ECE 529
Utility Applications of Power Electronics
Session 21
Three Phase VSC Locked Loop (PLL)

Cases where synchronization is needed
- Non-PWM switching schemes
- Synchronous PWM switching schemes
- When control loop operates in the synchronous DQ reference frame
- Control loop for α−β may or may not need synchronizing reference
  - Frequency comes along with measured α and β terms
  - May need depending on method for determining current references

Park's Transform Based PLL
- Measured voltages
  \[
  v_{sd} = V_s \cos(\omega_0 t + \theta_0 - \rho(t))
  \]
  \[
  v_{sq} = V_s \sin(\omega_0 t + \theta_0 - \rho(t))
  \]
- Output current equations in transformed domain
  \[
  L \left( \frac{d}{dt} i_d \right) = L \omega(t) i_q - (R + r_{on}) i_d + v_{td} - v_{sd}
  \]
  \[
  L \left( \frac{d}{dt} i_q \right) = L \omega(t) i_d - (R + r_{on}) i_q + v_{tq} - v_{sq}
  \]
- \( \frac{d}{dt} \rho(t) = \omega(t) \) is a free variable

The choice of \( \rho(t) \) makes a big difference. If it's 0, stay in α−β frame (no rotation)
In this case we want:
\[
\rho(t) = \omega_0 t + \theta_0 
\]
\[
\frac{d}{dt} \rho(t) = \omega_0 - \text{grid freq}
\]
- Then \( \frac{d}{dt} \rho(t) = \omega_0 \)
- If this is the case, then
  \[
  v_{sq} = 0 \quad \text{and} \quad v_{sd} = V_s
  \]
- Design a feedback controller to regulate \( v_{sq} \) to be 0
  \[
  \omega(t) = H(p) v_{sq}(t) \quad \text{where} \quad H(p) \text{ is a linear transfer function}
  \]
- Start it out from
  \[ \omega(0) = \omega_0 \]

- Limit frequency range to narrow variation from
  \[ \omega_{\text{min}} < \omega < \omega_{\text{max}} \]

- Small frequency variations imply
  \[ \sin(\omega_0 t + \theta_0 - \rho(t)) \approx \sin(\omega_0 t + \theta_0 - \rho(t)) \]

which simplifies control loop design

\[ \frac{d}{df} \rho(t) = V_s H(p)(\omega_0 t + \theta_0 - \rho(t)) \]

- Basic control diagram:

- Three phase implementation:
Blue Cut Fire

phase jump due to a fault

$U/I$
PERR and THETAR with phase jump due to load change

Synchronization

PERR and THETAR with sustained SLG Fault

Synchronization
Results with PLL--SLG Fault

Kp=100, Ti=8.3E-3

Kp=1000, Ti=8.3E-4

Results with PLL--Three Phase Fault

Kp=100, Ti=8.3E-3

Kp=1000, Ti=8.3E-4
Compare $\omega t$ with PLL THETAR (phase jump case)

Synchronization 13
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Compare $\omega t$ with PLL THETAR (SLG fault case)

Synchronization 14
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Two Axis Transformation - Unbalanced

*Imitation Measured Currents:*

- Define array of time and define angular frequency:
  \[ t := 0 \text{sec}, 0.0001 \text{sec}.. \frac{6}{60\text{Hz}} \]
  \[ \omega_0 := 2\cdot\pi\cdot60\text{rad/s} \quad \omega(t) := \omega_0 \]

- Voltage as a function of time (negative sequence rotation)
  \[ V_{\text{mag}} := 15\text{kV} \]
  \[ v_a(t) := \sqrt{2}\cdot V_{\text{mag}} \cdot \cos(\omega(t)\cdot t) \]
  \[ v_b(t) := \sqrt{2}\cdot V_{\text{mag}} \cdot \cos(\omega(t)\cdot t + 120\text{deg}) \]
  \[ v_c(t) := \sqrt{2}\cdot V_{\text{mag}} \cdot \cos(\omega(t)\cdot t - 120\text{deg}) \]

*Transform measured voltage and currents to the stationary dq0 (αβ) reference frame:*

- Use equations from the Clarke Transformation instead of matrix for now

\[ v_{ds}(t) := \frac{2}{3} \left( v_a(t) - 0.5 \cdot v_b(t) - 0.5 \cdot v_c(t) \right) \]

\[ v_{qs}(t) := \frac{v_b(t) - v_c(t)}{\sqrt{3}} \quad \text{Q axis 180 out of phase with some definitions} \]
Transformed voltages (note that $v_{ds}(t)$ is still in phase with $v_{a}(t)$). **But $v_{qs}(t)$ has shifted position**

\[ \theta r(t) := 2 \cdot \pi \cdot 60.7 \text{Hz} \cdot t \]

- Now apply positive sequence rotating reference frame transformation in steps

\[ v_{dr1}(t) := v_{ds}(t) \cdot \cos(\theta r(t)) \]
\[ v_{dr2}(t) := v_{qs}(t) \sin(\theta r(t)) \]

\[ v_{dr}(t) := v_{dr1}(t) + v_{dr2}(t) \]

\[ v_{qr1}(t) := v_{ds}(t) \sin(\theta r(t)) \]

\[ v_{qr2}(t) := v_{qs}(t) \cos(\theta r(t)) \]

\[ v_{qr}(t) := -v_{qr1}(t) + v_{qr2}(t) \]
• Note the 120 Hz variation.

**Repeat using** $-\theta$

$$\theta_r(t) := -2\pi \cdot 60.0\text{Hz} \cdot t$$

• Now apply positive sequence rotating reference frame transformation in steps, using the negative rotation angle

$$v_{dr1}(t) := v_{ds}(t) \cdot \cos(\theta_r(t)) \quad v_{dr2}(t) := v_{qs}(t) \cdot \sin(\theta_r(t))$$

$$v_{dr}(t) := v_{dr1}(t) + v_{dr2}(t)$$

$$v_{qr1}(t) := v_{ds}(t) \cdot \sin(\theta_r(t)) \quad v_{qr2}(t) := v_{qs}(t) \cdot \cos(\theta_r(t))$$

$$v_{qr}(t) := -v_{qr1}(t) + v_{qr2}(t)$$