21st Century Power System Dynamics

EECS 290

Spring 2019

March 4 2019 Lecture notes.

Introduction

- Today focus on Ch5 – "small" electromechanical dynamics

- Remember last week: Electromagnetic transients

- Today we merge those concepts with
  - conversion of energy from inertia to electrical power → changing speed and angle
  - changing electrical power transfer abilities as generator angle changes

Outline

- Newton's law (conservation of energy in inertia, damping, and electrical power)

- Damping due to damper windings → requires invoking electromagnetic ideas from last week.

- First major equation: Steady state power transfer
  - → use this to find equilibrium
  - → ignores AVR

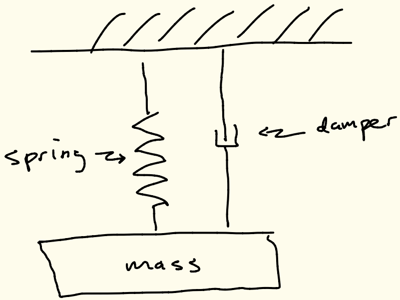
- Stability w/o AVR
  - → overview different models and assumptions to study swing dynamics.

- Stability <u>with</u> AVR
  - → here I'll just sketch some key ideas - in particular how AVR can increase transfer limits.

Newton's second law, $F = ma$

First, a few familiar mechanical examples:

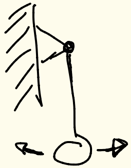
Spring-mass



System has damped oscillations, kinetic exchange w/ potential energy, energy dissipates in damper. x = displacement

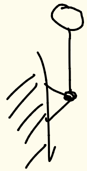
$$\boxed{ma = F \Rightarrow m\ddot{x} = -kx - c\dot{x}}$$

Pendulum



swinging pendulum exchanges kinetic w/ potential energy

At rest $\rightarrow$ stable eq. point



$\exists$ an eq. point in the vertical position, but it is unstable.

Newton's second law for a single generator

ω_m = frequency of total mass $\Rightarrow$ speed

$$ma = F$$

$$\Updownarrow$$

mechanical torque from turbine

$$J \frac{d\omega_m}{dt} = -D_d\, \omega_m - (\tau_e - \tau_t)$$

moment of inertia

acceleration

damping

difference between electrical and mechanical torque.

- In this chapter we'll spend all our time modeling D_d and τ_e to understand how ω_m (and angle) respond to disturbances.
- We'll ignore changes in τ_t

Let $\omega_m = \omega_{sm} + \Delta\omega_m = \omega_{sm} + \frac{d\delta_m}{dt}$

synchronous speed

deviation

δ_m is the "mechanical angle", i.e. the angle of the rotor relative to an electrical reference: in this chapter that is a neighboring infinite bus.

In steady state, $\frac{d\delta_m}{dt} = 0$, i.e. angles don't change relative to each other. Note w/ multi pole generators this distinction is particularly important

Substitute δ_m: $J\ddot{\delta}_m + D_d(\omega_{sm} + \dot{\delta}_m) = \tau_t - \tau_e$

$\tau_m = \tau_t - D_d\omega_{sm}$ (net torque)

$\Rightarrow J\ddot{\delta}_m + D_d\dot{\delta}_m = \tau_m - \tau_e$

Power is torque times speed...

$$J\omega_{sm}\ddot{\delta}_m + \omega_{sm} D_d \dot{\delta}_m = \omega_{sm}\tau_m - \omega_{sm}\tau_e$$

$$= \frac{\omega_{sm}}{\omega_m} P_m - \frac{\omega_{sm}}{\omega_m} P_e$$

$$= P_m - P_e$$ ← Assume $\omega_{sm} = \omega_m$

(drops important nonlinearities that matter for really big disturbances)

Set $D_m = D_d\,\omega_{sm}$, and

$M_m = J\omega_{sm}$ (angular momentum)

$$\Rightarrow \boxed{M_m \ddot{\delta}_m = P_m - P_e - D_m \dot{\delta}_m}$$

Note, assuming M_m is constant ignores nonlinearities! We won't assume D_m is constant, though.

Common Form

$$\delta = \frac{\delta_m}{p/2} \qquad p = \text{\# poles on generator.}$$

$$\omega_s = \frac{\omega_{sm}}{p/2}$$

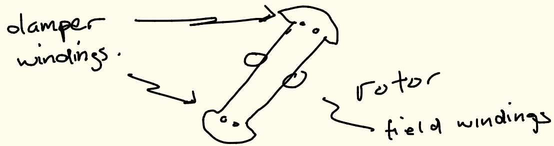
$$M = J\omega_{sm} \cdot \frac{p}{2}$$

$$P_D = \frac{2D_m}{p}\dot{\delta}$$

$$\Rightarrow \quad M\ddot{\delta} = P_m - P_e - P_D$$

Chapter focuses on these

Let's figure out P_D, damping power.



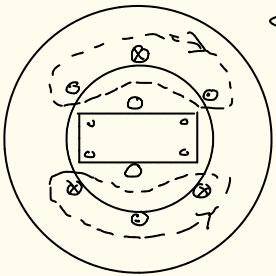
In wound rotor (uniform air gap single N-S pair) machines, the rotor body can serve as the winding path.

Basic idea:
- Dampers have high resistance
- speed deviation causes emf due to changing exposure to armature field
- this applies force that decreases speed deviation ⇒ "damping" b/c force is proportional to speed (deviation).

Assumptions for Analysis

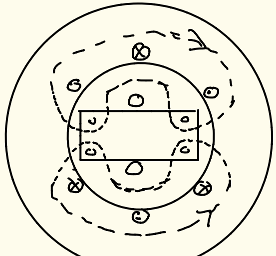
- Armature + field winding resistance are neglected
- Damping only due to damper windings
- Armature leakage reactance negligible.
- Rotor excitation level does not alter damping torque.

Subtransient and transient states



Subtrasient: armature field does not "penetrate" rotor at all.

X_d''



Transient: armature field penetrates damper but not rotor exciter field

X_d'

Each state has its own reactance

$X_d' > X_d''$

$X_q' > X_q''$

Let $D_d = \dfrac{X_d' - X_d''}{(X + X_d')^2} \dfrac{X_d'}{X_d''} T_d''$ $\qquad D_q = \dfrac{X_q' - X_q''}{(X + X_q')^2} \dfrac{X_q'}{X_q''} T_q''$

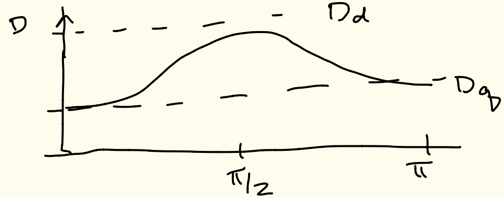
network reactance

time constants for armature field to penetrate damper.

⊛ Note, X, network reactance, has strong effect on damping power!

The result (see book for derivation) for small angle deviations

$$\Rightarrow \quad P_D = \left(D_d \sin^2 \delta + D_q \cos^2 \delta \right) \Delta\omega$$



It is hard to get intuition for the size of this power since it depends on both δ and $\dot{\delta}$ - so we need to solve the system odes. But you can see there is strong nonlinearity!

There is also a large deviation result in the book - but omitted here for sake of time

How big is P_D relative to Pe?

This is a question I hoped to answer but ran out of time.

Steady state power (Section 3.3)

- E_q is emf "behind" reactances X_d and X_q
- Eq'n assumes gen resistance is small.

generator emf, constant network voltage

$$P_e(\delta) = \frac{E_q V_s}{x_d} \sin\delta + \frac{V_s^2}{2} \frac{x_d - x_q}{x_q x_d} \sin 2\delta$$

x is lower case in this eq'n.

$x_d = X_d + X$

steady state d-axis reactance

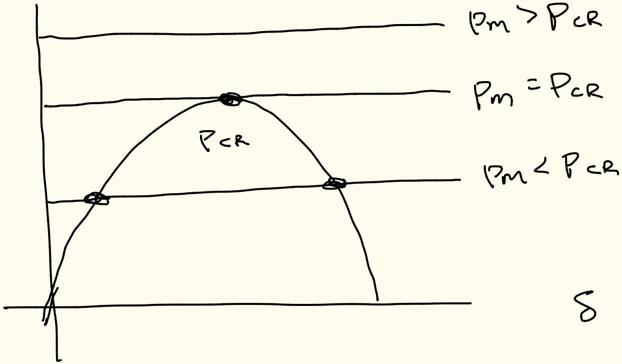
$x_q = X_q + X$

Swing Equation and equilibria

$$M\ddot{\delta} = P_m - P_e(\delta) - P_D = P_m - P_e(\delta) - D\dot{\delta}$$

Equilibrium $\Rightarrow$ $\ddot{\delta} = \dot{\delta} = 0$

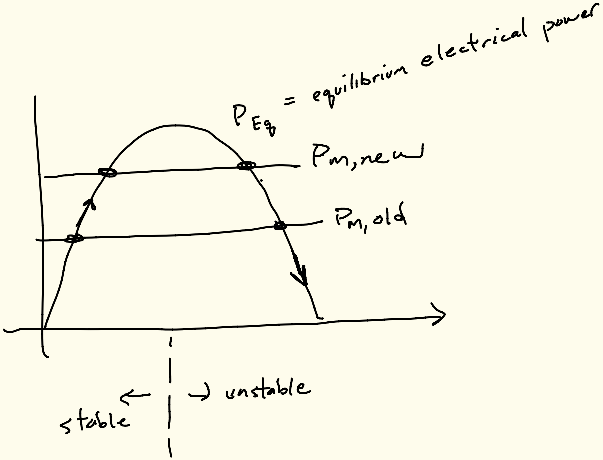
Assume $X_d = X_q$ (round rotor) $\Rightarrow$ $\boxed{P_e(\delta) = \frac{E_q V_s}{X_d} \sin\delta}$



Stability of the unregulated system

(no AVR)

1. "Small signal": Only considering the effect of small deviations



$$K_{Eq} = \left.\frac{\partial P_{Eq}}{\partial \delta}\right|_{\delta=\hat{\delta}} > 0 \Rightarrow \text{stable}$$

point in question

Stability of the unregulated system

(no AVR)

2. Transient dynamics.

Key assumption: Flux fully penetrates damper winding

(time scale is ~ 0.01 s)

Flux does not penetrate rotor

(time scale is ~ 1-2 s.)

$\Rightarrow$ ignore subtransient state

Stability of the unregulated system

(no AVR)

Simple model #1: "Constant flux linkage"

$$P_e = \frac{E_q' V_s}{X_d'} \sin\delta + \frac{E_d' V_s}{X_q'} \cos\delta - \frac{V_s^2}{2} \frac{X_q' - X_d'}{X_q' X_d'} \sin 2\delta$$

Contrast to steady state!

- using transient reactances and voltages
- includes a $\cos\delta$ term.

"Classical model"

Simple model #2: Same as #1, but also assume rotor is axi-symmetric ($x_d' = x_q'$) $\Rightarrow$ "classical model"

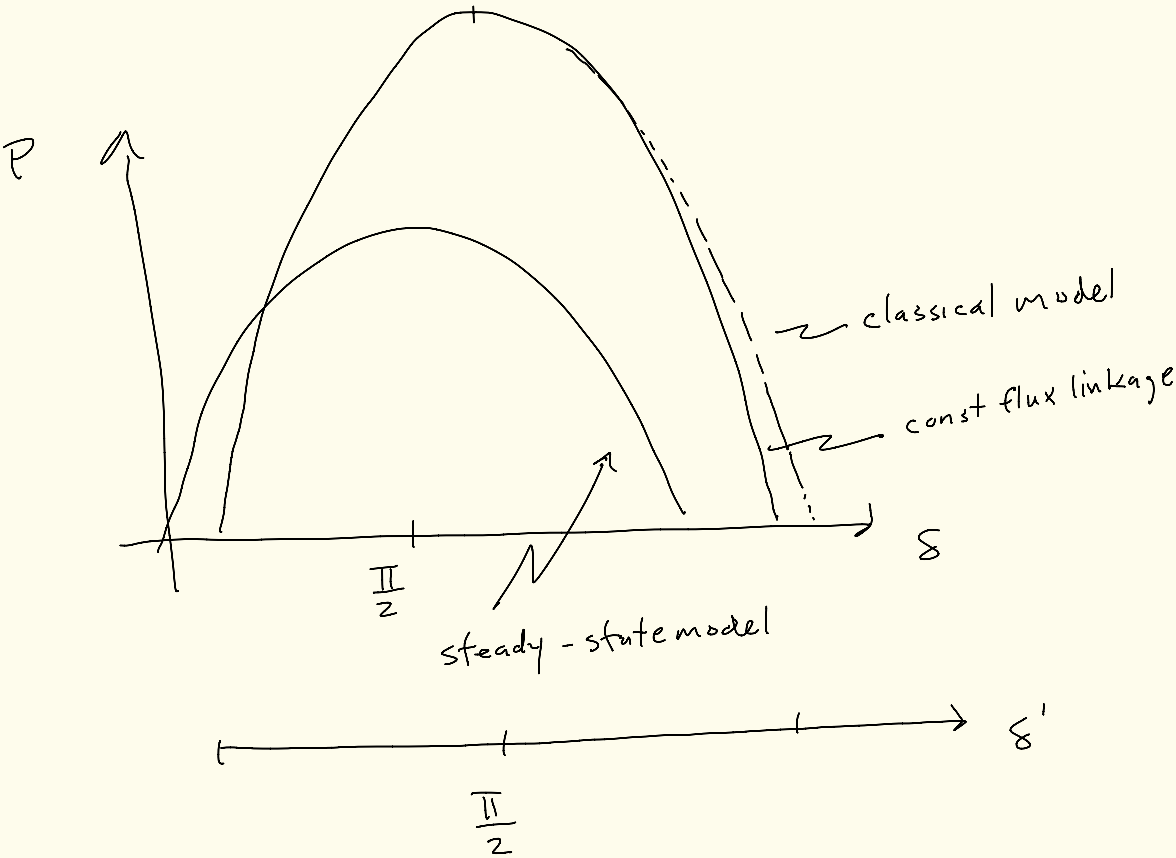
generator emf on either d- or q-axis

$$P_e = \frac{E' V_s}{X_d'} \sin\delta'$$

angle between $\underline{V}_s$ and $\underline{E}'$

(δ is angle between $\underline{V}_s$ and q-axis)

$$\Rightarrow M\ddot{\delta}' = P_m - \frac{E' V_s}{X_d'} \sin\delta' - D\dot{\delta}'$$


P
δ
$\frac{\pi}{2}$
classical model
const flux linkage
steady-state model
δ'
$\frac{\pi}{2}$

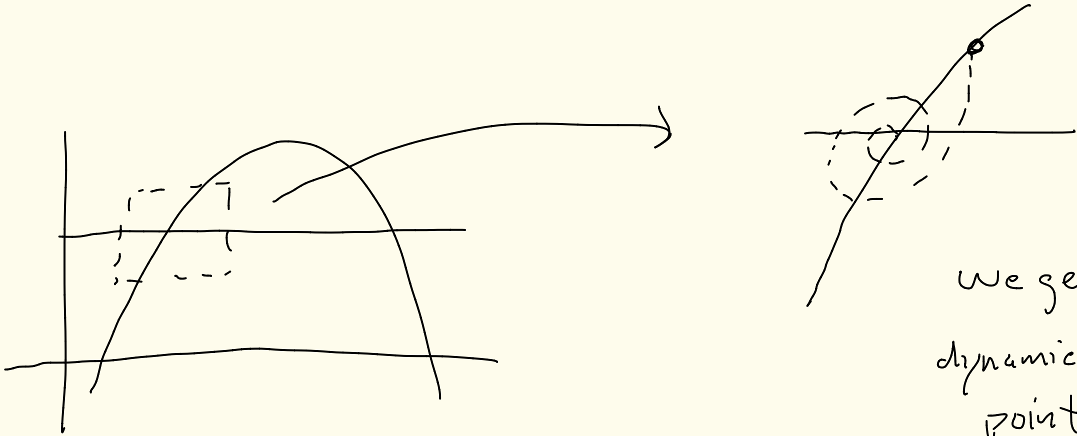
Observations for transient stability:

1. Can support much larger power transfer
2. Works for larger δ, since E' is shifted relative to q-axis
3. Though the simplified models promote analytical work, you can simulate the more sophisticated ones.

→ Super-fancy would be to directly model field penetrating the rotor over time. Here they just assume constant flux paths & transition between.

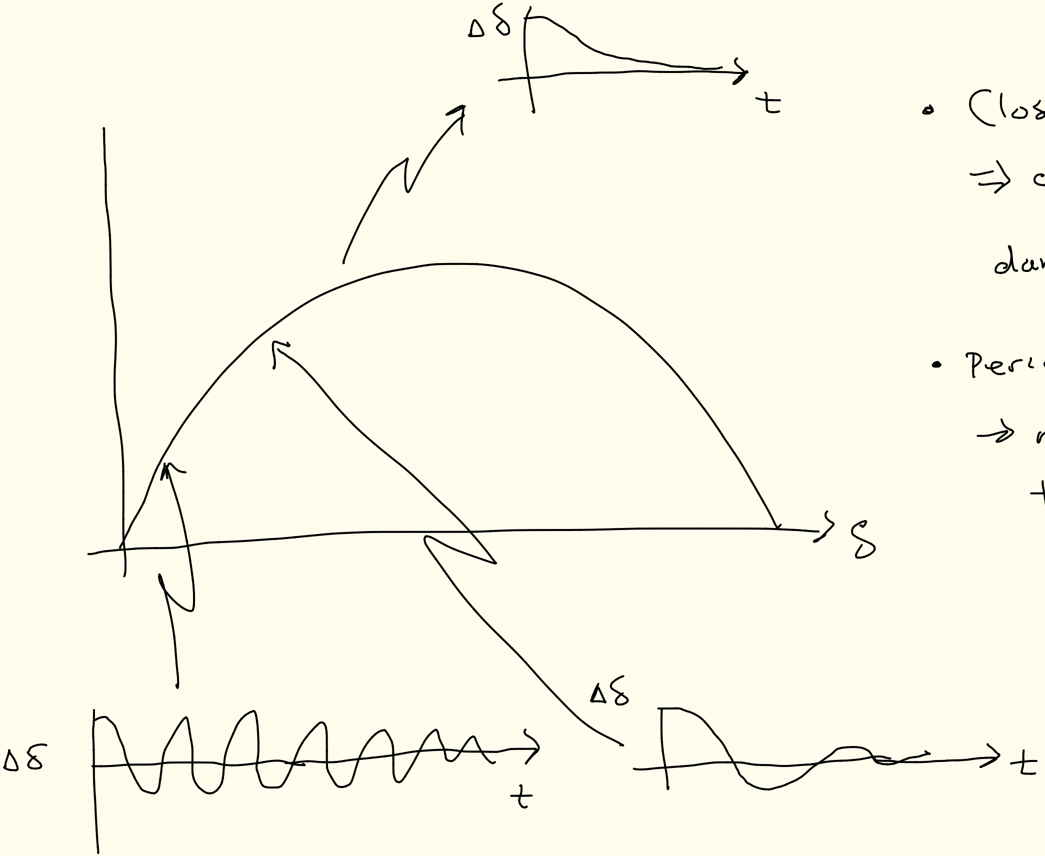
Effect of damper windings

Without damper windings, a shift in mechanical or electrical power would produce sustained oscillations. Instead:



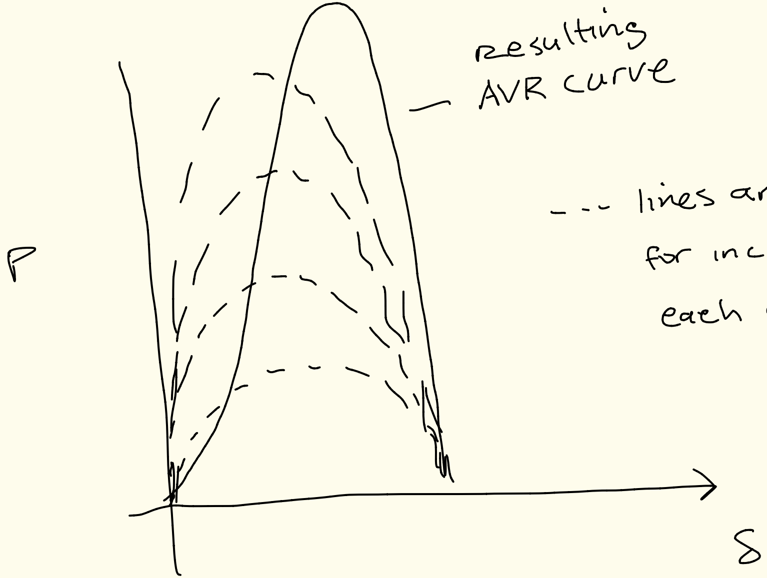
We get damped dynamics to new eq. point.

Unregulated system: Types of dynamics



- Closer to $\Delta\delta = 0$
  $\Rightarrow$ oscillations faster, damp more slowly.
- Period of oscillations
  $\rightarrow$ not clear from text! Did not have time to analyze.

Regulated system (AVR) - Steady State.



--- lines are curves are for increasing ~~E~~ (but constant on each curve) excitation voltages.

$\Rightarrow$ Larger δ and transfer capabilities are possible

Regulated system: Dynamics

Voltage controller only reacts to voltage error

→ this can weaken damping and even turn it negative.

⇒ AVRs can generate instability

⇒ Power System Stabilizers (PSS; ch10) can help here.

Summary

- Models used depend on if you want steady state or transient analysis
  → that determines how to model interaction between armature flux and rotor magnetics.
- $\pi/2$ is "critical" angle in steady state
- Higher power transfer and angles are possible in transient conditions.
- AVR can give higher power xfr, but stability may degrade.

Rotor flux linkage

→ mention in passing

N4 , N5

N3

5.51 or

discuss eq 5.52

N6

$$M\Delta\ddot{\delta} + D\Delta\dot{\delta} + K_E'\Delta\delta + D_\delta'\Delta E' = 0$$

Power angle for regulated...

Fig 5.21, Fig 5.22

discuss N7 N8

Other notes.

N9, N10

Extreme stability cases — close to or beyond $\pi/2$ — outside of scope but might matter a lot for multi machine w/ CIG.