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

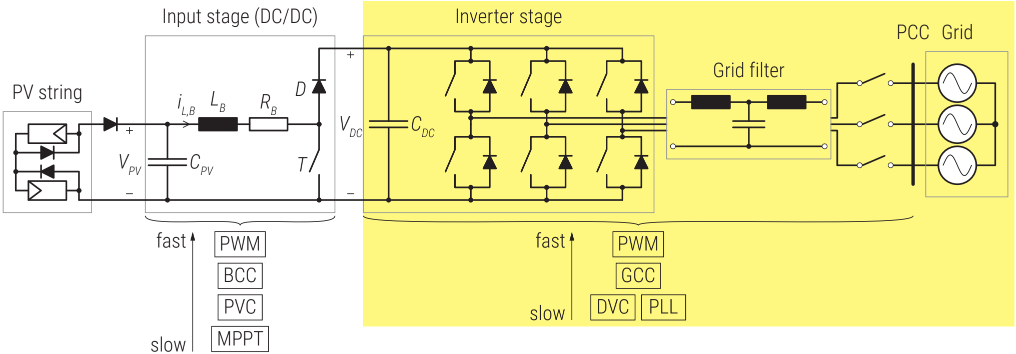

Figure 1 PV double-stage grid connected converter.

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

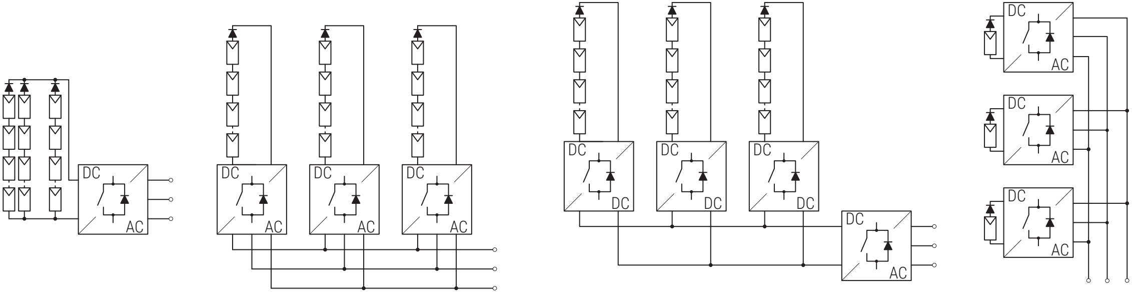

Figure 2 PV structures (from left to right): central inverter, string inverter (with AC and DC bus) and module (micro) inverter.

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)

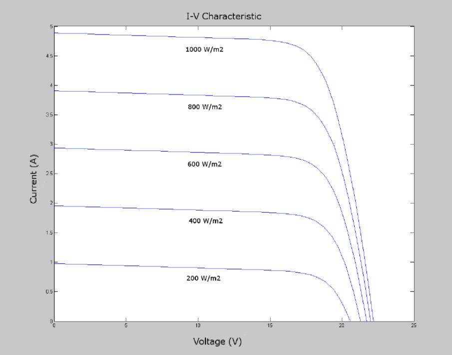

Figure 3 PV panel I-V characteristic under different irradiation.

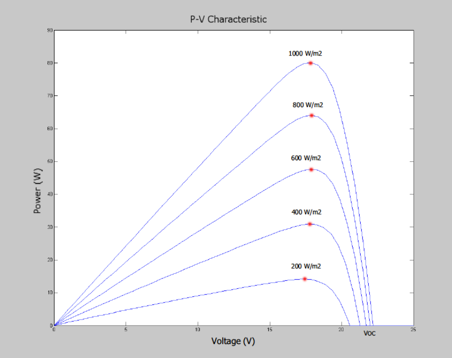

Figure 4 PV panel P-V characteristics.

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

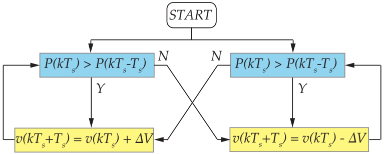

Figure 5 MPPT - Perturb and Observe Algorithm

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:

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

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

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

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

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

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

The power derivative can be expressed as:

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

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

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}

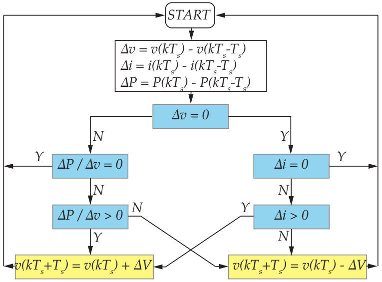

Figure 6 MPPT - Incremental Conductance Algorithm

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

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:

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

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

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

The phasor sequence components for phases b and c are:

$$\underline{V}_{b+} = \alpha^2\underline{V}_{a+}; \quad \underline{V}_{b-} = \alpha\underline{V}_{a-}$$
$$\underline{V}_{c+} = \alpha\underline{V}_{a+}; \quad \underline{V}_{c-} = \alpha^2\underline{V}_{a-}$$

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

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

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

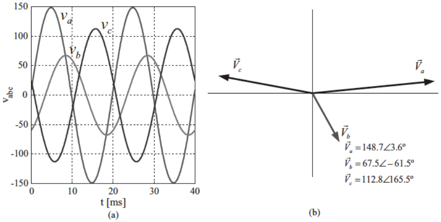

Figure 7 Unbalanced 3-phase system: a) instantaneous voltage waveforms; b) phase voltage phasors

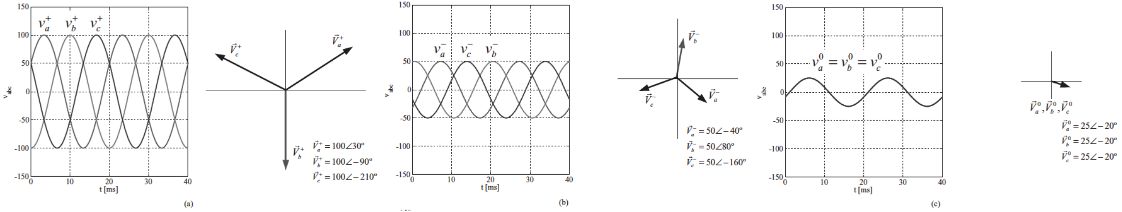

Figure 8 Sequence components of unbalanced 3-phase system: a) positive-sequence phasors; b) negative-sequence phasors; c) zero-sequence phasors

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:

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

Normally, Lyon Transformation considers different scaling ratio:

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

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 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:

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

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

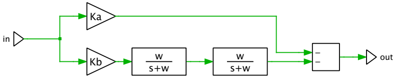

Figure 9 α-operator PLECS implementation, $K_a = 0.5, Kb = \sqrt{3}, \omega = 2\pi f$.

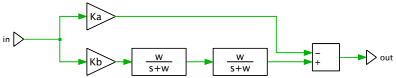

Figure 10 α^2-operator PLECS implementation, $K_a = 0.5, Kb = \sqrt{3}, \omega = 2\pi f$.

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* $\left[T_{\alpha\beta 0}\right]^{-1} = \left[T_{\alpha\beta 0}\right]^T$:

$$v_{\alpha\beta 0} = \left[T_{\alpha\beta 0}\right] v_{abc}$$

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

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:

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

Any voltage vector rotating on the $\alpha\beta$ plane can be expressed on a rotational dq reference frame using Park Transform:
The transformation matrix ($\left[T_{dq0}\right]^{-1} = \left[T_{dq0}\right]^{T}$) is defined as:

$$v_{dq0} = \left[T_{dq0}\right] v_{\alpha\beta0}$$

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

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

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

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

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

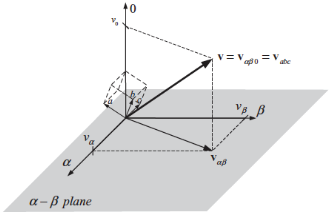

Figure 11 Graphical representation of the $\alpha\beta0$ plane.

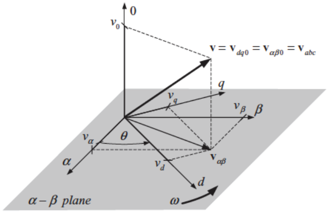

Figure 12 Graphical representation of the $dq0$ plane.

INSTANTANEOUS POWER THEORY

Active and Reactive powers in different reference frames

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:

$$v_{\alpha\beta0} = \left[T_{\alpha\beta0}\right] v_{abc}, \quad i_{\alpha\beta0} = \left[T_{\alpha\beta0}\right] i_{abc}$$

where: $v_{\alpha\beta0} = \left[v_\alpha, v_\beta, v_0\right]^T$ and $i_{\alpha\beta0} = \left[i_\alpha, i_\beta, i_0\right]^T$

The following instantaneous power are defined in $\alpha\beta0$ frame as:

$$\begin{bmatrix} p_{\alpha\beta} \\ q_{\alpha\beta} \\ p_0 \end{bmatrix} = \left[M_{\alpha\beta0}\right] i_{\alpha\beta0}, \quad \Rightarrow \quad \left[M_{\alpha\beta0}\right] = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix}$$

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*)
- $p_0 = v_0 i_0$ - 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

$$p_{3-phase} = p_{\alpha\beta} + p_0 = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 = v_a i_a + v_b i_b + v_c i_c$$

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...

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:

$$i^*_{\alpha\beta 0} = [M_{\alpha\beta 0}]^{-1} \begin{bmatrix} p^*_{\alpha\beta} \\ q^*_{\alpha\beta} \\ p^*_0 \end{bmatrix} \Rightarrow [M_{\alpha\beta 0}]^{-1} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta & 0 \\ v_\beta & v_\alpha & 0 \\ 0 & 0 & 1/v_0 \end{bmatrix}$$

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

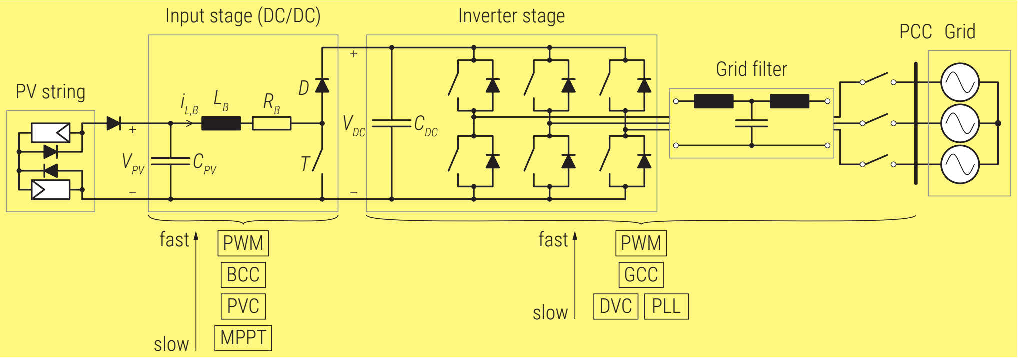

Figure 13 PV double-stage grid connected converter.

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

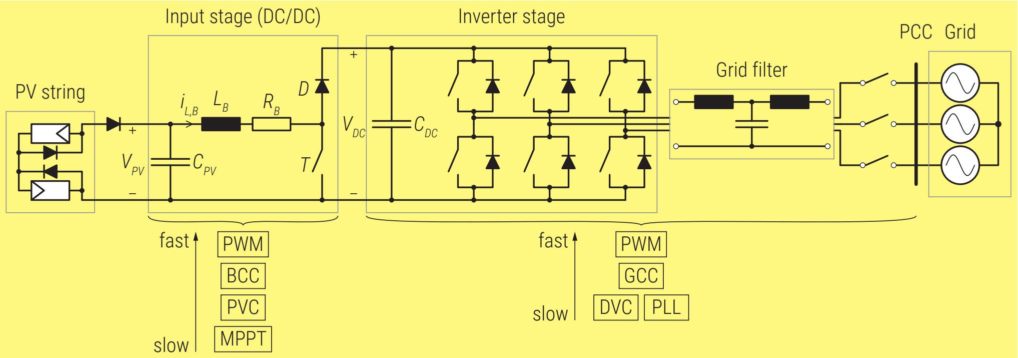

Figure 14 PV double-stage grid connected converter.