21st Century Power System Dynamics

EECS 290

Spring 2019

March 11 2019 Lecture notes.

Introduction

Focus today on large disturbances

→ "Equal area criterion" rather than small small signal.

→ I will set up for 3ϕ faults & discuss other issues in more general terms

1. Preliminaries
   - Pos-neg-zero sequence - will not cover, but basic assumption is that one can neglect the effects of phase imbalance. (but effect of unbalanced faults is captured in balanced representations of fault reactances.)
   - Recap subtransient, transient and steady state reactances.

2. Fault circuits and equivalent reactances

3. Simplified equal area criterion analysis of 3ϕ fault.

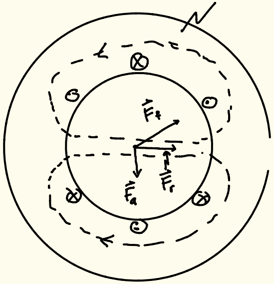
4. High level discussion for
   - alternative fault types
   - AVR
   - different line lengths

Common Form for swing equation (Recap from last time)

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

Review: Armature and rotor mmf: Steady State, no fault (ch 3.3)

ϕ_{arc} = armature flux



$\vec{F}_f$ = mmf due to rotor

$\vec{F}_a$ = mmf due to armature

$\vec{F}_r$ = resultant mmf

e_{rA} = "air gap emf" in phase A.

$$= -\frac{d}{dt}\left(N_\phi \frac{\vec{F}_{rA}}{\mathcal{R}} \right)$$

A-phase component of mmf

N_ϕ: ~ # windings in armature

$\mathcal{R}$: path reluctance – mostly prop. to air gap.

$$= e_{fA} + e_{aA}$$

e_{fA}: emf due to rotor

e_{aA}: emf due to armature

all on phase A.

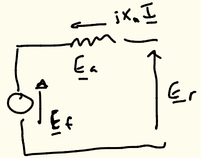
Review

Thanks to Faraday's Law, the air gap emf for the armature lags the current by $90°$ $\Rightarrow$ $\boxed{\underline{E}_a = -jX_a \underline{I}}$ is how the generator emf is manipulated due to armature reaction

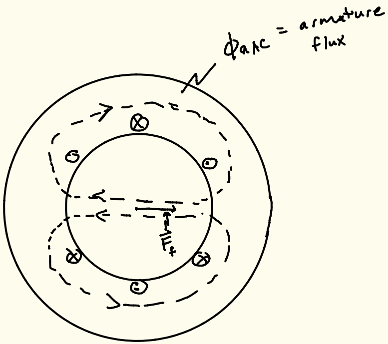
$$\Rightarrow \quad \underline{E}_r = \underline{E}_f + \underline{E}_a = \underline{E}_f - jX_a \underline{I}$$

$$\underline{E}_r = \underline{E}_f + \underline{E}_a$$

$\Rightarrow$



The mmf changes during a fault (Ch 4.2)



In particular, because there is no net electrical torque during a 3ϕ fault,

$\Rightarrow$ angle between $\vec{F}_f$ and ϕ_{AC} is 180°

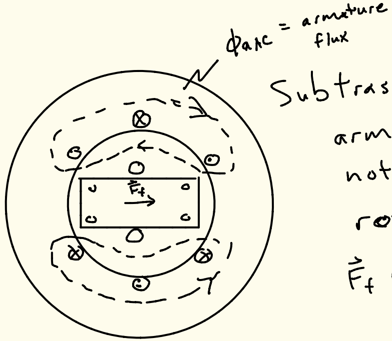
(on previous slide it was closer to 90°.)

steady state flux path during a fault...

Subtransient and Transient flux Paths

- Immediately following a fault we assume rotor flux is constant
- But damper & rotor windings get additional current due to changing rotor speed.
- To conserve rotor flux the armature flux is said to take a different path.

Subtransient and transient states

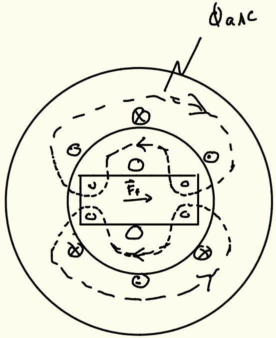


Subtrasient:

armature field does not "penetrate" rotor at all.

$\vec{F}_f$ is the rotor field mmf

X_d''



Transient:

armature field penetrates damper but not rotor exciter field

X_d'

Each state has its own reactance

$X_d > X_d' > X_d''$

$X_q > X_q' > X_q''$

effective armature reactance

$$\Rightarrow \underline{E}_r = \underline{E}_f - jX_a \underline{I} = \underline{E}_f - jX_d \underline{I} .$$

for round rotor we assume $X_d = X_q$

(Important follow-on point on next page)

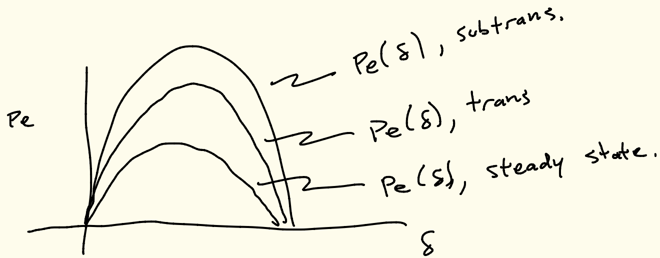
Internal generator voltages during sub, transient and steady-state fault:

Q: which condition produces the highest voltage?

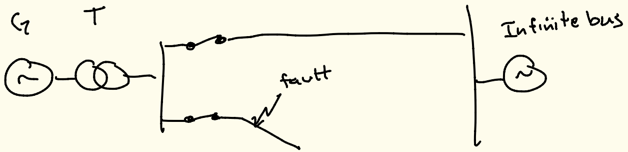
can be ss., trans. or sub trans.

$$\underline{E}_r'' = \underline{E}_f - j X_d'' \underline{I}$$

- $|\underline{E}_r''| < |\underline{E}_r'| < |E_r|$



Now, transient stability Ch 6.1



Objective:

- assessing whether a generator will remain synchronized during a fault.

Pre and post-fault reactance between Generator and ∞ bus:

$$X'_{dPRE} = \underset{\substack{\uparrow \\ \text{internal} \\ \text{generator} \\ \text{reactance}}}{X'_d} + \underset{\substack{\uparrow \\ \text{xfrmr}}}{X_T} + \underset{\substack{\uparrow \\ \text{tx line}}}{X_L} + \underset{\substack{\uparrow \\ \infty \text{ bus effective reactance}}}{X_s}$$

Fault reactance

$$X'_{dF} = X'_d + X_T + X_L + X_s + \frac{(X'_d + X_T)(X_L + X_s)}{\Delta X_F}$$

Important Assumptions for basic fault analysis

- Assume all fault event occurs during transient phase
    - Sub trans too short
    - never get to s.s.

  ⟹ ignore dynamics in damper & rotor windings

- Assume pure reactance (no resistance) on all elements.

- Ignore turbine governor dynamics

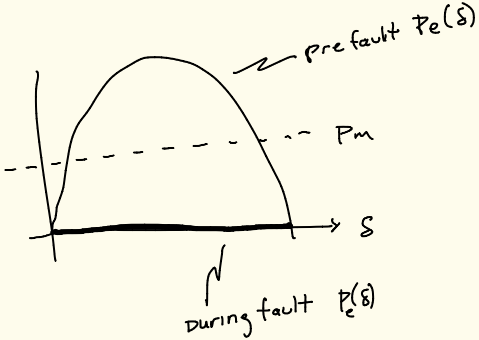
- Ignore damping

3ϕ fault

$\Delta x_F = 0$ when adjacent to generator

$\Rightarrow$ ∞ impedance connection to system.

$\Rightarrow$ All mechanical power returns to rotor speed.

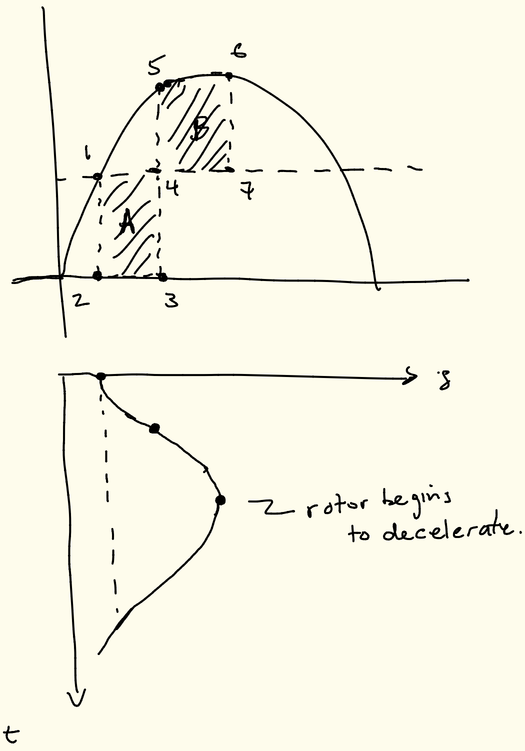


ε = rotor acceleration

$$= \ddot{\delta} = \frac{P_m}{M} = \text{constant}$$

i.e. ignore P_e and P_D.

Equal Area Criterion - Stable operation



1: Pre fault

2. Immediately during fault - δ hasn't changed but $P_e(\delta)$ has.

3. Rotor accelerates

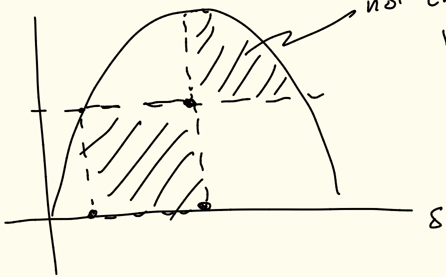
4. Fault clears.

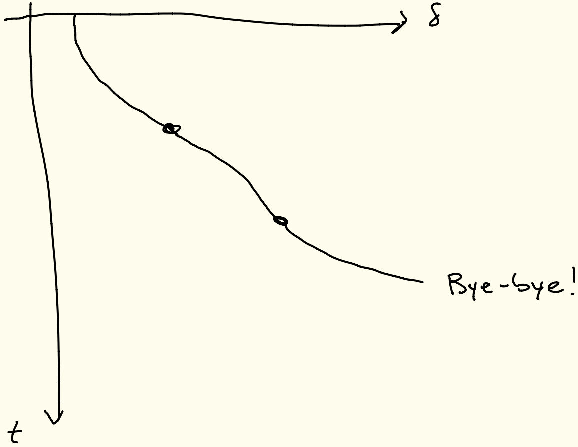
5. δ stays @ same value but now we are on new $P_e(\delta)$

   $\Rightarrow$ rotor decelerates.

6. Rotor speed equals original when two shaded areas are equal.

EAC - unstable





Q: What affects whether or not the rotor will remain synchronized?

- Time to clear fault
  - → more time = less stable
- Height of $P_e(\delta)$ curve
  - → Effect depends on conditions
  - → AVR can help.
  - → this is complicated!
- P_m before fault → lower loading gives more stability
- longer Fault distance ⇒ less impact on $P_e(\delta)$ during fault.

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- Auto-recloser
- Fault types (2ϕ, 1ϕ ...) see next slide

Different types of faults