

EEE269-Electrical Drives and Instrumentation

1905072-MAHIR LABIB DIHAN

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. $\frac{V_P}{a} = V_S + (R_{eq,s} + jX_{eq,s}) \times I_S$

iii. $VR = \frac{V_P - aV_{S,fl}}{aV_{S,fl}} \times 100\%$ (Referred to Primary)

1. $V_P = aV_S + (R_{eq,p} + jX_{eq,p}) \times \frac{I_S}{a}$

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. $n_{sync} = \frac{120f_{se}}{p}$
- ii. $f_{re} = sf_{se}$

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, $R_1 = \frac{V_{DC}}{2I_{DC}}$
2. Δ connected stator, $R_1 = 3 \frac{V_{DC}}{2I_{DC}}$

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

$$\text{i. } \tau_{load} = \frac{P_{out}}{\omega_m}$$

$$\text{ii. } \tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{AG}}{\omega_{sync}}$$

iii. At max torque

$$1. s_{max} = \frac{R_2}{|Z_{TH} + X_2|}$$

$$2. I_2 = \frac{V_{TH}}{Z_{TH} + X_2 + \frac{R_2}{s_{max}}}$$

$$3. P_{AG} = 3I_2^2 \frac{R_2}{s_{max}}$$

$$4. s_{max} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}$$

$$5. \tau_{max} = \frac{3V_{TH}^2}{2\omega_{sync} \left[R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2} \right]} = \frac{3V_{TH}^2}{2\omega_{sync} \left[R_{TH} + \frac{R_2}{s_{max}} \right]}$$

f. Power

$$\text{i. } P_{in} = \sqrt{3}V_T I_A \cos \theta = P_{out} + P_{RCL} + P_{F\&W} + P_{misc} + P_{SCL} + P_{core}$$

$$1. I_A = \frac{V_\phi}{Z_{eq}}$$

$$\text{ii. } P_{SCL} = 3I_1^2 R_1$$

$$\text{iii. } P_{AG} = 3I_2^2 \frac{R_2}{s}$$

$$\text{iv. } P_{RCL} = 3I_2^2 R_2 = sP_{AG}$$

$$\text{v. } P_{conv} = (1 - s)P_{AG}$$

$$\text{vi. } P_{out} = P_{conv} - P_{F\&W} - P_{misc}$$

g. Efficiency

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

4. Synchronous generator

a. Frequency

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

b. Internal generated voltage

$$\text{i. } E_A = k\phi\omega$$

c. Equivalent

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

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

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

d. Torque

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

e. Power

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

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

iii. Ignoring R_A

$$1. P_{conv} = P_{out} = \frac{3V_\phi E_A}{X_S} \sin \delta$$

$$2. P_{out} = P_{conv} = \sqrt{3}V_T I_L \cos \theta$$

$$3. \text{ Static stability limit, } P_{max} = \frac{3V_\phi E_A}{X_S}$$

$$4. E_A \sin \delta = X_S I_A \cos \theta$$

$$5. \pi_{ind} = \frac{3V_\phi E_A}{\omega_m X_S} \sin \delta$$

f. Voltage regulation

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

g. Efficiency

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

5. Synchronous generator

a. Frequency

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

b. Internal generated voltage

$$\text{i. } E_A = k\phi\omega$$

c. Equivalent

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

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

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

d. Torque

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

e. Power

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

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

iii. Ignoring R_A

$$1. P_{conv} = P_{out} = \frac{3V_\phi E_A}{X_S} \sin \delta$$

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$$4. E_A \sin \delta = X_S I_A \cos \theta$$

$$5. \pi_{ind} = \frac{3V\phi E_A}{\omega_m X_S} \sin \delta$$

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

$$i. V_T = E_A + I_A R_A$$

$$ii. I_F = \frac{V_T}{R_F}$$

$$iii. I_F^* = I_F - \frac{F_{AR}}{N_F}$$

$$iv. E_A = k\phi\omega_m$$

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

$$1. I_F^* = I_F + \frac{N_{SE}}{N_F} I_A - \frac{F_{AR}}{N_F}$$

$$2. I_F^* = I_F + \frac{N_{SE}}{N_F} I_A \text{ (Ignoring AR)}$$

v. Differentially Compounded

$$1. I_F^* = I_F - \frac{N_{SE}}{N_F} I_A - \frac{F_{AR}}{N_F}$$

$$2. I_F^* = I_F - \frac{N_{SE}}{N_F} I_A \text{ (Ignoring AR)}$$

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. $A_d = \text{Gain in differential mode}$
- v. $A_{cm} = \text{Gain in common mode} = \frac{V_o}{V_{i(cm)}}$

b. Instrumentation Amplifier

- i. $A = \frac{V_o}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right) \frac{R_3}{R_2} = 1 + \frac{2}{a} [R_2 = R_3 \text{ and } R_1 = R, R_{gain} = aR]$
- 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. $I_S = \text{Reverse saturation current}$
 - 2. $n = \text{Ideality factor}$
 - 3. $V_T = \text{Thermal voltage} = \frac{KT}{q} [\text{depends on temperature}]$

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. $R_1 = \text{Resistance at } T_1^\circ K$
 - ii. $R_2 = \text{Resistance at } T_2^\circ K$
 - iii. $\beta = \text{Temperature constant}$
- b. $R_\theta = R_{\theta_o} [1 + \alpha_{\theta_o} \Delta\theta]$
 - i. $\alpha_{\theta_o} = \text{Resistance temperature coefficient}$

2. Thermocouple

- a. $E \approx a(\Delta\theta)$
 - i. $a = \text{Sensitivity of thermocouple}$

ii. Piezoelectric transducer

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

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