EECS 290O

April 22, 2019

dq control

Announcements

1. Next week: no class
2. 5/6: Make up class, same time & place.
3. Today: end early to do course evals.
4. Last group presentations 5/6: Lin, Markovic.
5. I will post project writeup requirements this week.
6. Project due 5/14 11:30 am.

Objectives for today

1. Answer question: why not just control terminal voltage?

2. Basic issues in PLL control design

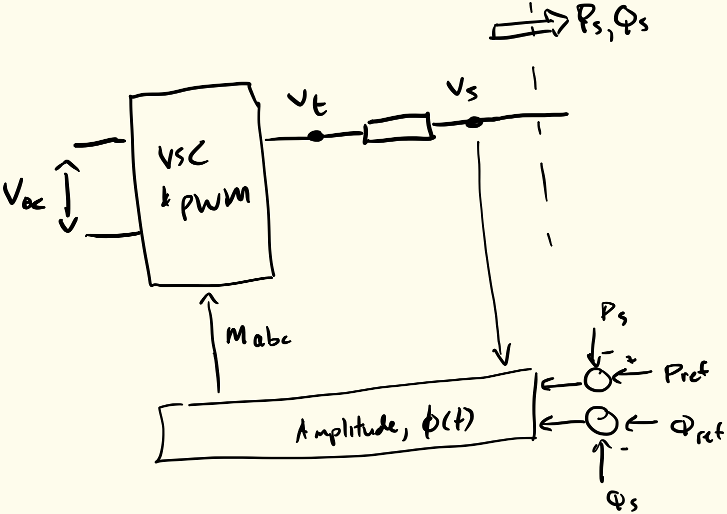
3. Simple extension of 1/2 bridge control to 3ϕ (dq) control.

4. Multimachine simulation discussion. Importance of local voltage angles.

5. Course evaluations

VSC: Voltage-mode or current-mode control?

Voltage

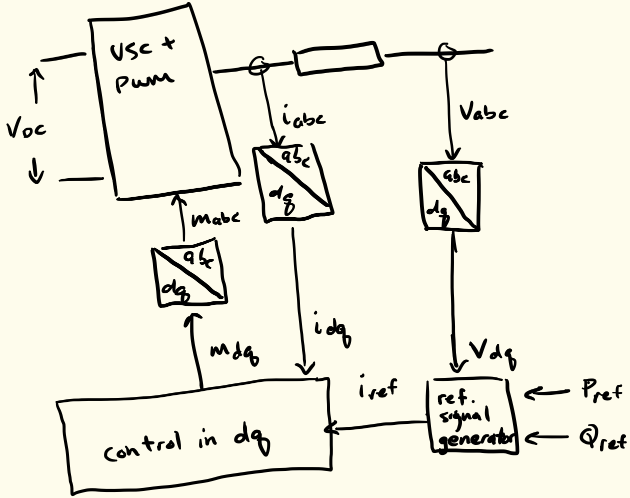


Pro: Simple control. Can even decouple Amplitude and ϕ if voltages are similar

Con: • No current protection (though it would seem easy enough to [illegible] a protective loop in?)

• Need filter parameters - could be wrong!

Current



Pro: Current limits - can saturate i_{ref}. Also allegedly better dynamics.

Con: More control complexity, though it's still low.

Dynamic Model of P-Q controller (8.3.3)

$$L \frac{d\vec{i}}{dt} = -(R + r_{on})\vec{i} + \vec{V}_t - \vec{V}_s$$

($\vec{\cdot}$ is a space phasor)

dq: $\vec{i} = \hat{i}_{dq}\, e^{j\rho}$ ← estimate of phase angle

Objective: Develop a controller to regulate i_d and i_q to reference values from signal generator.

Writing dynamic equations in dq

(In following, $R' = R + r_{on}$)

frequency and phase at PCC

$$L\frac{d\boxed{i_d}}{dt} = L\boxed{\omega}\boxed{i_q} - R'\boxed{i_d} + \boxed{v_{td}} - \underbrace{\hat{V}_s \cos(\omega_0 t + \theta_0 - \boxed{\rho})}_{v_{sd}}$$

$$L\frac{d\boxed{i_q}}{dt} = -L\boxed{\omega}\boxed{i_d} - R'\boxed{i_q} + \boxed{v_{tq}} - \underbrace{\hat{V}_s \sin(\omega_0 t + \theta_0 - \boxed{\rho})}_{v_{sq}}$$

$$\frac{d\boxed{\rho}}{dt} = \boxed{\omega}$$

$\boxed{}$ = state variables

$\boxed{}$ = control variables

- System nonlinear due to ωi terms and cos, sin terms.

PLL

dq requires good choice of ω and ρ.

E.g. consider $\rho(0) = 0$ and $\omega \equiv 0$

$\rightsquigarrow \rho = 0 \;\; \forall t$ and the dq transform is actually $\alpha\beta$.

So we need a PLL = Phase locked loop.

Remember $\quad V_{sq} = \hat{V} \sin(\omega_0 t + \theta_0 - \rho) \;\Rightarrow\; \rho = \omega_0 t + \theta_0 \rightsquigarrow V_{sq} = 0$

So we'll seek a feedback control law that drives $(\omega_0 t + \theta_0 - \rho)$ to zero.

But as we'll see it can't go all the way to zero.

PLL design

Foundational feedback control Law.

transfer function, design by classical methods.

$$\frac{d\rho}{dt} = H \hat{v}_s \sin\Big(\underbrace{\omega_o t + \theta_o - \rho}_{}\Big) = H v_{sq}$$

don't want this $\equiv 0$, otherwise $\frac{d\rho}{dt} \equiv 0$ and

we don't track the phase

$\Rightarrow$ There will be some error.

But good control design can make this

very small. Textbook is fuzzy on this.

$\Rightarrow$ Best case outcome

1. ρ has frequency $\omega_o \Rightarrow \omega_o t + \theta_o - \rho = \text{constant} = e$
2. e is small.

PLL design, CTD

Confounding issues

1. Phase (ABC) imbalance
2. Harmonics

example:

-ive seq. component

$$\Rightarrow \vec{V}_s = \hat{V}_s e^{j(\omega_o t + \theta_o)} + k_1 \hat{V}_s e^{-j(\omega_o t + \theta_o)}$$
$$+ k_5 \hat{V}_s e^{j(5\omega_o t + \phi_5)}$$

$\Rightarrow$ Steady state PLL

$$V_{sq} = -k_1 \hat{V}_s \sin(2\omega_o t + 2\theta_o) - k_5 \hat{V}_s \sin(6\omega_o t + \theta_o + \phi_5)$$

$$= \text{f'n of } 2\omega_o, 6\omega_o.$$

Since $\frac{\partial e}{\partial t} = H v_{sq}$, these harmonics can distort estimate of e.

PLL design, Ctd

Phase imbalance is the most severe factor. Solutions

1. Xfr fn has strong low pass characteristic.

   → But this compromises bandwidth

2. Plop zeros at $\pm j2\omega_0$ → eliminates ripple there.

   → But if $\omega \neq \omega_0$ your controller parameters may not work well.

Example in book shows phase imbalance generates inst. error of 3-4 Hz. — SEE PPT SLIDES.

This is a real thing - Converters have cut off line due to faulty measurements.

More on Current Control

PCC P & Q:

$$P_s(t) = \frac{3}{2}\left(V_{sd}\, i_d + V_{sq}\, i_q\right) = \frac{3}{2} V_{sd}\, i_d$$

$$Q_s = \frac{3}{2}\left(-V_{sd}\, i_q + V_{sq}\, i_d\right) = \underbrace{-\frac{3}{2} V_{sd}\, i_q}_{\text{if } V_{sq}=0 \text{ (true for a good PLL)}}$$

$$\Rightarrow \quad i_{dref} = \frac{2}{3}\frac{P_{sref}}{V_{sd}} \quad , \quad i_{qref} = -\frac{2}{3}\frac{Q_{sref}}{V_{sd}}$$

so with a good PLL and fast iref tracking, P & Q can be independently controlled.

Even More on current control

Let's return to current dynamics, assuming $\omega = \omega_0$

$$L\frac{di_d}{dt} = L\omega_0 i_q - R' i_d + V_{td} - V_{sd}$$

$$L\frac{di_q}{dt} = -L\omega_0 i_d - R' i_q + V_{tq} - V_{sq}$$

We can control V_{td} and V_{tq} to make i_q and i_d follow the references.

But the equations are coupled, which could complicate control design.

A cool trick.

1st, Remember,

$$V_{td} = m_d \frac{V_{DC}}{2} \quad , \quad V_{tq} = m_q \frac{V_{DC}}{2}$$

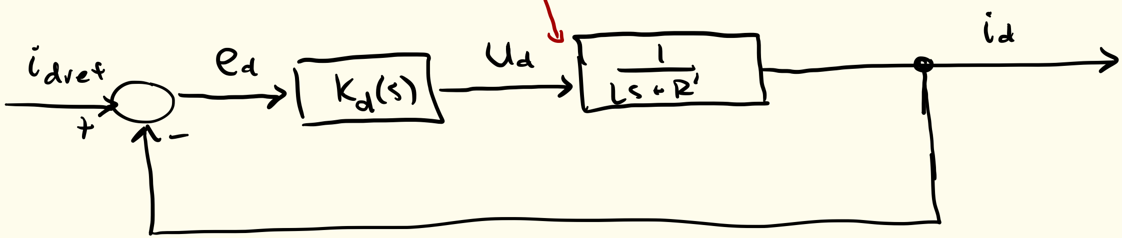
Here is the trick:

$$(\#) \quad m_d = \frac{2}{V_{DC}}\left(u_d - L\omega_0 i_q + V_{sd}\right) \qquad \Rightarrow \qquad L\frac{di_d}{dt} = -R' i_d + u_d$$

$$m_q = \frac{2}{V_{DC}}\left(u_q - L\omega_0 i_d + V_{sq}\right) \qquad\qquad L\frac{di_q}{dt} = -R' i_q + u_q$$

Now we can control i_d and i_q independently

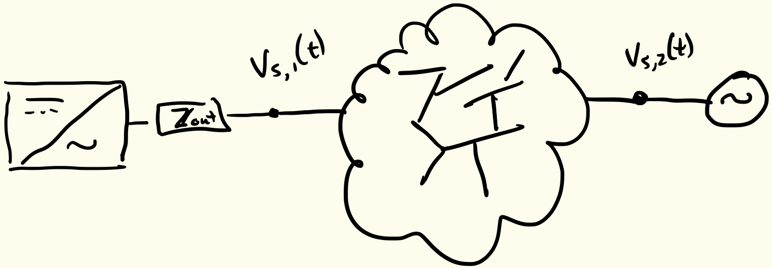
Here we need to construct m_d from # (previous page)



- We can construct exactly the same architecture for i_q.
- Also, since system is linear, we can set $k_q = k_d$
- Simple 1^{st} order filter $\rightsquigarrow$ PI control loop in $K(s)$.
- Design follows same procedure as Ch 3, half bridge control.

Have a look at today's power point slides ...

Comment on multi-machine models



Transformations and reference angles:

dq transform must be done relative to <u>local</u> V_s

Kundur Explanation for transformations (ch 13.3)

Let $\omega_0 = 2\pi f_0$ = nominal (constant) system frequency

$\Delta\omega_r$ = per unit rotor speed deviation $\left(\frac{\omega - \omega_0}{\omega_0} \right)$

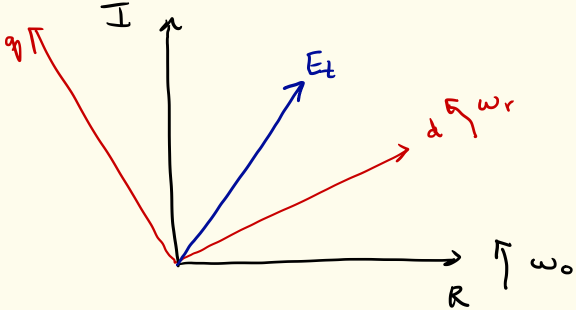
$$\frac{d\,\Delta\omega_r}{dt} = \frac{1}{2H}\left(T_m - T_e - K_D\,\Delta\omega_r\right)$$

$$\frac{d\delta}{dt} = \omega_0\,\Delta\omega_r$$

(= 0 if machine speed equals ω_0)

Kundur Explanation, Ctd

1. Define a <u>system</u> rotating reference frame. All network and static load calcs done here.



This has similar properties to d-q, <u>but does not change speed</u>

2. Measure local generator angle (or V_s in PLL) relative to this frame.

3. Convert voltage components btwn d-q & "R-I"

machine

network

4. Network currents follow Ohm's law.

AC side equivalent circuit

Let $v_{sa}(t) = \hat{V}_s \cos(\theta)$

(shift back $2\pi/3$, $4\pi/3$ for b & c.)

$v_{ta}(t) = \hat{V}_t \cos(\theta + \delta)$

$i_a(t) = \hat{i} \cos(\theta - \phi)$

$\Rightarrow$

$\vec{V}_s = \hat{V}_s e^{j\theta}$

$\vec{V}_t = \hat{V}_t e^{j\delta} e^{j\theta}$

$\vec{i} = \hat{i} e^{-j\phi} e^{j\theta}$