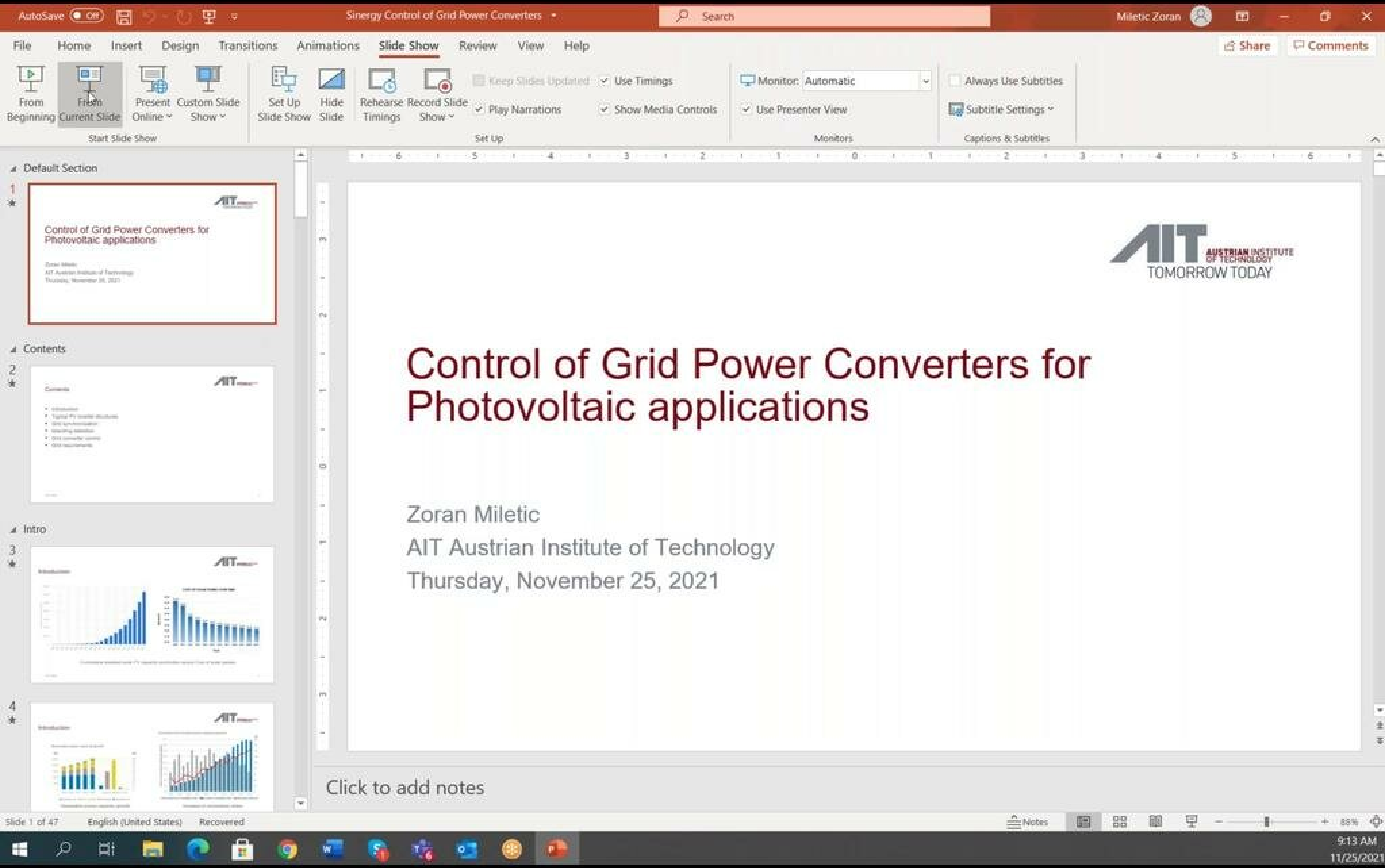
Sinergy Control of Grid Power Converters
Control of Grid Power Converters for Photovoltaic applications
Zoran Miletic
AIT Austrian Institute of Technology
Thursday, November 25, 2021
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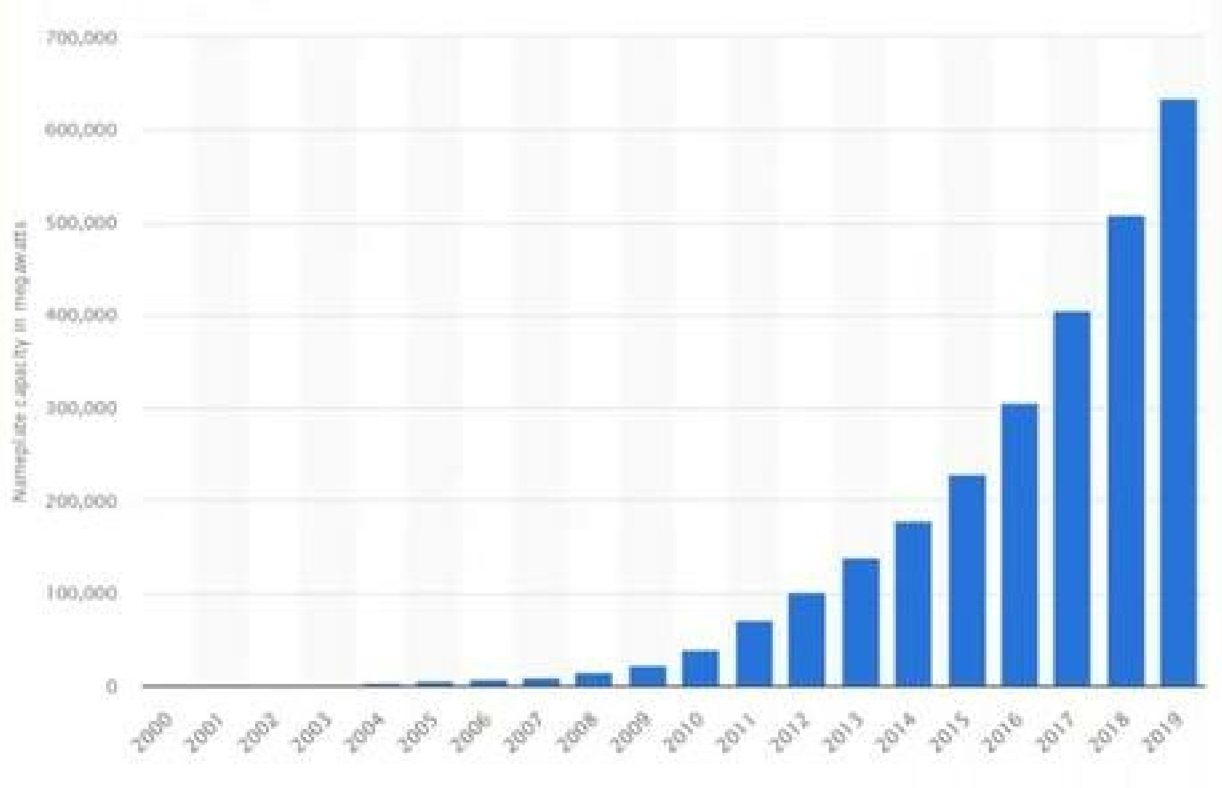
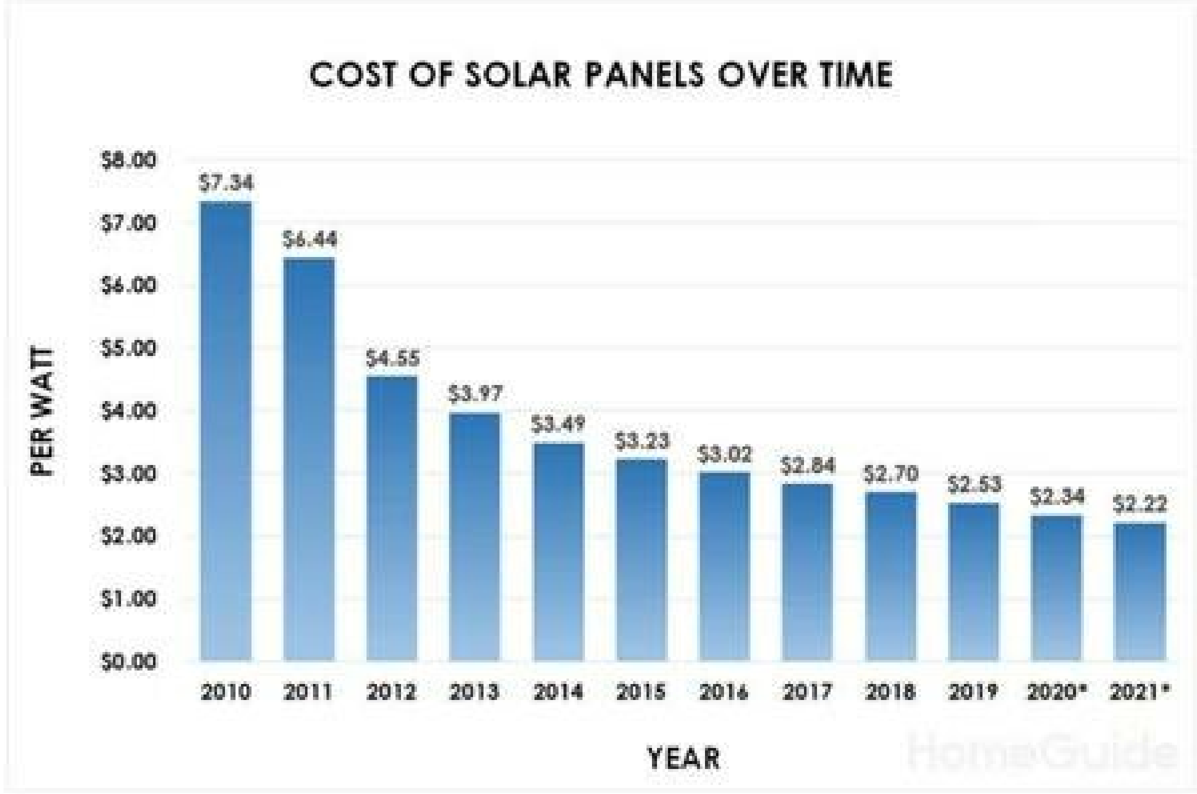
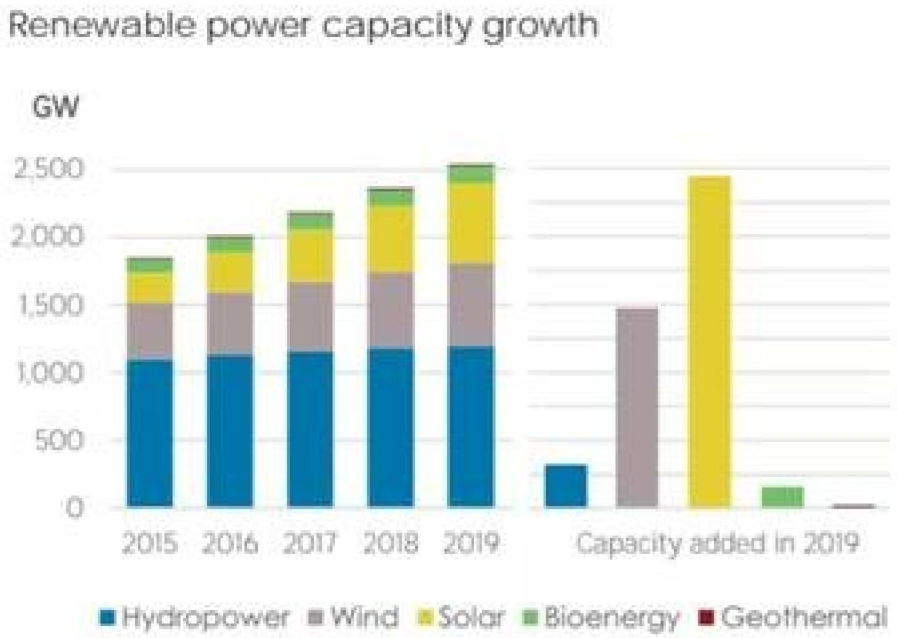
Introduction



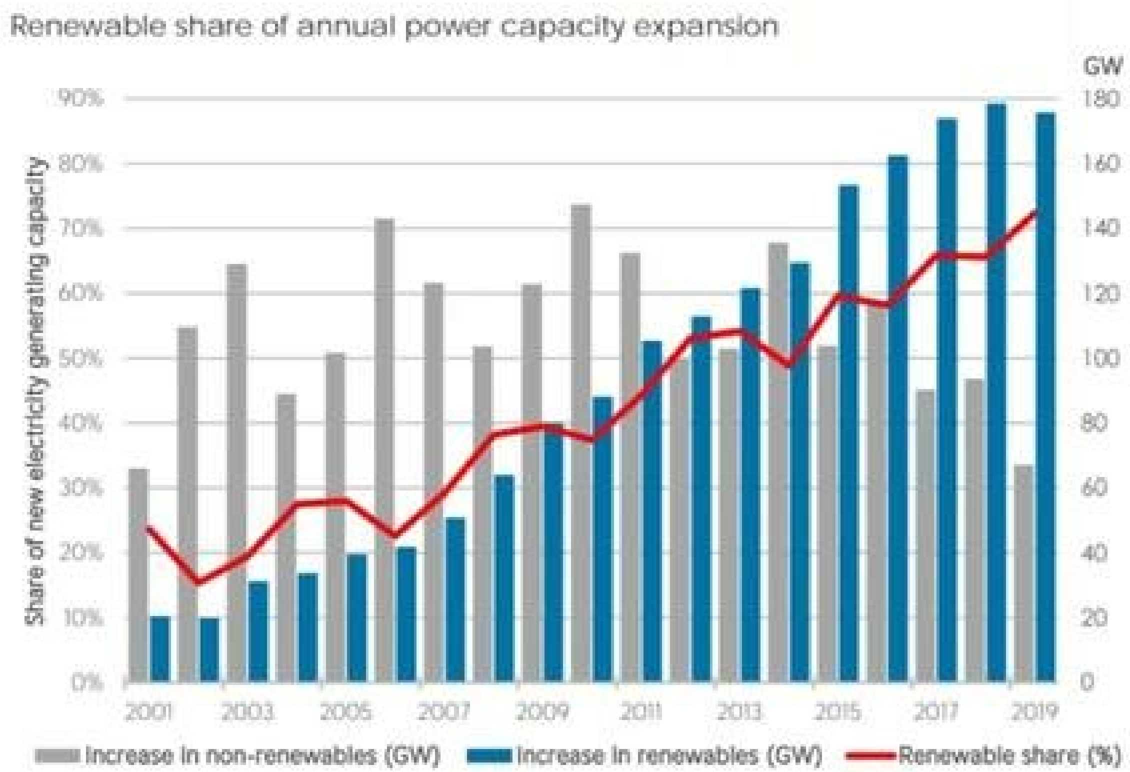


Cumulative installed solar PV capacity worldwide versus Cost of solar panels

Introduction



Renewable power capacity growth



Increase of renewables share

Decrease of rotating mass generation ⇒ Low inertia grids

Source: IRENA, Renewable Capacity Statistics 2020,https://www.irena.org/publications/2020/Mar/Renewable-Capacity-Statistics-2020

PV inverters classification

Per type

- Module integrated inverters – 50 – 400W
- String inverters – up to 15 kW – residential applications
- Multi sting inverters – up to 120 kW - roof-tops & commercial
- Utility scale inverters – up to 3 MW – distributed solar installations and solar parks

Per technology

- Single phase
- Three phase

Per isolation

- Transformer less
- With LF/HF transformer isolation

PV Capacitance to ground and leakage current

- $C_{PE} = C_1 + C_2 + C_3$ and $C_1 \gg C_2 \gg C_3$
- Crystalline silicon module
  - C=12 to 17nF per m^2
  - C=60 to 110nF per kW
- Thin-film module
  - C=16nF per m^2
  - C=100 to 160nF per kW
- Leakage current
  - $I_{lk} = C_{PE}\left(\frac{dU}{dt}\right)$
  - C_{PE} fixed per installation
  - $\frac{dU}{dt}$ depends on the modulation scheme and topology

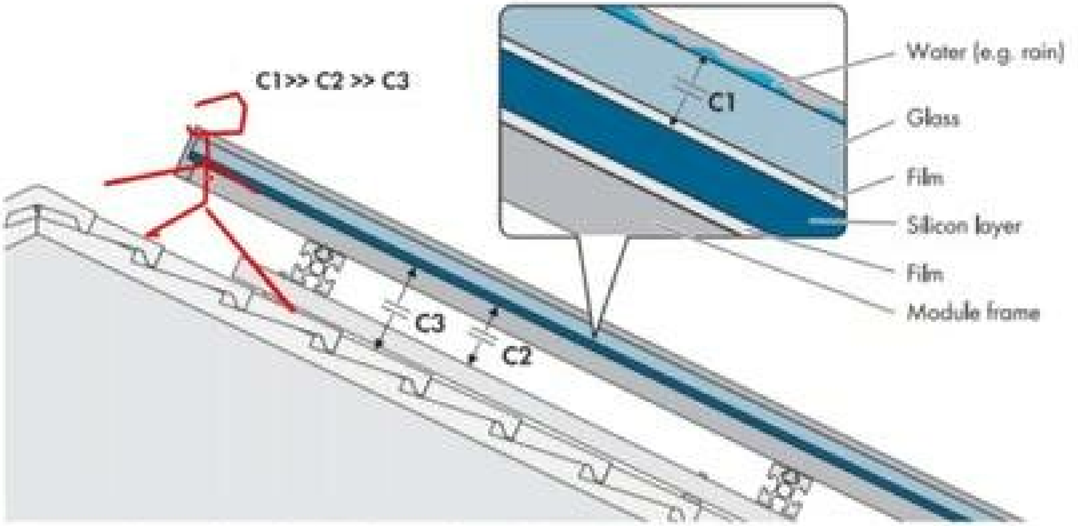


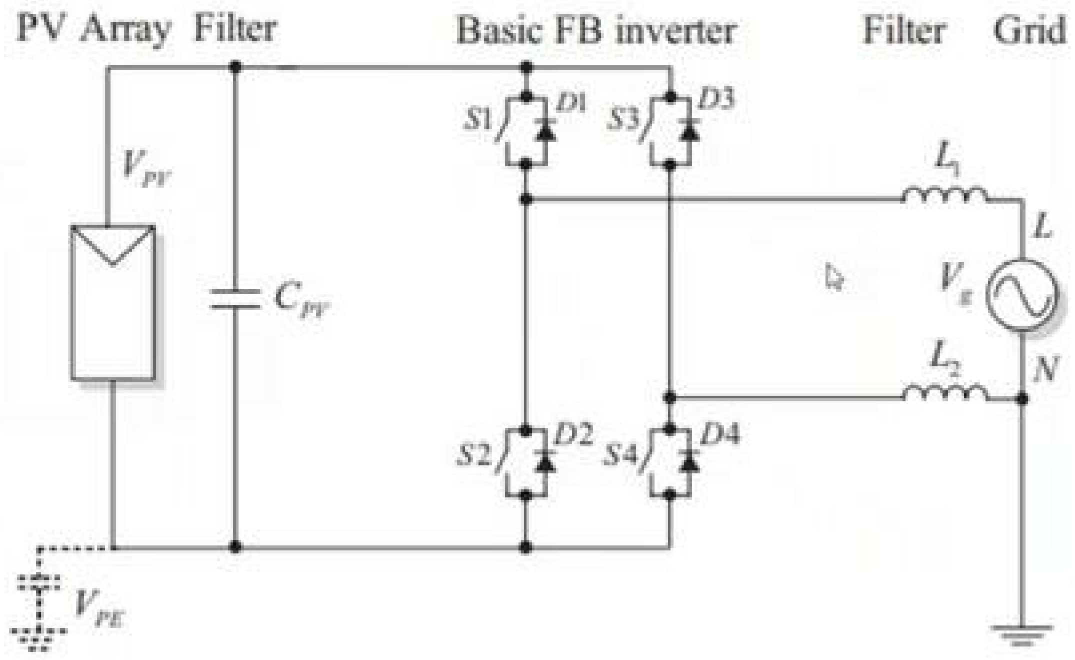
Figure 1: Illustration of a roof assembly of a PV module and schematic illustration of "parasitic capacitance"

C1	Parasitic capacitance due to film of water on the glass
C2	Parasitic capacitance due to grounded support frame
C3	Parasitic capacitance due to roof surface area

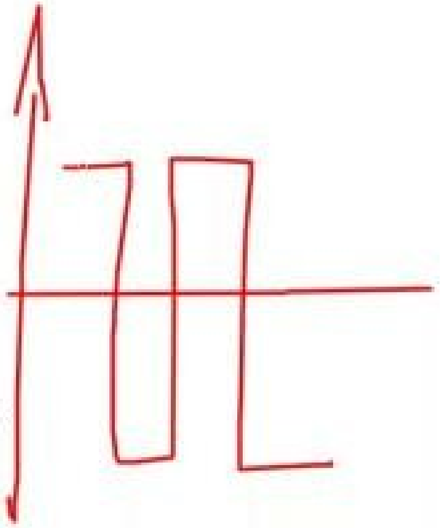
Source: Technical Information Leading Leakage Currents, https://files.sma.de/downloads/Ableitstrom-TI-en-26.pdf

Single phase PV inverters

- Single phase H- Bridge topology
- Bipolar modulation
  - S1/S4 and S2/S3 diagonally switched
  - VPE has only a grid freq component ⇒ low leakage current and EMI
- Unipolar modulation
  - S1/S4 and S2/S3 high freq switching ⇒ high leakage current, not suitable for transformer less applications
- Voltage across the filter is bipolar
- Electrical efficiency up to 96.5%



Single phase PV inverters



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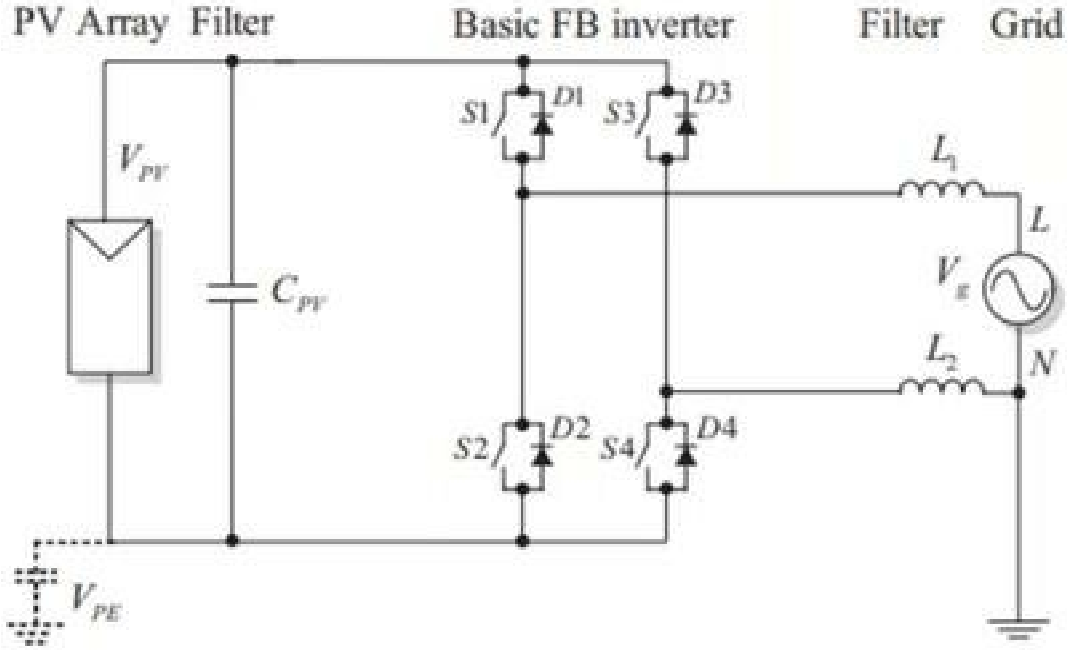
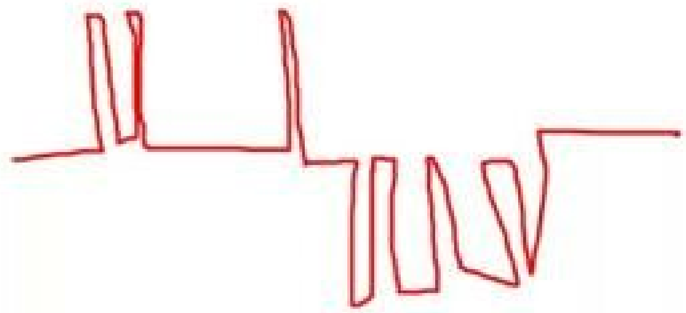
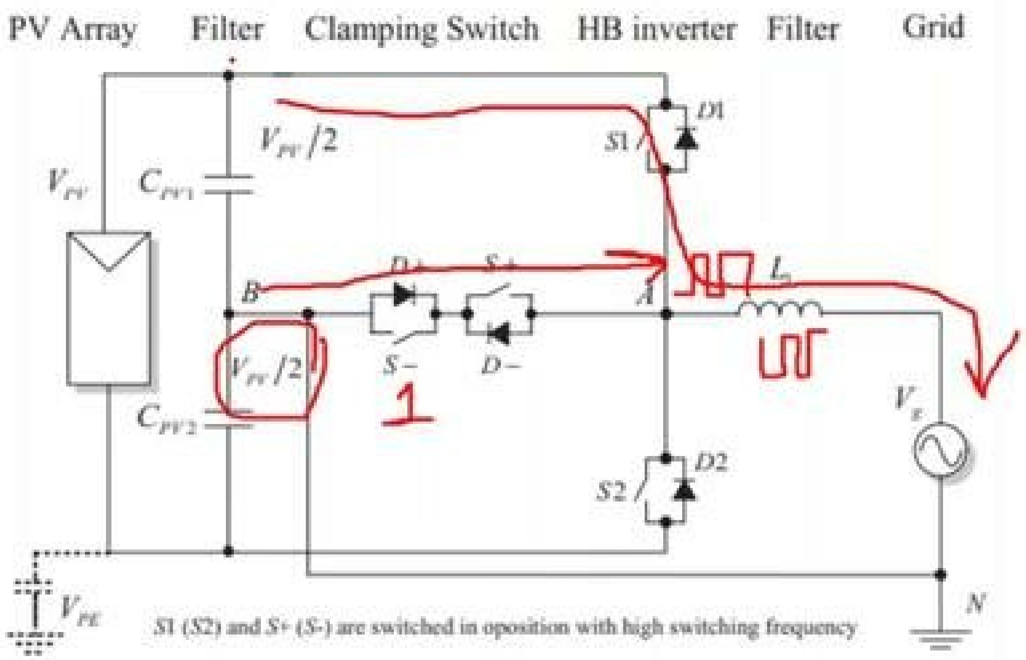


Single phase PV inverters



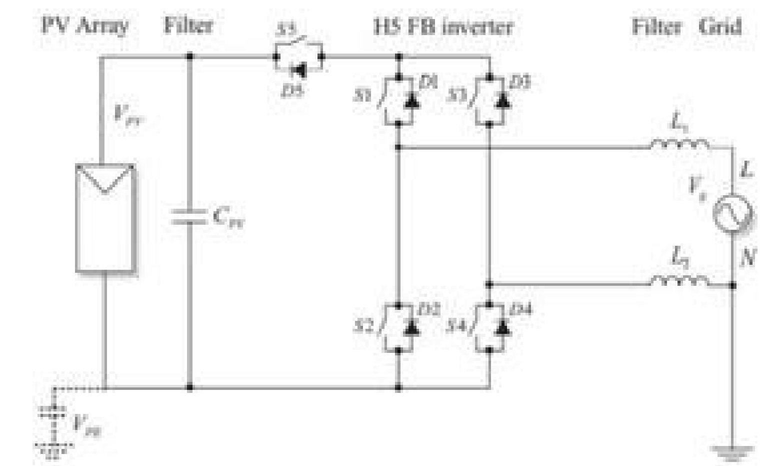
- Single phase 3L-T type topology
- Modulation
  - S1/2 and S+/S- HF
- Voltage across the filter is unipolar, yielding lower core losses
- Electrical efficiency up to 98.0%, no reactive power exchange between filter inductor and DC bus
- Reduce voltage rating of outer devices to Vpv/4
- Vpe no switching frequency components ⇒ low leakage current and EMI
- More devices vs H bridge
- Requires double voltage input
- Balanced switching losses vs 3L-NPC, however S1/S2 double voltage rating

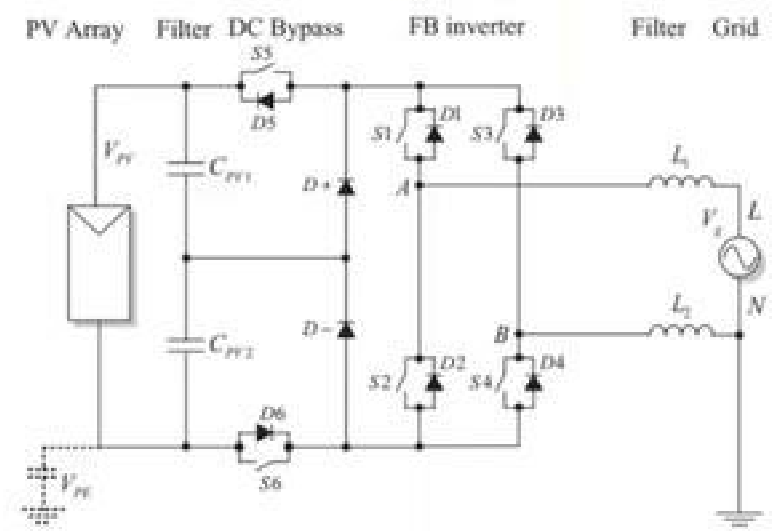


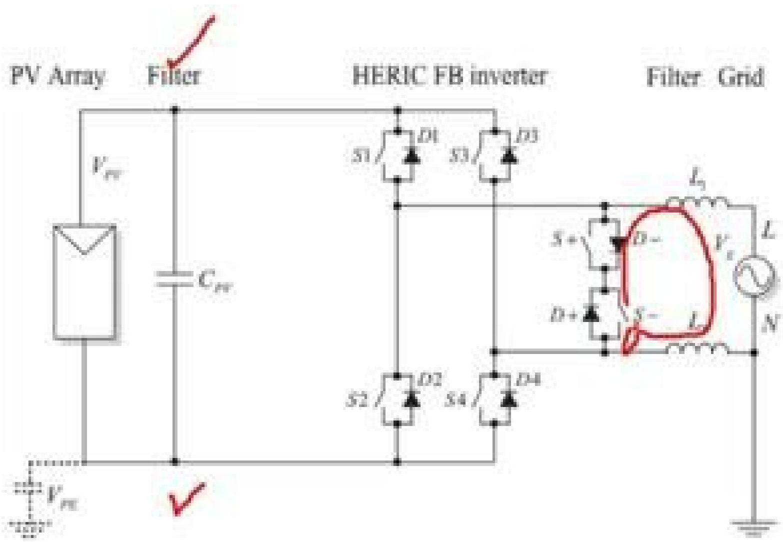
Single phase PV inverters

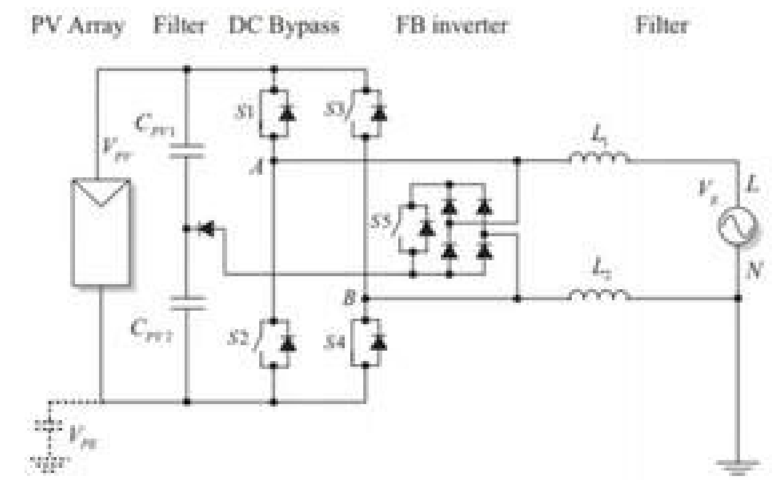
- Other popular single phase PV inverter topologies
- H5 (SMA)
- HERIC (Sunways)
- Full-Bridge inverter with DC bypass (Ingeteam)
- Full-Bridge Zero Voltage Rectifier

- Convert 2 level FB or HB into 3 level
- Half input voltage vs 3 level









Single phase PV inverters

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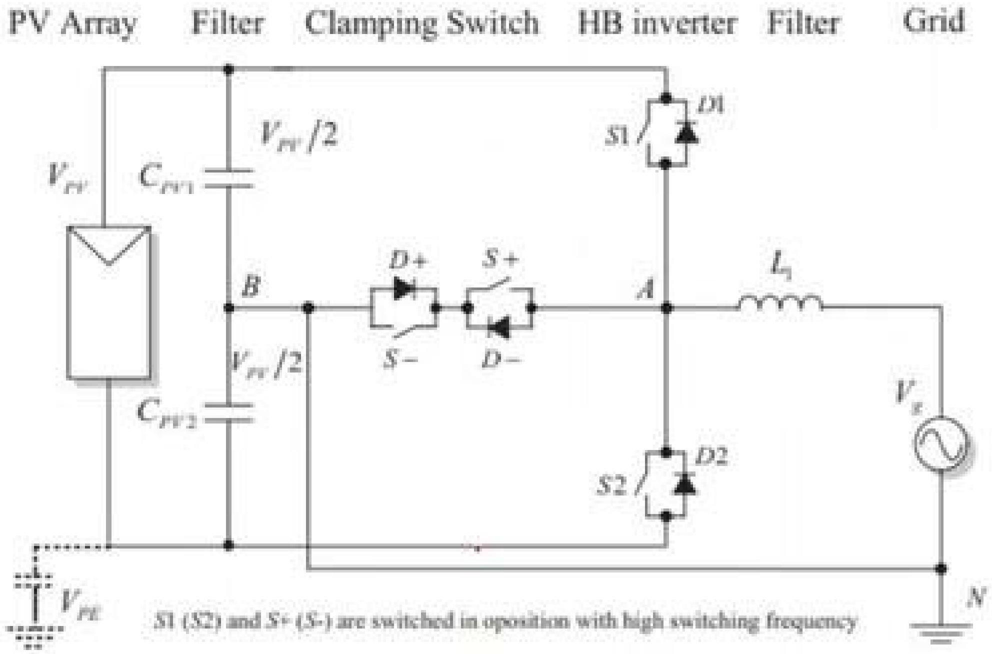
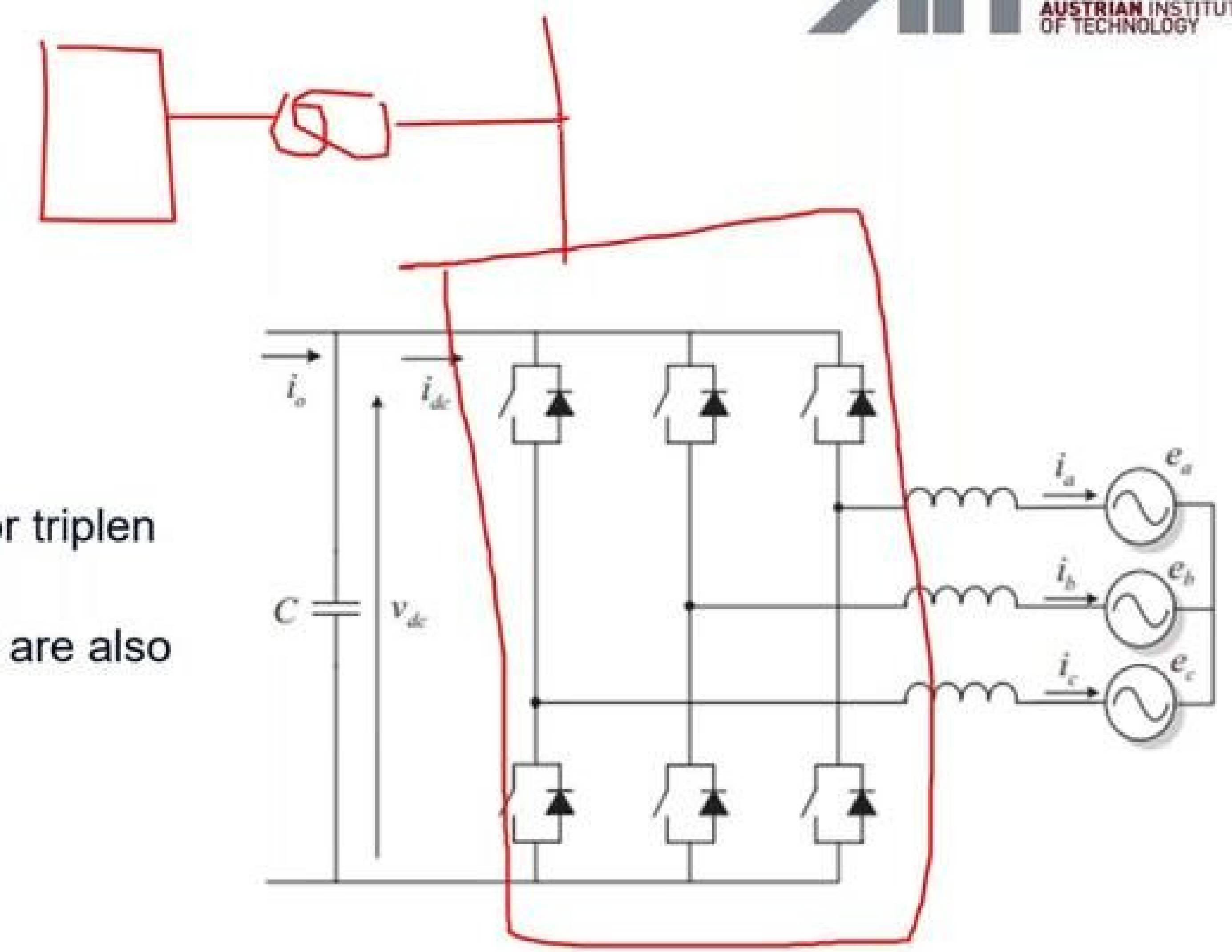


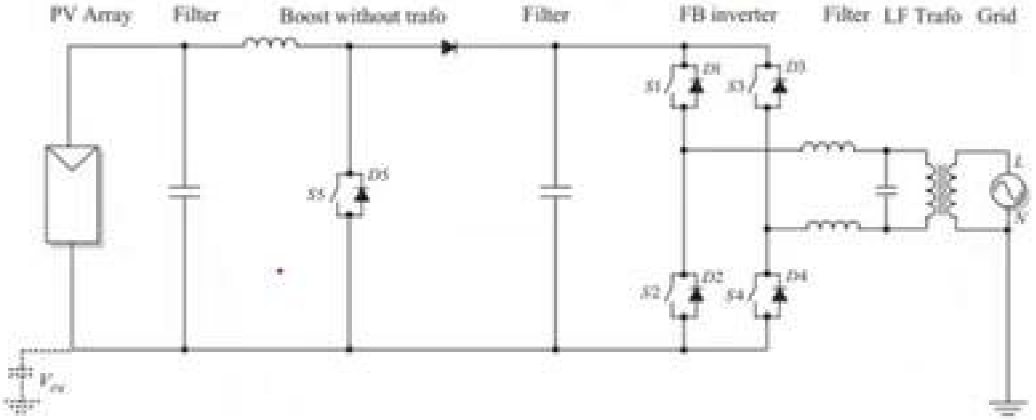
Three phase PV inverters

- Three phase 2L (B6) type topology
- Utility scale central PV inverters
- Three phase three wire
- Via interface transformer
- Modulation three phase (sinusoidal, 3rd or triplen harmonic injection), discontinuous
- Three phase 3L NPC, ANPC and T-type are also common

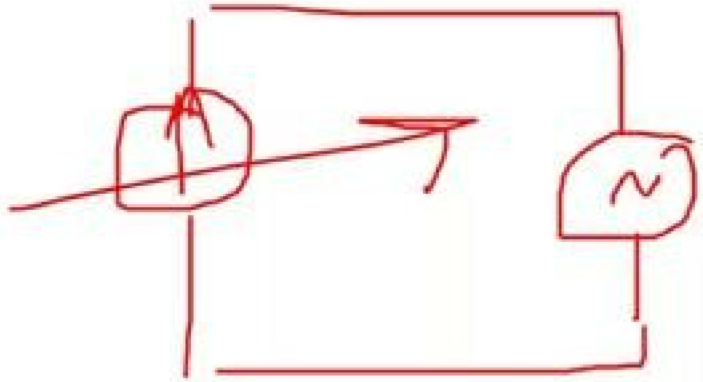


Three phase PV inverters

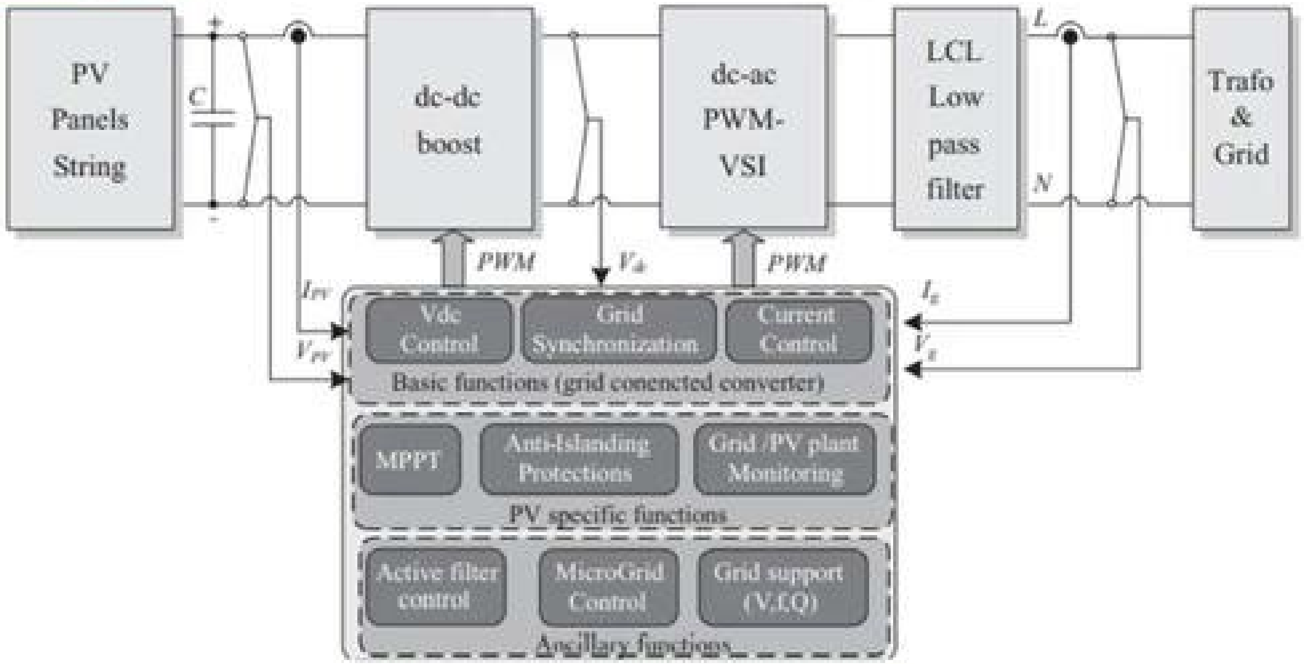
- Three phase made with single phase PV inverters
- Residential and commercial markets
- Three phase four wire
- Easer to pass German VDE-0126-1-1 standard as impedance monitoring can be replaced by line-to-line voltage monitoring



Control structures



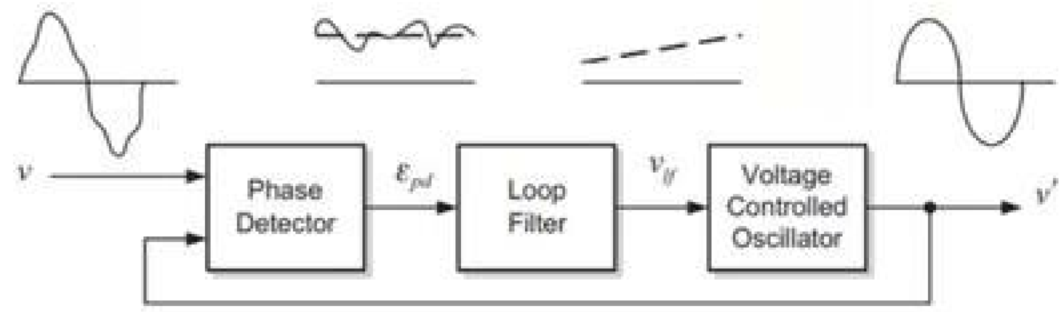
- Basic functions
  - Grid synchronization
  - Current control
  - DC bus control
- PV specific functions
  - Maximum Power Point tracking (MPPT)
  - Anti-islanding
  - Grid/PV plant monitoring
    - Residual current detection
    - Isolation monitoring
- Ancillary functions
  - Grid support
  - Active Filter control
  - MicroGrid control

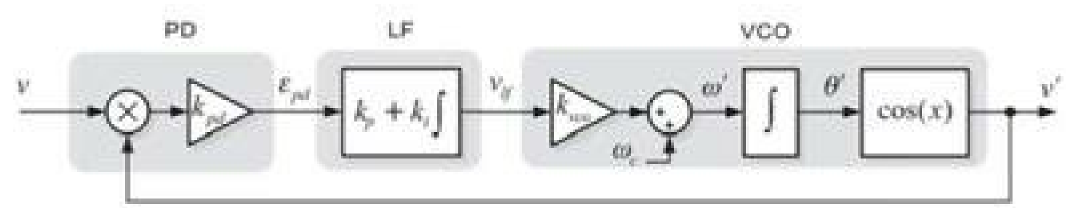


Grid Synchronization

$\sin(\alpha)\cdot\sin(\beta)$

- Fourier Analysis
- ~~Phase~~ Phase-Locked Loop
  - PD phase detector
  - LF loop filter
  - VCO voltage-controlled oscillator





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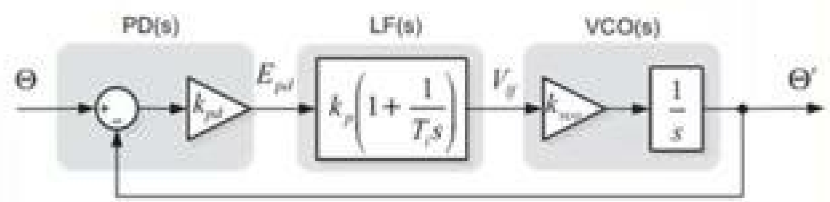
Grid Synchronization

- Phase Phase-Locked Loop
  - PD phase detector
  - LF loop filter
  - VCO voltage-controlled oscillator



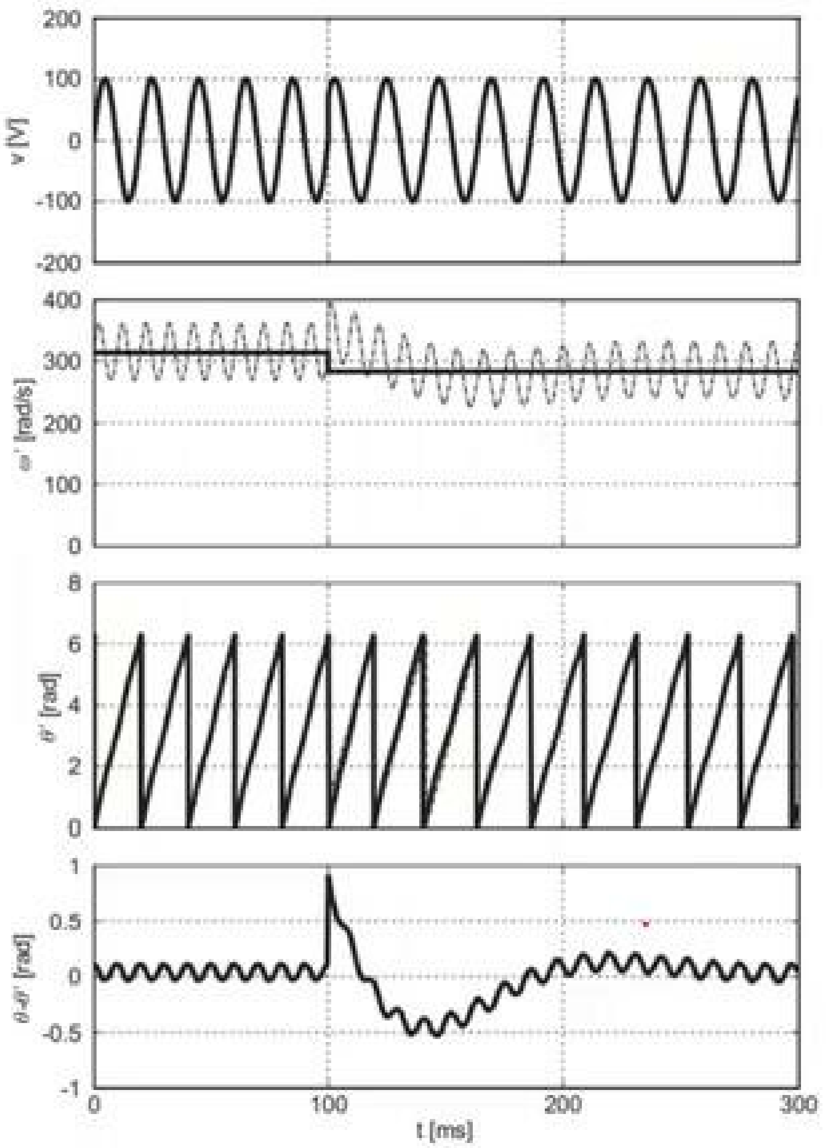
- Phase detector: $$E_{pd}(s) = \frac{V}{2}\left(\Theta(s) - \Theta'(s)\right)$$
- Loop filter: $$V_{lf}(s) = k_p\left(1 + \frac{1}{T_i s}\right)\varepsilon_{pd}(s)$$
- Controlled oscillator: $$\Theta'(s) = \frac{1}{s}V_{lf}(s) \quad .$$

Closed-loop phase transfer function:

$$H_\theta(s) = \frac{\Theta'(s)}{\Theta(s)} = \frac{LF(s)}{s + LF(s)} = \frac{K_p s + \frac{K_p}{T_i}}{s^2 + K_p s + \frac{K_p}{T_i}}$$

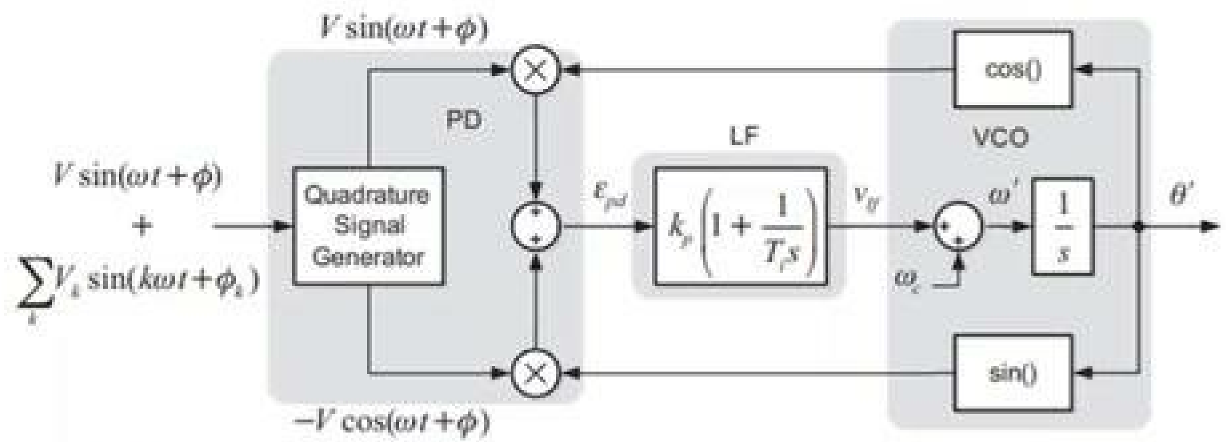
Grid Synchronization

- Phase Phase-Locked Loop step response
  - Error signal steady state oscillatory term
  - Poor bandwidth



Grid Synchronization

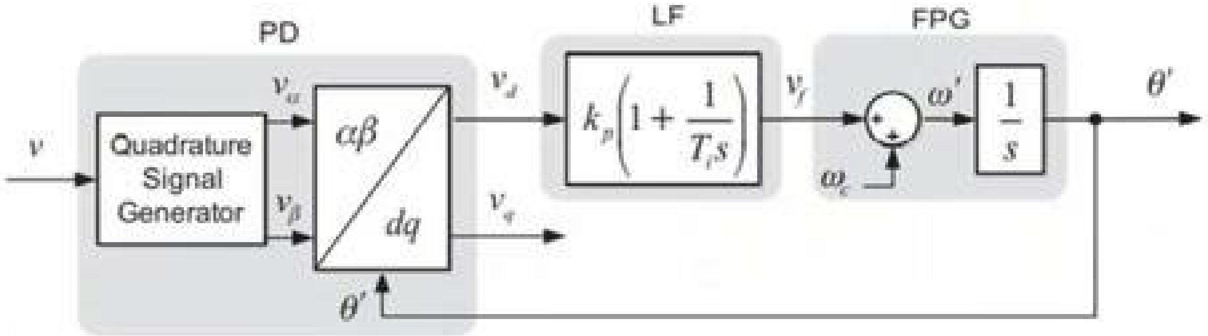
- Phase Phase-Locked Loop with ideal in-quadrature PD
  - No steady state oscillatory term
  - Increased bandwidth
  - VCO voltage-controlled oscillator

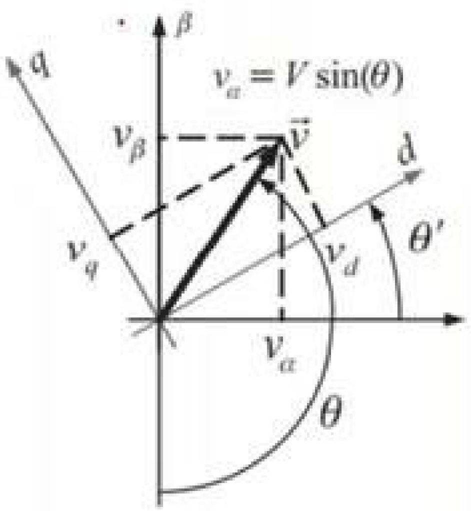


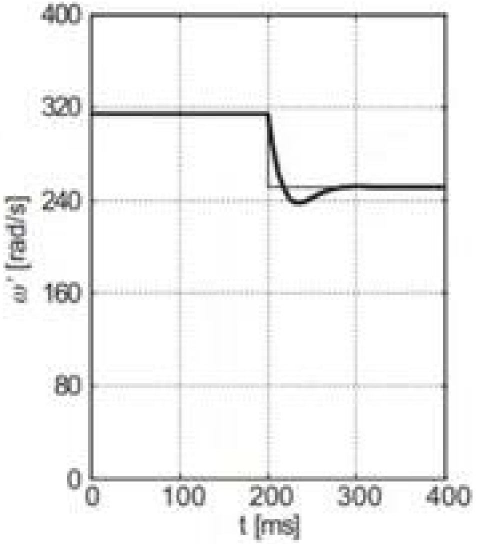
$$\varepsilon_{pd} = V\sin(\omega t+\phi)\cos(\omega' t+\phi') - V\cos(\omega t+\phi)\sin(\omega' t+\phi')$$
$$= V\sin((\omega-\omega')t+(\phi-\phi')) = V\sin(\theta-\theta')$$

Grid Synchronization

- Phase Phase-Locked Loop with ideal in-quadrature PD
  - No steady state oscillatory term
  - Increased bandwidth
  - VCO voltage-controlled oscillator

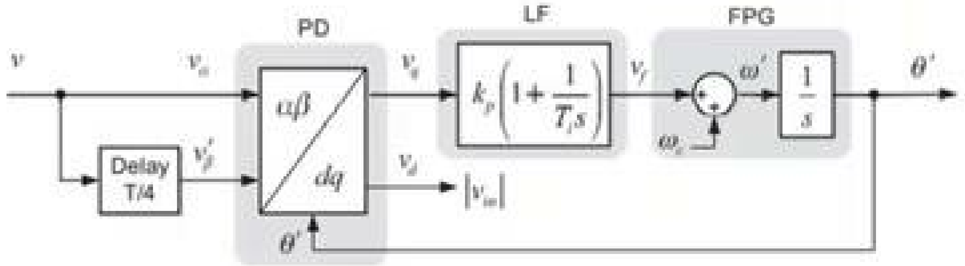


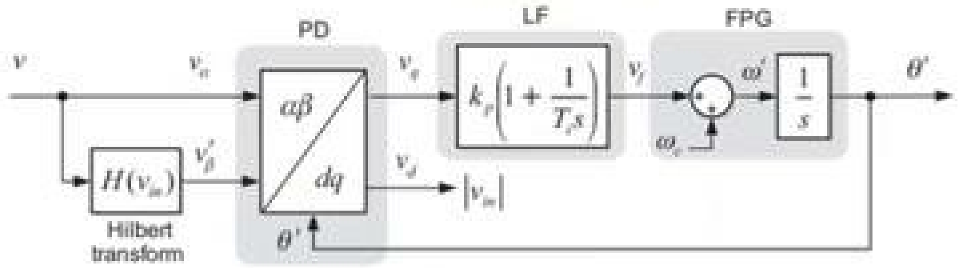


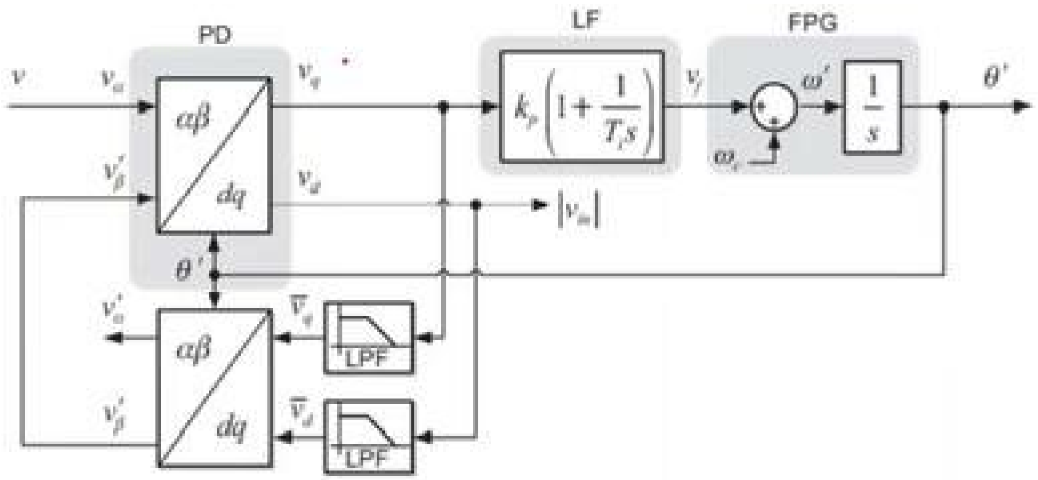


Grid Synchronization

- Other Phase Phase-Locked Loop based on in-quadrature PD
  - PLL Based on a T/4 Transport Delay
  - PLL Based on the Hilbert Transform
  - PLL Based on the Inverse Park Transform

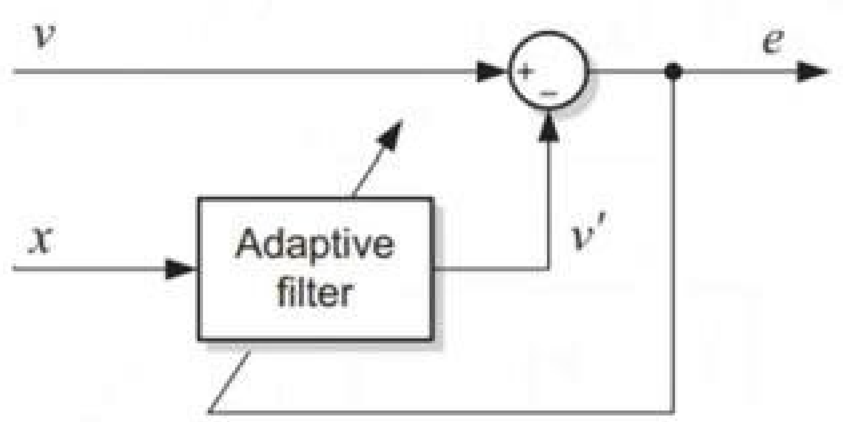


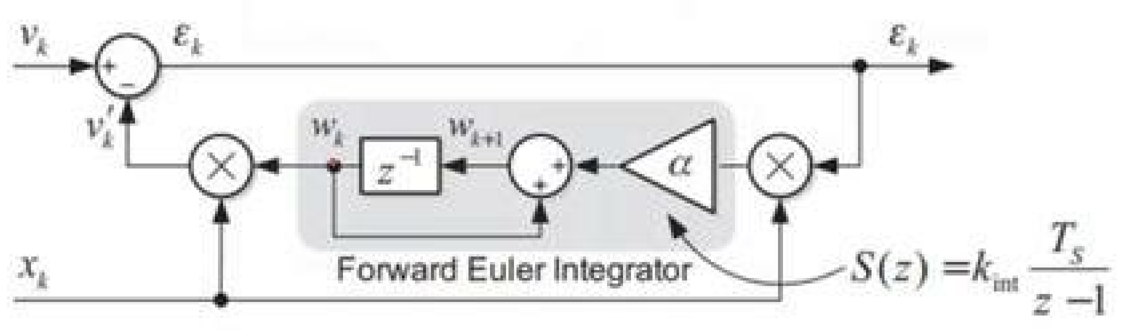




Grid Synchronization – PLLs based on adaptive filtering

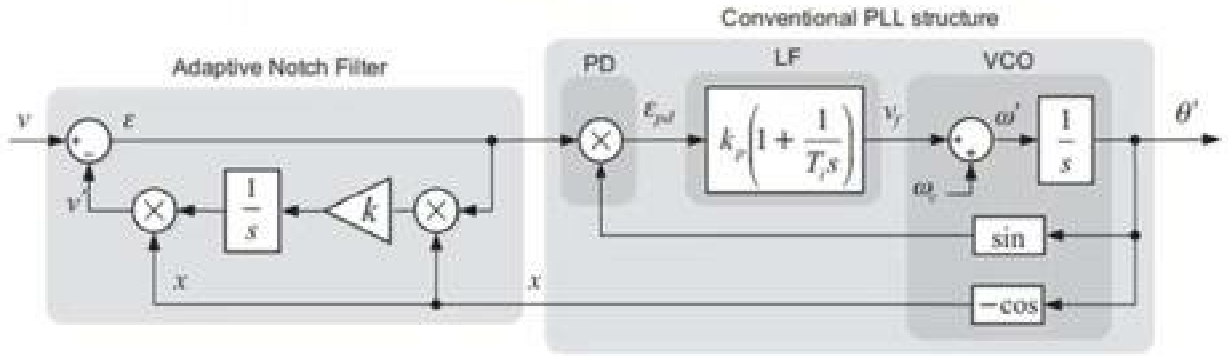
- Adaptive filter
  - Adaptive filter adjusts its own parameters according to optimization algorithm without prior knowledge of the signal
  - *v* input signal
  - *x* reference signal correlated to noise content
  - *e* output signal without noise

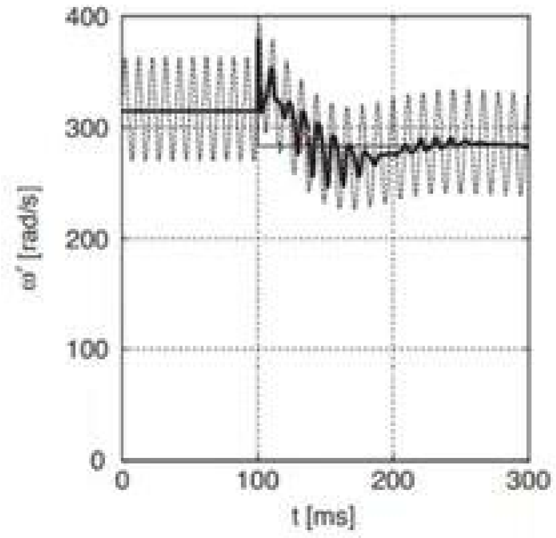


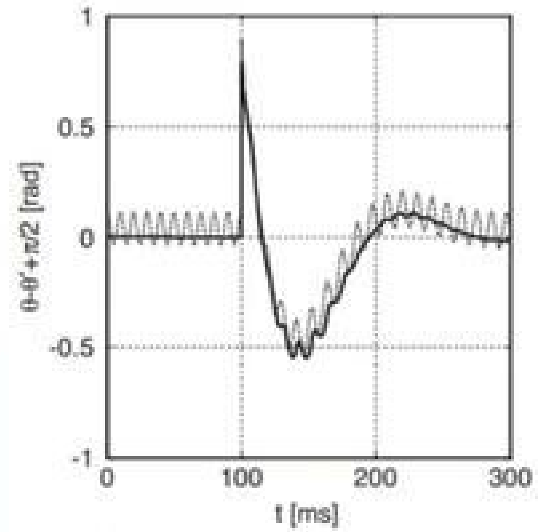


Grid Synchronization - PLLs based on adaptive filtering

- Enhanced PLL (EPLL)
  - Enhanced performance of PD
  - Adaptive Notch Filter
  - EPLL solid and conventional PLL dashed lines

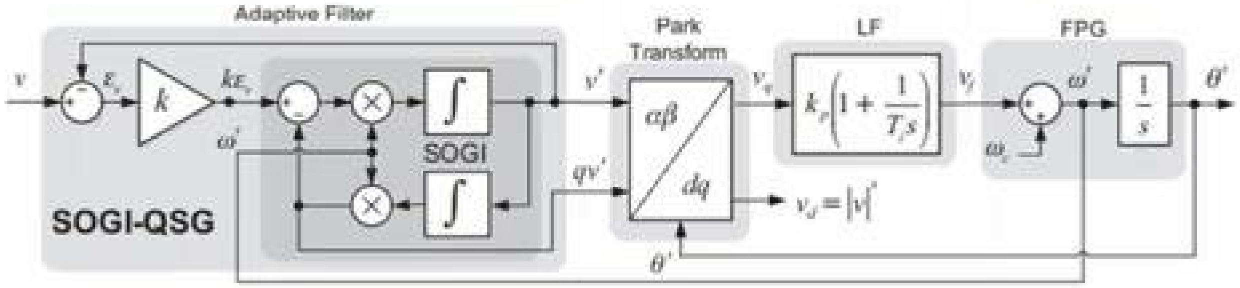


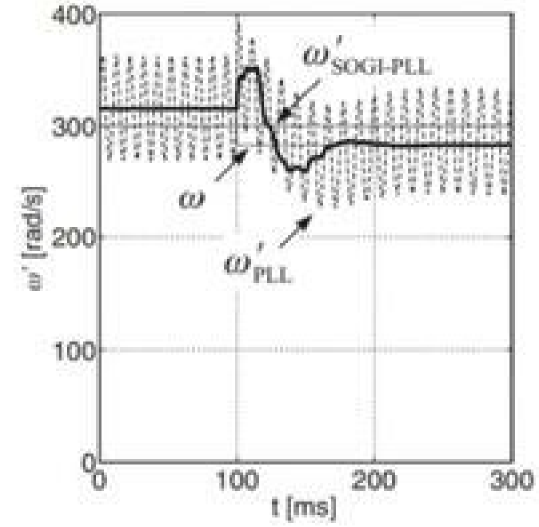


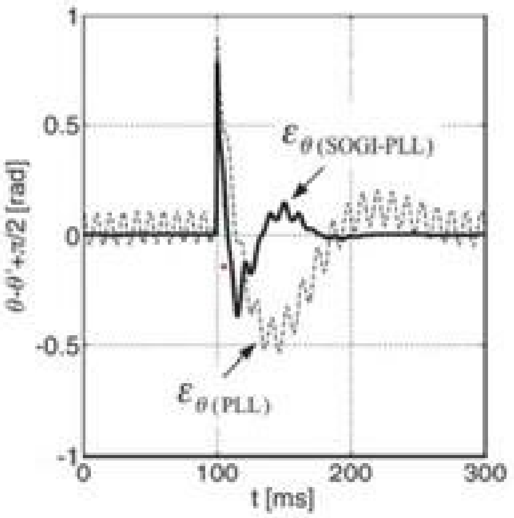


Grid Synchronization - PLLs based on adaptive filtering

- SOGI-based PLL
  - SOGI functions as QSG (in-quadrature signal generator)
  - SOGI is a notch filter
  - PLL locks the phase angle to the input frequency
  - the SOGI-PLL detects the input phase-angle faster than the conventional PLL and with no steady-state oscillations

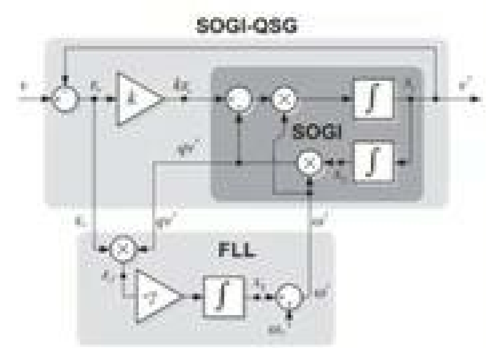




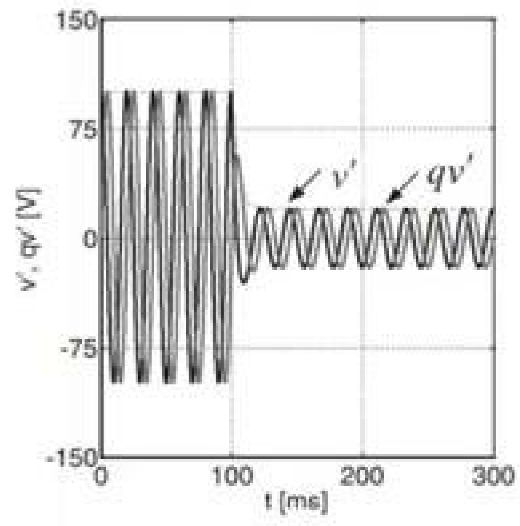


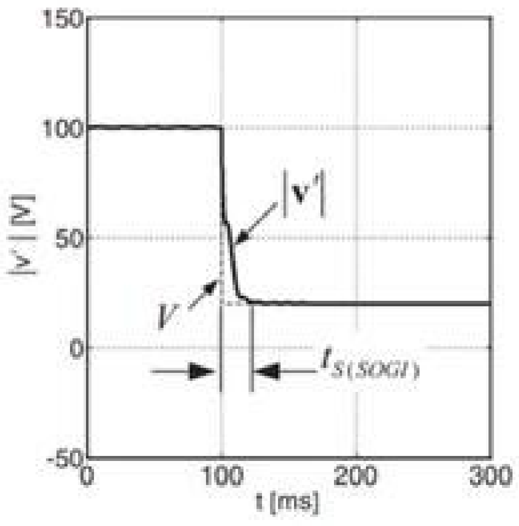
Grid Synchronization - PLLs based on adaptive filtering

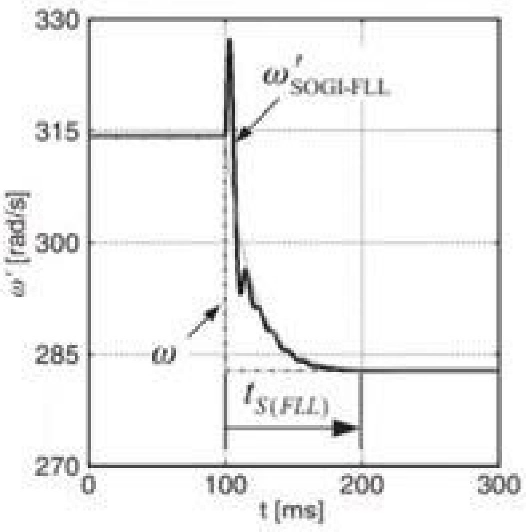
- SOGI-FLL
  - SOGI functions as QSG (in-quadrature signal generator)
  - Frequency Lock Loop
  - Magnitude and phase can be calculated from v and v' vectors

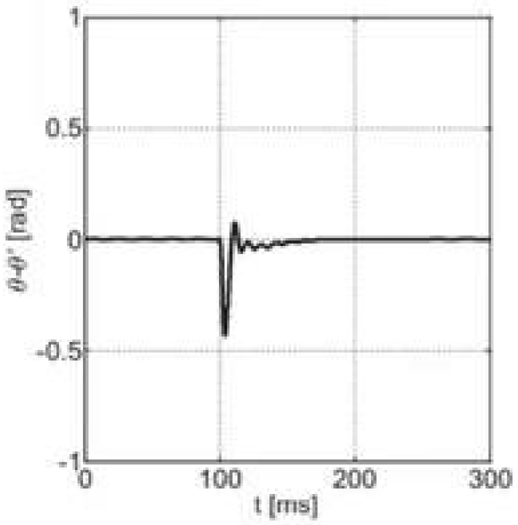


$$|\boldsymbol{v}'| = \sqrt{(v')^2 + (qv')^2}; \quad \underline{\boldsymbol{v}'} = \arctan\frac{qv'}{v'}$$



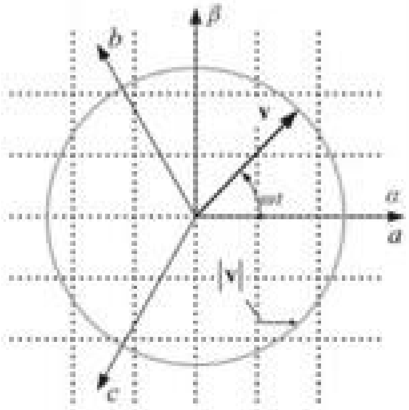






Grid Synchronization – Three-Phase Power Converters

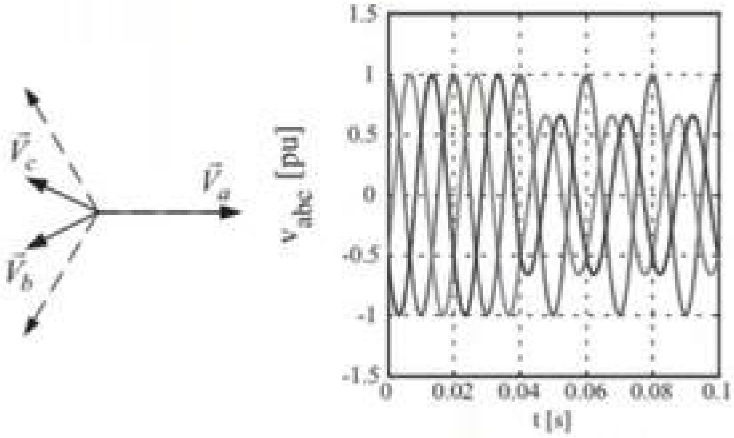
- 3-Phase PV inverter must synchronize and remain synchronized under
  - Balanced voltage conditions
  - Unbalanced voltage conditions
  - during voltage disturbances



$$\mathbf{v}_{abc} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V \begin{bmatrix} \cos(\omega t + \phi) \\ \cos(\omega t - \frac{2\pi}{3} + \phi) \\ \cos(\omega t + \frac{2\pi}{3} + \phi) \end{bmatrix}$$

$$|\mathbf{v}| = \sqrt{v_a^2 + v_b^2 + v_c^2} = \sqrt{\frac{3}{2}}V$$

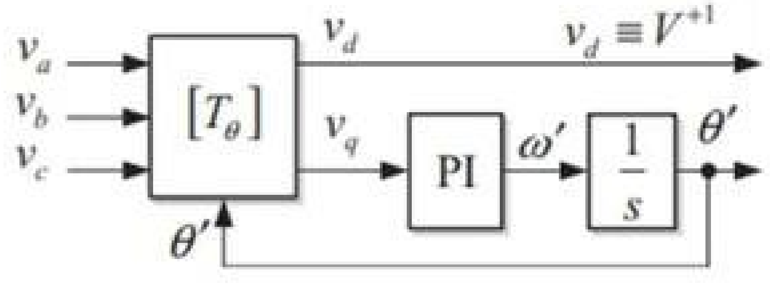
Balanced grid voltage

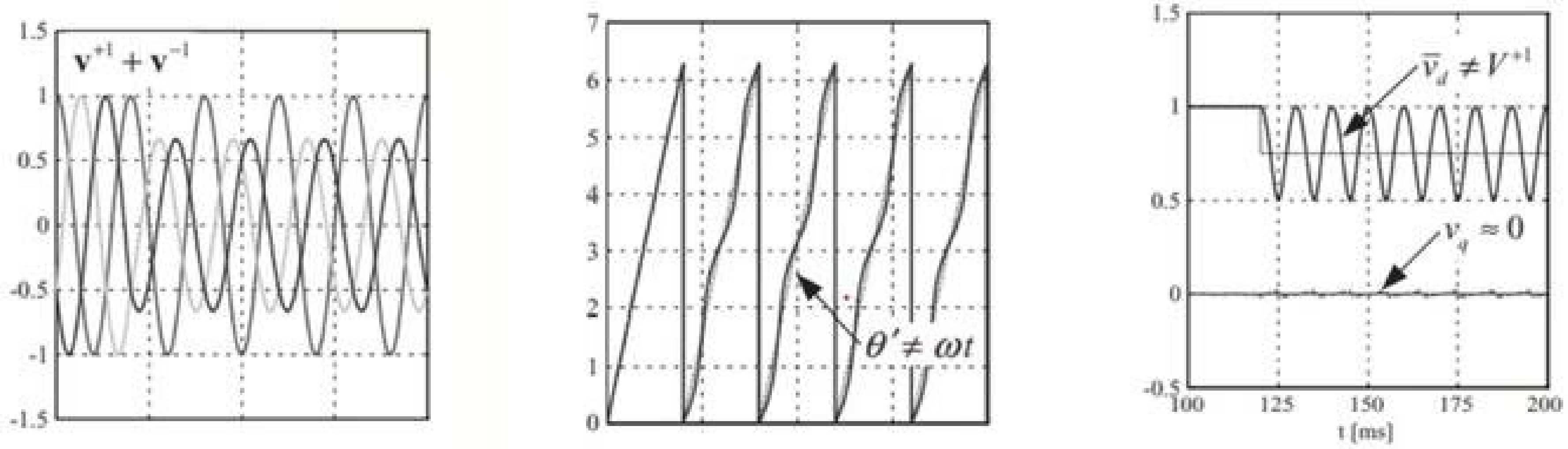


Type C Phase-to-phase fault

Grid Synchronization - Three-Phase Power Converters

- Synchronous Rotating Frame SRF-PLL
  - Magnitude and phase oscillations during unbalance
  - Not suitable for unbalance voltage conditions

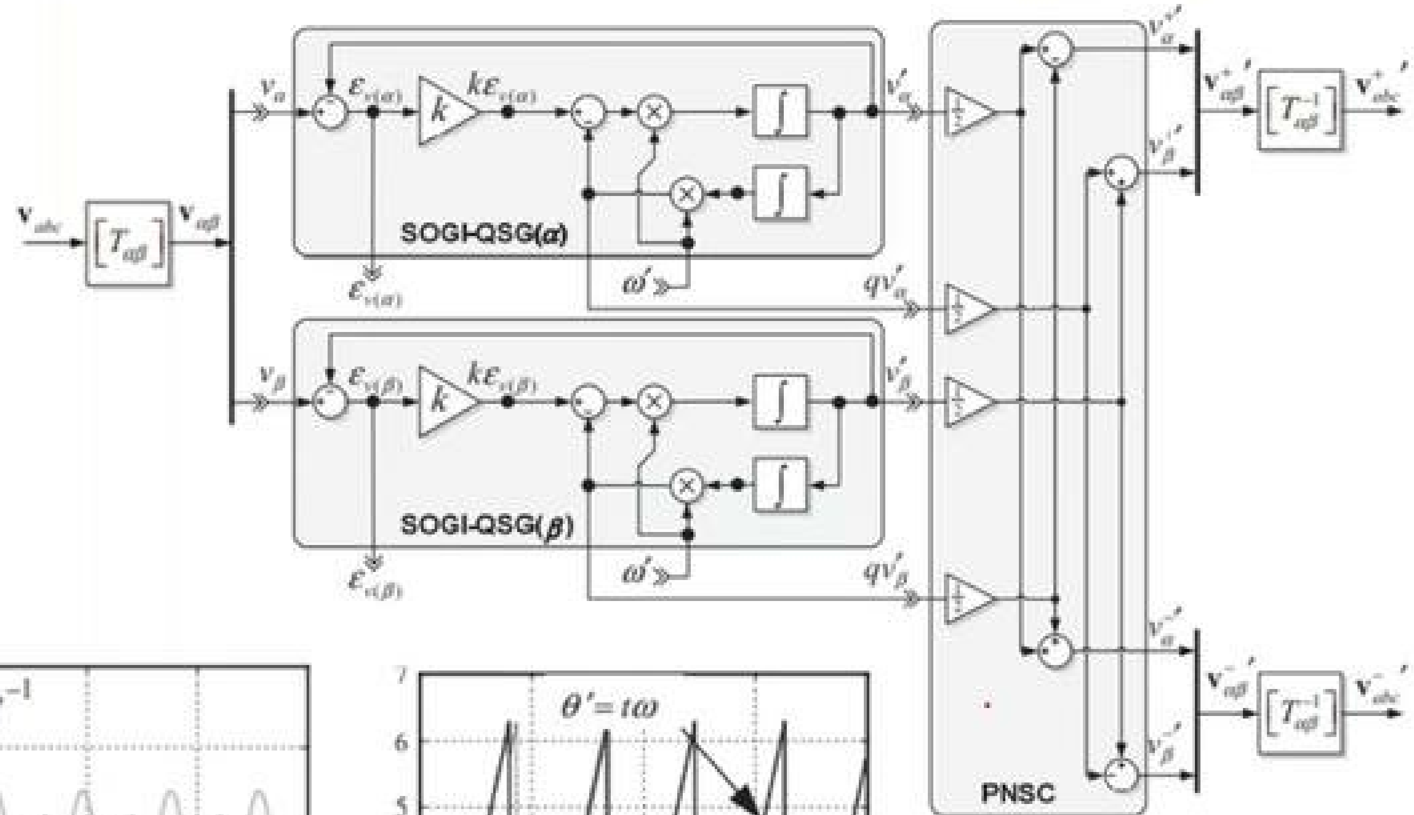




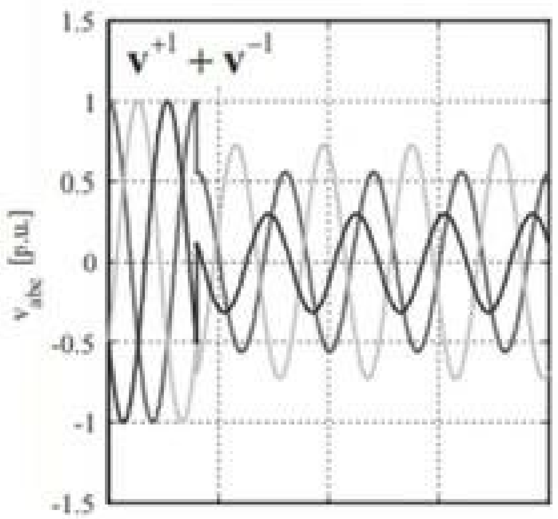
Grid Synchronization - Three-Phase Power Converters

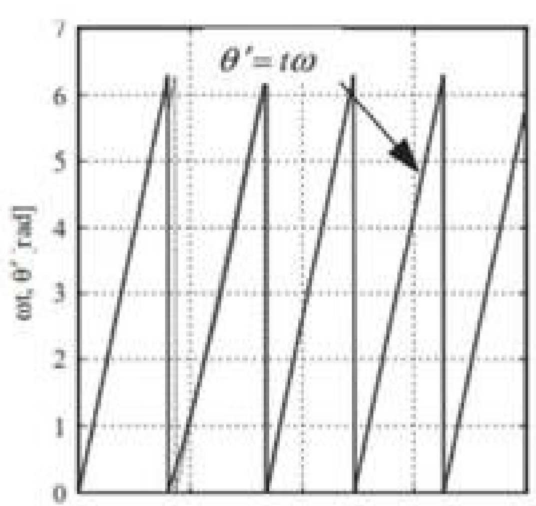
- Double SOGI -PLL
  - No oscillations of magnitude and phase during unbalance
  - Positive and Negative sequence magnitude and phase calculated from sequence vectors

$$|v'| = \sqrt{(v'_\alpha)^2 + (v'_\beta)^2}; \quad \theta' = \tan^{-1}\frac{v'_\beta}{v'_\alpha}$$



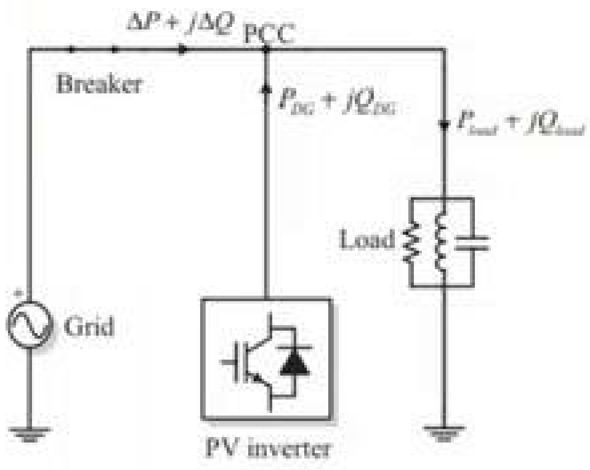
Positive Negative Sequence Calculation



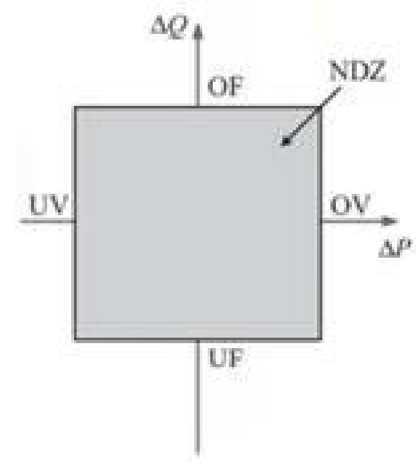


Islanding detection

- Anti-islanding protection
  - PV inverter should disconnect in case the main electric grid should cease to energize the distribution line
- NDZ – non-detection zone
- PV inverter must be immune to various grid disturbances
- According to EN 50160
  - fmin=49Hz and fmax=51Hz
  - Vmin=0.9 p.u. and Vmax=1.1 p.u.



$$P_{load} = P_{DG} + \Delta P$$
$$Q_{load} = Q_{DG} + \Delta Q$$



$$V' = KV$$

$$K = \sqrt{\frac{P_{DG}}{P_{load}}}$$

$$\omega' = \frac{-\frac{Q_{DG}}{CV'^2} + \sqrt{\left(\frac{Q_{DG}}{CV'^2}\right)^2 + \frac{4}{LC}}}{2}$$

Islanding detection

- Anti-islanding protection
  - PV inverter should disconnect in case the main electric grid should cease to energize the distribution line
- NDZ – non-detection zone
- PV inverter must be immune to various grid disturbances
- According to EN 50160
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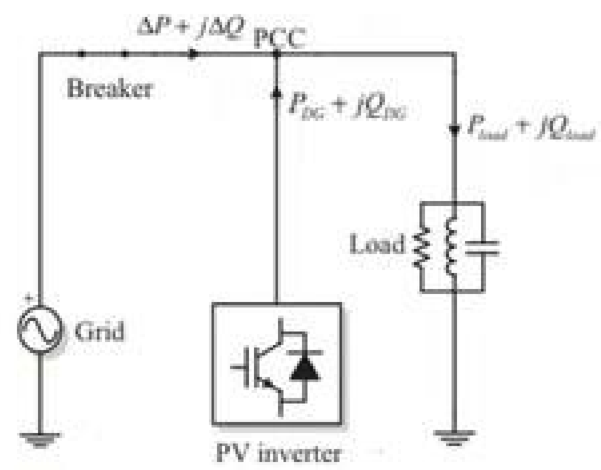

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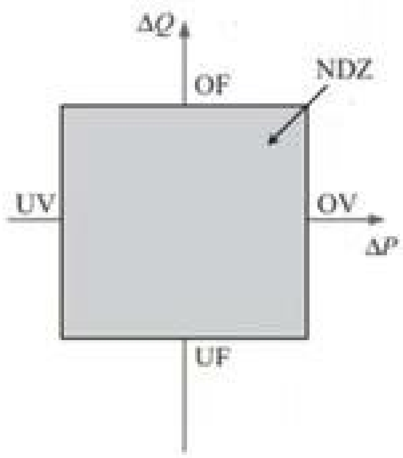

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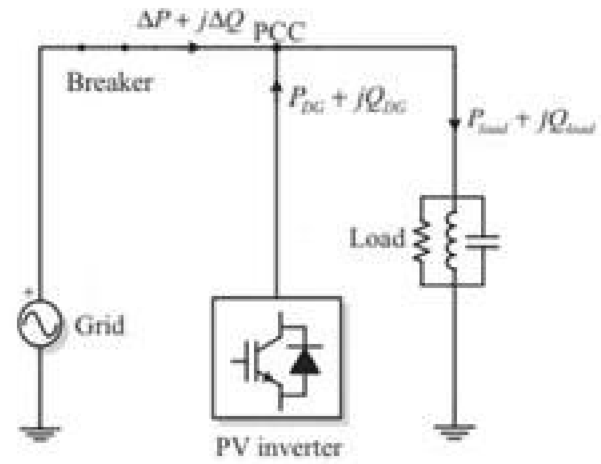

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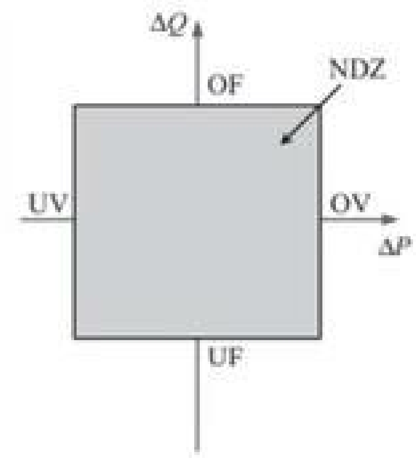

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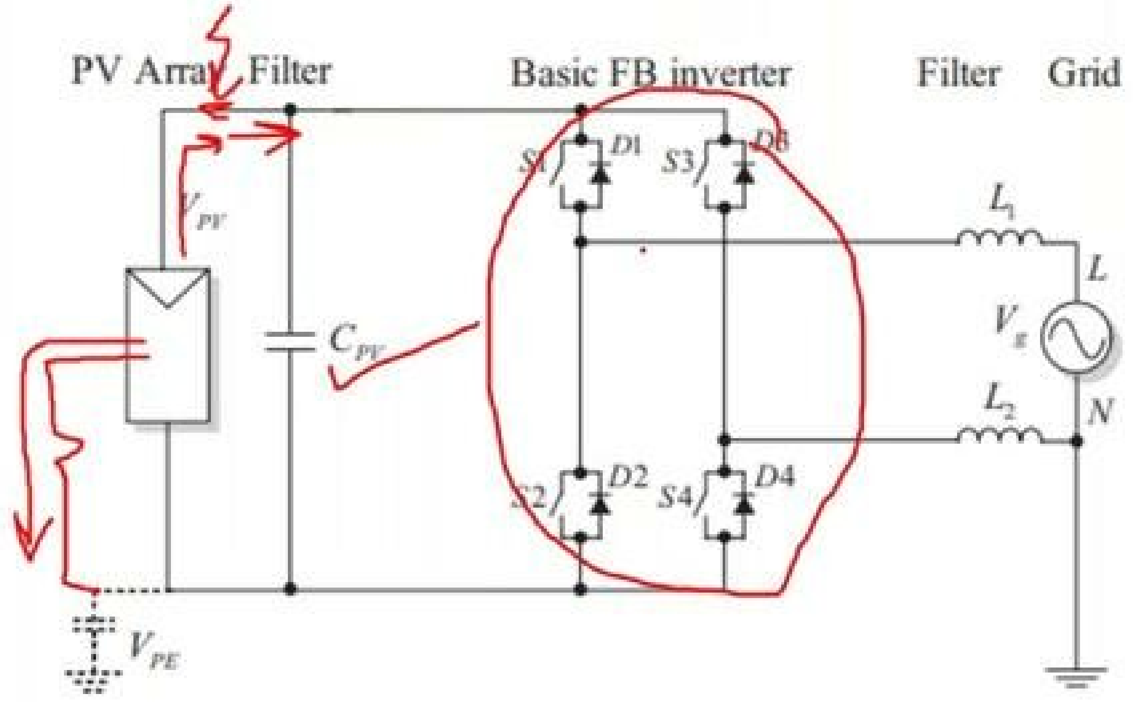
Single phase PV inverters

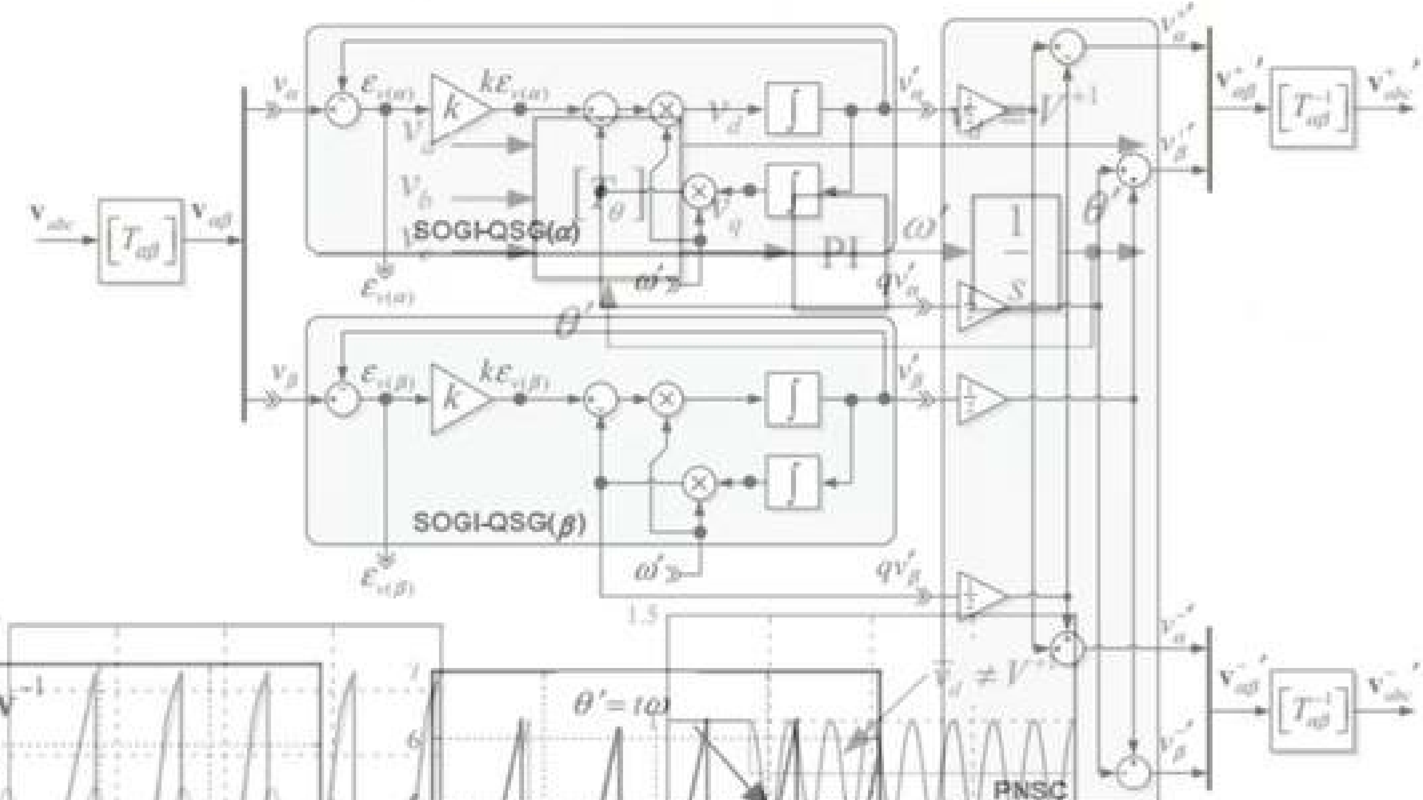
- Single phase H- Bridge topology
- Bipolar modulation
  - S1/S4 and S2/S3 diagonally switched
  - VPE has only a grid freq component ⇒ low leakage current and EMI
- Unipolar modulation
  - S1/S4 and S2/S3 high freq switching ⇒ high leakage current, not suitable for transformer less applications
- Voltage across the filter is bipolar
- Electrical efficiency up to 96.5%

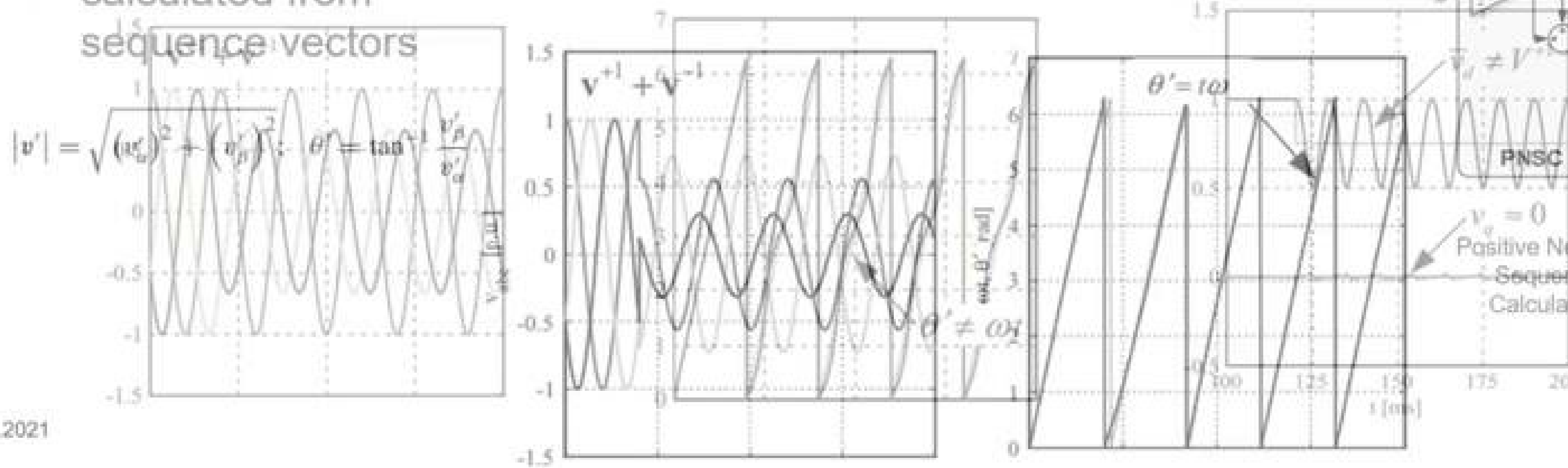


Grid Synchronization - Three-Phase Power Converters

- Double SOGI -PLL
  - No oscillations of magnitude and phase during unbalance
  - Positive and Negative sequence magnitude and phase calculated from sequence vectors

$$|v'| = \sqrt{(v'_\alpha)^2 + (v'_\beta)^2}; \quad \theta' = \tan^{-1}\frac{v'_\beta}{v'_\alpha}$$





Islanding detection methods

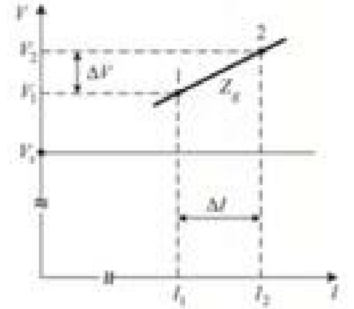
- Grid-resident detection
- External switched capacitor detection
- PV inverter-resident detection
  - Passive methods
    - Detection of a change of a power systems parameters (amplitude, frequency, phase, harmonics of the voltage)
  - Active methods
    - Generate a disturbance in order to force a change of power system parameters that can be detected by the passive method
    - May affect power quality and generate instability in the grid with high penetration of DERs

Islanding detection methods

- Passive methods
  - OverUnderFreq-OverUnderVoltage (OUF-OUV) detection
  - Phase Jump Detection (PJD)
    - due to reactive power mismatch prior or after disconnection
    - fast/slow PLL approach
  - Harmonic Detection (HD)
    - THD of most important harmonics (3^{rd}, 5^{th}, 7^{th} , 9^{th} ,11^{th}) be used as indicator
    - shortcomings
      - Connection/disconnection of nonlinear loads
      - No-load transformers – 3^{rd} harmonic
      - DER can increase voltage distortion.

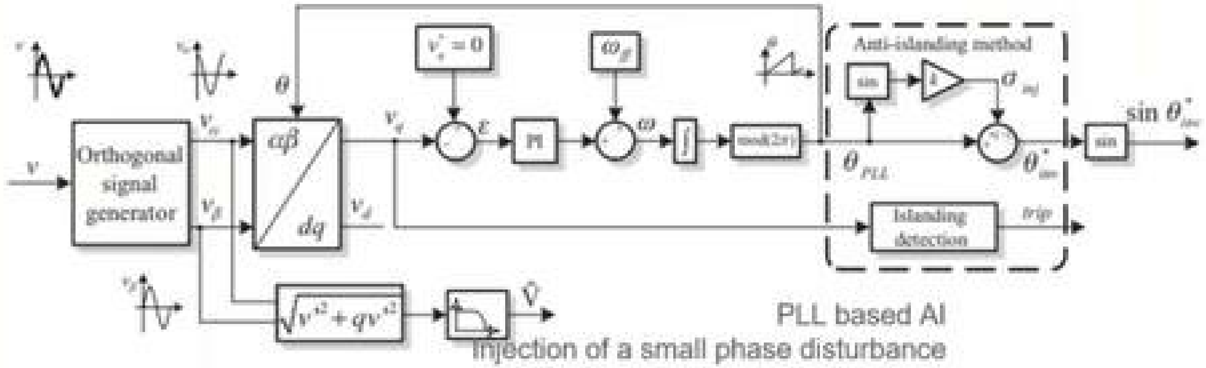
Islanding detection methods

- Active methods
  - Frequency drifts in order to activate OUF
    - Active Frequency drifts
    - Slip-Mode Frequency Shifts
    - Sandia Frequency Shifts…
  - Voltage drifts in order to activate OUV
  - Grid impedance detection
    - Harmonics Injection (HI) – injection of non-characteristic harmonic current and extraction of corresponding voltage harmonic
    - Active power variation
  - PLL based methods
  - Negative sequence detection



Islanding detection methods- PLLs based

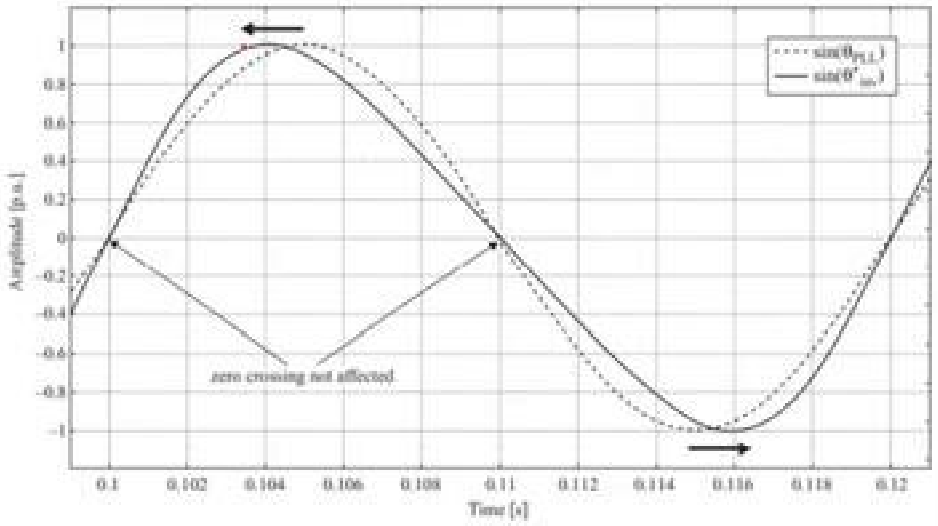
- PLL based AI
  - Injection of a small phase disturbance
  - Extraction of disturbance and trip



PLL based AI
Injection of a small phase disturbance

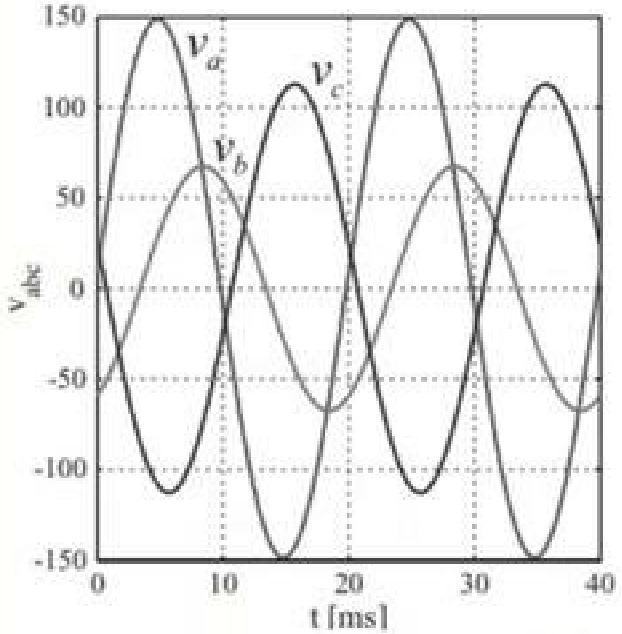
$$\sin\theta^*_{inv} = \sin(\theta_{PLL} + \sigma_{inj}) = \sin(\theta_{PLL} + k\sin\theta_{PLL})$$

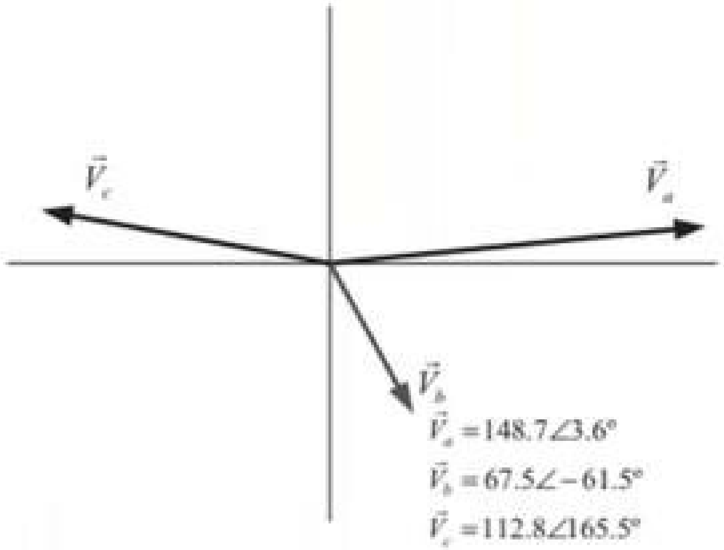
$$\sin\theta^*_{inv} = \sin\theta_{PLL} + \frac{k}{2}\sin 2\theta_{PLL}$$

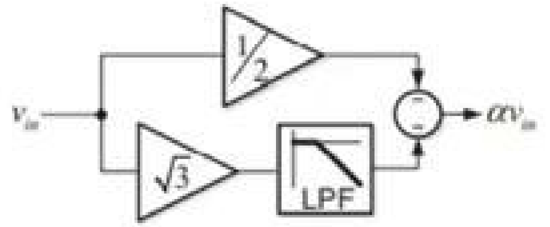


Space Vector Transformation of Three-Phase Systems

- Unbalanced three-phase system
  - Can be transferred into sequence phasors
  - $\alpha = e^{j\left(\frac{2\pi}{3}\right)}$ Fortescue operator







$$LPF(s) = \frac{\omega_{in}^2}{(s+\omega_{in})^2}$$

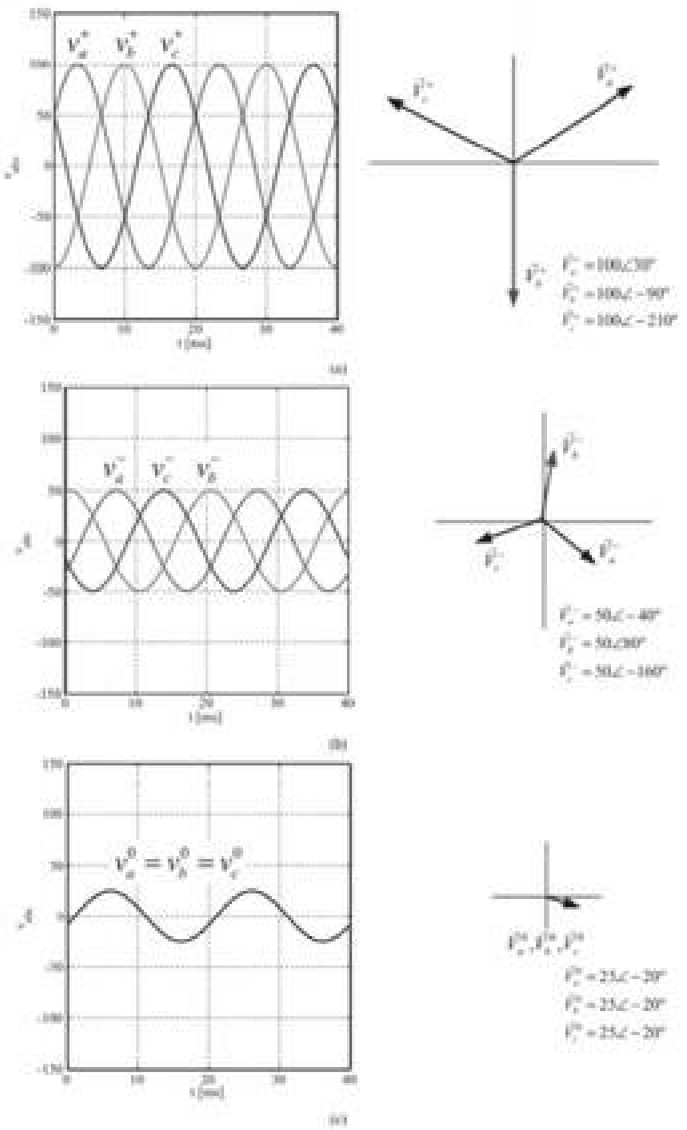
Space Vector Transformation of Three-Phase Systems

- Symmetrical components
  - Positive
  - Negative
  - Zero

$$\mathbf{V}_{+-0(a)} = [T_{+-0}]\,\mathbf{V}_{abc}$$

$$\mathbf{V}_{abc} = \begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} V_a\angle\theta_a \\ V_b\angle\theta_b \\ V_c\angle\theta_c \end{bmatrix} , \quad \mathbf{V}_{+-0(a)} = \begin{bmatrix} \vec{V}_a^{+} \\ \vec{V}_a^{-} \\ \vec{V}_a^{0} \end{bmatrix} = \begin{bmatrix} V_a^{+}\angle\theta_a^{+} \\ V_a^{-}\angle\theta_a^{-} \\ V_a^{0}\angle\theta_a^{0} \end{bmatrix}$$

$$[T_{+-0}] = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}$$



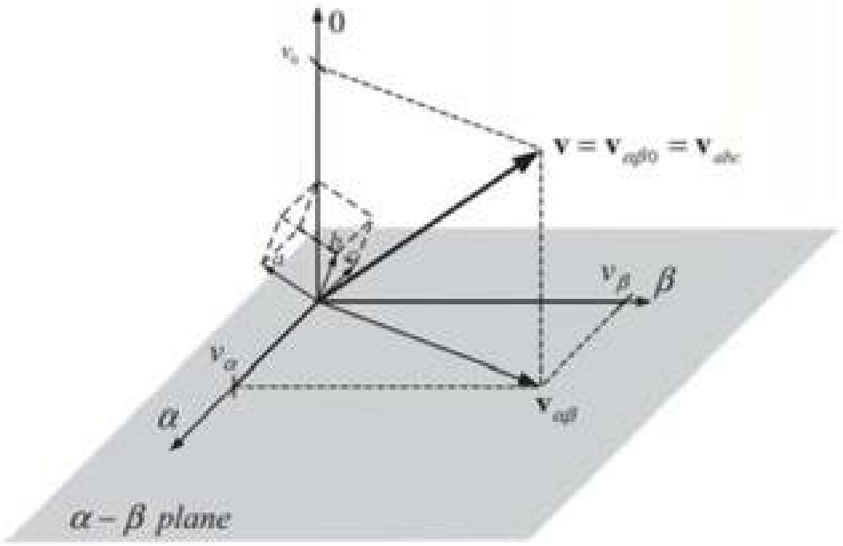
Space Vector Transformation of Three-Phase Systems

- Stationary αβ frame
  - 3-phase to 2-phase transformation

$$\boldsymbol{v}_{\alpha\beta 0} = \left[T_{\alpha\beta 0}\right] \boldsymbol{v}_{abc}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Clarke Transformation: Clarke, E., Circuit Analysis of AC Power Systems, Vol. 1, New York: John Wiley & Sons, Inc., 1950.



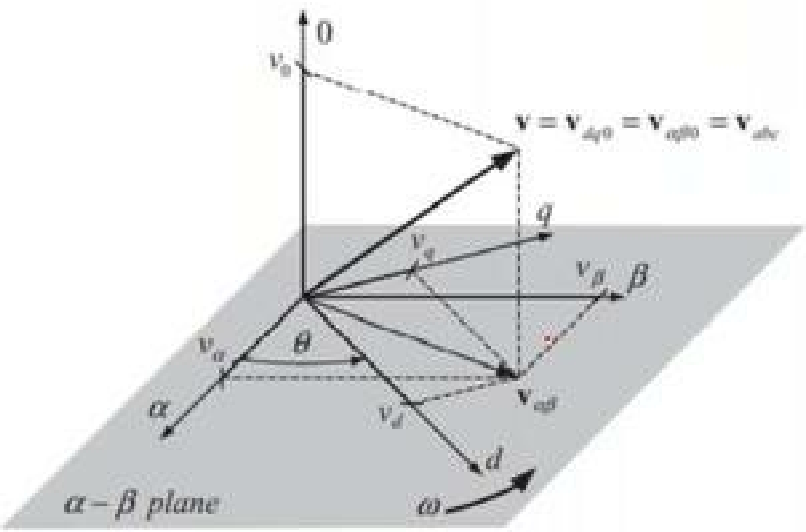
Graphical representation of the αβ0 reference frame

Space Vector Transformation of Three-Phase Systems

- Synchronous *dq0* frame
  - Transformation of vector rotating on the $\alpha\beta$ plane into synchronous dq0 plane rotating at frequency ω, which is placed at the $\theta=\omega t$ position on the $\alpha\beta$ plane

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix}$$

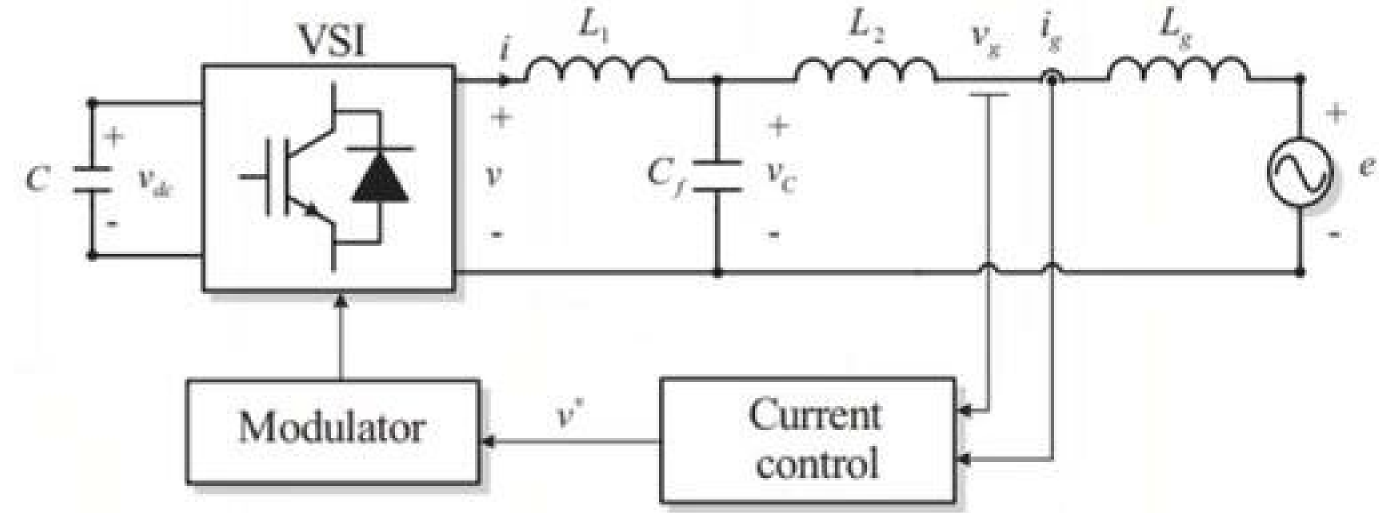
Park Transformation: Park, R. H., 'Two Reaction Theory of Synchronous Machines. Generalized Method of Analysis – Part I'. In Proceedings of the Winter Convention of the AIEE, 1929, pp. 716–730.



Graphical representation of the dq0 reference frame

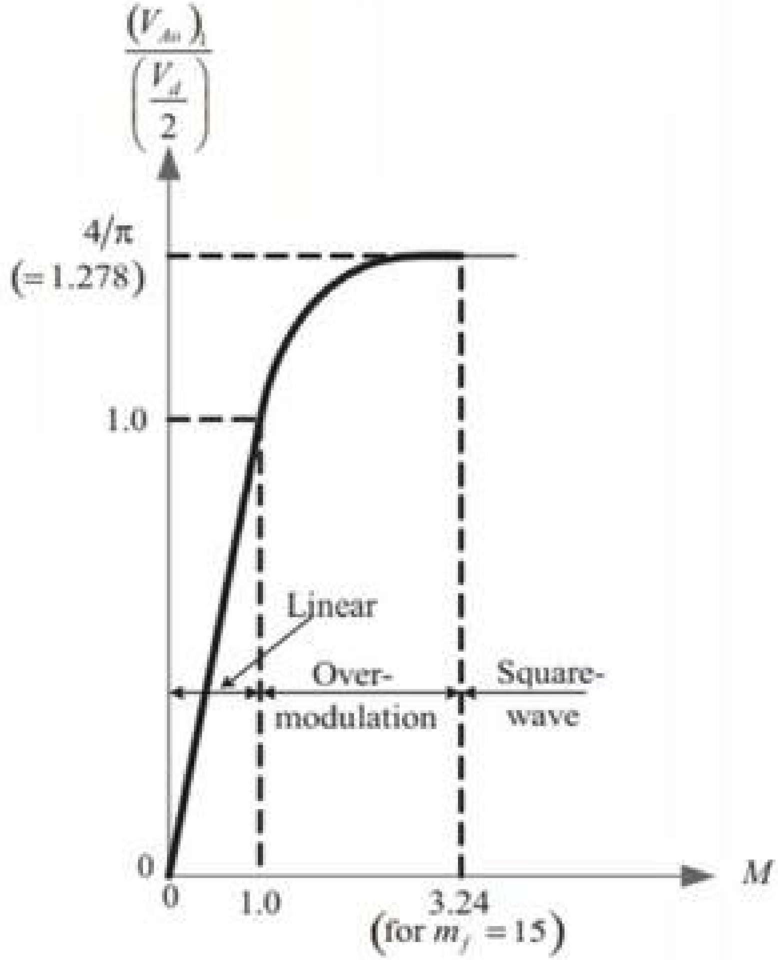
Grid Power Converter Control

- Typical Grid Power Converter Control block diagram
  - Modulator
  - Current control
  - DC bus voltage control



Grid Power Converter Control – Modulation Techniques

- Classification of Pulse Width Modulation techniques
  - Carrier-based – pulse widths are determined by comparing a modulating waveform and a triangle carrier
    - Modulation index M – the ration between amplitudes of modulating and carrier waves
    - Carrier index m – the ration between frequencies of the modulation and carrier waves
  - Space Vector Modulation (SVM) applicable to Three-Phase systems only
  - Objectives:
    - to obtain a lower harmonics distortion
    - reduce common mode currents
    - extend utilization of the DC bus (Three-Phase systems only)



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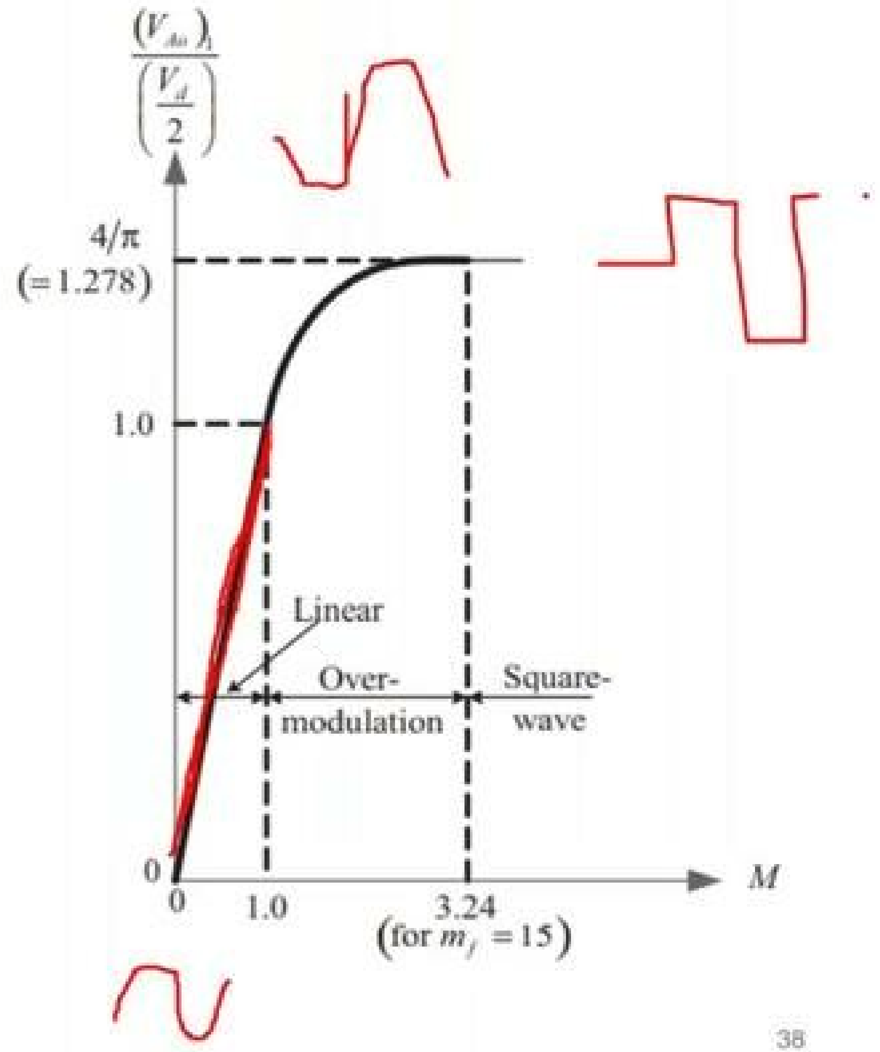
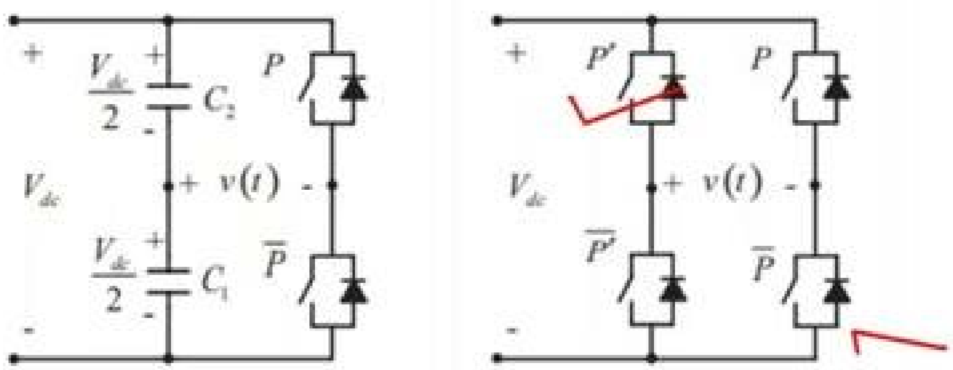


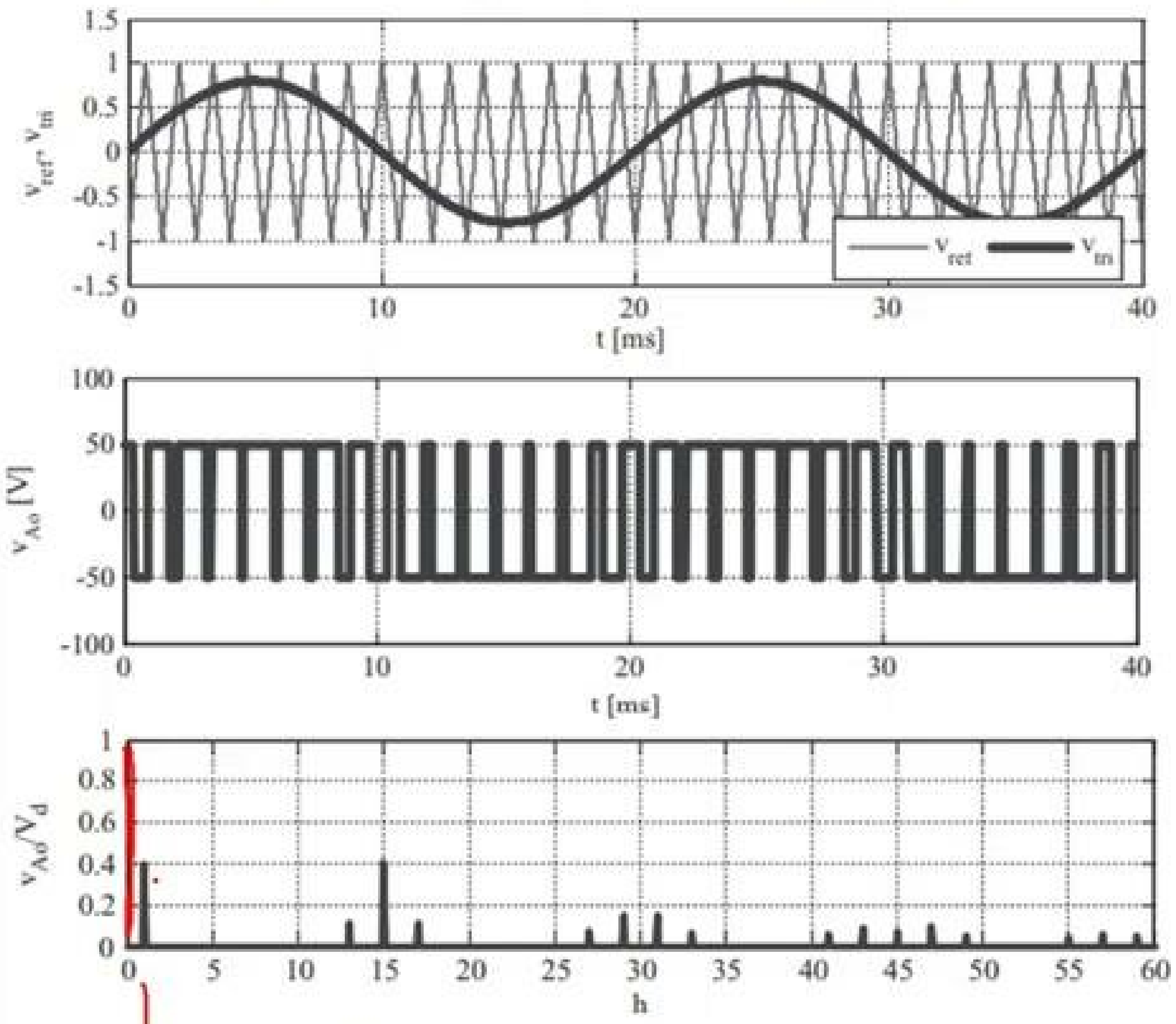
Grid Power Converter Control – Modulation Techniques

- Single Phase Carrier-based PWM modulation
  - Bipolar modulation



$$v(t) = \frac{4V_{dc}}{\pi}\sum_{\substack{m=0\\ m>0}}^{\infty}\sum_{\substack{n=1\\ n=-\infty}}^{\infty}\frac{1}{q}J_n\left(q\frac{\pi}{2}M\right)\sin\left([m+n]\frac{\pi}{2}\right)\cos\left(m\omega_c t + n\omega_0 t\right)$$

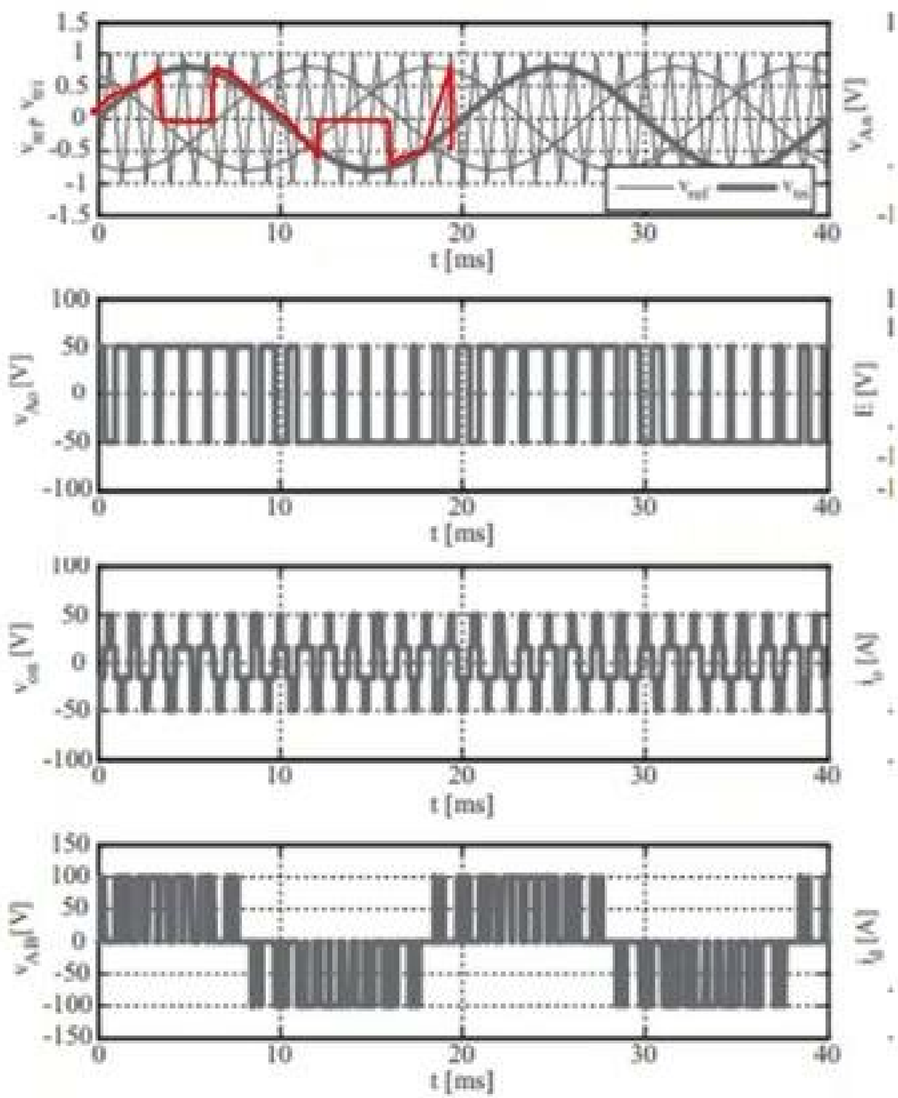
Jn – Bessel function of order n and q=m+n(ω_0/ω_c)



Single phase bipolar modulation

Grid Power Converter Control – Modulation Techniques

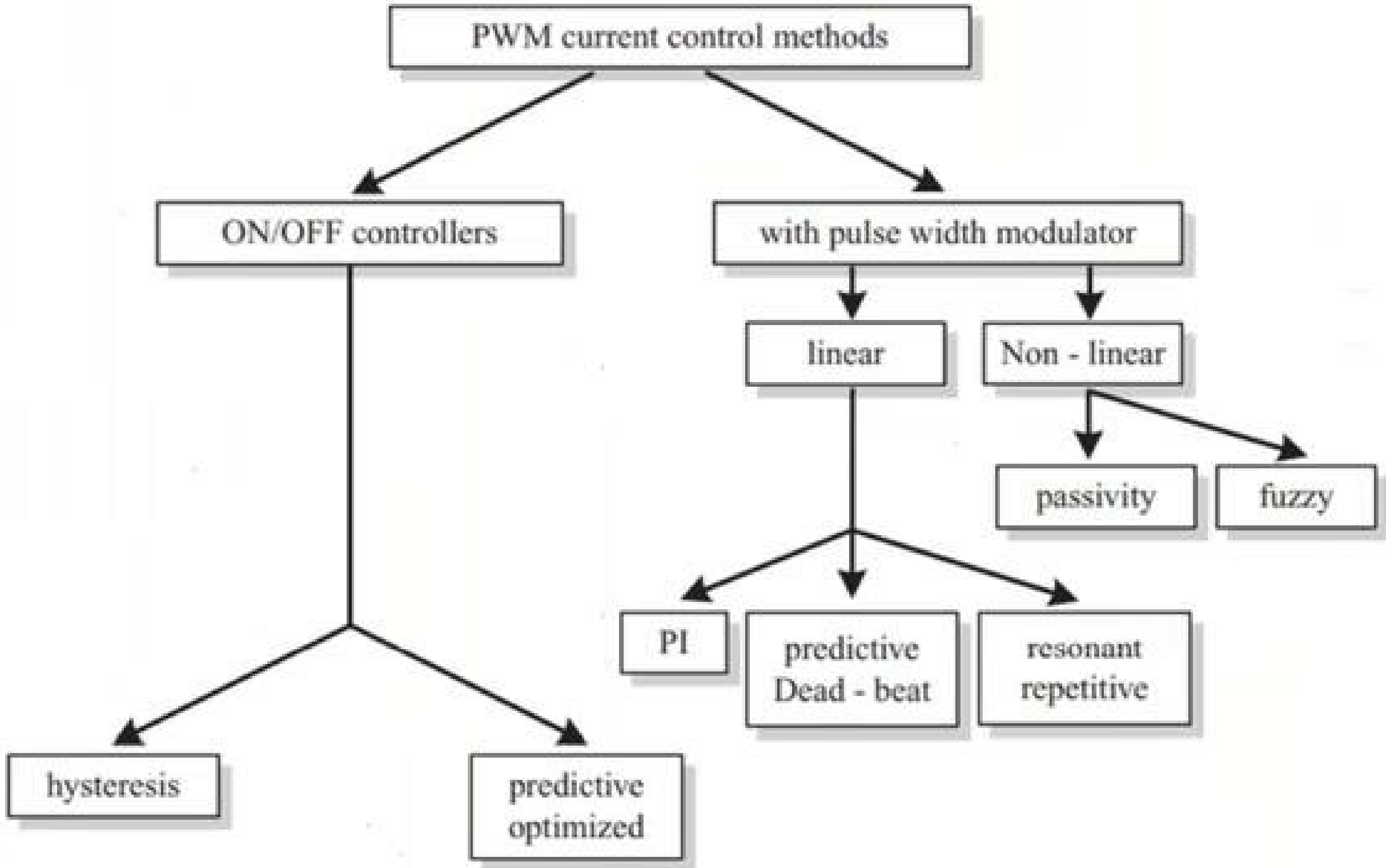
- Three Phase Carrier-based PWM modulation
  - Bipolar modulation
  - Increased linear modulation range by adding zero sequence signal into the modulating signal
  - No influence on the grid as Neutral is not connected
    - Sinusoidal with the third harmonic 17% (THIPWM)
    - Sinusoidal with triplen harmonics (subopt) – equivalent to SVPWM with symmetrical placement of the zero vectors in the sampling time
    - Discontinues PWM1, DPWM2 and DPWM10



Three phase sinusoidal modulation

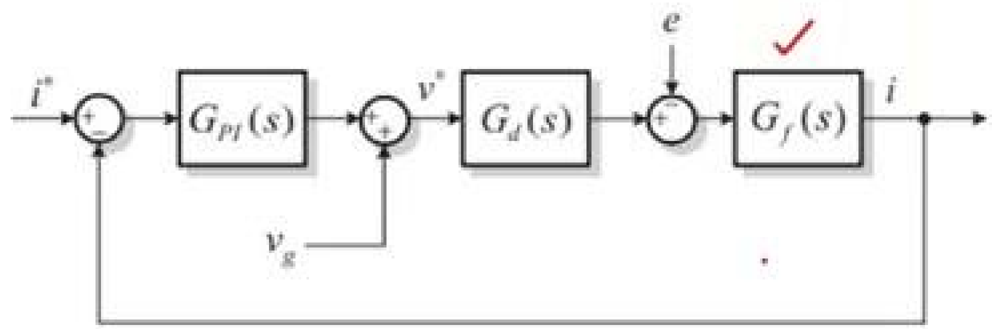
Grid Power Converter Control

- Classification of current control methods
  - PMW based PI and Resonant most prevailing



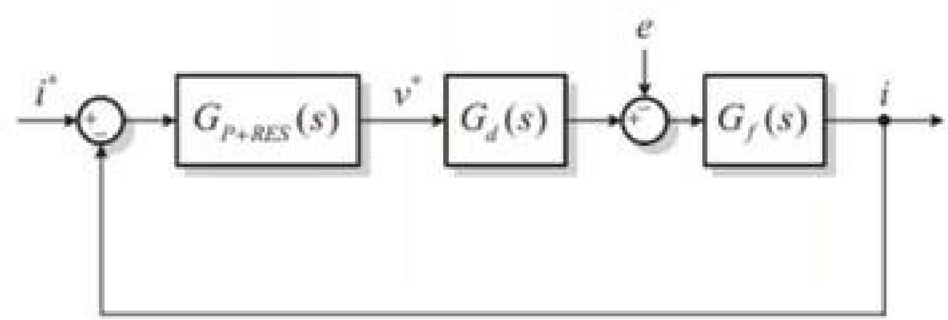
Grid Power Converter Control

- Current controller of a PI controller



$$G_f(s) = \frac{i(s)}{v(s)} = \frac{1}{R + Ls}$$

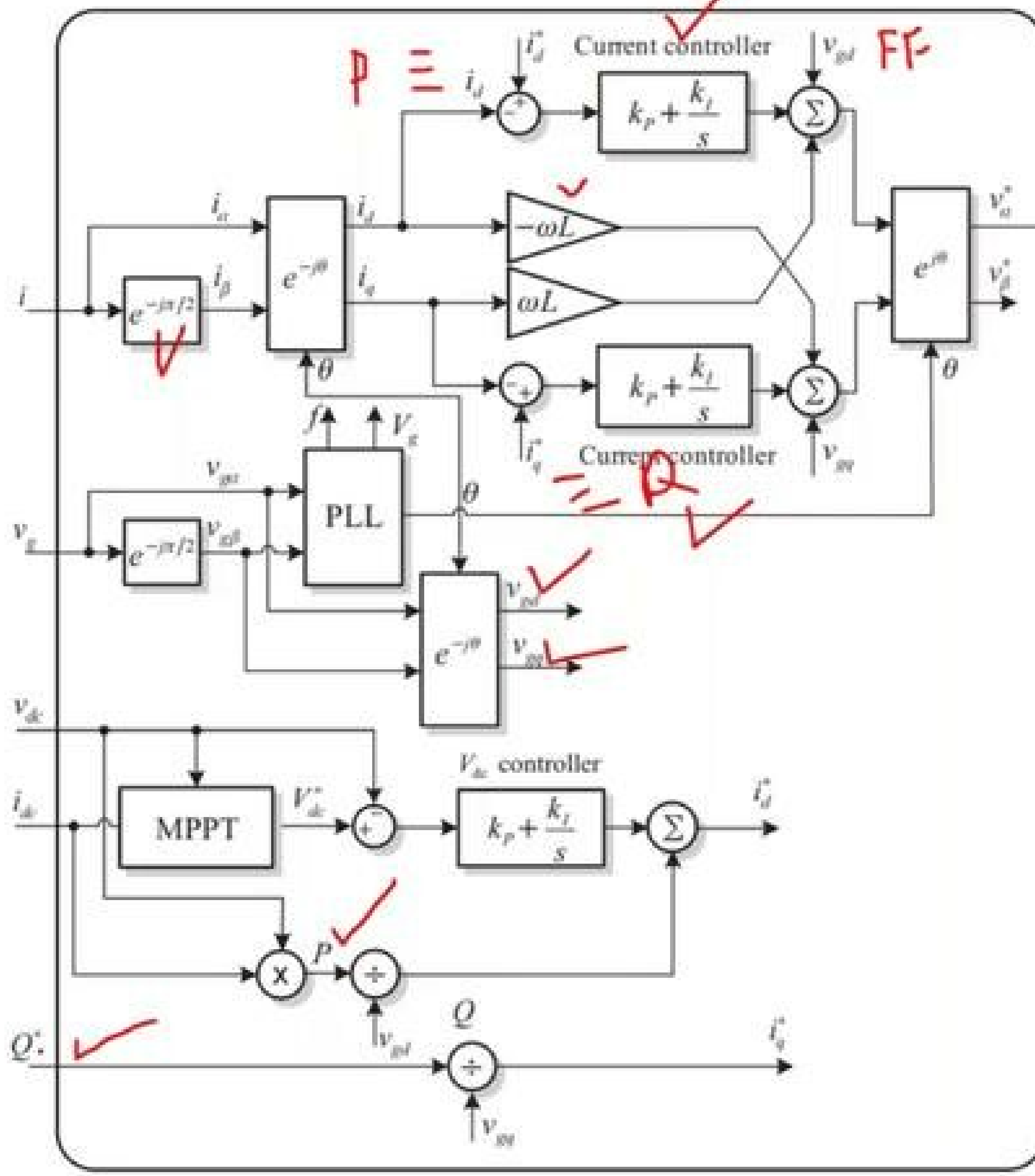
- Current controller of a P+resonant (PR) controller

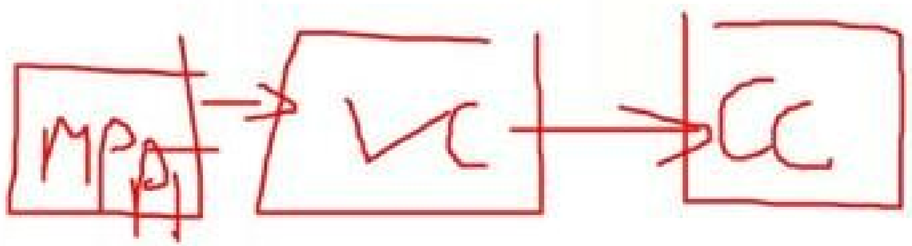


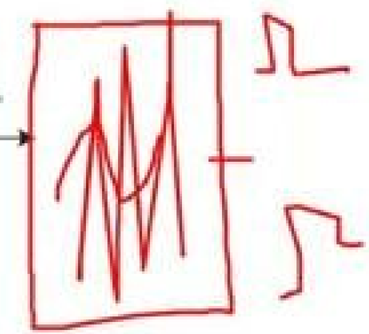
$$G_{AC}(s) = \frac{Y(s)}{E(s)} = \frac{2k_I\left(\omega_c s + \omega_c^2\right)}{s^2 + 2\omega_c s + \left(\omega_c^2 + \omega^2\right)} \approx \frac{2k_I\omega_c s}{s^2 + 2\omega_c s + \omega^2}$$

Grid Power Converter Control

- Single-Phase Synchronous PI dq current control
  - With Vdc controller and MPPT

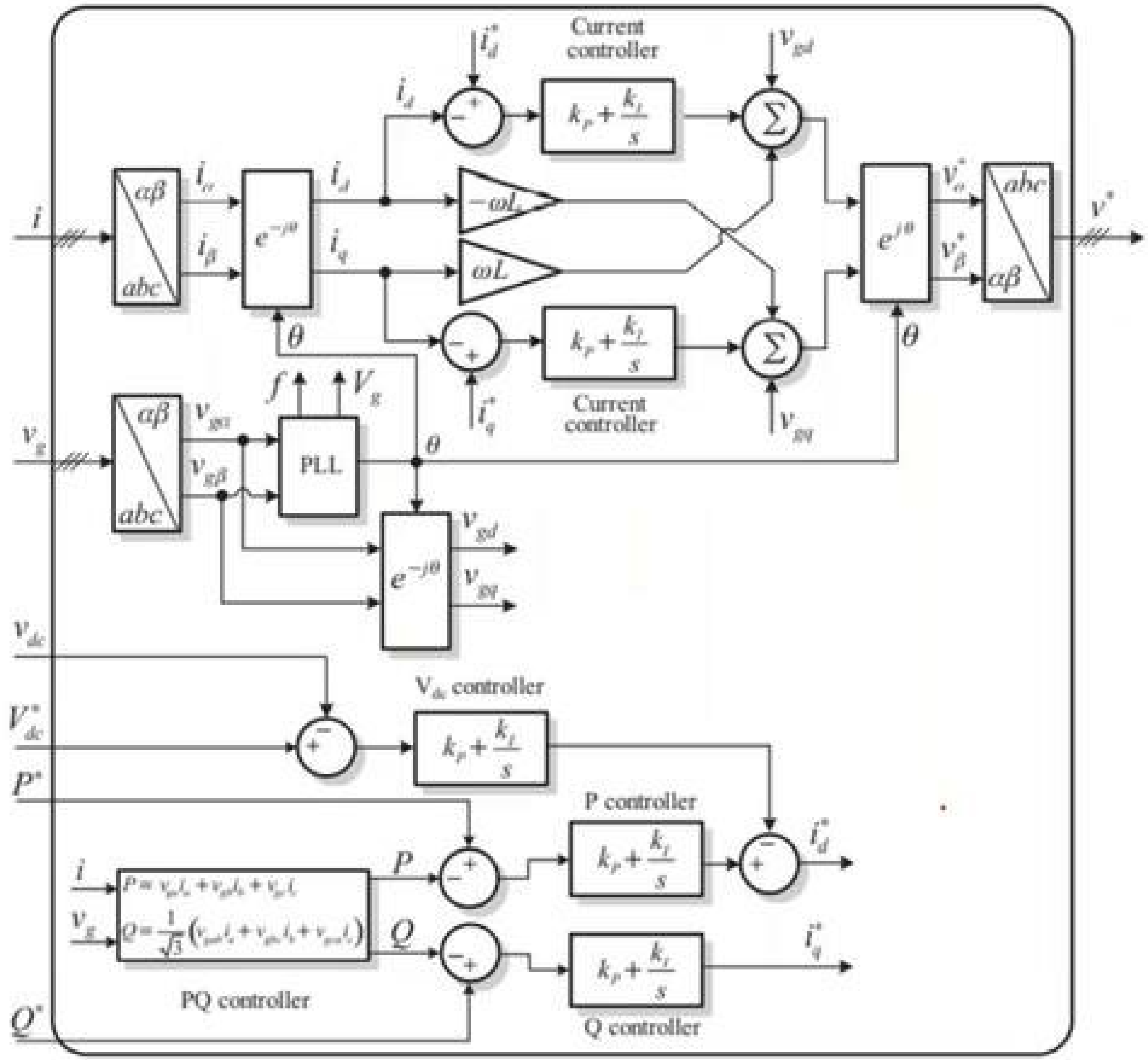






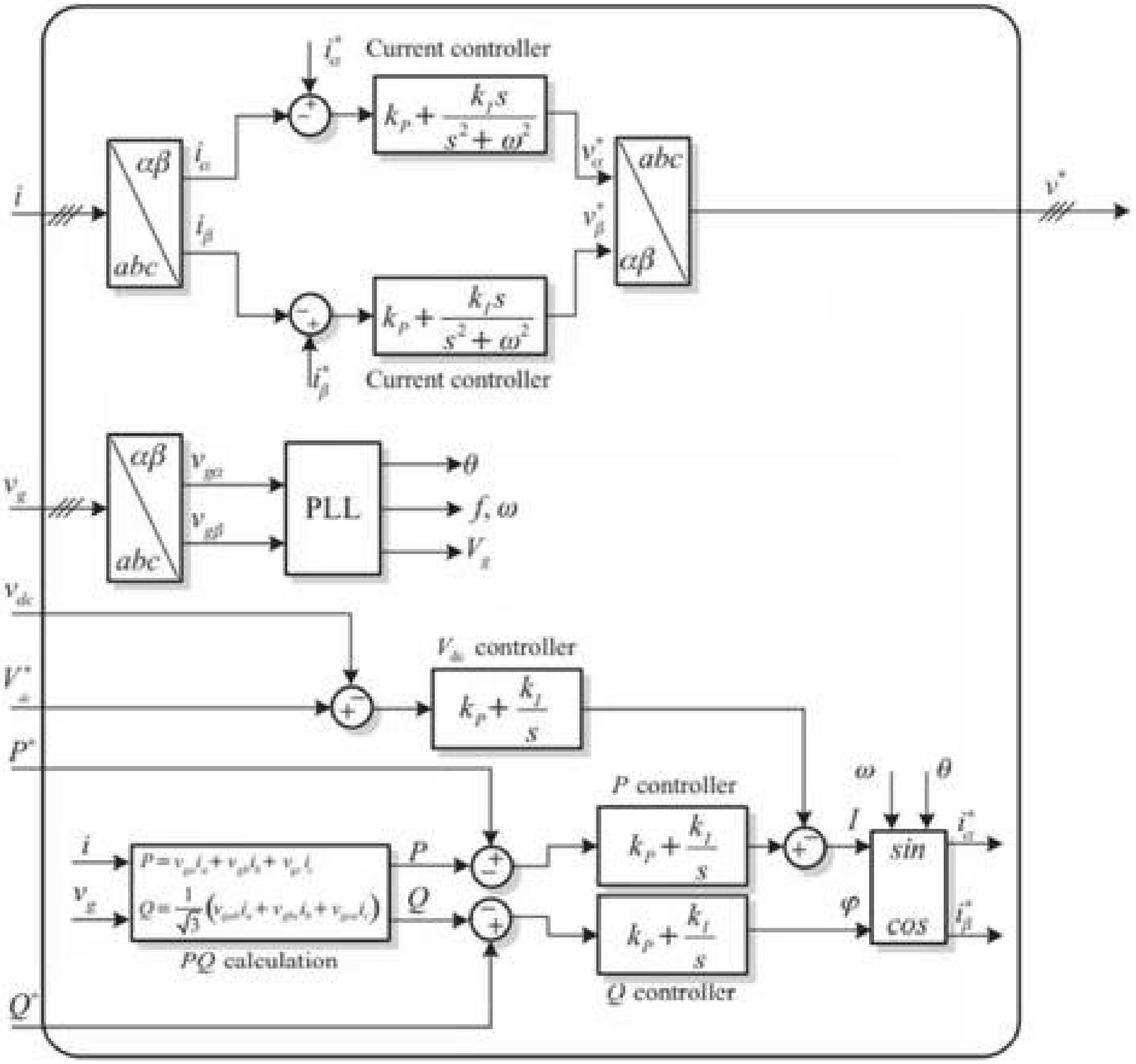
Grid Power Converter Control

- Three-Phase Synchronous PI dq current control



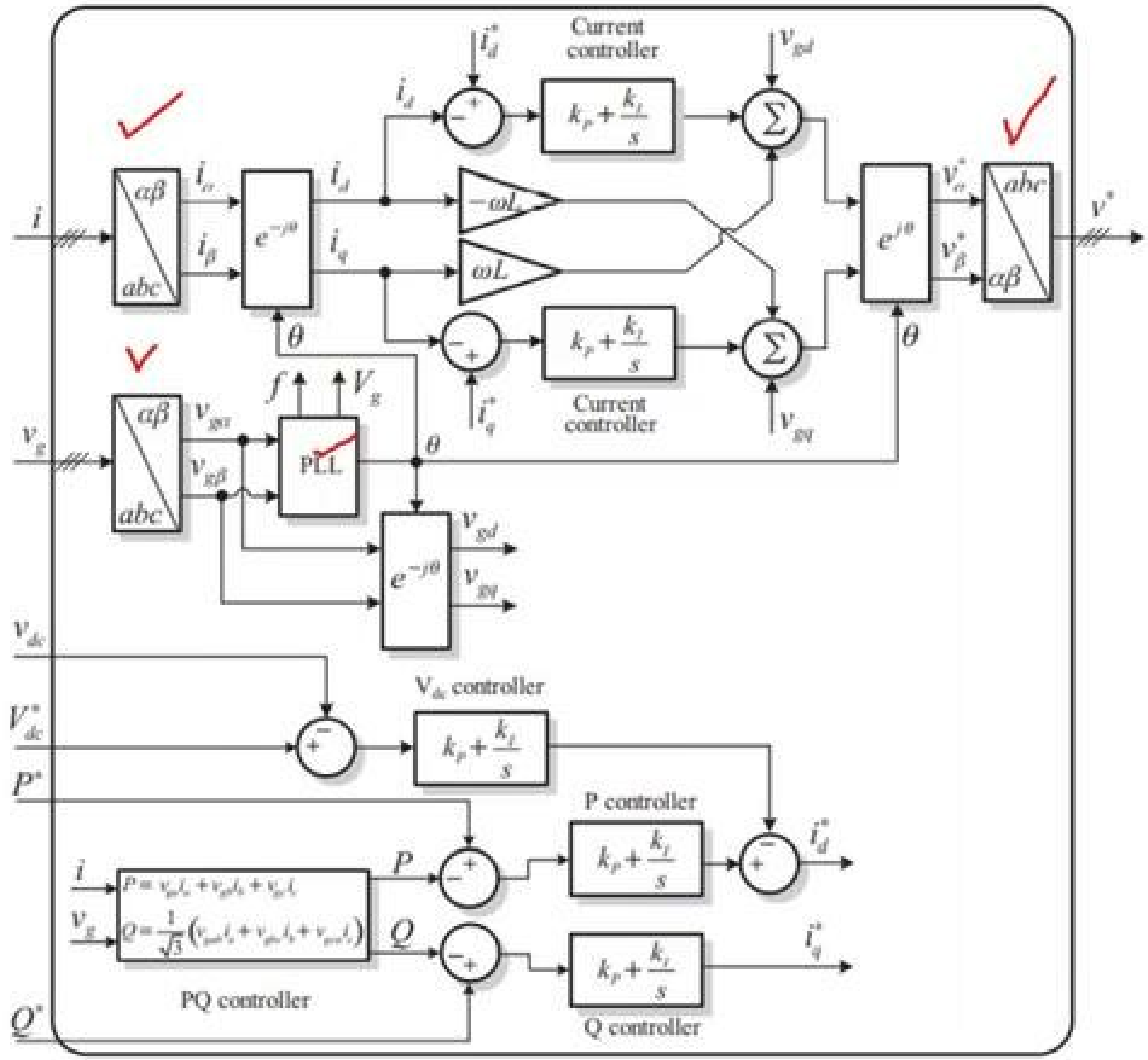
Grid Power Converter Control

- Stationary PR $\alpha\beta$ current control for three phase grid power converter



Grid Power Converter Control

- Three-Phase Synchronous PI dq current control



Literature

- GRID CONVERTERS FOR PHOTOVOLTAIC AND WIND POWER SYSTEMS Grid Converters for Photovoltaic and Wind Power Systems Remus Teodorescu, Marco Liserre and Pedro Rodríguez © 2011 John Wiley & Sons, Ltd. ISBN: 978-0-470-05751-3
- Holmes, D. G. and Lipo, T., Pulse Width Modulation for Power Converters, Principles and Practice, New York: IEEE Press, 2003