Synchronization and Control Methods for grid-connecting Renewable Energy Sources

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Outline

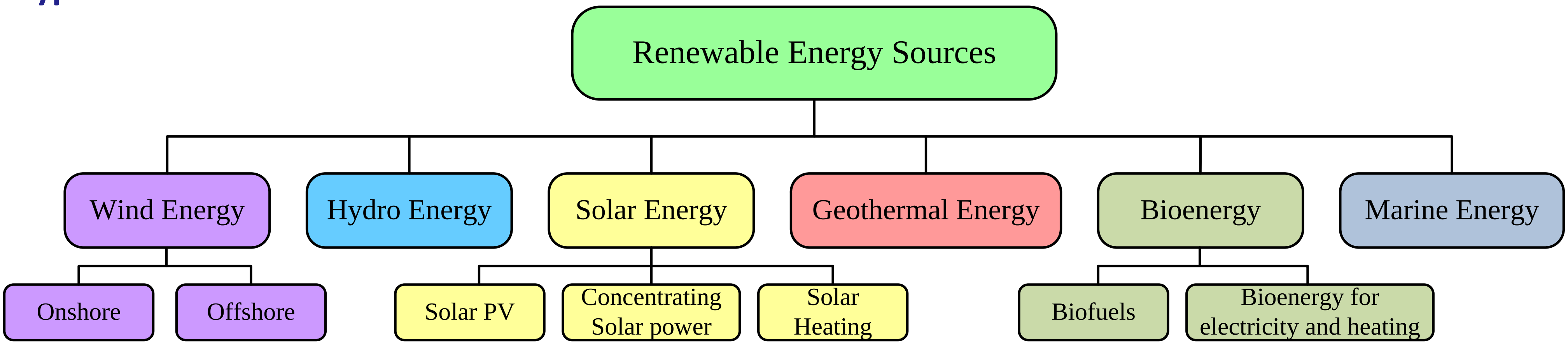
1. Introduction
2. Power electronics: The enabling technology for RES
3. Grid side converter controller
4. Synchronization methods
5. Conclusions

Renewable Energy Sources: Definition – Current Status – Future Prospect – Challenging Aspects

Renewable Energy Sources (RES) - definition

- Renewable energy is generally defined as the energy from a source that is not depleted when used or the energy from resources which are naturally replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat

Type of RES:



1. Introduction

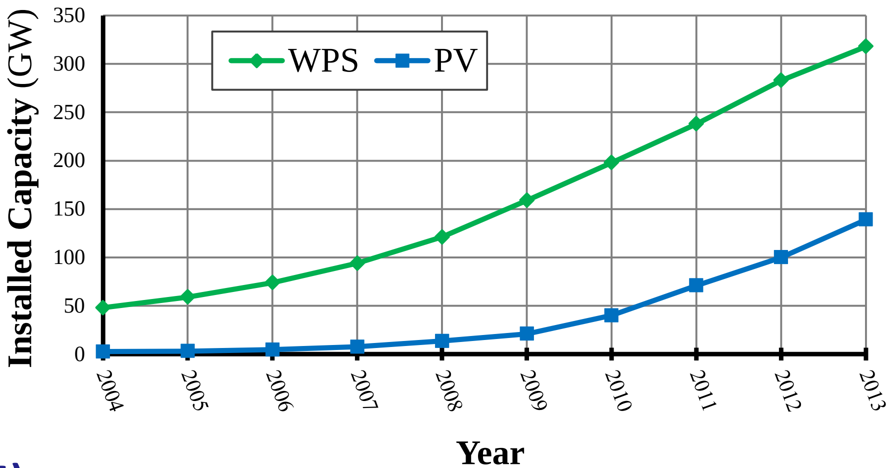
Renewable Energy Sources: Definition – **Current Status** – Future Prospect – Challenging Aspects

RES are receiving considerable attention throughout the world

- Price of fossil fuels
- Environmental impact of fossil fuels / Climate change

Worldwide installed capacity (GigaWatt)

for Wind Power Systems (WPS) and solar PV systems



Share of energy consumption originating from RES (2014)

- **European Union** → 14%
- **Cyprus** → 7%

1. Introduction

Renewable Energy Sources: Definition – Current Status – **Future Prospect** – Challenging Aspects

European Union aims → "20-20-20 targets" by 2020

- **20% reduction of green house gas emissions** compared to 1990 levels
- **20%** reduction in primary energy use through improved **energy efficiency**
- **20%** share of **energy consumption** originating from **renewable energy sources (RES)**

For Cyprus the target is define at 13% of energy consumption to produce from RES by 2020

- Autonomous-isolated power grid → Stability problems

European Union 2030 Framework for Climate & Energy

- **40% reduction of green house gas emissions** compared to 1990 levels
- **27%** reduction in primary energy use through improved **energy efficiency**
- **27%** share of **energy consumption** originating from **renewable energy sources (RES)**

Renewable Energy Sources: Definition – Current Status – Future Prospect – **Challenging Aspects**

The increasing penetration of RES:

- enables the **reduction of green house gas emissions** (environmental benefits)
- **can raise stability issues** regarding the operation of the power system
- **can affect the power quality** of the power system
- can lead to **cascading and blackout events** in the power system

Grid regulations for grid-connecting RES are evolving to ensure the proper power system operation

- RES should inject **high quality currents** even under highly harmonic distorted grid voltage
- RES should be **remain interconnected** under **balanced** or **unbalanced grid faults**
- RES should ensure a **fast** and **appropriate Fault Ride Through (FRT) operation** under grid faults
- RES should **provide frequency (active power)** and **voltage (reactive power) support** to the grid

1. Introduction

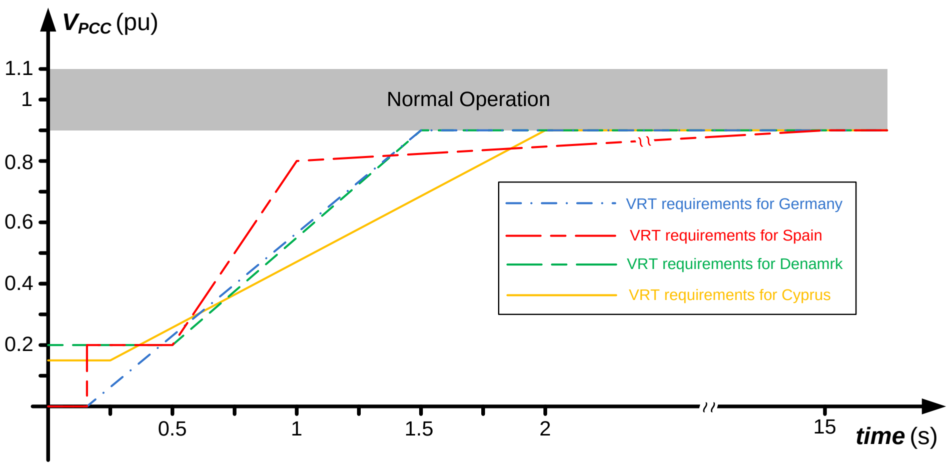
Renewable Energy Sources: Definition – Current Status – Future Prospect – **Challenging Aspects**

The design of RES should be advanced in order to achieve:

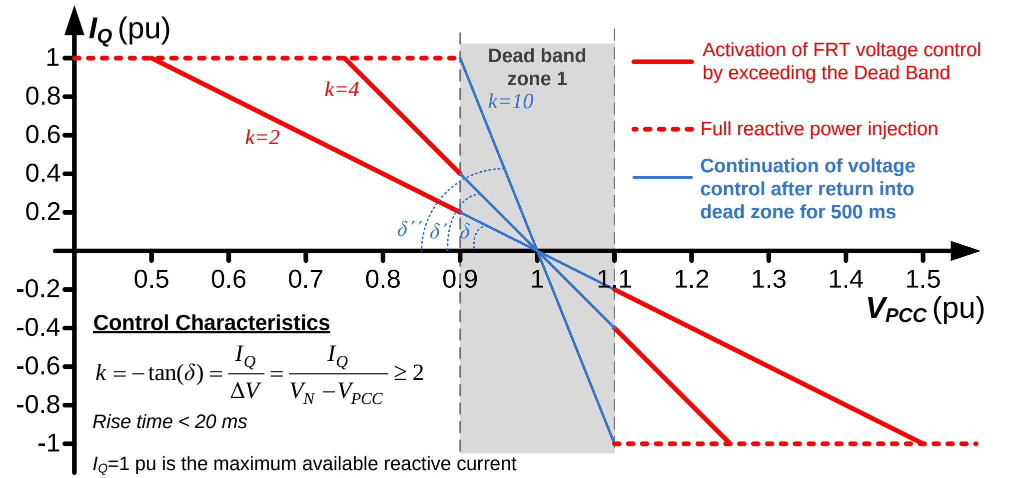
- **high quality current** injection
- **fast and dynamic** response
- **immunity** against **voltage harmonic distortion**
- proper **FRT operation** under abnormal grid conditions

Under a balanced or unbalanced grid faults

RES should keep its synchronization and remain grid-connected



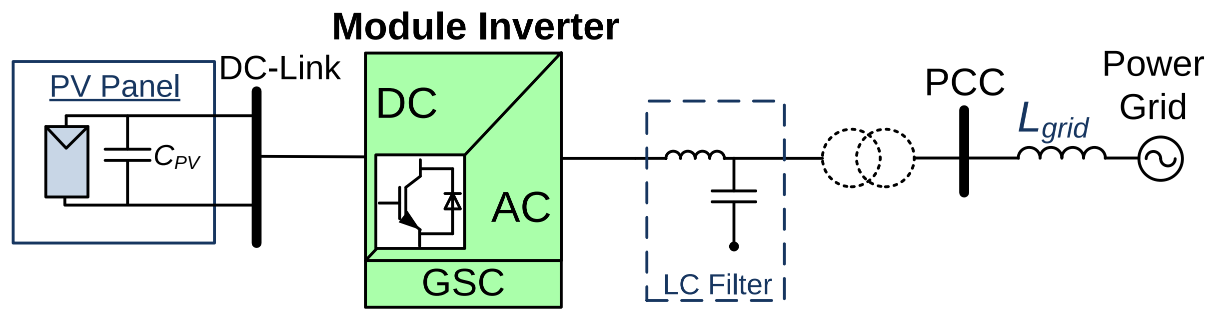
RES should ensure a dynamic FRT operation for supporting the voltage and the frequency of the grid



Power Electronics: **PV topologies** – WPS topologies – Grid Side Converter (Inverter)

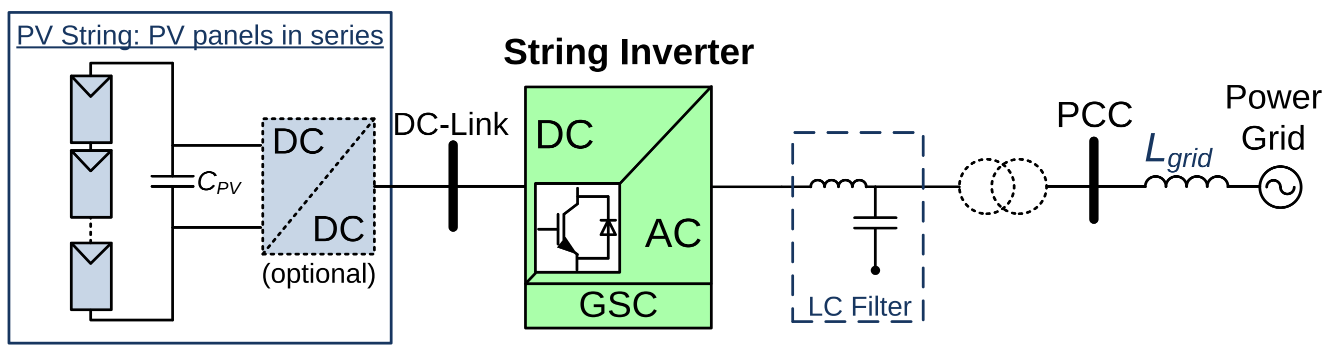
Grid-Connected PV system with Module Inverter

- Small systems
- ~ 300 W
- 1-phase Module Inverter



Grid-Connected PV system with String Inverter

- Residential Applications
- 1 – 10 kW
- 1- or 3-phase String Inverter

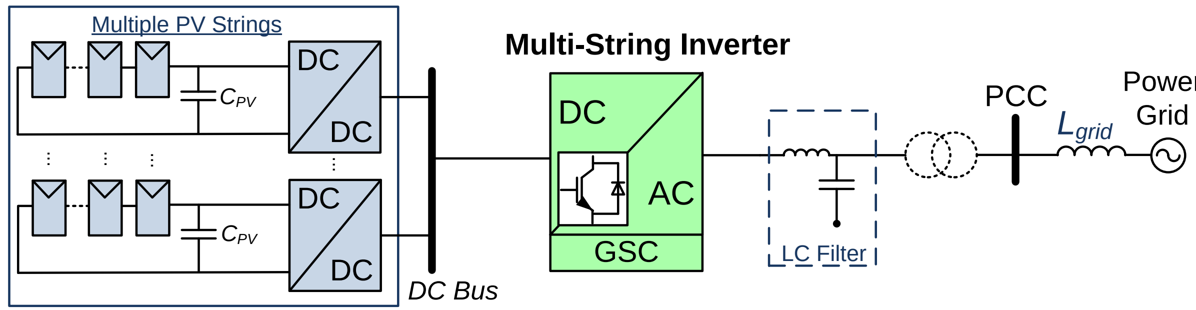


2. Power Electronics – The enabling technology for RES

Power Electronics: PV topologies – WPS topologies – Grid Side Converter (Inverter)

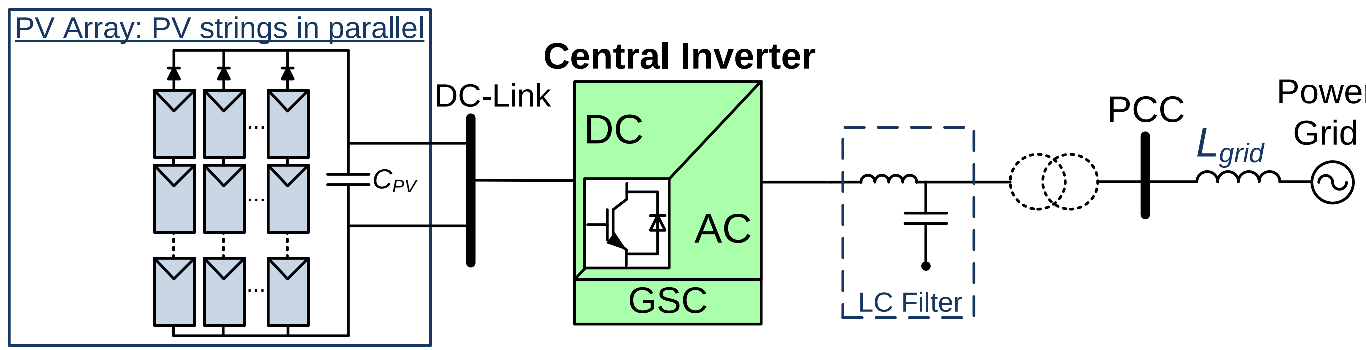
Grid-Connected PV system with Multi-String Inverter

- Residential/Commercial Applications
- 5 – 30 kW
- 1- or 3-phase Multi-String Inverter



Grid-Connected PV system with Central Inverter

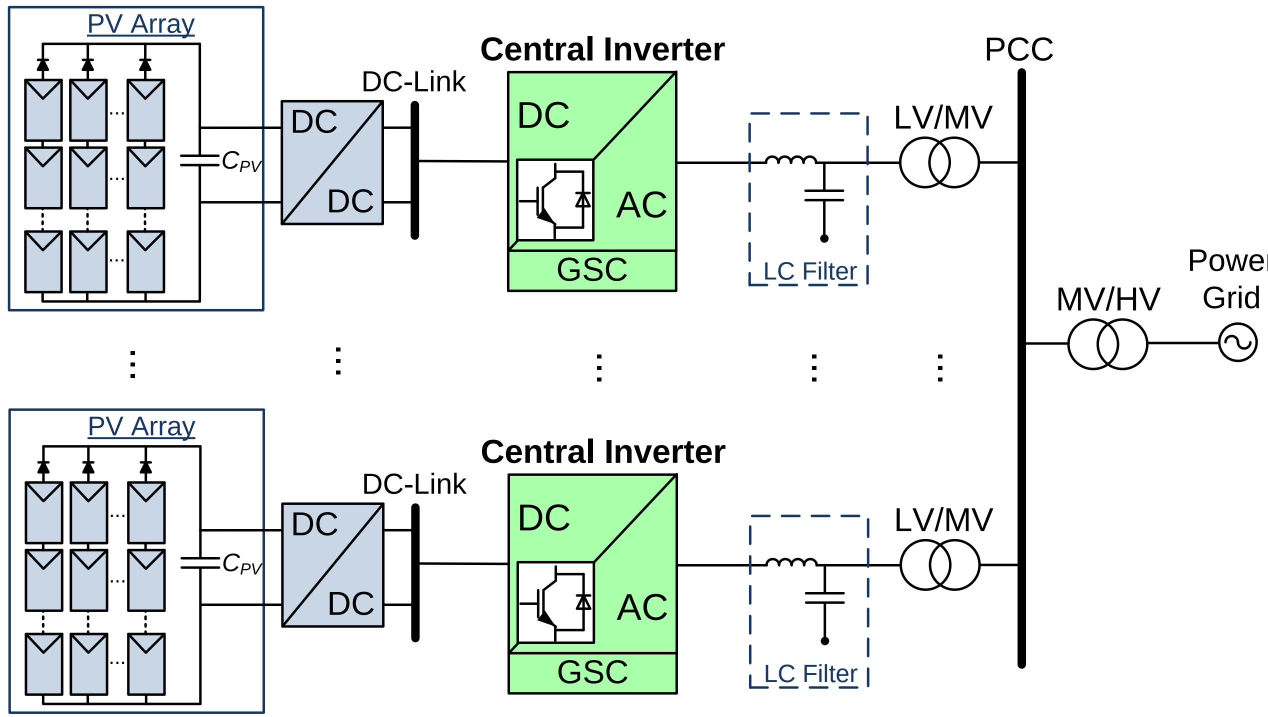
- Commercial Applications
- > 30 kW
- 3-phase Central Inverter



Power Electronics: **PV topologies** – WPS topologies – Grid Side Converter (Inverter)

Grid-Connected PV system with Multiple PV arrays and Central Inverters

- Utility scale/Commercial Applications
- > 100 kW
- Multiple 3-phase Central Inverters



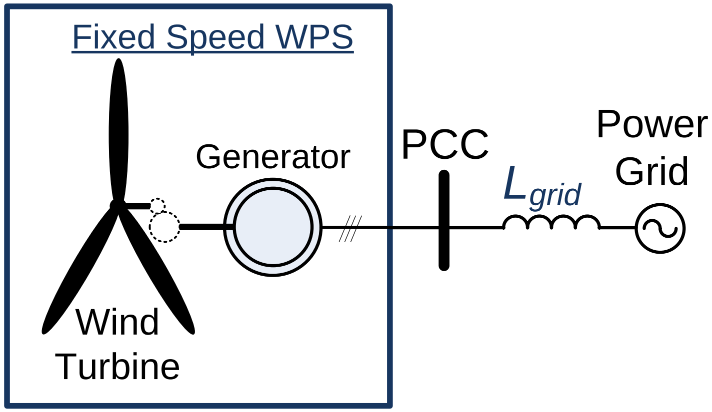
2. Power Electronics – The enabling technology for RES

Power Electronics: PV topologies – **WPS topologies** – Grid Side Converter (Inverter)

Direct Grid-Connected WPS system

- 1970-2000
- Fixed Speed → Low efficiency
- Generator Type: - usually Induction Generators

  - synchronous generators have also be used
- Vulnerable to grid disturbances

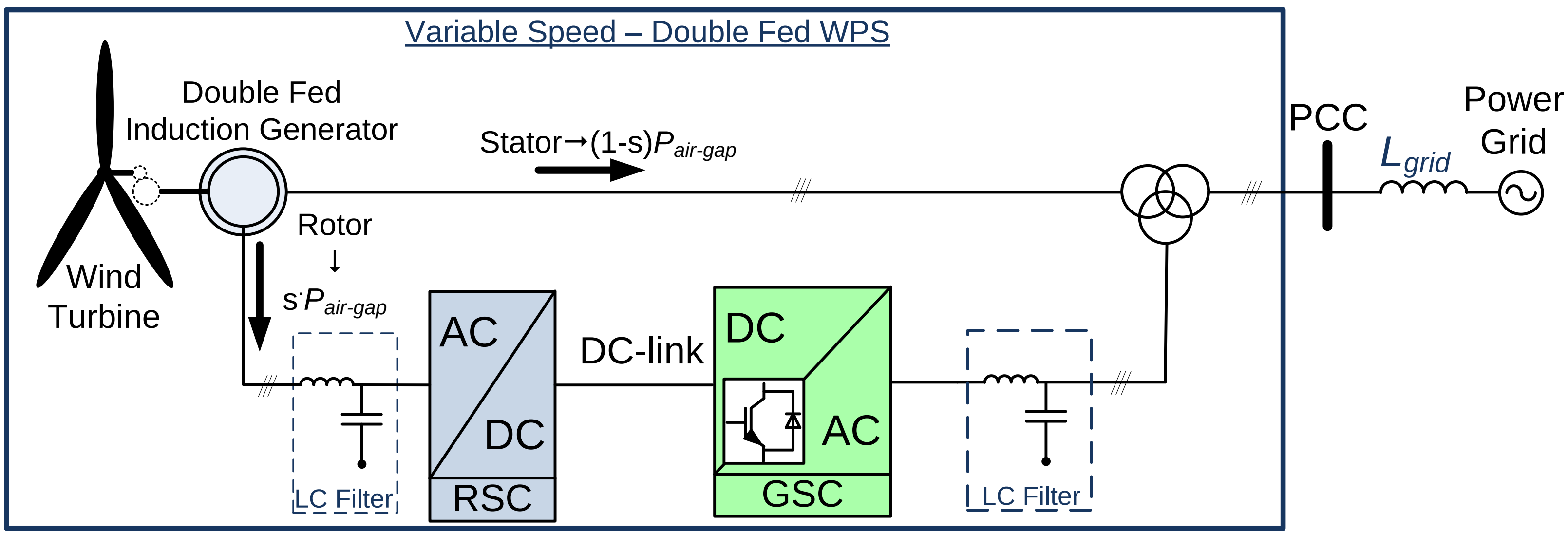


2. Power Electronics – The enabling technology for RES

Power Electronics: PV topologies – **WPS topologies** – Grid Side Converter (Inverter)

Double Fed WPS system

- 2000-today (most widely used solution)
- Variable Speed (within a range)→ Increased efficiency
- Absorbs reactive power
- Power Electronics: ~ 30% of the rated power (Rotor Side)
- Generator Type: Wound Rotor Induction Generator (use of slip rings: increased maintenance)
- Vulnerable to grid disturbances (difficult to meet modern grid requirements)

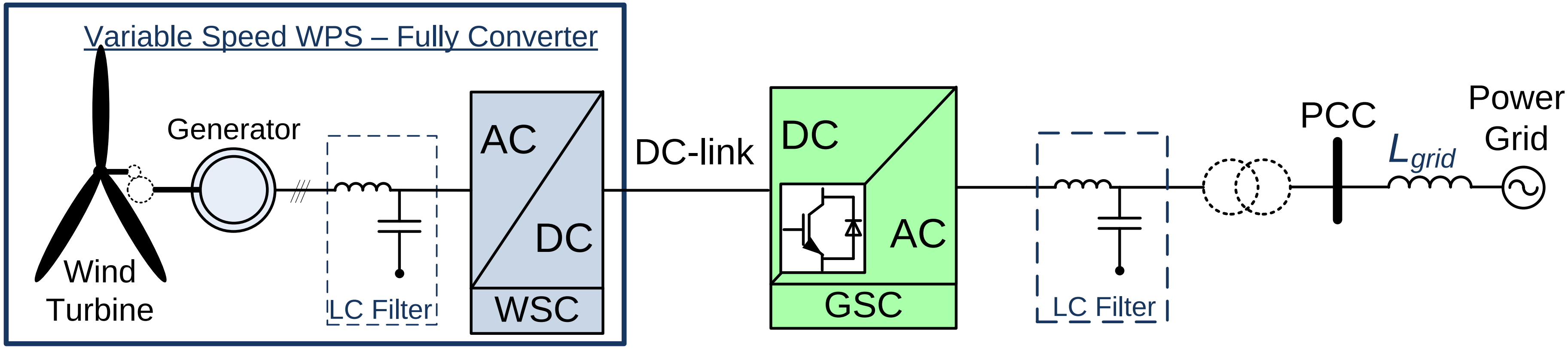


2. Power Electronics – The enabling technology for RES

Power Electronics: PV topologies – **WPS topologies** – Grid Side Converter (Inverter)

Fully Converter WPS system

- 2005-today (state-of-the-art)
- Variable Speed → High efficiency in any wind speed
- Power Electronics: 100% of the rated power (higher cost) (2 Back to Back bidirectional converters)
- Generator Type: Induction or Synchronous Generator
- Absorbs/Delivers reactive power (can provide voltage and frequency support to the power grid)
- Enables Fault Ride Through operation under grid faults (meet modern grid requirements)

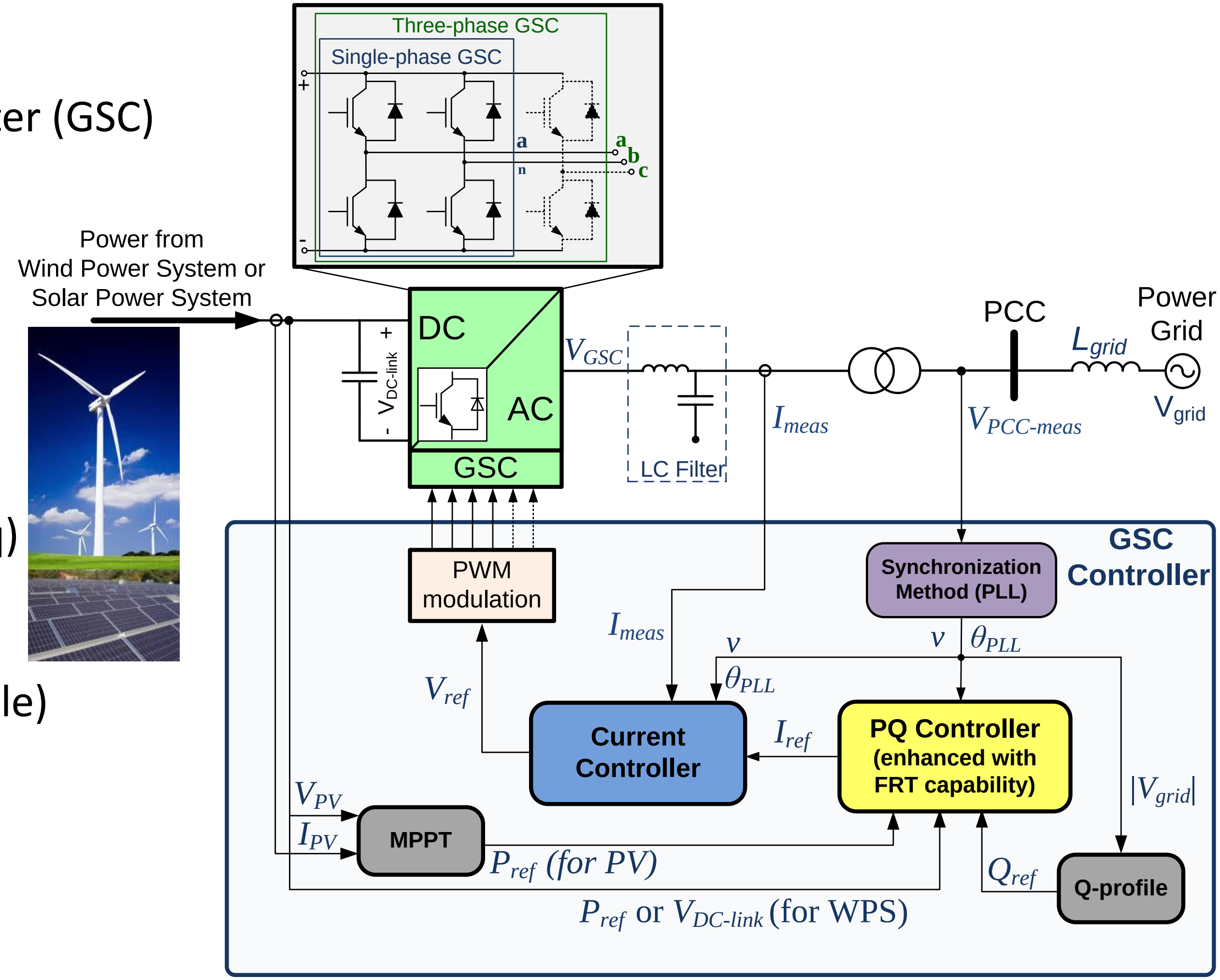


2. Power Electronics – The enabling technology for RES

Power Electronics: PV topologies – WPS topologies – **Grid Side Converter (Inverter)**

Similarity in PV and WPS topologies

- Grid Side power electronic Converter (GSC)
- Single- or three-phase inverter
- MOSFETs or IGBTs
- GSC Controller (Main modules)
  - V and I measurements
  - Park Transformations (αβ and dq)
  - **Synchronization method**
  - PQ controller (MPPT and Q-profile)
  - Current controller
  - PWM modulations

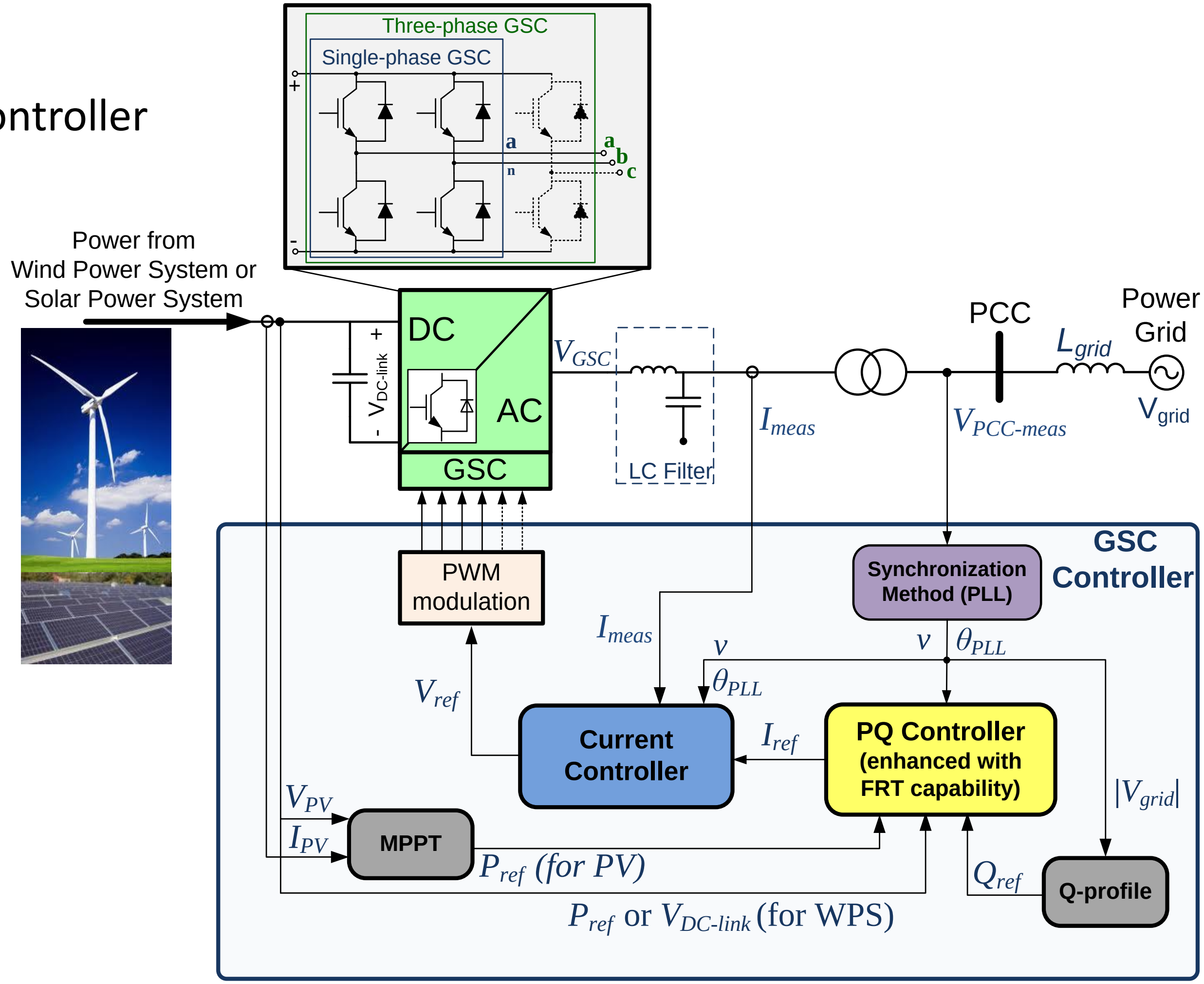


3. Grid Side Converter Controller

GSC Controller: PWM – Transformations – Synchronization – Current Controller – PQ controller

GSC controller

- Developed in an embedded microcontroller within the inverter
- Sampling frequency ~ 10 kHz (voltage and current sensors)
- Real-time control
- Ensure the proper operation of RES

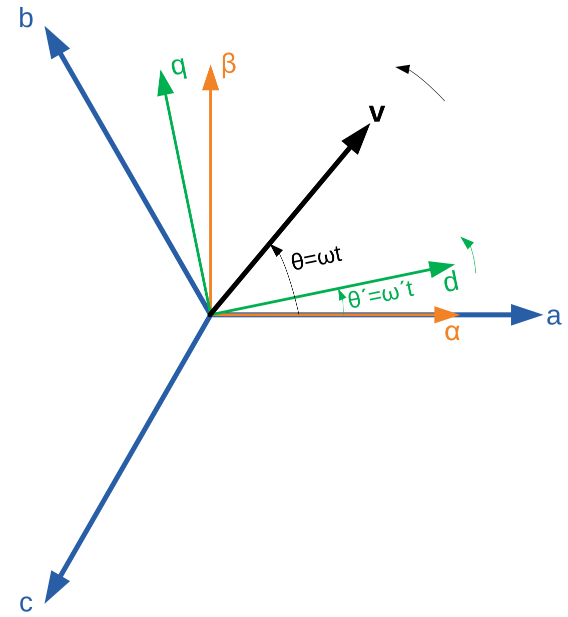


3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – Current Controller – PWM

Park Transformations

- a-b-c natural frame
- aβ-frame: stationary reference frame
- **dq-frame:** rotating frame with the synchronous rotational speed



abc-frame → αβ-frame

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} T_{\alpha\beta} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad where\ \theta' = 0$$

$$\begin{bmatrix} T_{\alpha\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta') & \cos(\theta' - 120^o) & \cos(\theta' + 120^o) \\ -\sin(\theta') & -\sin(\theta' - 120^o) & -\sin(\theta' + 120^o) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

αβ-frame → dq-frame

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} T_{dq^{n-m}} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad where\ n - m = 1$$

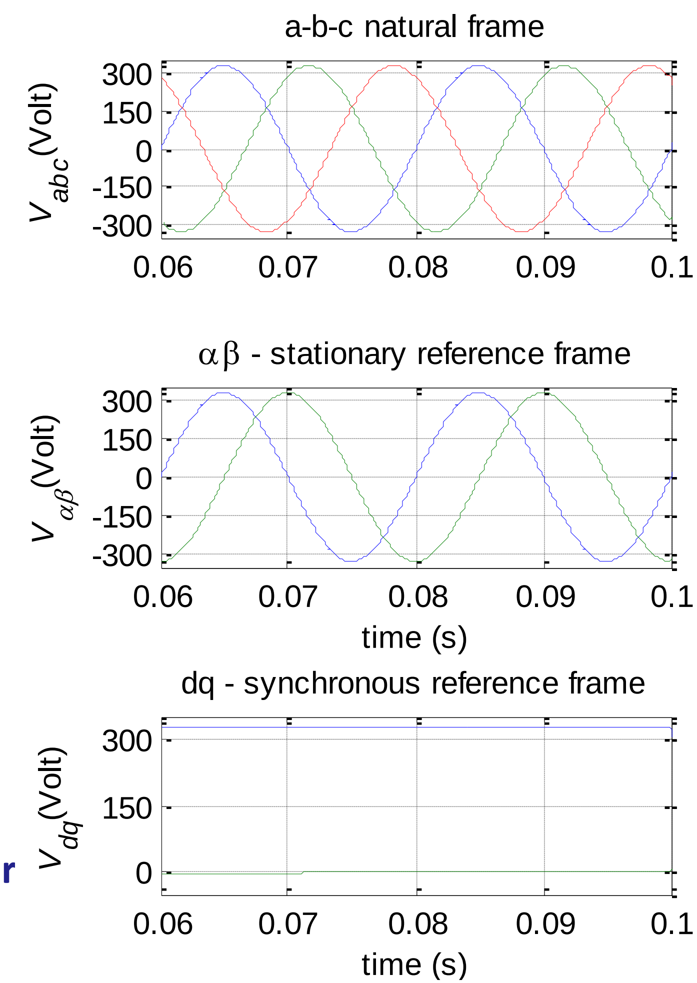
$$\begin{bmatrix} T_{dq^{n-m}} \end{bmatrix} = \begin{bmatrix} T_{dq^{m-n}} \end{bmatrix}^T = \begin{bmatrix} \cos(n-m)\omega'\mathrm{t} & \sin(n-m)\omega'\mathrm{t} \\ -\sin(n-m)\omega'\mathrm{t} & \cos(n-m)\omega'\mathrm{t} \end{bmatrix}$$

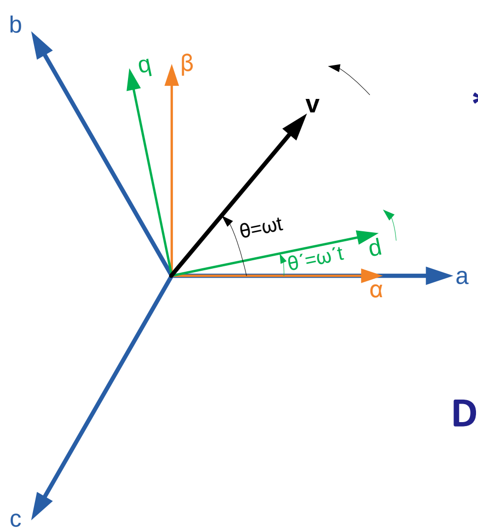
3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – Current Controller – PWM

Park Transformations

- a-b-c natural frame
- aβ-frame: stationary reference frame
- **dq-frame:** rotating with the synchronous rotational speed





***dq-transformation enables AC voltages and currents to be transformed to DC quantities**

↓

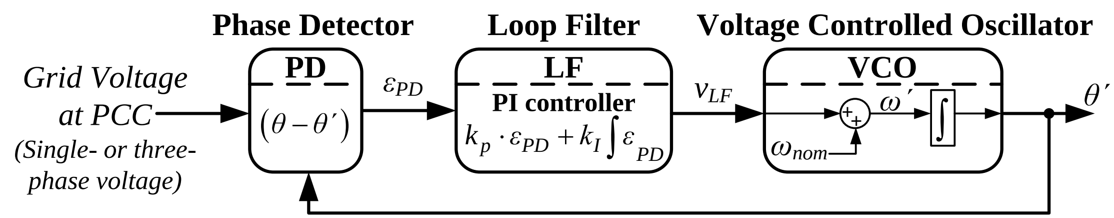
Easy to be controller (use of PI controller)

Decoupled control of active and reactive power

3. Grid Side Converter Controller

GSC Controller: Transformations – **Synchronization** –PQ controller – Current Controller – PWM

Synchronization Method



- The **most crucial unit** of the GSC controller
- Usually a phase locked loop algorithm (**PLL**)
- **Aim:** Dynamic and accurate **estimation of the voltage phase angle** (positive sequence phase angle of the fundamental voltage component)
- <u>**Important aspect:**</u>

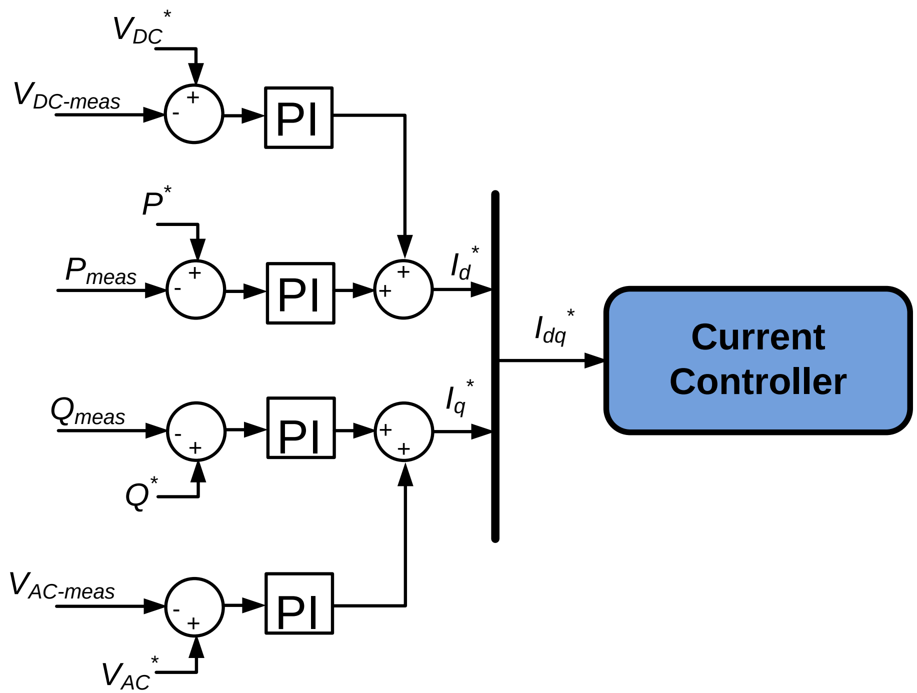
  - Dynamic performance
  - Accuracy against unbalanced voltage conditions (enable FRT operation under grid faults)
  - Immunity against voltage harmonic distortion (enhanced the power quality of RES)
  - Accuracy against frequency change
  - Accuracy against phase jump
  - Algorithms complexity (1/(Computational Efficiency))

3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –**PQ controller** – Current Controller – PWM

PQ controller

- Control the active and reactive power injection
- Ensures that all the produced energy by the RES will be injected to the grid (Control of DC-link voltage)
- Ensures a voltage support to the grid (reactive power)
- Enhanced with FRT capabilities (meet grid codes)
- Limits the GSC currents within the converter ratings

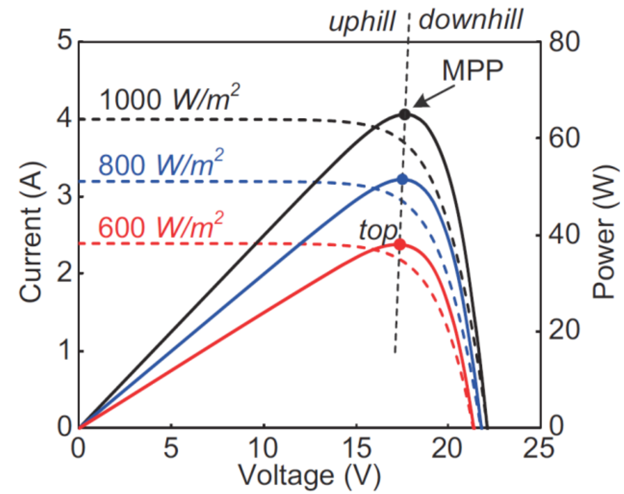


3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –**PQ controller** – Current Controller – PWM

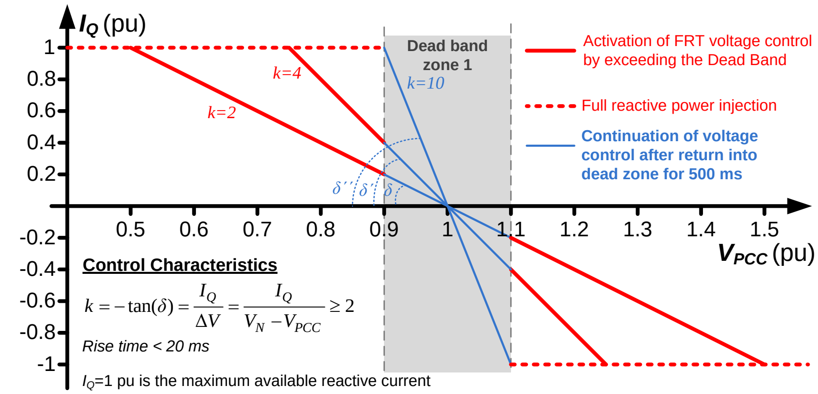
Maximum Power Point Tracking (PV only)

- Regulate the operating voltage of the PV module in order to maximize its power generation under variable sun irradiance conditions



Q-profile

- Inject or absorbs reactive power to support grid voltage (according to grid regulations)
- Voltage support under low-voltage grid faults

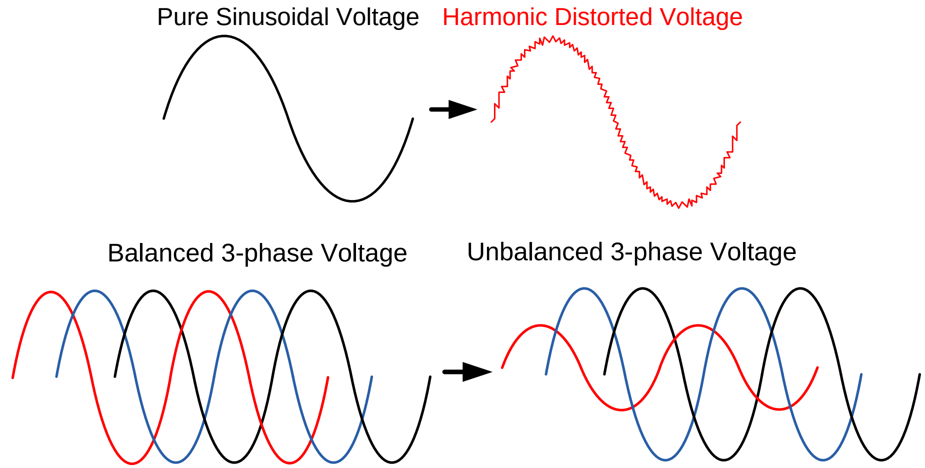


3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – **Current Controller** – PWM

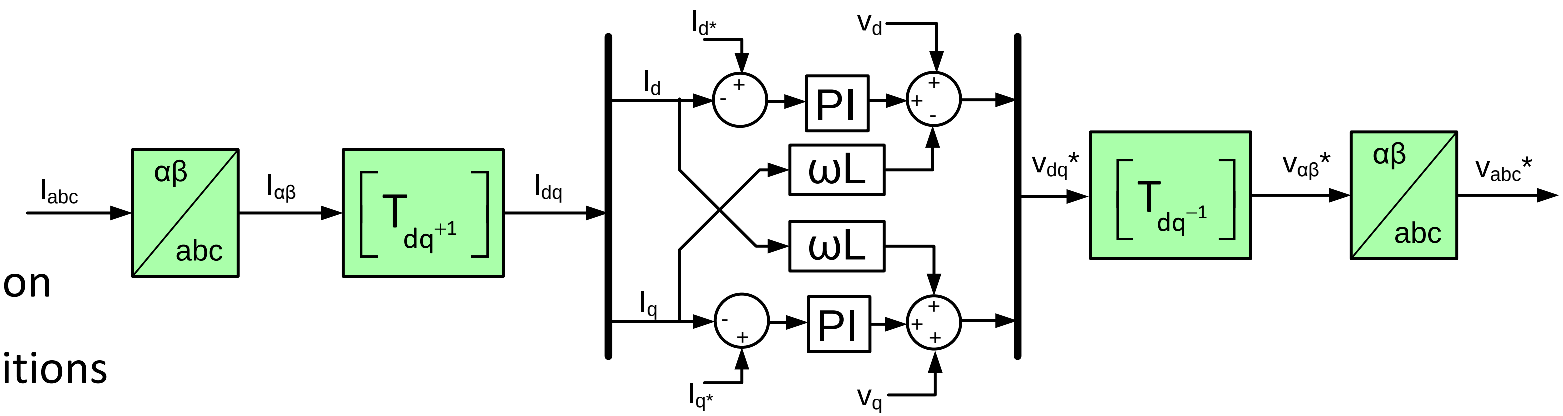
Current Controller

- Accurate current injection
- Immunity against harmonic distortion
- Immunity against unbalanced conditions



Conventional Current Controller

- Simplicity
- Design in dq-frame
- Problem under:
  - harmonic distortion
  - unbalanced conditions

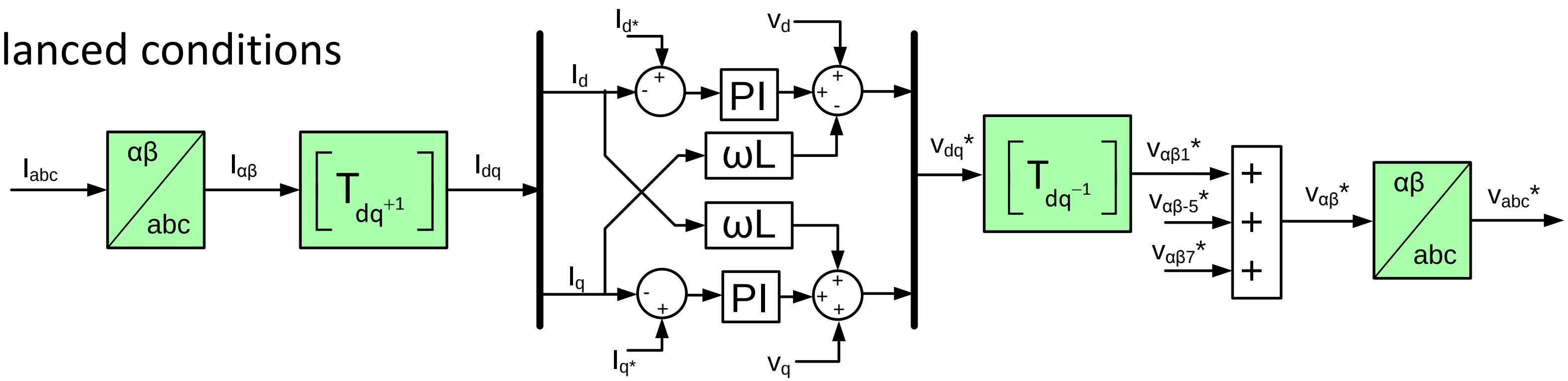


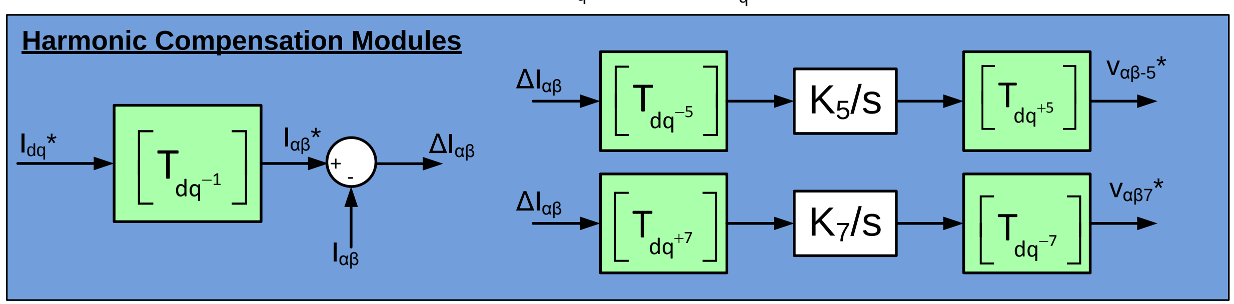
3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – **Current Controller** – PWM

Current Controller enhanced with harmonic compensation modules

- Modularized
- Design in multiple dq^n-frames
- Accurate under harmonic distortion (Harmonic Compensation Modules)
- Problem under unbalanced conditions



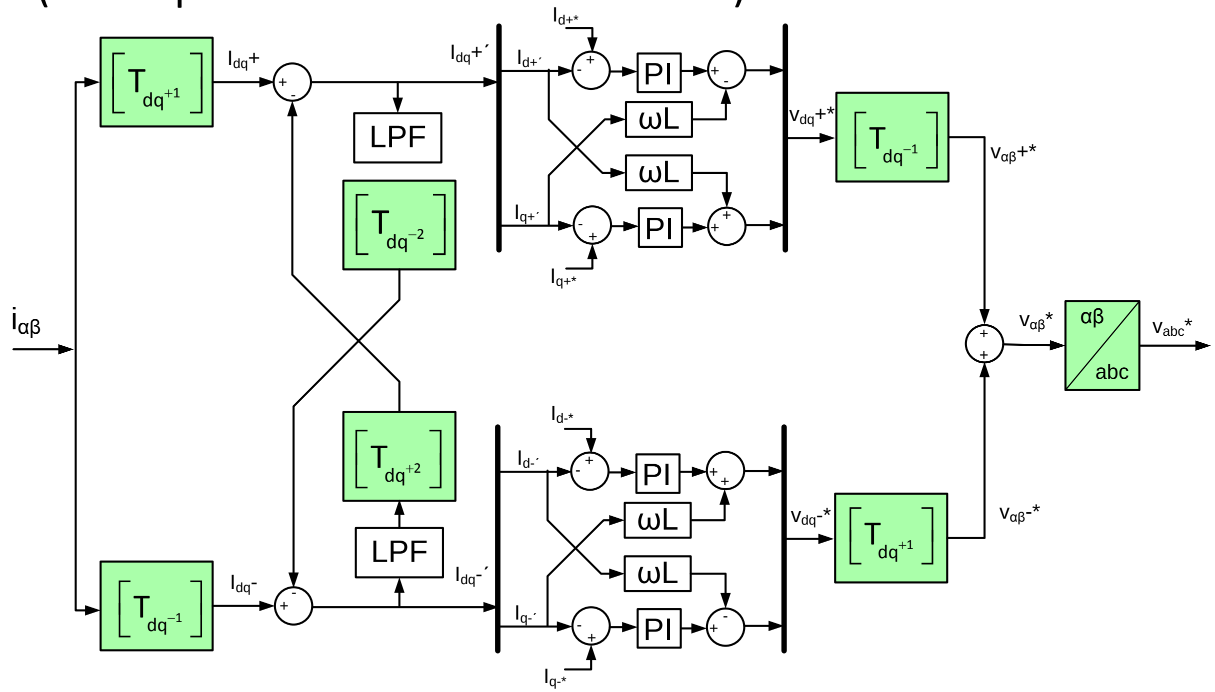


3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – **Current Controller** – PWM

Decoupled double synchronous reference frame current controller

- Complex
- Design in positive and negative dq^n-frames
- Accurate under unbalanced conditions (Decoupled double reference frame)
- Problems under harmonic distortion

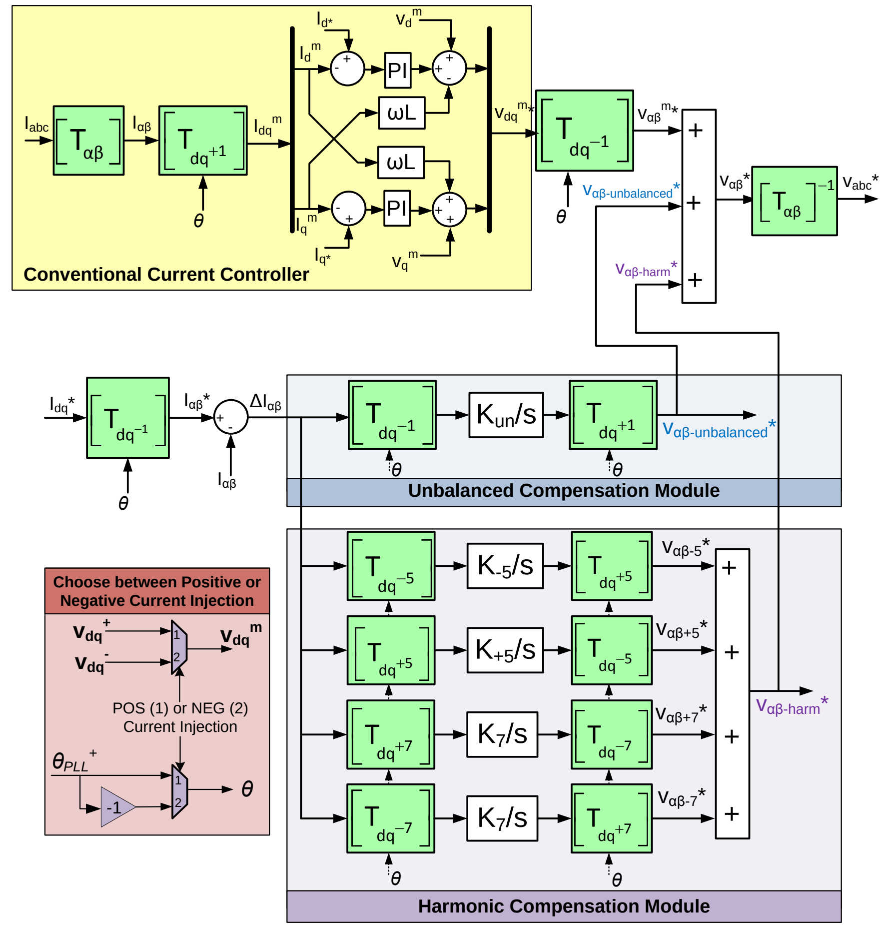


3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – **Current Controller** – PWM

A proposed current controller enhanced with harmonic and unbalanced compensation module

- Simplicity and modularized
- Design in multiple dq^n-frames
- Accurate under unbalanced conditions (UCM)
- Accurate under harmonic distortion (HCM)
- Enable the accurate injection of positive or negative sequence current



3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – **Current Controller** – PWM

Experimental results for the proposed Current Controller

Conditions:

Grid Fault: Type C (d=65%) at 1 sec

Harmonics: $|V_5|$=2% & $|V_7|$=1%

FRT operation: I_{peak}<4.5A & Q/P=3

Proposed Current Controller

-**HCM** is always activated

-**UCM** is activated at 1.1 sec

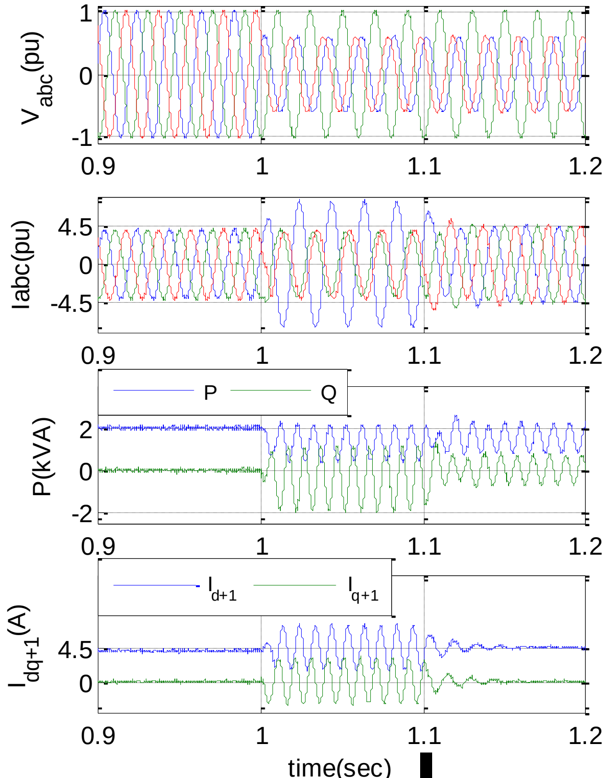
-The UCM enables the **pure (+ or -) sinusoidal current injection** under FRT

-**Fast and accurate current injection**

-**Settling time < 10ms**

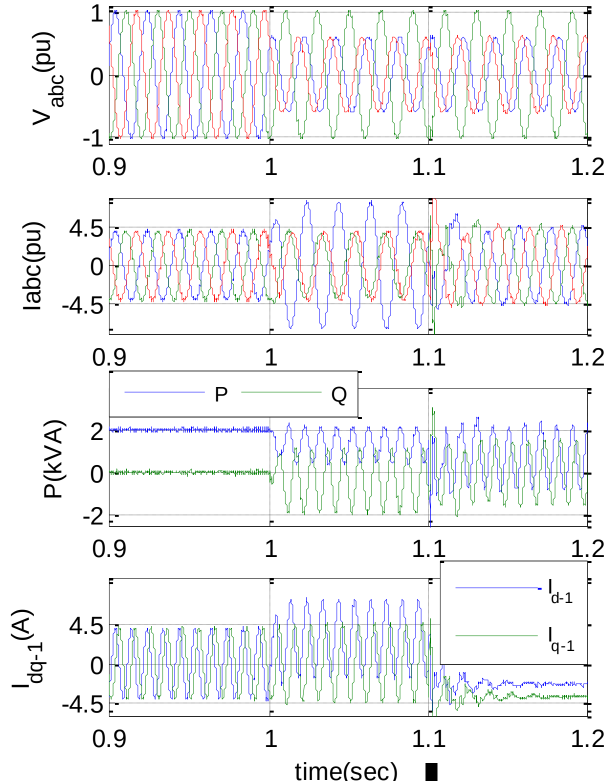
-**High quality current** injection (THD_i<3%)

Full positive current injection



UCM is activated

Full negative current injection



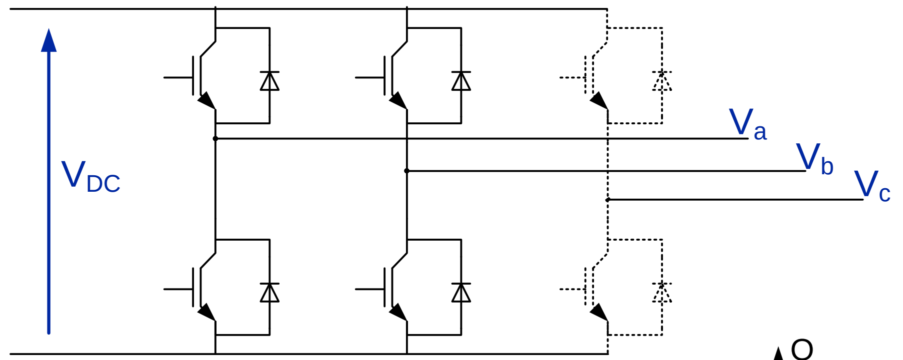
UCM is activated

3. Grid Side Converter Controller

GSC Controller: Transformations – Synchronization –PQ controller – Current Controller – **PWM**

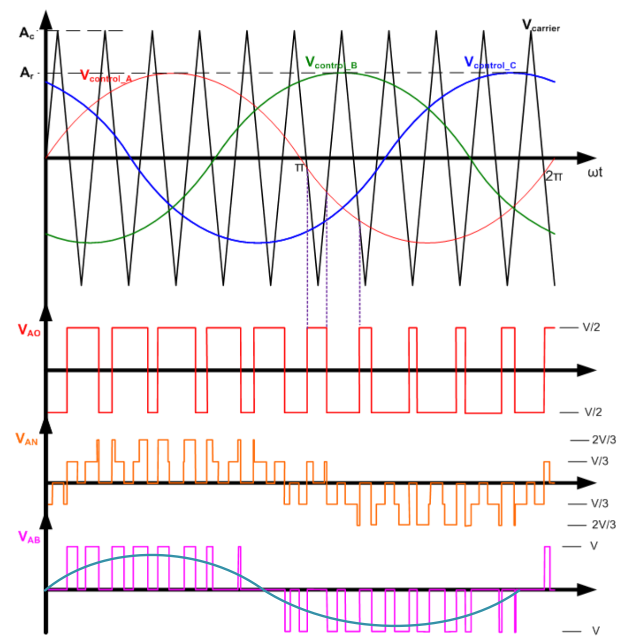
Grid Side power electronic Converter

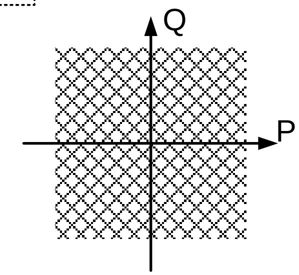
- Single-phase: H-bridge topology, 4 IGBT or MOSFETs
- Three-phase: 2 level bidirectional Voltage Source Converter , 6 MOSFETs or IGBTs



Sinusoidal Pulse Width Modulation (SPWM)

- Control GSC through high frequency pulses (2-20kHz)
- A reference signal ($V_{control}$) is compared with a high frequency triangle signal (carrier)
- GSC produce a high frequency switching voltage
- LC or LCL filter eliminates high-order harmonics
- Amplitude Modulation $\rightarrow m_a = A_{control\_A} / A_{carrier}$
- GSC output voltage $\rightarrow V_{L-L\_RMS} = m_a \frac{\sqrt{3} V_{dc}}{2\sqrt{2}} = 0.612 \cdot m_a \cdot V_{dc}$

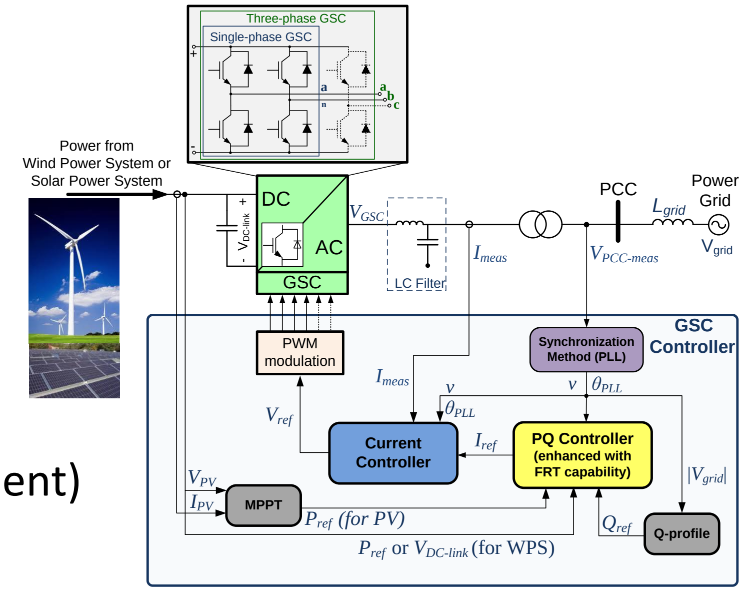




4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – Proposed methods

Synchronization Method / Phase-Locked Loop (PLL) algorithm



- The **most crucial unit** of the GSC controller

  (The response of the PLL can affect the response of:

  current controller, PQ controller and the entire GSC and RES)
- **Aim:** Dynamic and accurate estimation of the phase angle

  (of the positive sequence of the fundamental voltage component)
- **<u>Important aspect:</u>**

  - Dynamic performance
  - Algorithms complexity (1/(Computational Efficiency))
  - Accuracy against frequency change
  - Accuracy against phase jump
  - Accuracy against unbalanced voltage conditions (enable FRT operation under grid faults)
  - Immunity against voltage harmonic distortion (enhanced the power quality of RES)

4. Synchronization Methods

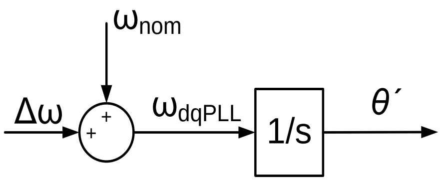
Three-phase synchronization method: Conventional methods – State of the art – Proposed methods

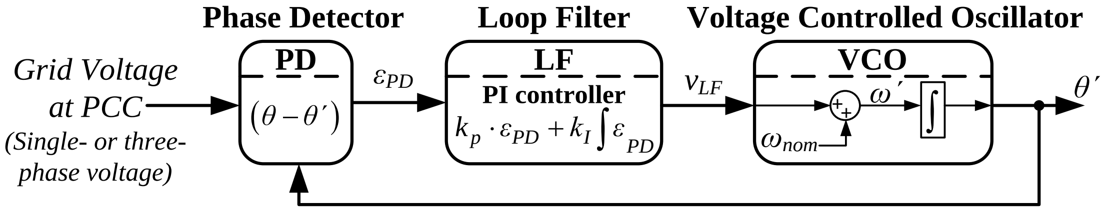
A simplified PLL algorithm

- Phase Detector: θ-θ'
- Loop filter: Proportional-Integral (PI) controller

$$PI\ controller \rightarrow Output_{PI} = error\left(k_P + k_I \frac{1}{s}\right)$$

- Voltage Controller Oscillator



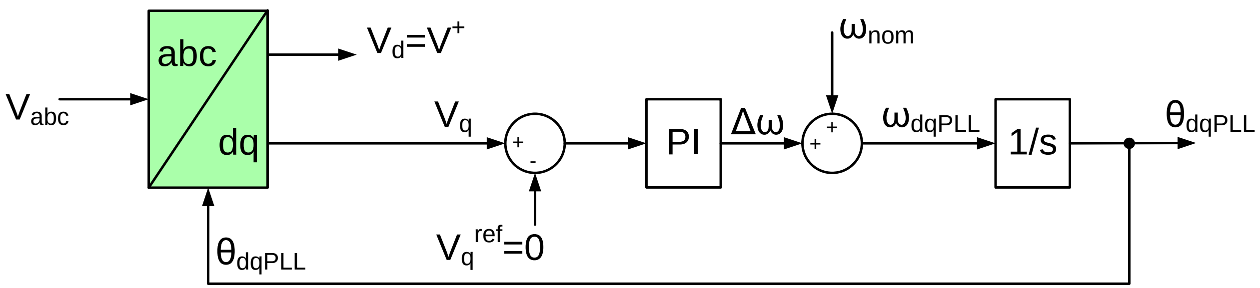


Structure of a simplified PLL algorithm

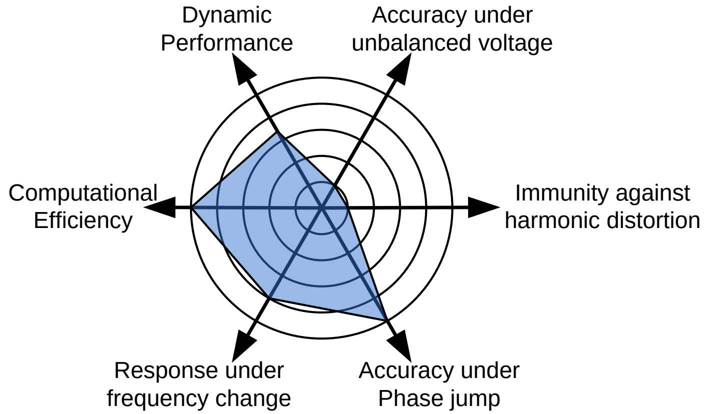
Three-phase synchronization method: Conventional methods – State of the art – Proposed methods

dq-PLL

- Design in dq-frame
- Phase Detector: : θ-θ' → $V_{dq^{+1}}^{*+1} \approx V_{dq^{+1}}^{+1} = \left[T_{dq^{+1}}(\theta')\right] \cdot v_{\alpha\beta}^{+1} = \begin{bmatrix} \cos\theta' & \sin\theta' \\ -\sin\theta' & \cos\theta' \end{bmatrix} \begin{bmatrix} V^1 \cdot \cos\theta \\ V^1 \cdot \cos(\theta - T/4) \end{bmatrix} = \begin{bmatrix} V^1 \cdot \cos(\theta-\theta') \\ V^1 \cdot \sin(\theta-\theta') \end{bmatrix} \approx \begin{bmatrix} V^1 \\ V^1 \Delta\theta \end{bmatrix}$



Structure of the dq-PLL

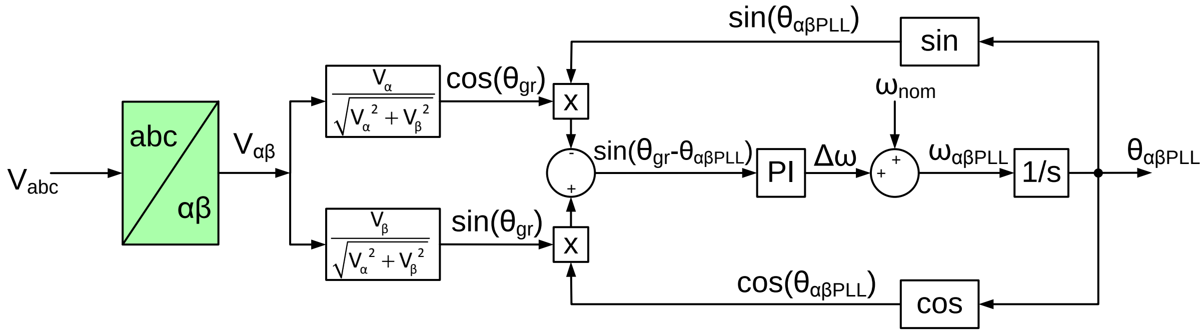


4. Synchronization Methods

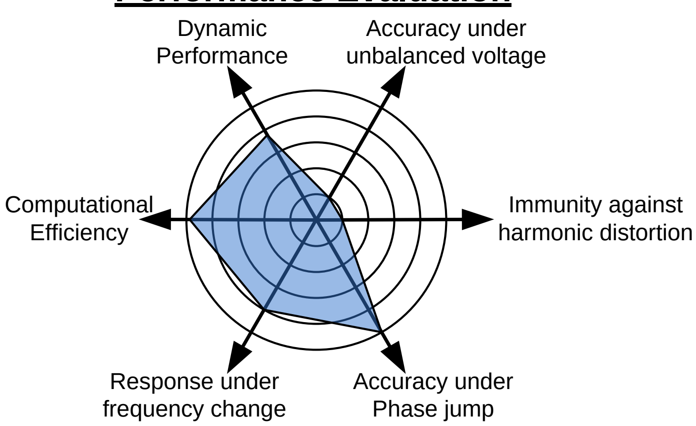
Three-phase synchronization method: Conventional methods – State of the art – Proposed methods

αβ-PLL

- Design in αβ-frame
- Phase Detector: θ-θ' → $\Delta\theta = \theta_{gr} - \theta_{ab-PLL} \approx \sin(\theta_{gr} - \theta_{\alpha\beta-PLL}) = \sin(\theta_{gr})\cos(\theta_{\alpha\beta-PLL}) - \sin(\theta_{\alpha\beta-PLL})\cos(\theta_{gr})$



Structure of the αβ-PLL



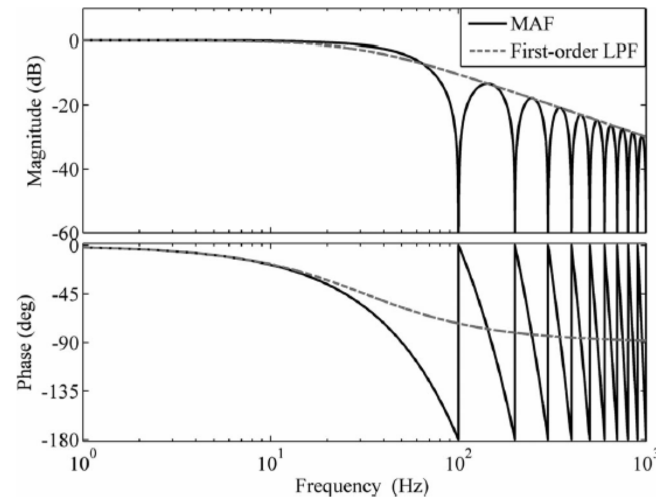
4. Synchronization Methods

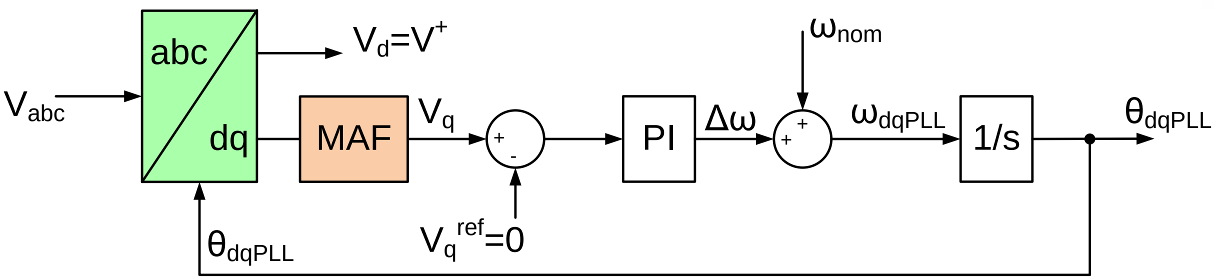
Three-phase synchronization method: Conventional methods – **State of the art** – Proposed methods

MAF-PLL (Moving Average Filter PLL)

- Inherits the structure of the dq-PLL
- Insert a MAF to minimize the effect of unbalanced and harmonic distorted voltage

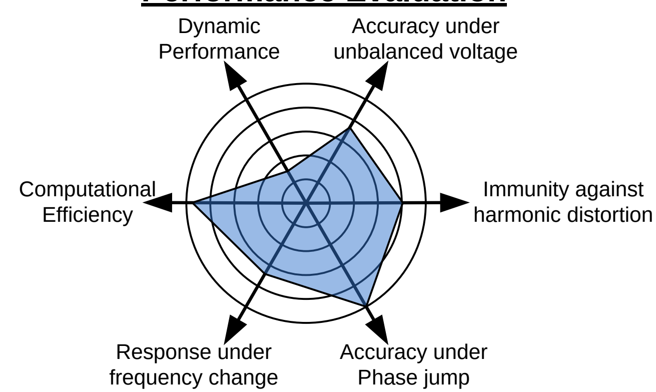
Bode Diagram of MAF





Structure of the MAF-PLL

Performance Evaluation

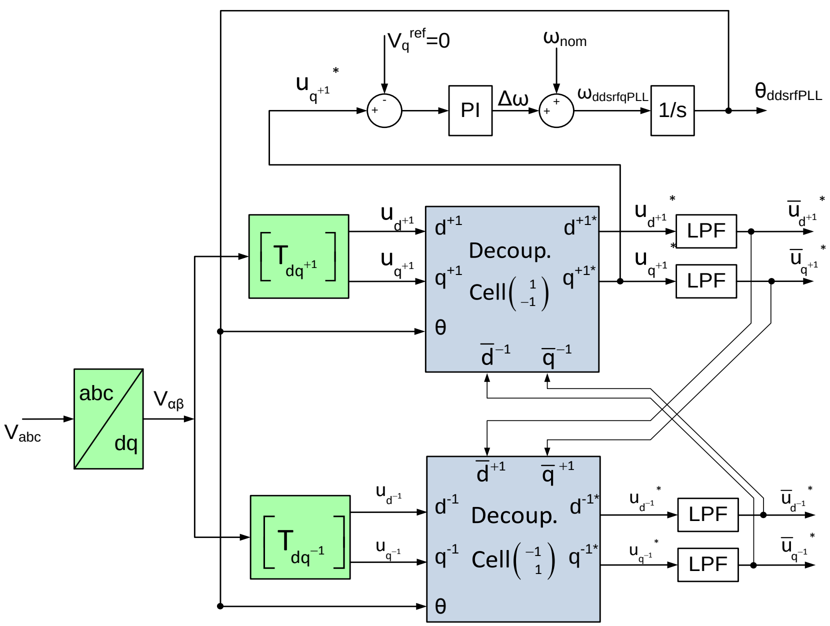


4. Synchronization Methods

Three-phase synchronization method: Conventional methods – **State of the art** – Proposed methods

ddsrf-PLL (Decoupled Double Synchronous Reference Frame PLL)

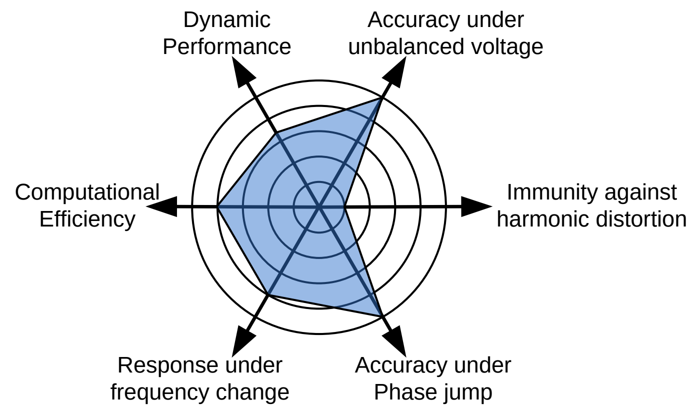
- Design in two dq-frame: dq^{+1}-frame & dq^{-1}-frame
- Phase Detector: θ-θ' → The same one with the dq-PLL
- Decoupling Cell to decouple the effect of negative sequence (unbalanced voltage)



Structure of the ddsrf-PLL

$$u_{dq^{+1}} = \begin{bmatrix} u_{d^{+1}} \\ u_{q^{+1}} \end{bmatrix} = \left[T_{dq^{+1}}\right]\cdot u_{ab} = \underbrace{V^{+1}\begin{bmatrix} 1 \\ 0 \end{bmatrix}}_{dc-term} + V^{-1}\begin{bmatrix} \cos(-2\omega t) \\ \sin(-2\omega t) \end{bmatrix}$$

Performance Evaluation

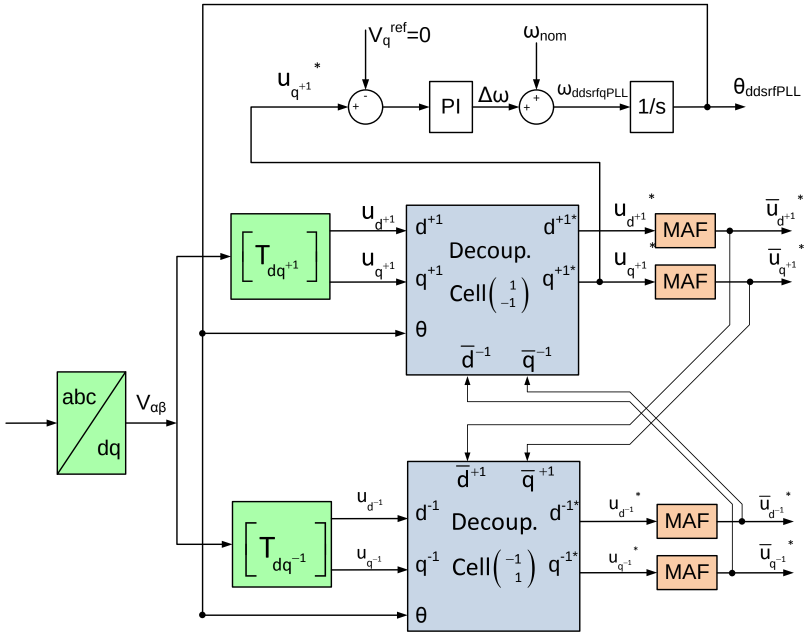


4. Synchronization Methods

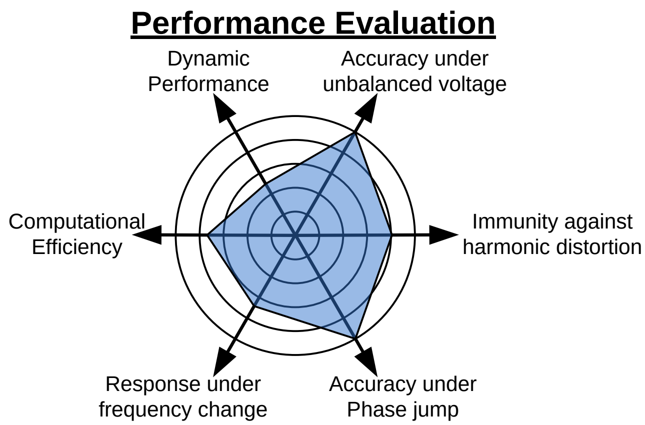
Three-phase synchronization method: Conventional methods – **State of the art** – Proposed methods

Modified MRF/MAF-PLL (Modified Multi Reference Frame / Moving Average Filter PLL)

- Inherits the structure of the ddsrf-PLL
- The Decoupling Cells eliminate the effect of unbalanced voltage
- Use of four MAF instead of LPFs to minimize the effect of harmonic distorted voltage



Structure of the MRF/MAF-PLL

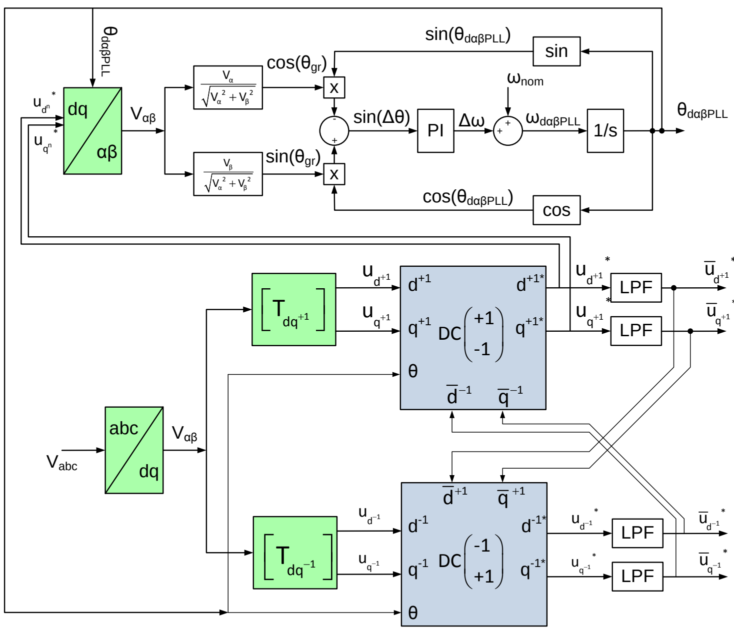


4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

dαβ-PLL (Decoupled in αβ stationary reference Frame PLL)

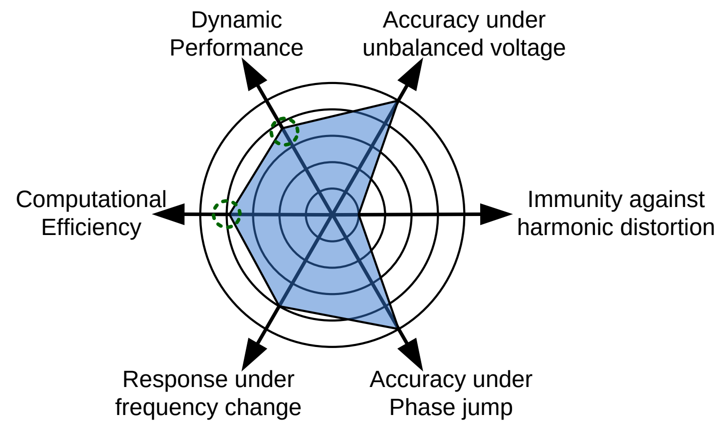
- Design in two dq-frame: dq^{+1}-frame & dq^{-1}-frame
- Phase Detector: θ-θ' → Inherits the phase detector method of αβ-PLL
- Decoupling Cell to decoupled the effect of negative sequence voltage (Same as ddsrf-PLL)



Structure of the dαβ-PLL

$$u_{dq^{+1}} = \begin{bmatrix} u_{d^{+1}} \\ u_{q^{+1}} \end{bmatrix} = \begin{bmatrix} T_{dq^{+1}} \end{bmatrix} \cdot u_{ab} = \underbrace{\mathbf{V}^{+1} \begin{bmatrix} \mathbf{1} \\ \mathbf{0} \end{bmatrix}}_{dc-term} + V^{-1} \begin{bmatrix} \cos(-2\omega t) \\ \sin(-2\omega t) \end{bmatrix}$$

Performance Evaluation

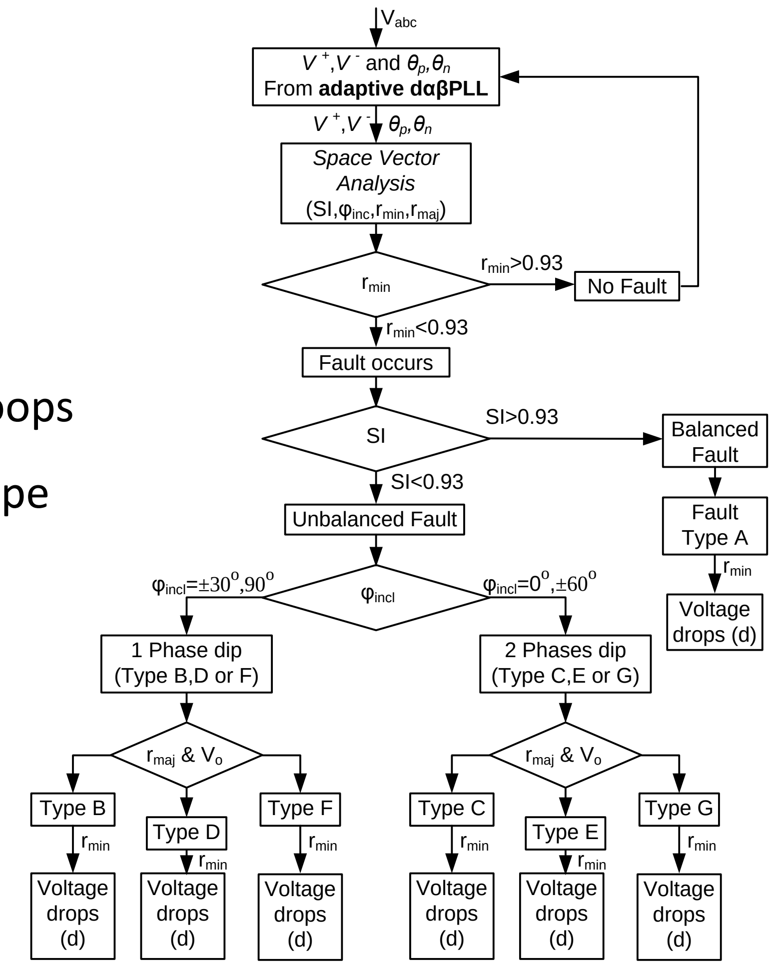


Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

Adaptive dαβ-PLL

- Inherits the structure of the dαβ-PLL
- Proposed tuning mechanism → adaptively change the tuning parameters (k_P, T_I) according to the type of the grid fault in order to accelerate the performance of the PLL
- A fault classification unit detect the type and the voltage droops
- The tuning parameters are adjusted according to the fault type based on a look-up table

Online Fault Classification Unit

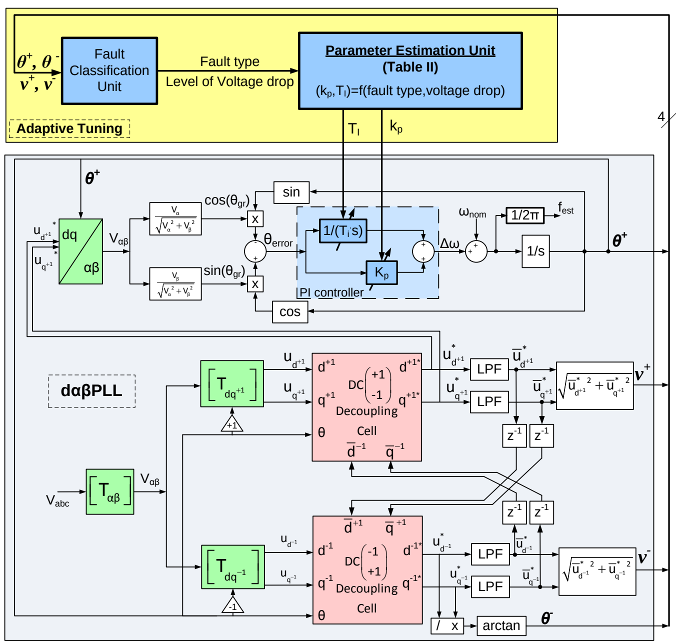


4. Synchronization Methods

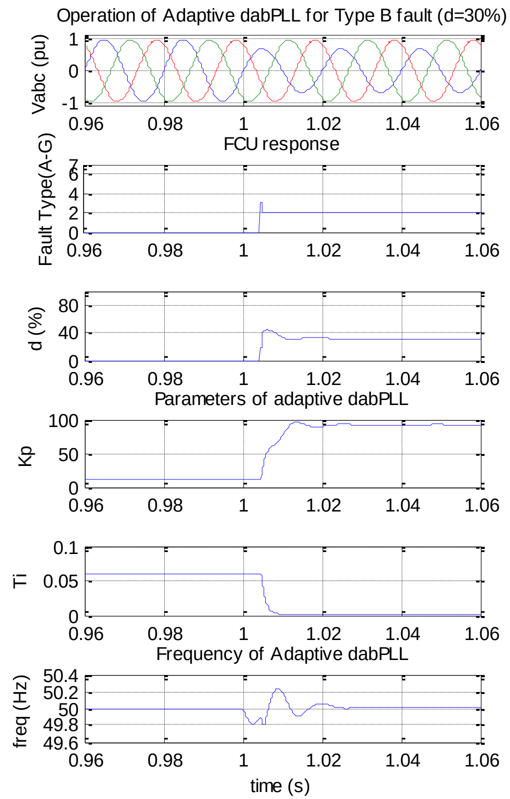
Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

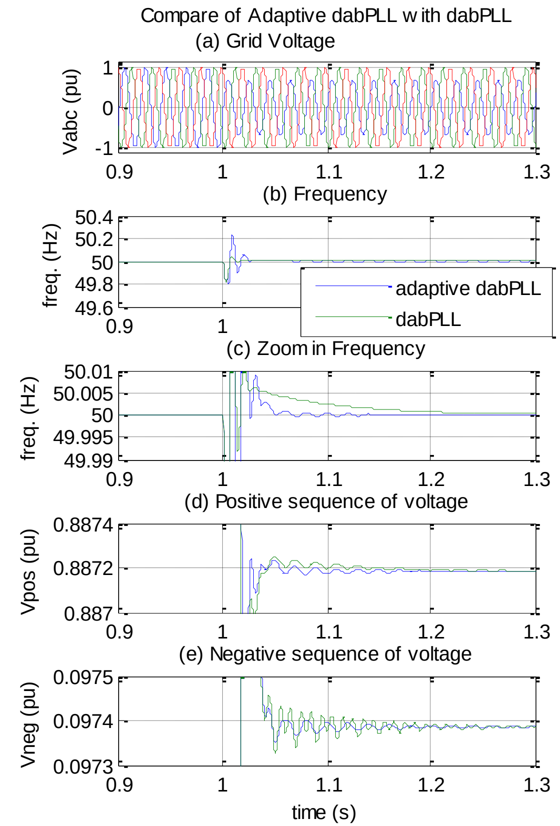
Adaptive dαβ-PLL

- Proposed tuning mechanism → adaptively change the tuning parameters (k_P, T_I) of the dαβ-PLL according to the FCU to accelerate the performance of the PLL



Structure of the adaptive dαβ-PLL



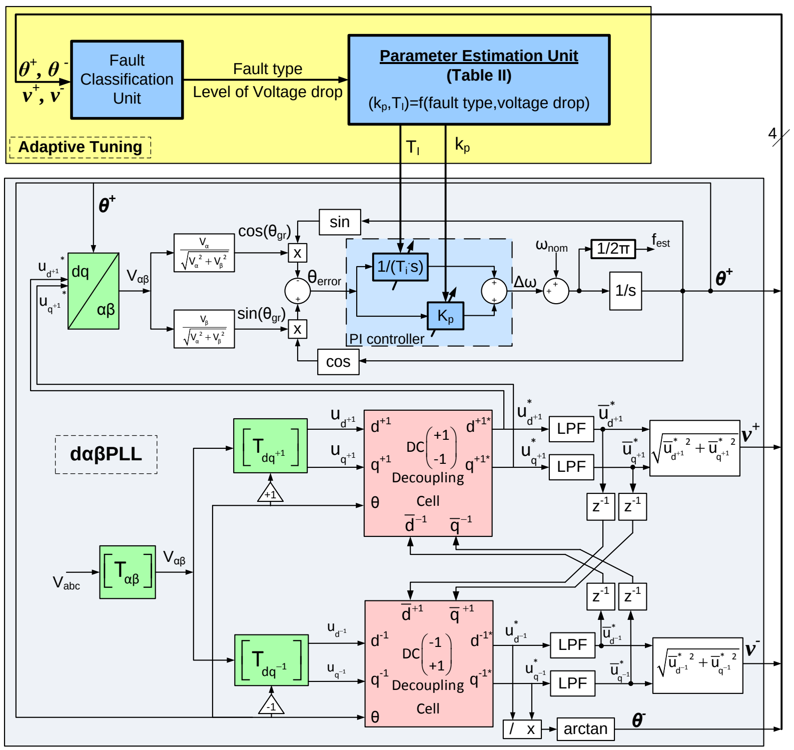


4. Synchronization Methods

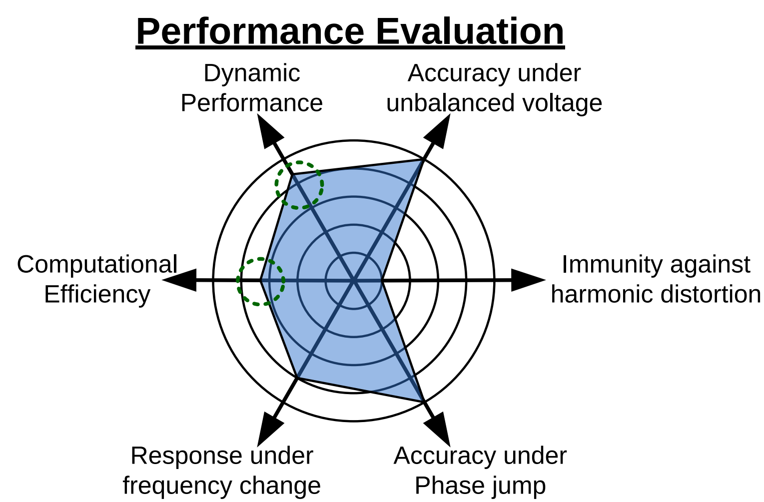
Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

Adaptive dαβ-PLL

- Proposed tuning mechanism → adaptively change the tuning parameters (k_P, T_I) of the dαβ-PLL according to the FCU to accelerate the performance of the PLL



Structure of the adaptive dαβ-PLL

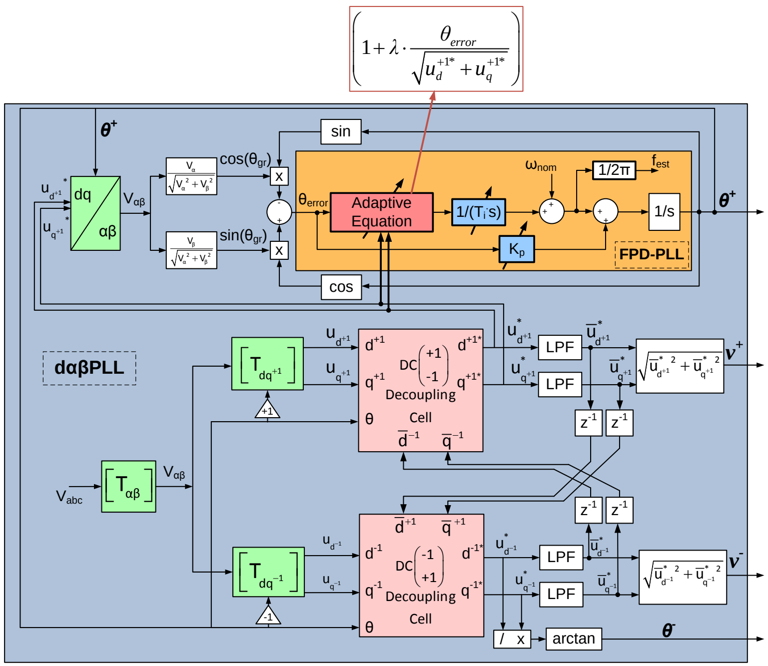


4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

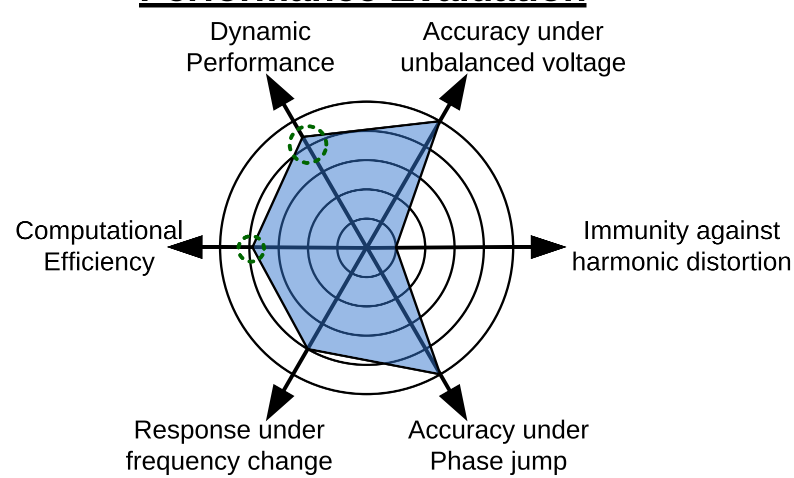
FPD-dαβ-PLL (Frequency phase decoupling PLL)

- Inherits the structure of dαβ-PLL
- The tuning parameters (T_I) is adjusted according to the disturbance faced by the PLL
- Reconstruction of the PI controller in order to decouple the frequency and the phase estimation



Structure of the FPD-dαβ-PLL

Performance Evaluation

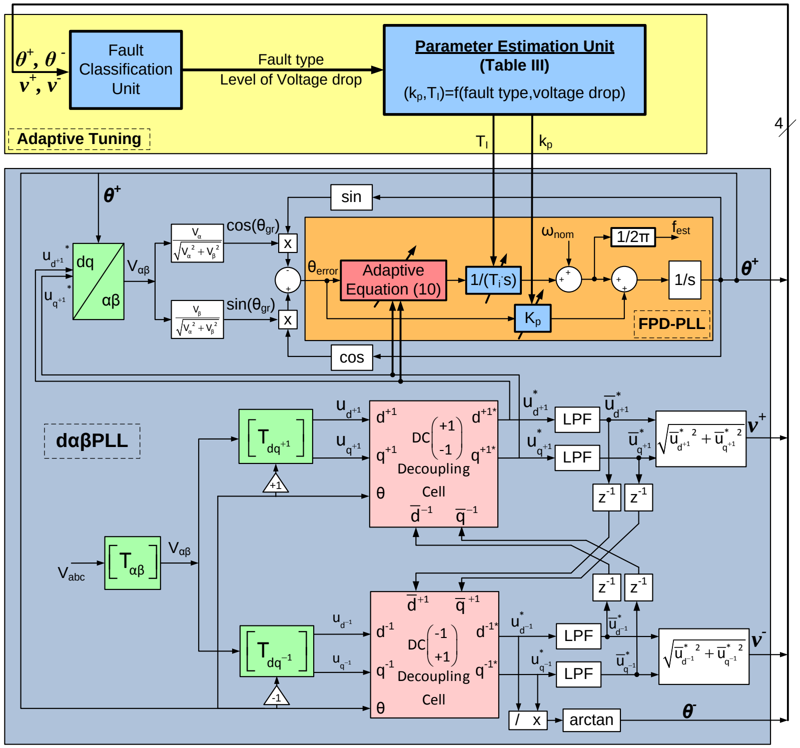


4. Synchronization Methods

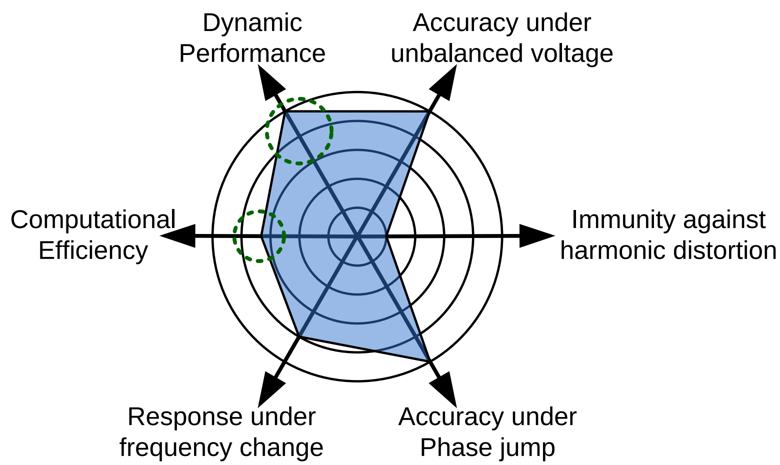
Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

Adaptive FPD-dαβ-PLL (Adaptive Frequency phase decoupling PLL)

- Inherits the structure of dαβ-PLL
- Inherits the tuning mechanism of adaptive dαβ-PLL & the tuning mechanism of FPD-dαβ-PLL



Structure of the Adaptive FPD-dαβ-PLL



4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

MSHDC-PLL (Multi-Sequence/Harmonic Decoupling Cell PLL)

- Extend the decoupling cell of the dαβ-PLL to consider unbalanced and harmonic conditions
- Voltage analysis under unbalanced and harmonic distorted (5th) conditions

$$u_{dq^{+1}} = \begin{bmatrix} u_{d^{+1}} \\ u_{q^{+1}} \end{bmatrix} = \left[T_{dq^{+1}}\right] \cdot u_{ab} = \underbrace{\mathbf{V}^{+1}\begin{bmatrix} \mathbf{1} \\ \mathbf{0} \end{bmatrix}}_{dc-term} + \underbrace{V^{-1}\begin{bmatrix} \cos(-2\omega t) \\ \sin(-2\omega t) \end{bmatrix}}_{-2\omega \text{ oscilation}} + \underbrace{V^{+5}\begin{bmatrix} \cos((+1-5)\omega t) \\ \sin((+1-5)\omega t) \end{bmatrix}}_{-4\omega \text{ oscilation}} + \underbrace{V^{-5}\begin{bmatrix} \cos((+1+5)\omega t) \\ \sin((+1+5)\omega t) \end{bmatrix}}_{+6\omega \text{ oscilation}}$$

- Express the voltage in each reference frame →

$$\begin{bmatrix} v_{dq^{+1}} \\ v_{dq^{-1}} \\ v_{dq^{+5}} \\ v_{dq^{-5}} \end{bmatrix} = \begin{bmatrix} T_{dq^{+1}} \\ T_{dq^{-1}} \\ T_{dq^{+5}} \\ T_{dq^{-5}} \end{bmatrix} v_{\alpha\beta} = \underbrace{\begin{bmatrix} V_{dq}^{+1} \\ V_{dq}^{-1} \\ V_{dq}^{+5} \\ V_{dq}^{-5} \end{bmatrix}}_{DC\ terms} + \underbrace{\begin{bmatrix} [0] & T_{dq^{+1-(-1)}} & T_{dq^{+1-(+5)}} & T_{dq^{+1-(-5)}} \\ T_{dq^{-1-(+1)}} & [0] & T_{dq^{-1-(+5)}} & T_{dq^{-1-(-5)}} \\ T_{dq^{+5-(+1)}} & T_{dq^{+5-(-1)}} & [0] & T_{dq^{+5-(-5)}} \\ T_{dq^{-5-(+1)}} & T_{dq^{-5-(-1)}} & T_{dq^{-5-(+5)}} & [0] \end{bmatrix} \begin{bmatrix} V_{dq}^{+1} \\ V_{dq}^{-1} \\ V_{dq}^{+5} \\ V_{dq}^{-5} \end{bmatrix}}_{Oscillation\ Terms}$$

- **Include this equation on a cross feedback Multi-Sequence/Harmonic Decoupling Cell (MSHDC)** in order to estimate **accurately** and **dynamically** the (dc-term) amplitude of each voltage harmonic

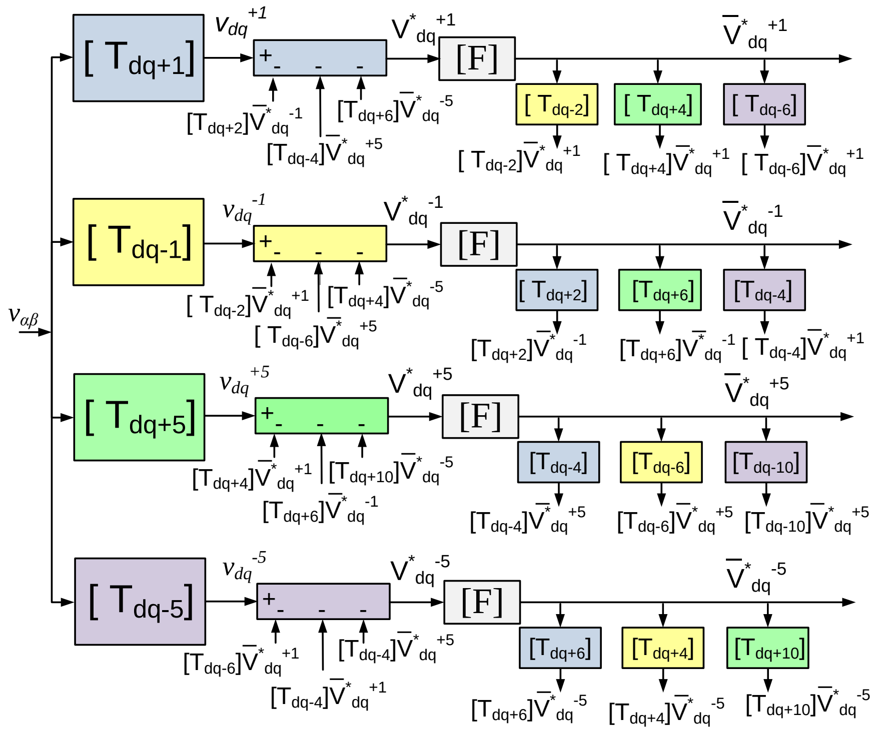
4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

MSHDC-PLL (Multi-Sequence/Harmonic Decoupling Cell PLL)

- Decoupling Network →

$$\bar{V}^{*(n)}_{dq} = [F]\left\{\begin{bmatrix}u_d^{(n)}\\ u_q^{(n)}\end{bmatrix} - \sum_{m\neq n}\left\{T_{dq^{(n-m)}}\cdot\begin{bmatrix}\bar{V}^{*(m)}_{dq}\\ \bar{V}^{*(m)}_{dq}\end{bmatrix}\right\}\right\} = \bar{V}^{*(n)}_{dq} = [F]\left\{T_{dq^{(n)}}\begin{bmatrix}v_a\\ v_\beta\end{bmatrix} - \sum_{m\neq n}\left\{T_{dq^{(n-m)}}\begin{bmatrix}\bar{V}^{*(m)}_{dq}\\ \bar{V}^{*(m)}_{dq}\end{bmatrix}\right\}\right\}$$

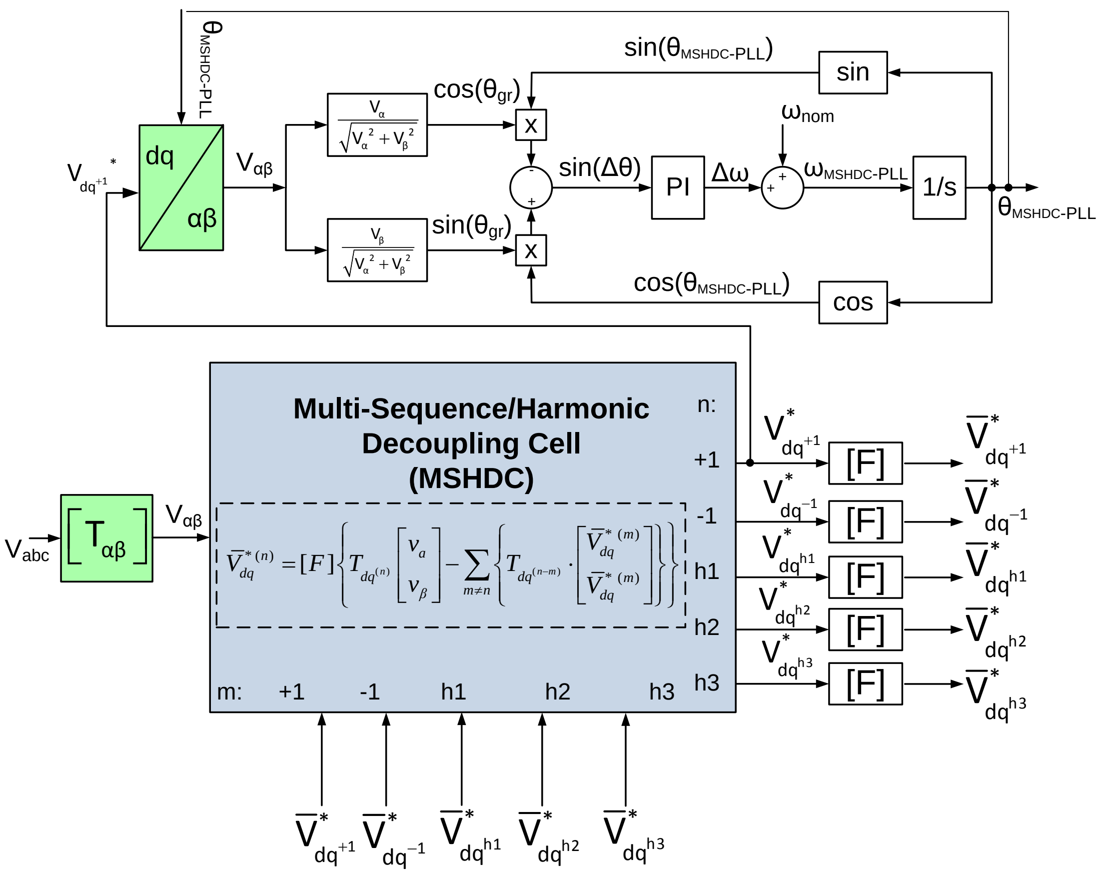


Structure of the MSHDC

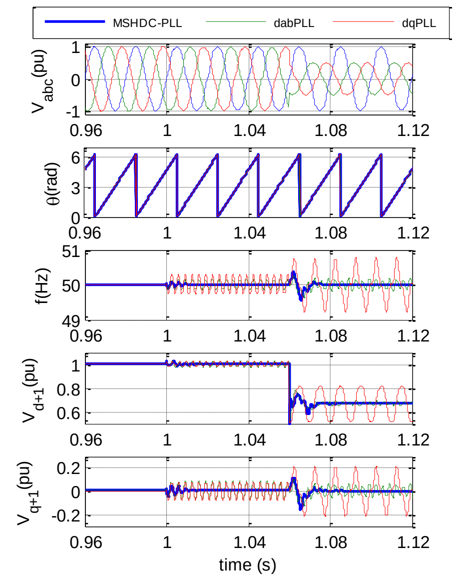
4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

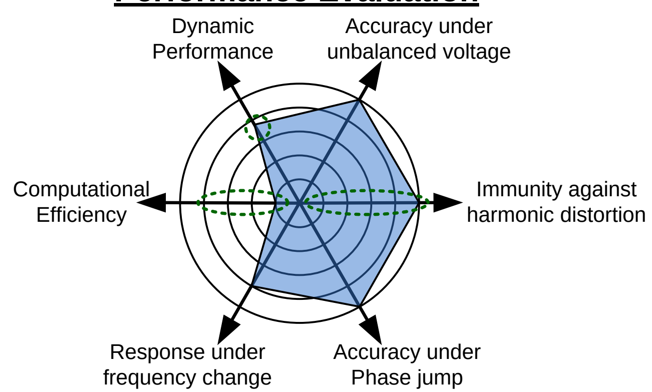
MSHDC-PLL (Multi-Sequence/Harmonic Decoupling Cell PLL)



Structure of the MSHDC-PLL



Performance Evaluation



4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

DNαβ-PLL (DN in αβ-frame PLL)

- MSHDC-PLL present very good accuracy under unbalanced and harmonic conditions
- MSHDC present high complexity (required processing time)

Re-design the MSHDC in αβ-frame (simplifies the complexity of the algorithm)

- MSHDC →

$$\bar{V}_{dq}^{*(n)} = [F]\left\{\begin{bmatrix} u_d^{(n)} \\ u_q^{(n)} \end{bmatrix} - \sum_{m \neq n}\left\{T_{dq^{(n-m)}} \cdot \begin{bmatrix} \bar{V}_{dq}^{*(m)} \\ \bar{V}_{dq}^{*(m)} \end{bmatrix}\right\}\right\} = \bar{V}_{dq}^{*(n)} = [F]\left\{T_{dq^{(n)}}\begin{bmatrix} v_a \\ v_\beta \end{bmatrix} - \sum_{m \neq n}\left\{T_{dq^{(n-m)}}\begin{bmatrix} \bar{V}_{dq}^{*(m)} \\ \bar{V}_{dq}^{*(m)} \end{bmatrix}\right\}\right\}$$

- DNαβ →

$$\boldsymbol{v}_{\boldsymbol{dq_n}}^{\boldsymbol{*n}} = \left[T_{dq^n}\right]\boldsymbol{v}_{\boldsymbol{\alpha\beta}}^{\boldsymbol{*n}} = \left[T_{dq^n}\right]\left(\boldsymbol{v}_{\boldsymbol{\alpha\beta}} - \sum_{m \neq n}\left[T_{dq^{-n}}\right]\left[F(s)\right]\left[T_{dq^n}\right]\boldsymbol{v}_{\boldsymbol{\alpha\beta}}^{\boldsymbol{*m}}\right)$$

- **DNαβ achieve equivalent performance with the MSHDC, however the computational efficiency of the method is sufficiently enhanced (61% less required processing time)**

COMPLEXITY COMPARISON BETWEEN THE DNab AND THE MSHDC

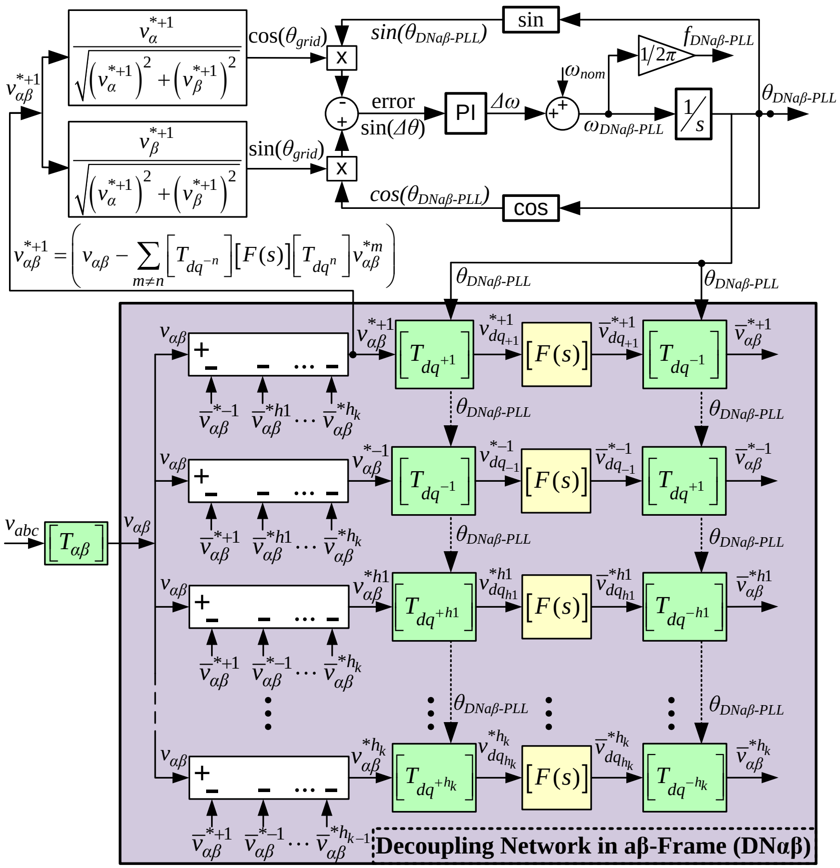
Decoupling Network	Complexity analysis in each control loop			
	$\left(\boldsymbol{v}_{dq_n} - \sum_{m \neq n} \bar{\boldsymbol{v}}_{dq_n}^{*m}\right)$ or $\left(\boldsymbol{v}_{\alpha\beta} - \sum_{m \neq n} \bar{\boldsymbol{v}}_{\alpha\beta}^{*m}\right)$	$[T_{dq}{}^{n}]$	$[F(s)]$	**Total**
MSHDC (N=10)	N	N^2	N	640 Multiplications 120 Additions 280 Subtractions
DNαβ (N=10)	N	$2N$	N	160 Multiplications 40 Additions 200 Subtractions

Notes:
- **Each** $\left(\boldsymbol{v}_{\alpha\beta} - \sum_{m\neq n}\bar{\boldsymbol{v}}_{\alpha\beta}^{*m}\right)$ **or** $\left(\boldsymbol{v}_{dq_n} - \sum_{m\neq n}\bar{\boldsymbol{v}}_{dq_n}^{*m}\right)$ →requires 2·(N-1) Subtractions
- **Each** $[\boldsymbol{T_{dq}}]$ → requires 6 Multiplications + 1 Addition + 1 Subtractions
- **Each** $[\boldsymbol{F(s)}]$ → requires 4 Multiplications + 2 Additions

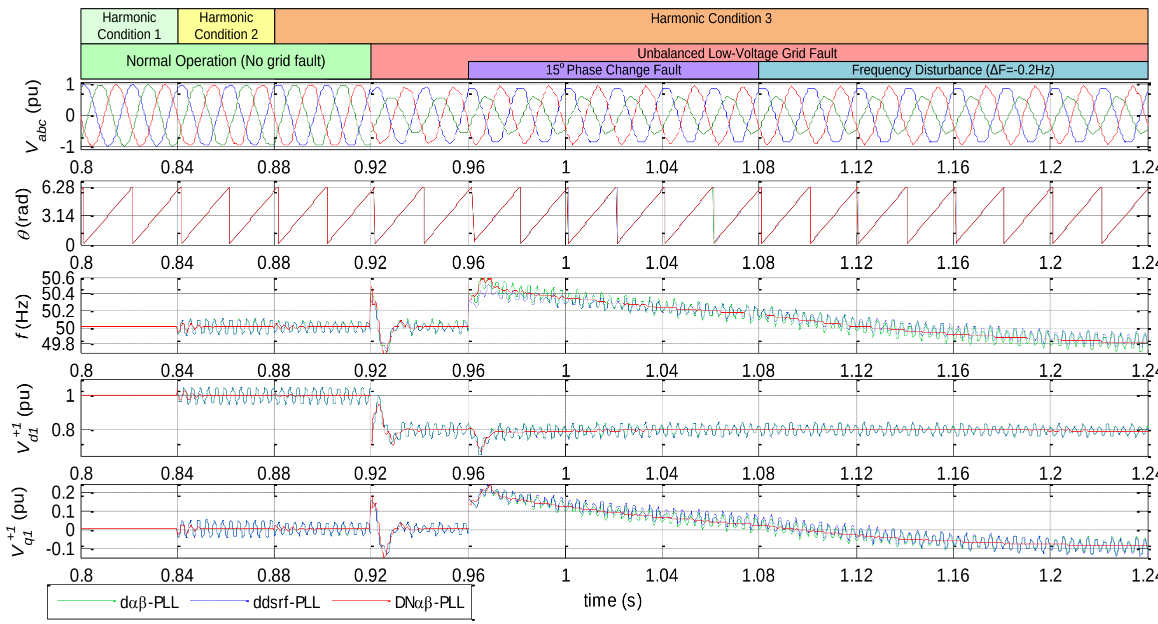
4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

DNαβ-PLL (DN in αβ-frame PLL)



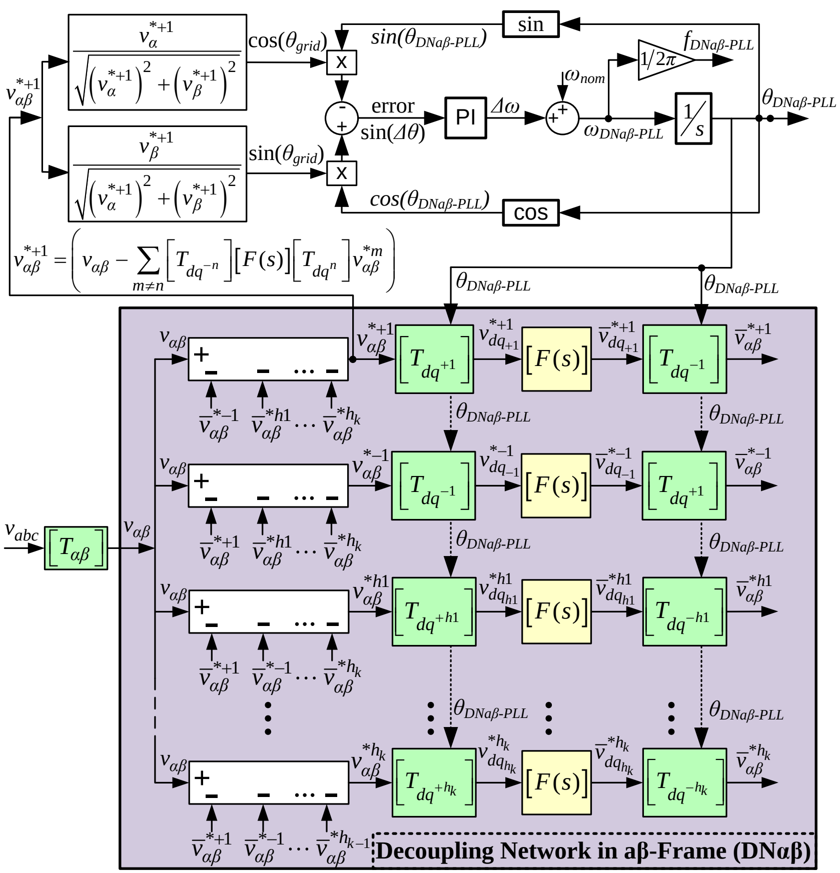
Structure of the DNαβ-PLL



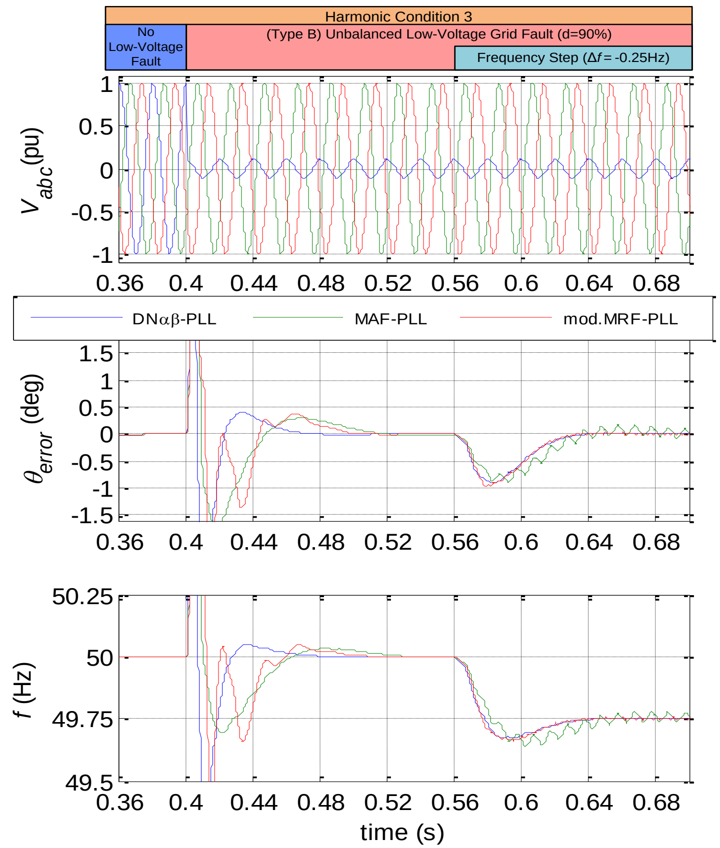
4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

DNαβ-PLL (DN in αβ-frame PLL)



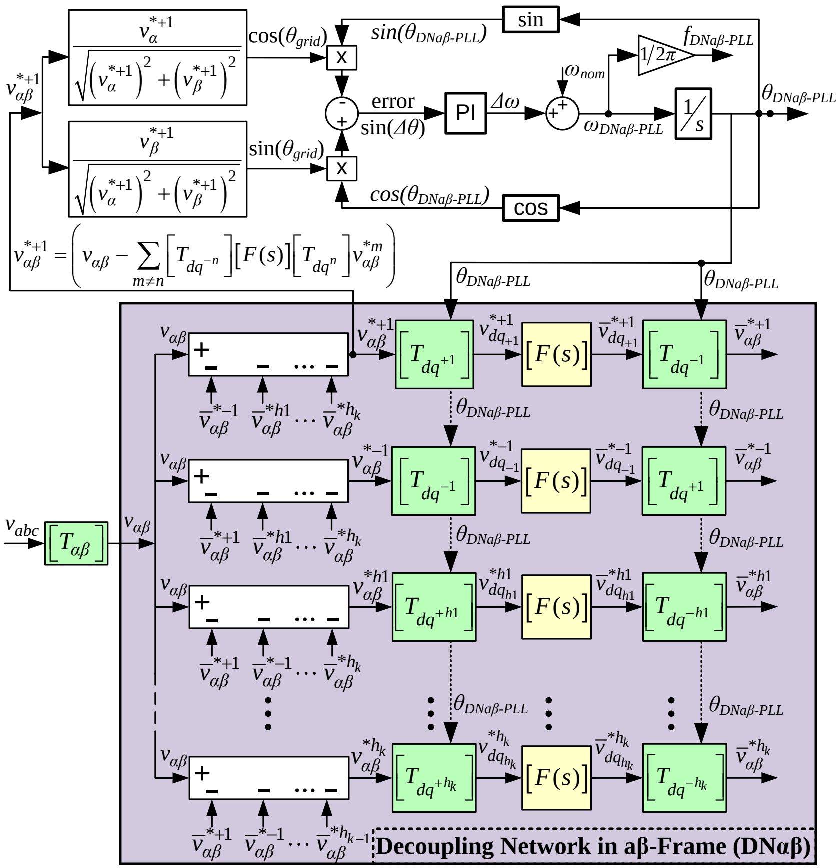
Structure of the DNαβ-PLL



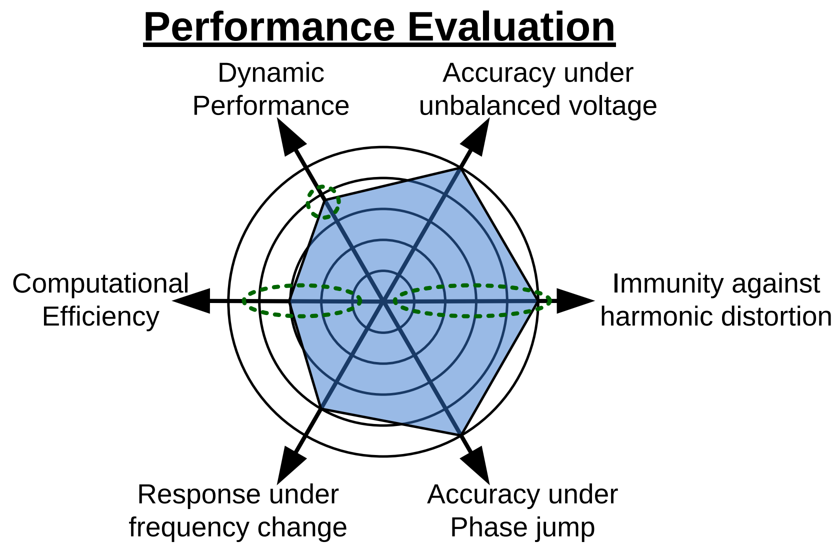
4. Synchronization Methods

Three-phase synchronization method: Conventional methods – State of the art – **Proposed methods**

DNαβ-PLL (DN in αβ-frame PLL)

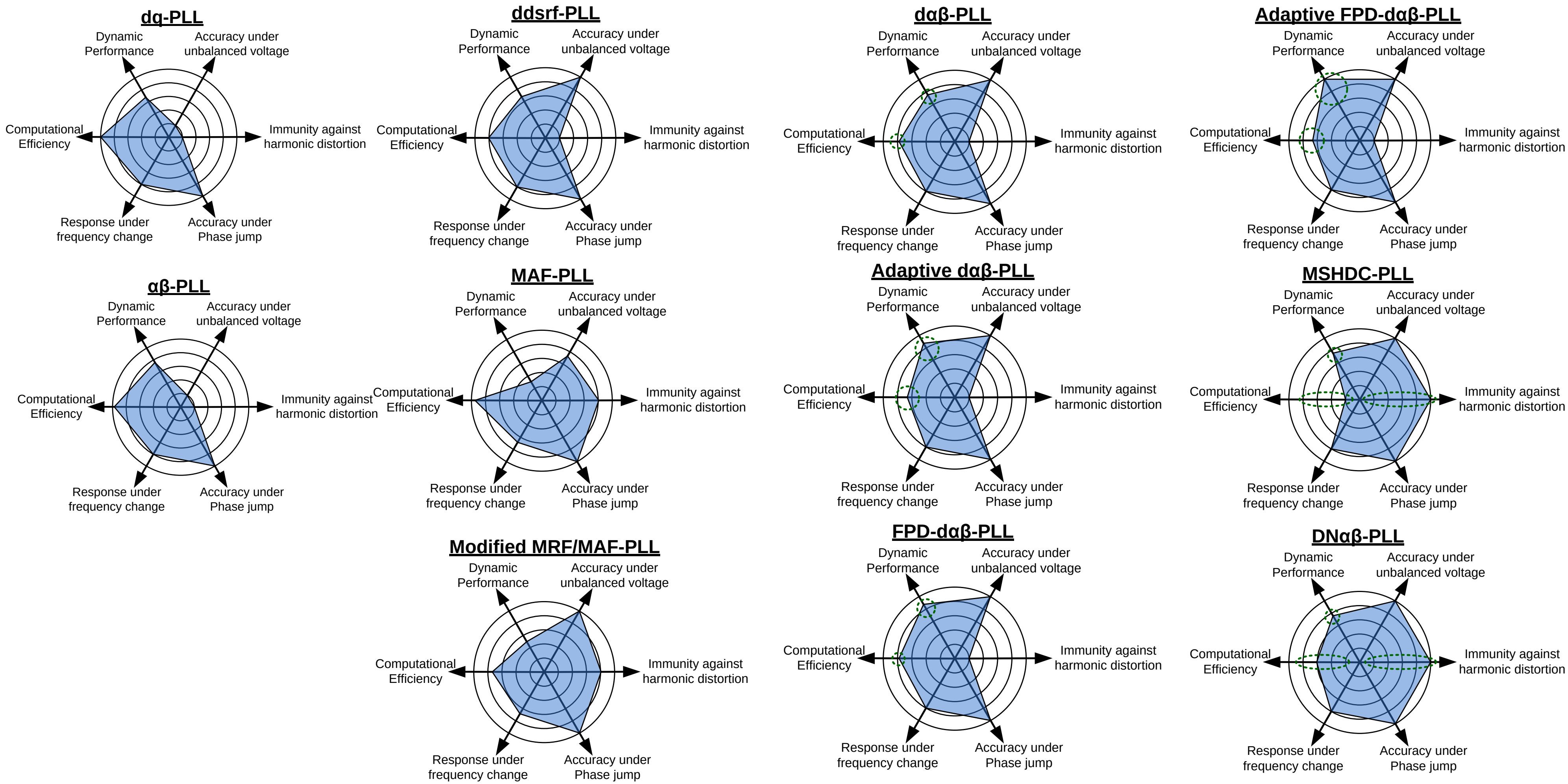


Structure of the DNαβ-PLL



4. Synchronization Methods

Synopsis



5. Conclusions

Conclusions

This work has presented the control methodologies for the GSC of RES (WPS and PV systems)

- The main topologies for WPS and PV systems
- The main units of the GSC controller has been presented

Proposed current controller

- Simplified and can enable the accurate current injection under unbalanced and harmonic conditions

Literature review on the synchronization methods

- Conventional and state-of-the-art PLLs

Six new synchronization methods has been proposed

- The proposed PLLs enhance the synchronization in regards:
  - the dynamic performance
  - the immunity against unbalanced voltage
  - The immunity against harmonic distortion

5. Conclusions

Future Work

- Propose new synchronization methods for single-phase systems
- Propose new advanced current controller for both single- and three-phase systems
- Enhance PQ controller for both single- and three-phase systems
- Investigate the effect of large RES on the dynamic operation of power systems
- Investigate novel control strategies for PV and their effect on distribution networks

Acknowledgements

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Thank you for your attention