

EE-465 - W10

MPPT

PQ THEORY

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So far, we have covered:

- ▶ Converter modeling for the purpose of control
- ▶ PI and PR regulators in s- and z-domain
- ▶ Tuning methods

To establish connection between PV source and grid, we need to consider:

- ▶ Maximum Power Point Tracking (MPPT) algorithm
- ▶ PQ definitions in different reference frames
- ▶ DC link voltage controller for 2-level 3-phase VSI

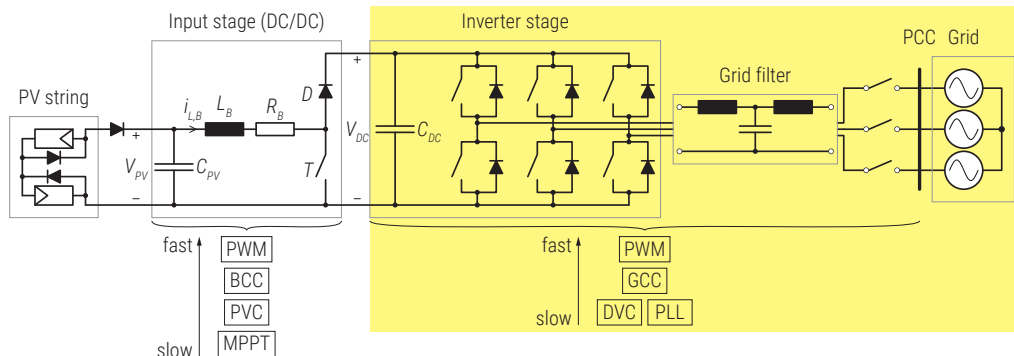


Figure 1 PV double-stage grid connected converter.

MPPT

Maximizing power extraction from the renewable energy source...

MAXIMUM POWER POINT TRACKING - MPPT

MPPT algorithm tasks is:

- ▶ to determine the panel operating voltage that allows maximum power output
- ▶ this may not be always easy, especially in case of large number of PV panels connected to single MPPT controller
- ▶ we will consider simple case of a small PV panel cluster connected to our converters
- ▶ PV panel output is not constant and it depends on irradiation, temperature and load

Avoiding to use MPPT controller with PV panels, may results in:

- ▶ wasted power, since PV panels are not utilized efficiently
- ▶ costly installation, since more panels would have to be installed to get desired power out

As the PV panel output voltage is typically low, several structures are used: central inverter, string inverter, module (micro) inverter

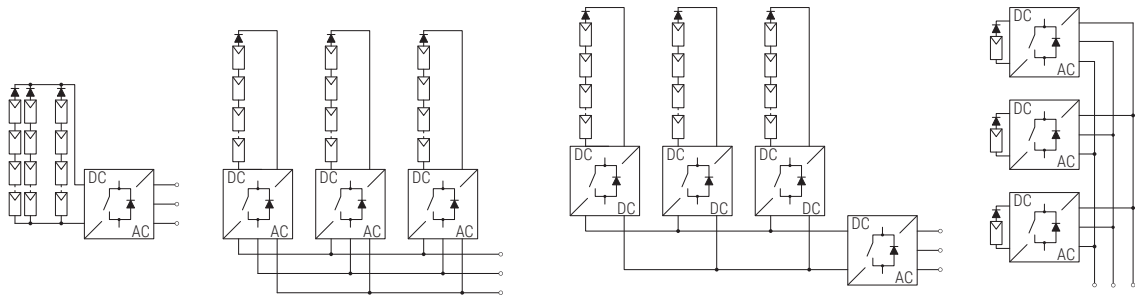


Figure 2 PV structures (from left to right): central inverter, string inverter (with AC and DC bus) and module (micro) inverter.

PV PANEL CHARACTERISTICS

PV panel output characteristic is influenced with:

- ▶ Irradiation - output current increases with higher irradiation - I-V characteristic up-shift
- ▶ Temperature - open circuit voltage increases with lower temperatures - I-V characteristic right-shift

Typical PV panel shows:

- ▶ v_{OC} - open circuit voltage (the maximum panel output voltage when no power is drawn)
- ▶ i_{SC} - short circuit current (the maximum panel output current)

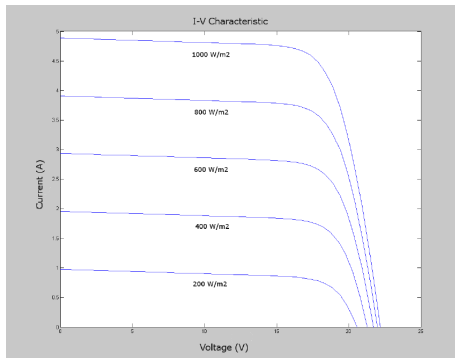


Figure 3 PV panel I-V characteristic under different irradiation.

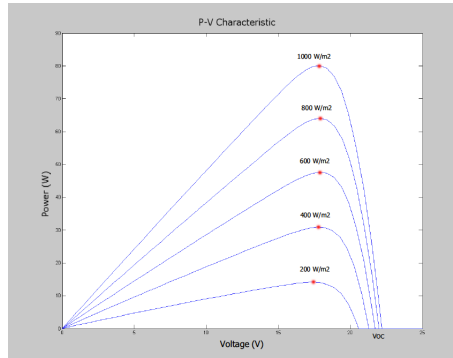


Figure 4 PV panel P-V characteristics.

MPPT - PERTURB AND OBSERVE

Perturb and Observe algorithm is relatively simple method for implementation:

- ▶ perturbation is introduced in the panel operating voltage: v_{PV}
- ▶ power is calculated after perturbation: $P_{PV}(kT_s)$
- ▶ and compared with power before perturbation: $P_{PV}(kT_s - T_s)$
- ▶ based on this voltage v_{PV} is adjusted accordingly to reach MPP
- ▶ decreasing voltage while on the right side of MPP, increases output power
- ▶ increasing voltage while on the left side of MPP, increases output power
- ▶ once MPP is reached, algorithm oscillates around MPP value

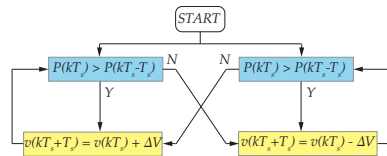


Figure 5 MPPT - Perturb and Observe Algorithm

For Perturb and Observe algorithm, panel output voltage and current must be measured

- ▶ fixed voltage step Δv_{PV} can be used to increase or decrease voltage
- ▶ size of voltage step determines the size of oscillation around MPP
- ▶ smaller voltage step reduce oscillations, but slow down tracking
- ▶ bigger voltage steps speed up tracking, but increase oscillations (power loss)

PV output power is compared considering different instants in time:

$$v_{PV}(kT_s)i_{PV}(kT_s) = P_{PV}(kT_s) \Leftrightarrow P_{PV}(kT_s - T_s) = v_{PV}(kT_s - T_s)i_{PV}(kT_s - T_s)$$

Sampling frequency for MPPT algorithm will be rather low, compared to other control parts

MPPT - INCREMENTAL CONDUCTANCE

Incremental Conductance algorithm use the facts that power curve derivative is:

$$\frac{dP_{PV}}{dv_{PV}} = 0 \Rightarrow \text{at MPP} \Rightarrow \frac{\Delta i_{PV}}{\Delta v_{PV}} = -\frac{i_{PV}}{v_{PV}}$$

$$\frac{dP_{PV}}{dv_{PV}} > 0 \Rightarrow \text{left of MPP} \Rightarrow \frac{\Delta i_{PV}}{\Delta v_{PV}} > -\frac{i_{PV}}{v_{PV}}$$

$$\frac{dP_{PV}}{dv_{PV}} < 0 \Rightarrow \text{right of MPP} \Rightarrow \frac{\Delta i_{PV}}{\Delta v_{PV}} < -\frac{i_{PV}}{v_{PV}}$$

The power derivative can be expressed as:

$$\frac{dP_{PV}}{dv_{PV}} = \frac{di_{PV}v_{PV}}{dv_{PV}} = i_{PV} \frac{dv_{PV}}{dv_{PV}} + v_{PV} \frac{di_{PV}}{dv_{PV}} = i_{PV} + v_{PV} \frac{di_{PV}}{dv_{PV}}$$

$$i_{PV} + v_{PV} \frac{di_{PV}}{dv_{PV}} \approx i_{PV} + v_{PV} \frac{\Delta i_{PV}}{\Delta v_{PV}}$$

We compare the incremental conductance $\frac{\Delta i_{PV}}{\Delta v_{PV}}$ with instantaneous conductance $\frac{i_{PV}}{v_{PV}}$

Depending on the results, v_{PV} is either increased or decreased until MPP is reached

Once MPP is reached, Incremental Conductance algorithm stops modifying v_{PV}

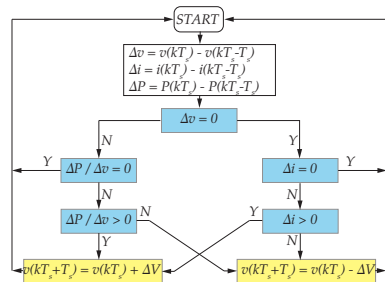


Figure 6 MPPT - Incremental Conductance Algorithm

- ▶ $\Delta v_{PV}(kT_s) = v_{PV}(kT_s) - v_{PV}(kT_s - T_s)$
- ▶ $\Delta i_{PV}(kT_s) = i_{PV}(kT_s) - i_{PV}(kT_s - T_s)$
- ▶ $\Delta P_{PV}(kT_s) = P_{PV}(kT_s) - P_{PV}(kT_s - T_s)$

SEQUENCE DECOMPOSITION

Dealing with unbalanced grid conditions

SYMMETRICAL COMPONENTS (I)

To analyse unbalanced polyphase networks, *Fortescue* has proposed *method of symmetrical components*

Steady-state phasors of an unbalanced (3-phase) system can be decomposed into:

- ▶ Positive-sequence components
- ▶ Negative-sequence components
- ▶ Zero-sequence components

For an unbalanced 3-phase system, different sequence phasors of phase a can be calculated as:

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

where steady-state phasors and transformation matrix T are (*Fortescue* operator is $\alpha = e^{j2\pi/3} = 1 \angle 120^\circ$):

$$\mathbf{V}_{abc} = \begin{bmatrix} \underline{V}_a \\ \underline{V}_b \\ \underline{V}_c \end{bmatrix} = \begin{bmatrix} \underline{V}_a \angle \phi_a \\ \underline{V}_b \angle \phi_b \\ \underline{V}_c \angle \phi_c \end{bmatrix}, \quad \mathbf{V}_{(a)+-0} = \begin{bmatrix} \underline{V}_{a+} \\ \underline{V}_{a-} \\ \underline{V}_{a0} \end{bmatrix} = \begin{bmatrix} \underline{V}_a \angle \phi_{a+} \\ \underline{V}_a \angle \phi_{a-} \\ \underline{V}_a \angle \phi_{a0} \end{bmatrix}, \quad [T_{+-0}] = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}$$

The phasor sequence components for phases b and c are:

$$\begin{aligned} \underline{V}_{b+} &= \alpha^2 \underline{V}_{a+}; & \underline{V}_{b-} &= \alpha \underline{V}_{a-} \\ \underline{V}_{c+} &= \alpha \underline{V}_{a+}; & \underline{V}_{c-} &= \alpha^2 \underline{V}_{a-} \end{aligned}$$

Inverse Transformation T^{-1} (phase a as example) is:

$$\mathbf{V}_{abc} = [T_{+-0}]^{-1} \mathbf{V}_{(a)+-0}, \quad [T_{+-0}]^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}$$

SYMMETRICAL COMPONENTS (II)

Example: Application of Fortescue transformation on an unbalanced 3-phase system:

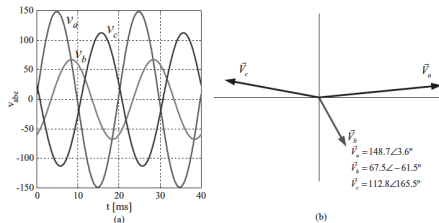


Figure 7 Unbalanced 3-phase system: a) instantaneous voltage waveforms; b) phase voltage phasors

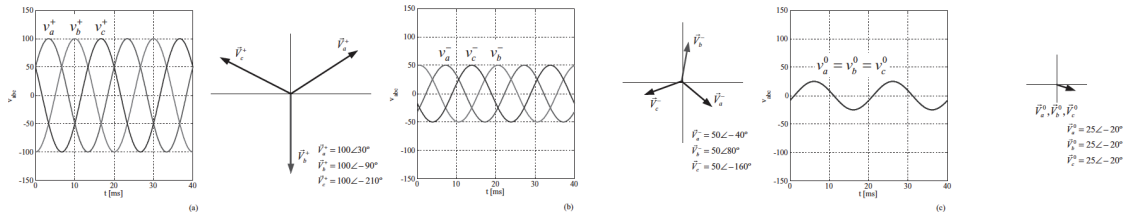


Figure 8 Sequence components of unbalanced 3-phase system: a) positive-sequence phasors; b) negative-sequence phasors; c) zero-sequence phasors

SYMMETRICAL COMPONENTS IN TIME DOMAIN (I)

Fortescue work has been extended by Lyon and applied in time domain:

$$v_{abc} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = v_{abc}^+ + v_{abc}^- + v_{abc}^0 = V^+ \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t - 2\pi/3) \\ \cos(\omega t + 2\pi/3) \end{bmatrix} + V^- \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t + 2\pi/3) \\ \cos(\omega t - 2\pi/3) \end{bmatrix} + V^0 \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t) \\ \cos(\omega t) \end{bmatrix}$$

Application of Fortescue transformation to above signals gives instantaneous values as:

$$v_{+-0} = [T_{+-0}] v_{abc} \Rightarrow v_{+-0} = \begin{bmatrix} \underline{v}^+ \\ \underline{v}^- \\ v^0 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} V^+ e^{j\omega t} + \frac{1}{2} V^- e^{-j\omega t} \\ \frac{1}{2} V^+ e^{-j\omega t} + \frac{1}{2} V^- e^{j\omega t} \\ V^0 \cos(\omega t) \end{bmatrix}$$

Normally, Lyon Transformation considers different scaling ratio:

$$[T'_{+-0}] = \sqrt{3} [T_{+-0}] = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}$$

Resulting vectors can be characterized as:

- ▶ two complex elements \underline{v}^+ and \underline{v}^- and one real element v^0
- ▶ \underline{v}^+ and \underline{v}^- can be understood as two space vectors of the same amplitude rotating in opposite direction
- ▶ \underline{v}^+ and \underline{v}^- should not be mistaken or confused with positive- and negative-zero sequence voltage vectors v_{abc}^+ and v_{abc}^-
- ▶ the real element v^0 is directly related to zero-sequence component of original 3-phase voltage vector

SYMMETRICAL COMPONENTS IN TIME DOMAIN (II)

To calculate positive- and negative-sequence voltage vectors v_{abc}^+ and v_{abc}^- :

- ▶ operator α must be translated from the frequency domain to time domain
- ▶ for a well known frequency of sinusoidal signal this is performed by time-shifting
- ▶ $\alpha = -1/2 + j\sqrt{3}/2$ and 90° phase shifting is required to mimic operator j
- ▶ this can be done using second-order low-pass filter

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

Filter is tuned to the input frequency $\omega_m = 2\pi f$, and damping factor is $\xi = 1$

Operator α^2 is realized by multiplying LPF output signal by -1

Instantaneous positive- and negative-sequences of v_{abc} can be calculated as:

$$v_{abc}^+ = [T_+] v_{abc} \Rightarrow \begin{bmatrix} v_a^+ \\ v_b^+ \\ v_c^+ \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ \alpha^2 & 1 & \alpha \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$v_{abc}^- = [T_-] v_{abc} \Rightarrow \begin{bmatrix} v_a^- \\ v_b^- \\ v_c^- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha^2 & \alpha \\ \alpha & 1 & \alpha^2 \\ \alpha^2 & \alpha & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$



Figure 9 α -operator PLECS implementation, $K_a = 0.5$, $K_b = \sqrt{3}$, $\omega = 2\pi f$.

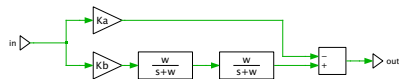


Figure 10 α^2 -operator PLECS implementation, $K_a = 0.5$, $K_b = \sqrt{3}$, $\omega = 2\pi f$.

COMPONENTS $\alpha\beta 0$ IN THE STATIONARY REFERENCE FRAME

Complex components \underline{v}^+ and \underline{v}^- :

- ▶ are not independent from each other
- ▶ three independent real components can be found among the elements
- ▶ a possible set can be defined as $[\Re(\underline{v}^+), \Im(\underline{v}^+), v^0]$, while other combinations are also possible

Real transformation matrix can be defined as:

$$\begin{bmatrix} \Re(\underline{v}^+) \\ \Im(\underline{v}^+) \\ v^0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \Re(\alpha) & \Re(\alpha^2) \\ 0 & \Im(\alpha) & \Im(\alpha^2) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Similar proposal was made by *Clarke* $[T_{\alpha\beta 0}]^{-1} = [T_{\alpha\beta 0}]^T$:

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

Scaling factor will define relation between powers in abc and $\alpha\beta 0$ frames

CLARKE TRANSFORMATION - SCALING

Depending on the objectives Clarke Transform scaling can be adjusted accordingly:

Power Invariant form - $K = \sqrt{\frac{2}{3}}$

Amplitudes are not the same in abc and $\alpha\beta 0$ frames

$$|v_{\alpha\beta 0}| = \sqrt{\frac{3}{2}} v_{abc}^{peak}, \quad |i_{\alpha\beta 0}| = \sqrt{\frac{3}{2}} i_{abc}^{peak}$$

Powers are identical in abc and $\alpha\beta 0$ frames

$$P_{\alpha\beta 0} = P_{abc}$$

Clarke Transform form is:

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

Power Non-Invariant form - $K = \frac{2}{3}$

Amplitudes are the same in abc and $\alpha\beta 0$ frames

$$|v_{\alpha\beta 0}| = v_{abc}^{peak}, \quad |i_{\alpha\beta 0}| = i_{abc}^{peak}$$

Powers are not identical in abc and $\alpha\beta 0$ frames

$$P_{\alpha\beta 0} = \frac{2}{3} P_{abc}$$

Clarke Transform form is:

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

COMPONENTS $dq0$ IN THE ROTATIONAL REFERENCE FRAME

Any voltage vector rotating on the $\alpha\beta$ plane can be expressed on a rotational dq reference frame using Park Transform:

The transformation matrix ($[T_{dq0}]^{-1} = [T_{dq0}]^T$) is defined as:

$$v_{dq0} = [T_{dq0}] v_{\alpha\beta 0}$$

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

We can combine Clarke and Park Transform ($[T_\theta]^{-1} = [T_\theta]^T$) and obtain directly:

$$v_{dq0} = [T_\theta] v_{abc}$$

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin(\theta) & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Again, used scaling factor will result in powers being identical in abc and $dq0$ frames

For balanced 3-phase system, we will not consider zero-sequence part

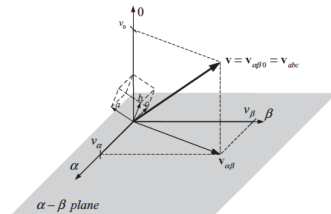


Figure 11 Graphical representation of the $\alpha\beta 0$ plane.

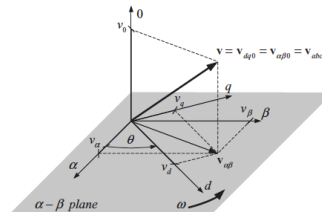


Figure 12 Graphical representation of the $dq0$ plane.

INSTANTANEOUS POWER THEORY

Active and Reactive powers in different reference frames

THE P-Q THEORY (I)

While there are several definitions for *powers*, we will consider instantaneous power theory (*Akagi*)

For a given phase-to-neutral voltage and currents in *abc* domain, we can apply Clarke Transform:

$$v_{\alpha\beta 0} = [T_{\alpha\beta 0}] v_{abc}, \quad i_{\alpha\beta 0} = [T_{\alpha\beta 0}] i_{abc}$$

where: $v_{\alpha\beta 0} = [v_{\alpha}, v_{\beta}, v_0]^T$ and $i_{\alpha\beta 0} = [i_{\alpha}, i_{\beta}, i_0]^T$

The following instantaneous power are defined in $\alpha\beta 0$ frame as:

$$\begin{bmatrix} p_{\alpha\beta} \\ q_{\alpha\beta} \\ p_0 \end{bmatrix} = [M_{\alpha\beta 0}] i_{\alpha\beta 0}, \quad \Rightarrow \quad [M_{\alpha\beta 0}] = \begin{bmatrix} v_{\alpha} & v_{\beta} & 0 \\ -v_{\beta} & v_{\alpha} & 0 \\ 0 & 0 & v_0 \end{bmatrix}$$

Terms are defined as:

- ▶ $p_{\alpha\beta} = v_{\alpha}i_{\alpha} + v_{\beta}i_{\beta}$ - instantaneous real power (*instantaneous active power*)
- ▶ $q_{\alpha\beta} = v_{\alpha}i_{\beta} - v_{\beta}i_{\alpha}$ - instantaneous imaginary power (*instantaneous reactive power*)
- ▶ $p_0 = v_0i_0$ - instantaneous zero-sequence power

The addition of $p_{\alpha\beta}$ and p_0 gives instantaneous active power delivered collectively by 3-phases of a system

$$p_{3-phase} = p_{\alpha\beta} + p_0 = v_{\alpha}i_{\alpha} + v_{\beta}i_{\beta} + v_0i_0 = v_a i_a + v_b i_b + v_c i_c$$

Care should be taken about scaling since in *abc* domain we work with RMS values, while with magnitude values in $\alpha\beta$ and *dq* frames

Use Clarke Transform scaling carefully...

THE P-Q THEORY (II)

Further interpretation of these definitions can be extended considering that they contain both constant and oscillatory terms:

$$p_{\alpha\beta} = \bar{p}_{\alpha\beta} + \tilde{p}_{\alpha\beta}$$

$$q_{\alpha\beta} = \bar{q}_{\alpha\beta} + \tilde{q}_{\alpha\beta}$$

$$p_0 = \bar{p}_0 + \tilde{p}_0$$

This can be interpreted as:

- ▶ $p_{\alpha\beta}$ and $q_{\alpha\beta}$ - are result of interactions of voltage and currents with positive- and negative-sequences
- ▶ p_0 - is a result of a single phase v_0 and i_0 interactions giving rise to power oscillations \tilde{p}_0 and can have \bar{p}_0 different from zero
- ▶ v_0 and i_0 - zero-sequence voltage and current components do not contribute to $p_{\alpha\beta}$ and $q_{\alpha\beta}$
- ▶ $\bar{p}_{\alpha\beta}$ and $\bar{q}_{\alpha\beta}$ - (the constant terms) result from the interaction between positive- and negative-sequence voltage and currents with the same frequency and sequence
- ▶ $\tilde{p}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$ - (the oscillatory terms) result from the interaction between positive- and negative-sequence voltage and currents with either different frequency or sequence
- ▶ $p_{3-phase}$ - is always result of the sum of the real power $p_{\alpha\beta}$ and zero-sequence power p_0
- ▶ $q_{\alpha\beta}$ - does not contribute to energy transfer in the system at any time
- ▶ $q_{\alpha\beta}$ - however, it represents the energy that is exchanged between phases of the system

THE P-Q THEORY (III)

By inversion of matrix $[M_{\alpha\beta 0}]$, it is possible to find currents to be injected, to achieve desired instantaneous active and reactive powers

For a given phase-to-neutral voltage and currents in abc domain, we can apply Clarke Transform:

$$\mathbf{i}_{\alpha\beta 0}^* = [M_{\alpha\beta 0}]^{-1} \begin{bmatrix} p_{\alpha\beta}^* \\ q_{\alpha\beta}^* \\ p_0 \end{bmatrix} \Rightarrow [M_{\alpha\beta 0}]^{-1} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta & 0 \\ v_\beta & v_\alpha & 0 \\ 0 & 0 & 1/v_0 \end{bmatrix}$$

By removing zero-sequence injection (forcing it to zero), we simplify to (dq frame is also added):

$$\mathbf{i}_{\alpha\beta}^* = \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_{\alpha\beta}^* \\ q_{\alpha\beta}^* \end{bmatrix} \Rightarrow \mathbf{i}_{dq}^* = \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \frac{1}{v_d^2 + v_q^2} \begin{bmatrix} v_d & -v_q \\ v_q & v_d \end{bmatrix} \begin{bmatrix} p_{dq}^* \\ q_{dq}^* \end{bmatrix}$$

Power definitions are preserved with change of a reference from $\alpha\beta$ to dq :

- ▶ $p_{dq} = v_d i_d + v_q i_q$ - instantaneous real power (*instantaneous active power*)
- ▶ $q_{dq} = v_d i_q - v_q i_d$ - instantaneous imaginary power (*instantaneous reactive power*)

By orienting dq frame in such a way that d -axis is perfectly aligned with grid voltage space vector ($v_q = 0$), we have:

- ▶ $p_{dq} = v_d i_d$ - instantaneous active power is proportional to i_d - we can control it in this axis
- ▶ $q_{dq} = v_d i_q$ - instantaneous reactive power is proportional to i_q - we can control it in this axis

Previous power expressions assume Clarke scaling of $K = \sqrt{2/3}$.

For Clarke scaling with $K = 2/3$, power expressions are: $p_{dq} = \frac{3}{2}(v_d i_d + v_q i_q)$; $q_{dq} = \frac{3}{2}(v_d i_q - v_q i_d)$

DC LINK VOLTAGE CONTROL (I)

Introduction of these power definitions allow us to interface correctly Boost converter and 3-Phase VSI controllers:

- ▶ MPPT set the input voltage reference v_{PV} for the Boost converter
- ▶ Boost voltage controller receives this as input, acts on it, and set the reference for Boost current controller
- ▶ Boost current controller receives the current reference from boost voltage controller and regulate the boost inductor current
- ▶ we have established that grid current control of the VSI can be done in many ways
- ▶ predominantly we are interested into PI controllers in dq frame and PR controllers in $\alpha\beta$ frame
- ▶ however, DC link voltage of VSI has to be controlled as well
- ▶ this is achieved, similar to Boost, through the control of AC grid current

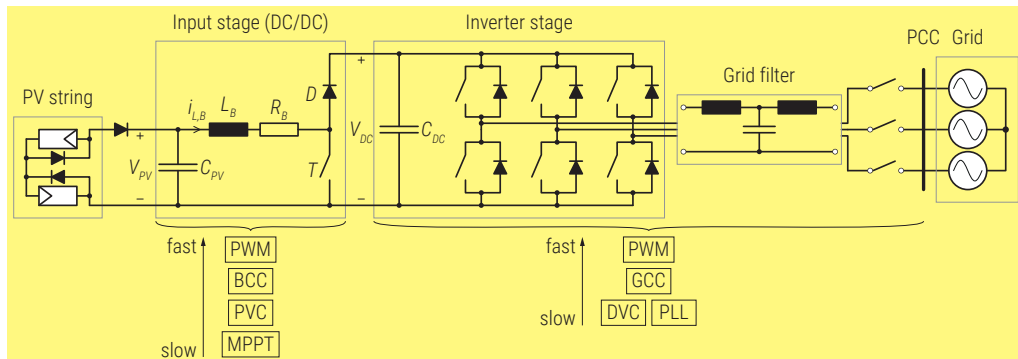


Figure 13 PV double-stage grid connected converter.

DC LINK VOLTAGE CONTROL (II)

Plant relevant for the DC link voltage control has been already identified as:

$$G_v(s) = \frac{v_{DC}}{i_{boost} - i_{DC}} = \frac{1}{sC_{DC}}$$

- ▶ i_{boost} - is the output current of the Boost converter
- ▶ i_{DC} - is the DC link current of the VSI: $i_{DC} = i_{boost} - i_{C_{DC}}$
- ▶ v_{DC} - is the DC link voltage of the VSI

Considering instantaneous real powers of interest, we have;

- ▶ $p_{dq} = \frac{3}{2}(v_d i_d + v_q i_q)$ - VSI AC side power
- ▶ $p_{DC} = v_{DC} i_{DC}$ - VSI DC side power

Neglecting losses, instantaneous input-output power balance in dq frame is:

$$v_{DC} i_{DC} = \frac{3}{2}(v_d i_d + v_q i_q)$$

Again, with d -axis perfectly aligned with grid voltage space vector ($v_q = 0$), we have:

$$v_{DC} i_{DC} = \frac{3}{2} v_d i_d$$

DC link voltage controller of a VSI will act in d -axis - instantaneous active power

SUMMARY

PV system of interest is now having two converters connected together:

- ▶ Boost converter extracts maximum amount of power from PV panel
- ▶ VSI converter transfer that power to the grid (active power)
- ▶ power theory provides hints for control implementation
- ▶ we have considered ideal grid conditions, but this is not the case in real world
- ▶ advanced PLL concepts are needed to deal with grid unbalances

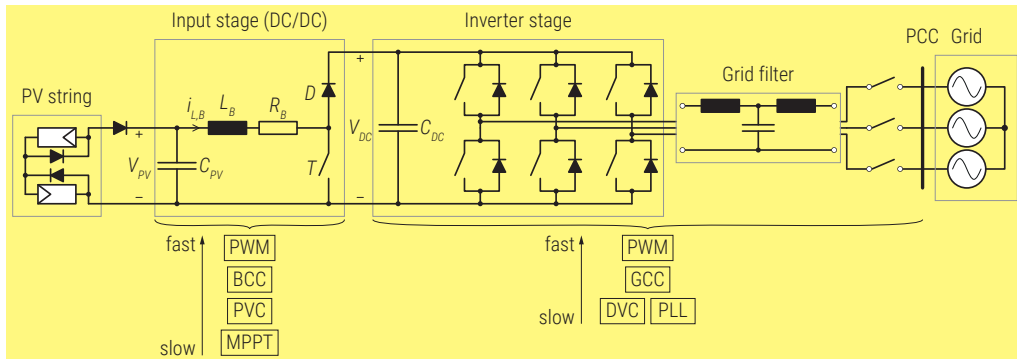


Figure 14 PV double-stage grid connected converter.