Inverter-level control

ELEN0445 – microgrids

ULiège

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Types of inverter control

Grid-following, grid-forming, etc.

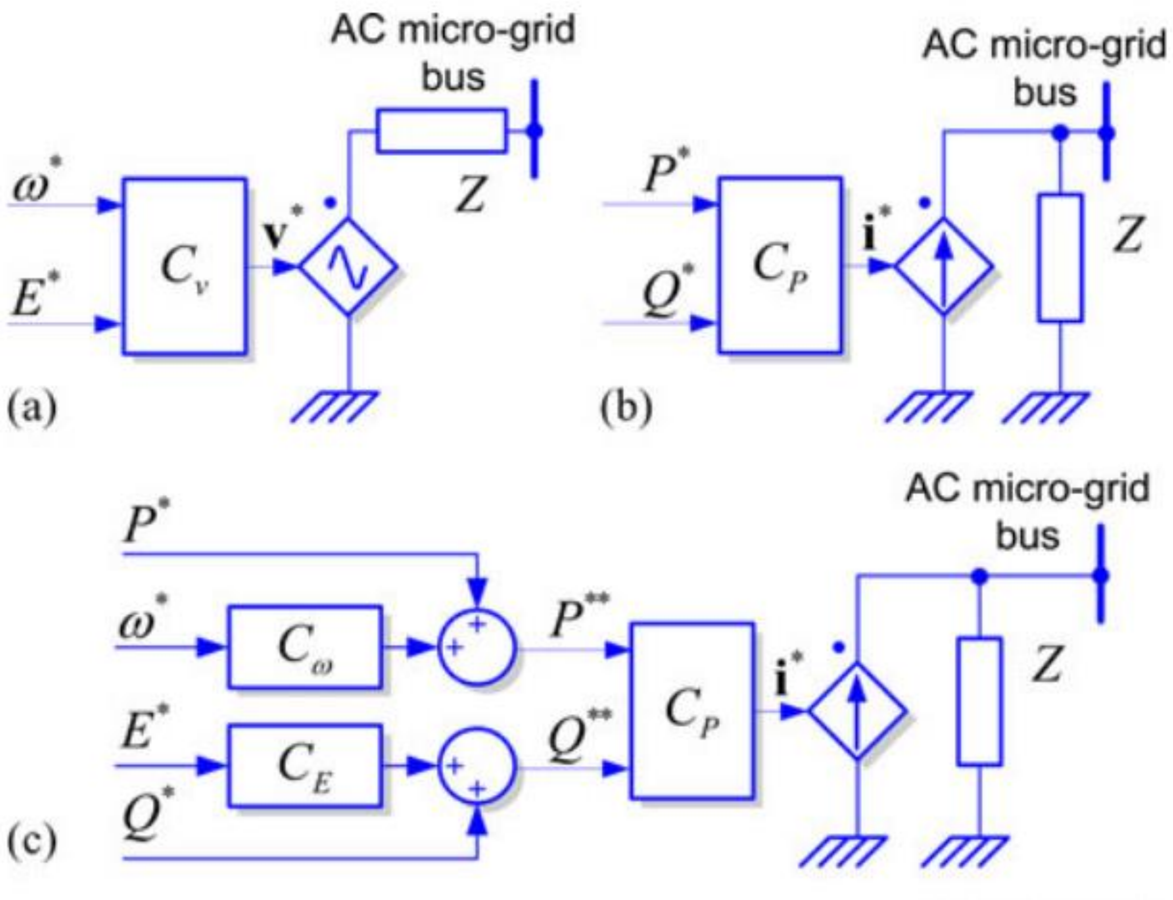
Types of power electronics interfaces (from [1])

Grid-following converters (Fig (b)): can be represented as an ideal current source setting the active and reactive power injected into / withdrawn from the grid.

Grid-forming converters (Fig (a)): can be represented as an ideal AC voltage source setting the voltage amplitue and frequency of the local electrical grid.

Grid-supporting converters (Fig (c)): "inbetween the two others", implementing functions to support the grid, e.g. droop control.

All these functions are achieved using several nested control loops.



[1] Rocabert, J., Luna, A., Blaabjerg, F., & Rodríguez, P. (2012). Control of power converters in AC microgrids. *IEEE Transactions on Power Electronics*, *27*(11), 4734–4749. https://doi.org/10.1109/TPEL.2012.2199334

Grid-following converters

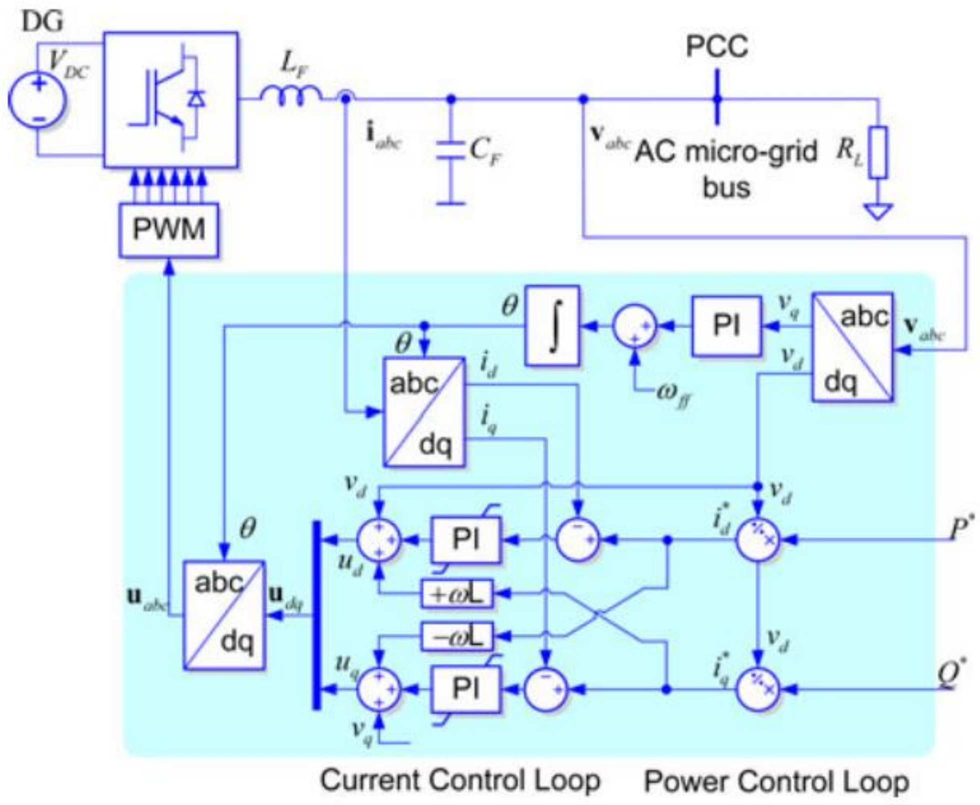


Fig. 3. Basic control structure in a three-phase grid-feeding power converter.

Closed-loop control of $P\star$ and $Q\star$

Grid-following converters: principle

- A grid-following unit is based on a power converter whose injected currents are controlled with a specific phase displacement with respect to the grid voltage at the PCC.
- As a consequence, the knowledge of the fundamental frequency phasor of the grid voltage at the PCC (PLL) is needed at any time for the correct calculation of the converter reference currents (DQ transform).
- The currents amplitude and angle with respect to the grid voltage phasor are properly modified by outer control loops so as to inject the required amount of active and reactive power or control the RMS.

Source: Paolone, M., et al. (2020). Fundamentals of power systems modelling in the presence of converter-interfaced generation. Electric Power Systems Research, 189(April), 106811.

Grid-following converters: comments

- If connected to a battery, it means that the battery is controllable, i.e., it can absorb or deliver power depending on a setpoint.
- the setpoint is fixed by a higher-level controller
- Several grid-following converters can work in parallel in a system
- But they require another device to regulate the imbalances, the grid frequency, and the grid voltage (e.g., grid-forming inverter).

Grid-forming converters (from [2])

Closed-loop control of $v\star$ and $\omega\star$

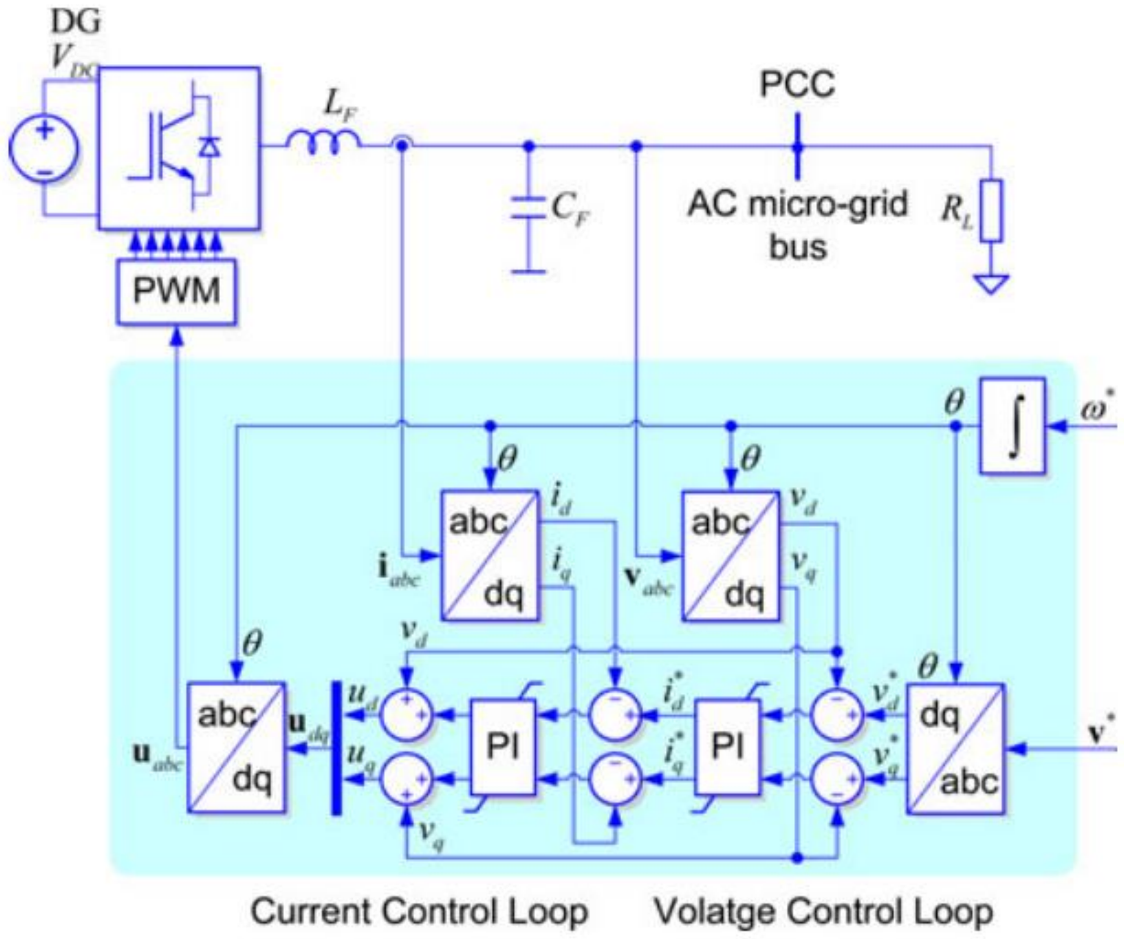


Fig. 2. Basic control structure in a three-phase grid-forming voltage source inverter generating a sinusoidal voltage determined by a nominal voltage amplitude v^* and reference frequency ω^*.

Grid-forming converters: comments

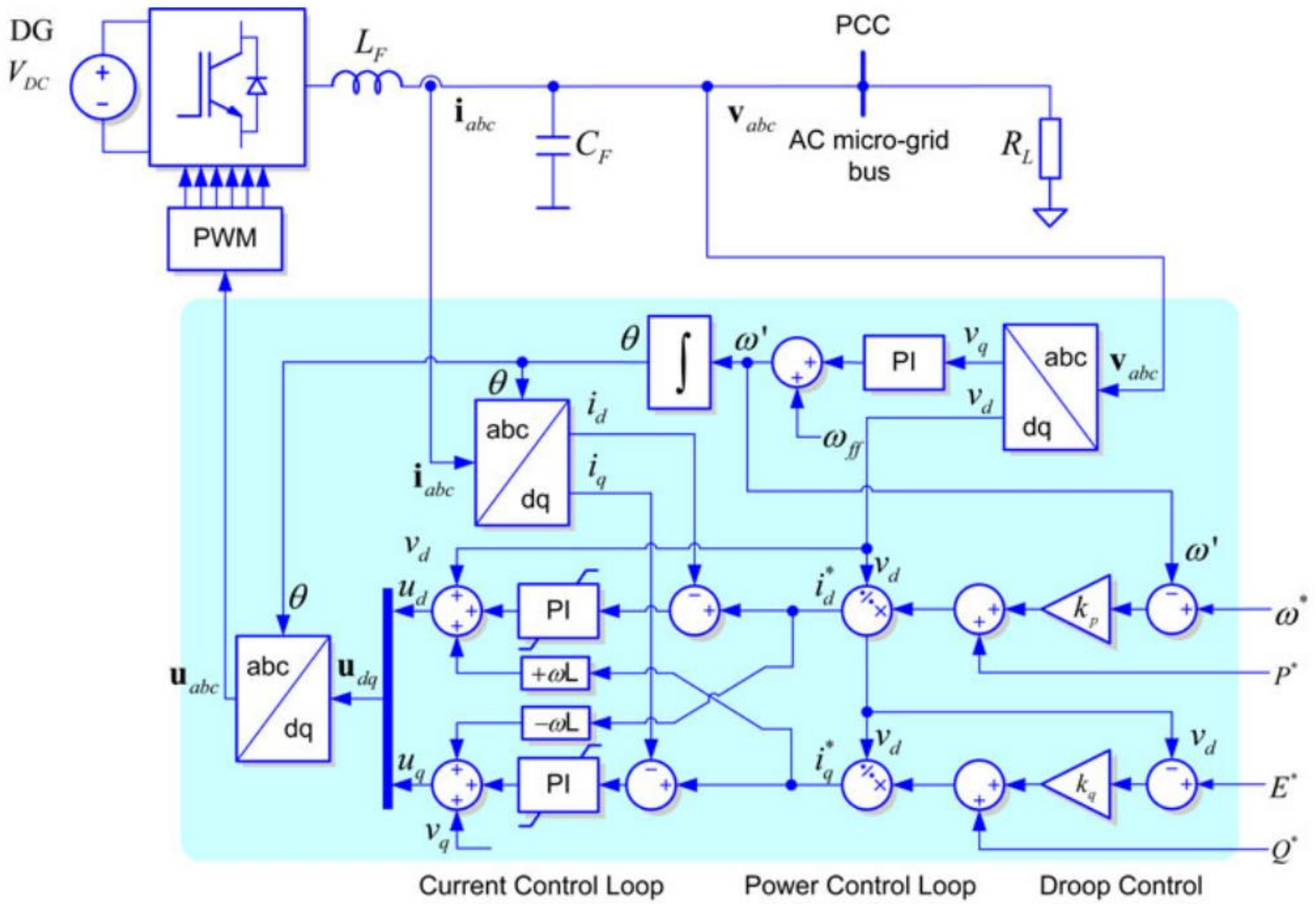
- In general, there is only one grid-forming device at a time, else some coordination is necessary:
  - " As voltage sources, they present a low-output impedance, so they need an extremely accurate synchronization system to operate in parallel with other grid-forming converters. Power sharing among grid-forming converters connected in parallel is a function of the value of their output impedances." [2]
- If connected e.g. to a battery, means that the battery follows the residual between generation and demand.
  - "A practical example of a grid-forming power converter can be a standby UPS. This system remains disconnected from the main grid when the operating conditions are within certain limits. In the case of a grid failure, the power converter of the UPS forms the grid voltage." [2].
  - "In a microgrid, the AC voltage generated by the grid-forming power converter will be used as a reference for the rest of grid-feeding power converters connected to it." [2].

Grid-forming inverter will likely be more and more present in bulk power systems

- "Grid-forming inverters are able to operate AC grids with or without rotating machines. In the past, they have been successfully deployed in inverter dominated island grids or in uninterruptable power supply (UPS) systems. It is expected that with increasing shares of inverter-based electrical power generation, grid-forming inverters will also become relevant for interconnected power systems. In contrast to conventional current-controlled inverters, grid-forming inverters do not immediately follow the grid voltage. They form voltage phasors that have an inertial behavior. In consequence, they can inherently deliver momentary reserve and increase power grid resilience."
- Source: Unruh, P., Nuschke, M., Strauß, P., & Welck, F. (2020). Overview on grid-forming inverter control methods. Energies, 13(10)

grid-supporting converters

- Can be seen as a grid-following converter with additional control loops to support the grid -> frequency and voltage regulation.

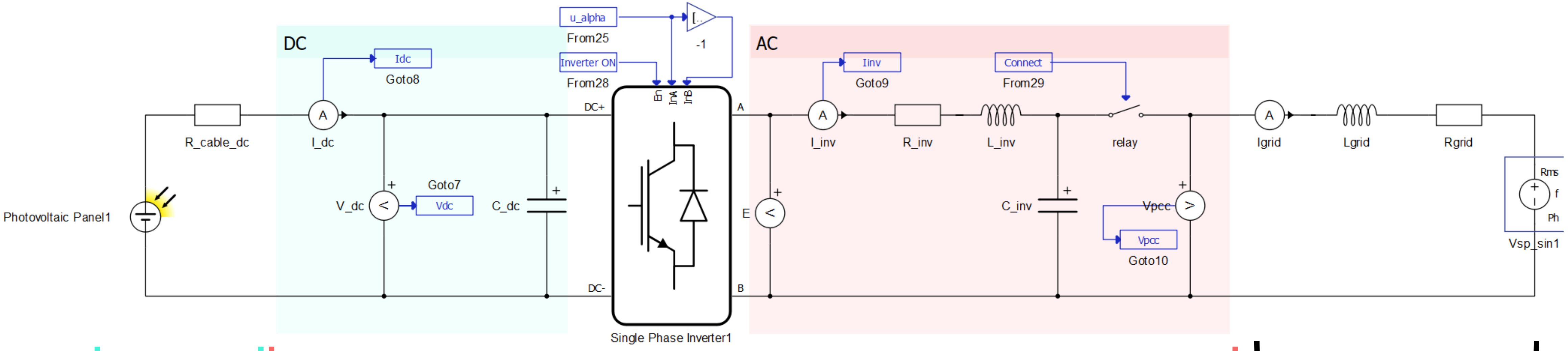


(a)

Typhoon HiL implementation explanation

PV inverter control

PV Inverter System



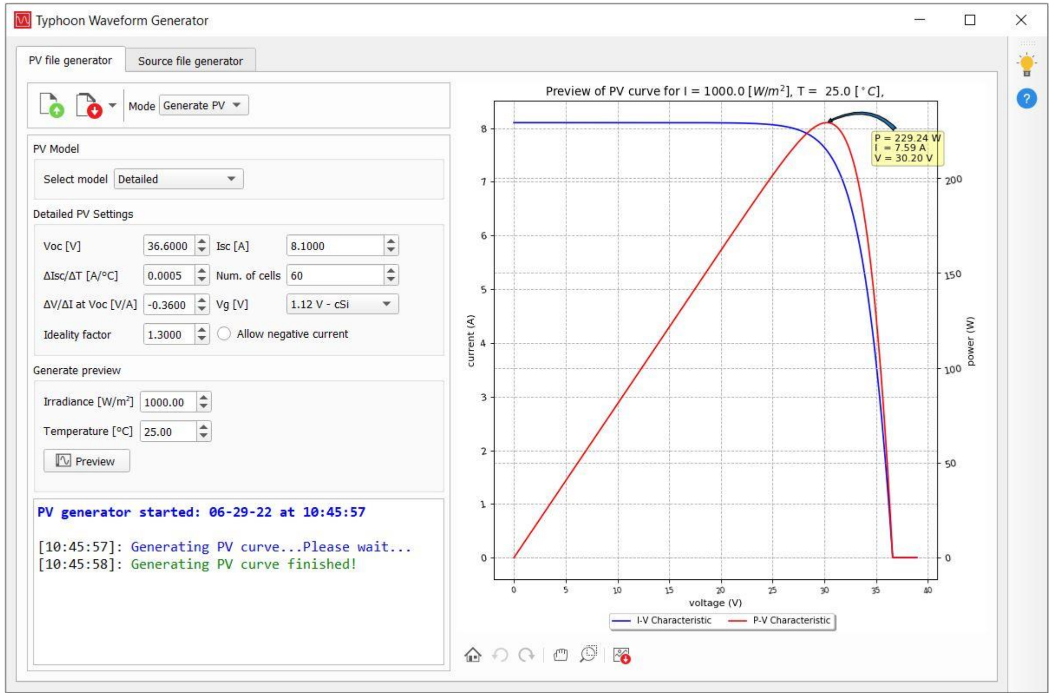
PV panels

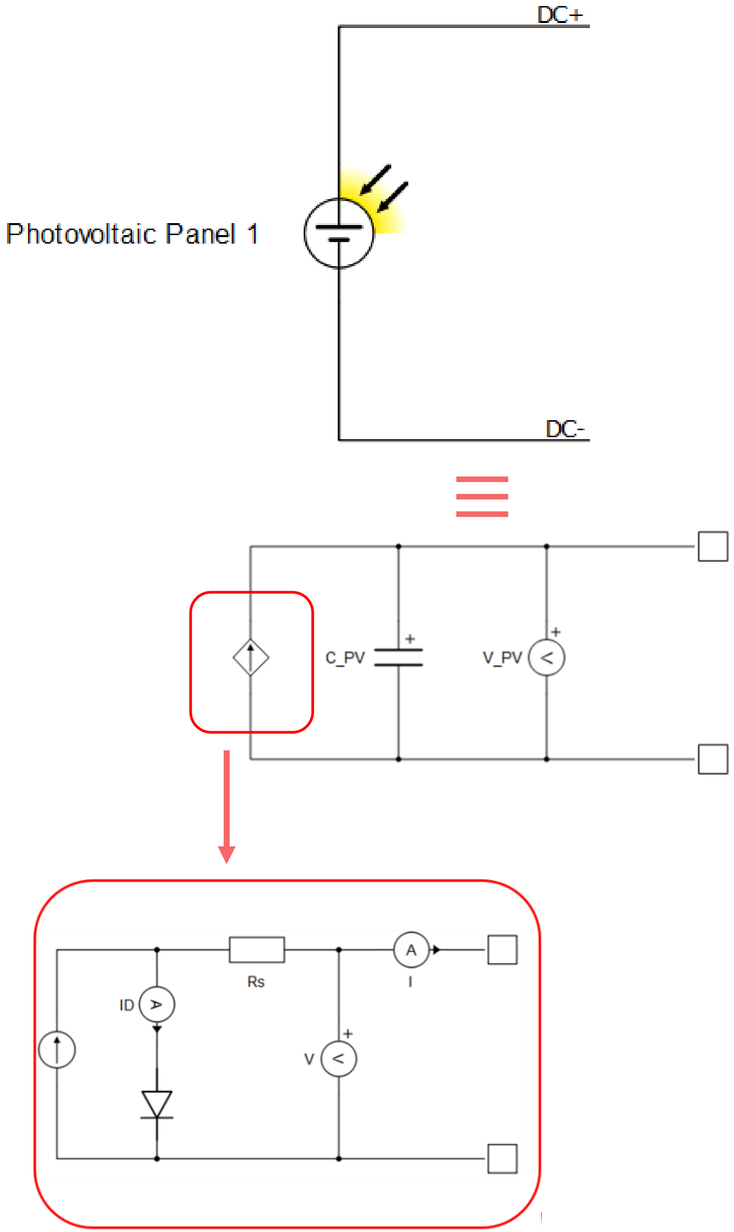
Inverter Hardware

Grid/Home Connection

Model of PV Panels

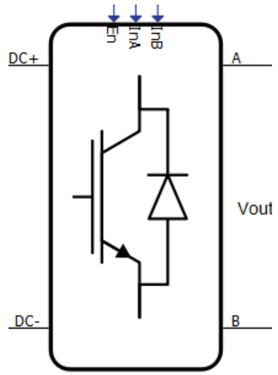
- Classical current source + diode model
- Models the I-V curve





Inverter Model

a) IGBT/FET modeled as ideal switch
b) PWM modulation



Single Phase Inverter

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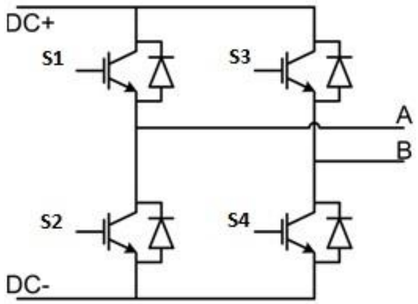
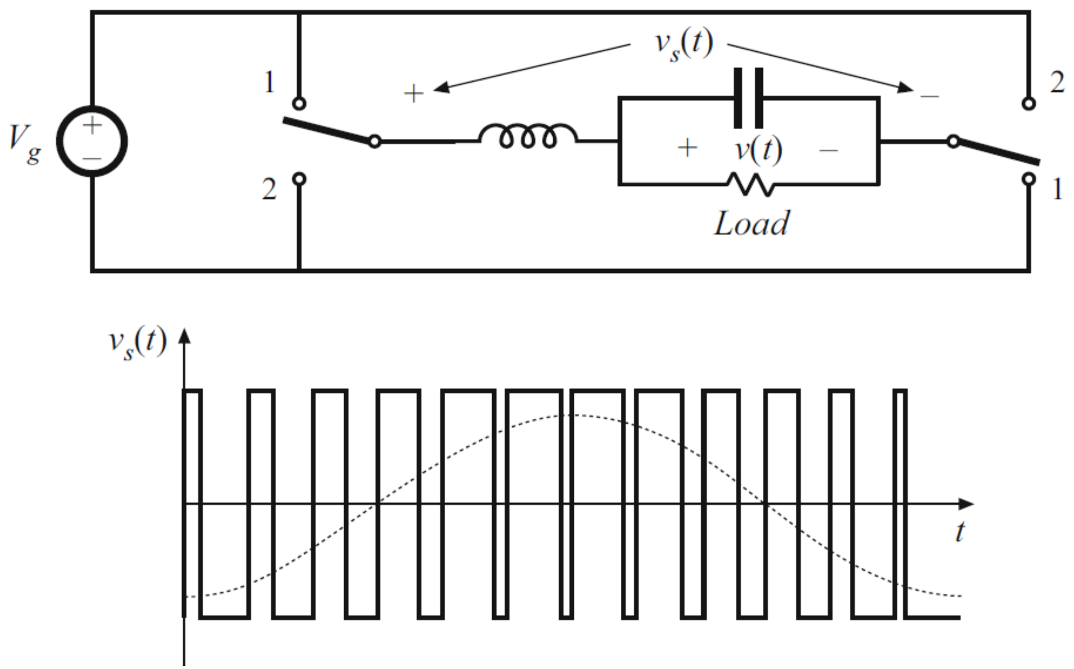


(a)
(b)



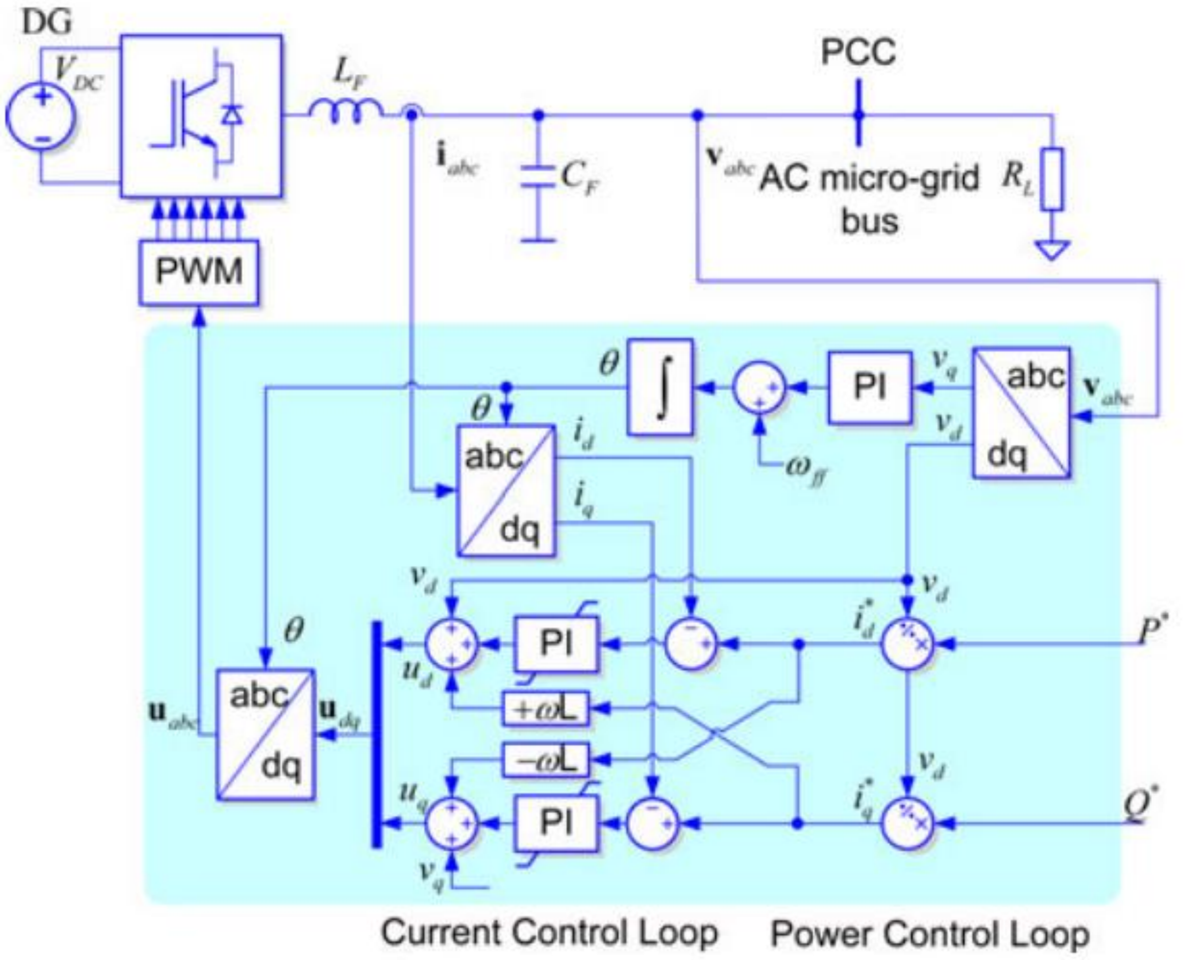
Output Filter design

- The L–C filter cutoff frequency is selected to pass the desired low-frequency components of $\mathrm{V}_s(t)$, but to attenuate the high-frequency switching harmonics

- $L = \frac{V_{dc}}{8\ \Delta i_L\ f_{sw}} * \%$
- $C\ = 15\%\ \frac{S_{inv,max}}{2\pi f\ V_{peak}^2}$

In our example f_{sw} = 10 kHz

Inverter Control



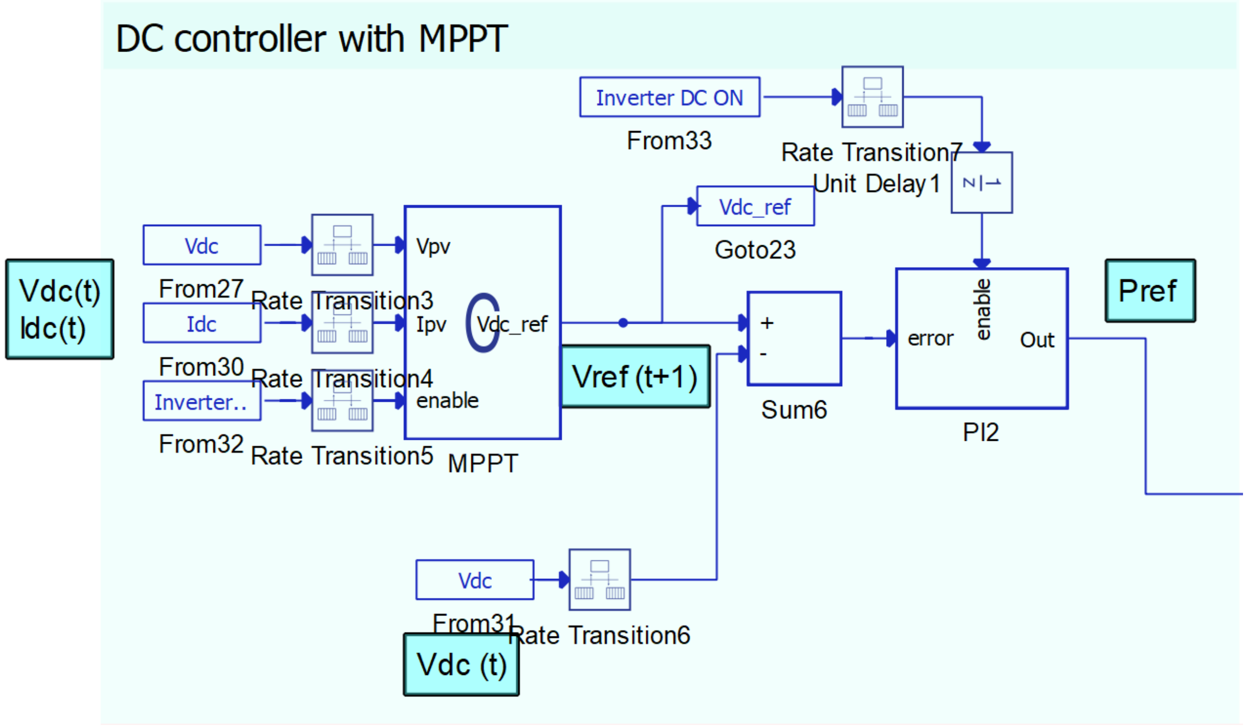
Inverter Control

How is the inverter controlled?

This is a grid-following converter

1. It thus requires active and reactive setpoints P_{ref} and Q_{ref}
   - P_{ref} is obtained from MPPT (relatively slow control loop)
   - Q_{ref} is set by the user here (could be from a voltage droop controller)
2. V_a The AC grid voltage is read -> for synchronization + for Power control
3. I_a The AC inverter ouput current is read -> for Power control
4. It generates the signal to modulate the switches so as to produce the right I_a , in amplitude and phase. (relatively fast control loop)

1. P_{ref}: MPPT control

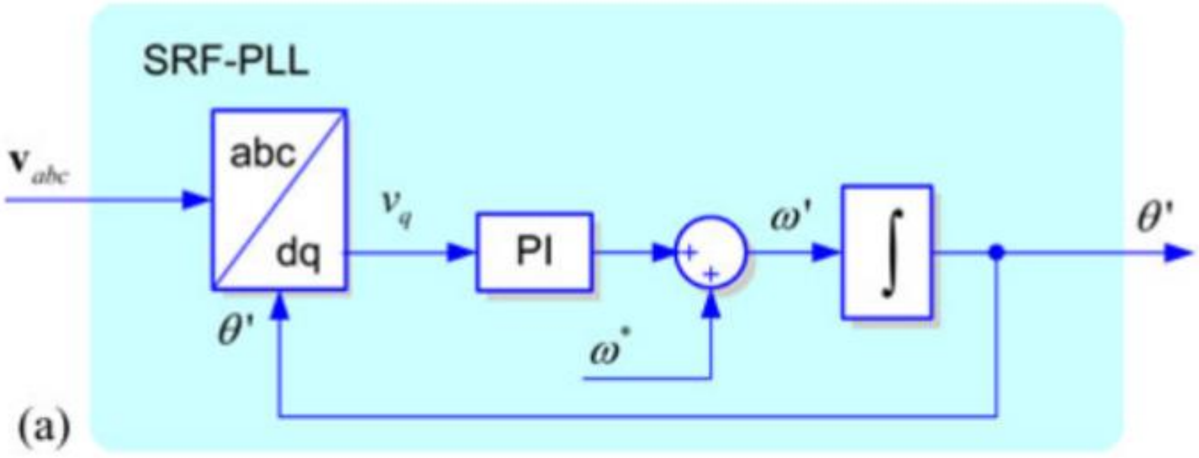


1) MPPT algorithm (see assignment 2 😉) determine the DC V_{ref} that track the MPP

2) Simple PI controller ensure zero steady state error between the $V_{dc}(t)$ and V_{ref} by generating the P_{ref} of the inverter. Intuition, it draws more power if $V_{dc}(t) > V_{ref}$ or draws less power if $V_{dc}(t) < V_{ref}$ and the goal is to have $V_{dc}(t) = V_{ref}$ to meet MPP.

2. Phase Lock Loop (PLL)

Input :
$Vgrid(t)$



Output :
1) $\theta(t) = \omega t$
2) $frequency$

Goal : Synchronize with the grid

How does it work ?

→Answer : It adjusts his output frequency using a PI controller until the quadrature component reach 0. V_q can be seen as the "error of synchronisation" with the phase of the grid.

DQ transform ??

DQ Transform

- Instead of working with instantaneous values that change all the time, apply a transformation to obtain important information for control:
  - How is the grid current phasor placed with respect to voltage phasor
  - “Kind of equivalent to working in DC”
- The *dq* transform is the composition of the Clarke and Park transforms
  - Clarke transform: “Encode time-varying values on fixed $\alpha - \beta$ axes (2D)”
  - Park transform: Let the axes rotate to “get rid of the $e^{j\omega t}$”

- See for instance: O’Rourke, C. J., Qasim, M. M., Overlin, M. R., & Kirtley, J. L. (2019). A Geometric Interpretation of Reference Frames and Transformations: Dq0, Clarke, and Park. *IEEE Transactions on Energy Conversion*, *34*(4), 2070–2083. https://doi.org/10.1109/TEC.2019.2941175

A bit of history

The Clark and Park transforms, both foundational in the field of electrical engineering, were introduced in the early 20th century:

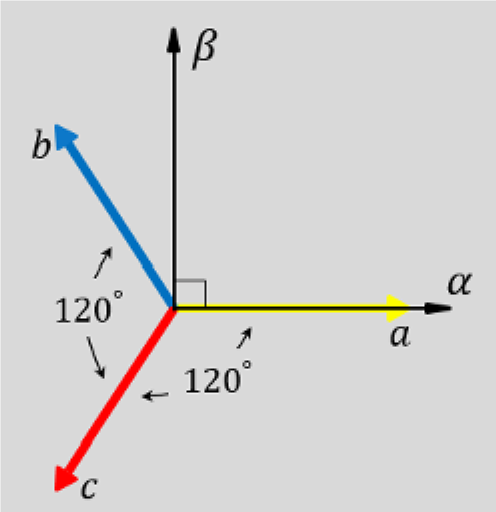
1. **Clark Transform (α-β transform)**: Introduced by **Edouard Clarke** in 1937, *this transform converts three-phase AC currents or voltages into a two-axis orthogonal system (α-β) to simplify the analysis of AC systems.*
2. **Park Transform (dq0 transform)**: Developed by **Robert H. Park** in 1929, *the Park transform is used to convert three-phase AC quantities into a rotating reference frame, simplifying the control of AC machines, particularly in the context of synchronous machines.*

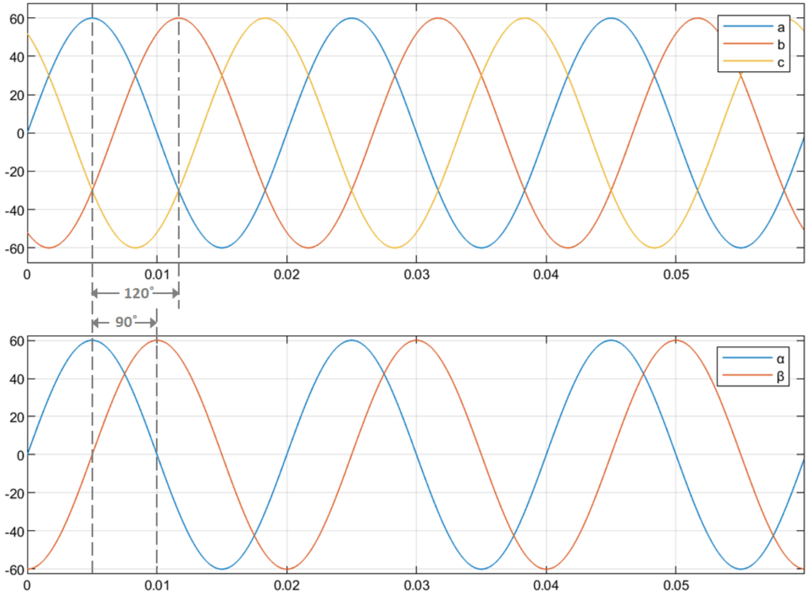
DQ Transform

1) Clarke Transform (or α-β Transorm)

3 phase system

$$\begin{pmatrix} i_\alpha(t) \\ i_\beta(t) \\ i_o(t) \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{pmatrix}$$





DQ Transform

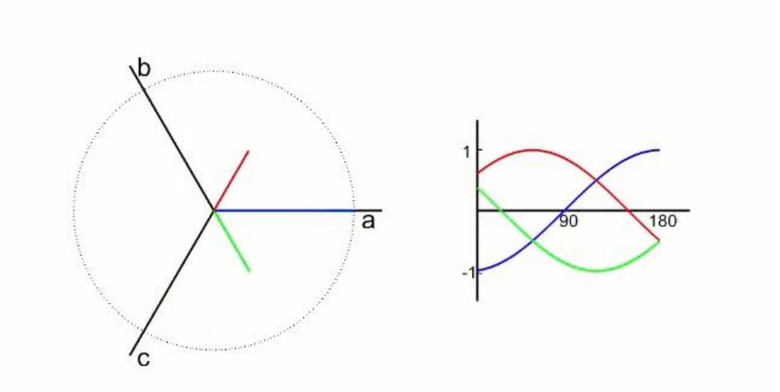
1) Clarke Transform (or α-β Transform)

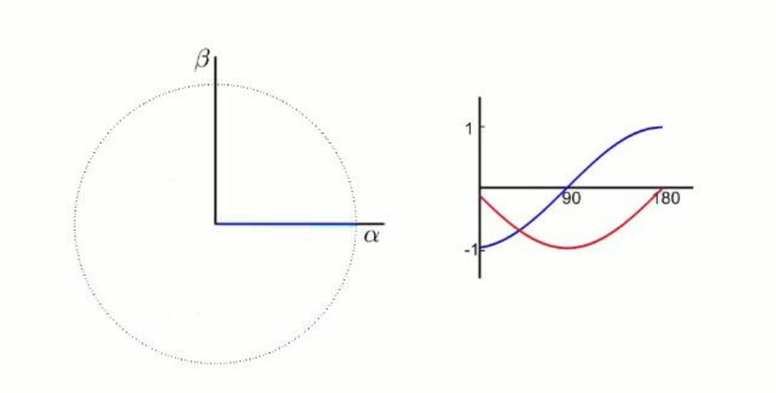
1 phase system :

$$\begin{pmatrix} i_\alpha(t) \\ i_\beta(t) \\ i_o(t) \end{pmatrix} = \begin{pmatrix} 1 & \frac{-1}{\omega}\frac{d}{dt} & 0 \end{pmatrix} \begin{pmatrix} i_a(t) \end{pmatrix}$$

$$i_a(t) = I_a \cos(\omega t + \phi_i)$$

→ $i_\alpha(t) = I_a \cos(\omega t + \phi_i)$
→ $i_\beta(t) = I_a \sin(\omega t + \phi_i)$





DQ Transform

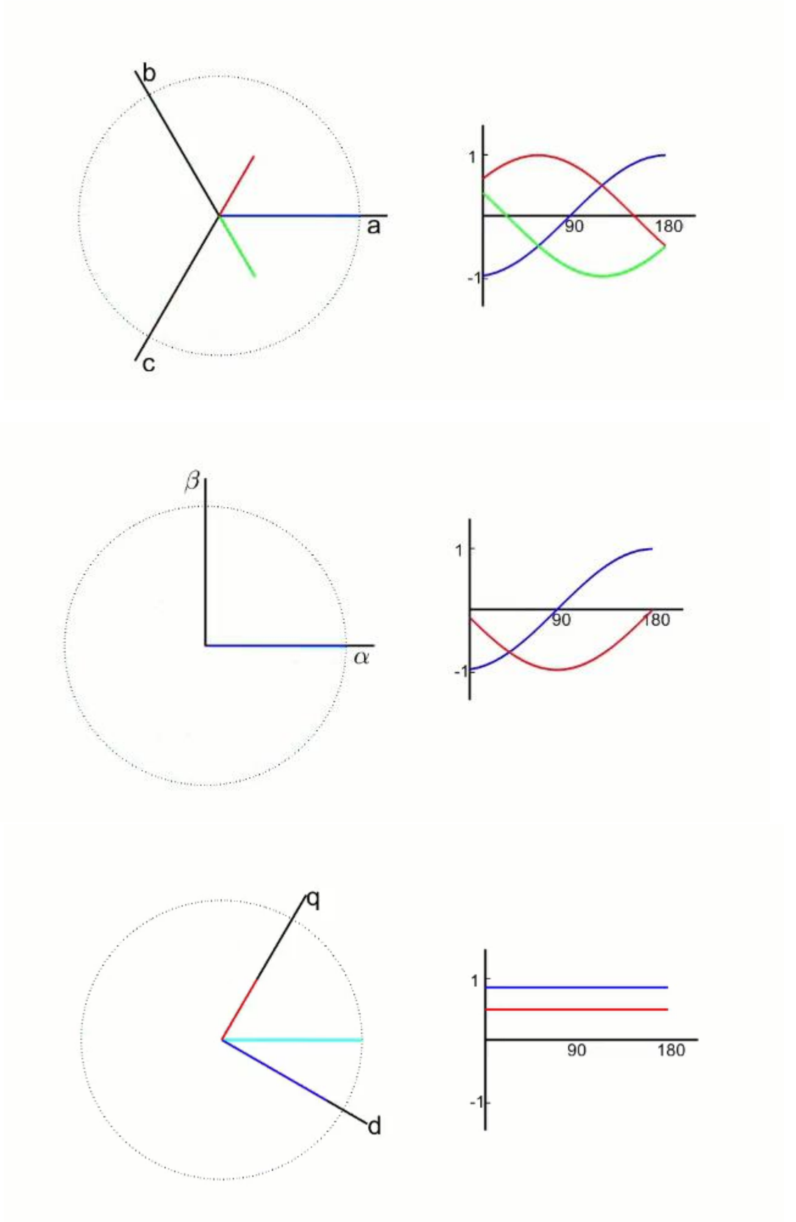
2) Park Transform (or d-q Transform)

$$\begin{pmatrix} i_d(t) \\ i_q(t) \\ i_o(t) \end{pmatrix} = \begin{pmatrix} \cos(\omega t) & \sin(\omega t) & 0 \\ -\sin(\omega t) & \cos(\omega t) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} i_\alpha(t) \\ i_\beta(t) \\ i_o(t) \end{pmatrix}$$

(Rotation matrix around z axis)

$$i_\alpha(t) = I_a \cos(\omega t + \phi_i)$$
$$i_\beta(t) = I_a \sin(\omega t + \phi_i)$$

→ $i_d(t) = I_a\,(\cos(\omega t + \phi_i)\cos(\omega t) + \sin(\omega t + \phi_i)\sin(\omega t))$
→ $i_q(t) = I_a\,(-\cos(\omega t + \phi_i)\sin(\omega t) + \sin(\omega t + \phi_i)\sin(\omega t))$



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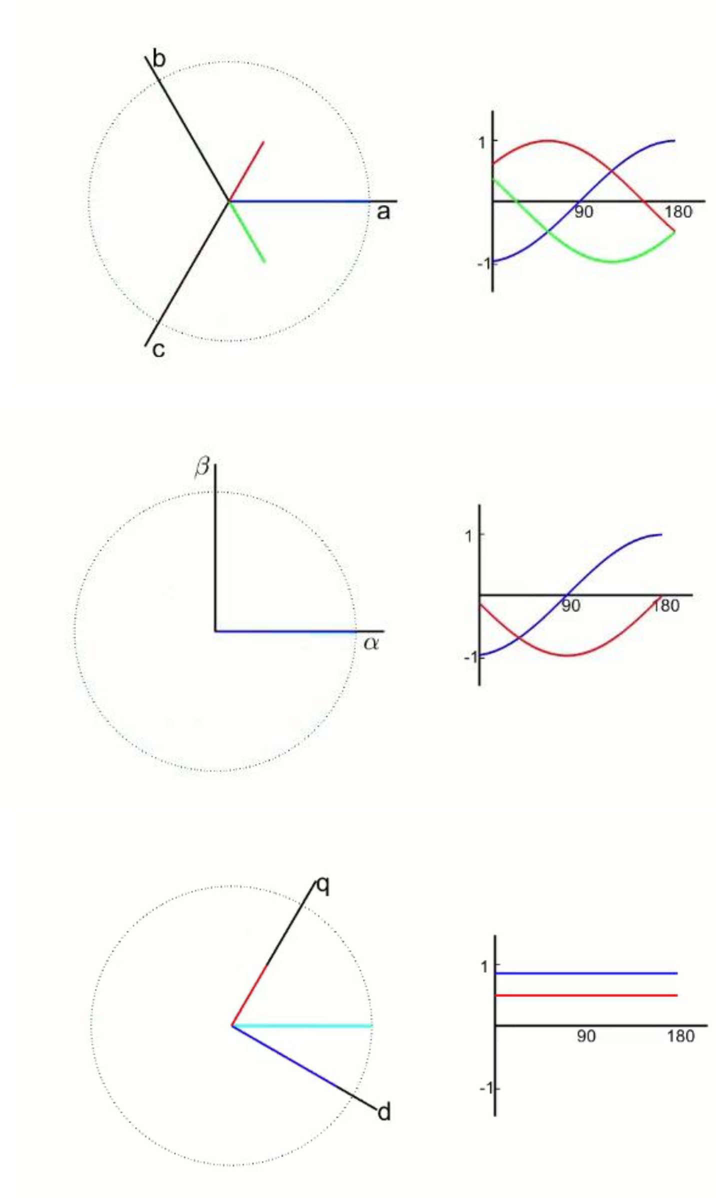
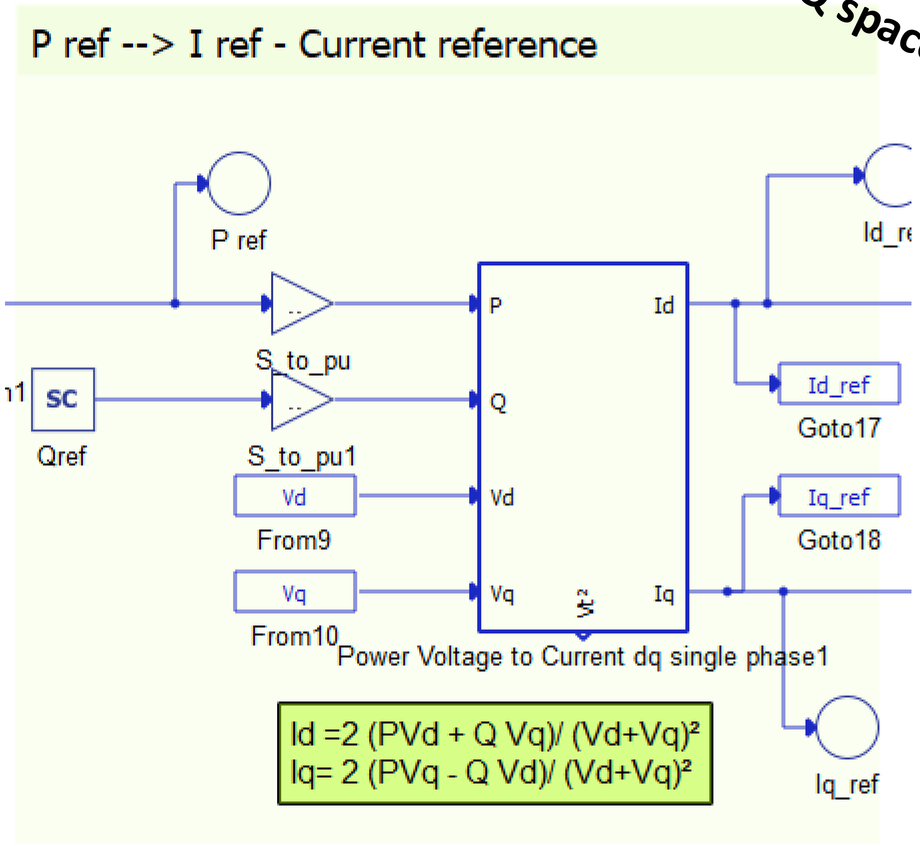


DQ component describe « DC » phase and magnitude information

3. Power Control → Current Control

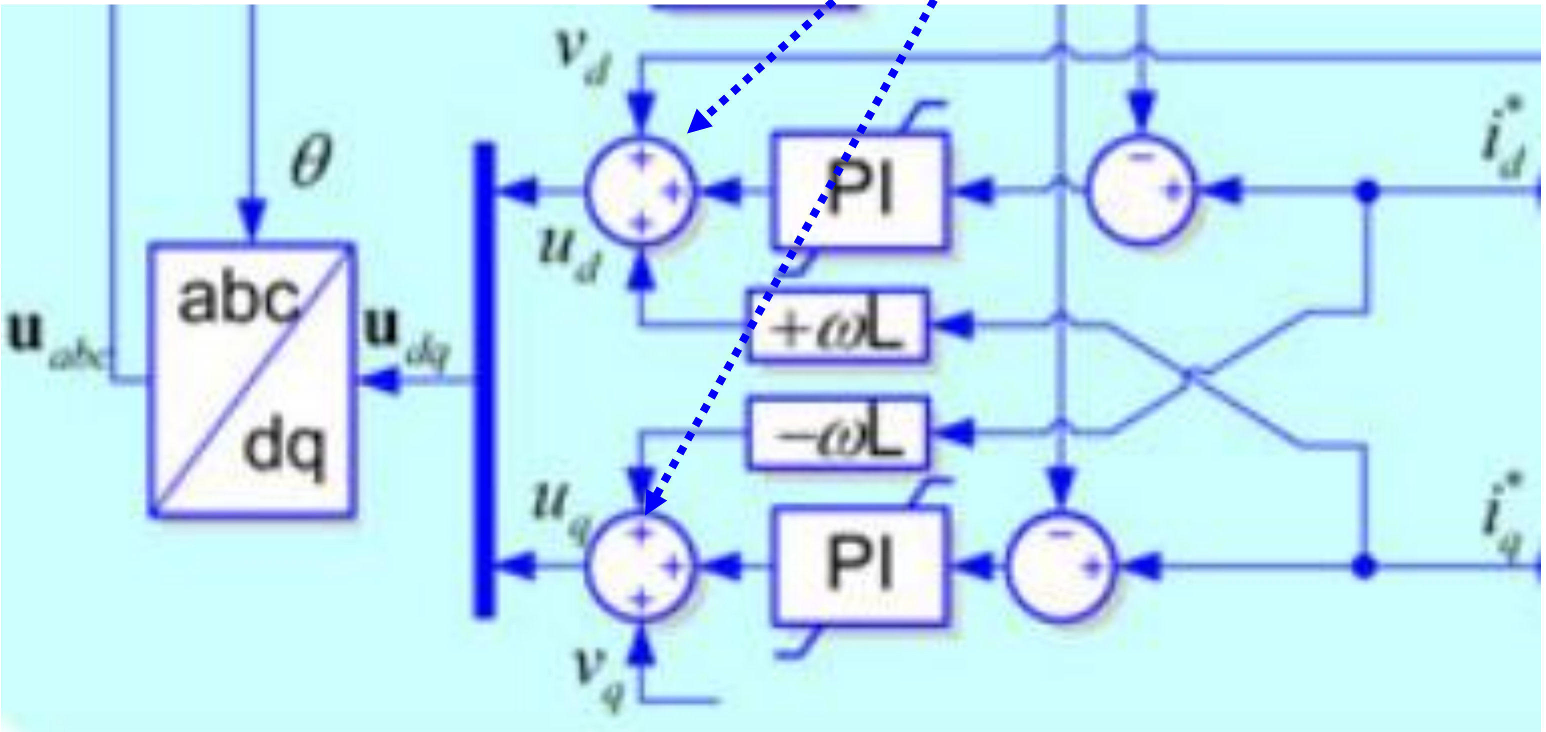
DQ space



4. Current controller

Feed-forward terms used to improve the performance of the controller (stability and response time).

$V_{mod,PWM}$



$I_{d,ref}$

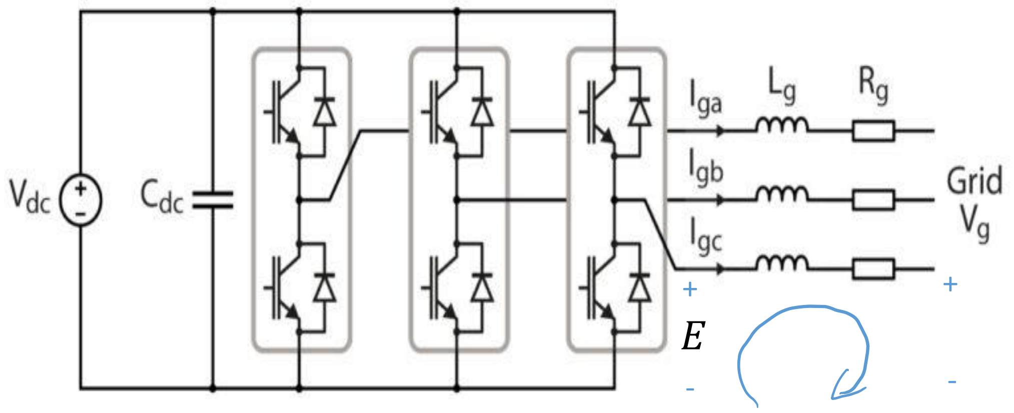
$I_{q,ref}$

4. Current controller

Feedforward term ?

SLK

$$\begin{pmatrix} E_a \\ E_b \\ E_c \end{pmatrix} = R_g \begin{pmatrix} I_{g,a} \\ I_{g,b} \\ I_{g,c} \end{pmatrix} + L_g \frac{d}{dt} \begin{pmatrix} I_{g,a} \\ I_{g,b} \\ I_{g,c} \end{pmatrix} + \begin{pmatrix} V_{g,a} \\ V_{g,b} \\ V_{g,c} \end{pmatrix}$$



NB : Don’t forget all V and I signals are time dependent

DQ transform

$$T_\theta^{-1} \begin{pmatrix} E_d \\ E_q \\ E_o \end{pmatrix} = R_g T_\theta^{-1} \begin{pmatrix} I_d \\ I_q \\ I_o \end{pmatrix} + L_g \frac{d}{dt} \left(T_\theta^{-1} \begin{pmatrix} I_d \\ I_q \\ I_o \end{pmatrix} \right) + T_\theta^{-1} \begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix}$$

$$\begin{pmatrix} E_d \\ E_q \\ E_o \end{pmatrix} = R_g \begin{pmatrix} I_d \\ I_q \\ I_o \end{pmatrix} + L_g T_\theta \frac{d}{dt} (T_\theta^{-1}) \begin{pmatrix} I_d \\ I_q \\ I_o \end{pmatrix} + L_g \cancel{T_\theta T_\theta^{-1}} \frac{d}{dt} \begin{pmatrix} I_d \\ I_q \\ I_o \end{pmatrix} + T_\theta^{-1} \begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix}$$

$T_\theta * \text{abc} \rightarrow \text{dq}$

$T_\theta^{-1} * \text{dq} \rightarrow \text{abc}$

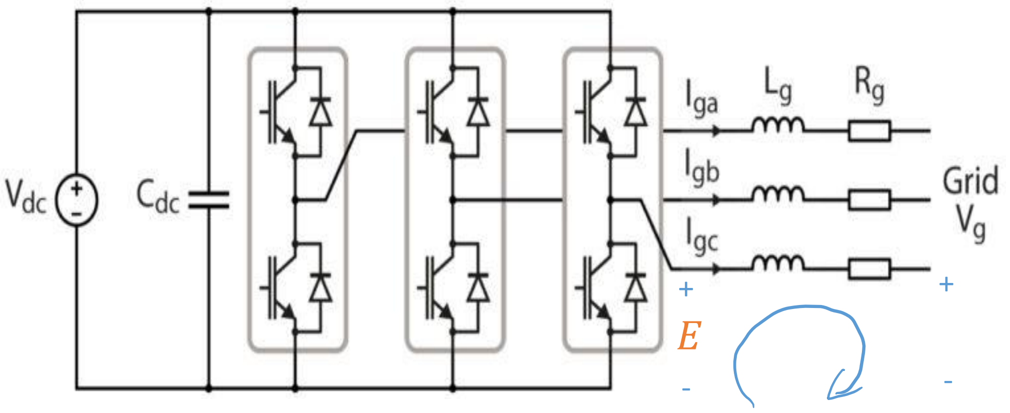
$$T_\theta \frac{d}{dt} (T_\theta^{-1}) = \begin{pmatrix} 0 & \omega & 0 \\ -\omega & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

4. Current controller

Feedforward term ?

SLK

$$\begin{pmatrix} E_a \\ E_b \\ E_c \end{pmatrix} = R_g \begin{pmatrix} I_{g,a} \\ I_{g,b} \\ I_{g,c} \end{pmatrix} + L_g \frac{d}{dt} \begin{pmatrix} I_{g,a} \\ I_{g,b} \\ I_{g,c} \end{pmatrix} + \begin{pmatrix} V_{g,a} \\ V_{g,b} \\ V_{g,c} \end{pmatrix}$$



NB : Don't forget all V and I signals are time dependent

DQ transform

$$E_d = \underbrace{R_g I_d + L_g \frac{d\,I_d}{dt}}_{\text{PID}} + \underbrace{\omega L I_q}_{\text{Feed Forward (1)}} + \underbrace{V_d}_{\text{Feed Forward (2)}}$$

$$E_q = R_g I_q + L_g \frac{d\,I_q}{dt} - \omega L I_d + V_q$$

The AC Voltage we want to generate with the switching

PID

Feed Forward (1)

Feed Forward (2)

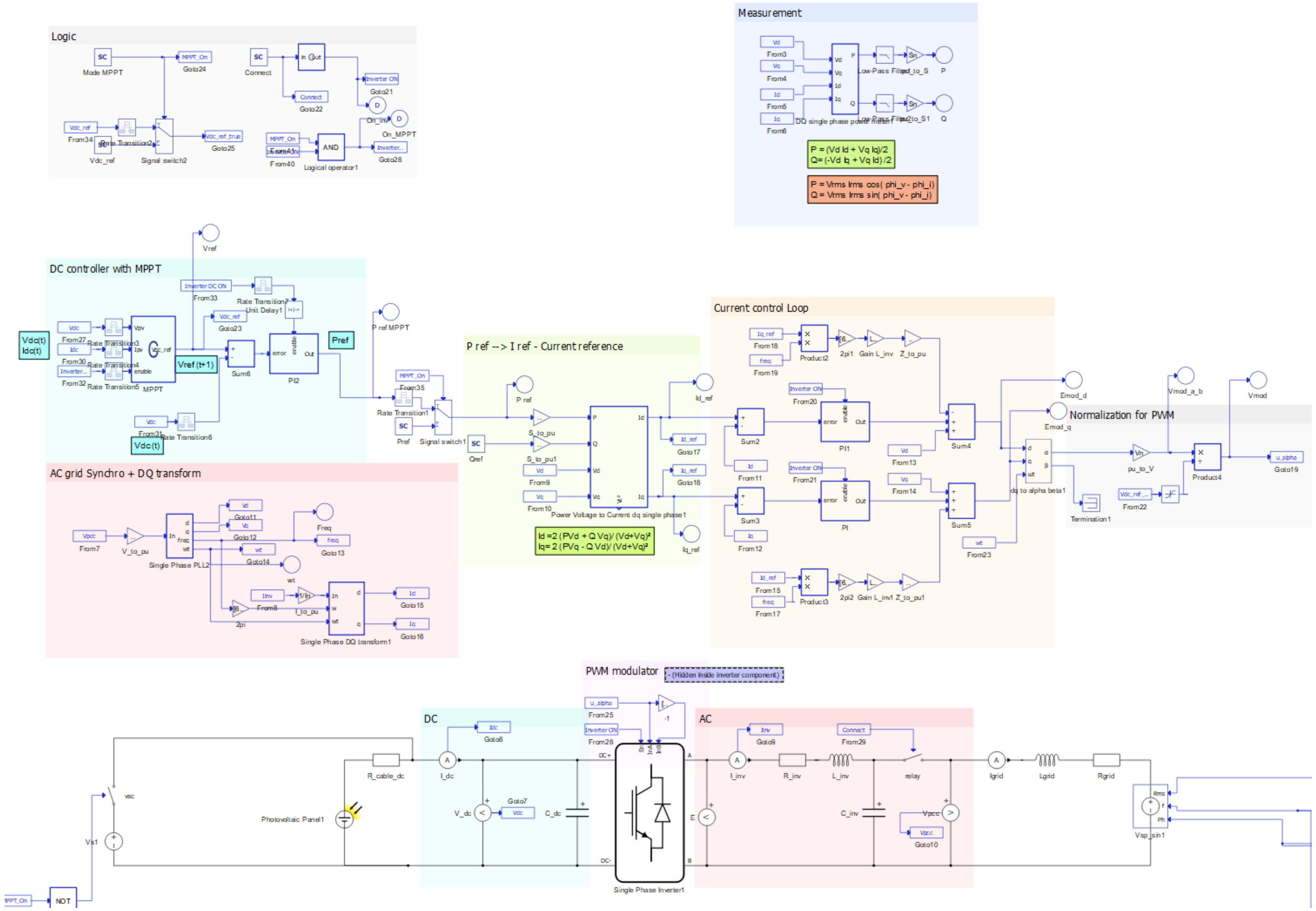
True also for single phase

$T_\theta \ * \text{abc} \ \rightarrow \text{dq}$

$T_\theta^{-1} \ * \ \text{dq} \ \rightarrow \ \text{abc}$

$$T_\theta \frac{d}{dt}\left(T_\theta^{-1}\right) = \begin{pmatrix} 0 & \omega & 0 \\ -\omega & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

5. Time for a Live Demo !



References

- See Rocabert, J., Luna, A., Blaabjerg, F., & Rodríguez, P. (2012). Control of power converters in AC microgrids. *IEEE Transactions on Power Electronics*, *27*(11), 4734–4749. https://doi.org/10.1109/TPEL.2012.2199334