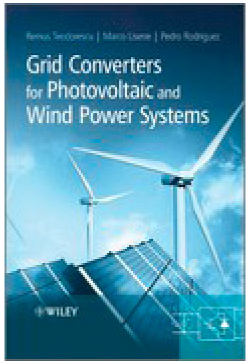

Grid Converters for Photovoltaic and Wind Power Systems

by R. Teodorescu, M. Liserre and P. Rodriguez

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Chapter 10

Control of Grid Converters under Grid Faults

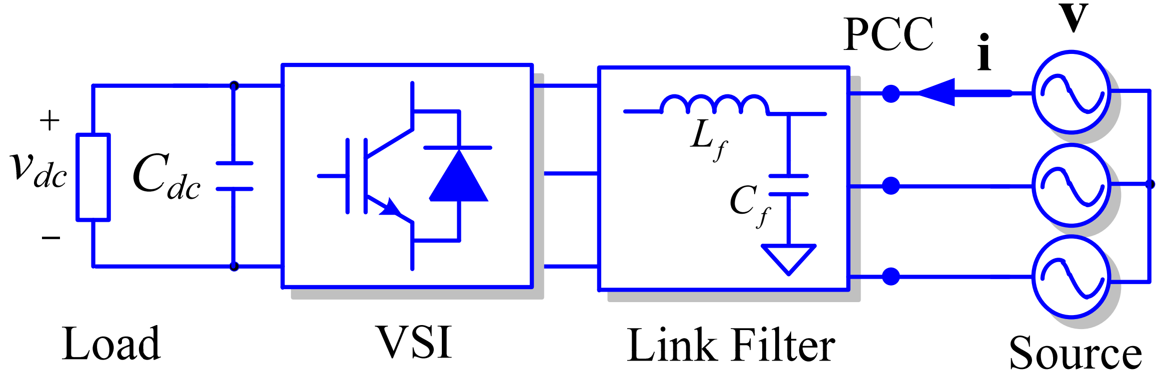
Outline

- Introduction
- Instantaneous power under unbalanced grid voltage conditions
- Unbalanced currents control structures
- Power control under unbalanced grid conditions
  - Instantaneous active reactive control (IARC)
  - Positive- Negative-Sequence Compensation (PNSC)
  - Average Active-Reactive Control (AARC)
  - Balanced positive sequence control (BPSC)
  - Flexible positive-negative sequence control (FPNSC)
- Flexible power control with current limitation
- Performance of the FPNSC
- Conclusions

Introduction

- Modern grid connected power converters should provide a reliable response under grid fault conditions
- The interaction between the power converter and the grid under fault is a important matter, since it is not only necessary to guarantee that any protection of the converter will trip but also to support the grid voltage under such faulty operating conditions
- The injection of a proper set of unbalanced currents under unbalanced grid voltage conditions allow attenuating power oscillations, maximizing the instantaneous power delivery, or balancing the grid voltage at the point of connection
- Improved control structures allow injecting unbalanced currents into the grid to support the grid voltage under fault conditions
- Reference current generation under grid faults is another crucial issue in the control of power converters
- There exists a maximum value for the power to be delivered to a faulty grid, without overpassing the current limits of the power converter

Instantaneous power under unbalanced grid voltage conditions



- Unbalanced and distorted voltages and currents

$$\mathbf{v} = \sum_{n=1}^{\infty}\left(\mathbf{v}^{+n} + \mathbf{v}^{-n} + \mathbf{v}^{0n}\right)$$

$$= \sum_{n=1}^{\infty}\left\{V^{+n}\begin{bmatrix}\cos(n\omega t + \phi^{+n})\\ \cos(n\omega t - \frac{2\pi}{3} + \phi^{+n})\\ \cos(n\omega t + \frac{2\pi}{3} + \phi^{+n})\end{bmatrix} + V^{-n}\begin{bmatrix}\cos(n\omega t + \phi^{-n})\\ \cos(n\omega t + \frac{2\pi}{3} + \phi^{-n})\\ \cos(n\omega t - \frac{2\pi}{3} + \phi^{-n})\end{bmatrix} + V^{0n}\begin{bmatrix}\cos(n\omega t + \phi^{0n})\\ \cos(n\omega t + \phi^{0n})\\ \cos(n\omega t + \phi^{0n})\end{bmatrix}\right\}.$$

$$\mathrm{i} = \sum_{n=1}^{\infty}\left\{I^{+n}\begin{bmatrix}\sin(n\omega t + \delta^{+n})\\ \sin(n\omega t + \delta^{+n} - \frac{2\pi}{3})\\ \sin(n\omega t + \delta^{+n} + \frac{2\pi}{3})\end{bmatrix} + I^{-n}\begin{bmatrix}\sin(n\omega t + \delta^{-n})\\ \sin(n\omega t + \delta^{-n} + \frac{2\pi}{3})\\ \sin(n\omega t + \delta^{-n} - \frac{2\pi}{3})\end{bmatrix}\right\}$$

Instantaneous power under unbalanced grid voltage conditions

- Instantaneous active power

$$\bar{p} = \frac{3}{2}\sum_{n=1}^{\infty}\left[V^{+n}I^{+n}\cos(\phi^{+n}-\delta^{+n}) + V^{-n}I^{-n}\cos(\phi^{-n}-\delta^{-n})\right]$$

$$\begin{aligned}
\tilde{p} = \frac{3}{2}\Bigg\{ & \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty}V^{+m}I^{+n}\cos((\omega_m-\omega_n)t+\phi^{+m}-\delta^{+n})\right] \\
+ & \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty}V^{-m}I^{-n}\cos((\omega_m-\omega_n)t+\phi^{-m}-\delta^{-n})\right] \\
+ & \sum_{m=1}^{\infty}\left[\sum_{n=1}^{\infty}-V^{+m}I^{-n}\cos((\omega_m+\omega_n)t+\phi^{+m}+\delta^{-n})\right] \\
+ & \sum_{m=1}^{\infty}\left[\sum_{n=1}^{\infty}-V^{-m}I^{+n}\cos((\omega_m+\omega_n)t+\phi^{-m}+\delta^{+n})\right]\Bigg\},
\end{aligned}$$

Instantaneous power under unbalanced grid voltage conditions

- Instantaneous reactive power

$$\bar{q} = \frac{3}{2}\sum_{n=1}^{\infty}\left[V^{+n}I^{+n}\sin(\phi^{+n}-\delta^{+n}) - V^{-n}I^{-n}\sin(\phi^{-n}-\delta^{-n})\right]$$

$$\begin{aligned}
\tilde{q} = \frac{3}{2}\Bigg\{ & \sum_{\substack{m=1\\m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} V^{+m}I^{+n}\sin((\omega_m-\omega_n)t+\phi^{+m}-\delta^{+n})\right] \\
+ & \sum_{\substack{m=1\\m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -V^{-m}I^{-n}\sin((\omega_m-\omega_n)t+\phi^{-m}-\delta^{-n})\right] \\
+ & \sum_{m=1}^{\infty}\left[\sum_{n=1}^{\infty} -V^{+m}I^{-n}\sin((\omega_m+\omega_n)t+\phi^{+m}+\delta^{-n})\right] \\
+ & \sum_{m=1}^{\infty}\left[\sum_{n=1}^{\infty} V^{-m}I^{+n}\sin((\omega_m+\omega_n)t+\phi^{-m}+\delta^{+n})\right]\Bigg\}.
\end{aligned}$$

Instantaneous power under unbalanced grid voltage conditions

- Unbalanced voltages and currents (pos-/neg-sequence)

$$p = P_0 + P_{c2}\cos(2\omega t) + P_{s2}\sin(2\omega t)$$

$$q = Q_0 + Q_{c2}\cos(2\omega t) + Q_{s2}\sin(2\omega t)$$

$$P_0 = \frac{3}{2}\cdot\left(v_d^+\cdot i_d^+ + v_q^+\cdot i_q^+ + v_d^-\cdot i_d^- + v_q^-\cdot i_q^-\right)$$

$$P_{c2} = \frac{3}{2}\cdot\left(v_d^-\cdot i_d^+ + v_q^-\cdot i_q^+ + v_d^+\cdot i_d^- + v_q^+\cdot i_q^-\right)$$

$$P_{s2} = \frac{3}{2}\cdot\left(v_q^-\cdot i_d^+ - v_d^-\cdot i_q^+ - v_q^+\cdot i_d^- + v_d^+\cdot i_q^-\right)$$

$$Q_0 = \frac{3}{2}\cdot\left(v_p^+\cdot i_d^+ - v_d^+\cdot i_q^+ + v_q^-\cdot i_d^- - v_d^-\cdot i_q^-\right)$$

$$Q_{c2} = \frac{3}{2}\cdot\left(v_q^-\cdot i_d^+ - v_d^-\cdot i_q^+ + v_q^+\cdot i_d^- - v_d^+\cdot i_q^-\right)$$

$$Q_{s2} = \frac{3}{2}\cdot\left(-v_d^-\cdot i_d^+ - v_d^-\cdot i_q^+ + v_d^+\cdot i_d^- + v_q^+\cdot i_q^-\right)$$

Instantaneous power under unbalanced grid voltage conditions

- Powers

$$\begin{bmatrix} P_0 \\ Q_0 \\ P_{c2} \\ P_{s2} \end{bmatrix} = \frac{3}{2} \cdot \underbrace{\begin{bmatrix} v_d^+ & v_q^+ & v_d^- & v_q^- \\ v_q^+ & -v_d^{+1} & v_q^- & -v_d^- \\ v_d^- & v_q^- & v_d^+ & v_q^+ \\ v_q^- & -v_d^- & -v_q^+ & v_d^+ \end{bmatrix}}_{M_{4\times4}} \cdot \begin{bmatrix} i_d^+ \\ i_q^+ \\ i_d^- \\ i_q^- \end{bmatrix}$$

- Currents

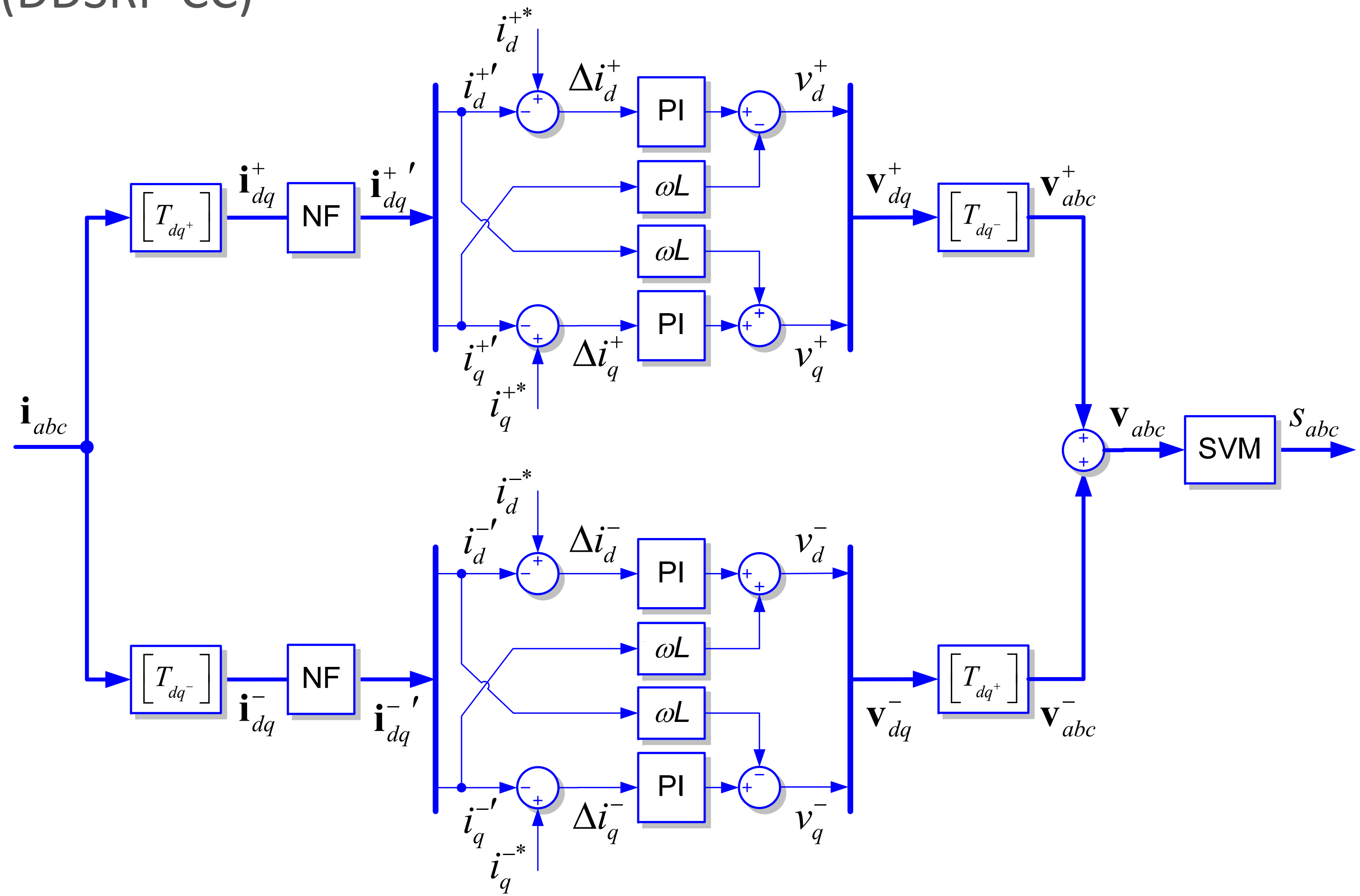
$$\begin{bmatrix} i_d^{+*} \\ i_q^{+*} \\ i_d^{-*} \\ i_q^{-*} \end{bmatrix} = M_{4\times4}^{-1} \cdot \frac{2}{3} \cdot \begin{bmatrix} P_0 \\ Q_0 \\ P_{c2} \\ P_{s2} \end{bmatrix}$$

- Balanced active currents

$$\begin{bmatrix} i_d^{+*} \\ i_q^{+*} \\ i_d^{-*} \\ i_q^{-*} \end{bmatrix} = M_{4\times4}^{-1} \cdot \frac{2}{3} \cdot \begin{bmatrix} P_0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Unbalanced currents control structures

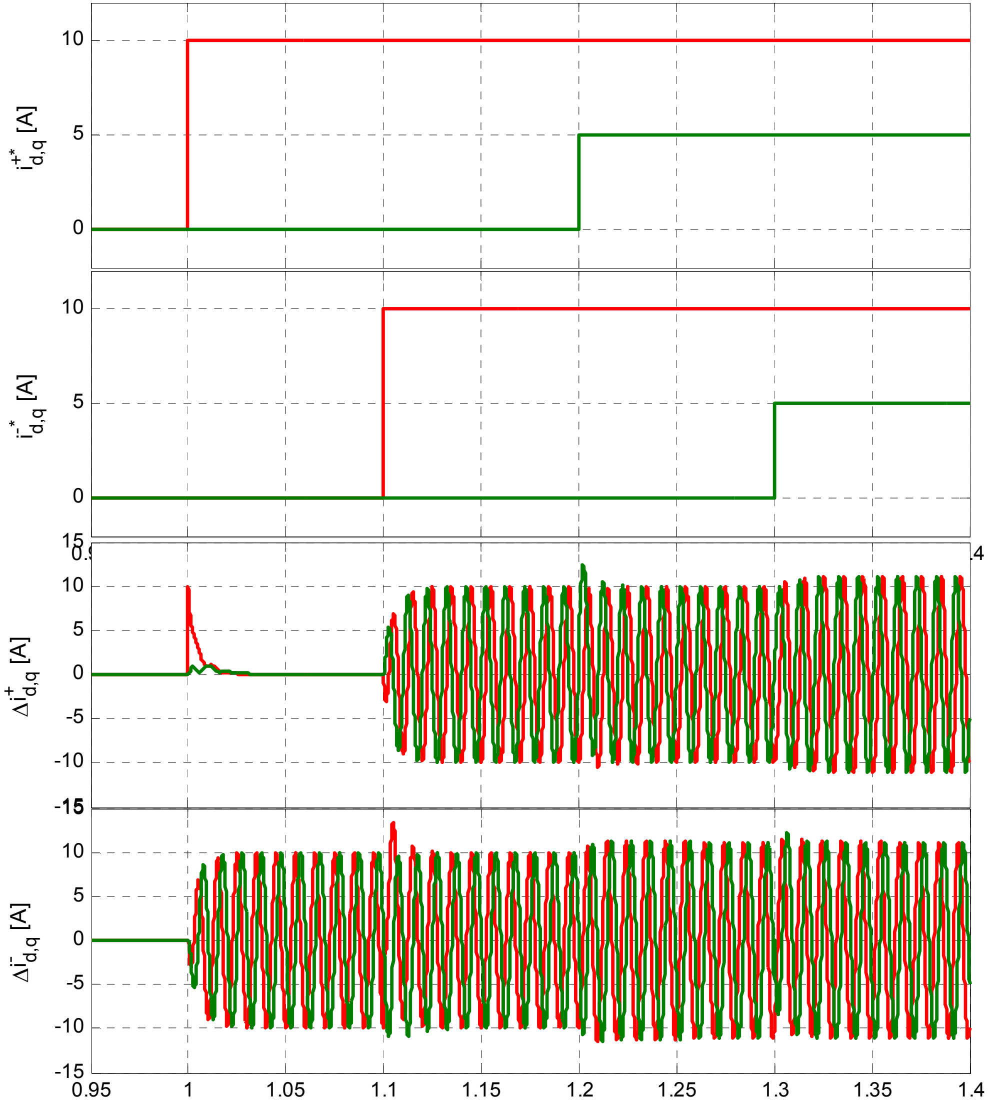
- Double synchronous reference frame current controller (DDSRF-CC)



Unbalanced currents control structures

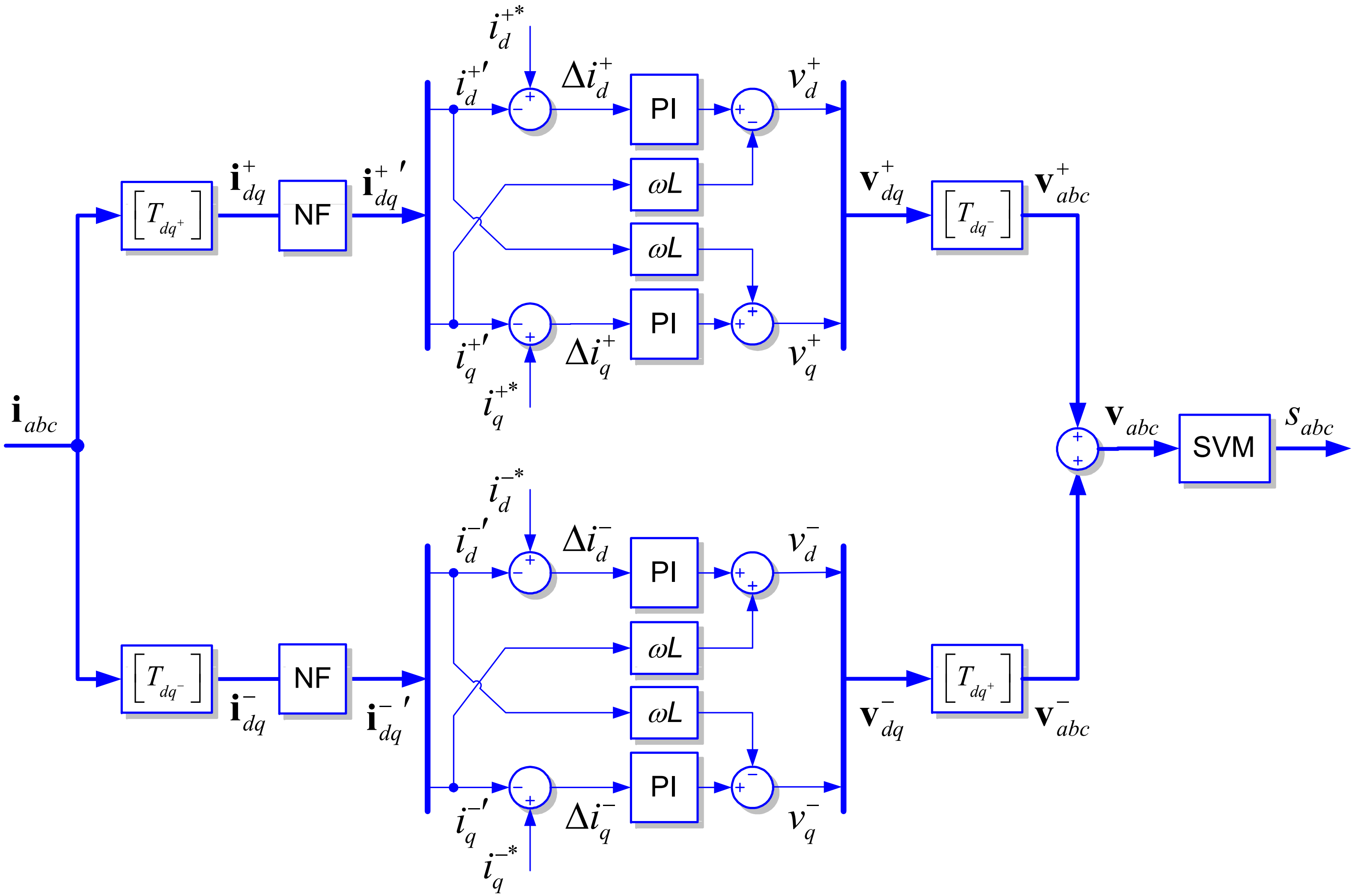
- Double synchronous reference frame current controller (DDSRF-CC)

The positive-sequence current vector gives rise to error signals at 2ω in the negative-sequence controller, which can not be cancelled by PI controllers. A similar statement can be made for the positive-sequence controller.



Unbalanced currents control structures

- DDSRF-CC using a notch filter (NF)

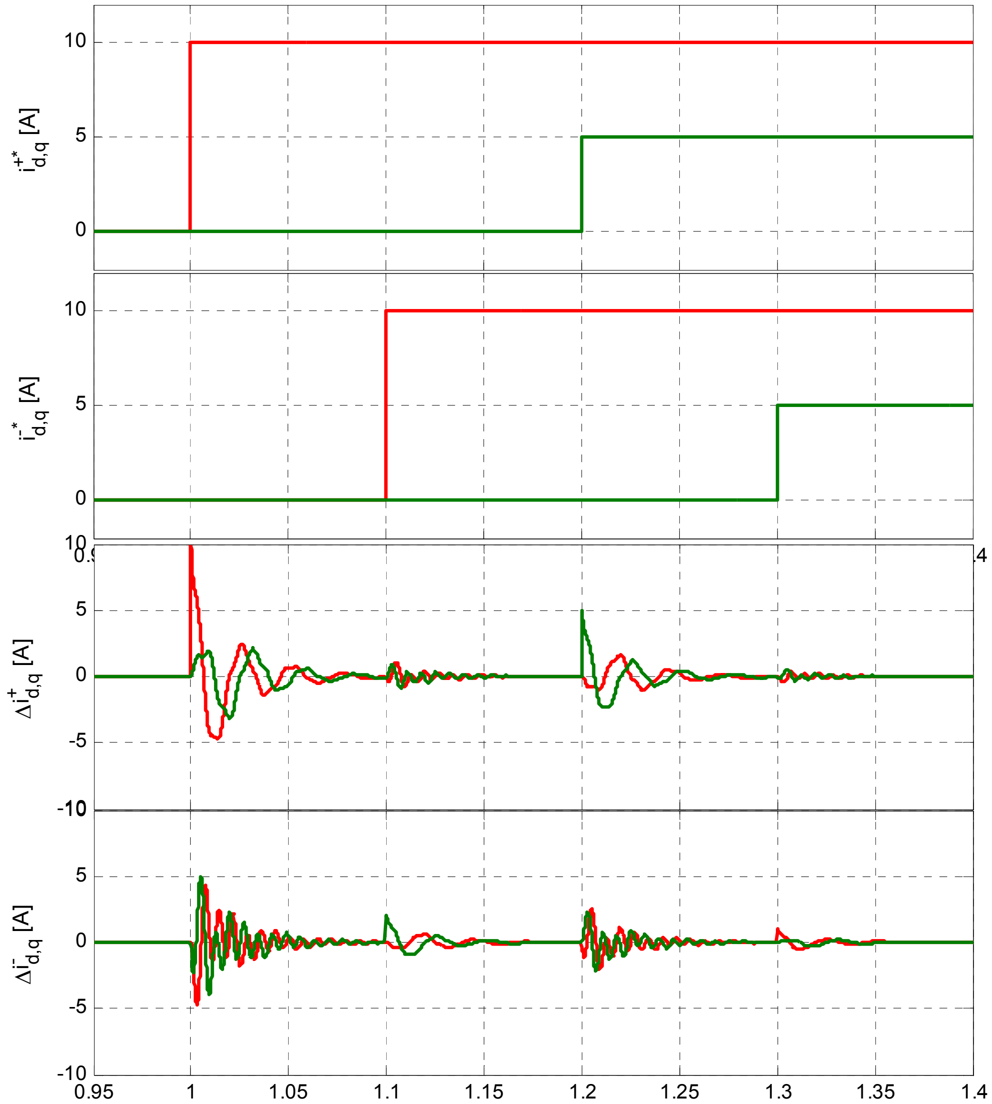


Unbalanced currents control structures

- DDSRF-CC using a notch filter (NF)

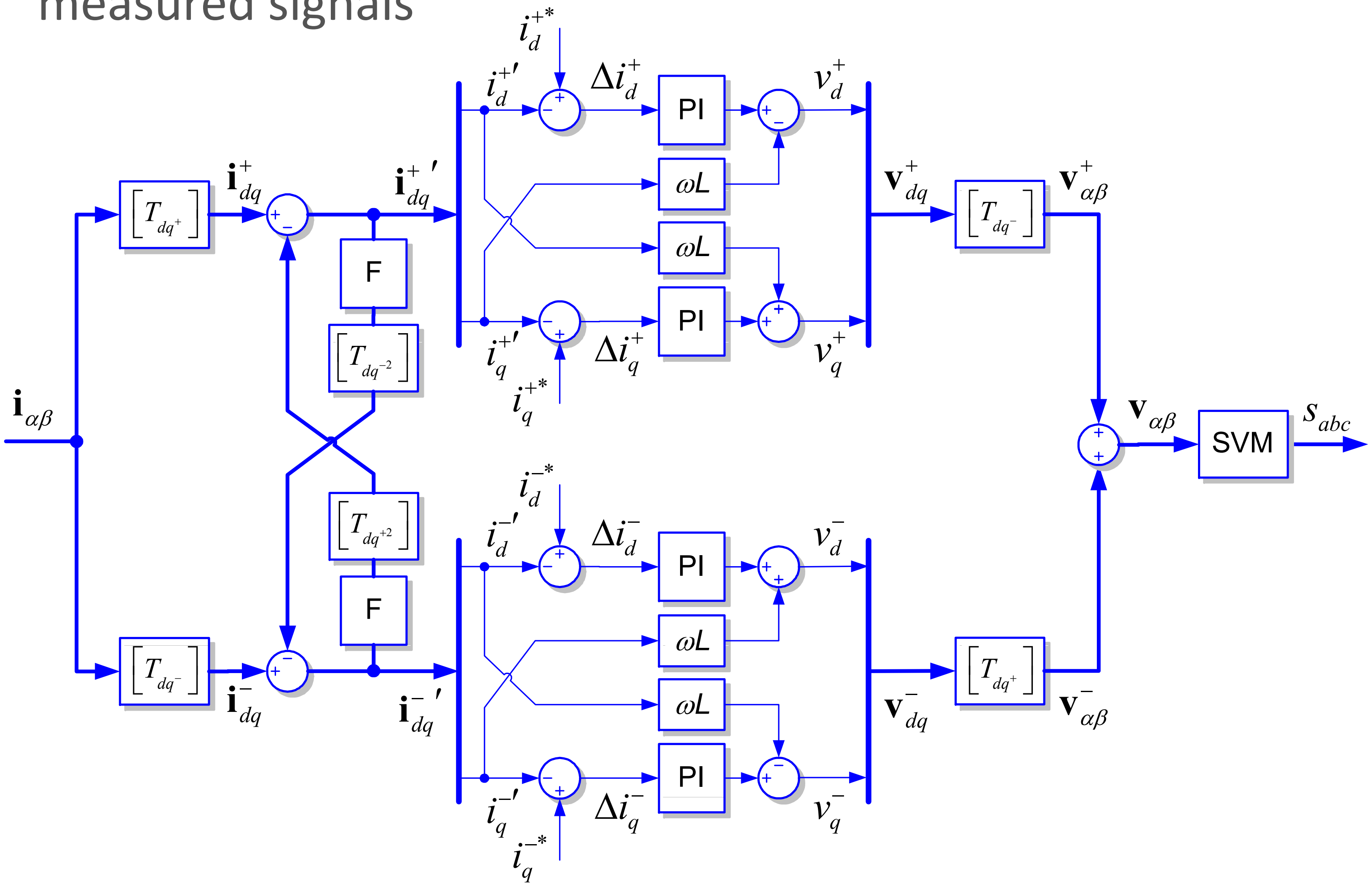
A notch filter (NF) tuned at 2ω can be used to attenuate the oscillations in the currents measured by each synchronous controller.

However, the selectivity of this filter can not be too high to avoid making the system unstable.



Unbalanced currents control structures

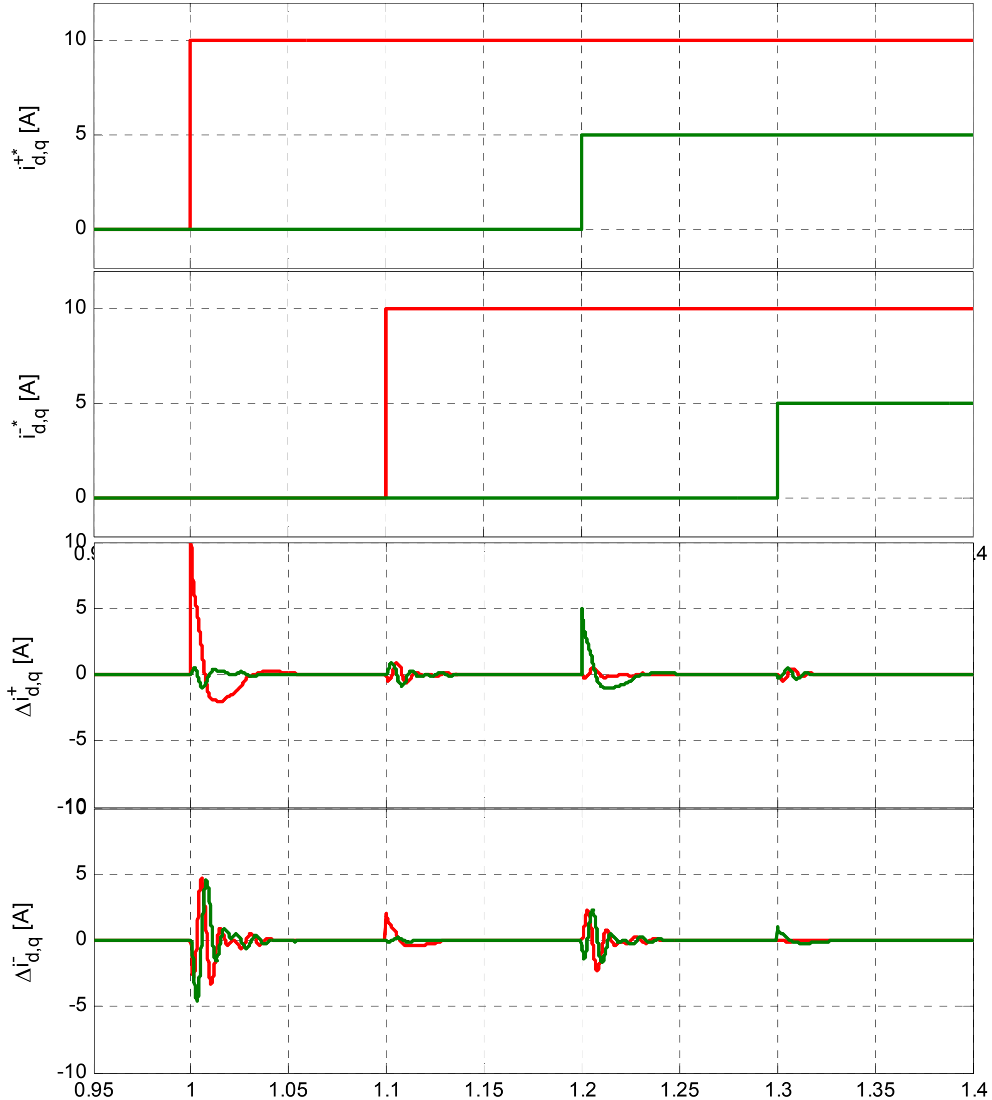
- DDSRF-CC using a decoupling network based on the measured signals



Unbalanced currents control structures

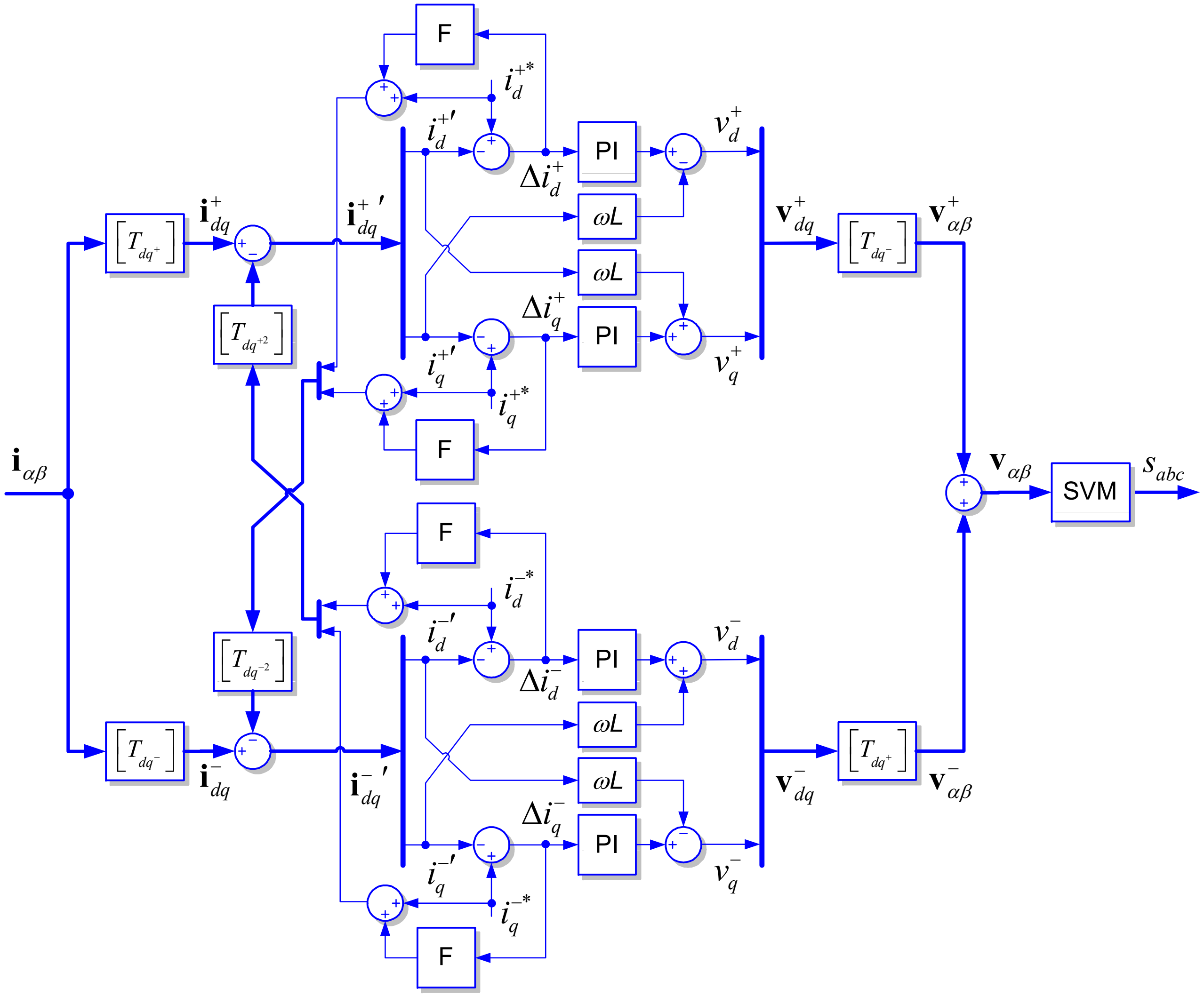
- DDSRF-CC using a decoupling network based on the measured signals

Since the amplitude of the current error oscillations in the negative-sequence reference frame matches the amplitude of the injected positive-sequence current, a decoupling network can be used to cancel out the oscillations at 2ω in the measured currents.



Unbalanced currents control structures

- DDSRF-CC using a decoupling network based on the reference and the error signals

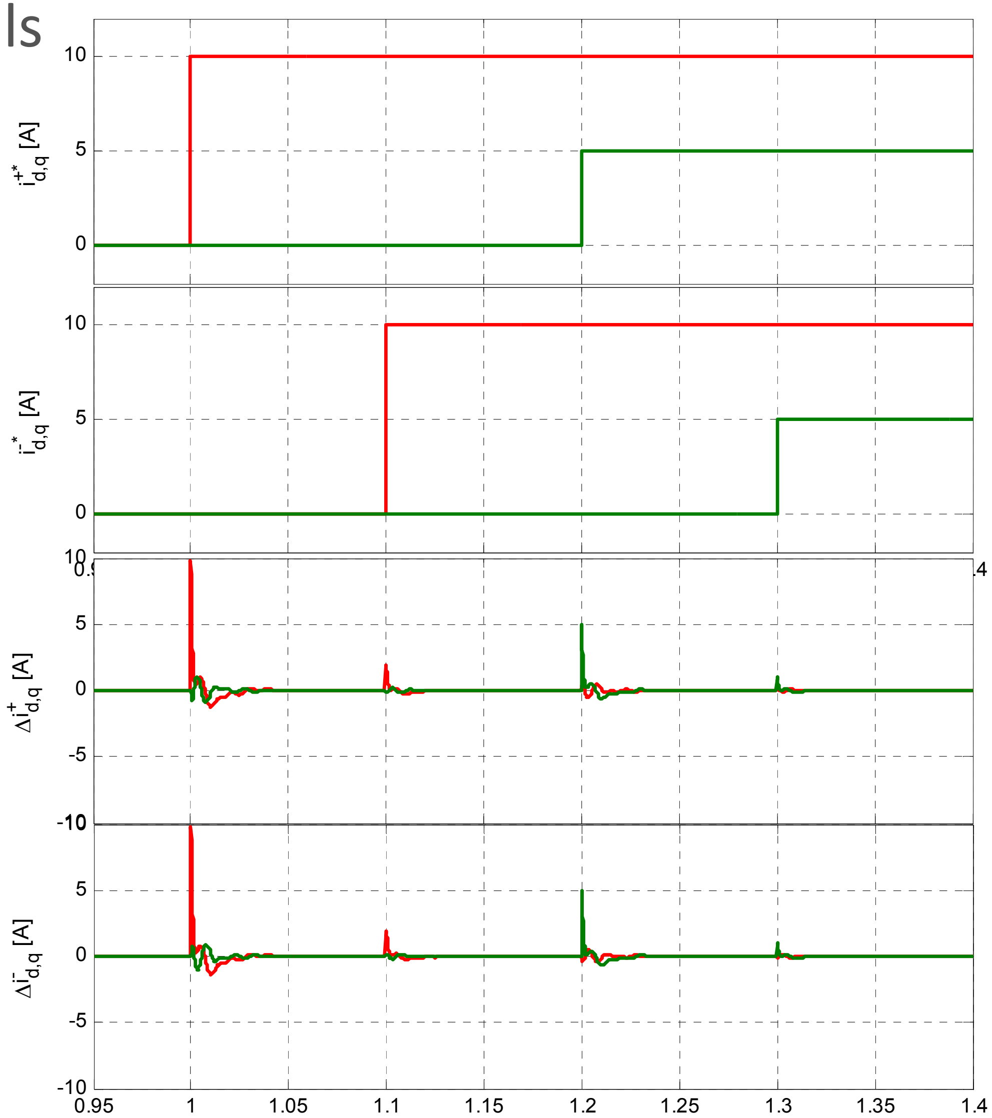


Unbalanced currents control structures

- DDSRF-CC using a decoupling network based on the reference and the error signals

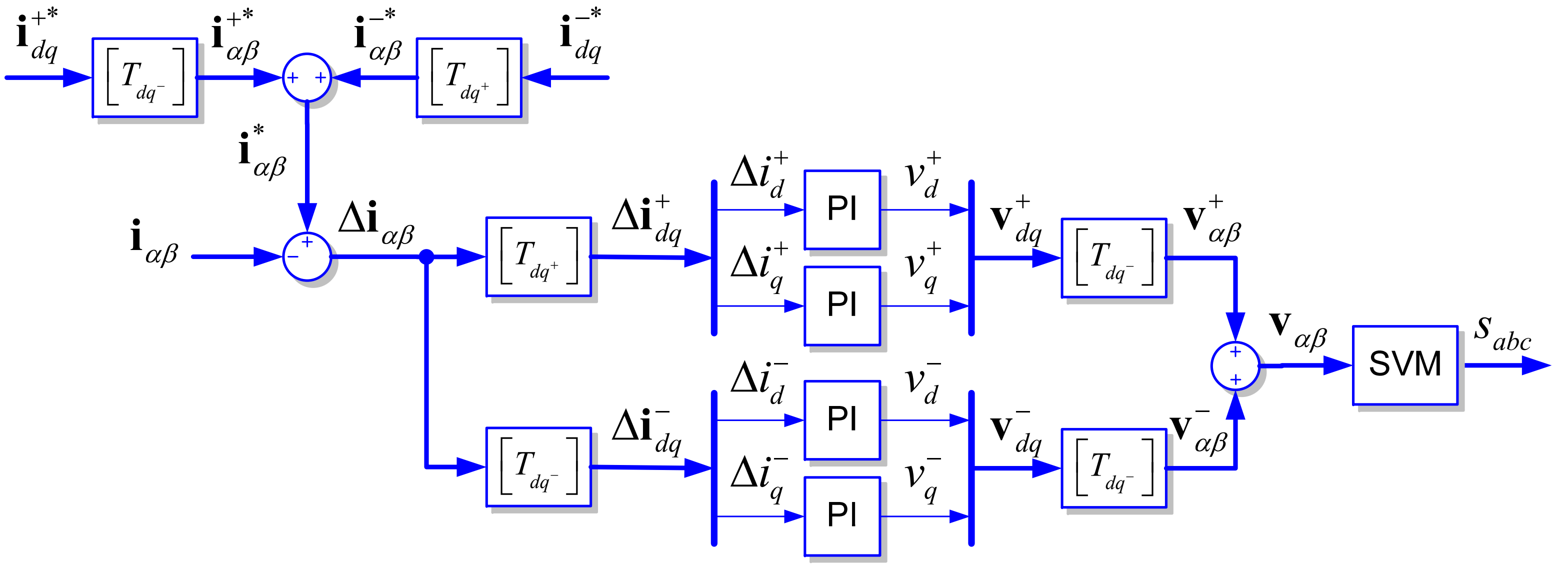
The reference signal for the positive-sequence current can be used to cancel out the oscillations at 2ω in the measured currents in the negative-sequence synchronous controller.

An additional controller (F) can be added to the decoupling network to cancel out any feasible 2ω oscillation resulting from tracking errors in the synchronous controllers.



Unbalanced currents control structures

- Current error controller on the synchronous reference frame



Synchronous Reference Frame

$$\mathbf{v}_{dq^+} = \begin{bmatrix} v_{d^+} \\ v_{q^+} \end{bmatrix} = \left[PI(t)\right] * \Delta\mathbf{i}_{dq^+} = \begin{bmatrix} k_p + k_i\int & 0 \\ 0 & k_p + k_i\int \end{bmatrix} * \begin{bmatrix} \Delta i_{d^+} \\ \Delta i_{q^+} \end{bmatrix}$$

$$\mathbf{v}_{dq^-} = \begin{bmatrix} v_{d^-} \\ v_{q^-} \end{bmatrix} = \left[PI(t)\right] * \Delta\mathbf{i}_{dq^-} = \begin{bmatrix} k_p + k_i\int & 0 \\ 0 & k_p + k_i\int \end{bmatrix} * \begin{bmatrix} \Delta i_{d^-} \\ \Delta i_{q^-} \end{bmatrix}$$

Stationary Reference Frame

$$\mathbf{v}(s)_{\alpha\beta^+} = \left[PI(s)_{\alpha\beta^+}\right]\Delta\mathbf{i}(s)_{\alpha\beta^+},$$

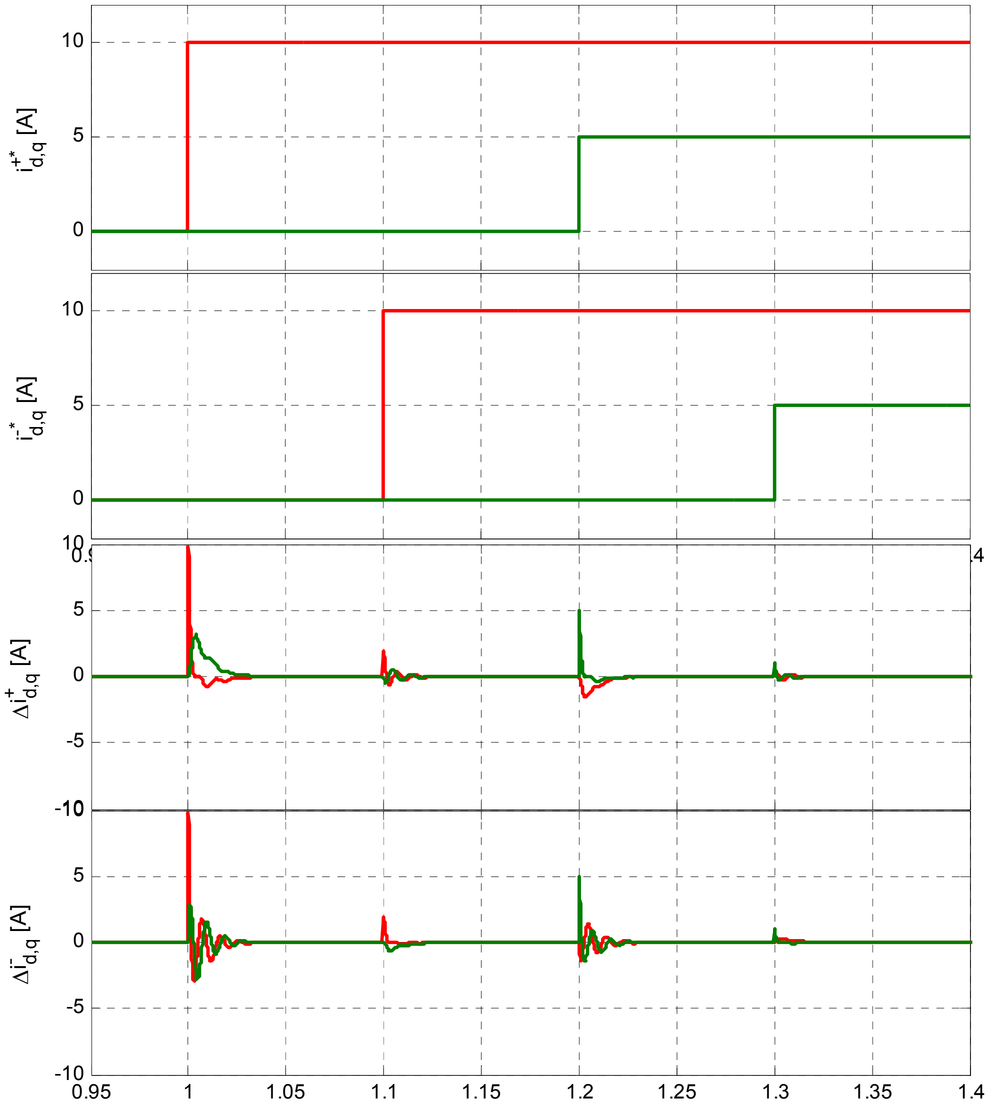
$$\mathbf{v}(s)_{\alpha\beta^-} = \left[PI(s)_{\alpha\beta^-}\right]\Delta\mathbf{i}(s)_{\alpha\beta^-}$$

Unbalanced currents control structures

- Current error controller on the synchronous reference frame

The synchronous controller can works on the current errors, instead on the measured currents.

In such case, only there exists a transient coupling between the signals of the positive- and negative-sequence synchronous controllers, since the error in steady-state is equal to zero.



Unbalanced currents control structures

- From the synchronous to the stationary reference frame

$$G_{\alpha\beta} = \frac{1}{2}\left[G_{dq}(s+j\omega) + G_{dq}(s-j\omega)\right]$$

$$\left[PI(s)_{\alpha\beta^+}\right] = \left[T_{dq^-}\right]\left[PI(s)\right]\left[T_{dq^+}\right] = \frac{1}{2}\begin{bmatrix} \left(PI(s+j\omega)+PI(s-j\omega)\right) & j\left(PI(s+j\omega)-PI(s-j\omega)\right) \\ j\left(-PI(s+j\omega)+PI(s-j\omega)\right) & \left(PI(s+j\omega)+PI(s-j\omega)\right) \end{bmatrix}$$

$$= \begin{bmatrix} k_p + \dfrac{k_i s}{s^2+\omega^2} & \dfrac{k_i \omega}{s^2+\omega^2} \\ -\dfrac{k_i \omega}{s^2+\omega^2} & k_p + \dfrac{k_i s}{s^2+\omega^2} \end{bmatrix},$$

$$\left[PI_{\alpha\beta^-}(s)\right] = \left[T_{dq^+}\right]\left[PI(s)\right]\left[T_{dq^-}\right] = \frac{1}{2}\begin{bmatrix} \left(PI(s+j\omega)+PI(s-j\omega)\right) & j\left(-PI(s+j\omega)+PI(s-j\omega)\right) \\ j\left(PI(s+j\omega)-PI(s-j\omega)\right) & \left(PI(s+j\omega)+PI(s-j\omega)\right) \end{bmatrix}$$

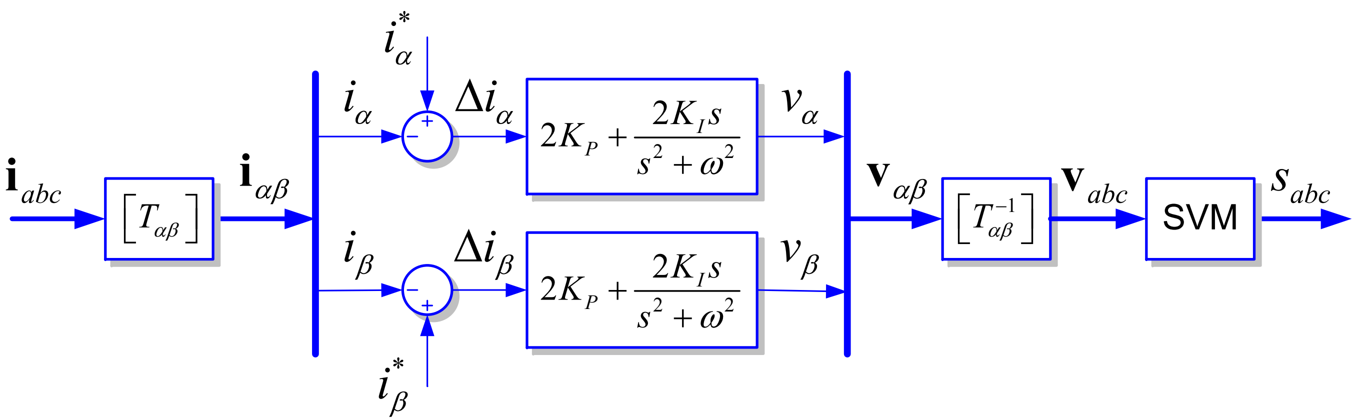
$$= \begin{bmatrix} k_p + \dfrac{k_i s}{s^2+\omega^2} & -\dfrac{k_i \omega}{s^2+\omega^2} \\ \dfrac{k_i \omega}{s^2+\omega^2} & k_p + \dfrac{k_i s}{s^2+\omega^2} \end{bmatrix}.$$

$$\mathbf{v}(s)_{\alpha\beta} = \mathbf{v}(s)_{\alpha\beta^+} + \mathbf{v}(s)_{\alpha\beta^-}$$

$$\boxed{\begin{bmatrix} v(s)_\alpha \\ v(s)_\beta \end{bmatrix} = 2\begin{bmatrix} k_p + \dfrac{k_i s}{s^2+\omega^2} & 0 \\ 0 & k_p + \dfrac{k_i s}{s^2+\omega^2} \end{bmatrix}\begin{bmatrix} \Delta i_\alpha \\ \Delta i_\beta \end{bmatrix}}$$

Unbalanced currents control structures

- Current error controller on the stationary reference frame



Transfer Function on the Stationary Reference Frame

$$\begin{bmatrix} v(s)_\alpha \\ v(s)_\beta \end{bmatrix} = 2\begin{bmatrix} k_p + \dfrac{k_i s}{s^2+\omega^2} & 0 \\ 0 & k_p + \dfrac{k_i s}{s^2+\omega^2} \end{bmatrix}\begin{bmatrix} \Delta i_\alpha \\ \Delta i_\beta \end{bmatrix}$$

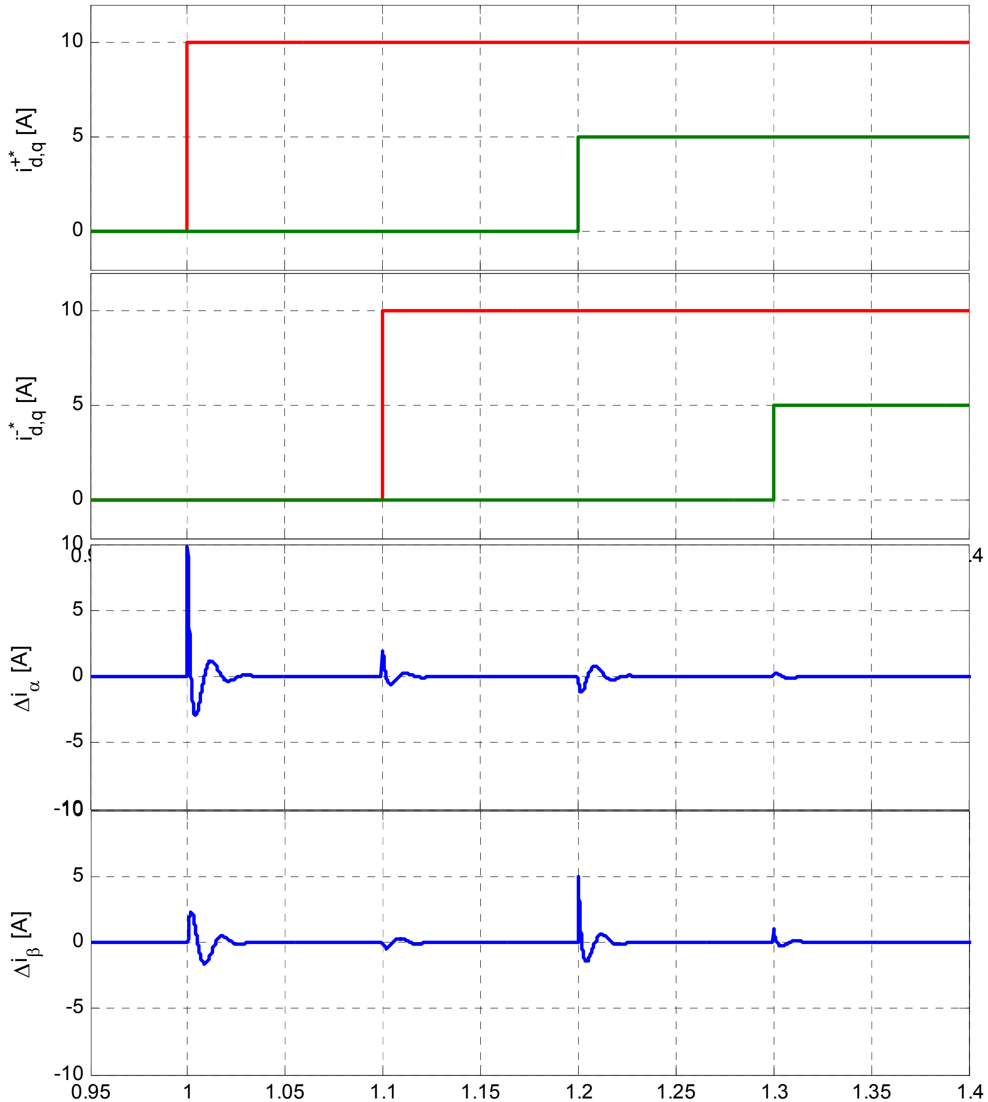
Unbalanced currents control structures

- Current error controller on the stationary reference frame

The synchronous controller working on the current errors is equivalent to a stationary controller working on the current errors as well.

Therefore, both controllers present a similar performance.

However, the stationary controller exhibits a more robust performance in case of grid disturbances since the grid frequency is a more stable magnitude than the phase-angle of the grid voltage.



Power control under unbalanced grid conditions

- Instantaneous active reactive control (IARC)

From the instantaneous power theory

$$p = \mathbf{v} \cdot \mathbf{i} = \mathbf{v} \cdot \mathbf{i}_p \qquad q = \left| \mathbf{v} \times \mathbf{i} \right| = \mathbf{v}_{\perp} \cdot \mathbf{i} = \mathbf{v}_{\perp} \cdot \mathbf{i}_q$$

Current references:

$$\mathbf{i}_p^* = g\mathbf{v} \quad ; \quad g = \frac{P}{|\ \mathbf{v}\ |^2} \qquad \mathbf{i}_q^* = b\mathbf{v}_{\perp} \quad ; \quad b = \frac{Q}{|\ \mathbf{v}\ |^2}$$

- A perfect control of the power injected into the grid is achieved but currents are extremely distorted because the squared voltage amplitude in the denominator of the formulas
- It is difficult to inject such a current by using standard linear controllers
- Distorted voltage drops are generated
- Resonances can be excited

Power control under unbalanced grid conditions

- Positive- Negative-Sequence Compensation (PNSC)

From the sequence components

$$p = \mathbf{v}^{+} \cdot \mathbf{i}_p^{+} + \mathbf{v}^{-} \cdot \mathbf{i}_p^{-} + \mathbf{v}^{+} \cdot \mathbf{i}_p^{-} + \mathbf{v}^{-} \cdot \mathbf{i}_p^{+}$$

$$q = \mathbf{v}_{\perp}^{+} \cdot \mathbf{i}_q^{+} + \mathbf{v}_{\perp}^{-} \cdot \mathbf{i}_q^{-} + \mathbf{v}_{\perp}^{+} \cdot \mathbf{i}_q^{-} + \mathbf{v}_{\perp}^{-} \cdot \mathbf{i}_q^{+}$$

Condition:

$$P = \mathbf{v}^{+}\mathbf{i}_p^{*+} + \mathbf{v}^{-}\mathbf{i}_p^{*-} \quad ; \quad 0 = \mathbf{v}^{+}\mathbf{i}_p^{*-} + \mathbf{v}^{-}\mathbf{i}_p^{*+}$$

$$Q = \mathbf{v}_{\perp}^{+}\mathbf{i}_q^{*+} + \mathbf{v}_{\perp}^{-}\mathbf{i}_q^{*-} \quad ; \quad 0 = \mathbf{v}_{\perp}^{+}\mathbf{i}_q^{*-} + \mathbf{v}_{\perp}^{-}\mathbf{i}_q^{*+}$$

Current references:

$$\mathbf{i}_p^{*} = \mathbf{i}_p^{*+} + \mathbf{i}_p^{*-} = g^{\pm}\left(\mathbf{v}^{+} - \mathbf{v}^{-}\right) \quad ; \quad g^{\pm} = \frac{P}{|\,\mathbf{v}^{+}\,|^2 - |\,\mathbf{v}^{-}\,|^2}$$

$$\mathbf{i}_q^{*} = \mathbf{i}_q^{*+} + \mathbf{i}_q^{*-} = b^{\pm}\left(\mathbf{v}_{\perp}^{+} - \mathbf{v}_{\perp}^{-}\right) \quad ; \quad b^{\pm} = \frac{Q}{|\,\mathbf{v}_{\perp}^{+}\,|^2 - |\,\mathbf{v}_{\perp}^{-}\,|^2}$$

- The interaction between voltage and current components in-quadrature with different sequences gives rise to power oscillations at twice the fundamental utility frequency

Power control under unbalanced grid conditions

- Average Active-Reactive Control (AARC)

Current references:

$$\mathbf{i}_p^* = \mathbf{i}_p^{*+} + \mathbf{i}_p^{*-} = G\ \mathbf{v} \quad ; \quad G = \frac{P}{V_\Sigma^2}$$

$$\mathbf{i}_q^* = \mathbf{i}_q^{*+} + \mathbf{i}_q^{*-} = B\ \mathbf{v}_\perp \quad ; \quad B = \frac{Q}{V_\Sigma^2}$$

$$V_\Sigma = \sqrt{\frac{1}{T}\int_0^T |\mathbf{v}|^2\, dt} = \sqrt{\left|\mathbf{v}^+\right|^2 + \left|\mathbf{v}^-\right|^2}$$

- Active and reactive reference current vectors are monotonously proportional to the direct and in-quadrature positive-sequence voltage vectors, respectively
- The current injected are based on averaged calculations, therefore there are instantaneous oscillations in both the active and the reactive powers

Power control under unbalanced grid conditions

- Balanced positive sequence control (BPSC)

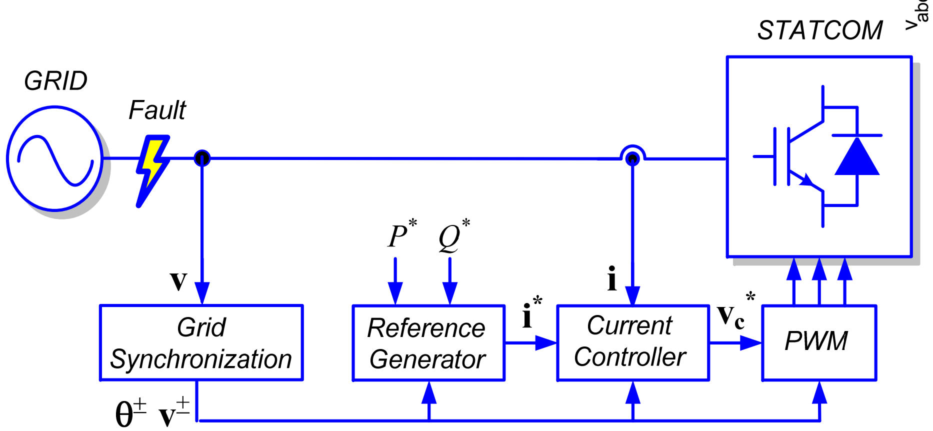
Current references:

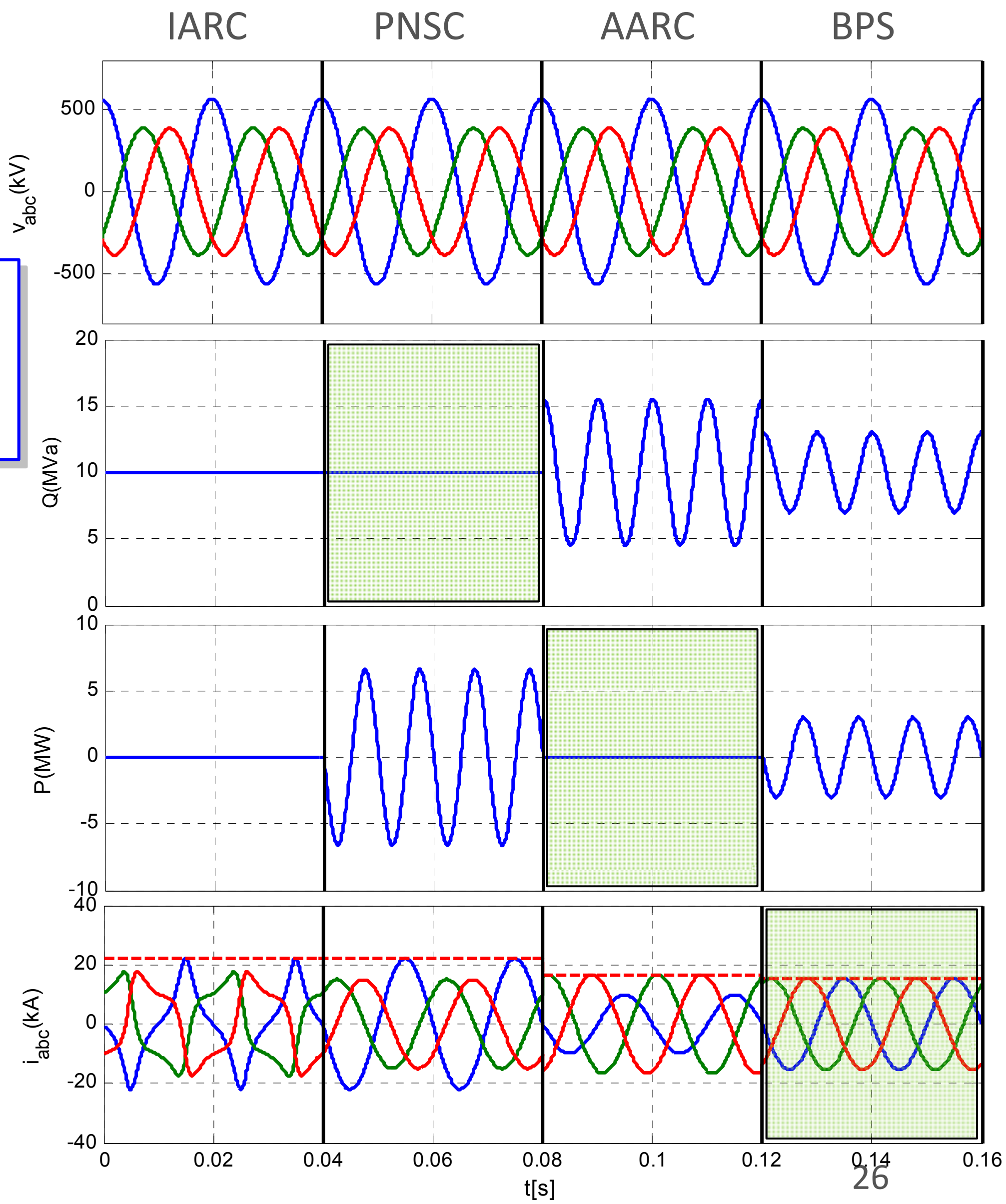
$$\mathbf{i}_p^* = G^+ \mathbf{v}^+ \quad ; \quad G^+ = \frac{P}{\left|\mathbf{v}^+\right|^2}$$

$$\mathbf{i}_q^* = B^+ \mathbf{v}_\perp^+ \quad ; \quad B^+ = \frac{Q}{\left|\mathbf{v}^+\right|^2}$$

- The current vectors consist of a set of perfectly balanced positive-sequence sinusoidal waveforms
- Under unbalanced operating conditions, the instantaneous active and reactive power delivered to the grid differs from P and Q because of the interaction between the positive-sequence injected current and the negative-sequence grid voltage
- The instantaneous active and the reactive powers will be affected by oscillations under unbalanced grid conditions

Performance of IARC, PNSC, AARC and BPSC





The peak value of the reactive current injected into the grid for a given reactive power level depends on the selected current reference strategy

Flexible positive-negative sequence control (FPNSC)

- Current references

$$\mathbf{i}_p^* = k_1 \frac{P}{\left|\mathbf{v}^+\right|^2}\mathbf{v}^+ + \left(1-k_1\right)\frac{P}{\left|\mathbf{v}^-\right|^2}\mathbf{v}^-$$

$$\mathbf{i}_q^* = k_2 \frac{Q}{\left|\mathbf{v}^+\right|^2}\mathbf{v}_\perp^+ + \left(1-k_2\right)\frac{Q}{\left|\mathbf{v}^-\right|^2}\mathbf{v}_\perp^-$$

$$\mathbf{i}^* = P\cdot\left(\frac{k_1}{\left|\mathbf{v}^+\right|^2}\cdot\mathbf{v}^+ + \frac{\left(1-k_1\right)}{\left|\mathbf{v}^-\right|^2}\cdot\mathbf{v}^-\right) + Q\cdot\left(\frac{k_2}{\left|\mathbf{v}^+\right|^2}\cdot\mathbf{v}_\perp^+ + \frac{\left(1-k_2\right)}{\left|\mathbf{v}^-\right|^2}\cdot\mathbf{v}_\perp^-\right)$$

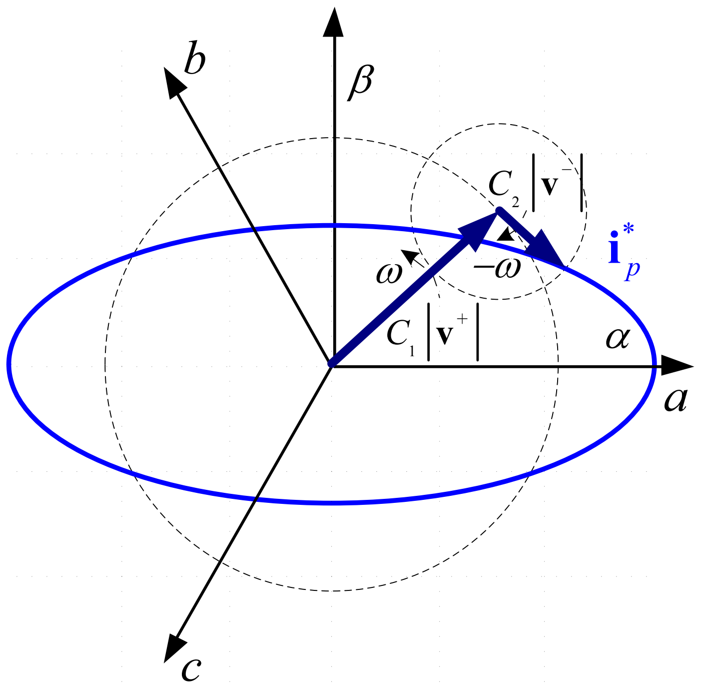
- By means of changing the value of k_1 and k_2, the relationship between positive- and negative-sequence current components, in both, the active and the reactive currents can be easily modified
- This feature is very interesting when the interaction between the power converter and the grid is studied

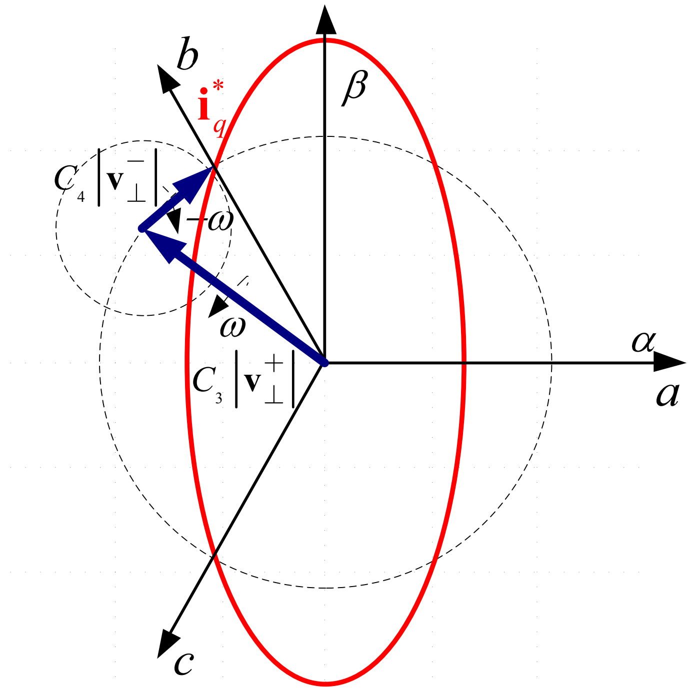
Flexible power control with current limitation

- Locus of the current vector under unbalanced grid conditions

$$\mathbf{i}^* = \underbrace{C_1 \cdot \mathbf{v}^+ + C_2 \cdot \mathbf{v}^-}_{\mathbf{i}_p^*} + \underbrace{C_3 \cdot \mathbf{v}_\perp^+ + C_4 \cdot \mathbf{v}_\perp^-}_{\mathbf{i}_q^*}$$

$$C_1 = \frac{P \cdot k_1}{\left|\mathbf{v}^+\right|^2}; C_2 = \frac{P \cdot (1 - k_1)}{\left|\mathbf{v}^-\right|^2}; C_3 = \frac{Q \cdot k_2}{\left|\mathbf{v}^+\right|^2}; C_4 = \frac{Q \cdot (1 - k_2)}{\left|\mathbf{v}^-\right|^2}$$



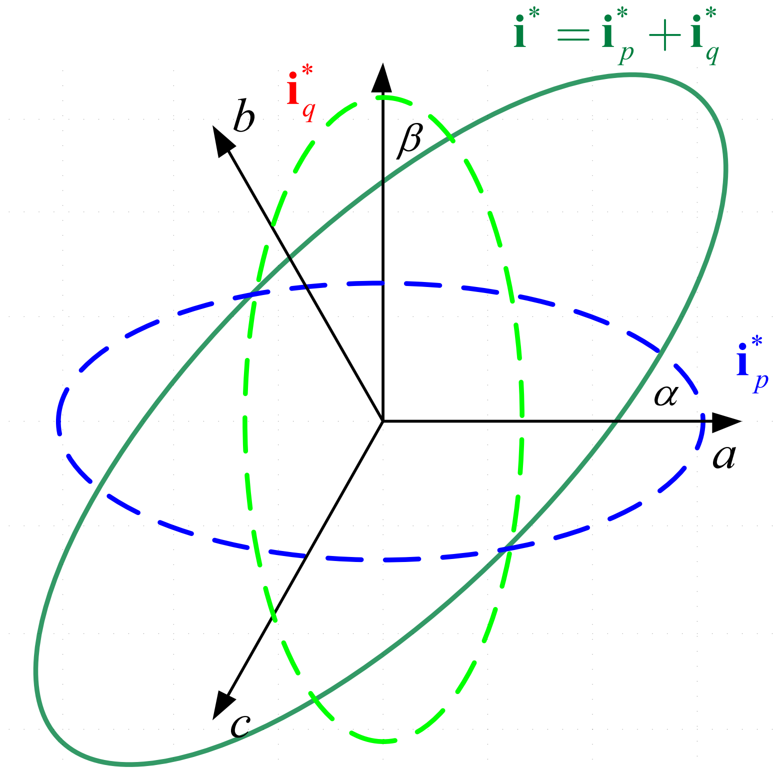


Flexible power control with current limitation

- Locus of the current vector under unbalanced grid conditions

$$\mathbf{i}^* = \underbrace{C_1 \cdot \mathbf{v}^+ + C_2 \cdot \mathbf{v}^-}_{\mathbf{i}_p^*} + \underbrace{C_3 \cdot \mathbf{v}_\perp^+ + C_4 \cdot \mathbf{v}_\perp^-}_{\mathbf{i}_q^*}$$

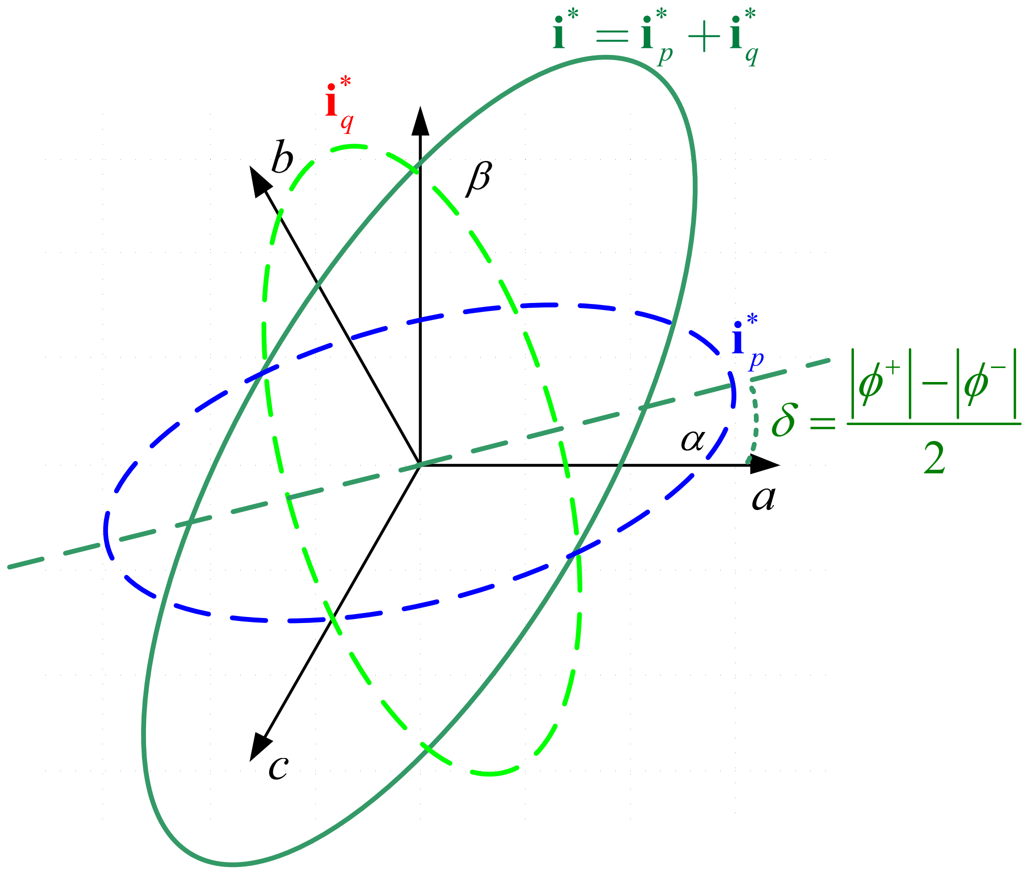
$$C_1 = \frac{P \cdot k_1}{\left|\mathbf{v}^+\right|^2}; C_2 = \frac{P \cdot (1-k_1)}{\left|\mathbf{v}^-\right|^2}; C_3 = \frac{Q \cdot k_2}{\left|\mathbf{v}^+\right|^2}; C_4 = \frac{Q \cdot (1-k_2)}{\left|\mathbf{v}^-\right|^2}$$



Flexible power control with current limitation

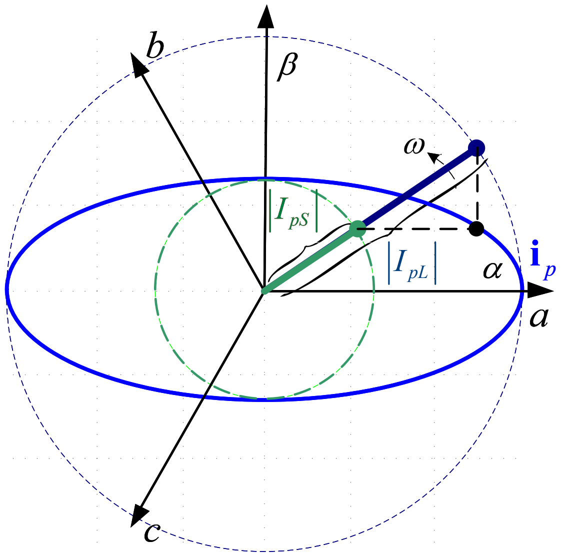
- Locus of the current vector under unbalanced grid conditions

$$\mathbf{i}^* = \underbrace{C_1 \cdot \mathbf{v}^+ + C_2 \cdot \mathbf{v}^-}_{\mathbf{i}_p^*} + \underbrace{C_3 \cdot \mathbf{v}_\perp^+ + C_4 \cdot \mathbf{v}_\perp^-}_{\mathbf{i}_q^*}$$



Flexible power control with current limitation

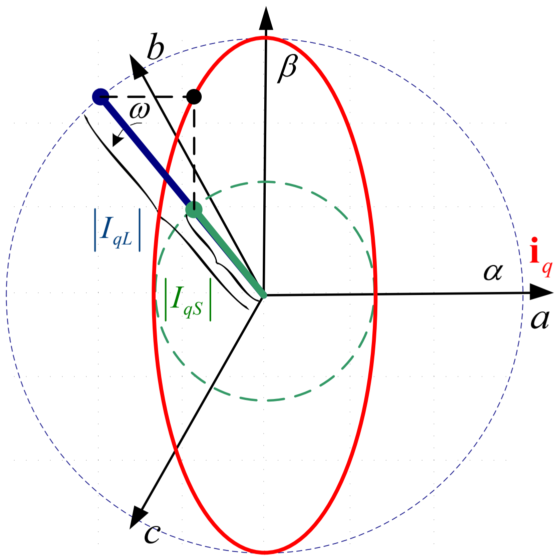
- Instantaneous value of the three phase currents



$$\mathbf{i}_p^* = \begin{bmatrix} i_{p\alpha}^* \\ i_{p\beta}^* \end{bmatrix} = \begin{bmatrix} I_{pL} \cdot \cos \omega t \\ I_{pS} \cdot \sin \omega t \end{bmatrix}$$

$$I_{pL} = P \cdot \left(\frac{k_1}{|\mathbf{v}^+|} + \frac{(1-k_1)}{|\mathbf{v}^-|} \right)$$

$$I_{pS} = P \cdot \left(\frac{k_1}{|\mathbf{v}^+|} - \frac{(1-k_1)}{|\mathbf{v}^-|} \right)$$



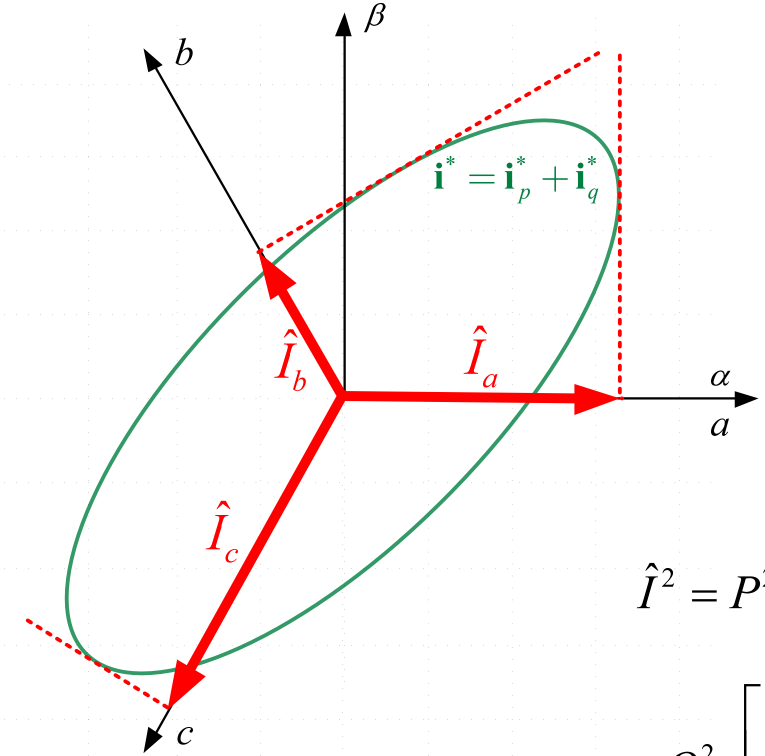
$$\mathbf{i}_q^* = \begin{bmatrix} i_{q\alpha}^* \\ i_{q\beta}^* \end{bmatrix} = \begin{bmatrix} -I_{qS} \cdot \sin \omega t \\ I_{qL} \cdot \cos \omega t \end{bmatrix}$$

$$I_{qL} = Q \cdot \left(\frac{k_2}{|\mathbf{v}^+|} + \frac{(1-k_2)}{|\mathbf{v}^-|} \right)$$

$$I_{qS} = Q \cdot \left(\frac{k_2}{|\mathbf{v}^+|} - \frac{(1-k_2)}{|\mathbf{v}^-|} \right)$$

Flexible power control with current limitation

- Estimation of the maximum current in each phase



$$\mathbf{i}^* = \mathbf{i}_p^* + \mathbf{i}_q^* = \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \begin{bmatrix} I_{pL} \cdot \cos \omega t - I_{qS} \cdot \sin \omega t \\ I_{pS} \cdot \sin \omega t + I_{qL} \cdot \cos \omega t \end{bmatrix}$$

$$\hat{I}_a = \hat{I}\left(\gamma = \delta\right),$$
$$\hat{I}_b = \hat{I}\left(\gamma = \delta + \pi/3\right),$$
$$\hat{I}_c = \hat{I}\left(\gamma = \delta - \pi/3\right).$$

$$\begin{aligned}\hat{I}^2 = P^2 &\cdot \left[\frac{k_1^2 \cdot \left|\mathbf{v}^-\right|^2 + \left(1-k_1\right)^2 \cdot \left|\mathbf{v}^+\right|^2 + 2k_1\left(1-k_1\right)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right|}{\left|\mathbf{v}^+\right|^2 \cdot \left|\mathbf{v}^-\right|^2} \right] \\ +Q^2 &\cdot \left[\frac{k_2^2 \cdot \left|\mathbf{v}^-\right|^2 + \left(1-k_2\right)^2 \cdot \left|\mathbf{v}^+\right|^2 - 2k_2\left(1-k_2\right)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right|}{\left|\mathbf{v}^+\right|^2 \cdot \left|\mathbf{v}^-\right|^2} \right] \\ -PQ &\cdot \left[\frac{\left(2k_1 + 2k_2 - 4k_1k_2\right) \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \cdot \sin 2\gamma}{\left|\mathbf{v}^+\right|^2 \cdot \left|\mathbf{v}^-\right|^2} \right].\end{aligned}$$

Flexible power control with current limitation

- Estimation of the maximum active and reactive power setpoint

$$0 = Q^2 \cdot \left[k_2^2 \cdot \left|\mathbf{v}^-\right|^2 + (1-k_2)^2 \cdot \left|\mathbf{v}^+\right|^2 - 2k_2(1-k_2)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \right]$$
$$-PQ \cdot \left[(2k_1 + 2k_2 - 4k_1k_2) \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \cdot \sin 2\gamma \right]$$
$$+P^2 \cdot \left[k_1^2 \cdot \left|\mathbf{v}^-\right|^2 + (1-k_1)^2 \cdot \left|\mathbf{v}^+\right|^2 + 2k_1(1-k_1)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \right] - \hat{I}^2 \cdot \left|\mathbf{v}^+\right|^2 \cdot \left|\mathbf{v}^-\right|^2$$

- Estimation of the maximum Q setpoint for $P=P^*$

$$0 = Q^2 \cdot \underbrace{\left[k_2^2 \cdot \left|\mathbf{v}^-\right|^2 + (1-k_2)^2 \cdot \left|\mathbf{v}^+\right|^2 - 2k_2(1-k_2)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \right]}_{a}$$
$$-Q \cdot \underbrace{P^* \left[(2k_1 + 2k_2 - 4k_1k_2) \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \cdot \sin 2\gamma \right]}_{b}$$
$$\underbrace{+P^{*2} \cdot \left[k_1^2 \cdot \left|\mathbf{v}^-\right|^2 + (1-k_1)^2 \cdot \left|\mathbf{v}^+\right|^2 + 2k_1(1-k_1)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right| \right] - \hat{I}^2 \cdot \left|\mathbf{v}^+\right|^2 \cdot \left|\mathbf{v}^-\right|^2}_{c}$$

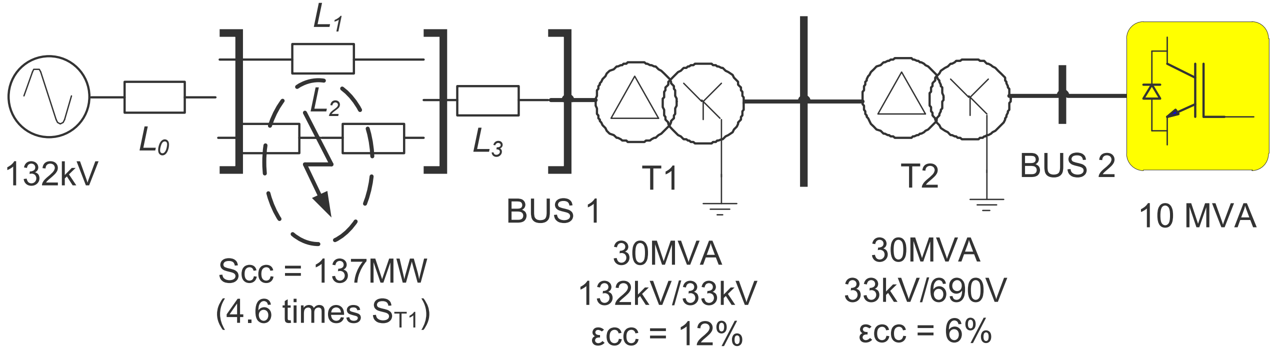
$$0 = aQ^2 + bQ + c$$

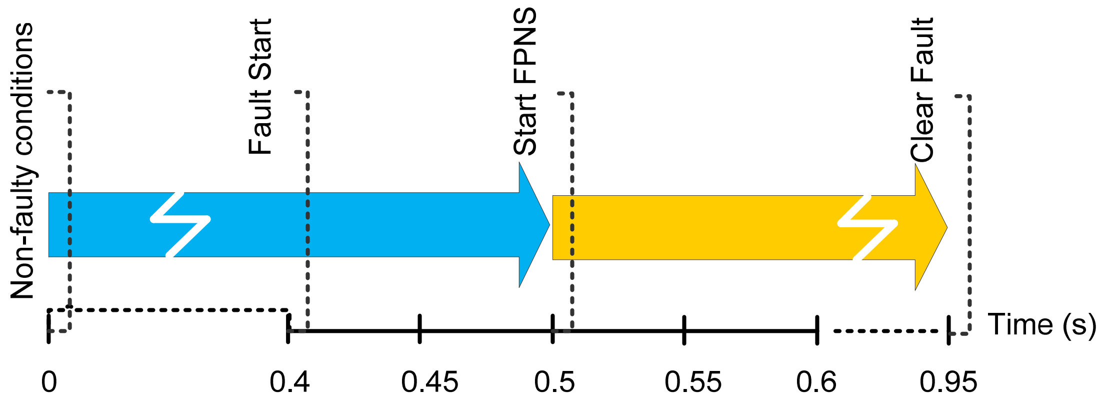
- Estimation of the maximum Q setpoint for $P=0$

$$Q = \sqrt{\frac{\hat{I}^2 \cdot \left|\mathbf{v}^+\right|^2 \cdot \left|\mathbf{v}^-\right|^2}{k_2^2 \cdot \left|\mathbf{v}^-\right|^2 + (1-k_2)^2 \cdot \left|\mathbf{v}^+\right|^2 - 2k_2(1-k_2)\cos 2\gamma \cdot \left|\mathbf{v}^+\right| \cdot \left|\mathbf{v}^-\right|}}$$

Performance of the FPNSC

- Estimation of the maximum current in each phase

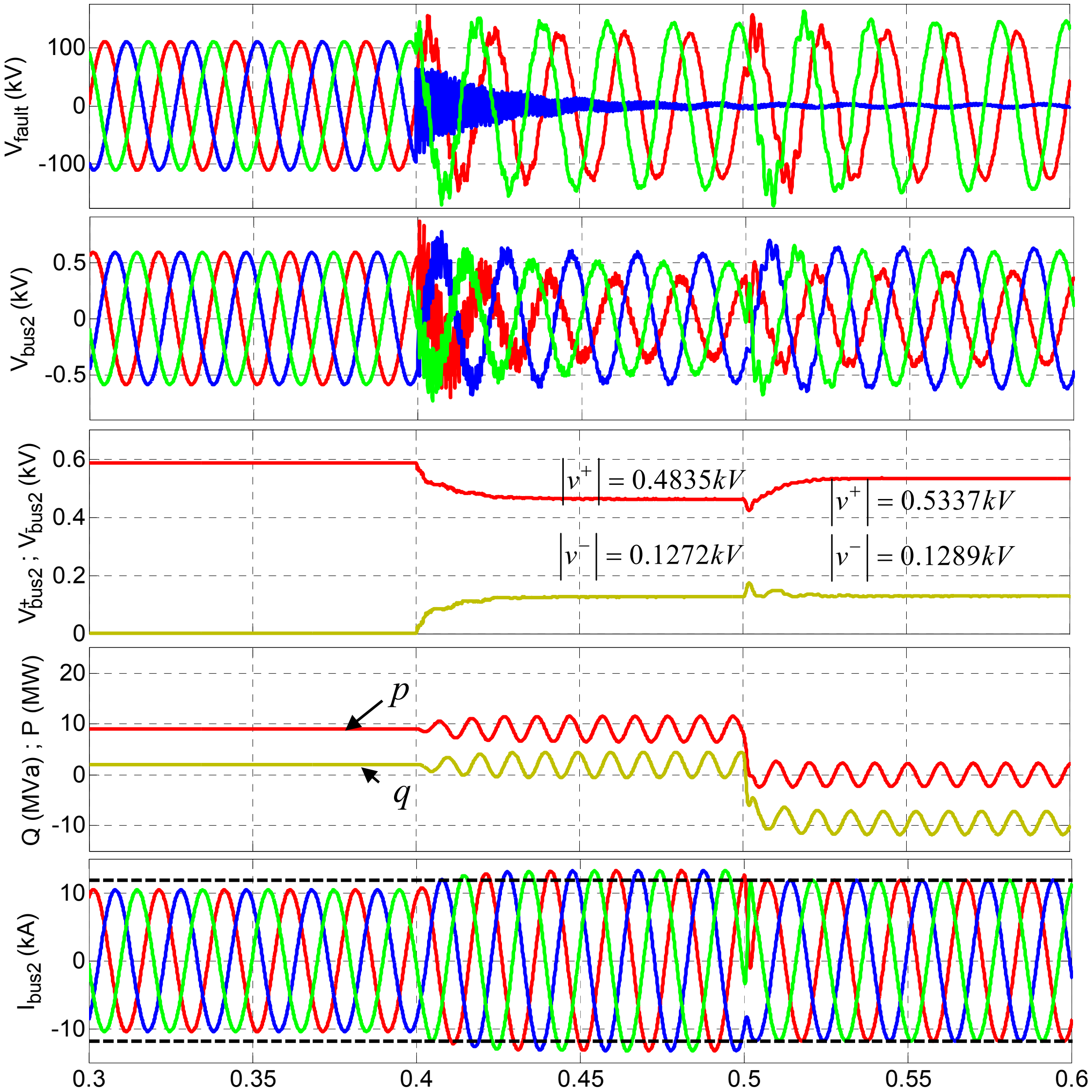




Case A	**Injection of P = 8.665MW Q = 2.5MVar**	**Injection of Q_{max} and k_2=0**
Case B	**Injection of P = 8.665MW Q = 2.5MVar**	**Injection of Q_{max} and k_2=1**
Case C	**Injection of P = 8.665MW Q = 2.5MVar**	**Injection of Q_{max} and 0<k_2<1**

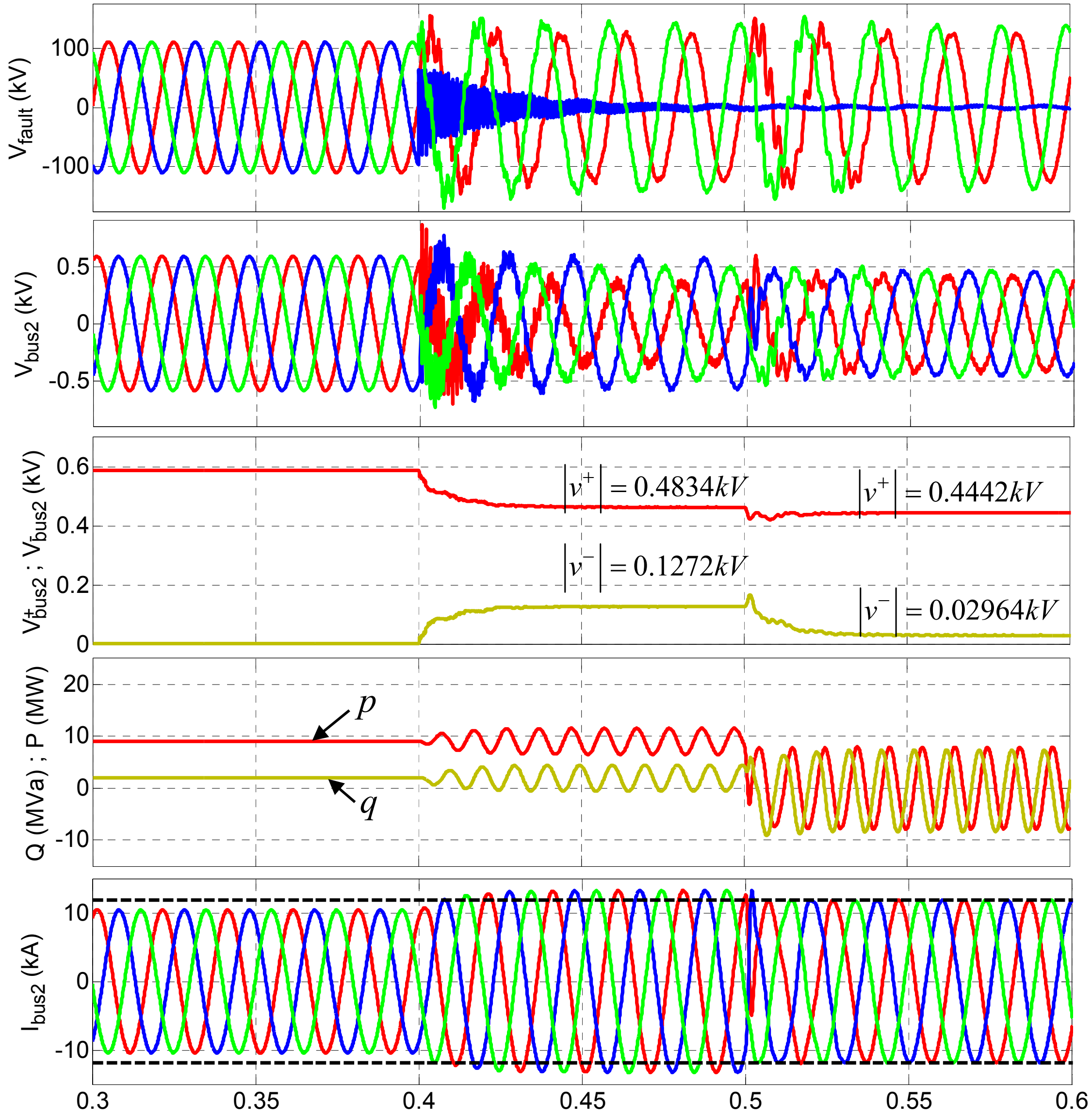
Response of the FPNSC

- Case A: Injection of positive sequence reactive power



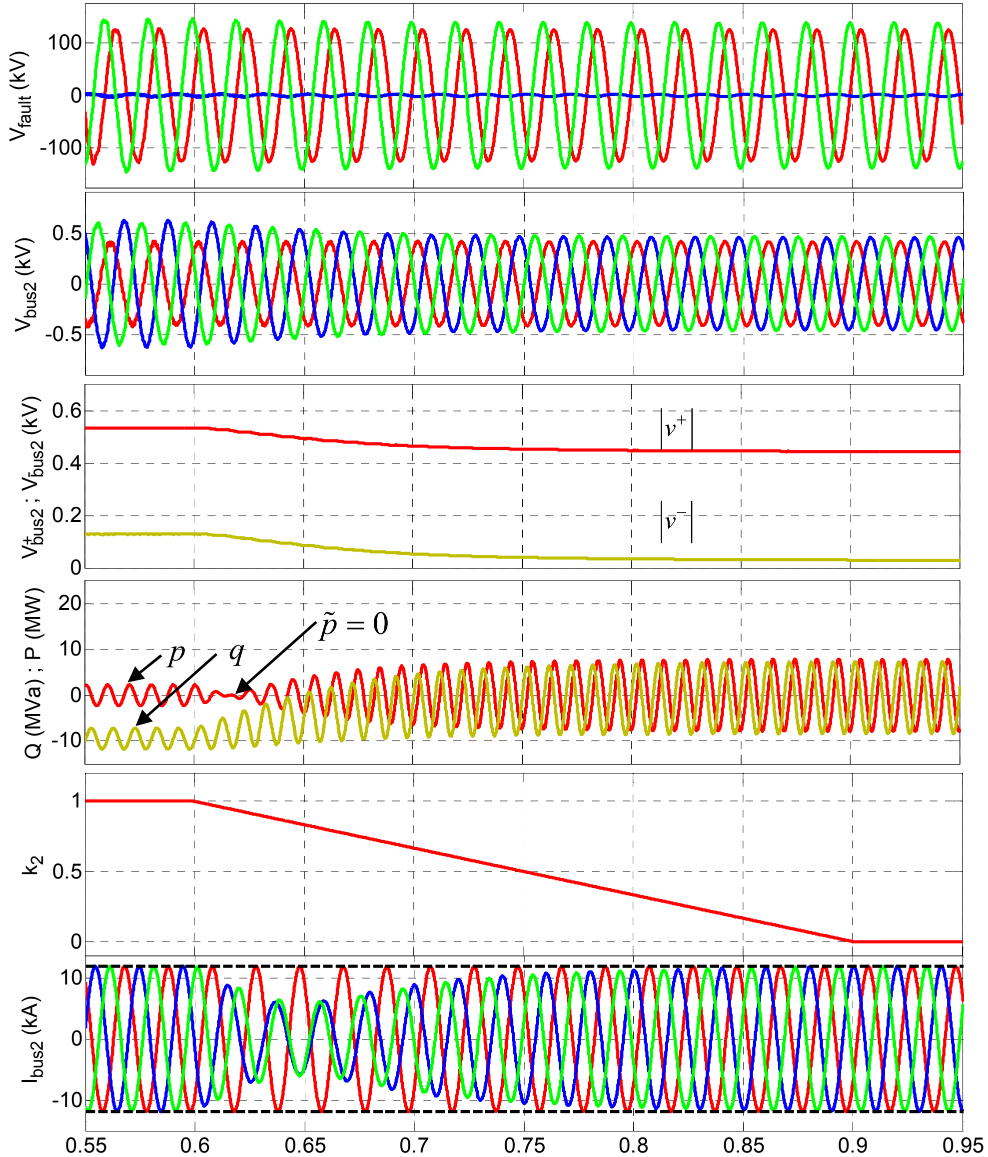
Response of the FPNSC

- Case B: Injection of negative sequence reactive power



Response of the FPNSC

- Case C: Injection of positive- and negative-sequence reactive power



Conclusion

- The occurrence of unbalanced grid faults gives rise to negative sequence voltages in the network, which affect the operation of grid connected power converters
- The implementation of specific control structures, able to deal with the injection of both symmetrical components of the current, is a key issue in the design of modern power converters
- There are multiple reference current generation strategies that can be selected to manage the P and Q oscillations in different ways during unbalanced grid faults
- The maximum power injected by the power converter under unbalanced faults, and consequently the maximum current drawn at its output, should be limited in order to not exceed the converter's specifications