MECHATRONIC SYSTEMS

- ACTUATORS $\longrightarrow$ SOLENOID, DC MOTORS, PNEUMATICS
- SENSORS $\longrightarrow$ SWITCH, POT. METER, ACC. METER
- IN. SIGNAL $\longrightarrow$ AMP., A/D, D/D
- OUT. SIGNAL $\longrightarrow$ D/A, D/D, AMP., PWM, OP AMP.
- DIG. CONTROL ARCHI. $\longrightarrow$ PLC, MICROCONT., LOGIC CIRC.
- GRAPHICAL DISP. $\longrightarrow$ LED, LCD, DIG. DISP.

ELECTRIC CIRC.

emf E
current I
resistance R
conductivity σ

$E = IR$

$R = \frac{\ell}{\sigma A}$

MAGNETIC CIRC.

mmf F
flux ϕ
reluctance $\mathcal{R}$
permeability μ

$F = \phi \mathcal{R}$

$\mathcal{R} = \frac{\ell}{\mu A}$

CONVERSIONS

$\text{rpm} \times \frac{\pi}{30} = \text{rads}^{-1}$

$\text{rads}^{-1} \times \frac{30}{\pi} = \text{rpm}$

ELECTRIC HORSEPOWER

$\text{hp} \times 746 = \text{W}$

MAGNETIC CIRCUITS

MAG. INTENSITY

$H = \frac{i}{2\pi r}$ $\quad H = \frac{Ni}{2\pi r}$

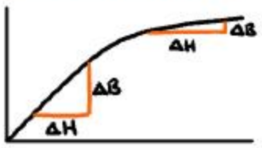
MAG. RELUCTANCE

$\mathcal{R} = \frac{\ell}{\mu A}$ $\quad \mathcal{R} = \frac{Ni}{\phi}$

$H\ell = \phi \mathcal{R}$ $\quad \mathcal{R} = \frac{\ell}{\mu_0 \mu_r A}$

$\mu_0 = 4\pi \times 10^{-7}$

B-H SATURATION



$\mu = \frac{\Delta B}{\Delta H} = \frac{B}{H}$ $\frac{\text{FLUX DENS.}}{\text{FIELD DENS.}}$

SOFT MAG.

HARD MAG.

ELECTROMAGNETIC INDUCTION

FARADAY'S $\quad \varepsilon = \frac{d\phi}{dt}$

LENZ'S $\quad \varepsilon = -\frac{d\phi}{dt}$

N-TURNS $\quad \varepsilon = -N\frac{d\phi}{dt}$

FLUX CHANGE $\quad \varepsilon = -N\frac{\phi_2 - \phi_1}{t}$

MOTORS

$P_{OUT} = P_{IN} - P_{LOSS}$

POWER INPUT $\quad \phi$ = phase ∠

$P_{IN} = V_{IN} I_{IN}$ DC MOTOR

$P_{IN} = V_{IN} I_{IN} \cos\phi$ 1-PHASE

$P_{IN} = \sqrt{3}\, V_{IN} I_{IN} \cos\phi$ 3-PHASE

POWER OUTPUT

$\tau_{OUT} = \omega_m \tau_m = \frac{2\pi N}{60}\tau_m$

FORCE IN MOTOR

$F = BIL$

FORCE ON A CHARGE

$F = QE$

HYSTERESIS LOSS

$P_h = f \oint B\, dH$

EDDY CURRENT LOSS

$P_e = \frac{\pi^2 B_m^2 f^2 t^2}{6\rho}$

DC MOTORS

$V = E_a^{\text{EMF}} + I_a R_a^{\text{ARMAT.}}$

MECH POWER

$P = \tau\omega$

POWER DELIVERED

$P_d = E_b I_a$

ELEC. CIRCUIT

$V = L\frac{di_a}{dt} + Ri_a + k_e\omega$

$\frac{E_a}{E_b}^{\text{EMF}} = \frac{\omega_a}{\omega_b}^{\text{RADS}^{-1}} = \frac{N_a}{N_b}^{\text{RPM}}$

MOTOR TORQUE

$\tau = K_a \phi i_a = k_t i_a$

$\tau = J\frac{d\omega}{dt} + B\omega$

$\omega = \frac{d\theta}{dt}$

LOAD

$\tau_L \propto \omega_m^k$

$\tau_1 \omega_1 = \tau_2 \omega_2$

$\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1}$

BACK EMF

$E = K_a \phi \omega = k_e \omega$ $\quad P \Rightarrow$ poles

$K_a = \frac{PZ}{2\pi a}$ $\quad Z \Rightarrow$ conductors

DYNAMICS OF ELECTRIC MOTOR

ELECTRIC CIRCUIT

$V = E_b + R_a i_a + L\frac{di}{dt}$

$DV_s = K_t W + I_a R_a$

MECHANICAL EQ'N

$\tau_m = \tau_1 + B\omega + J\frac{d\omega}{dt}$

BACK EMF

$E_b = K\omega$

$E_b = K_b \phi \omega$

TORQUE

$\tau_m = K_t i_a$ LOAD

$E_a I_a = \tau \omega_m$ DEVEL.

TRANSFORMERS

IDEAL TRANSFORMERS

- ZERO LEAKAGE FLUX
- NO RESIST. WINDINGS
- CORE W/ ∞ PERM.
- LOSSLESS MAG. CORE

$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$

OUTPUT POWER

$P_{OUT} = V_{OUT}\, I_{OUT} \sqrt{3}$

EFFICIENCY

$\eta = \frac{P_{OUT}}{P_{IN}}\% = \frac{P_{OUT}}{P_{OUT} + P_{LOSS}}$

$\eta = \frac{V_s I_s \cos\theta}{P_{CU} + P_{CORE} + V_s I_s \cos\theta}$

OPEN CIRCUIT TEST

$I_0 = \sqrt{I_m^2 + I_c^2}$ $\quad X = \frac{V_0}{I_m}$

$I_m = I_\mu = I_0 \sin\phi_0$ $\quad R = \frac{V_0}{I_c}$

$I_c = I_w = I_0 \cos\phi_0$

$W_{oc} = V_0 I_0 \cos\phi$ $\quad B_0 = \frac{I\mu}{V_0}$

$W_{oc} = V_0^2 G_0$

$P_{c(i)} = IV$ $\quad B_0 = \sqrt{Y_0^2 - G_0^2}$

SHORT CIRCUIT TEST

$P_{CU} = I_{SC} V_{SC} \cos\theta$ $\quad R = \frac{P_{CU}}{I_{SC}^2}$

$= I_{SC}^2 R$

$W_{SC} = I_{SC}^2 R_{01}$

$Z = \frac{V_{SC}}{I_{SC}}$ $\quad X = \sqrt{Z^2 - R^2}$

EDDY CURRENT LOSS

$W_h = K_h f (B_m)^{1.6}$

$W_e = K_e f^2 K_f^2 B_m^2$

HYSTERESIS LOSS

$W_h = \eta B_{max}^{1.6} f V$

COPPER LOSS

$W_{CU} = I_1^2 R_1 + I_2^2 R_2$

VOLTAGE REGULATION

UP $\quad \frac{V_{SNL} - V_{SFL}}{V_{SFL}}\%$

DOWN $\quad \frac{V_{SNL} - V_{SFL}}{V_{SNL}}\%$

NO LOAD $\quad k = \frac{V_S}{V_P}$

$\% = \frac{V_1\left(\frac{N_2}{N_1}\right) - V_2}{V_1\left(\frac{N_2}{N_1}\right)}$

DC MOTOR SPEED CONTROL

TRANSFER FUNCTION

$G_c(s) = K_p + \frac{K_I}{s} + K_D s$

$u(t) = K_p e(t) + K_I \int e(t)\,dt + K_D \frac{de(t)}{dt}$

$u(t) = K_c\left[e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d \frac{de(t)}{dt}\right]$

DUTY RATIO

$D = \tau_1/\tau_2 \times 100\%$

DIFF. EQUATIONS GOVERNING DC MOTOR

ELECTRICAL

$V = E_b + R_a I_a + L_a \frac{dI_a}{dt}$ $\quad E_b = K\omega$

MECHANICAL

$\tau_m = \tau_1 + B\omega + J\frac{d\omega}{dt}$ $\quad \tau_m = K I_a$

STATE SPACE

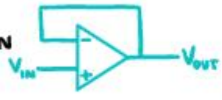
$x = Ax + Bu$

$y = Cx + Du$

u = input
x = output

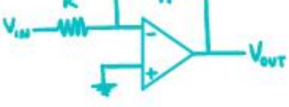
OP AMPS

$V_{OUT} = V_{IN}$

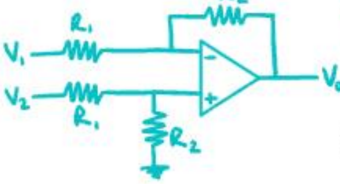


$V_{OUT} = -\frac{R_2}{R_1} V_{IN}$

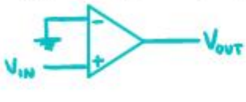
$V_{OUT} = -\frac{1}{j\omega CR} V_{IN}$



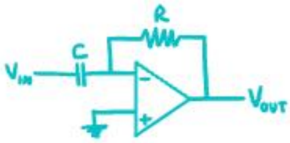
$V_{OUT} = \frac{R_2}{R_1}(V_2 - V_1)$



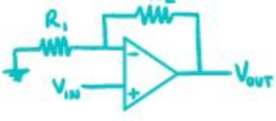
$V_{OUT} = V_{CC} \sin(V_{IN})$



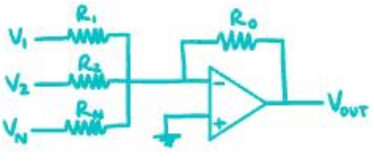
$V_{OUT} = -\frac{R}{1/j\omega C} V_{IN}$



$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right) V_{IN}$



$V_{OUT} = -\left(V_1\frac{R_0}{R_1} + V_2\frac{R_0}{R_2} + \cdots + V_N\frac{R_0}{R_N}\right)$



INDUCTION MOTORS

ROTATING MAG. FIELD SPEED

$$n_{sync} = \frac{120 f_e}{P}$$

TORQUE FROM 2 MAG. FIELDS

$$\tau_{IND} = k B_R B_s$$

ROTOR FREQUENCY

$$f_r = \frac{Pn}{120} \qquad f_r = \frac{P(n_s - n_m)}{120} = \frac{Psn_s}{120}$$

$$f_r = s f_e$$

POWER RELATIONS

$$P_{IN} = \sqrt{3} V_L I_L \cos\theta$$

$$P_{IN} = 3 V_{ph} I_{ph} \cos\theta$$

$$P_{SCL} = 3 I_1^2 R_1$$

$$P_{RCL} = 3 I_2^2 R_2$$

$$P_{AG} = P_{IN} - (P_{SCL} - P_{core}) = \frac{P_{RCL}}{s}$$

$$P_{conv} = P_{AG} - P_{RCL} = \frac{P_{RCL}(1-s)}{s} = (1-s) P_{AG}$$

$$P_{OUT} = P_{conv} - (P_{f+w} + P_{stray})$$

$$\tau_{IND} = \frac{P_{conv}}{\omega_m} = \frac{(1-s) P_{AG}}{(1-s)\omega_s}$$

THEVENIN'S THEOREM

$$V_{TH} \approx V_\phi \frac{X_M}{X_1 + X_M} \qquad R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M}\right)^2$$

$$\tau_{IND} = \frac{1}{\omega_s} \frac{3 V_{TH}^2 \left(\frac{R_2}{s}\right)}{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}$$

BLOCKED-ROTOR TEST

$$PF = \cos\theta = \frac{P_{IN}}{\sqrt{3} V_1 I_1}$$

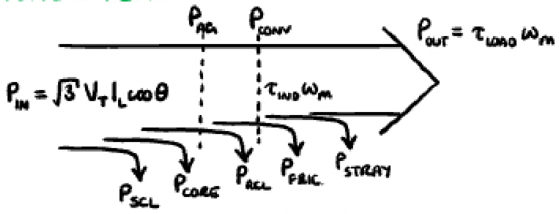
$$|Z_{LR}| = \frac{V_\phi}{I}$$

MAX TORQUE

$$\tau_{max} = \frac{1}{2\omega}\left(\frac{3V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}\right)$$

$$s_{T_{MAX}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}$$

POWER FLOW



SLIP

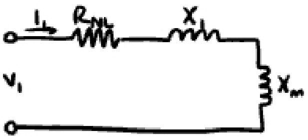
$$n_{slip} = n_{sync} - n_m$$

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

TORQUE

$$\tau_{LOAD} = \frac{P_{OUT}}{P_{IN}} \qquad \omega_m = \frac{2\pi n_m}{60}$$

EQUIV. CIRC. NO LOAD TEST



$$R_{NL} = \frac{P_{NL}}{3 I_1^2} \qquad Z_{NL} = \frac{V_1}{I_1}$$

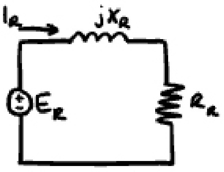
$$V_1 = \frac{V_L}{\sqrt{3}} \qquad X_{NL} = \sqrt{Z_{NL}^2 - R_{NL}^2}$$

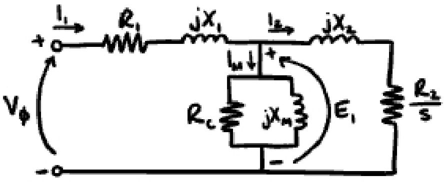
$$P_{NL} = P_{ROT} + SCL$$

EQUIVALENT CIRCUIT

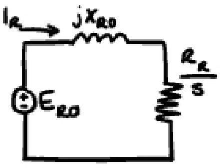
$$E_R = s E_{RO}$$

$$X_r = s X_{ro} = \omega_r L_r = 2\pi f_r L_r$$





$$I_R = \frac{E_{RO}}{R_R/s + jX_{RO}}$$



$$X_2 = a_{eff}^2 X_{RO} \qquad E_1 = a_{eff} E_{RO}$$

$$R_2 = a_{eff}^2 R_2 \qquad a_{eff} = \frac{N_S}{N_R}$$

$$I_2 = \frac{I_R}{a_{eff}}$$

HYDRAULICS

PRESSURE

$$P = \frac{F}{A}$$

PASCAL'S LAW

$$P = \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

LIQUID FLOW RATE

$$Q = VA \quad \text{VELOC.} \times \text{AREA}$$

$$Q_1 = Q_2 \quad \text{CONTINUITY}$$

BERNOULLI'S EQ'N

$$\text{CONST.} = p + \tfrac{1}{2}\rho v^2 + \rho g y$$

KE OF BULK MOTION OF FLUID; GPE FOR LOCATION OF FLUID

$$v_1 = \sqrt{\frac{2 g h \rho_m}{\rho_f\left[\left(\frac{A_1}{A_2}\right)^2 - 1\right]}}$$

CONVERSIONS

$1\ Pa = 1\ Nm^{-2}$

$10\ bar = 10^6\ Pa = 1\ MPa$

PNEUMATICS

GAS LAWS

$$PV = C \qquad \frac{P_1}{P_2} = \frac{T_1}{T_2} \qquad \frac{V_1}{V_2} = \frac{T_1}{T_2} \qquad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

POWER TO DRIVE COMPRESSORS

$$kW = \frac{\underbrace{p_{in} Q}_{\text{FLOW}}}{17.1}\left[\underbrace{\left(\frac{p_{in}}{p_{out}}\right)^{0.286}}_{\text{PRESSURE}} - 1\right]$$

SIZE OF AIR RESERVOIR

$$V_r = \frac{101 t (Q_r - Q_c)}{p_{max} - p_{min}} \sim \text{flow - consumption}$$

AIR PRESSURE LOSS

$$p_{loss} = \frac{c L Q^2}{3600 \underbrace{(CR)}_{\text{compression ration}} d^5} \qquad c = \frac{0.1205}{d^{31}}$$

Time Domain → State Space

- $$\frac{dI_a}{dt} = -\frac{R_a}{L_a} I_a - \frac{k_b \phi \omega}{L_a} + \frac{I}{L_a} V$$
- $$\frac{d\omega}{dt} = \frac{k_t \phi}{J} I_a - \frac{B}{J}\omega - \frac{\tau_l}{J}$$

$$\begin{bmatrix} \frac{d}{d_t} I_a \\ \frac{d}{d_t}\omega \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{La} & -\frac{K_b\phi}{L_a} \\ \frac{K_t\phi}{J} & \frac{B}{J} \end{bmatrix} \begin{bmatrix} I_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix} V$$

$$\dot{x} = A x + B u$$

$$\begin{bmatrix} \omega \end{bmatrix} = [0 \quad 1]\begin{bmatrix} I_a \\ \omega \end{bmatrix} + [\,0\,] V$$

$$y = C x + D u$$

OPERATIONS ON BLOCKS