EEE269-Electrical Drives and Instrumentation

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1. Ideal Transformer
   a. $a = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$
2. Real Transformer
   a. Basic
      i. $E = 4.44Nf\phi_{max}$
      ii. $\phi_{max} = B_{max} \times A$
         1. B = Magnetic Flux density
      iii. $H = \frac{N_p I_M}{l}$
         1. H = magnetic field intensity (A-t/m)
         2. N_P = Turns in primary winding
         3. I_M = Magnetizing current (A)
         4. l = Mean length of core
   b. Determining components
      i. Open circuit test
         1. Performed on low voltage side in rated voltage
         2. $PF = \frac{P_{OC}}{V_{OC}I_{OC}}$
         3. $Y_E = \frac{I_{OC}}{V_{OC}} \angle - \cos^{-1} PF = \frac{1}{R_C} - j\frac{1}{X_M}$
      ii. Short circuit test
         1. Performed on high voltage side in rated current
         2. $PF = \frac{P_{SC}}{V_{SC}I_{SC}}$
         3. $Z_{SE} = \frac{V_{SC}}{I_{SC}} \angle \cos^{-1} PF = R_{eq,s} + jX_{eq,s}$
   c. Voltage regulation
      i. $VR = \frac{V_{S,nl} - V_{S,fl}}{V_{S,fl}} \times 100\%$
      ii. $VR = \frac{\left|\frac{V_P}{a}\right| - |V_{S,fl}|}{|V_{S,fl}|} \times 100\%$ (Referred to Secondary)
         1. $\frac{V_P}{a} = V_S + \left(R_{eq,s} + jX_{eq,s}\right) \times I_S$
      iii. $VR = \frac{V_P - aV_{S,fl}}{aV_{S,fl}} \times 100\%$ (Referred to Primary)
         1. $V_P = aV_S + \left(R_{eq,p} + jX_{eq,p}\right) \times \frac{I_S}{a}$
   d. Transformer efficiency

i. $\eta = \frac{P_{out}}{P_{in}} \times 100\%$
ii. $P_{in} = P_{out} + P_{Cu} + P_{core} = V_P I_P \cos\theta$
iii. $P_{out} = V_s I_s \cos\theta$
iv. $P_{core} = \frac{\left(\frac{V_P}{a}\right)^2}{R_{c,s}} = \frac{V_P^2}{R_{c,p}}$
v. $P_{Cu} = I_S^2 R_{eq,s}$
vi. $I_P = I_{EX} + \frac{I_S}{a} = \frac{V_P}{R_c} + \frac{V_P}{X_M} + \frac{I_S}{a}$

3. Induction motor
   a. Slip
      i. $n_{slip} = n_{sync} - n_m$
      ii. $s = \frac{n_{slip}}{n_{sync}} \times 100\% = \frac{n_{sync} - n_m}{n_{sync}} \times 100\% = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} \times 100\%$
   b. Speed
      i. $n_m = (1 - s) n_{sync}$
      ii. $\omega_m = (1 - s)\omega_{sync}$
      iii. $\omega_m = \frac{2\pi}{60} n_m$
   c. Frequency
      i. $n_{sync} = \frac{120 f_{se}}{P}$
      ii. $f_{re} = s f_{se}$
   d. Determine parameters
      i. No load test (Open circuit)
         1. $\frac{V_{\phi,nl}}{I_{1,nl}} = X_1 + X_M$
         2. Y connected stator, $V_\phi = \frac{V_T}{\sqrt{3}}, I_1 = I_L \rightarrow \frac{V_T}{\sqrt{3} I_L} = X_1 + X_M$
         3. Δ connected stator, $V_\phi = V_T, I_1 = \frac{I_L}{\sqrt{3}} \rightarrow \frac{\sqrt{3} V_T}{I_L} = X_1 + X_M$
      ii. DC test
         1. Y connected stator, $R_1 = \frac{V_{DC}}{2 I_{DC}}$
         2. Δ connected stator, $R_1 = 3\frac{V_{DC}}{2 I_{DC}}$
      iii. Locked rotor test (Short circuit)
         1. $|Z_{LR}| = \frac{V_\phi}{I_1}$
         2. $Z_{LR} = R_{LR} + jX'_{LR} = |Z_{LR}|\cos\theta + j|Z_{LR}|\sin\theta$
         3. $R_{LR} = R_1 + R_2 = |Z_{LR}|\cos\theta$
         4. $X'_{LR} = X'_1 + X'_2 = |Z_{LR}|\sin\theta$
         5. $X_{LR} = \frac{f_{rated}}{f_{test}} X'_{LR} = X_1 + X_2$

6. $\text{PF} = \cos\theta = \frac{P_{in}}{\sqrt{3}V_T I_L}$

e. Torque
   i. $\tau_{load} = \frac{P_{out}}{\omega_m}$
   ii. $\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{AG}}{\omega_{sync}}$
   iii. At max torque
      1. $s_{max} = \frac{R_2}{|Z_{TH}+X_2|}$
      2. $\boldsymbol{I_2} = \frac{V_{TH}}{Z_{TH}+X_2+\frac{R_2}{s_{max}}}$
      3. $P_{AG} = 3I_2^2\frac{R_2}{s_{max}}$
      4. $s_{max} = \frac{R_2}{\sqrt{R_{TH}^2+(X_{TH}+X_2)^2}}$
      5. $\tau_{max} = \frac{3V_{TH}^2}{2\omega_{sync}\left[R_{TH}+\sqrt{R_{TH}^2+(X_{TH}+X_2)^2}\right]} = \frac{3V_{TH}^2}{2\omega_{sync}\left[R_{TH}+\frac{R_2}{s_{max}}\right]}$

f. Power
   i. $P_{in} = \sqrt{3}V_T I_A\cos\theta = P_{out} + P_{RCL} + P_{F\&W} + P_{misc} + P_{SCL} + P_{core}$
      1. $I_A = \frac{V_\phi}{Z_{eq}}$
   ii. $P_{SCL} = 3I_1^2R_1$
   iii. $P_{AG} = 3I_2^2\frac{R_2}{s}$
   iv. $P_{RCL} = 3I_2^2R_2 = sP_{AG}$
   v. $P_{conv} = (1-s)P_{AG}$
   vi. $P_{out} = P_{conv} - P_{F\&W} - P_{misc}$

g. Efficiency
   i. $\eta = \frac{P_{out}}{P_{in}} \times 100\%$

4. Synchronous generator
   a. Frequency
      i. $f_{se} = \frac{n_m P}{120}$
   b. Internal generated voltage
      i. $E_A = k\phi\omega$
   c. Equivalent
      i. $V_\phi = E_A - jX_S I_A - R_A I_A$
      ii. Δ connected, $V_\phi = V_T, I_A = \frac{I_L}{\sqrt{3}}$
      iii. Y connected, $V_\phi = \sqrt{3}V_T, I_A = I_L$
   d. Torque

i. $\tau_{app} = \frac{P_{in}}{\omega_m}$

e. Power

i. $P_{out} = \sqrt{3} V_T I_L \cos\theta$

ii. $P_{in} = P_{out} + P_{elec} + P_{core} + P_{mech} + P_{stray}$

iii. Ignoring R_A

1. $P_{conv} = P_{out} = \frac{3V_\phi E_A}{X_S} \sin\delta$
2. $P_{out} = P_{conv} = \sqrt{3} V_T I_L \cos\theta$
3. Static stability limit, $P_{max} = \frac{3V_\phi E_A}{X_S}$
4. $E_A \sin\delta = X_S I_A \cos\theta$
5. $\pi_{ind} = \frac{3V_\phi E_A}{\omega_m X_S} \sin\delta$

f. Voltage regulation

i. $VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$

g. Efficiency

i. $\eta = \frac{P_{out}}{P_{in}} \times 100\%$

5. Synchronous generator

a. Frequency

i. $f_{se} = \frac{n_m P}{120}$

b. Internal generated voltage

i. $E_A = k\phi\omega$

c. Equivalent

i. $V_\phi = E_A - jX_S I_A - R_A I_A$

ii. Δ connected, $V_\phi = V_T, I_A = \frac{I_L}{\sqrt{3}}$

iii. Y connected, $V_\phi = \sqrt{3} V_T, I_A = I_L$

d. Torque

i. $\tau_{app} = \frac{P_{in}}{\omega_m}$

e. Power

i. $P_{out} = \sqrt{3} V_T I_L \cos\theta$

ii. $P_{in} = P_{out} + P_{elec} + P_{core} + P_{mech} + P_{stray}$

iii. Ignoring R_A

1. $P_{conv} = P_{out} = \frac{3V_\phi E_A}{X_S} \sin\delta$
2. $P_{conv} = \sqrt{3} V_T I_L \cos\theta$
3. Static stability limit, $P_{max} = \frac{3V_\phi E_A}{X_S}$

        4. $E_A \sin\delta = X_S I_A \cos\theta$
        5. $\pi_{ind} = \frac{3V_\phi E_A}{\omega_m X_S} \sin\delta$
  f. Voltage regulation
    i. $VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$
  g. Efficiency
    i. $\eta = \frac{P_{out}}{P_{in}} \times 100\%$

6. DC Motor
  a. Separately excited
    i. $I_F = \frac{V_F}{R_F}$
    ii. $I_A = I_L$
  b. Shunt
    i. $V_T = E_A + I_A R_A$
    ii. $I_F = \frac{V_T}{R_F}$
    iii. $I_F^* = I_F - \frac{\mathcal{F}_{AR}}{N_F}$
    iv. $E_A = k\phi\omega_m$
    v. Linear magnetization curve (Assume when curve is not given)
        1. Flux is proportional to field current
        2. $\frac{\phi_1}{\phi_2} = \frac{I_{F1}}{I_{F2}}$
  c. Series
    i. $V_T = E_A + I_A(R_A + R_S)$
    ii. $I_s = I_A = I_L$
  d. Compounded
    i. $I_F = \frac{V_T}{R_F}$
    ii. $I_L = I_F + I_A$
    iii. $I_A = I_S$
    iv. Cumulatively Compounded
        1. $I_F^* = I_F + \frac{N_{SE}}{N_F} I_A - \frac{\mathcal{F}_{AR}}{N_F}$
        2. $I_F^* = I_F + \frac{N_{SE}}{N_F} I_A$ (Ignoring AR)
    v. Differentially Compounded
        1. $I_F^* = I_F - \frac{N_{SE}}{N_F} I_A - \frac{\mathcal{F}_{AR}}{N_F}$
        2. $I_F^* = I_F - \frac{N_{SE}}{N_F} I_A$ (Ignoring AR)

7. Measurement
  a. Differential Amplifier

i. $V_o = \frac{R_2}{R_1}(V_1 - V_2)$
ii. $\frac{R_2}{R_1} = \frac{R_4}{R_3}$
iii. $CMMR(in\ dB) = 20\log_{10}\frac{|A_d|}{|A_{cm}|}$
iv. $A_d = Gain\ in\ differential\ mode$
v. $A_{cm} = Gain\ in\ common\ mode = \frac{V_o}{V_{i(cm)}}$

b. Instrumentation Amplifier
i. $A = \frac{V_o}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2} = 1 + \frac{2}{a}\left[R_2 = R_3\ and\ R_1 = R, R_{gain} = aR\right]$
ii. Gain from buffer $= \left(1 + \frac{2R_1}{R_{gain}}\right)$
iii. Gain from differential amplifier $= \frac{R_3}{R_2}$

c. Logarithmic Amplifier
i. $V_o = -nV_T \ln\frac{V_i}{RI_S}$
1. $I_S = Reverse\ saturation\ current$
2. $n = Ideality\ factor$
3. $V_T = Thermal\ voltage = \frac{KT}{q}\left[depends\ on\ temparature\right]$

d. Transducer
i. Thermoelectrical transducer
1. Thermistor
a. $R_1 = R_2 e^{\beta\left[\frac{1}{T_1} - \frac{1}{T_2}\right]}$
i. R_1 = Resistance at $T_1°K$
ii. R_2 = Resistance at $T_2°K$
iii. β = Temperature constant
b. $R_\theta = R_{\theta_o}\left[1 + \alpha_{\theta_o}\Delta\theta\right]$
i. α_{θ_o} = Resistance temperature coefficient
2. Thermocouple
a. $E \approx a(\Delta\theta)$
i. a = Sensitivity of thermocouple

ii. Piezoelectric transducer
1. Charge, $Q = d \times F = dAE\left(\frac{\Delta t}{t}\right)$
2. Output voltage, $E_o = \frac{Q}{C_P} = \frac{d\ F}{\epsilon_r\epsilon_0 A/t} = \frac{d\ t}{\epsilon_r\epsilon_0}\frac{F}{A} = gtP$
a. Capacitance between electrodes, $C_P = \epsilon_r\epsilon_0 A/t$
b. Voltage sensitivity, $g = d/\epsilon_r\epsilon_0$
c. $t = thickness$

    d. $\epsilon_r\epsilon_0$ = Permittivity of quartz
3. d = charge sensitivity of the crystal
4. F = applied force