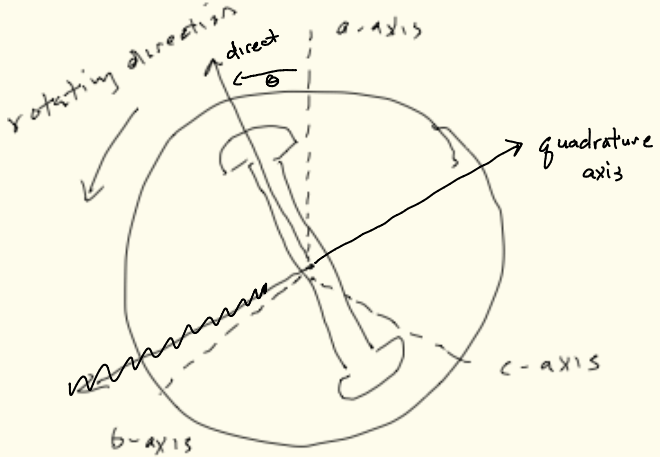
21st Century Power System Dynamics

EECS 290

Spring 2019

Feb 11 2019 Lecture notes.

Park's transformation, a.k.a. dq transform



Example currents

$$i_a = I_{a,max} \cos\theta$$

$$i_b = I_{b,max} \cos(\theta + \pi/3)$$

$$i_c = I_{c,max} \cos(\theta + 2\pi/3)$$

$$i_0 = \frac{1}{\sqrt{3}}(i_a + i_b + i_c)$$

$$i_d = \sqrt{\frac{2}{3}}\left[i_a \cos\theta + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3)\right]$$

$$i_q = \sqrt{\frac{2}{3}}\left[+i_a \sin\theta + i_b \sin(\theta - 2\pi/3) + i_c \sin(\theta + 2\pi/3)\right]$$

note, $\theta = \omega t + \theta_0$ $\Rightarrow$ transformation is time dependent.

Park's transformation, ctd.

Let $x_{abc} = \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$ and $x_{odq} = \begin{bmatrix} x_o \\ x_d \\ x_q \end{bmatrix}$

These are any quantity (voltage, current, magnetic flux)

Then Park's tranformation (a.k.a the dq-transformation) is

$$x_{abc} = P x_{odq}$$

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ +\sin\theta & +\sin(\theta - 2\pi/3) & +\sin(\theta + 2\pi/3) \end{bmatrix}$$

Park's transformation, ctd

A nice feature! (here u is terminal voltage)

$$p(t) = u_a i_a + u_b i_b + u_c i_c = u_0 i_0 + u_d i_d + u_q i_q$$

Note: The transformation is not unique - different papers and books might point d and q in different directions, so check.

As with pos-neg-zero sequence, the zero component is negligible in balanced conditions.

Why use the dq transform?

- The dq coordinates rotate with the rotor.

  $\Rightarrow$ sinusoidal quantities transform to constant values in dq-frame.

- This simplifies the analysis in many situations.

Ch2 - Power system components.

I'll focus on

- Basic generator components

    rotor

    armature

    damper

    exciter + voltage regulator

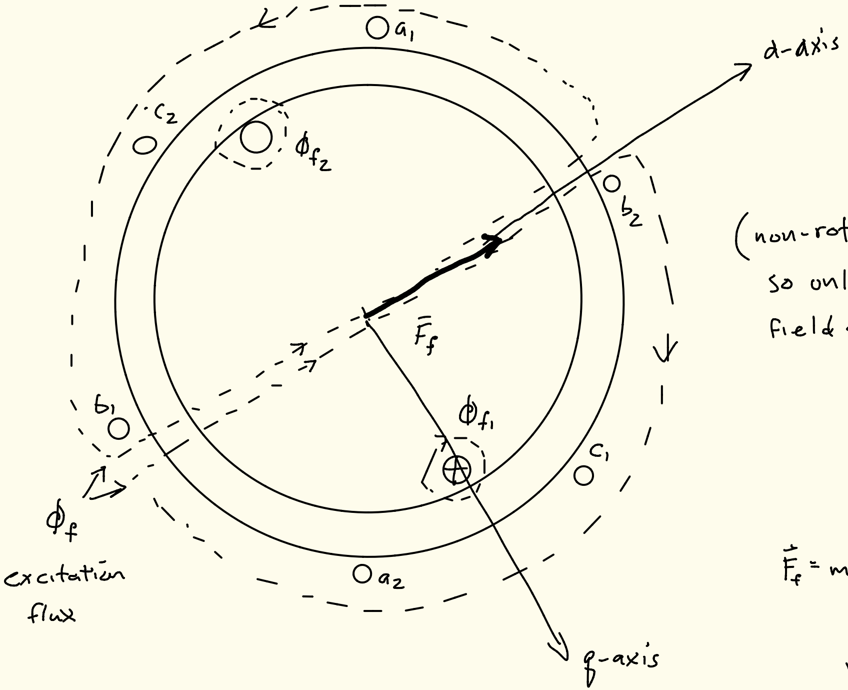
    turbine governors

Basic Generator Components

Fig 2.2.

Synchronous Generators

MBB Fig 3.9



(non-rotating - so only rotor field shown.)

$\vec{F}_f$ = magnetomotive force: magnetic equivalent to voltage

- Rotor flux ϕ_f induced by field windings
- When the rotor rotates, emf induced in armature
- This leads to current flow, which also produces a magnetic field (not shown)
- Also not shown - damper windings. More on these in a moment.

Damper windings

- If a synchronous machine "falls out of step" with grid frequency, oscillations in the relative speed of the machine could ensue
- Damper windings are short circuited loops in the stator.
- Currents induced here produce magnetic fields that oppose the asynchrony
  - $\Rightarrow$ helps restore synchrony.
- very important for dynamic modelling
- won't be considered in today's static discussions

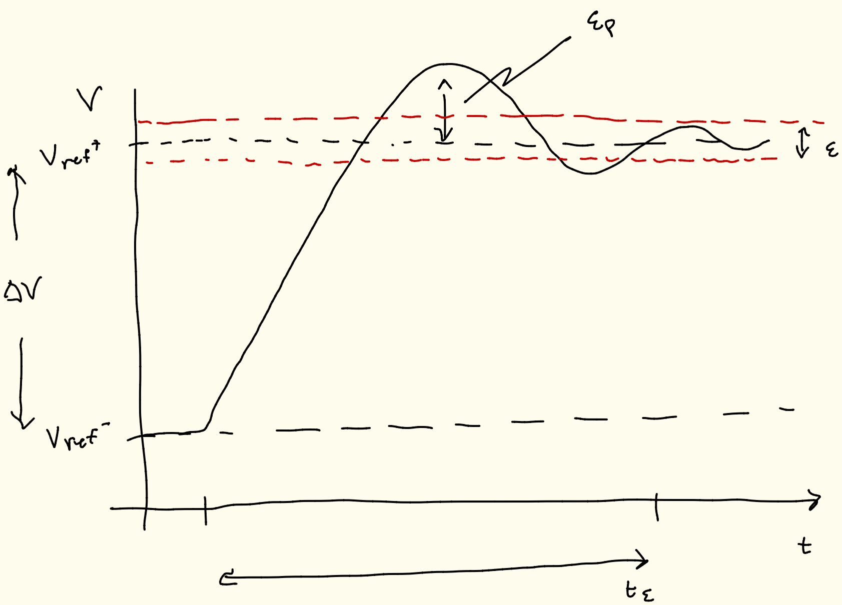
Exciter systems

- The exciter induces a magnetic field in the rotor.
- Many means of doing this. Key features
  - Produce a dc current
  - Adjustable voltage → vary field strength and in turn vary SG output voltage.
- Different configurations ⇒ different output voltage dynamics!
- This one, w/ thyristor control AVR, is common.

Fig 2.3e.

SR = slip ring ; SG = synch generator ;
ET = excitation xfrmr ; AVR = thyristor controlled voltage regulator.

Automatic Voltage regulators



t_r = time to go from $V_{ref^-} + 0.1\,\Delta V$ to $V_{ref^-} + 0.9\,\Delta V$.

ε_p = overshoot

t_ε = time to arrive to within ε of V_{ref^+}

If $\varepsilon = +/- \, 0.5\%$ and $\Delta V = 10\%$ of original

$\Rightarrow t_\varepsilon \leq 0.3\,s$ for static (thyristor-controlled) AVR

Steam turbines

- Many forms in MBB
  - Steam
  - Combustion
  - combined cycle

- Key point: Each has it's own control and process flow.
  - These lead to different dynamics
  - Important to get these details right. We will explore as interest and time permits.

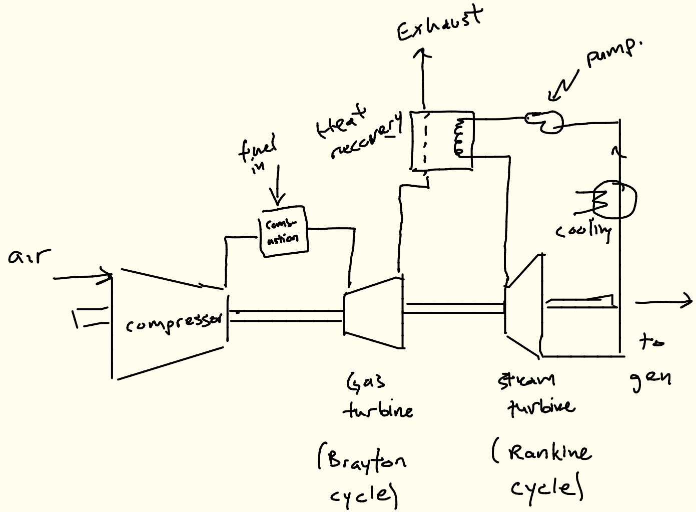
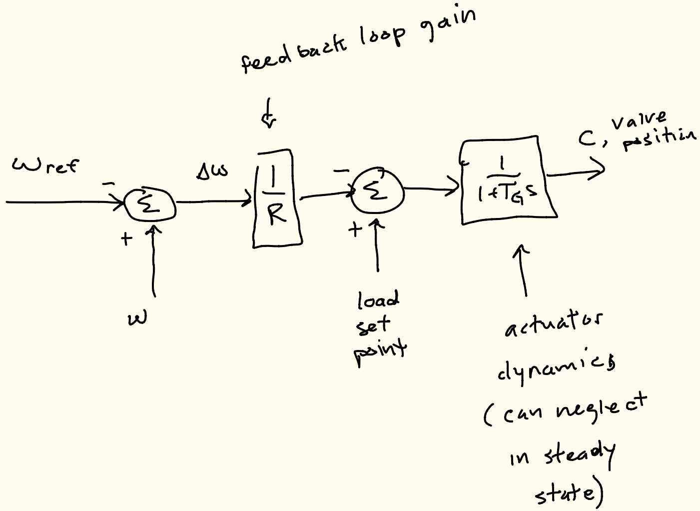


Fig 2.9

Turbine governing

$$\rho = \frac{R}{\omega_n}$$

$$K = \frac{\omega_n}{R}$$



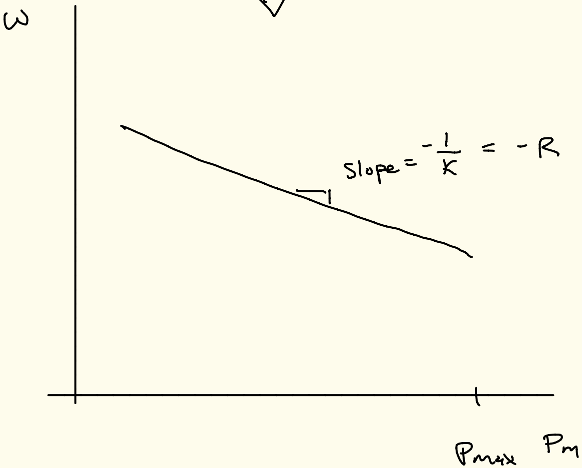
T_G : not sure what this is, not listed in MBB. Look in Kundur?

Turbine governing, ctd.

$$\Rightarrow \quad \frac{\Delta P}{P_n} = -K\frac{\Delta\omega}{\omega_n} = -\frac{1}{R}\Delta\omega$$

nominal values.

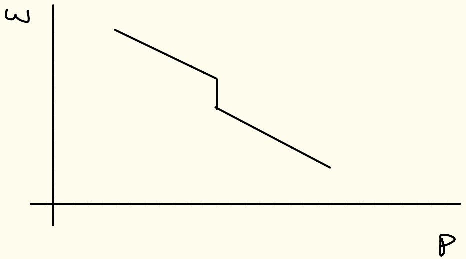
$$\Downarrow$$



Turbine governing, ctd

Note:

Most systems have a deadband



- Mechanical systems can't avoid this
- But even in electrical-hydraulic systems it is desirable
  - recognizes some normal frequency variation ok.
  - avoids wear and tear.
- In U.S., deadband is ~ 35 mHz.

$\boxed{\text{Ch 3 - Power system in steady state}}$

I'll focus on

- Generator terminal voltage

- Non salient pole rotors

  - i.e. rotors w just one N-S pole pair

  - These have constant airgap flux, so analysis is simpler.

  - salient pole: for slow spinning things (hydro, wind).

Generator - no load

flux through magnetic circuit

rotor windings

rotor current

$$\Phi_f = \frac{N_f \, i_f}{\mathcal{R}}$$

$\mathcal{R}$ ← magnetic circuit reluctance (mostly due to air gap)

ψ_{fa} = flux linkage in armature a

$$= N_\phi \Phi_f \cos\omega t = M_f i_f \cos\omega t$$

↑ # armature windings

← mutual inductance $\frac{N_\phi N_r}{\mathcal{R}}$

$$e_{fa} = -\frac{d\psi_{fa}}{dt} = \omega M_f i_f \sin\omega t$$ ← no load terminal voltage

Generator - with load

Stator phase currents

$$i_A = I_m \cos(\omega t - \delta)$$

peak value of current.

delay relative to rotor.

This generates another field

$$\vec{F}_A = N_a i_A e^{j0}$$

The total is

$$\vec{F}_a = \vec{F}_A + \vec{F}_B + \vec{F}_C$$

Now let's refer to how things add up in $\boxed{\text{fig } 3.11}$

Here the total field is

$$\vec{F}_r = \vec{F}_a + \vec{F}_f$$

Air Gap EMF

(under bar ⇒ phasor)

$$\underline{E}_r = \underline{E}_f + \underline{E}_a = \underline{E}_f - j\underbrace{X_a}_{\text{armature reaction reactance}}\underline{I}$$

Terminal Voltage

See Fig 3.12a

$$\Rightarrow \boxed{\underline{V}_g = \underline{E}_f - j\overbrace{X_a}^{\text{armature reactance}}\underline{I} - j\overbrace{X_L}^{\text{leakage flux}}\underline{I} - \underbrace{R}_{\text{armature resistance,}}\underline{I}}$$

$\boxed{\text{Time Constants.}}$

Simple 1^{st} order LTI system:

$$\dot{x} = -ax$$

$$\Rightarrow x(t) = X_0 e^{-at}$$

$$x\left(\frac{1}{a}\right) = X_0 e^{-1} = \frac{\cancel{X_0}}{e} \simeq 0.37 X_0$$

$\frac{1}{a}$ is the "time constant"

- Often called τ
- Time when -1 is in the exponential.

Time constants - higher order systems.

- Higher order system time constants harder to characterize
- But if
  - all eigenvalues are negative, and
  - one eigen value for the system is real and much closer to zero
  - then the largest eigenvalue can be thought of as the inverse of the dominant time constant for the system