Topics for Today:

- Project Grading Criteria:
  - References: **min of 2 texts, 2 journal papers**
  - Formal part: introduction, overview, summary, reference list. Informal part: You can attach computer output, detailed results, etc.
- Grading:
  - Clear scope
  - Writing - Organization and grammar
  - Complete treatment, summarized results
  - Valid results
  - Technically correct, adequate references
  - **Conclusions & Recommendations**

Topics for Today:
- Wrapup of Short-circuit studies
- Unbalanced fault calculations
  - Shunt Unbalanced
  - Series Unbalanced
- Transformer phase shift in pos-neg seq.
- Computer methods for fault studies
  - Avoiding singularity
  - Reduced order models, effect on dc offset
- Introduction to system stability
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<th>Projects:</th>
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<tr>
<td>Landreman</td>
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<td>Nickels, Parkinson</td>
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- Paper Review

- Submit Outline of Project
  - Friday 9:00 am
Fig. 4.17 Box sequence connections for shunt balanced and unbalanced conditions:
(a) balanced load or three-phase-to-ground fault with impedances; (b) three-phase fault;
(c) three-phase to ground fault; (d) shunt circuit open; (e) phase-to-ground fault through
an impedance; (f) phase-to-phase fault; (g) phase-to-phase fault through impedance;
h) phase-to-phase fault; (i) two-phase-to-ground fault through impedance; (j) two-phase
to-ground fault; (k) three-phase-to-ground fault with impedance in phase a; (l) unbalanced
load or three-phase-to-ground fault with impedance. (From E. L. Harder, Sequence Network
Connections for Unbalanced Load and Fault conditions, *The Electrical Journal*, December 1937.)
Series unbalance in loads, connect.

Fig. 4.18 Box sequence connections for series unbalanced conditions: (a) equal impedances in three phases; (b) normal balanced conditions; (c) neutral circuit open; (d) any three or four phases open; (e) phases b and c open and impedances in phase a and neutral; (f) phases b and c open; (g) phases a and neutral open and impedances in phases b and c; (h) phase a and neutral open; (i) phase a open and impedances in phases b, c, and neutral; (j) phase a open; (k) impedance in phase a; (l) equal impedances in phases b and c, impedance in neutral; (m) equal impedances in phases b and c; (n) equal impedances in phases b and c, neutral open; (o) impedances in phase a and neutral. (From E. L. Harder, Sequence Network Connections for Unbalanced Load and Fault Conditions, The Electrical Journal, December 1937.)
EX: HV Substation

25 ft between supports (~ 8 m)

Parallel Conductors:

Re-bar "cage"

L-L 3Φ Fault, 40,000 ARMS = 56,570 A peak

What is max induced force?

\[ f = i (L \times B) \, N \]

\[ f_{\text{insul}} = (56,570 \times 8 \text{m}) \times (0.0377) \]

\[ = 1706 \times \frac{\text{kgf}}{9.8N} \times \frac{2.216}{\text{kgf}} \]

\[ = 383 \text{ lbs (max)} \]

Max Groundline Moment: \( 383 \times 12 = 4600 \text{ ft-lbs} \)

Note:

\[ H = \frac{I}{2\pi r} \]

\[ B = \mu_0 H = \frac{\mu_0 I}{2\pi r} \]

\[ = \frac{(4\pi \times 10^7)(56,570)}{2\pi (\text{in})} \]

\[ 0.00377 \text{ T} \]
Either side.

\[ Z = \frac{V}{I} \]

\[ V_a = I_a R \]

\[ Z = \frac{V_a}{I_a} \]

Phase Shifts & Impedances
Problem:

ECE5200 - Advanced Methods in Power Systems

- Leads to singularity (Y)

Computer Methods
\[ Q_{out} = \frac{E}{\sqrt{V}} \cos \theta - \sqrt{V} \]

\[ V_5 = \sqrt{100} \]

\[ V_6 = \sqrt{625} \]

\[ E_6 = E_7 \]

\[ I_{out} = \frac{V_5}{R_{out}} \sin (\theta - 0) \]

\[ \text{Diagram with various symbols and connections} \]
\[ P_{in} = P_{in} \]

- **P stays constant**
- **P changes suddenly**
- **Load switching**
- **Clear**

\[ \Rightarrow P_{e} = P_{out} \]
SYSTEM STABILITY

Stability: Ability of machines in system to recover from system disturbances and still remain synchronized and return to a steady-state operating point.

Types:

**Steady-State Stability** - Use load flow to check for:
1. Phase angle across T-line $\leq 90^\circ$
2. $0.95 < V_{bus} < 1.05$

Also - do incremental changes in operating points to check system sensitivities. - Voltage Collapse

* Transient Stability - Check major disturbances
  - Loss of generator
  - Line switching
  - Faults
  - Load switching

Track frequency changes ($f_s = 60$ Hz) and $S$ changes.

Objective: See if machines return to synch frequency with new $S$'s power angles.

Assumptions:

- So-called "first swing"
- $P_h$ constant, include inertial dynamics.
- Eg doesn't change, use load flow on electrical model, good for $\sim 1.0$ sec
- dc offsets & harmonics ignored on side.

* This is what we'll focus on in this course.
Transient Stability (contd):
If $t>1.0$ sec is desired ("multi-swing") then can include governor & exciter.

**Dynamic Stability** — out to several minutes.
Effects also included:
- Governors
- Exciters
- LTC XFMRs
- Dispatch/SCADA controls

Interactions can destabilize system even several minutes after disturbance occurs.
(Even when transient stability is maintained.)
Steady-State Stability - Like power transfer

\[ P = \frac{E_s E_m}{X} \sin \delta \]

\[ P_{E} = \frac{E_s E_m}{X} \sin \delta \]

\[ P_{E_{\text{MAX}}} = \frac{E_s E_m}{X} \]

Too High \( P_m \)

OK \( \rightarrow P_{\text{MECH}} \)

\[ P = P_{\text{acc}} \text{ (depends on } s) \]

\[ S \]

\[ 90^\circ \]

\[ 180^\circ \]

If \( P_m > P_{E_{\text{MAX}}} \), lose sync so must disconnect from system.

Keep \( P_{\text{MECH}} \leq P_{\text{ELECT}_{\text{MAX}}} \) to assure stability.

To increase stability, we can:

- Increase \( E_s \) or \( E_m \)
- Decrease \( X \) by
  a) Parallel lines:
  b) Series Cap:
    \[ X = X_{\text{LINE}} - X_{\text{CAP}} \]
  c) Shunt Cap even helps:
    \[ \frac{jX}{2} \]
    \[ \frac{3X/2}{-jX_c} \]

Transfer Impedance:

\[ j \left( X - \frac{X^2}{4X_c} \right) \]
For cylindrical rotor machines:

Keep $S < 90^\circ$

For salient machines, $S$ even less, since $P_{\text{max}}$ occurs at $p_i$

In reality, dangerous to operate close to $P_{\text{max}}$, since small increase in $P_{\text{max}}$ will put $S$ "over the top". Usually try to keep $S < 40^\circ$. 
Transient Stability: The Problem

\[ T_m = \text{mechanical torque, N-m} \]
\[ T_e = \text{electromagnetic counter torque, N-m} \]
\[ J = \text{mass polar moment of inertia} \]
\[ B = \text{Damping torque coefficient} \]
- Bearing Friction
- Damper Winding Torque
- Windage
- Exciter Torque
- Magnetic Losses (leakage)
- Any Drag Torques in General

\[ \omega_r = \text{mechanical rotor speed, rad/sec} \]

Steady-State: \( \bar{P}_m = \bar{P}_e, \ bar{T}_m = \bar{T}_e \). But:
* Loss of line, fault, load, etc., reduces \( \bar{P}_e \)
\( \bar{P}_m \) will stay constant (gradually reduce, \( t > 1 \text{ sec} \))

\( P_a = P_m - P_e = \text{Accelerating power, speeds up rotor} \)
* Loss of generator in system makes \( P_e > P_m \) and
  decelerates other generators in system.

Oscillations of machine \$S\$ w.r.t. each other is called SWING.
Adding Detail to Model

1) Governor - Measures $f$ and (each machine)
   a) increases $P_m$ if $f < 60$ Hz
   b) decreases $P_m$ if $f > 60$ Hz

2) Add excitation -
   Measure $V_t$ (bus voltage)
   a) Reduce $I_f$ if $V_t > 1.0 \text{ p.u.}$
   b) Increase $I_f$ if $V_t < 1.0 \text{ p.u.}$

3) Fast Valving
4) Power System Stabilizer
5) Single Pole Reclosing - Japan
6) Fast Reclosing
7) Load Shedding
8) Switched Capacitors
9) Braking Resistors

So computer simulation is a must.

To improve stability
1) Make $H$ large
2) Reduce $P_m$ during fault
   a) Fast Valving
   b) Gov - slow down during fault
      but too slow to react
10.1 The Swing Equation:

\[ T_a = T_{ac} = T_m - T_e = \frac{J \alpha}{m} = J \frac{d\omega_m}{dt} \]

\[ \uparrow \quad (T = J \alpha \iff F = ma) \]

In terms of Power,

\[ \begin{align*}
  & P_m - P_e = W_{rm} J \frac{d\omega_m}{dt} \\
  & \uparrow \quad \uparrow \\
  & P_m = W_{rm} \dot{T}_m \\
  & P_e = W_{rm} \dot{T}_e
\end{align*} \]

\[ \frac{\dot{T}_m}{\dot{T}_e} = \sqrt{ \frac{E_f}{\sqrt{r} } } \]

Review: \( S' = \text{electrical} \quad \text{torque angle} = \frac{\dot{B}_r}{\dot{B}_s} \)

Here, \( S \) taken as angle between \( w_{ref} \) and rotor

\[ S = \frac{\dot{B}_r}{\dot{B}_s} = \frac{w_{ref}}{w_{ref}} \text{ see fig 12.2} \]

\( w_{ref} \) can be synch, or set to match some other machine in system. Usually, it is both, i.e. matches \( w \) of \( \infty \) infinite bus. If there is no infinite bus, then probably set to \( w \) of machine having largest "H".

For an \( N \)-Pole machine,

\[ w_{ref} = W_{rm} \left( \frac{N_p}{2} \right) \]
The electrical angular velocity:

\[ \omega_{re} = \omega_{ref} + \frac{d \delta}{dt} \]

\[ \omega_{rm} = \frac{\omega_{re}}{N_p/2} \]

\[ P_m - P_e = \omega_{rm} J \frac{d \omega_{rm}}{dt} \]

Substituting,

\[ P_m - P_e = \left( \frac{\omega_{re}}{N_p/2} \right) J \frac{d}{dt} \left( \frac{\omega_{re}}{N_p/2} \right) \]

\[ = \frac{\omega_{re}}{N_p^2/4} J \frac{d}{dt} \left( \omega_{ref} + \frac{d \delta}{dt} \right) \]

\[ P_m - P_e = \frac{\omega_{re} J}{N_p^2/4} \left( \frac{d \omega_{ref}}{dt} + \frac{d^2 \delta}{dt^2} \right) \]

Converting to per unit,

\[ P_{m,pu} - P_{e,pu} = \frac{\omega_{re} J}{N_p^2/4 \cdot S_{3\phi \text{ base}}} \left( \frac{d \omega_{ref}}{dt} + \frac{d^2 \delta}{dt^2} \right) \]

At this point we define

\[ H = \text{Kinetic Energy of all rotating parts at } \omega_s = \frac{1}{2} J \omega_s^2 \]

Units:

- Joules
- Watts
- Seconds
\[ H = \frac{1}{2} J \left( \frac{\omega_{se}}{Np} \right)^2 \]

Substituting, \[ J = \frac{2 H S_{3\phi, base} N_p^2}{4 \omega_{se}^2} \]
\[ J = \frac{H N_p^2 S_{3\phi, base}}{2 \omega_{se}^2} \]

If \( \omega_{se} = \omega_{re} \) (not too far wrong if stability maintained)

Substituting, \[ P_m - P_e = \omega_{re} \left[ \frac{H N_p S_{3\phi, base}}{Np K} \right] \left( \frac{d\omega_{ref}}{dt} + \frac{d^2\delta}{dt^2} \right) \]

\[ P_m - P_e = \frac{H}{2f} \left( \frac{d\omega_{ref}}{dt} + \frac{d^2\delta}{dt^2} \right) \]

Again, \[ P_m = \text{turbine input power (mech)} \] for Unit
\[ P_e = \text{generator output} \]
\[ H = \text{Inertia Constant in seconds} \]
\[ \delta = \frac{L}{B} - \frac{\omega_{ref}}{\omega_{se}} \text{, radians} \]
\[ \omega_{ref} = \text{ang. velocity of reference machine, rad/sec} \]
\[ t = \text{time in seconds} \]

Term = 0 if infinite bus \( \omega_{ref} = \omega_{se} \) is used.
12.2 - Inertia

Newton's second Law:  \( F = ma \)

Tangential force on differential element:
\[ F_t = (dm) \frac{at}{t} = dm \frac{d\omega}{dt} \]
\[ = r(dm) \frac{d\omega r m}{dt} \]
\[ = r \omega r m \]

The accelerating Torque:
\[ T_a = r F_t = r^2(dm) \frac{d\omega r m}{dt} \]
\[ = J \alpha \quad N\cdot m \]

\[ dJ = r^2 dm = \text{mass polar moment of inertia of element, (kg}\cdot\text{m}^2) \]

If material has density \( \rho \), \( dm = \rho \frac{dv}{volume} \)
\[ dv = (rdr)(d\theta)(dz) \]
\[ J = \int_{0}^{2\pi} \int_{0}^{z} \int_{0}^{R} \rho r^3 dr \, dz \, d\theta \]
For actual rotor, field slots and use of different materials can make this complex problem.

i.e. \[ R = f(\theta, z) \]
\[ z = f(z) \]

If rotor is homogeneous,

\[ J = \frac{\rho R^4 z}{4} \cdot 2\pi = \frac{\pi\rho R^4 z}{2} \]

Total cylinder mass is

\[ M = \rho \int_0^{2\pi} \int_0^z \int_0^R rdr dz d\theta \]

\[ = \frac{\rho R^2 z}{2} \cdot 2\pi = \frac{\pi\rho R^2 z}{2} \text{ Kg} \]

Substituting,

\[ J = \frac{MR^2}{2} \text{ Kg-m}^2 \]

If rotor not homogeneous, use numerical integration.
General Case:

$$\mathbf{\tau} = J \frac{d\omega_{\text{rm}}}{dt}$$

Sometimes, radius of gyration is given:

$$K = \text{radius from axis of rotation that a concentrated mass } M \text{ could be placed to give identical } M.$$

For different mass or point mass, \(J = MK^2\)

$$K = \sqrt{\frac{J}{M}}$$

If \(K > M\) are given, \(J\) can be calculated.

Possible confusion:

<table>
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<tr>
<th>SI</th>
<th>Mass</th>
<th>Weight</th>
<th>(g)</th>
<th>accel. of grav</th>
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<tbody>
<tr>
<td></td>
<td>Kg</td>
<td>N</td>
<td>9.81 m/\text{sec}^2</td>
<td>\text{m/sec}^2</td>
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\(W = Mg\) \(\text{lb}\)

\(\text{Eng: slugs}\) \(\text{lb}\) \(32.2 \text{ ft/sec}^2\)

also \(\text{lbm vs. lbf}\)

\(M' = Mg\) \(\text{lbm}\)

\(W = Mg\) \(\text{lbf}\)

Common Practice in US: (Unfortunately):

\(J\) given as \(WK^2\)

\(W = \text{mass in lbm}\)

\(K = \text{rad. gyration in feet}\)
\[ J = \text{W} K^2 \text{ lbm} - \text{ft}^2 \left( \frac{0.3048 \text{ m}^2}{\text{ft}} \right) \left( \frac{0.4536 \text{ kg}}{\text{lbm}} \right) \]

\[ = \text{Kg} - \text{m}^2 \]

"If" several masses are on same shaft.

Then \( J_{\text{tot}} = J_1 + J_2 + J_3 + \ldots + J_n \)

Then: Convert
\[
H = \frac{1}{2} J_{\text{tot}} (2 \omega s/Np)^2
\]

\[ S_3 \Phi, \text{BASE} \]

Conversion of \( H \) to different system base.

Ex: Gen base is 500 MVA, system base is 100 MVA

\[ H_{\text{new base}} = \frac{H_{\text{old base}} S_{3\Phi, \text{old base}}}{S_{3\Phi, \text{new base}}} \]

\[ H_{\text{new}} = 5 \times H_{\text{old}} \]

Typical \( H \) values:
- 2-pole thermal: 2.5 - 6.0 \( \text{on machine base} \)
- 4-pole thermal: 4.0 - 10.0 \( \text{on machine base} \)
- Hydro: 2.0 - 4.0
Nuclear Generator, \( W R^2 = 5.82 \times 10^6 \text{ lbm-ft}^2 \)
\( MVA = 1333 \text{ MVA} \)
\( N_s = 1800 \)

\[ J = W R^2 \times \text{conversion factor} \]
\[ = (5.82 \times 10^6 \text{ lbm-ft}^2) \left( \frac{\text{Kg}}{221 \text{lbm}} \right) \left( \frac{\text{m}}{3.28 \text{ ft}} \right)^2 \]
\[ = 2.459 \times 10^5 \text{ Kg-m}^2 \]

\[ H = \frac{\sqrt{2 \times 2.459 \times 10^5}}{1333 \times 10^6} \left( \frac{2 \pi (22 \times 1800)}{e_0} \right)^2 = 3.27 \text{ sec} \]

On 100 MVA system base,
\[ H = 3.27 \left( \frac{1333}{100} \right) = 43.56 \text{ sec} \]

Shortcut:
\[ H = 2.31 \times 10^{10} \frac{WR^2 \times RPM^2}{S \text{ machine base}} \]
\[ = \frac{WR^2 \text{ in lbm-ft}^2}{MVA} \]
Coherent Machines: 2 or more machines operating in parallel, whose rotors swing together \((S_1 = S_2)\).
(Only possible if sharing equal p.u. loads, and running on same droop characteristic.)

**Ex:**

Unit 1: 500 MVA 0.85 PF
20 kV 3600 RPM
\(H_1 = 4.8\)

Unit 2: 1333 MVA 0.9 PF
22 kV 1800 RPM
\(H_2 = 3.27\)

System base = 100 MVA

To combine, must convert to same base.

\[H_{\text{tot}} = 4.8 \frac{500}{100} + 3.27 \frac{1333}{100} = 67.59 \text{ sec}\]

Alternate Method: \(H = \left(\frac{\text{MVA}}{\text{MVA}}\right)\)

\[H = \left(\frac{4.8 \text{ MVA}}{100}\right)\text{MVA} + \left(3.27 \text{ MVA}\right)\text{MVA}\]

100 MVA

\(S\) & \(W\) must be in electrical units --
Since one machine is 4-pole, other is 2-pole.