TSTE26 Powergrid and technology for renewable production

Lecture 7
Converter control

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Outline

- Grid inverter
  - Power control
  - Current control
- Coordinate transforms
  - DQ-frame
- Phase Locked Loop
- PV with MPPT + Grid inverter (Lab3)

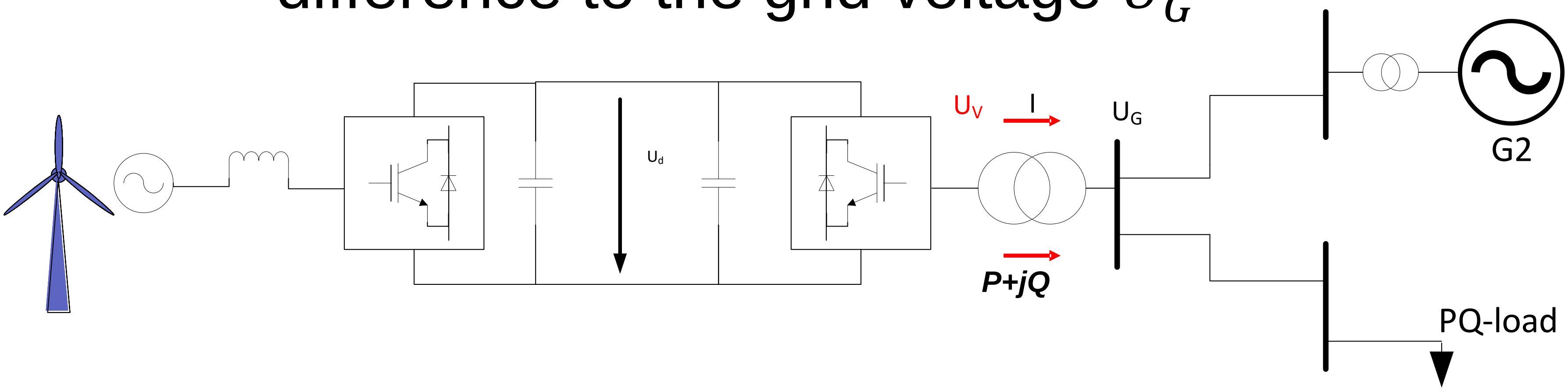
Grid Converters for Photovoltaic and Wind Power Systems by Remus Teodorescu, Marco Liserre, Pedro Rodriguez

Chapter 4.2.2 Grid synchronization using PLL

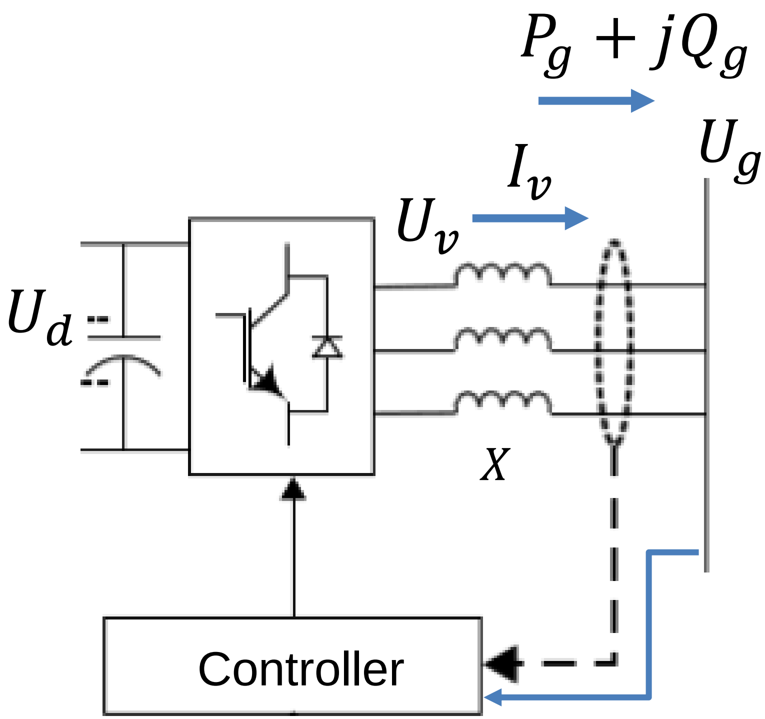
Appendix A: Space Vector Transformations of Three-Phase Systems

Grid power infeed

- Converter infeed of $P + jQ$ through the current injection I by controlling $\overline{U}_v$
- $\overline{U}_v = U_v \angle \delta$, where δ is the angle difference to the grid voltage $\overline{U}_G$



VSC power flow control



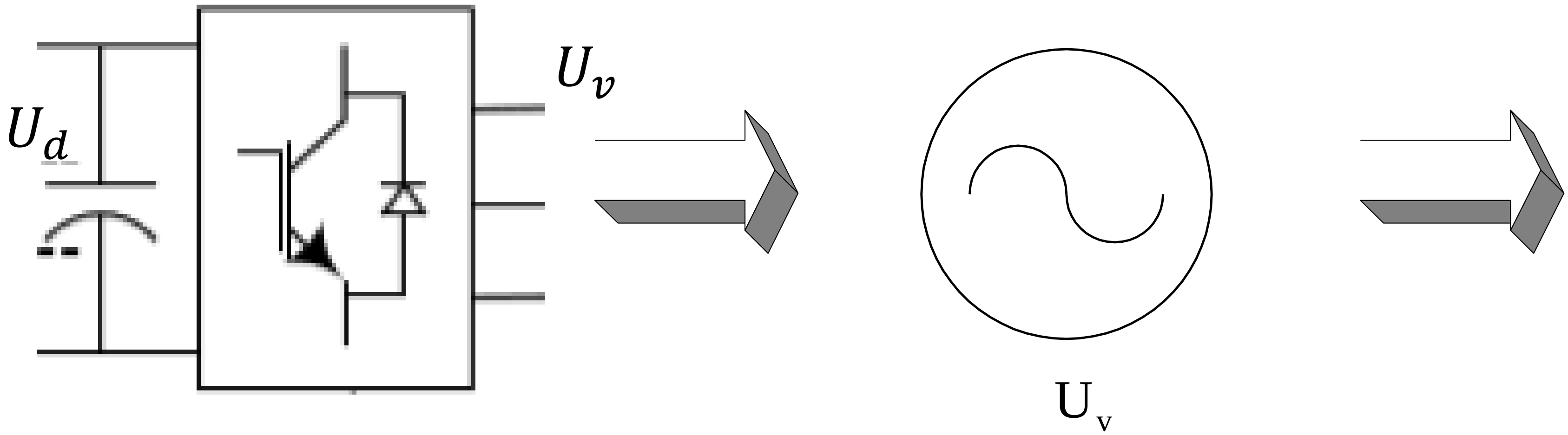
$$\bar{I}_v = \frac{U_v \angle \delta - U_g}{jX\sqrt{3}}$$

Note $\sqrt{3}$ in the denominator since the voltages are ph-ph

$$P_g + jQ_g = \sqrt{3} \cdot U_g \cdot \bar{I}_v^*$$

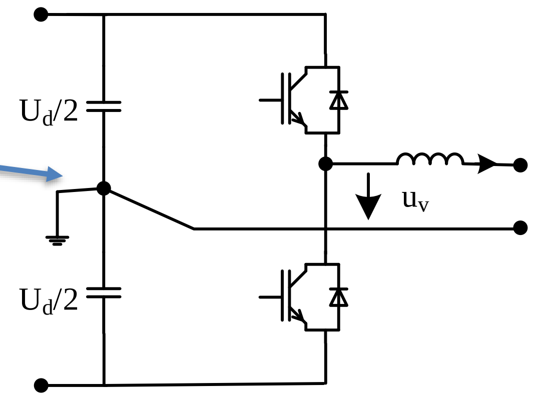
- The converter ph-ph rms voltage U_v
- δ the angle difference between U_v and U_g

Voltage Source Converter (VSC)



U_v **adjustable**
- amplitude
- phase angle
- frequency

Half-bridge (2-level) converter



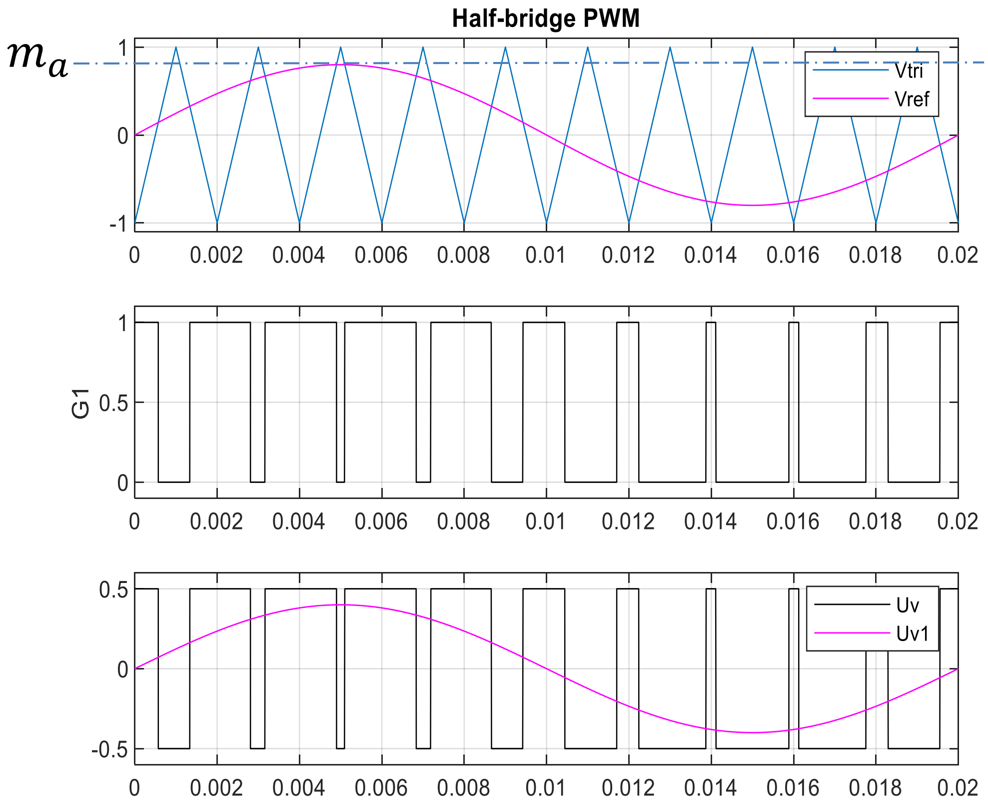
- DC-side midpoint reference point for ac-output
- Output voltage, u_v, switched between $+\frac{U_d}{2}$ and $-\frac{U_d}{2}$
- Output peak phase voltage defined by modulation index m_a

$$\hat{u}_{v1} = m_a \frac{U_d}{2}$$

Pulse-width modulated (PWM) switching scheme

- Constant switching frequency (triangle wave) f_s
- Amplitude modulation ratio

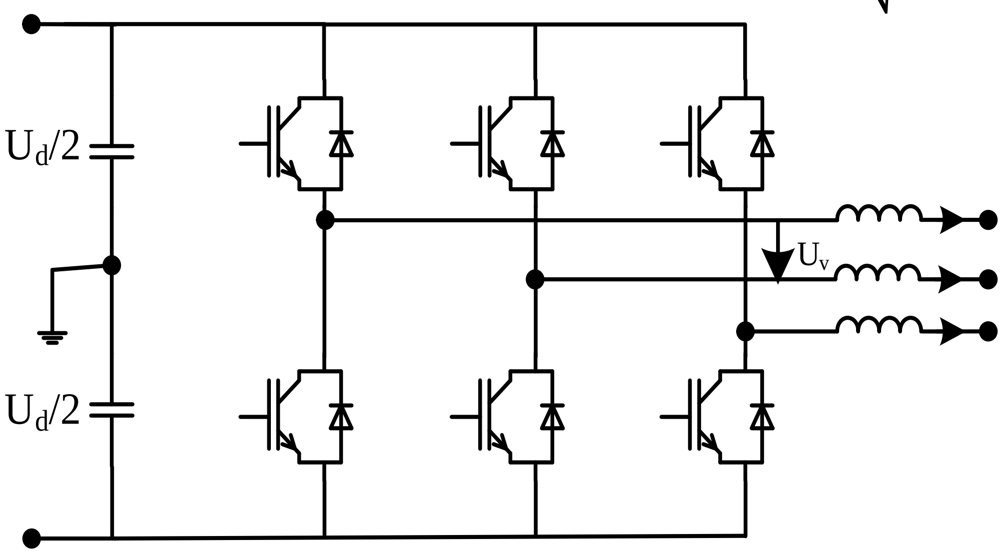
$$m_a = \frac{\hat{U}_v}{U_d/_2} = \frac{\hat{U}_{v\_ref}}{\hat{U}_{tri}}$$



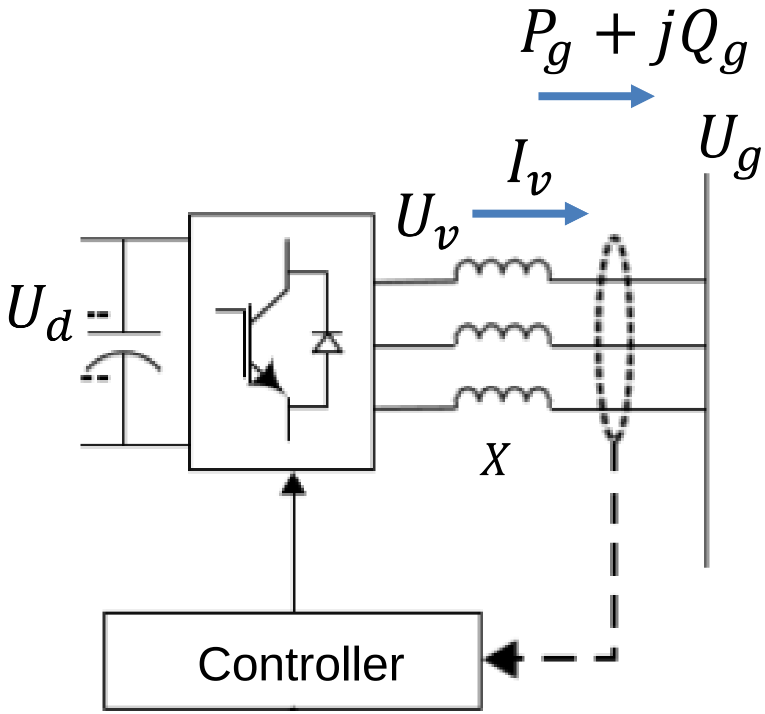
Three-phase inverters

- Three legs
- Controls phase shifted 120°
- Midpoint not used
- Output ph-ph rms voltage

$$U_v = \sqrt{\frac{3}{2}} \cdot m_a \frac{U_d}{2}$$



VSC power flow control



$$\bar{I}_v = \frac{U_v \angle \delta - U_g}{jX\sqrt{3}}$$

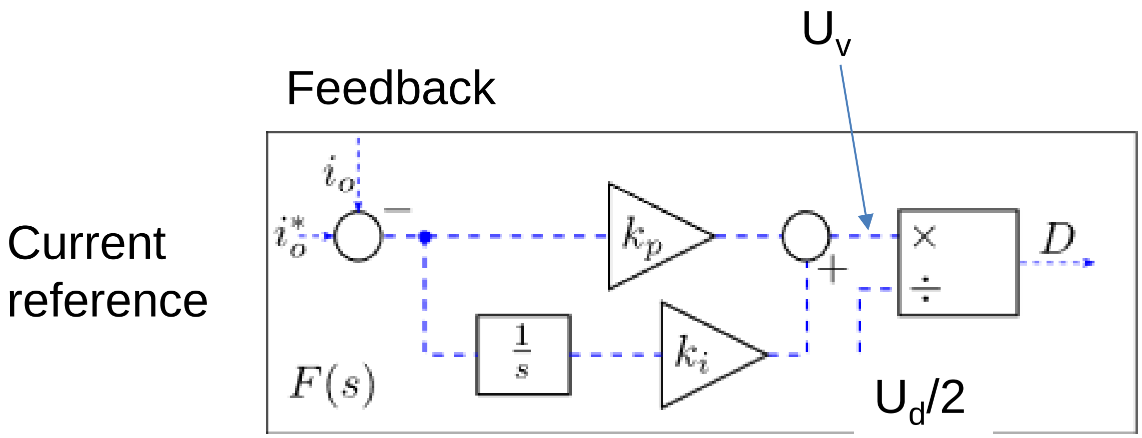
Note $\sqrt{3}$ in the denominator since the voltages are ph-ph

$$P_g + jQ_g = \sqrt{3} \cdot U_g \cdot \bar{I}_v^*$$

- The converter ph-ph rms voltage U_v

$$U_v = \sqrt{\frac{3}{2}} \cdot m_a \frac{U_d}{2}$$

PI-control



Uv
Feedback
Current reference
i_o
i_o^*
$-$
k_p
$+$
$\frac{1}{s}$
k_i
$\times$
$\div$
D
$F(s)$
Ud/2

Load angle control of P and Q

- Active power $\sim \sin\delta$
- Reactive power $\sim V_S - V_R$

P and Q not independent
- **Q also depend on δ**
- **P also depend on $V_S V_R$**

$$P_R = \frac{V_S V_R}{X}\sin\delta$$

$$Q_R = \frac{V_S V_R \cos\delta}{X} - \frac{V_R^2}{X}$$

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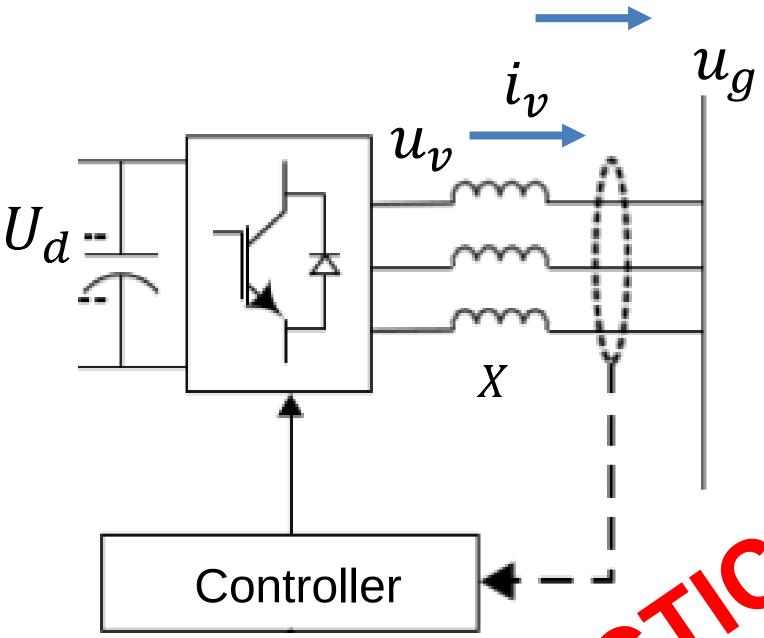
Current control in abc-frame

$$P_g + jQ_g = 3 \cdot u_g \cdot i_v$$



- u_v is controlled to achieve $i_v = i_{vRef}$
- u_g and i_v are measured
- $u_v = u_g + L\frac{di_v}{dt}$

➢ Each phase controlled separately

➢ PI-control not practical due to sinusoidal reference

➢ $i_{vRef} = \hat{I}_{vRef}\cos(\omega t + \varphi)$

NOT PRACTICAL

Three-Phase Voltages

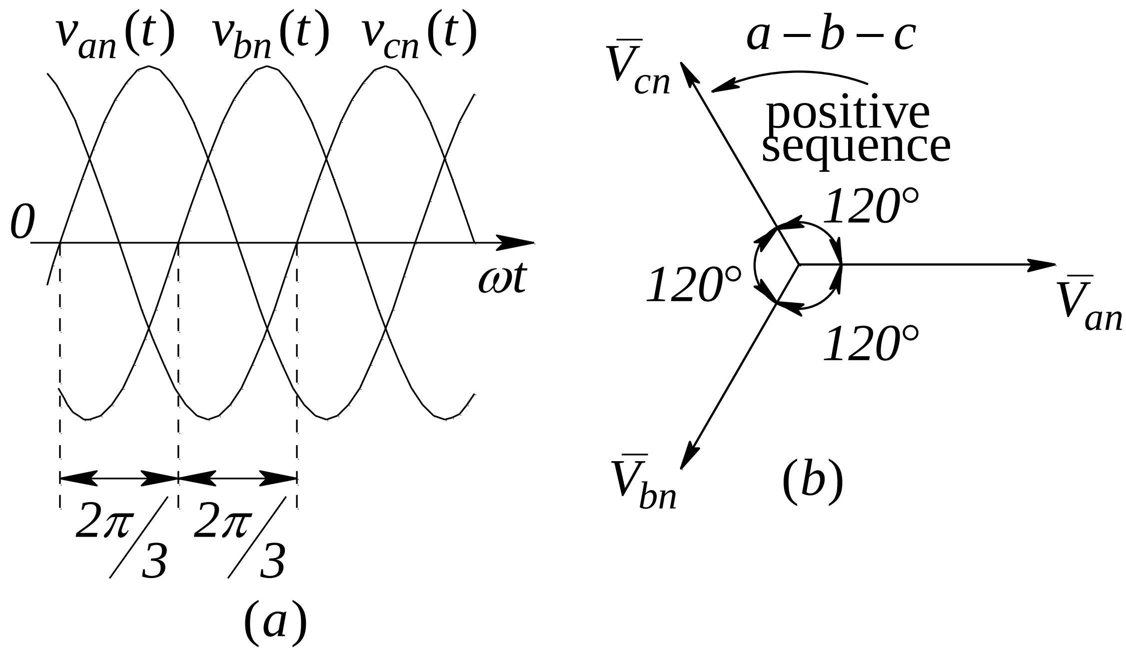


Fig. 2-11 Three-phase voltages in time and phasor domain.

$$v_{an} = \sqrt{2}V\cos(\omega t)$$
$$v_{bn} = \sqrt{2}V\cos(\omega t - 120°)$$
$$v_{cn} = \sqrt{2}V\cos(\omega t - 240°)$$

$$\bar{V}_{an} = V\angle 0°$$
$$\bar{V}_{bn} = V\angle -120°$$
$$\bar{V}_{cn} = V\angle -240°$$

V is the RMS phase to neutral voltage

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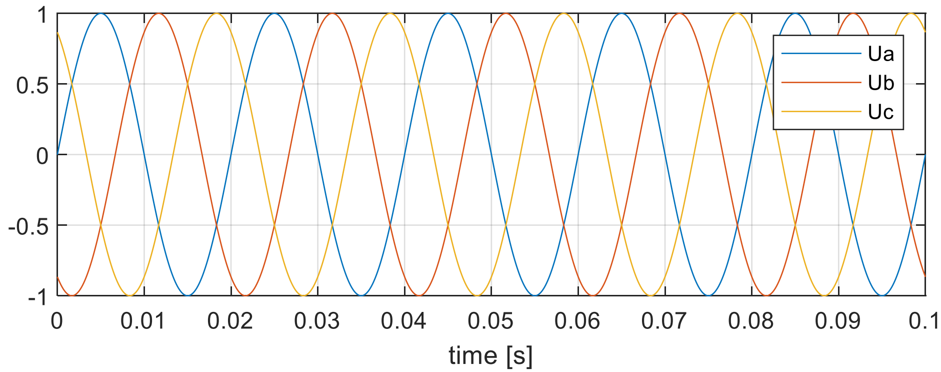
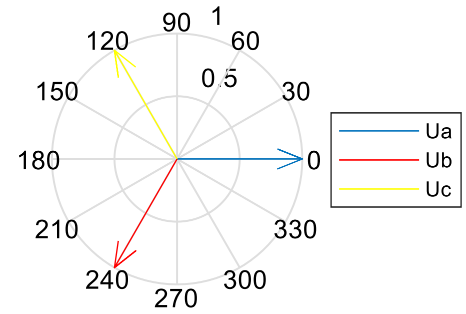
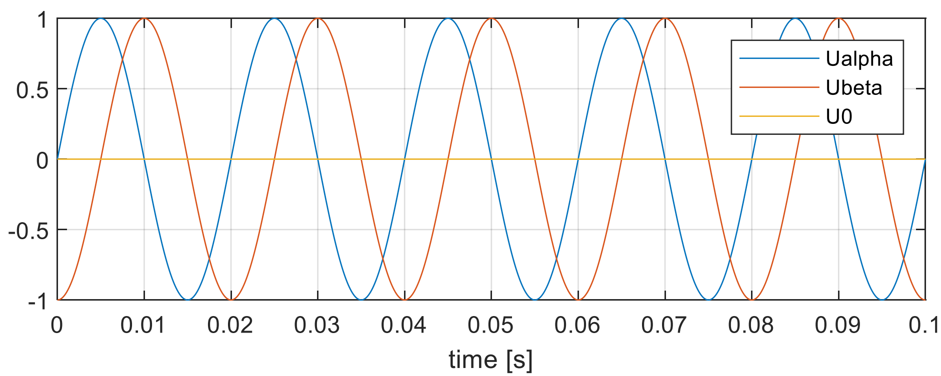
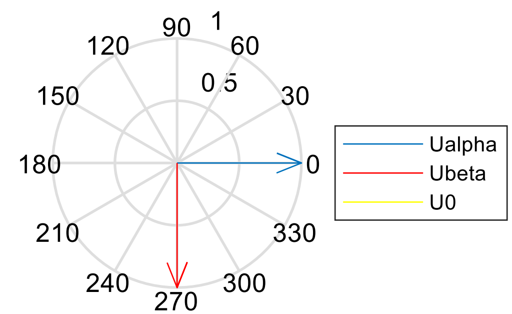
Transformation 3-ph to 2-ph









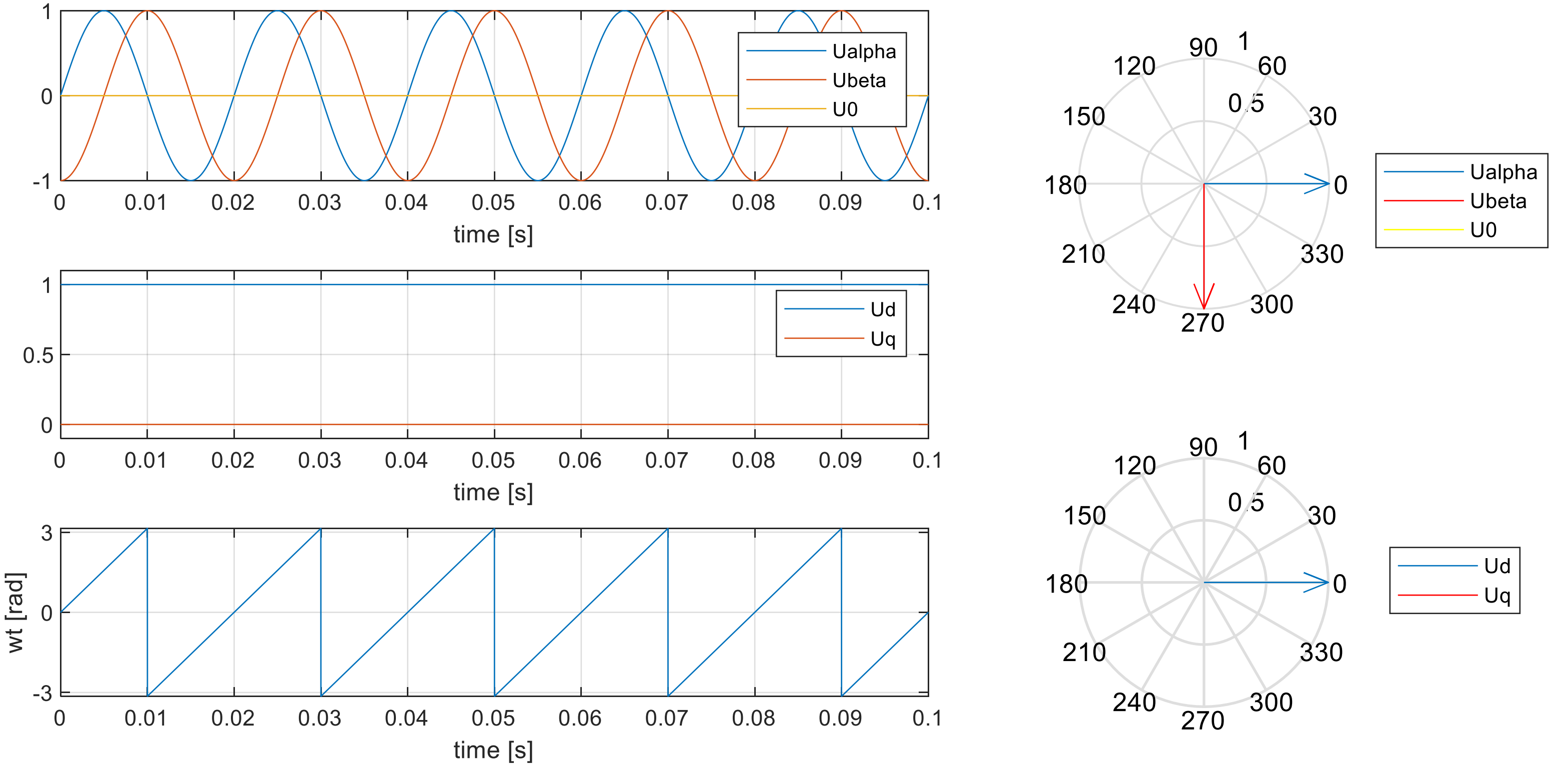
Clarke transform

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$u_0 = \frac{u_a + u_b + u_c}{3}$$

Transformation to DQ

Transformation to defined synchronous angle reference frame $\theta = \omega t$



Park transform

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t & 0 \\ \cos\omega t & \sin\omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix}$$

DQ transformation, Q: 90deg behind A-axis

alpha/beta to DQ

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t & 0 \\ \cos\omega t & \sin\omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix}$$

abc to DQ

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} sin(\omega t) & sin\left(\omega t - \frac{2\pi}{3}\right) & sin\left(\omega t + \frac{2\pi}{3}\right) \\ cos(\omega t) & cos\left(\omega t - \frac{2\pi}{3}\right) & cos\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} sin(\omega t) \\ sin\left(\omega t - \frac{2\pi}{3}\right) \\ sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix}$$

abc to DQ ⇒

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

DQ transformation, Q: Aligned with A-axis

alpha/beta to DQ

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t & 0 \\ -\sin\omega t & \cos\omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix}$$

abc to DQ

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos(\omega t) & cos\left(\omega t - \frac{2\pi}{3}\right) & cos\left(\omega t + \frac{2\pi}{3}\right) \\ -sin(\omega t) & -sin\left(\omega t - \frac{2\pi}{3}\right) & -sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} sin(\omega t) \\ sin\left(\omega t - \frac{2\pi}{3}\right) \\ sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix}$$

abc to DQ →

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$$

Phase synchronization

Angle reference,
$\theta = \omega t$

Oscillator output,
$v' = \cos(\omega t)$

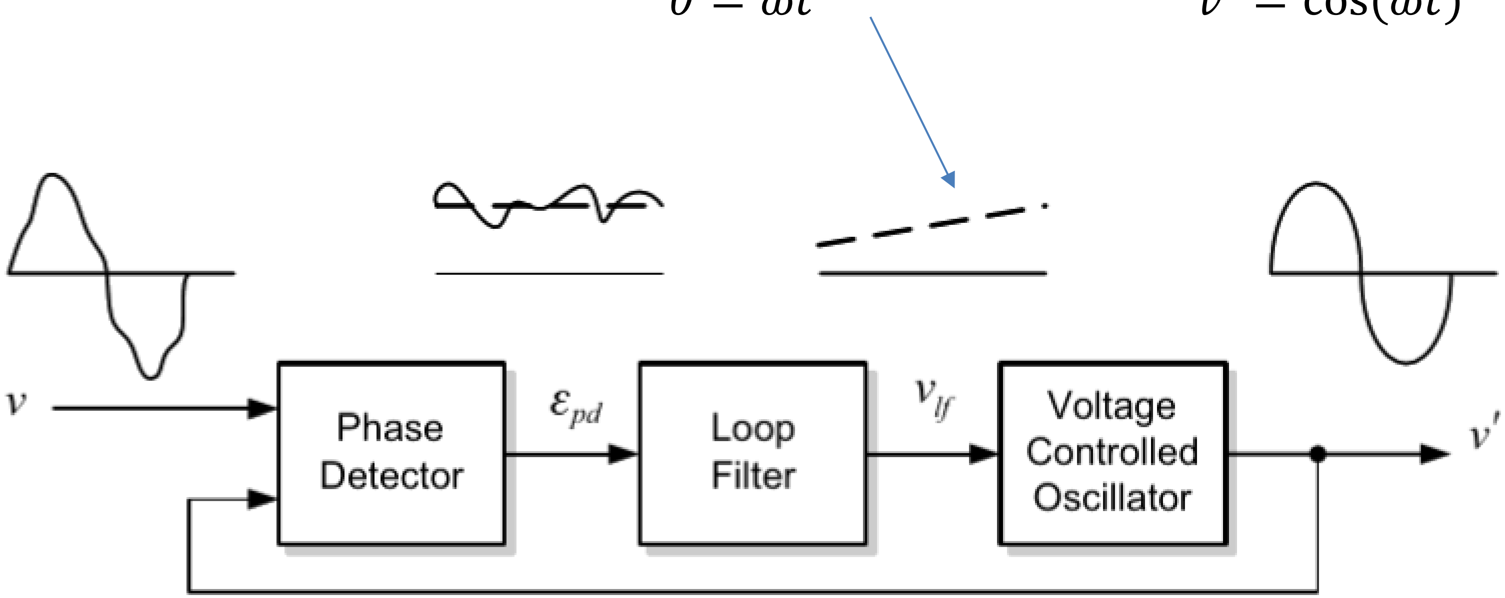


Figure 4.4 Basic structure of a PLL

Phase Locked Loop

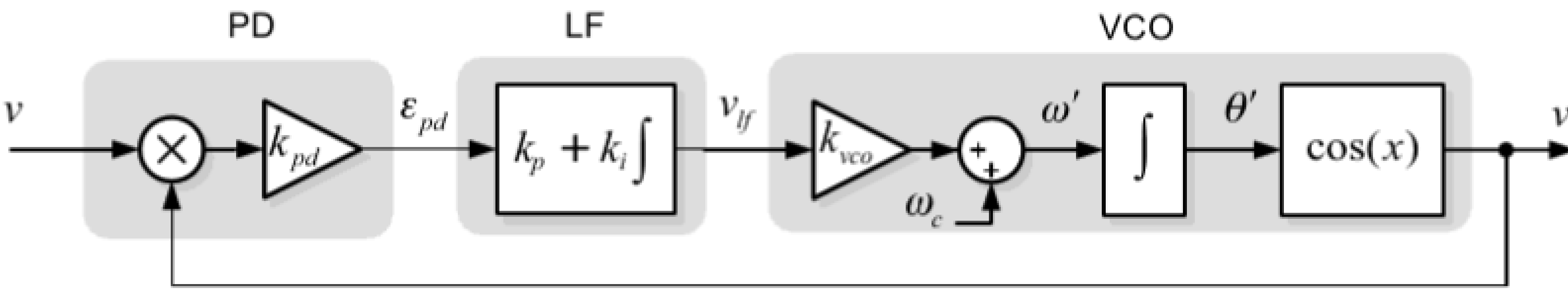
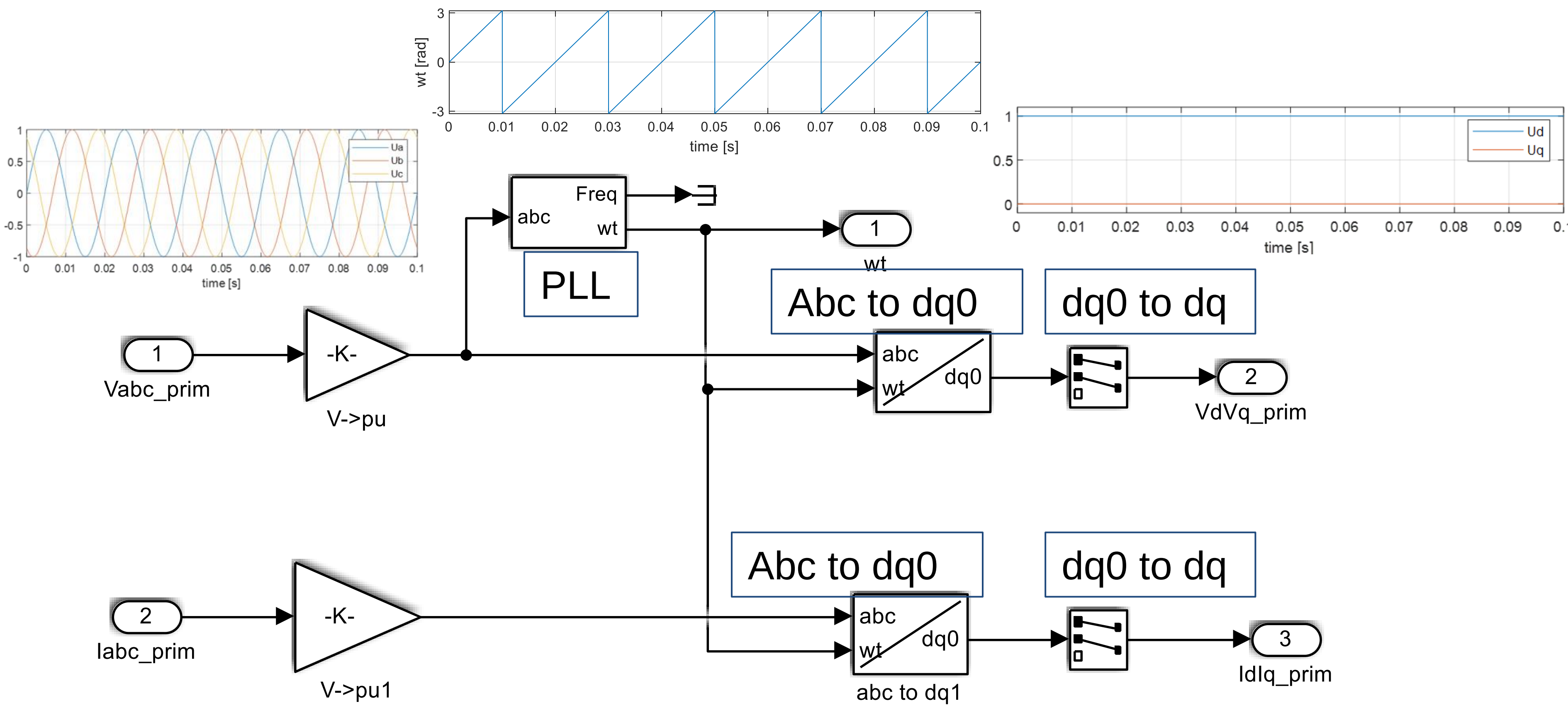


Figure 4.5 Block diagram of an elementary PLL

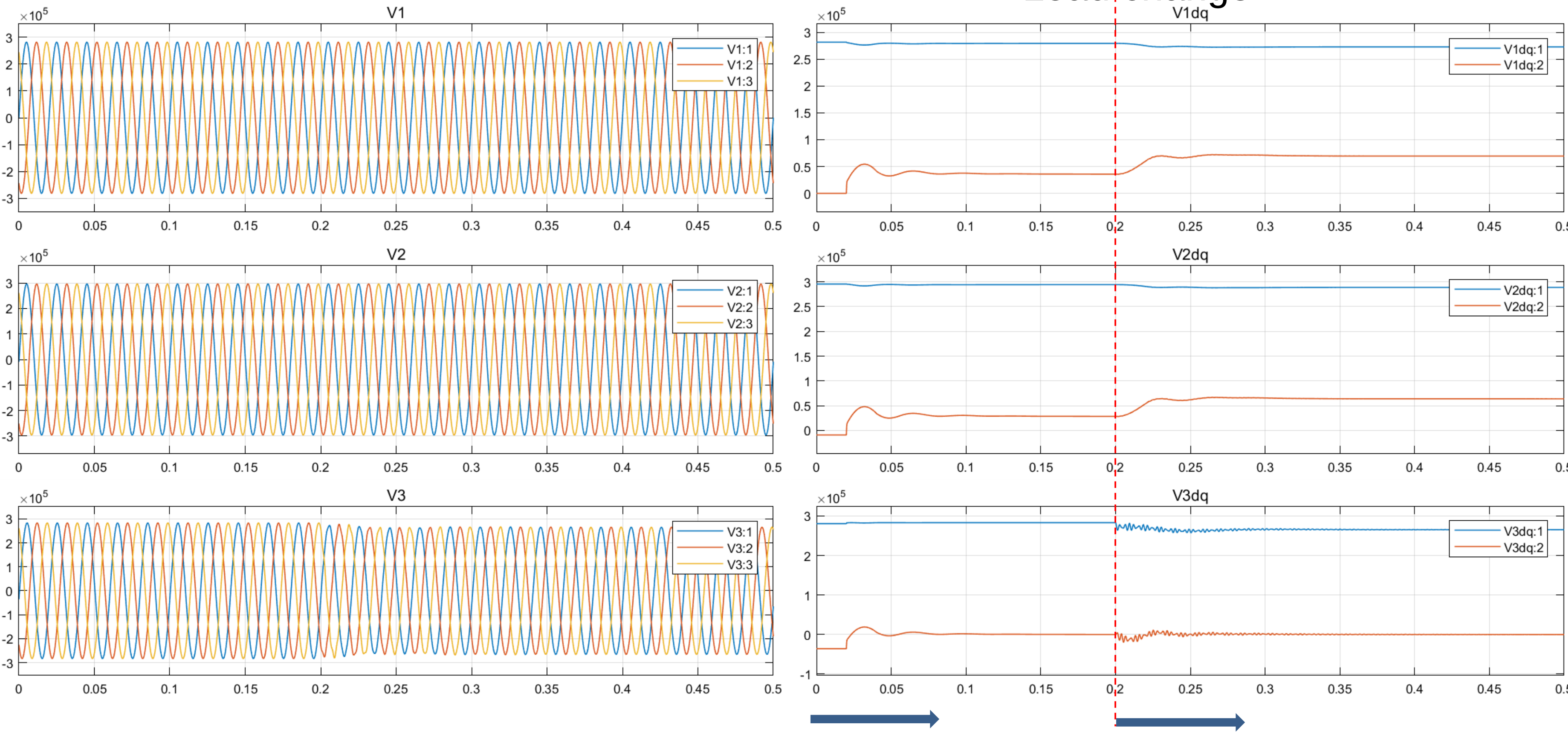
PI control of error $\varepsilon_{pd} = 0$
Makes v and v' in phase

PLL and coordinate transform of grid voltage and current



PLL to define DQ-frame

Load change



PLL synch time

PLL synch time

PLL synchronized to V3

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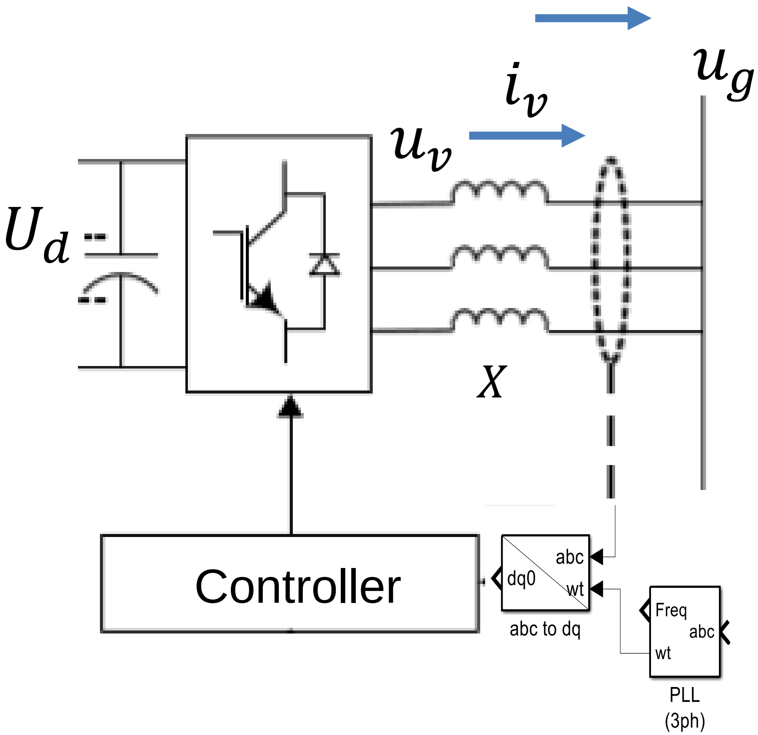
Current control in dq-frame

$$P_g + jQ_g = 3 \cdot u_g \cdot i_v$$



- u_v is controlled to achieve $i_v = i_{vRef}$
- u_g and i_v are measured
- $\bar{U}_{vDQref} = \bar{U}_{gDQ} + j\omega L \bar{I}_{vDQ}$
  - Individual phase control not needed
  - PI-control possible due to dc reference
  - $i_{vRef} = \hat{I}_{vDRef}$+j $\hat{I}_{vQRef}$
  - P_g and Q_g independently controlled through I_{vd} and I_{vq}

Vector control

$$P_g + jQ_g = \sqrt{3} \cdot U_g \cdot I_v^*$$

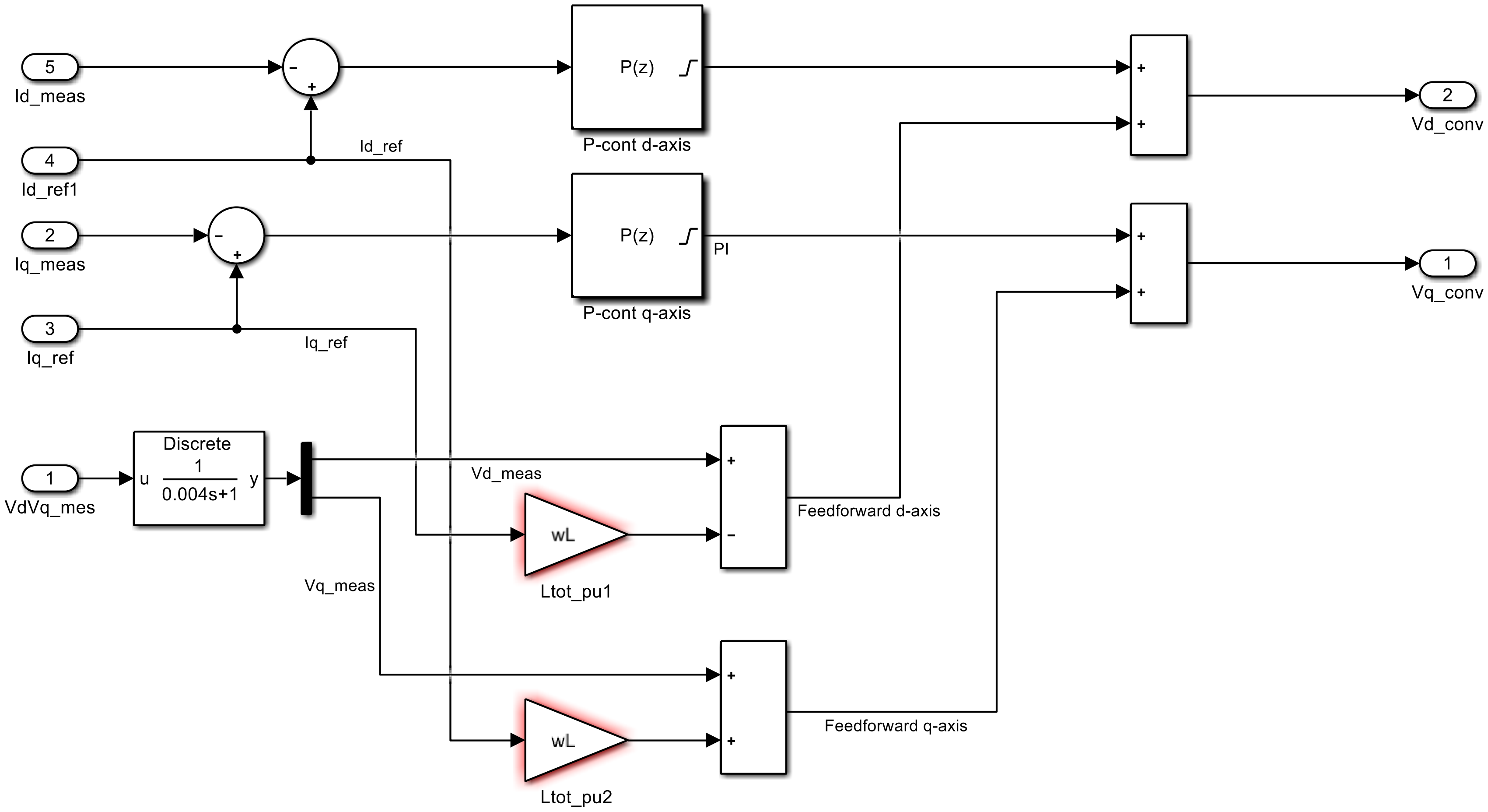
- Control current in DQ-frame: I_{vd}, I_{vq}
- Based on grid voltage: U_{gd}, U_{gq}
- PLL synchronized to U_g makes $U_{gq} = 0$
- $P_g + jQ_g = \frac{3}{2}\left(U_{gd} + jU_{gq}\right) \cdot conj\left(I_{vd} + jI_{vq}\right)$

$$= \frac{3}{2}\, U_{gd}\, \left(I_{vd} - jI_{vq}\right)$$

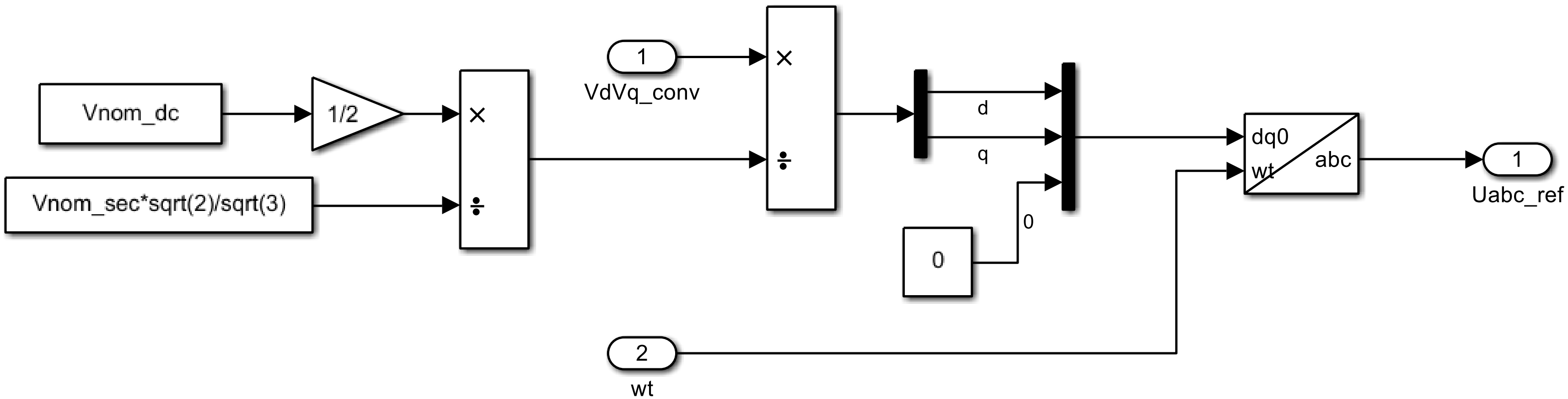
Vector control, …

- $\bar{U}_v = \bar{U}_g + j\omega L\bar{I}_v$ (Here $\bar{U}_v$ and $\bar{U}_g$ are ph-gnd voltages)
- $\bar{I}_{vDQ}$, transform from ABC to DQ
- $\bar{U}_{vDQref} = \bar{U}_{gDQ} + j\omega L\bar{I}_{vDQref} + \underbrace{k\left(\bar{I}_{vDQ} - \bar{I}_{vDQref}\right)}_{proportional\ control}$
- PLL (Phase Locked Loop) required to define ωt

DQ current controller



Vd/Vq to Uabc

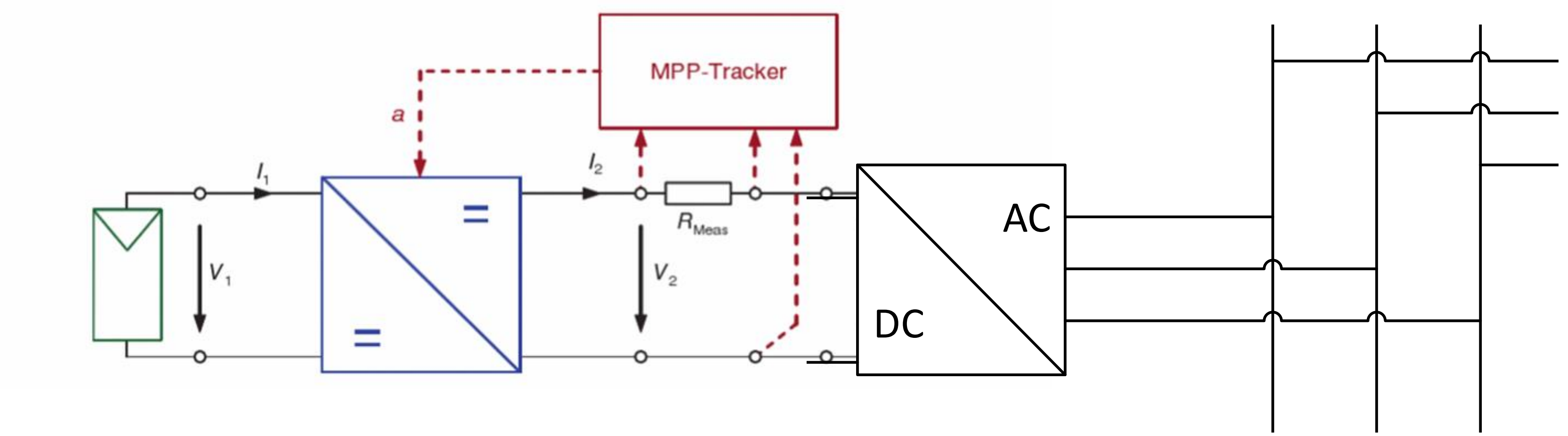


$$U_v = \sqrt{\frac{3}{2}} \cdot m_a \frac{U_d}{2}$$

$$m_a = \frac{U_v \sqrt{\frac{2}{3}}}{\frac{U_d}{2}}$$

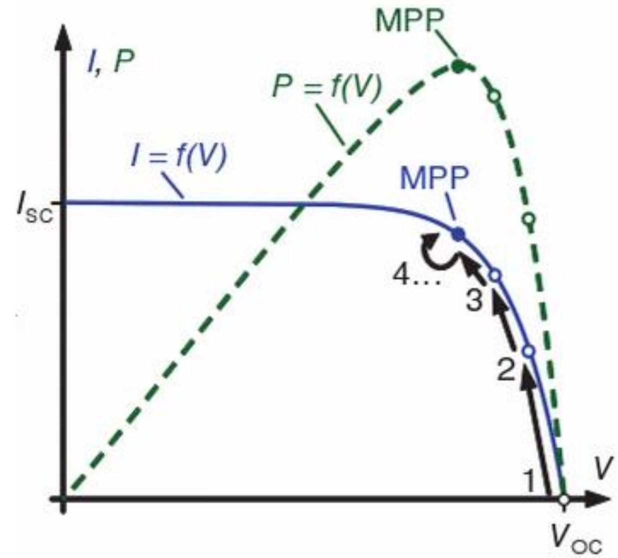
PV-system MPPT for grid infeed

- DC/DC conversion
  - to increase voltage from PV to inverter
  - to optimize PV-panel voltage, V1, for maximum power
- DC/AC inverter for grid connection
  - Reactive power grid support
  - DC voltage V2 control



MPPT, Maximum Power Point Tracking

- DC/DC converter to allow different pv- and load voltage
- PV-voltage is optimized to reach MPP



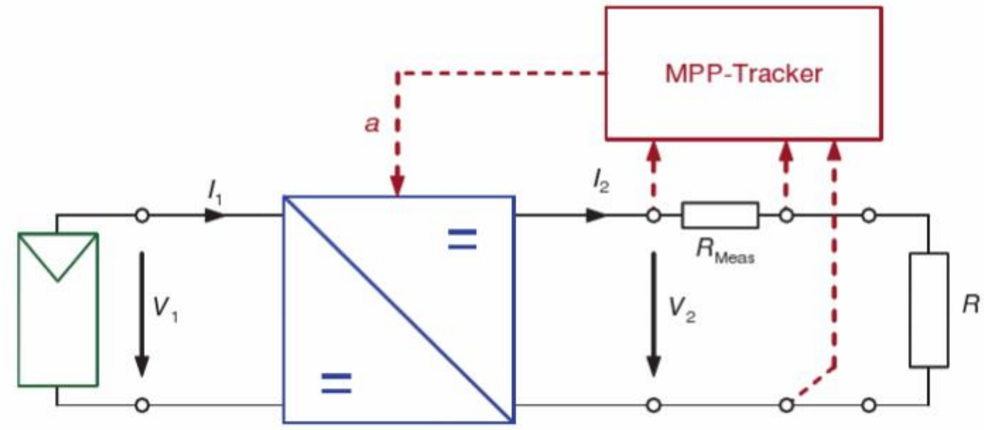
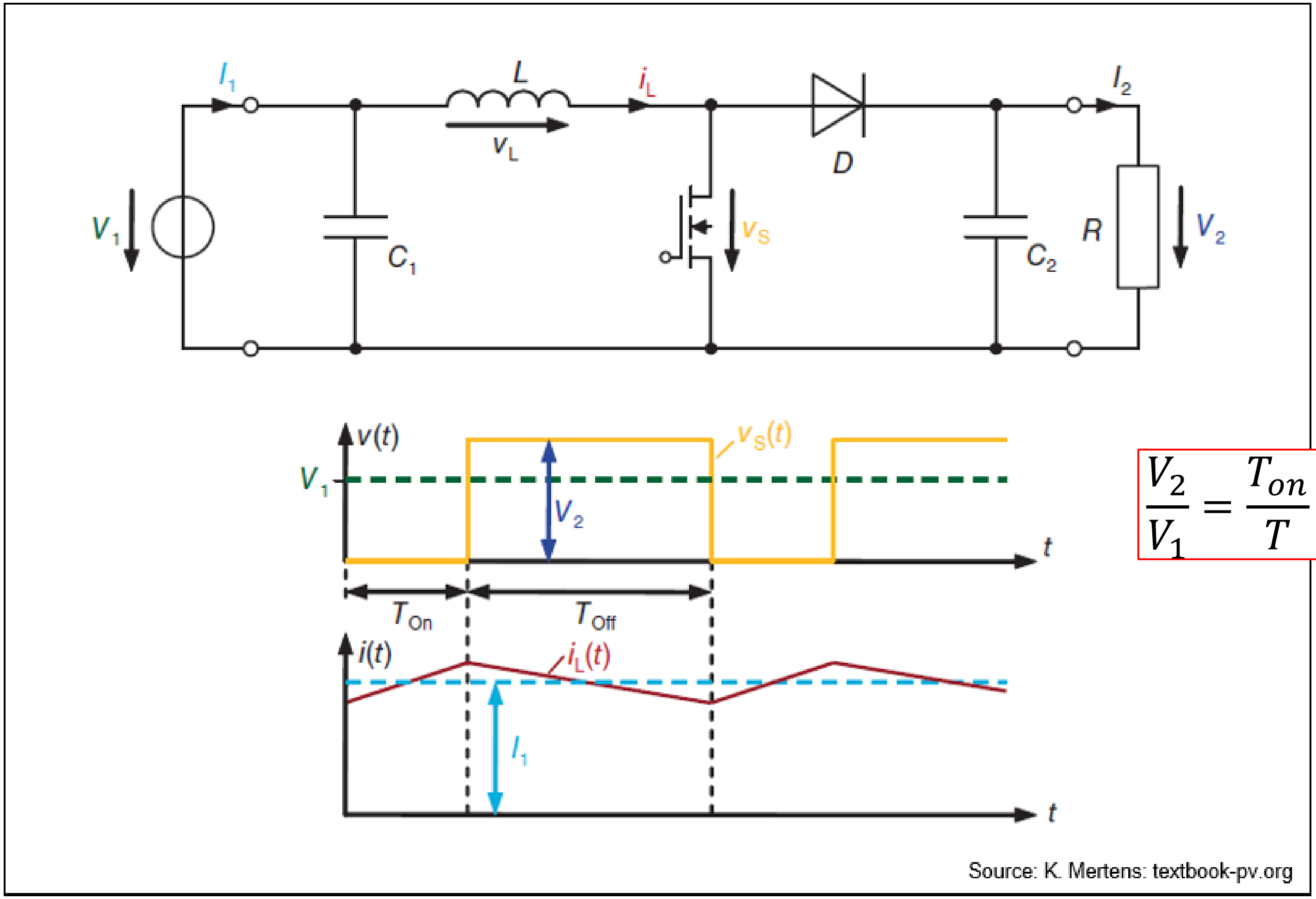


Figure 7.6 Principle of MPP tracking: The output power is maximized by measuring the current and voltage with the simultaneous variation of the duty factor

DC/DC step-up(boost) converter

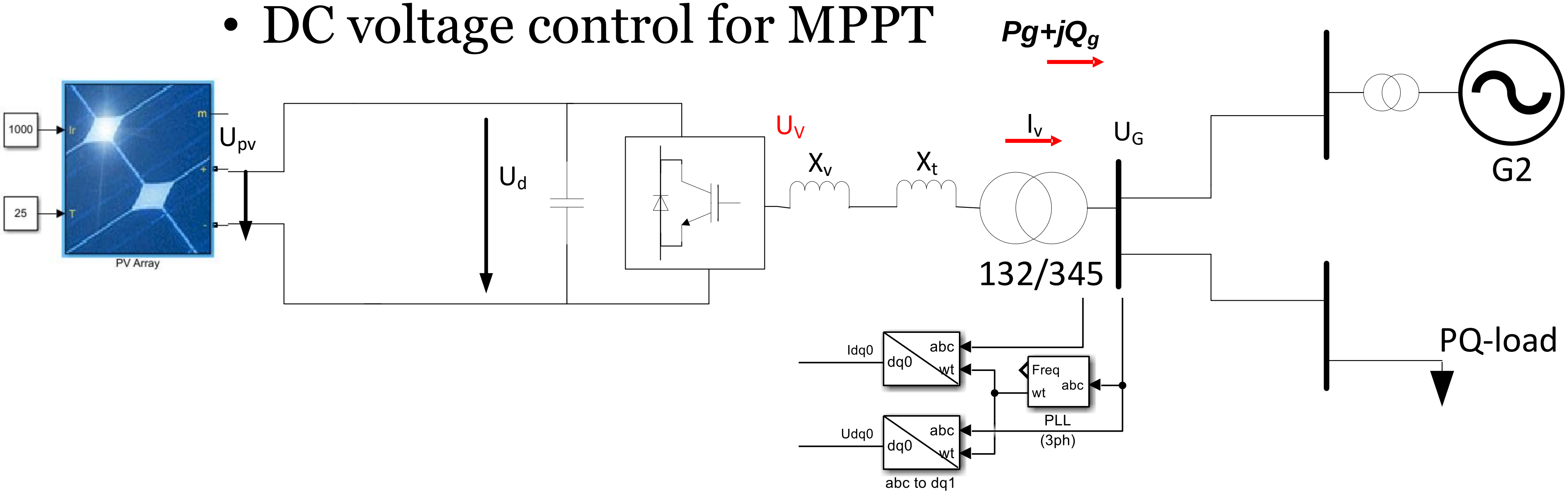


$$\frac{V_2}{V_1} = \frac{T_{on}}{T} = \frac{1}{1-D}$$

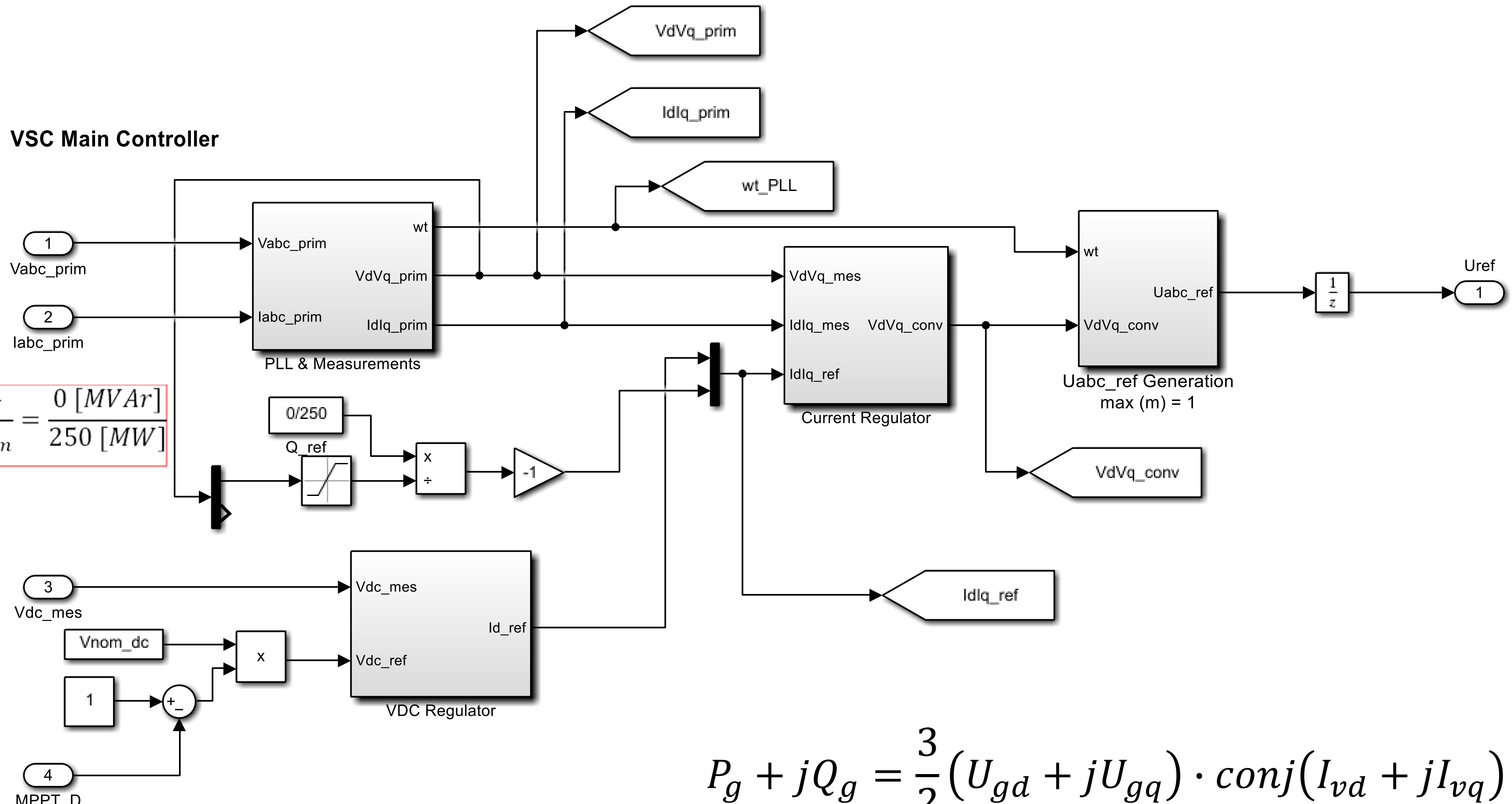
PV-system MPPT for grid infeed

- DC/DC not needed when PV output voltage is high enough
- DC/AC inverter for grid connection
  - Reactive power grid support
  - DC voltage control for MPPT

$$U_v = \sqrt{\frac{3}{2}} \cdot m_a \frac{U_d}{2}$$



Inverter control



$$\frac{Q_{ref}}{P_{dNom}} = \frac{0\ [MVAr]}{250\ [MW]}$$

$$1 - D = \frac{V_1}{V_2} = \frac{U_{pv}}{U_{dNom}}$$

$$P_g + jQ_g = \frac{3}{2}\left(U_{gd} + jU_{gq}\right) \cdot conj\left(I_{vd} + jI_{vq}\right)$$
$$= \frac{3}{2}\, U_{gd}\, \left(I_{vd} - jI_{vq}\right)$$

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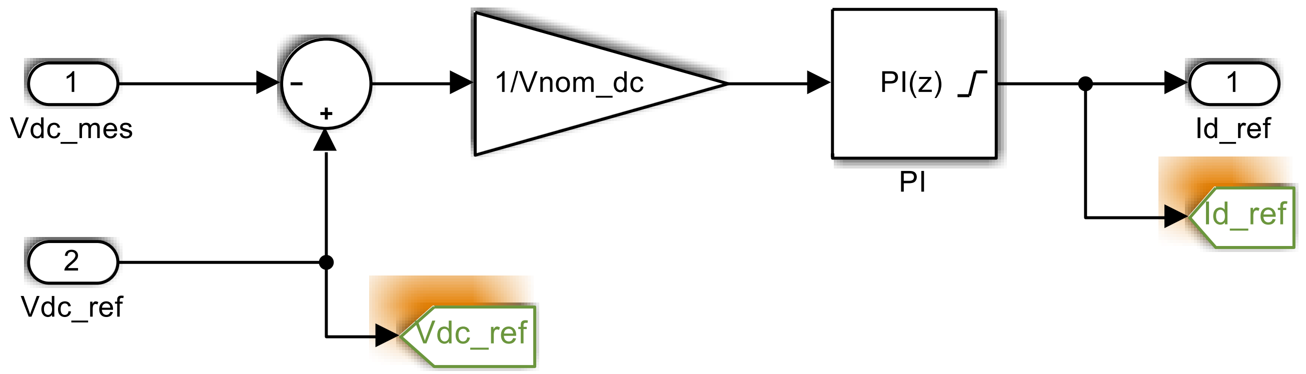
DC/AC grid inverter control

- DC voltage control to define $\bar{I}_{vDref}$



- Reactive defined by $\bar{I}_{vQref}$

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