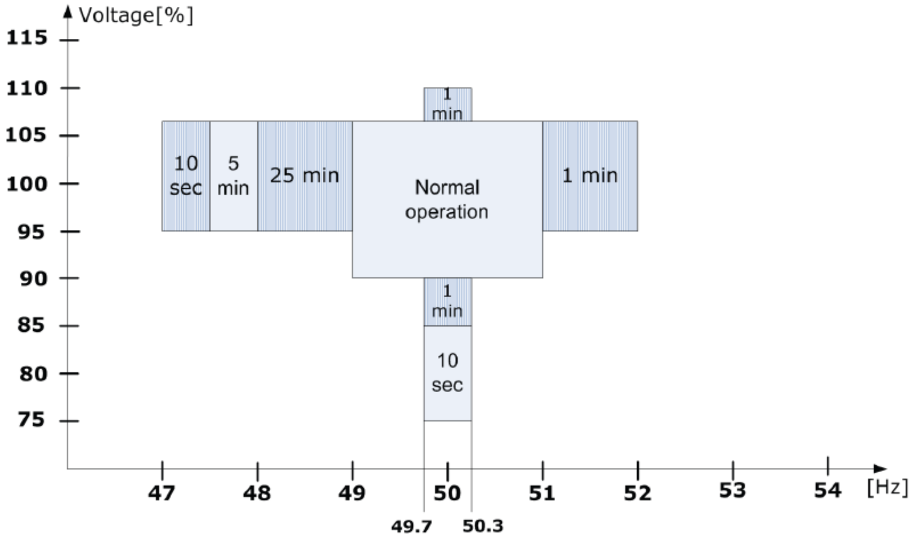
- Grid Monitoring
- Grid Disturbances. Unbalanced Grid Faults
- SRF-PLL
- DDSRF-PLL
- DSOGI-PLL
- DSOGI-FLL
- Conclusions

# Grid Monitoring

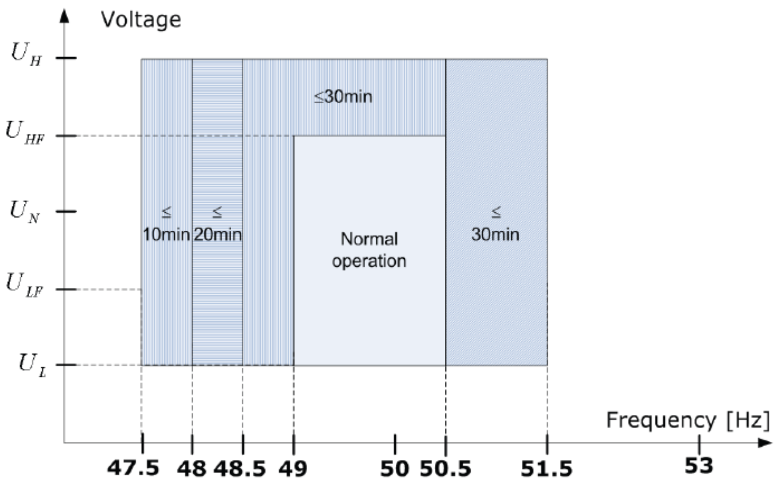
WT generators shall be designed to deliver power for a specified range of voltages and frequencies.

- Monitoring is based on grid connection requirements
- Boundaries for voltage and frequency are defined around their nominal values
- On-line Information from WT monitoring increasingly important for daily operation management in power plants, future distributed network planning and grid control

Voltage and frequency boundaries according to Energinet.dk

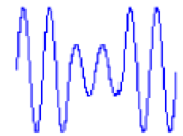
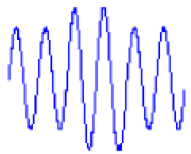
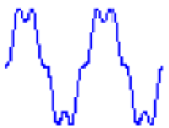
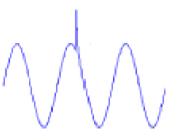
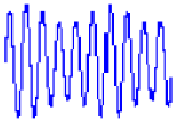
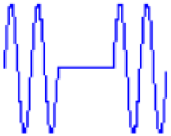
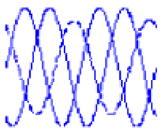



Voltage and frequency boundaries according to EoN



# Grid Disturbances

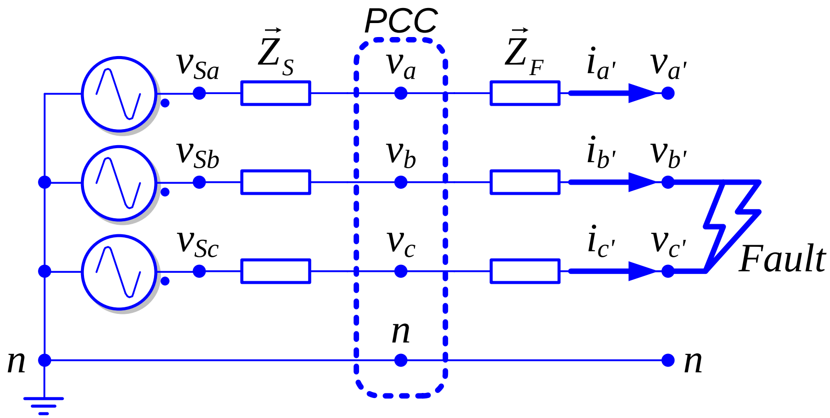
Grid disturbances are not at all a new issue, and the utilities are aware of them. However, they have to take a new look because of the rapidly changing customers' needs and the nature of loads (CIGRE WG14-31, 1999)

| Disturbance | | Origin | Consequences |
|---|---|---|---|
| Voltage sag undervoltage<br><br>2.2 |  | Short circuits in the network grid passing or on another radial.<br>Start up of large motors | Disconnection of sensitive loads<br>Fail functions. |
| Voltage swell Overvoltages<br><br>2.3 |  | Earth fault on another phase<br>Shut down of large loads<br>Lightning strike on net-work structure<br>Incorrect setting in sub-stations | Ageing of insolation<br>Disconnection of equipment<br>May harm equip-ment with inadequate design margins |
| Harmonic dis-tortion<br><br>5.2-5.3 |  | Nonlinear loads<br>Resonance-phenomena<br>Transformer saturation<br>Notches | Extended heating .<br>Fail function of electronic equipment |
| Transients<br><br>1.1-1.2 |  | Lightning strike<br>Switching event | Insulation failure<br>Reduced lifetime of transformers, motors etc. |
| Voltage-fluctuations/ flicker<br><br>6.0 |  | Arc furnaces<br>Sawmill, crushing mill<br>Welding<br>Wind turbines<br>Start up of large motors | Ageing of insulation<br>Fail functions<br>Flicker |
| Short duration interruptions<br><br>2.1 |  | Direct short circuit<br>Disconnection<br>False tripping<br>Load shedding | Disconnection<br><br>Disconnection |
| Unbalanced<br><br>4.0 |  | One phase loads<br>Weak connections in the network | Voltage quality for overloaded phase<br>Overload and noise from 3-phase equip-ment |

# Unbalanced Grid Faults

**What are the unbalanced grid voltages and how they are generated?**

Line-to-line fault




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

Symmetrical components

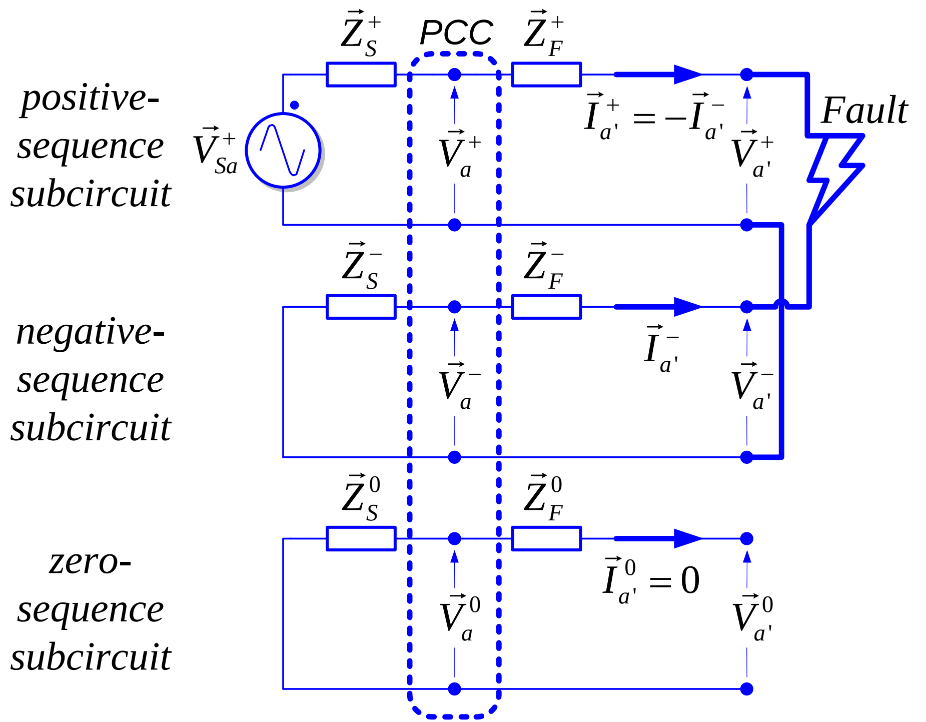
$$\mathbf{V}_{+-0(a')} = \begin{bmatrix} \vec{V}_{a'}^{+} \\ \vec{V}_{a'}^{-} \\ \vec{V}_{a'}^{0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \vec{V}_{a'} \\ \vec{V}_{b'} \\ \vec{V}_{c'} \end{bmatrix} = \frac{1}{3}\begin{bmatrix}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

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

# Unbalanced Grid Faults

## What are the unbalanced grid voltages and how they are generated?

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 Faults

## What are the unbalanced grid voltages and how they are generated?

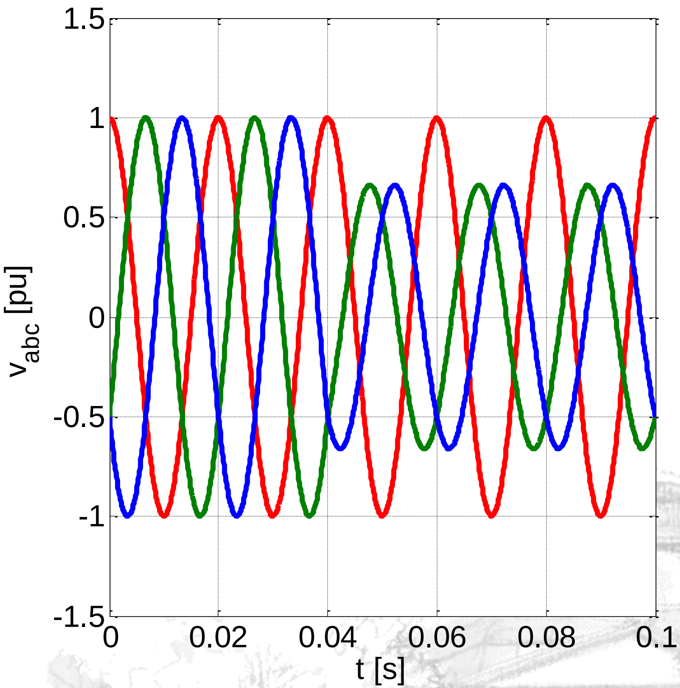
Sag characteristic parameter

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

Unbalanced voltage at the PCC

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

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

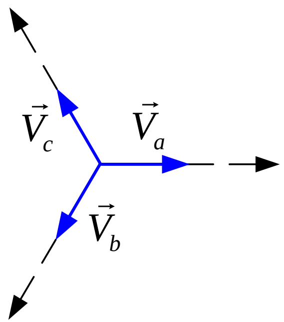


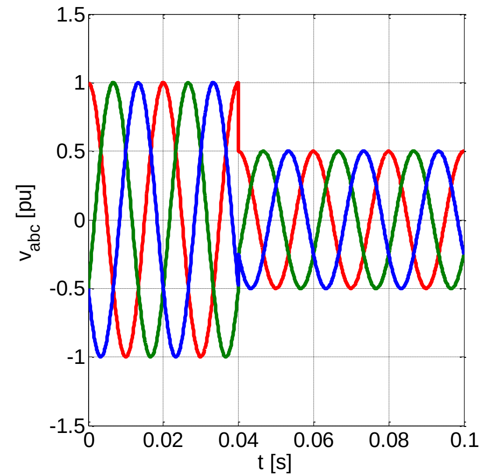
# Unbalanced Grid Faults

## Types of voltage sags [2]

### Sag A

Three-phase fault



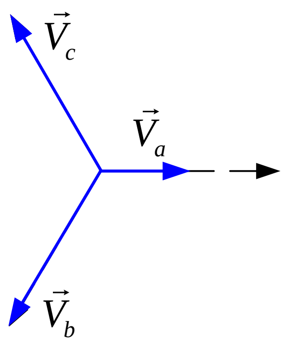

$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix} = \begin{bmatrix}1\\ -\frac{1}{2}-j\frac{\sqrt{3}}{2}\\ -\frac{1}{2}+j\frac{\sqrt{3}}{2}\end{bmatrix}\vec{D}\vec{V}_{Sa}^{+},$$

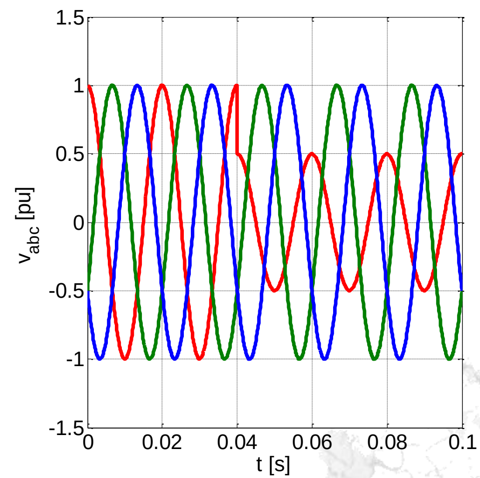
$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix} = \begin{bmatrix}1\\ 0\\ 0\end{bmatrix}\vec{D}\vec{V}_{Sa}^{+},$$

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

### Sag B

Single-phase to ground fault




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

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

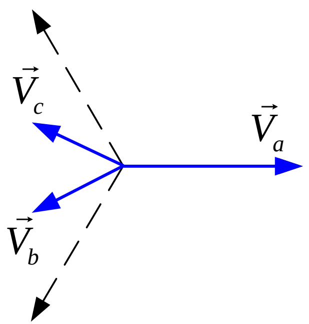
$$\vec{D} = \frac{\vec{Z}_F^{+}+\vec{Z}_F^{-}+\vec{Z}_F^{0}}{3\vec{Z}_S+\vec{Z}_F^{+}+\vec{Z}_F^{-}+\vec{Z}_F^{0}}$$

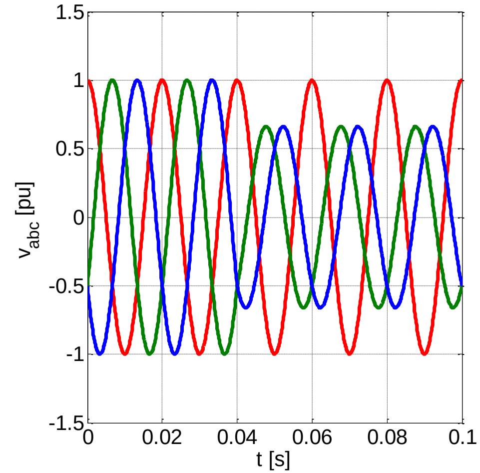
# Unbalanced Grid Faults

## Types of voltage sags

### Sag C

Phase-to-phase fault



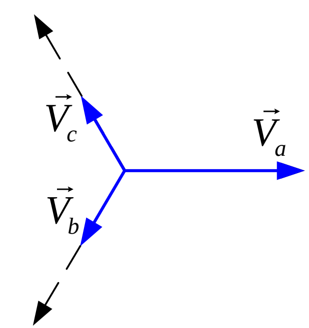

$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix} = \begin{bmatrix}1\\ -\frac{1}{2} - j\frac{\sqrt{3}}{2}\vec{D}\\ -\frac{1}{2} + j\frac{\sqrt{3}}{2}\vec{D}\end{bmatrix}\vec{V}_{Sa}^{+},$$

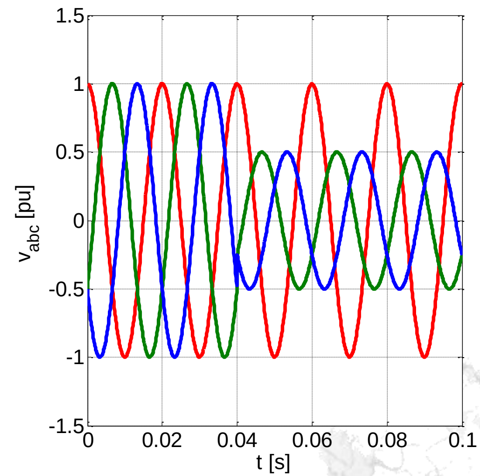
$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix} = \begin{bmatrix}\frac{1}{2}\left(1+\vec{D}\right)\\ \frac{1}{2}\left(1-\vec{D}\right)\\ 0\end{bmatrix}\vec{V}_{Sa}^{+},$$

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

### Sag E

Single-phase to ground fault



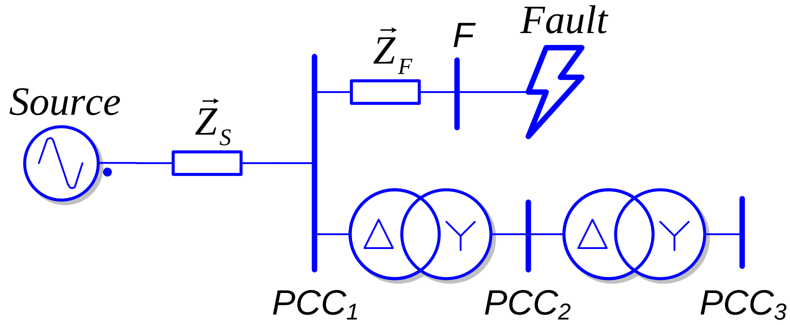

$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix} = \begin{bmatrix}1\\ -\frac{1}{2}\vec{D} - j\frac{\sqrt{3}}{2}\vec{D}\\ -\frac{1}{2}\vec{D} + j\frac{\sqrt{3}}{2}\vec{D}\end{bmatrix}\vec{V}_{Sa}^{+},$$

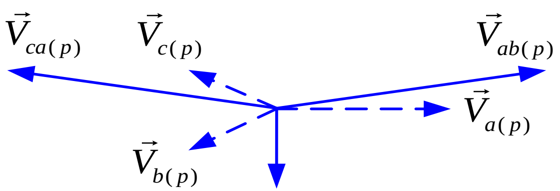
$$\begin{bmatrix}\vec{V}_a^{+}\\ \vec{V}_a^{-}\\ \vec{V}_a^{0}\end{bmatrix} = \begin{bmatrix}\frac{1}{3}\left(1+2\vec{D}\right)\\ \frac{1}{3}\left(1-\vec{D}\right)\\ \frac{1}{3}\left(1-\vec{D}\right)\end{bmatrix}\vec{V}_{Sa}^{+},$$

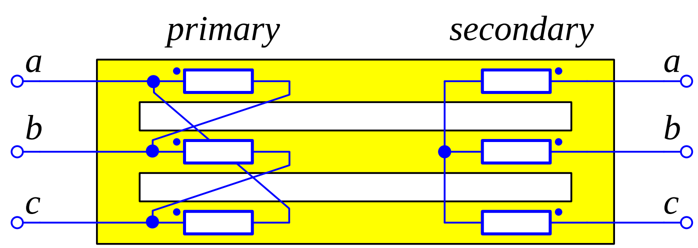
$$\vec{D} = \frac{\vec{Z}_F}{\vec{Z}_S + \vec{Z}_F}$$

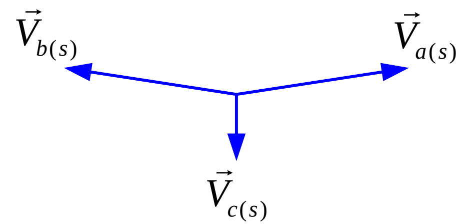
# Unbalanced Grid Faults

## Unbalanced voltage propagation



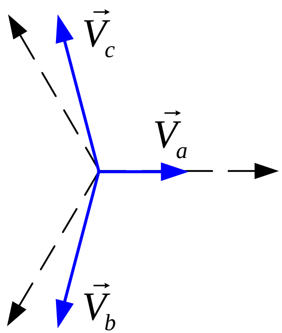

| Fault type | Point of common coupling | | |
|---|---|---|---|
| | PCC1 | $PCC_2$ | $PCC_3$ |
| Three-phase / Three-phase to ground | A | A | A |
| Single-phase to ground | B | C | D |
| Two-phase | C | D | C |
| Two-phase to ground | E | F | G |

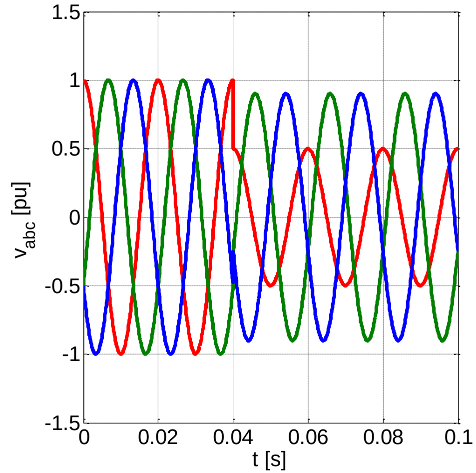
# Unbalanced Grid Faults

## Types of voltage sags

### Sag D

Propagation of a sag type C



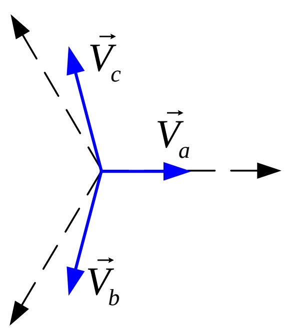



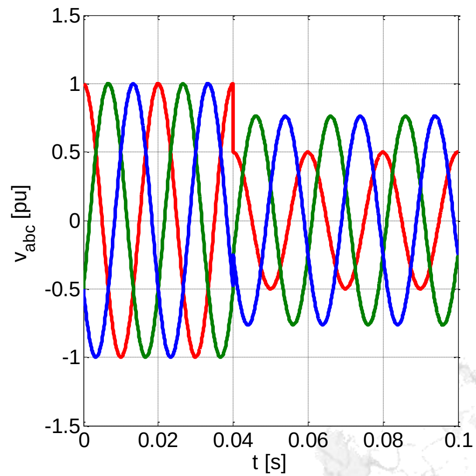

$$\begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} \vec{D} \\ -\frac{1}{2}\vec{D} - j\frac{\sqrt{3}}{2} \\ -\frac{1}{2}\vec{D} + j\frac{\sqrt{3}}{2} \end{bmatrix} \vec{V}_{Sa}^{+},$$

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

### Sag E

Propagation of a sag type E



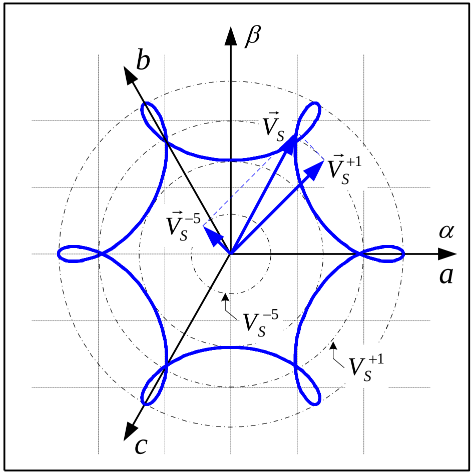




$$\begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} \vec{D} \\ -\frac{1}{2}\vec{D} - j\left(\frac{2+\vec{D}}{\sqrt{12}}\right) \\ -\frac{1}{2}\vec{D} + j\left(\frac{2+\vec{D}}{\sqrt{12}}\right) \end{bmatrix} \vec{V}_{Sa}^{+},$$

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

# Three-phase Voltage Characterization

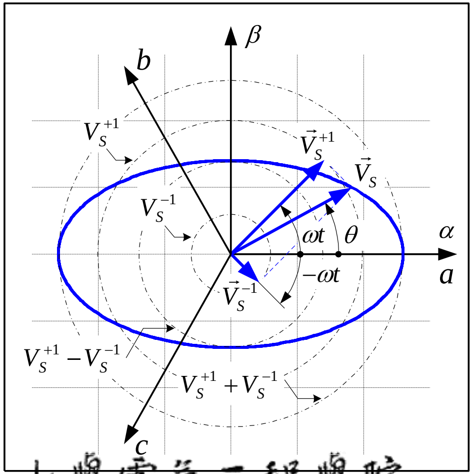
## Distorted and unbalanced three-phase voltage vector




$$|\mathbf{v}_S| = \sqrt{\left(V_S^{+1}\right)^2 + \left(V_S^{n}\right)^2 + 2V_S^{+1}V_S^{n}\cos\left[(n-1)\omega t\right]}$$

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

Neither constant amplitude nor rotation speed

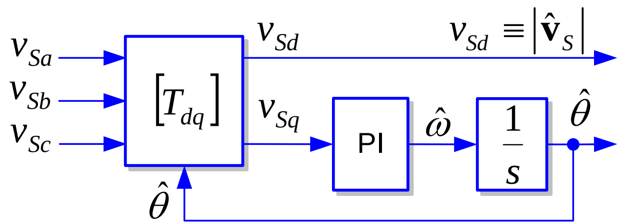



$$|\mathbf{v}_S| = \sqrt{(V_S^{+1})^2 + (V_S^{-1})^2 + 2V_S^{+1}V_S^{-1}\cos(-2\omega t + \phi^{-1})}$$

$$\theta = \omega t + \tan^{-1}\left(\frac{V_S^{-1}\sin(-2\omega t + \phi^{-1})}{V_S^{+1} + V_S^{-1}\cos(-2\omega t + \phi^{-1})}\right)$$

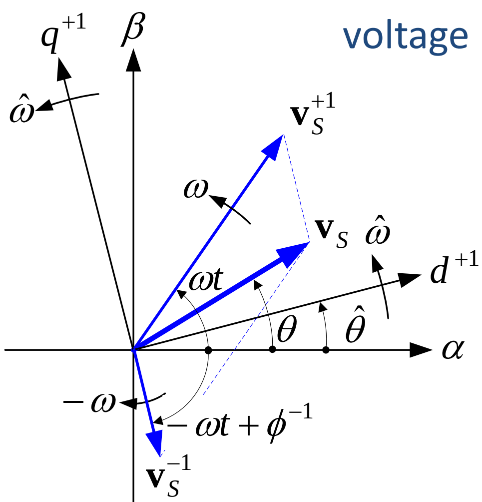
# Three-phase Voltage Characterization

## Conventional Synchronous Reference Frame PLL

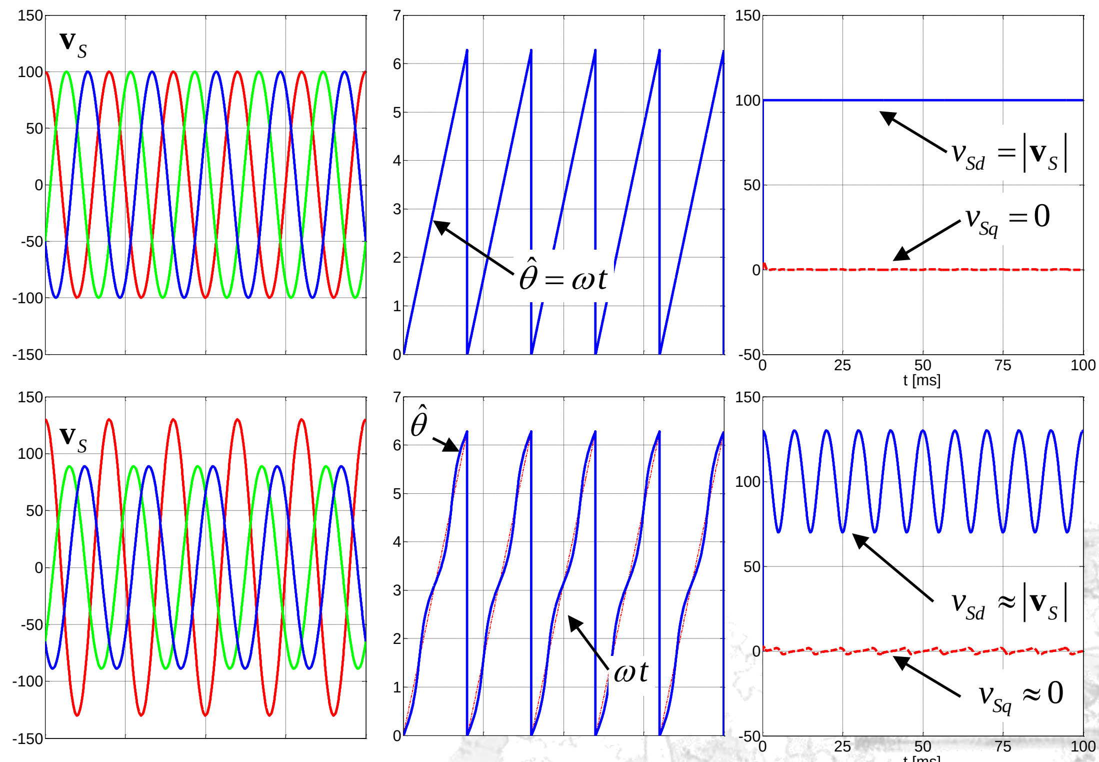



$$\mathbf{v}_{S(dq)} = \begin{bmatrix} v_{Sd} \\ v_{Sq} \end{bmatrix} = V_S^{+1} \begin{bmatrix} \cos(\omega t - \hat{\theta}) \\ \sin(\omega t - \hat{\theta}) \end{bmatrix} + V_S^{-1} \begin{bmatrix} \cos(-\omega t + \phi^{-1} - \hat{\theta}) \\ \sin(-\omega t + \phi^{-1} - \hat{\theta}) \end{bmatrix}$$

Balanced voltage

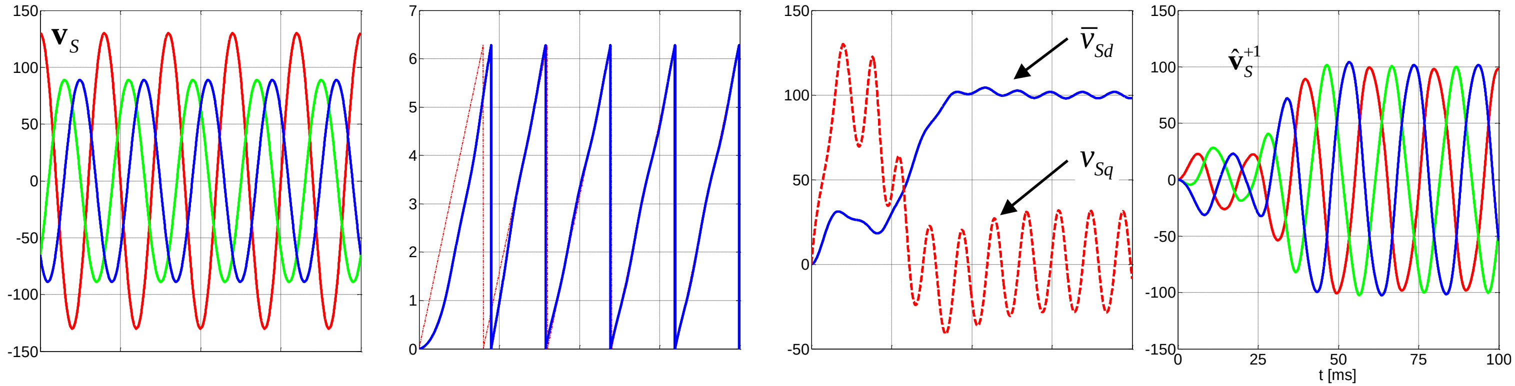



Unbalanced voltage



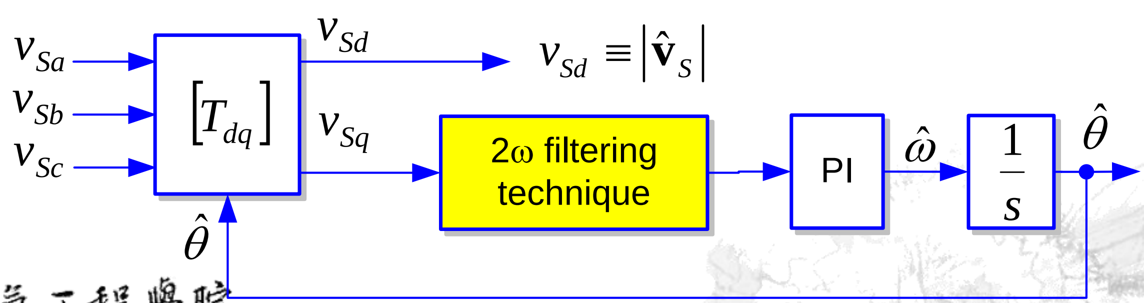
# Three-phase Voltage Characterization

## Conventional Synchronous Reference Frame PLL

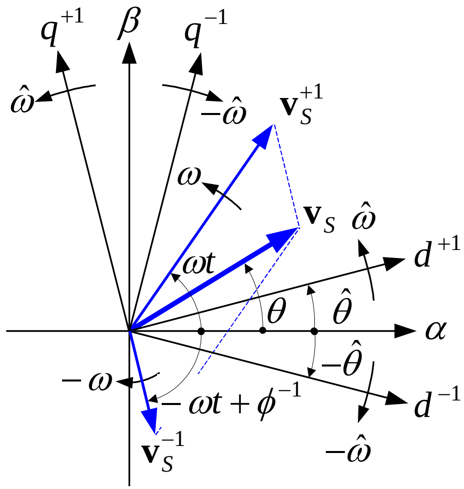



Setting a low PLL bandwidth and using a low-pass filter it is possible to obtain a reasonable approximation of the positive sequence voltage but the dynamic is too slow.

Other filtering strategies can be used to cancel out the double frequency oscillation keeping high locking dynamics, e.g., decoupling cells, repetitive controller based on a DFT algorithm, move average filters, Kalman filters, etc.



# Decoupled Double SRF-PLL




$$\mathbf{v}_{S_{(dq^{+1})}}=\begin{bmatrix} v_{Sd^{+1}} \\ v_{Sq^{+1}} \end{bmatrix}=\begin{bmatrix} T_{dq^{+1}} \end{bmatrix}\cdot \mathbf{v}_{S_{(\alpha\beta)}}=V_S^{+1}\begin{bmatrix} \cos(\omega t-\hat{\theta}) \\ \sin(\omega t-\hat{\theta}) \end{bmatrix}+V_S^{-1}\begin{bmatrix} \cos(-\omega t+\phi^{-1}-\hat{\theta}) \\ \sin(-\omega t+\phi^{-1}-\hat{\theta}) \end{bmatrix}$$

$$\mathbf{v}_{S_{(dq^{-1})}}=\begin{bmatrix} v_{Sd^{-1}} \\ v_{Sq^{-1}} \end{bmatrix}=\begin{bmatrix} T_{dq^{-1}} \end{bmatrix}\cdot \mathbf{v}_{S_{(\alpha\beta)}}=V_S^{+1}\begin{bmatrix} \cos(\omega t+\hat{\theta}) \\ \sin(\omega t+\hat{\theta}) \end{bmatrix}+V_S^{-1}\begin{bmatrix} \cos(-\omega t+\phi^{-1}+\hat{\theta}) \\ \sin(-\omega t+\phi^{-1}+\hat{\theta}) \end{bmatrix}$$

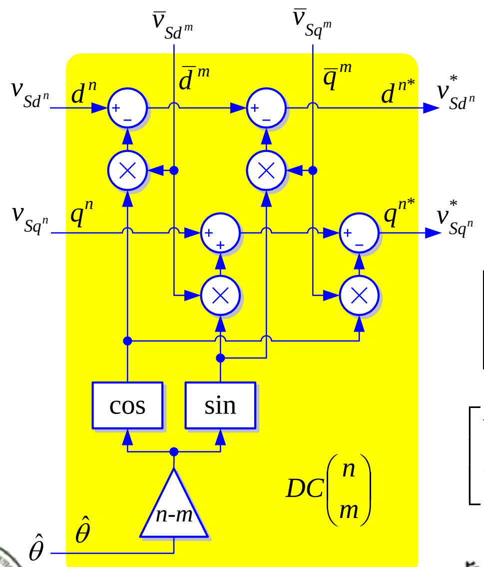
Near of synchronization: $\theta' \approx \omega t$

$$\mathbf{v}_{S_{(dq^{+1})}}\approx V_S^{+1}\begin{bmatrix} 1 \\ \omega t-\hat{\theta} \end{bmatrix}+V_S^{-1}\begin{bmatrix} \cos(-2\omega t+\phi^{-1}) \\ \sin(-2\omega t+\phi^{-1}) \end{bmatrix}$$

$$\mathbf{v}_{S_{(dq^{-1})}}\approx V_S^{+1}\begin{bmatrix} \cos(2\omega t) \\ \sin(2\omega t) \end{bmatrix}+V_S^{-1}\begin{bmatrix} \cos(\phi^{-1}) \\ \sin(\phi^{-1}) \end{bmatrix}$$

These terms act as interferences on the SRF $dq^n$ rotating at $n\omega$ frequency and viceversa

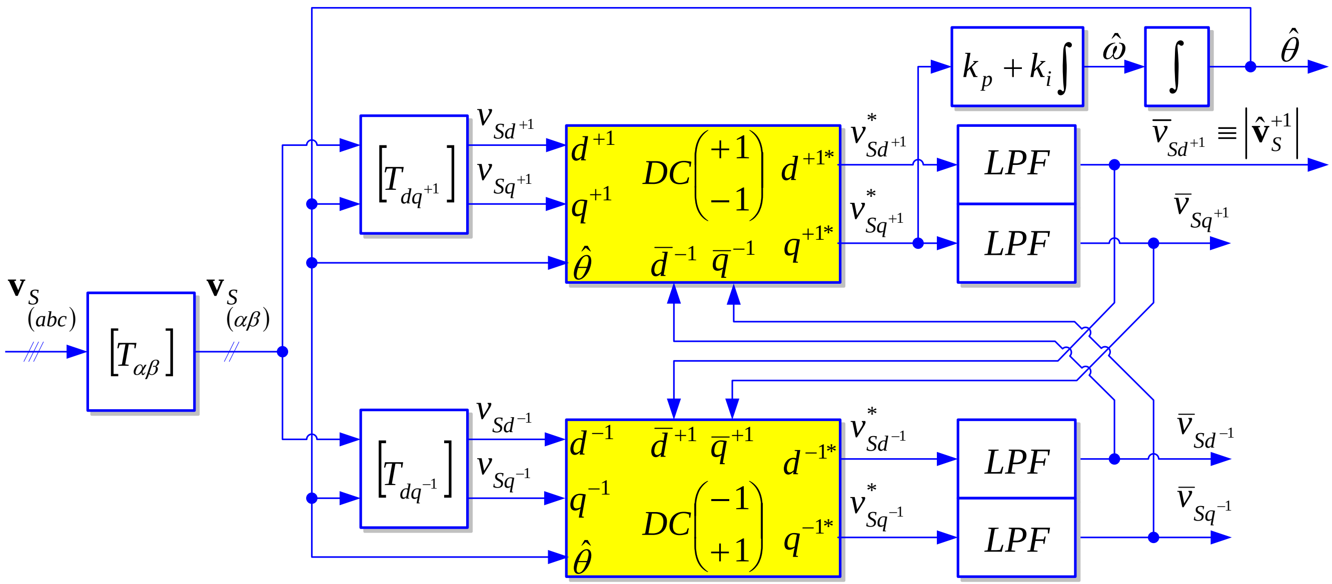
Generic decoupling cell:

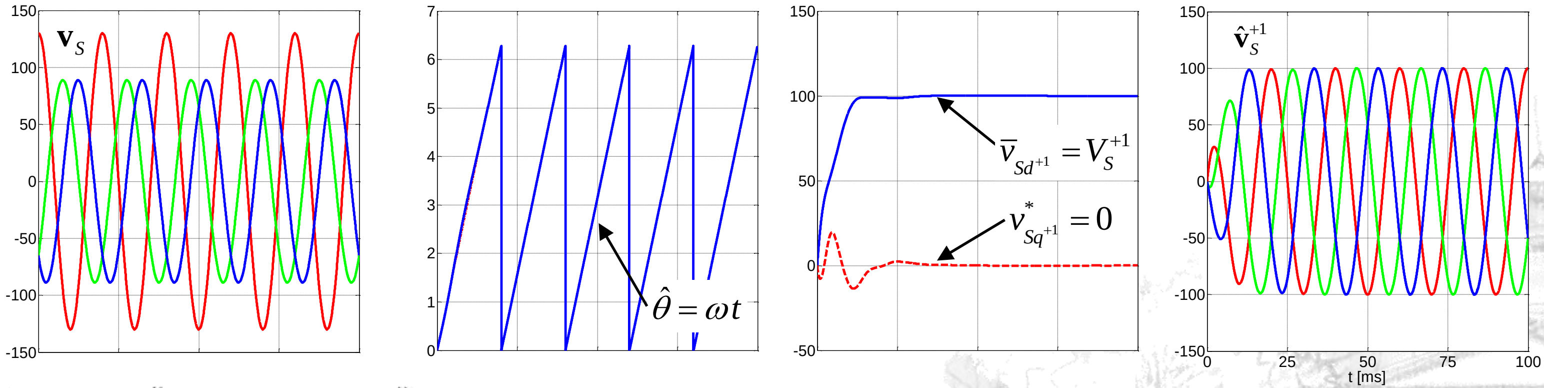



$$\begin{bmatrix} v_{Sd^n} \\ v_{Sq^n} \end{bmatrix}=\begin{bmatrix} V_S^n\cos(\phi^n) \\ V_S^n\sin(\phi^n) \end{bmatrix}+V_S^m\cos(\phi^m)\begin{bmatrix} \cos((n-m)\omega t) \\ -\sin((n-m)\omega t) \end{bmatrix}+V_S^m\sin(\phi^m)\begin{bmatrix} \sin((n-m)\omega t) \\ \cos((n-m)\omega t) \end{bmatrix}$$

$$\begin{bmatrix} v_{Sd^m} \\ v_{Sq^m} \end{bmatrix}=\begin{bmatrix} V_S^m\cos(\phi^m) \\ V_S^m\sin(\phi^m) \end{bmatrix}+V_S^n\cos(\phi^n)\begin{bmatrix} \cos((n-m)\omega t) \\ \sin((n-m)\omega t) \end{bmatrix}+V_S^n\sin(\phi^n)\begin{bmatrix} -\sin((n-m)\omega t) \\ \cos((n-m)\omega t) \end{bmatrix}.$$

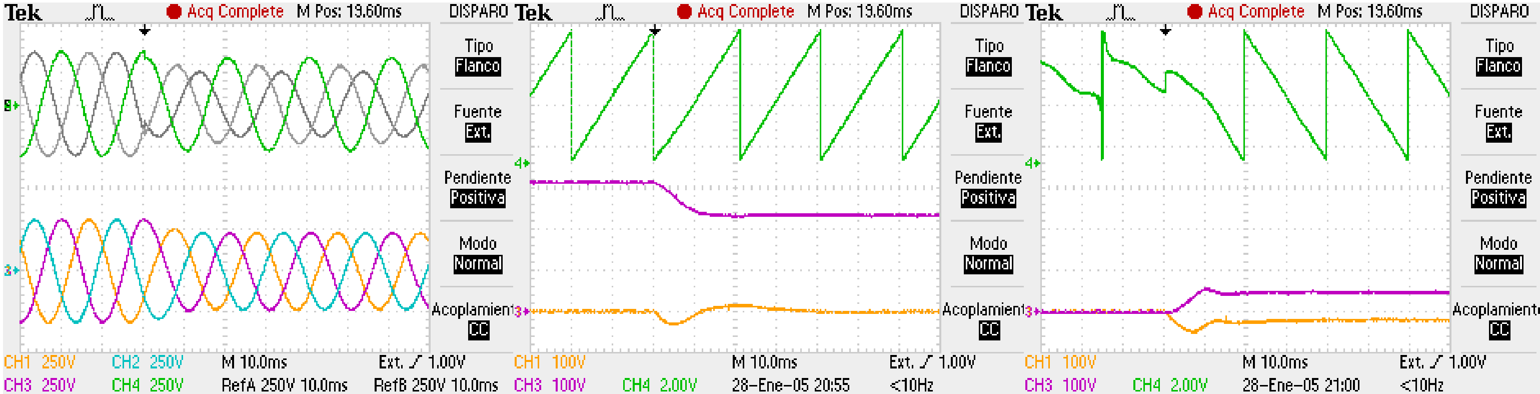
# Decoupled Double SRF-PLL



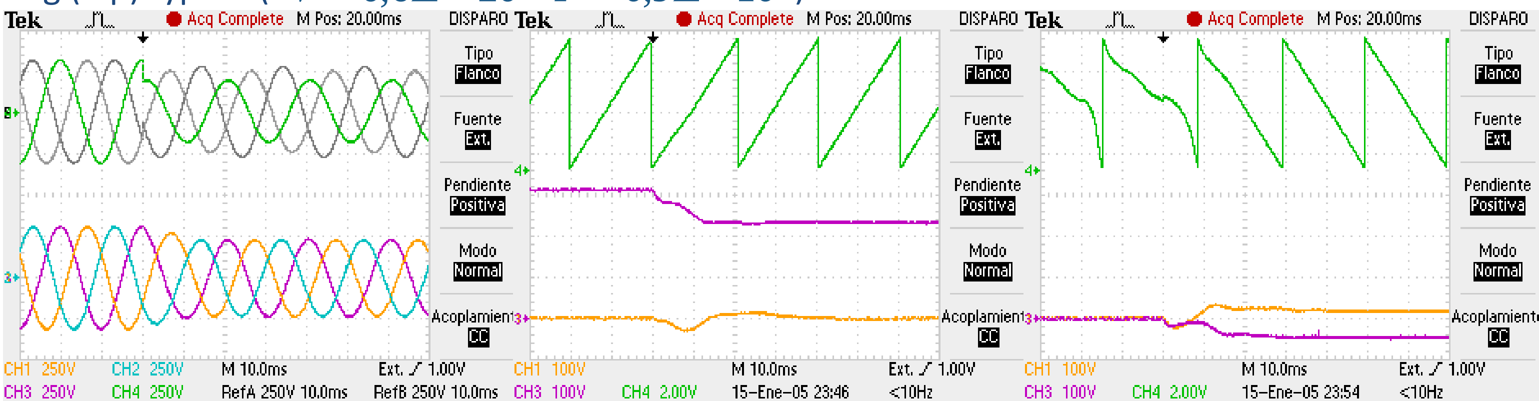



# Decoupled Double SRF-PLL

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




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



# Three-phase Voltage Component

## Instantaneous symetrical components

$$\mathbf{v}_{abc}^{+}=\left[v_a^{+}\quad v_b^{+}\quad v_c^{+}\right]^T=\left[T_+\right]\mathbf{v}_{abc}\qquad \left[T_+\right]=\frac{1}{3}\begin{bmatrix}1 & a & a^2\\ a^2 & 1 & a\\ a & a^2 & 1\end{bmatrix}$$

$$\mathbf{v}_{abc}^{-}=\left[v_a^{-}\quad v_b^{-}\quad v_c^{-}\right]^T=\left[T_-\right]\mathbf{v}_{abc}\qquad \left[T_-\right]=\frac{1}{3}\begin{bmatrix}1 & a^2 & a\\ a & 1 & a^2\\ a^2 & a & 1\end{bmatrix}$$

*Fortescue* operator

$$a=e^{j\frac{2\pi}{3}}=-1/2+e^{j\frac{\pi}{2}}\sqrt{3}/2$$

Symmetrical components are expressed as a function of the *j* operator

$$\begin{bmatrix}v_a^{+}\\ v_c^{+}\end{bmatrix}=\begin{bmatrix}\frac{1}{3} & -\frac{1}{6}-j\frac{1}{2\sqrt{3}} & -\frac{1}{6}+j\frac{1}{2\sqrt{3}}\\ -\frac{1}{6}-j\frac{1}{2\sqrt{3}} & -\frac{1}{6}+j\frac{1}{2\sqrt{3}} & \frac{1}{3}\end{bmatrix}\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix}\qquad v_b^{+}=-v_a^{+}-v_c^{+}$$

Symmetrical components can be also calculated on the $\alpha\beta$ domain

$$\mathbf{v}_{\alpha\beta}=\left[T_{\alpha\beta}\right]\mathbf{v}_{abc}\ ;\ \left[T_{\alpha\beta}\right]=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}$$

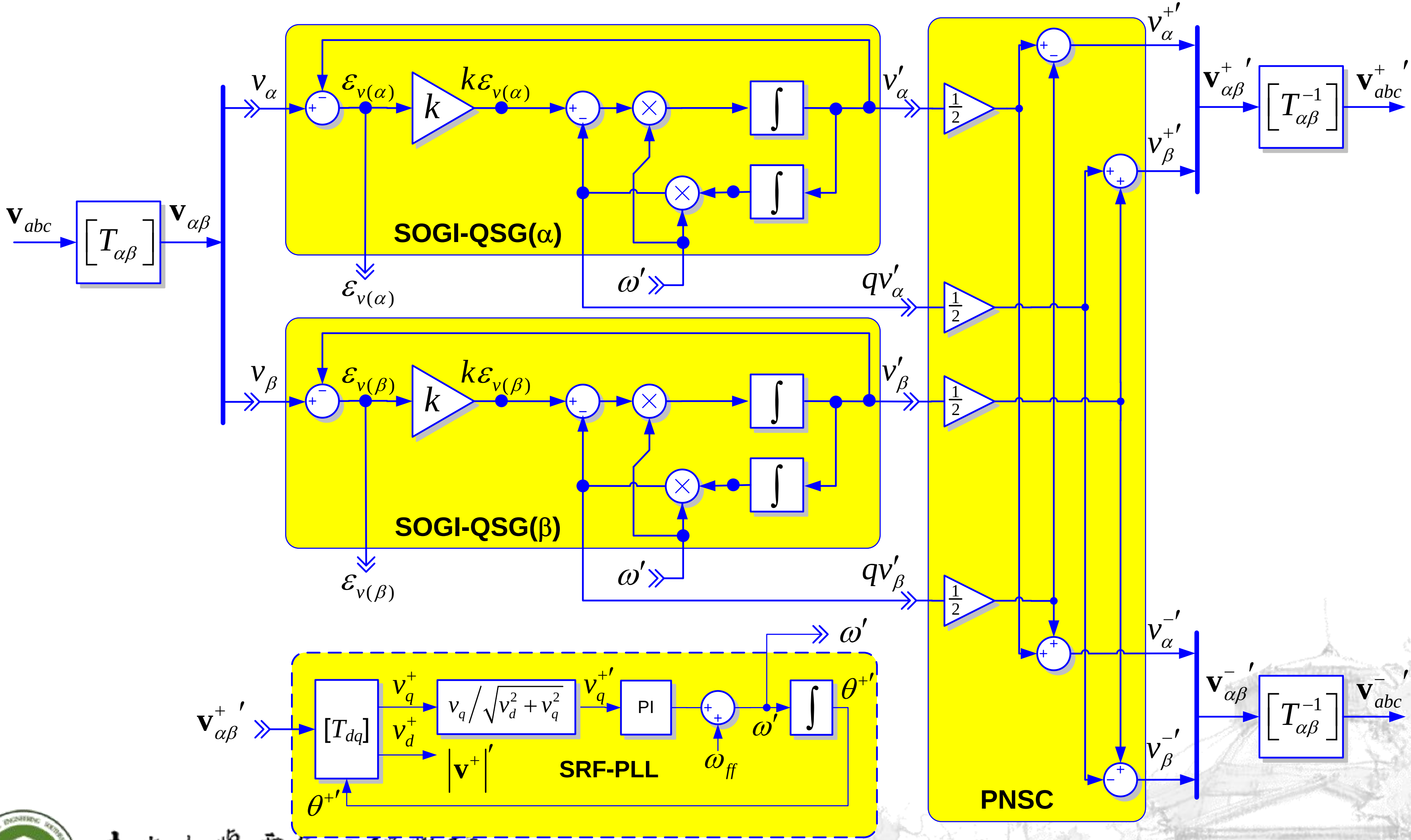
$$\boxed{\mathbf{v}_{\alpha\beta}^{+}=\left[T_{\alpha\beta}\right]\mathbf{v}_{abc}^{+}=\left[T_{\alpha\beta}\right]\left[T_+\right]\mathbf{v}_{abc}=\left[T_{\alpha\beta}\right]\left[T_+\right]\left[T_{\alpha\beta}\right]^T\mathbf{v}_{\alpha\beta}=\frac{1}{2}\begin{bmatrix}1 & -q\\ q & 1\end{bmatrix}\mathbf{v}_{\alpha\beta},}$$

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

*Quadrature* operator

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

# PLL With A Dual SOGI (DSOGI-PLL)



# Conclusions

- Grid monitoring is performed by grid-converters to determine connection conditions and to support grid services
- In three-phase systems, grid synchronization, estimating the instantaneous positive and negative sequence components, is essential to ride through transient faults
- Conventional SRF-PLL is not the most suitable technique for synchronizing unbalanced grid voltages
- The DDSRF-PLL makes possible a good synchronization during unbalanced conditions by decoupling axis signals on the positive- and negative-reference frames

# Grid Synchronization in Power Converters

- PLL basics and single-phase PLL
- Grid synchronization in three-phase power converters
- PLL-less converter: an introduction

# Motivation

- The **evolution of the power system** toward distributed energy resources has caused **concerns among system operators** worldwide about decrease of system inertia and stability.
- Since 2006 grid operators worldwide have introduced **requirements** for wind energy converters **to contribute to system inertia** (e.g. Hydro Quebec).
- **Projects** have been **funded by the European community** to study frequency stabilization in future grids (e.g. VSYNCH Project).
- The concept of **Virtual Synchronous Machines (VSMs)** has gained interest during the last decade.

# Characteristics of VSMs

Why are SMs considered fundamental components for the Power system ?

1. Inertia of rotating masses

- VSMs are often associated to "**virtual inertia**".
- First works on VSMs focused mainly on reproducing the **dynamic behavior of a synchronous machine** to provide additional inertia.
- **Extra energy sources** (e.g. batteries, supercapacitors, etc..) are needed for a converter in order to reproduce this characteristic.

# Characteristics of VSMs

Why are SMs considered fundamental components for the Power system ?

1. Inertia of rotating masses

2. Synchronisation mechanism

- The synchronization mechanism of SMs is an **intrinsic characteristic**.
- The synchronization process is achieved **by means of transient power transfer**.
- It allows SMs to **maintain** the **synchronism** with each other **even under critical conditions** for standard vector controlled converter.

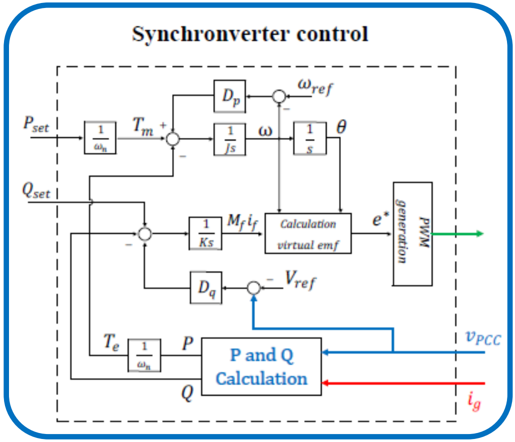
# Characteristics of VSMs

– the converter has to **behave as a voltage source behind a reactance** within a specified frequency range.

– The converter can **operate in extremely low fault levels**, indeed the fully islanded case including black-start scenarios.

– The converter does **not need a dedicated synchronization unit** in order to achieve the synchronization to the main grid, but rather this is achieved by means of power transfer.

# The Synchroconverter: Basic Structure




- The **Active power loop** is described by the **swing equation** of a SM:

$$J\dot{\omega} = T_m - T_e - D_p\omega$$

Mechanical inertia — Rotor speed — Mechanical torque — Electrical torque — Mechanical friction

- The **reactive power loop** reproduces a **Q-V droop behaviour** according to the coefficient $D_q$:

$$\Delta_Q = -D_q\Delta_V$$

Reactive power setpoint variation — Voltage deviation at the PCC

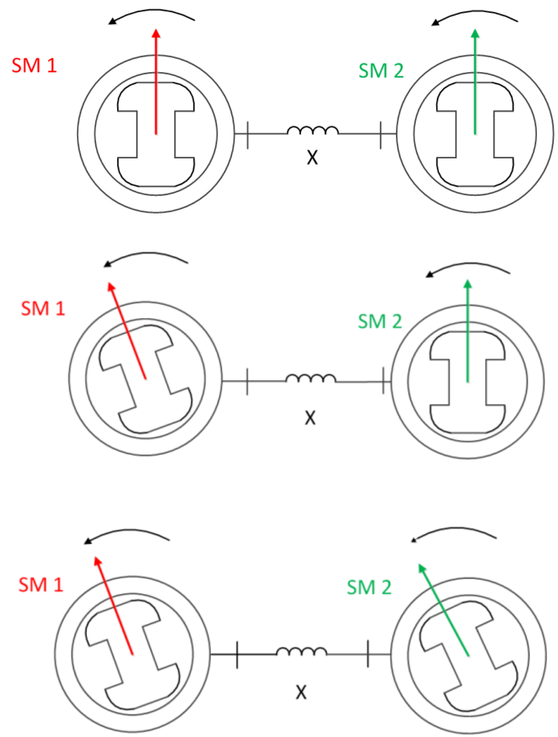
# Power Synchronization Mechanism

The power Synchronization Mechanism is the underlying principle that holds in power system!

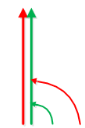
$$J_1 \frac{d\boldsymbol{\omega}_{m1}}{dt} = T_{m1} - T_{e1}$$

$$J_2 \frac{d\boldsymbol{\omega}_{m2}}{dt} = T_{e2} - T_{m2}$$

$$\boxed{P = \frac{3V_g E}{2X} sin(\theta_1 - \theta_2)}$$



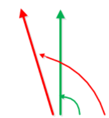

$$\frac{d\boldsymbol{\omega}_{m1}}{dt} = 0$$



$\theta_1 = \theta_2$

$T_{m1} > T_{e1}$

$$\frac{d\boldsymbol{\omega}_{m1}}{dt} > 0$$



$\theta_1 \neq \theta_2$

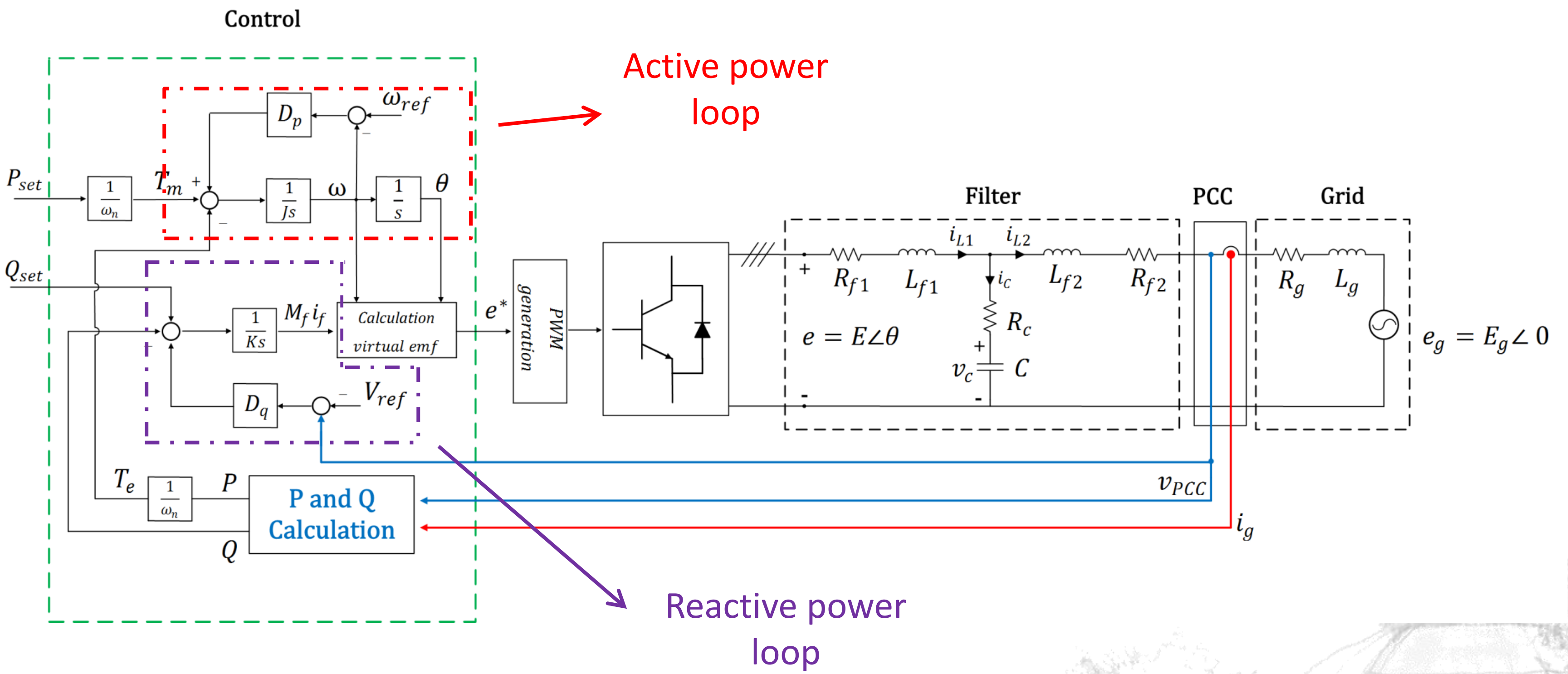
$T_{e2} > T_{m2}$

$$\frac{d\boldsymbol{\omega}_{m2}}{dt} > 0$$

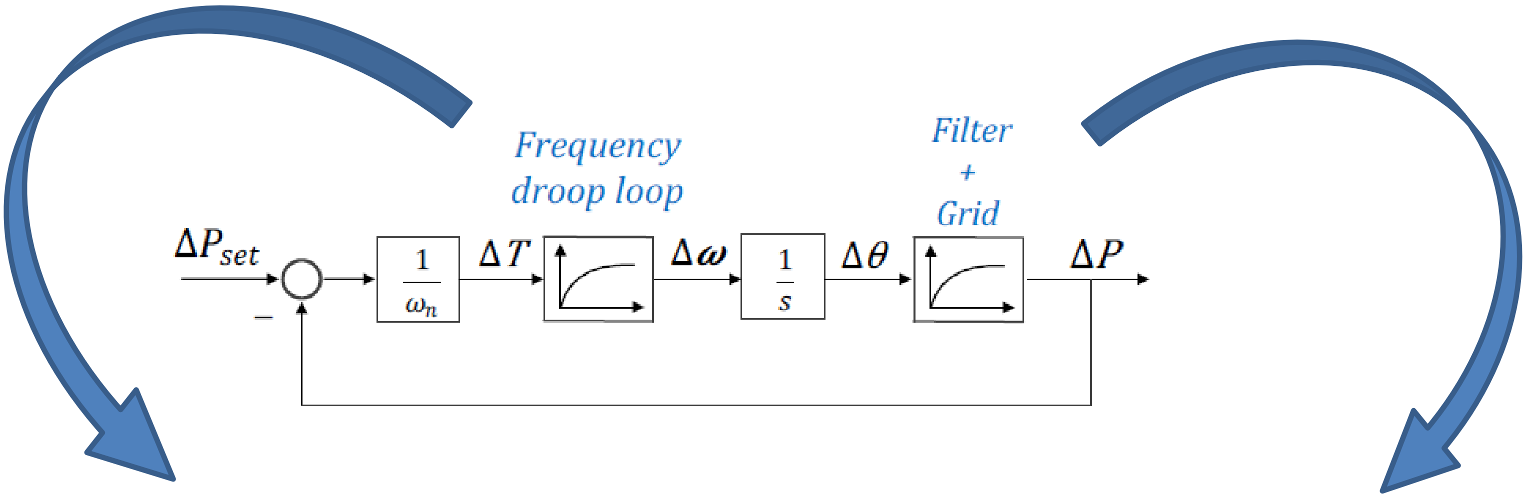
$\theta_1 = \theta_2$

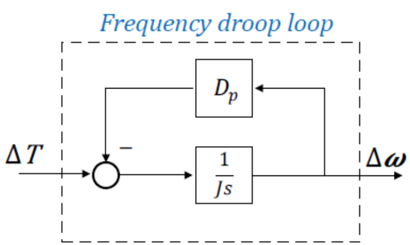
# Synchronverter

The **synchronverter** is among the most common control structures proposed in the literature based on the power-synchronization mechanism of a SM.

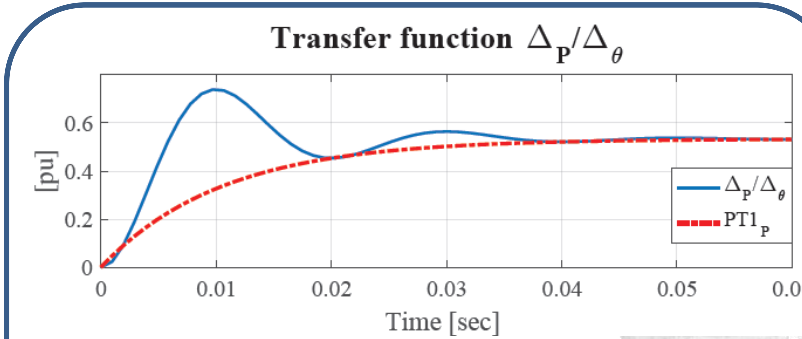


# Active Power Loop



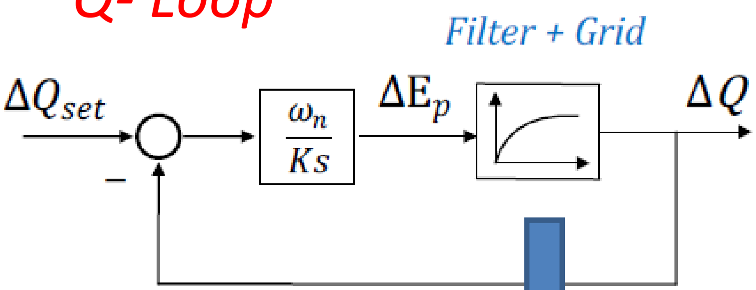

$$\frac{\boldsymbol{\Delta\omega}}{\boldsymbol{\Delta T}}(s) = \frac{\frac{1}{D_p}}{1 + s\ \frac{J}{D_p}} = \frac{K_f}{1 + s\ \boldsymbol{\tau}_f}$$

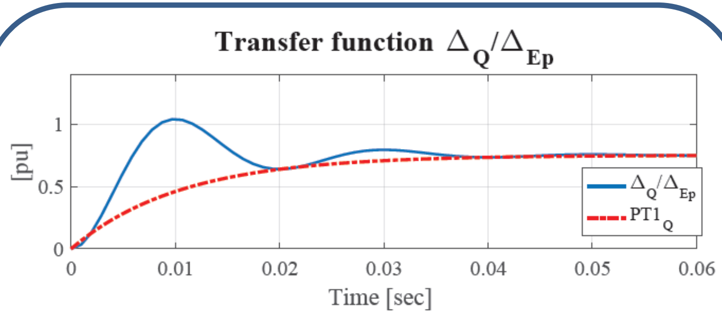



$$\frac{\boldsymbol{\Delta P}}{\boldsymbol{\Delta \theta}}(s) \cong PT1_P(s) = \frac{G_P}{1 + s\ \boldsymbol{\tau}_{refP}}$$

# Reactive Power Loop

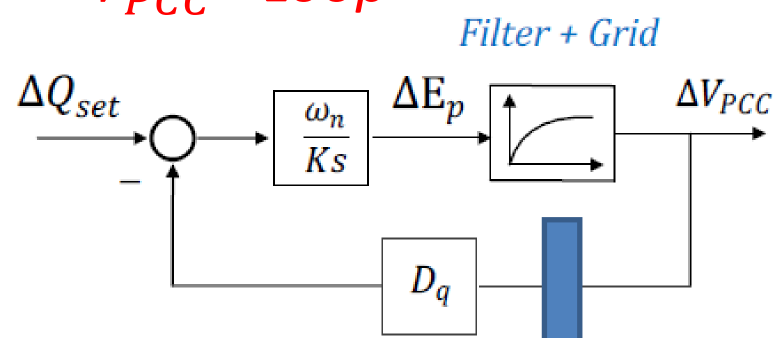
## *Q- Loop*

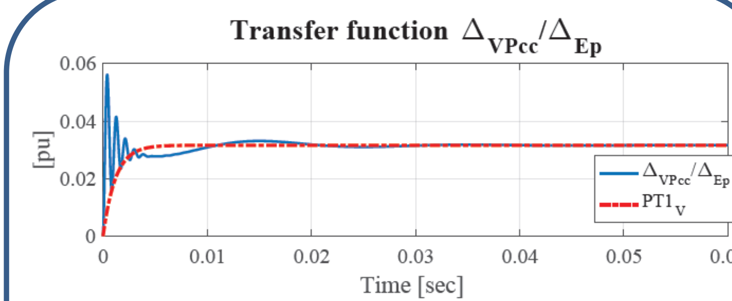



$$PT1_Q(s) = \frac{G_q}{1 + s\ \boldsymbol{\tau}_{refq}}$$

## *$V_{PCC}$ - Loop*




$$PT1_v(s) = \frac{G_v}{1 + s\ \boldsymbol{\tau}_{refv}}$$

# Conclusions

- VSMs have been proposed as possible solutions for gradually increase power electronics-based penetration in the actual power system.
- Since they can reproduce to some extents the behaviour of standard SMs:
  - are **able to provide additional virtual inertia** in combination with extra energy sources as batteries or supercapacitors.
  - Are able of **self-synchronization** to the grid without the need of a dedicated unit.
- The synchronverter is among the most common VSM implementations.
- In contrast to standard PLL-based converters, **synchronverters** (and VSMs in general) are **suitable for** operation under **weak grid** conditions.