Module 3

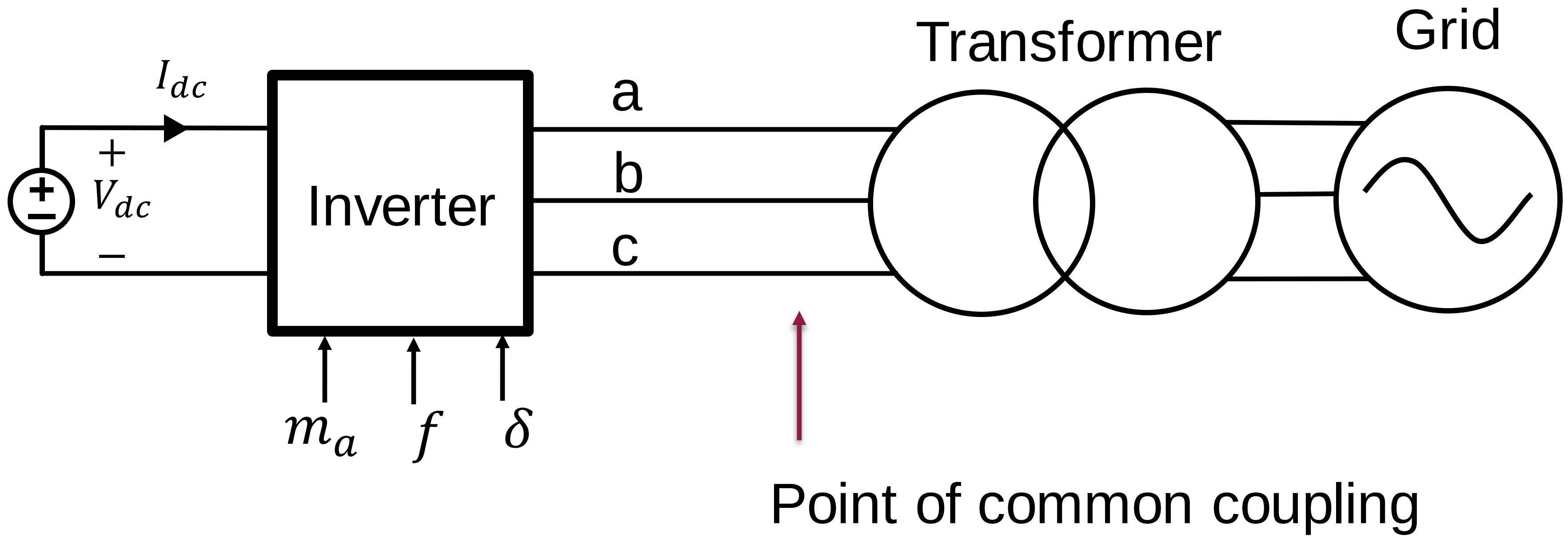
# Grid-Following Inverters

*How do they work and what are they expected to do?*

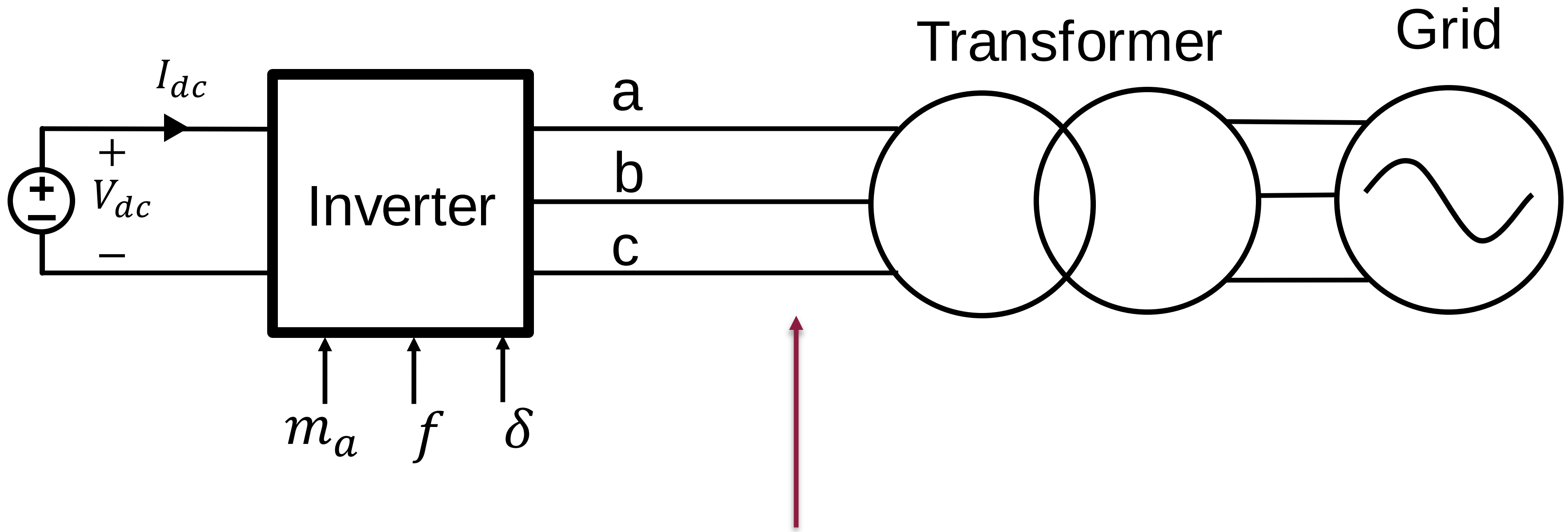
Arizona State University

# Key Assumption: The Stiff Grid

- Philosophy: “The grid exists, how do we connect to it?”

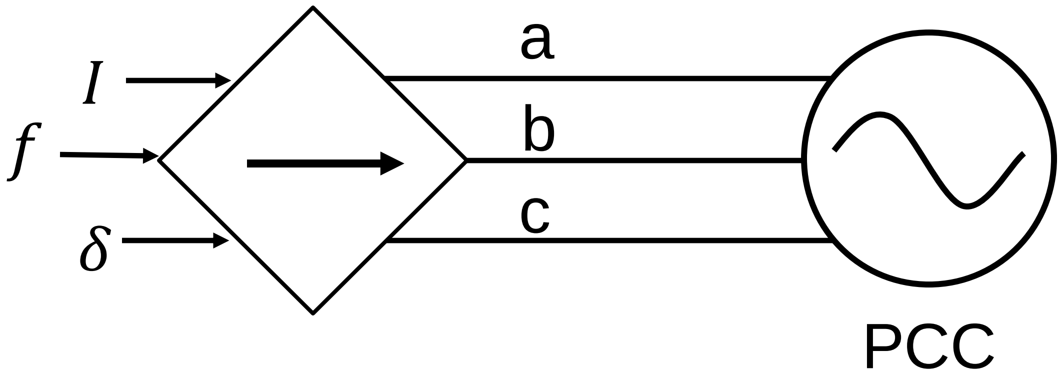


# Key Assumption: The Stiff Grid




- Constant voltage magnitude
- Constant frequency
- Balanced
- Not only do we not provide inertia, we *rely* on inertia

# Create a Controlled Current Source



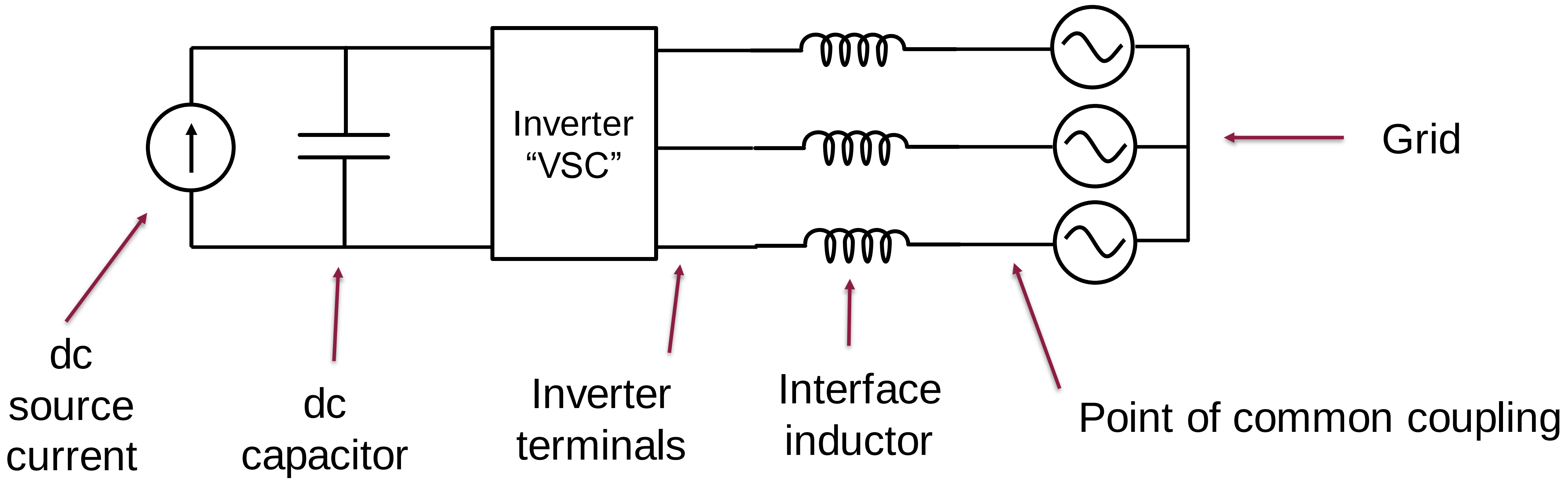

- Commanding magnitude and phase gives us power control
- Frequency must be equal to PCC

# Reminder: Sinusoidal Power Transfer

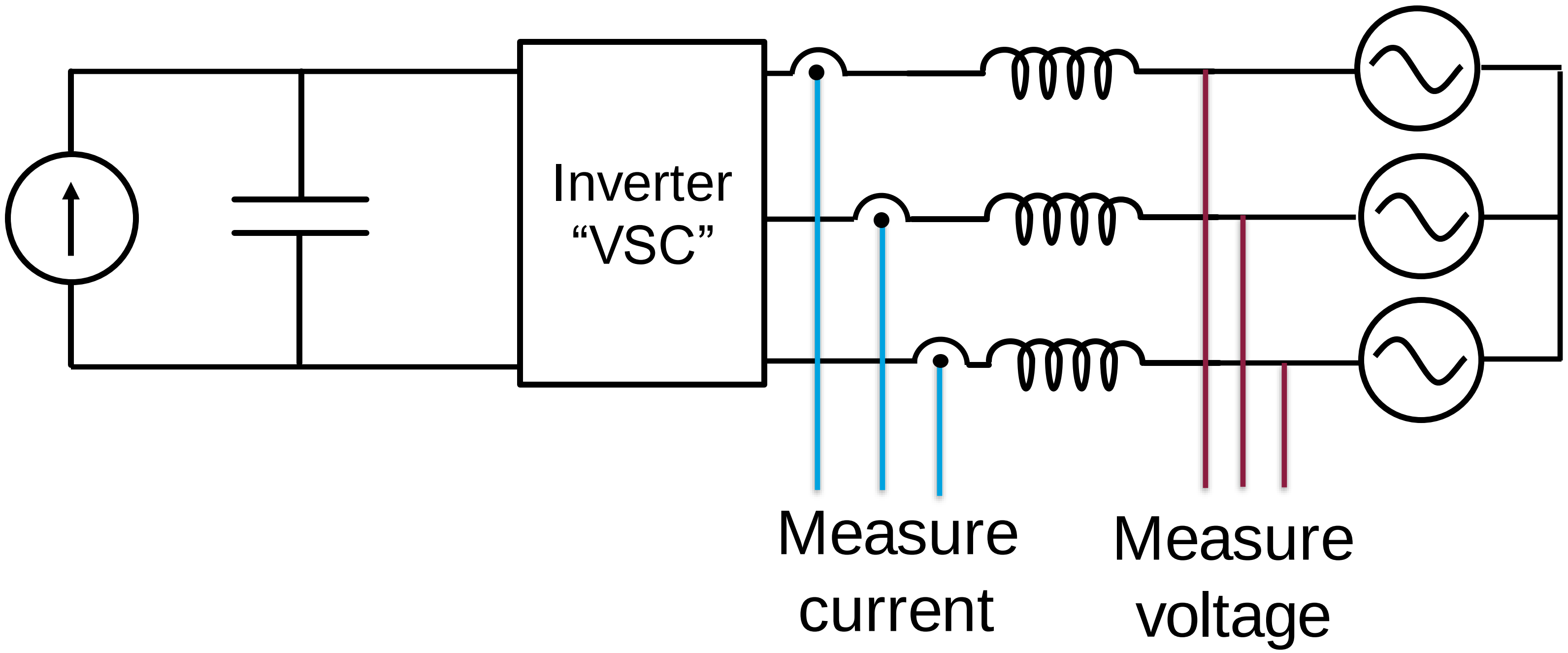
- The only way to transfer between sources is for them to have the same frequency
- $v(t) = V\sin(\omega_1 t)$
- $i(t) = I\sin(\omega_2 t)$
- $p(t) = VI\,\sin(\omega_1 t)\sin(\omega_2 t)$
- $p(t) = \frac{VI}{2}[\cos((\omega_1 - \omega_2)t) - \cos((\omega_1 + \omega_2)t)]$
- Average = 0 unless $\omega_1 = \omega_2$

# Voltage-Sourced Converter System

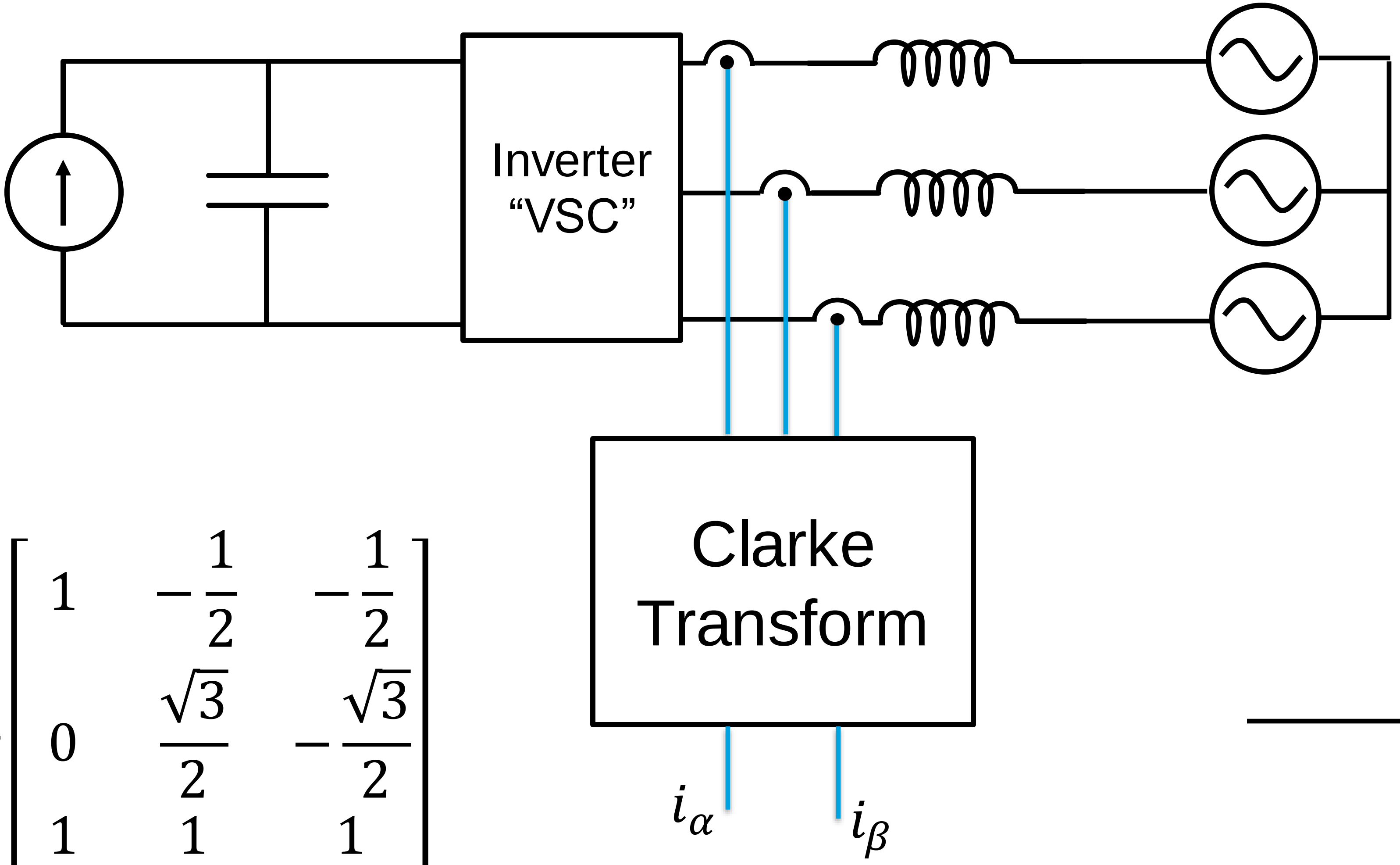
- The inverter system in practice is as follows



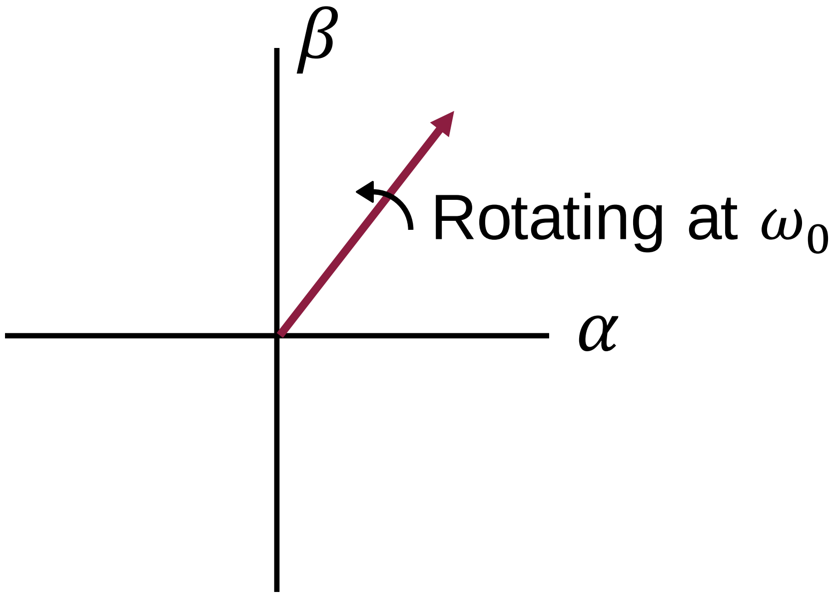
# Voltage-Controlled Current Source



# Alpha-beta Frame via Clarke Transform




$$C = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$



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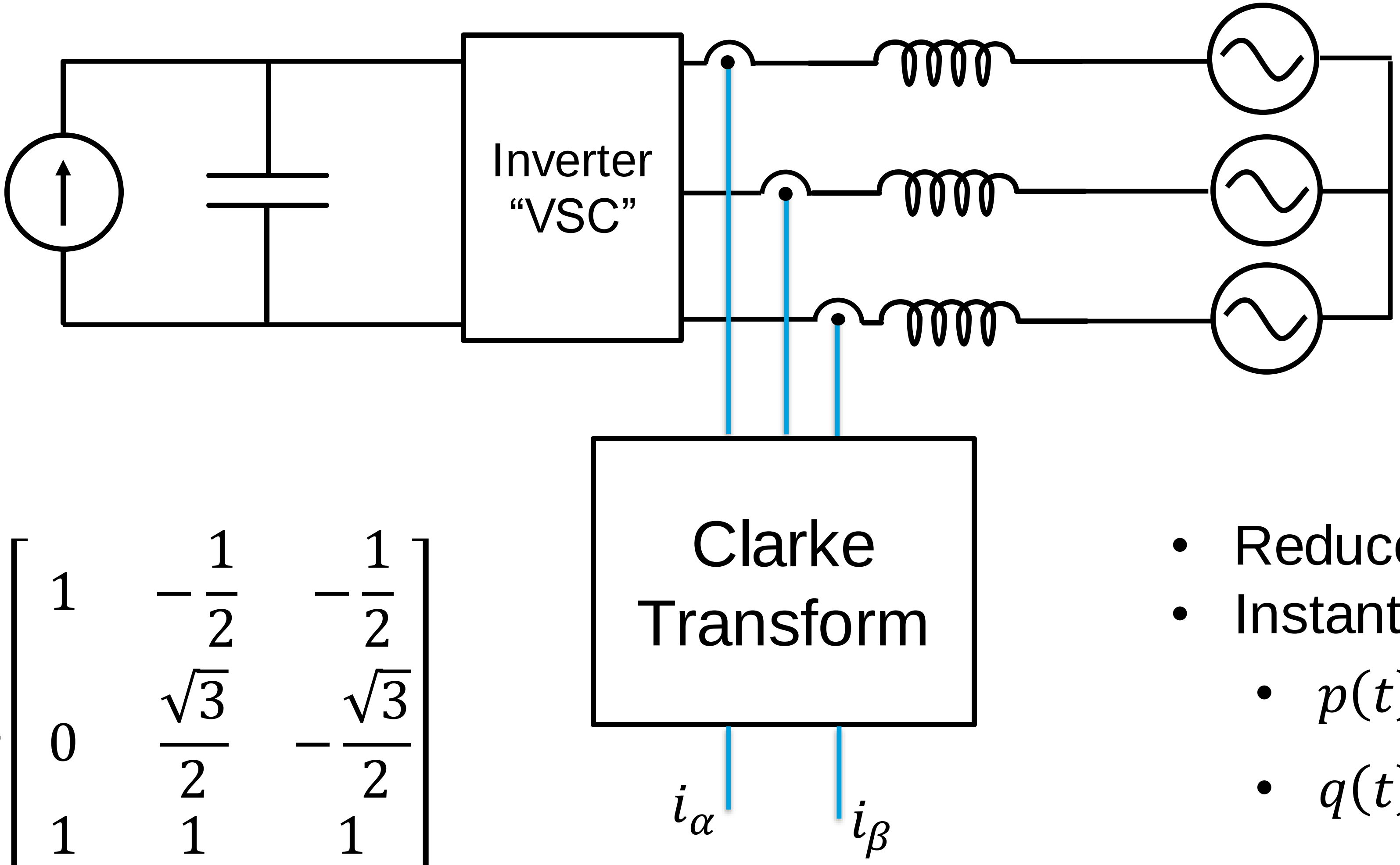


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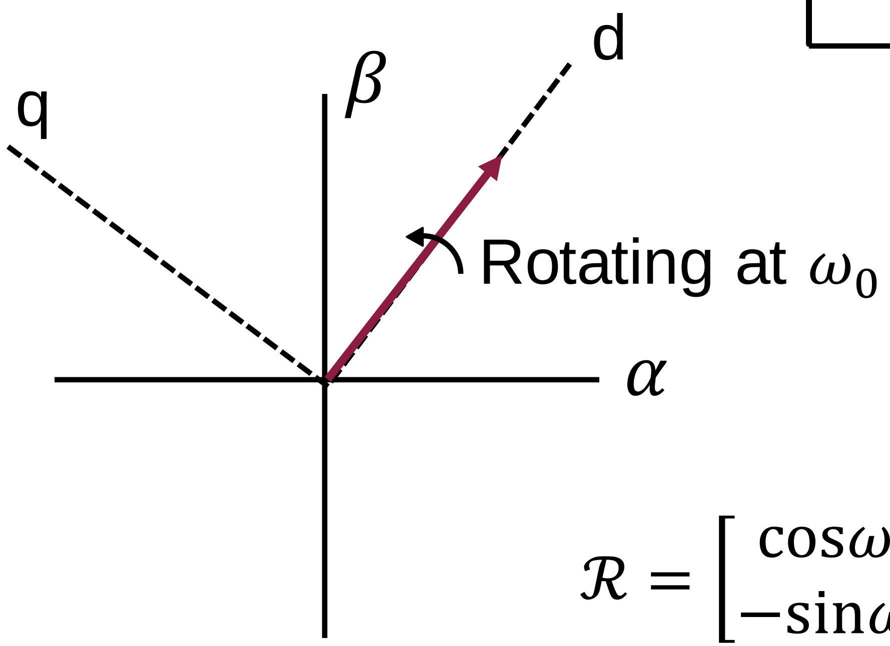
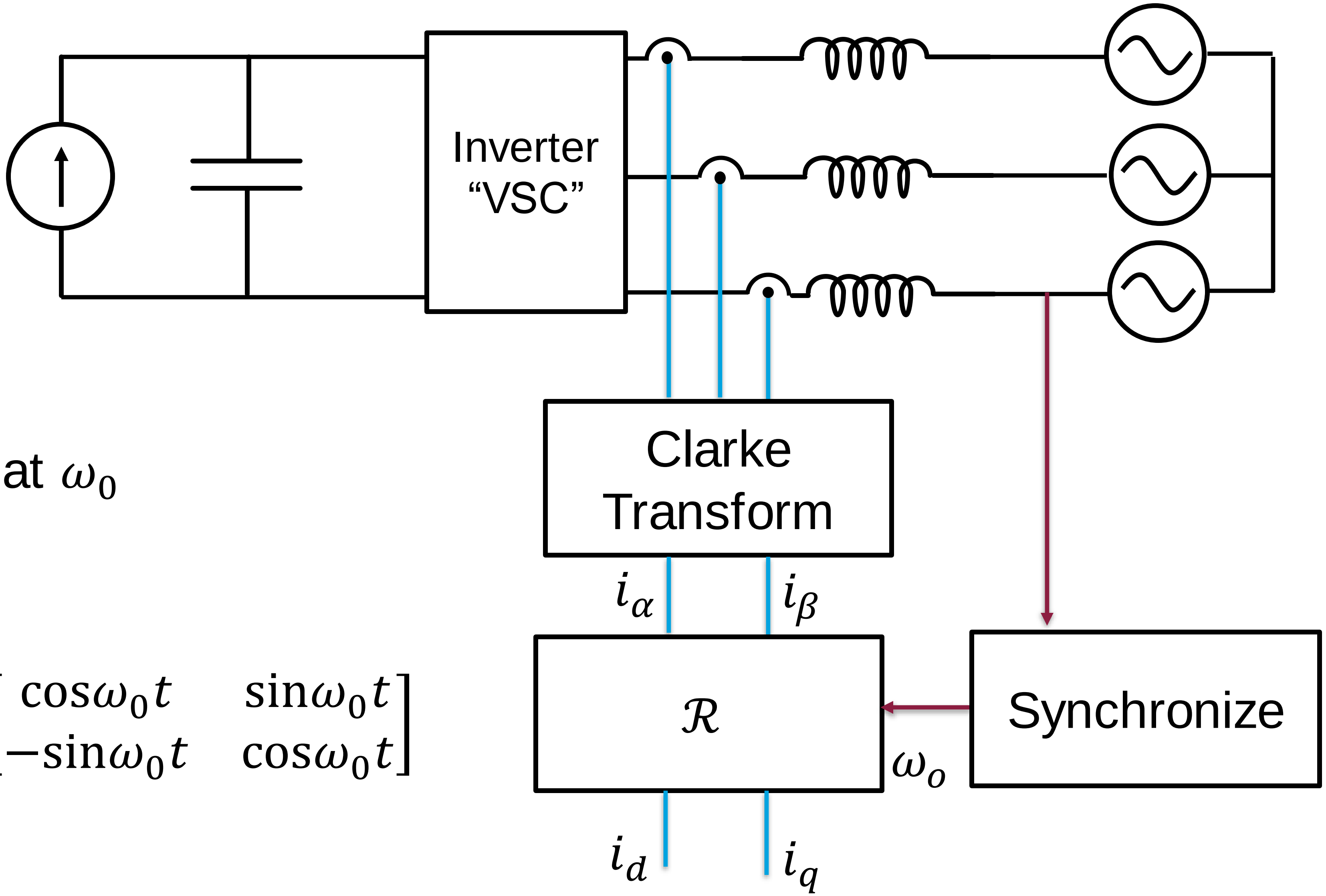
- Reduce to two parameters
- Instantaneous measurements:
  - $p(t) = \frac{3}{2}\left(v_\alpha i_\alpha + v_\beta i_\beta\right)$
  - $q(t) = \frac{3}{2}\left(v_\beta i_\alpha - v_\alpha i_\beta\right)$

# Stationary "dq" Reference Frame




$$\mathcal{R} = \begin{bmatrix} \cos\omega_0 t & \sin\omega_0 t \\ -\sin\omega_0 t & \cos\omega_0 t \end{bmatrix}$$



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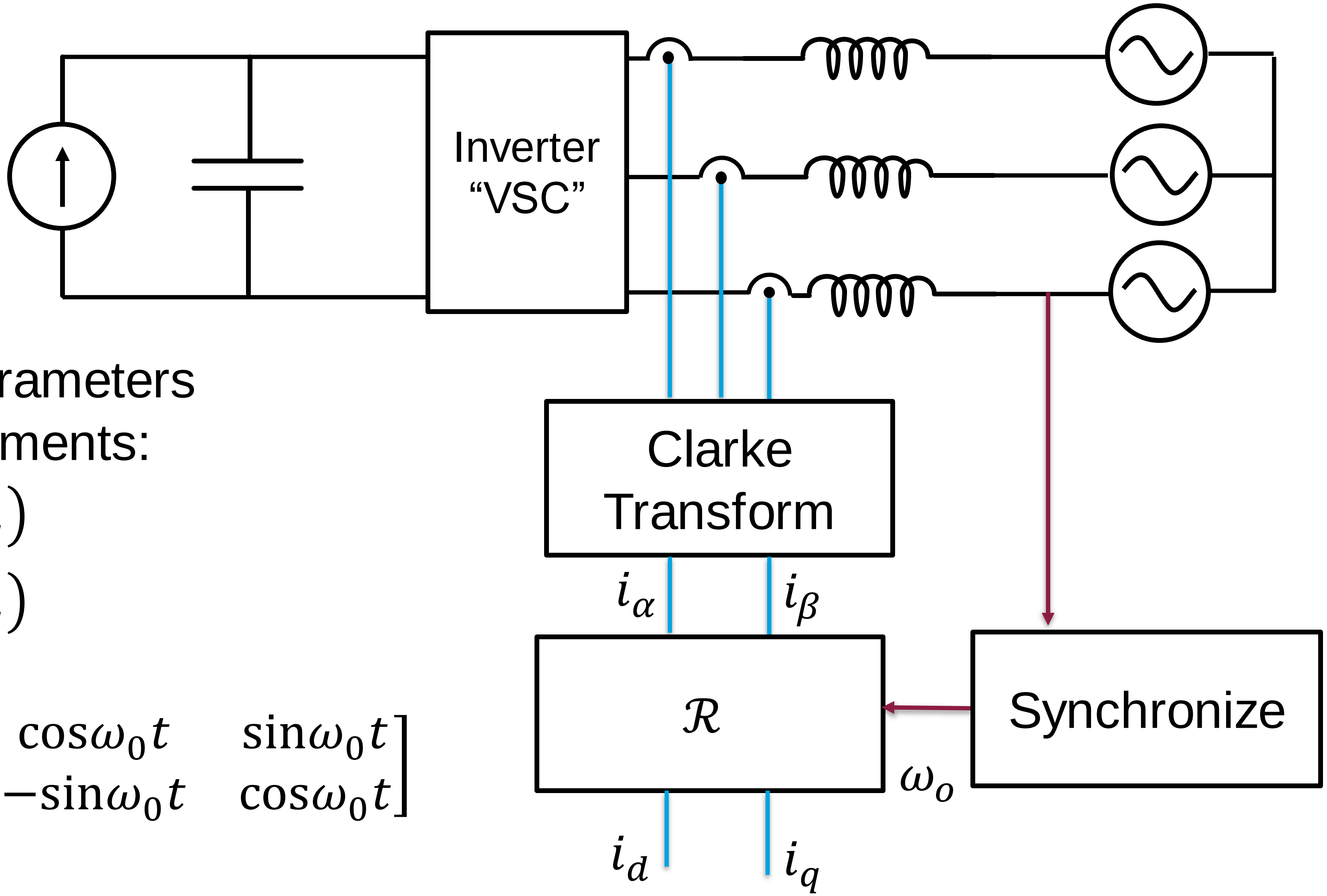
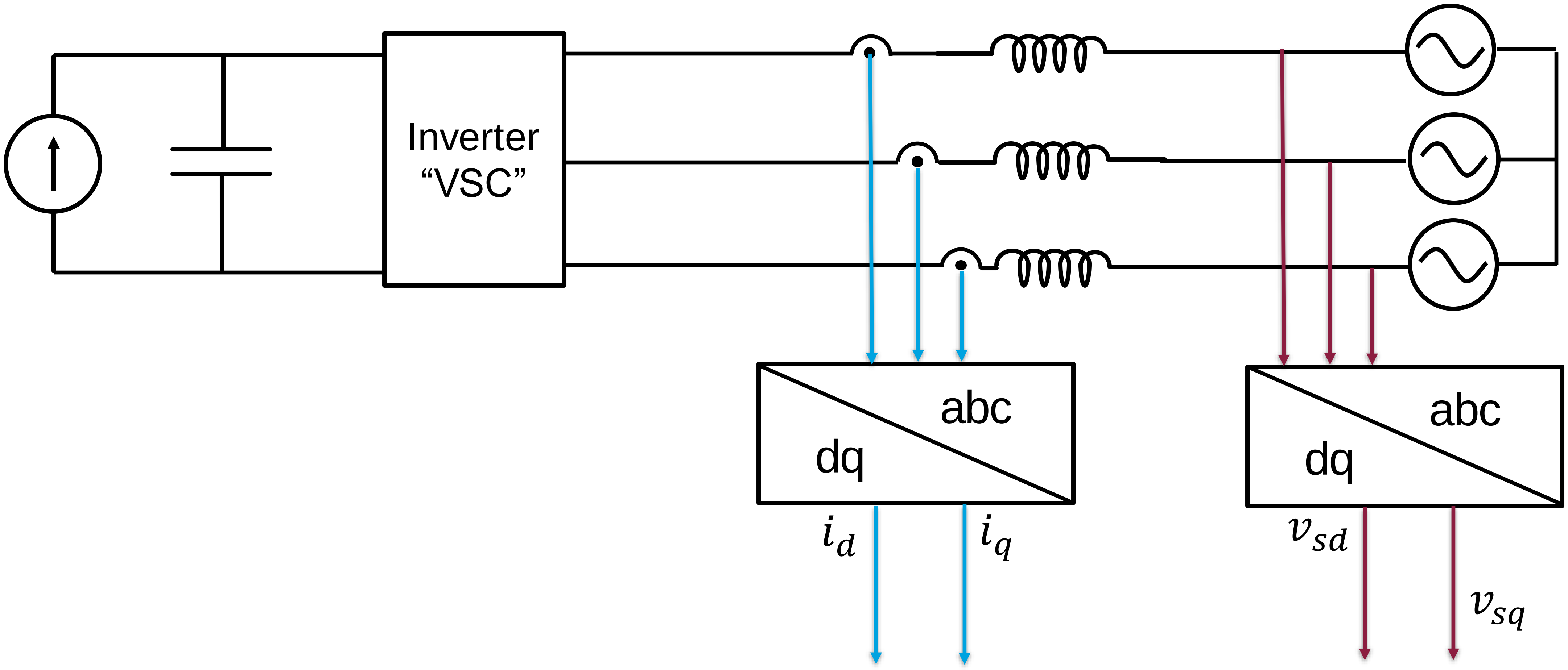



- Two **stationary (dc)** parameters
- Instantaneous measurements:
  - $p(t) = \frac{3}{2}\left(v_d i_d + v_q i_q\right)$
  - $q(t) = \frac{3}{2}\left(v_q i_d - v_d i_q\right)$

$$\mathcal{R} = \begin{bmatrix} \cos\omega_0 t & \sin\omega_0 t \\ -\sin\omega_0 t & \cos\omega_0 t \end{bmatrix}$$

# Voltage-controlled Current Source



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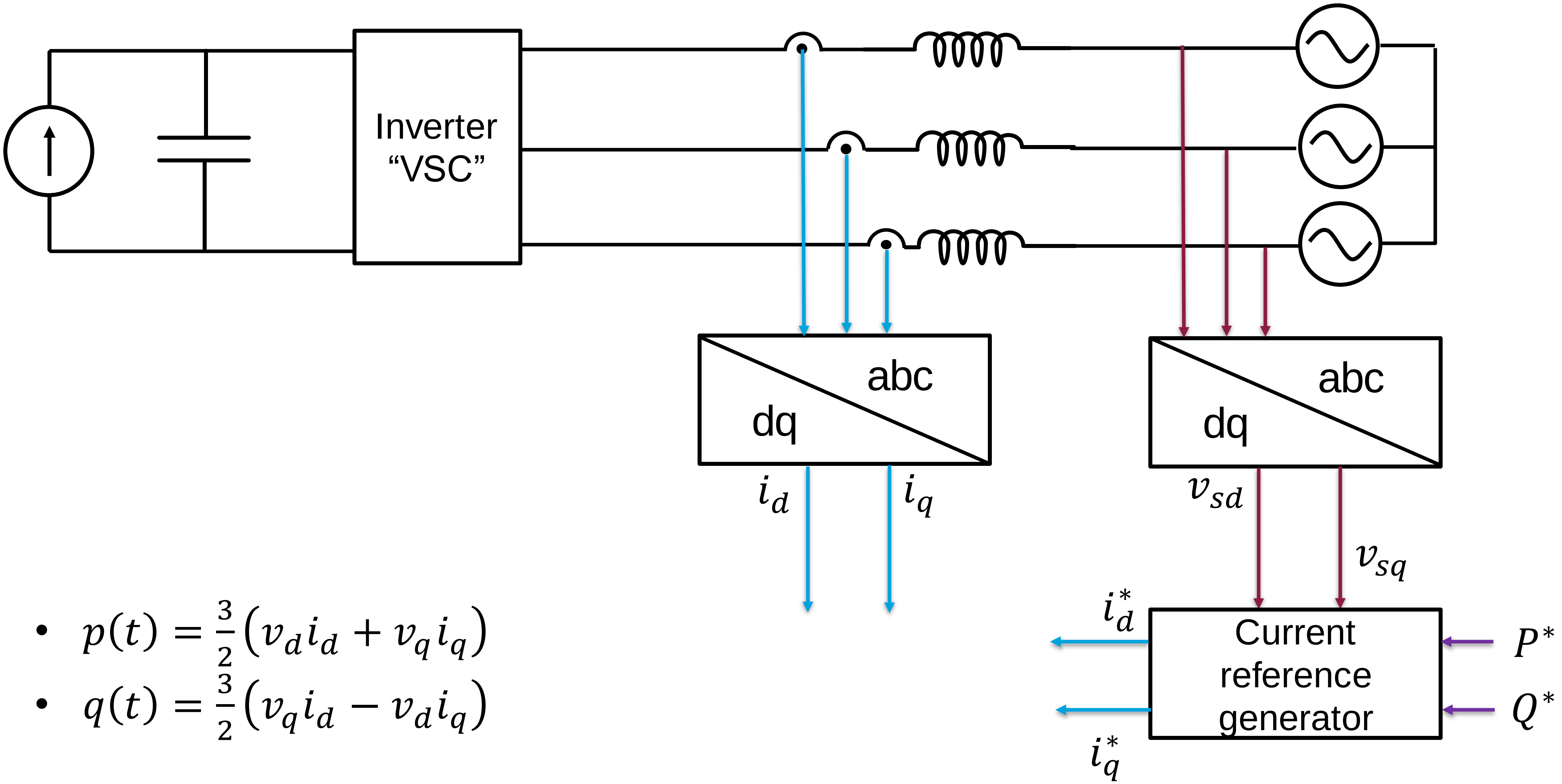


- $p(t) = \frac{3}{2}\left(v_d i_d + v_q i_q\right)$
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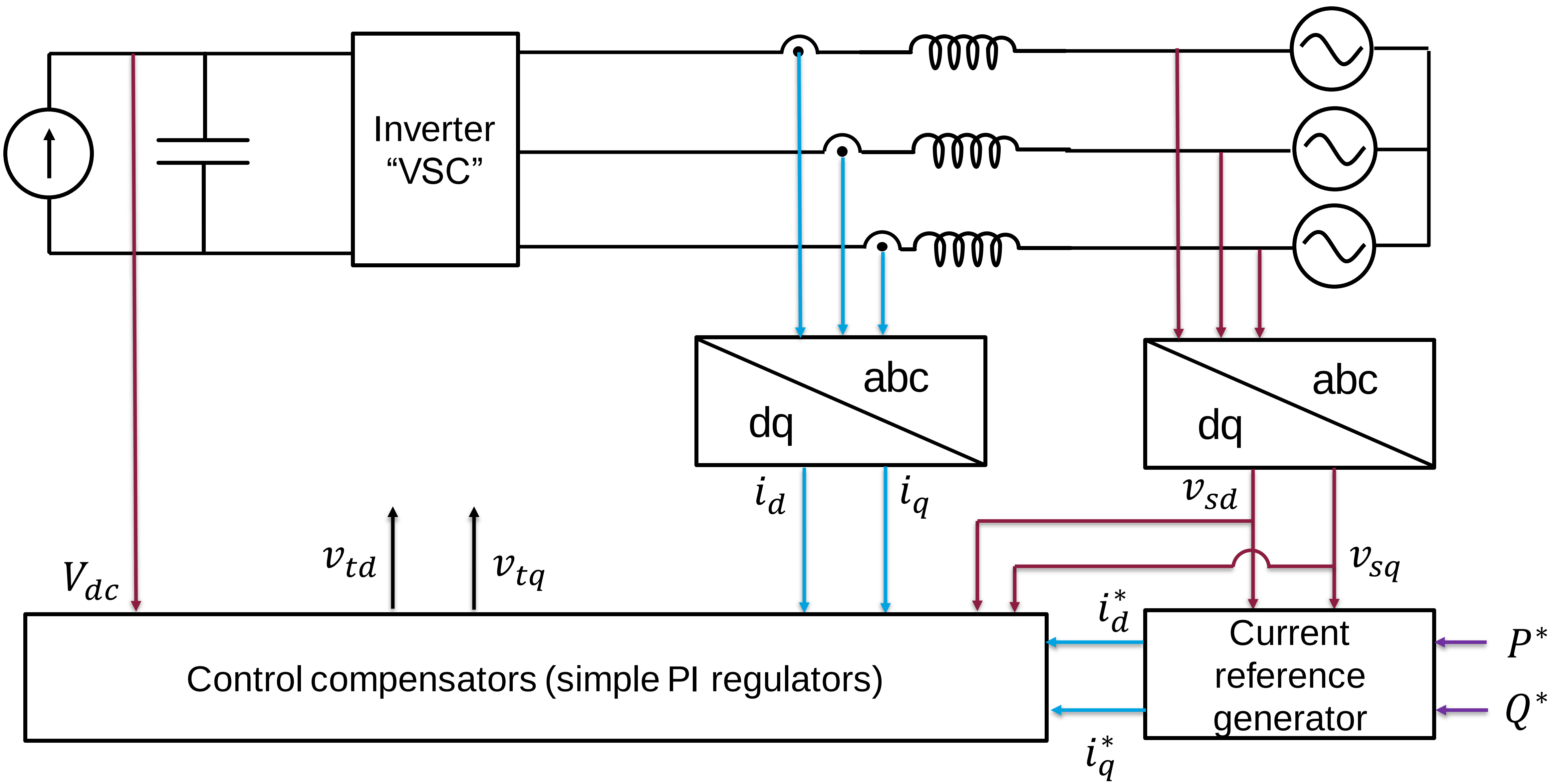
# Voltage-controlled Current Source



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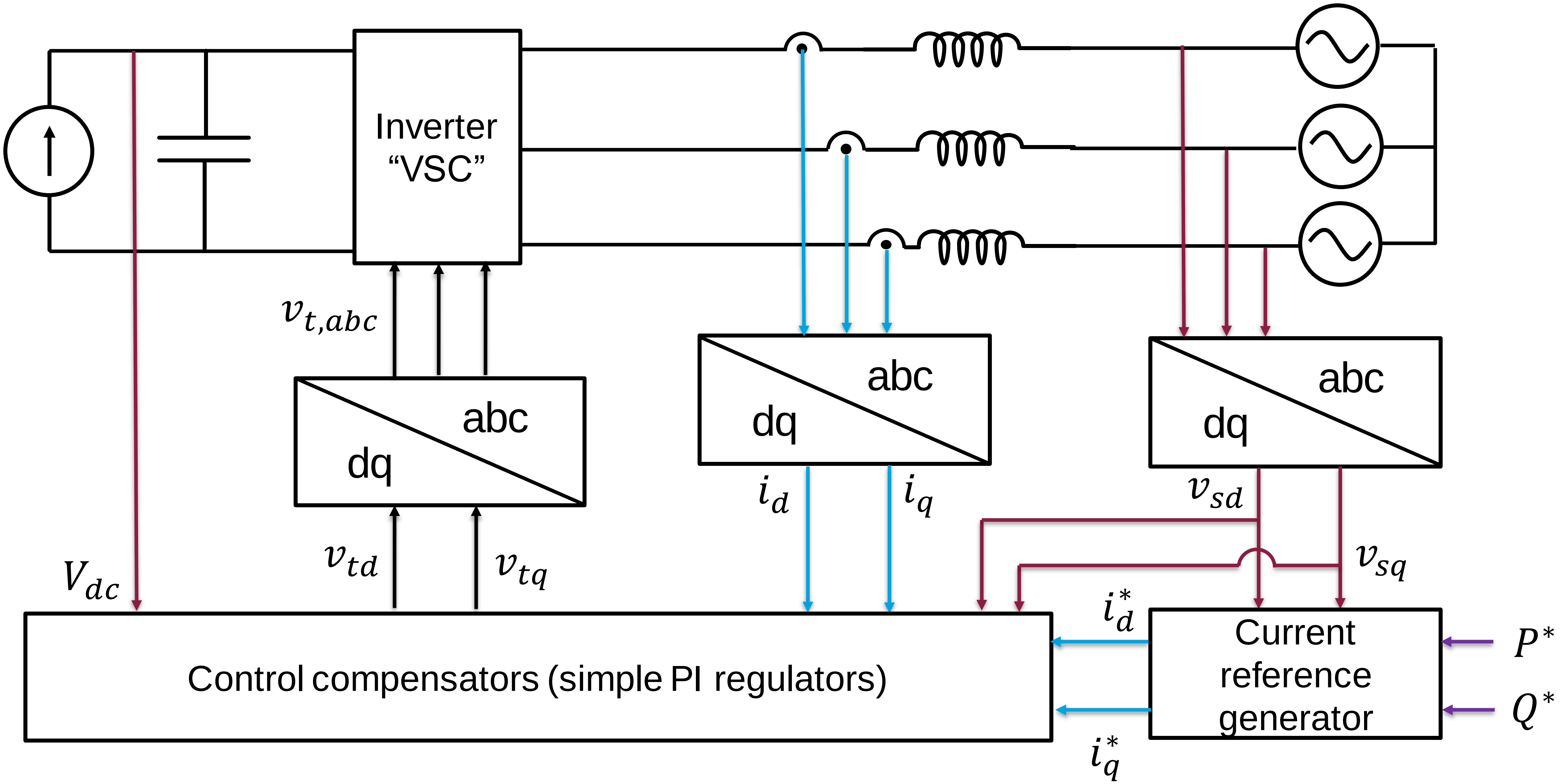
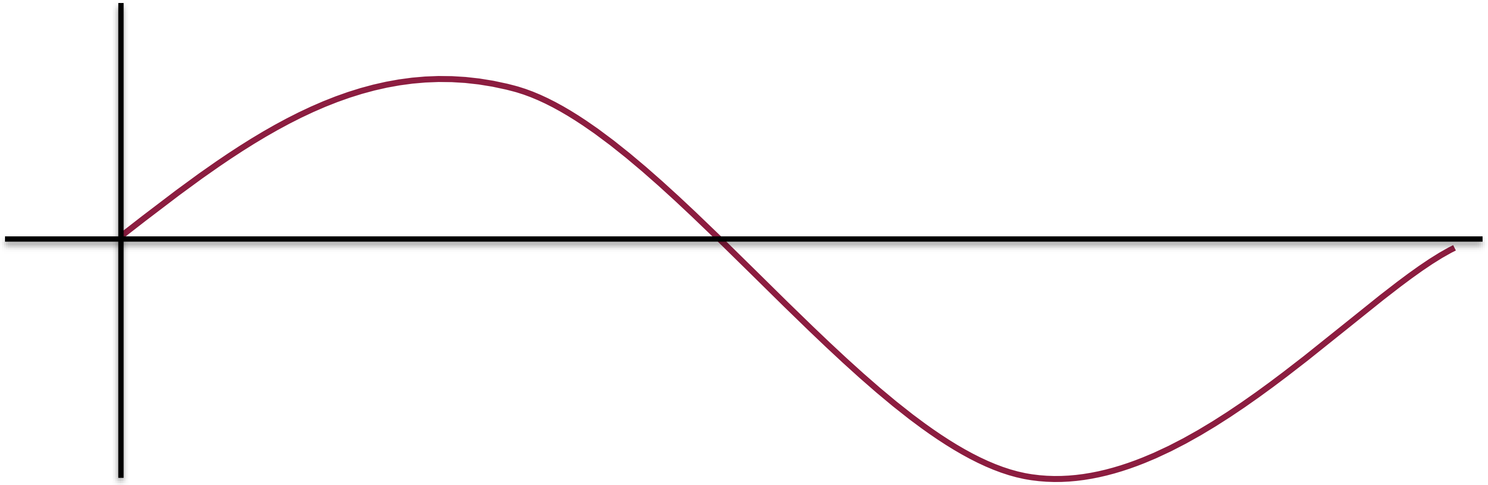


# Important Detail: Synchronization

- If you have some sampled voltage $v(t)$, how do you track magnitude, frequency, and phase?
  - Magnitude: retain max value
  - Phase more complicated



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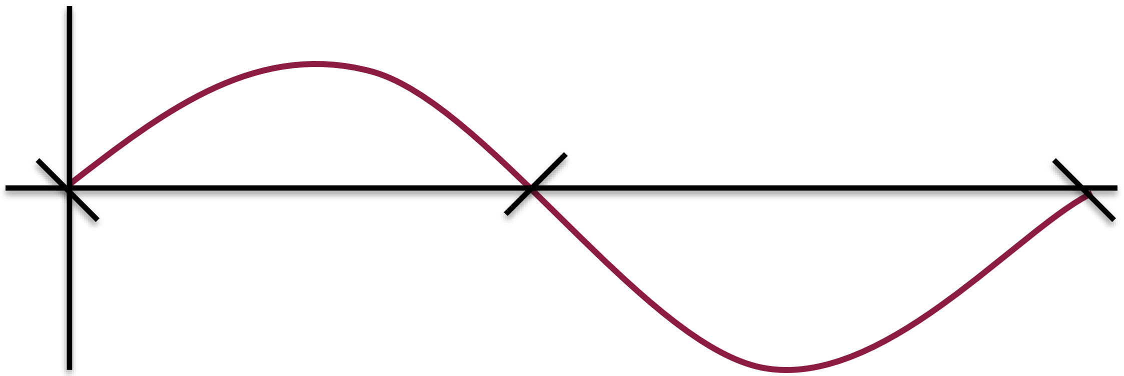
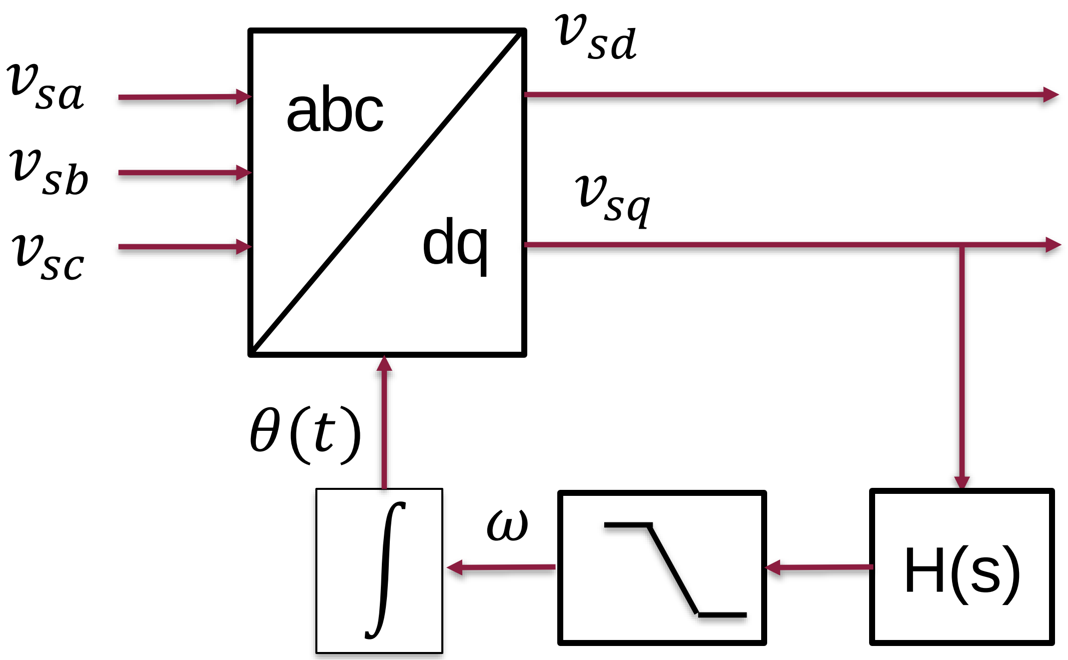


Crudely:

- zero-crossing detection
- Correlate sample time with sinusoidal LUT at assumed frequency

# Synchronization: Phase-Locked Loop

- Most popular, robust
- $\sin(\omega t + \phi) = \sin(\theta(t))$
  - Pull out $\theta(t)$ then we have what we need

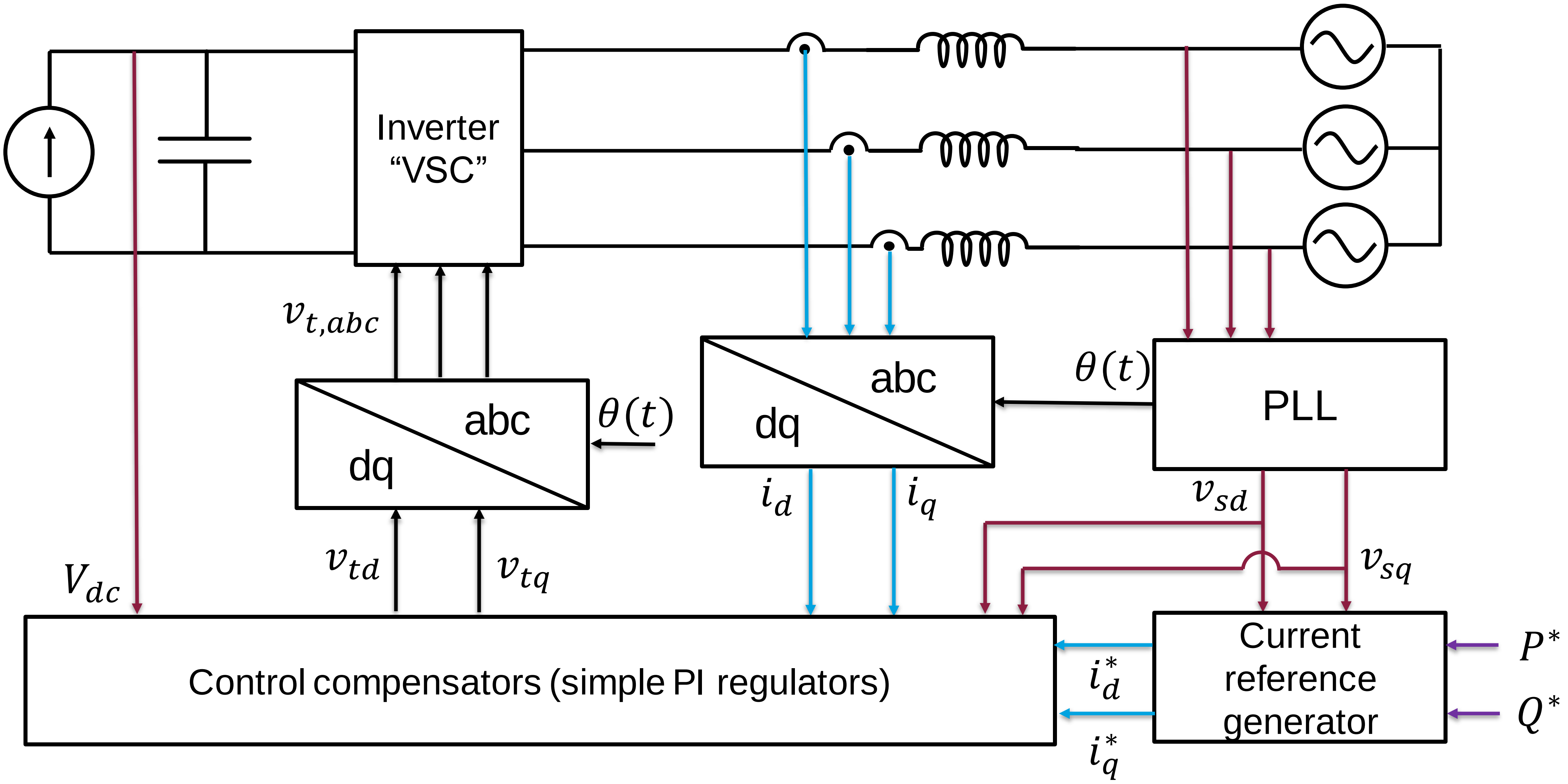



By definition, regulate $v_{sq}$ to zero means synchronized to grid

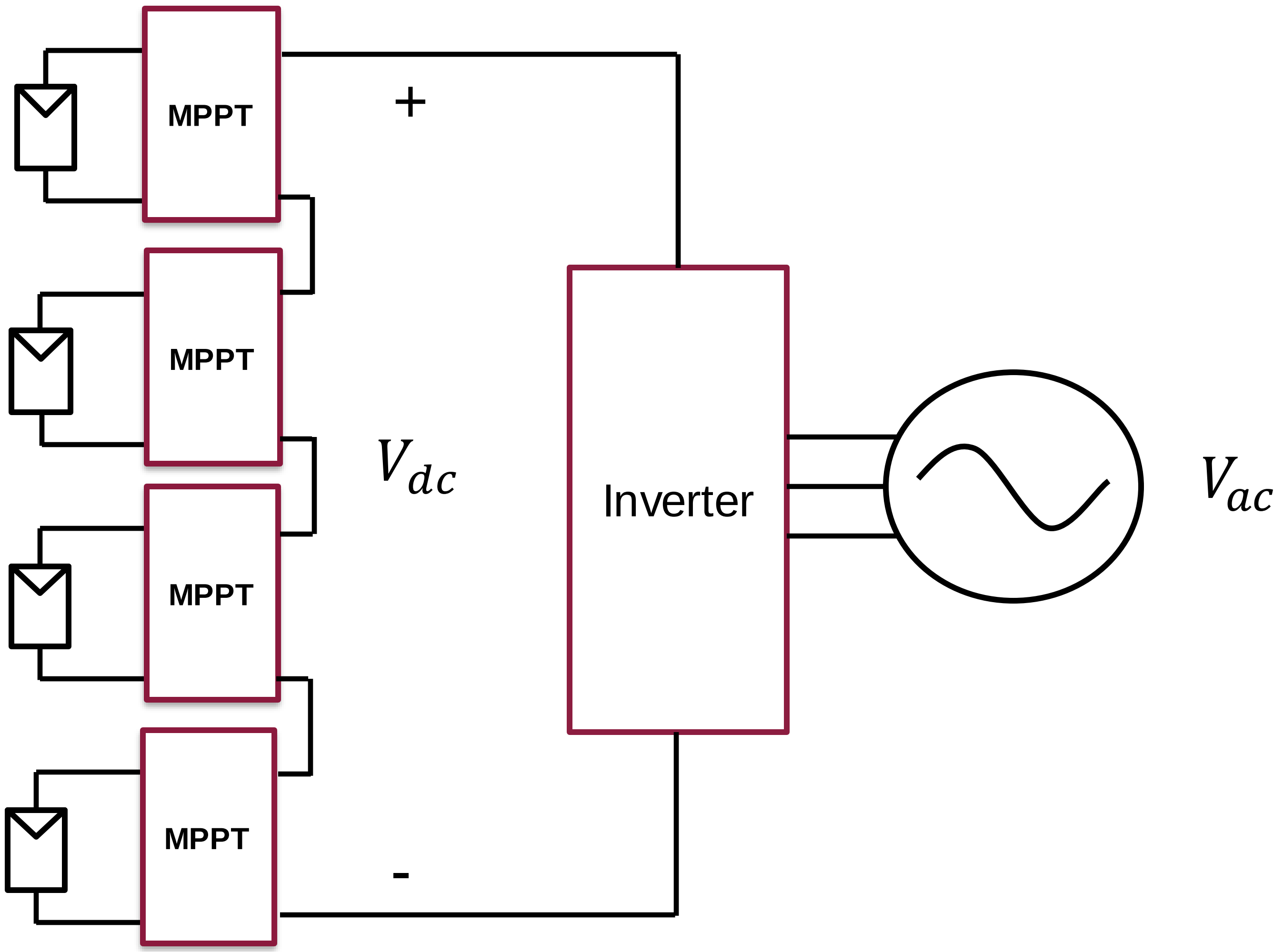
Saturation – inherent assumption on min and max frequency

A. Yazdani and R. Iravani, "Voltage-sourced Converters in Power Systems", Wiley 2010.

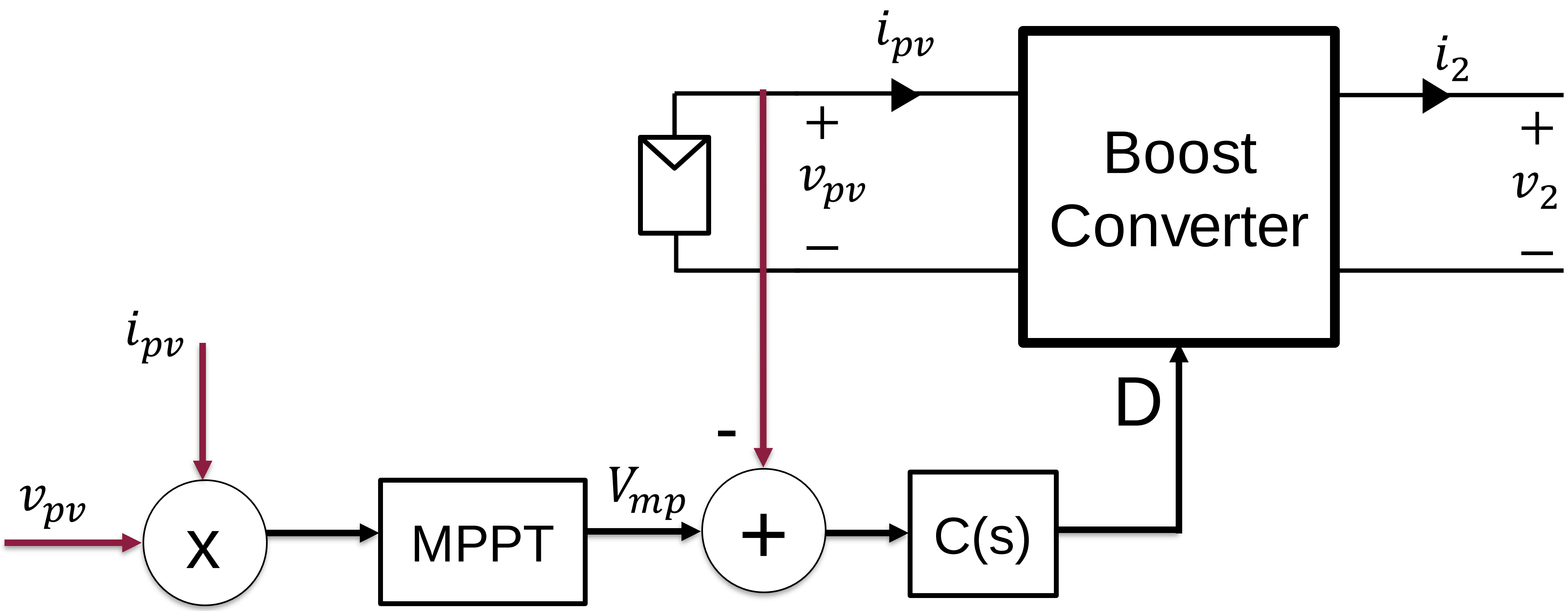
# Voltage-controlled Current Source



# Typical Solar PV Architecture

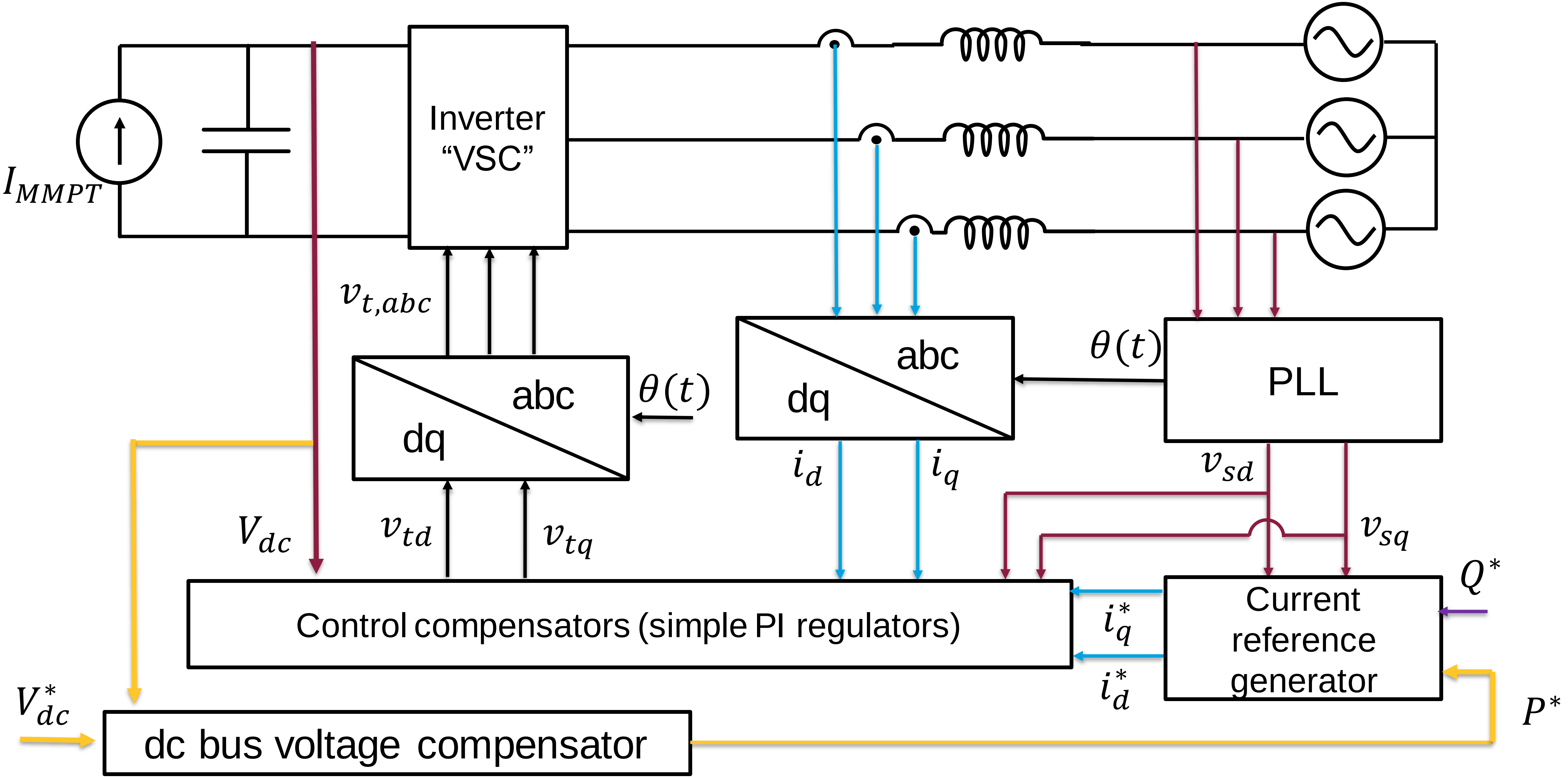


# MPPT Tracker




Control D to extract maximum power

# Inverter Regulates dc Bus



# Operation During Atypical Conditions

- Previously, if *V, f* out of nominal conditions, disconnect!
- Today: regulations are being introduced which demand grid-support
  - "Ride-through" or "Grid supporting" capability
- Disadvantageous for revenue, since only rewarded for P generation.

# Conclusions

- Grid-following inverters assume nominal voltage and frequency at point of common coupling
- System is “stiff” $\Rightarrow$ Converter cannot change grid voltage
- Grid-following control synchronizes to the grid, typically with PLL