4. DC Machines

Tuesday, October 27, 2020 3:44 AM

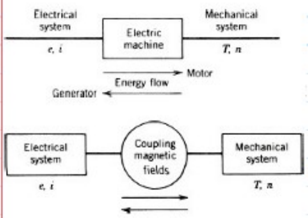
4.1 Electromagnetic Conversion

1. conductor moves in magnetic field, voltage induced in conductor
2. Conductor placed in magnetic field, conductor experiences mech. force

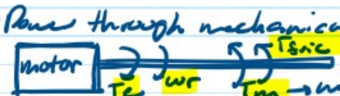
↳ occur simultaneously when energy converted

↳ Motoring: conductors in B-field, force produced on each conductor
conductors on rotating structure @ speed
voltage induced in each conductor

↳ Generating: Rotating structure driven by mover (turbine/engine)
voltage induced in conductors rotating
Load connected to conductors, current delivers power to load
& interact w/ B-field → Reaction torque opposes applied torque



– Power through mechanical shaft:



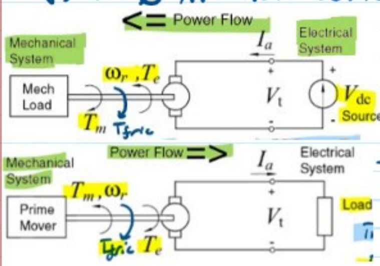
T_m → mech. torque

T_e → electromagnetic Torque

– Mech power on shaft: $P_m = T_m \cdot \omega_r$

Motoring & Generating Power

– flux & Armature current produce torque



– Mechanical load torque T_m applied opposite to rotation ω_r (Generating)

$T_e = T_{fric} + T_m$

$P_{out} = \omega_r T_m = P_m$

$P_{in} = V_t I_a$

– Mechanical Torque T_m applied in direction of rotation ω_r (Motoring)

$T_m = T_{fric} + T_e$

$P_{in} = \omega_r T_m$

$P_{out} = V_t I_a$

Motional Voltage e

– Voltage induced in conductor moving in magnetic field

– Faraday's Law: $e = \frac{d\varphi}{dt}$ (V induced emf)

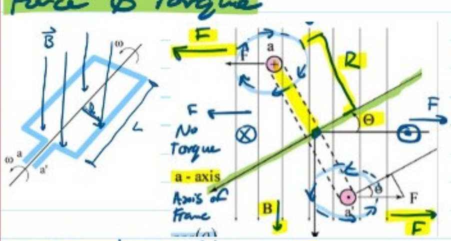
– conductor length l moves at speed v in field B: $e = Blv$

Electromagnetic Force f

– conductor moves in magnetic field

– Lorentz Force: $f = Bli_a$ (Mechanical force)

Force & Torque



– Lorentz Force: $F = lBi_a \perp A$ loop

– Torque $T_e = 2RlBi_a\cos\theta$
$= ABi_a\cos\theta = \varphi_p i_a \cos\theta$

– Max Torque @ a-axis $\perp B$ & $T_e \sim \varphi_p i_e$

Induced Voltage

$\varphi = BA\sin\theta = B2Rl\sin\theta$

↳ rotate frame @ speed ω: $\theta = \omega t$

$\varphi = BA\sin(\omega t) = \varphi_p \sin(\omega t)$ → φ_p = peak flux

Faraday's law: $e = \frac{d\varphi}{dt} = \omega\varphi_p\cos(\omega t)$ $\therefore e \sim \omega\varphi_p$

4.2 DC Machines

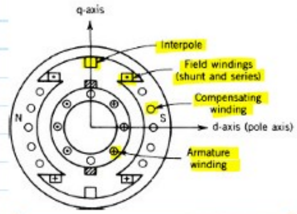
– Operate as either generator/motor

Construction

– Armature winding placed on rotor

– Field windings placed on stator

Construction



- Armature winding placed on rotor
- Field winding placed on stator
- Stator shunt & series field windings excited
- V induced in armature windings alternates
- Commutator brush → Mech rectifier
- Current through brushes b/w armature coil changes direction

Armature windings & Commutation

- Current flows a → b
- Turn shorted → to avoid shorting, need min. 3 layers
- Current flows b ← a

Induced voltage: $e_a = \omega_r L i_f \sin(\theta_r)$

$v_a = r_a i_a + \frac{d\lambda}{dt} \to i_a = 0$ $\quad \theta_r = \omega_r t$

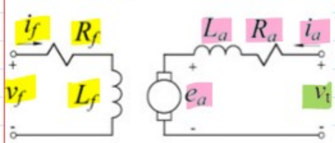
$\lambda_a = L_a i_a + L_{af} i_f$

$e_{tem} \sim \omega \varphi_p$ $\quad E_a = K_a \omega_r \varphi_p \to K_a$ = armature const.

$T_{em} \sim \varphi_p i$ $\quad T_e = K_a \varphi_p I_a$ $\quad E_a$ = Generated V, back emf

Armature Power: $P_e = E_a I_a = T_e \omega_r = P_m$

Separately Excited DC Machine



w/
- f → field components
- a → armature component → connects to rotor
- v_t → terminal voltage

Conversion Power: $P_e = e_a \cdot i_a$

Input power: $P_{in} = v_t i_a$

Field windings Eqn

$v_f = R_f i_f + \left[\frac{d\lambda_f}{dt}\right]$ → V drop inductor

$\lambda_f = N_f \varphi_p = L_f i_f$

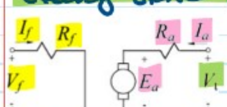
Armature Eqn

$v_t = \pm R_a i_a + L_a\left[\frac{di_a}{dt}\right] + e_a$ → $\frac{d\lambda_a}{dt}$

$e_a = K_a \varphi_p \omega_r$

$T_e = K_a \varphi_p i_a$

Steady State Equivalent (No L):



Field: $V_f = R_f I_f$

$\lambda_f = N_f \varphi_p = L_f i_f$

Armature: $V_t = \pm R_a I_a + E_a$

$E_a = K_a \varphi_p \omega_r$

Torque: $T_e = K_a \varphi_p I_a = T_m + T_{loss} = T_m + K_{fric}\omega_r = T_m + T_{fric}(\omega_r)$

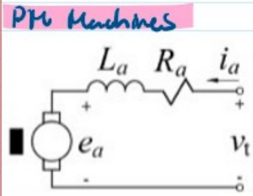
Torque/Speed const.

- winding flux φ_p, Electromagnetic Torque T_e, Back emf e_a
- Mutual Inductance b/w field & rotating armature coils

$L_{af} = K_a \frac{L_f}{N_f} \to e_a = L_{af} I_f \omega_r$

$T_e = \underbrace{L_{af} I_f}_{\lambda \text{ flux linkage}} I_a$

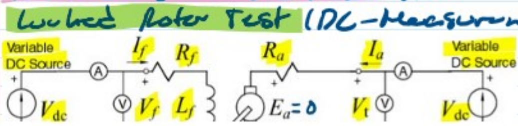
PM Machines



- $P_{in} = V_t i_a$
- $e_a = K_v \omega_r \to K_t = K_v$
- $T_e = K_t i_a$

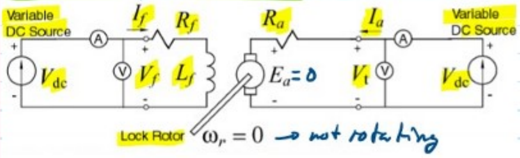
Parameters of DC Machine

Locked Rotor Test (DC-Measurements)



- Find R of armature & Field windings

$R_f = \underline{V_f}$ $\quad R_a = \underline{V_t}$

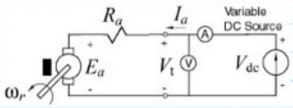


– Find R of armature & Field windings

$R_f = \frac{V_f}{I_f}$ $R_a = \frac{V_t}{I_a}$

– lock rotor, $E_a = 0$

No Load Test for PM Motors (Friction vs. Speed)



– Knowing R_a, measure I_a, V_t, ω_r

$V_t = R_a I_a + E_a$

$P_e = I_a E_a = \omega_r T_e \rightarrow n(rpm) \rightarrow \omega(rad/sec): \omega = \frac{2\pi n}{60}$

$T_e = T_{fric}(\omega_r) = \omega_r K_{fric}$

$T_e = K_a \varphi_p I_a = K_t I_a$

$E_a = K_a \varphi_p \omega_r = K_v \omega_r$

$K_t = K_v = \frac{E_a}{\omega_r} = \frac{V_t - R_a I_a}{\omega_r}$

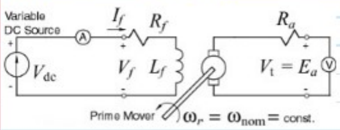
↳ T/V const.

Transient (Inertia)

$T_{fric}(\omega_r) = -J \frac{\Delta \omega_r}{\Delta t} = -J \frac{\Delta E_a}{K_v \Delta t}$

$J = \frac{T_{fric}(\omega_r) K_v \Delta t}{\Delta E_a}$

Open Circuit Test



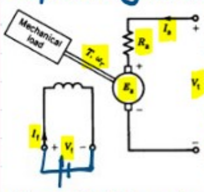
$E_a = K_a \varphi_p \omega_r = K_a \frac{L_f}{N_f} I_f \omega_r = L_{af} I_f \omega_r = K_v \omega_r$

$\varphi_p = \frac{\lambda_f}{N_f} = \frac{L_f}{N_f} I_f$

Classification of DC Machines

Basic DC Machines

Separately Excited DC Motor



$V_t = E_a + R_a I_a = I_t R_{load} = I_a R_{load}$

$E_a = K_a \varphi_p \omega_r = L_{af} I_f \omega_r$

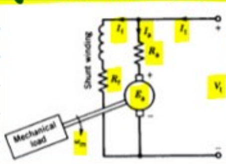
$T = K_a \varphi_p I_a = L_{af} I_f I_a$

$V_f = R_f I_f$

Speed Torque Characteristic:

$\omega_r = \frac{V_t - I_a R_a}{K_a \varphi_p} = \frac{V_t - I_a R_a}{L_{af} I_f} = \underbrace{\left[\frac{V_t}{L_{af} I_f}\right]}_{\text{NL speed}} - \underbrace{\left[\frac{R_a}{(L_{af} I_f)^2}\right]}_{\text{slope}} T$

Shunt DC Machine

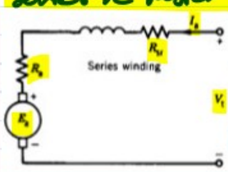


$L_{af} I_f = \frac{L_{af} V_t}{R_f}$

Speed Torque Characteristic

$\omega_r = \frac{V_t}{L_{af} I_f} - \frac{R_a}{(L_{af} I_f)^2} T = \underbrace{\left[\frac{R_f}{L_{af}}\right]}_{\text{NL Speed}} - \underbrace{\left[\frac{R_a R_f^2}{(L_{af} V_t)^2}\right]}_{\text{slope}} T$

Series DC Motor



$V_t = I_a(R_a + R_{sr}) + \overbrace{L_{af} I_a \omega_r}^{E_a}$

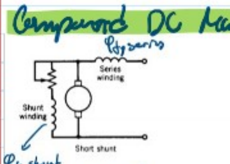
$I_a = \frac{V_t}{R_a + R_{sr} + L_{af}\omega_r}$

$T_e = L_{af} I_a^2 = L_{af} I_f I_a$

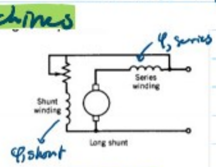
Torque Speed Characteristic

$T = \frac{L_{af} V_t^2}{(R_a + R_{sr} + L_{af}\omega_r)^2}$

Compound DC Machines



Short-Shunt Compound DC Machine

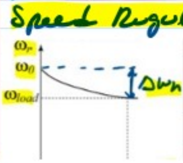


Long-Shunt Compound DC Machine

$\varphi_{f,total} = \varphi_{f,shunt} \pm \varphi_{f,series}$

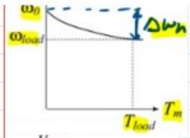
DC Machines Regulation

Speed Regulation (Motors)

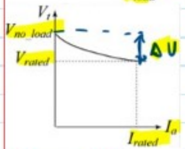


$SR = \frac{\omega_{r,NL} - \omega_{r,L}}{\omega_{r,L}} 100\% = \frac{n_{NL} - n_L}{n_L} \times 100\%$

$= \frac{\Delta\omega_r}{\omega_{r}\ \text{under load}}$

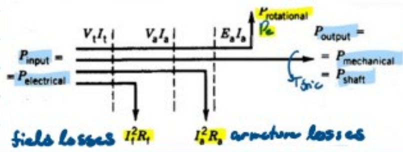


$$SR = \frac{\omega_{r,NL} - \omega_{r,L}}{\omega_{r,L}} 100\% = \frac{n_{NL} - n_L}{n_L} \times 100\%$$
$$= \frac{\Delta\omega_r}{\omega_{nominal\ under\ load}}$$



$$VR = \frac{V_{t,nl} - V_{t,load}}{V_{t,load}} 100\% = \frac{V_{NL} - V_{nom}}{V_{nom}} 100\%$$
$$= \frac{\Delta V}{V_{nominal\ under\ load}}$$

Power Flow & Efficiency



$P_{rot\ losses} = T_{fric} \cdot \omega_r$

$\eta = \frac{P_{out}}{P_{in}} \rightarrow P_{out} = P_m = T_m \omega_r$, $P_{in} = V_t I_t$

Starting Current

- $I_{a,rated} = \frac{P}{V_t}$
- $I_{a,start} = \frac{V_t - E_a}{R_a}$

If $I_{a,start} \gg I_{a,rated}$ → will burn motor!

Speed/Torque Control of DC Motors

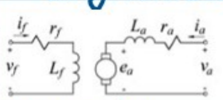
- Vary Terminal Voltage
- Vary armature current

$v_a = r_a i_a + K_v \omega_r$

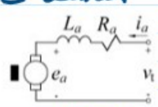
$K_v = L_{af} i_f$ $\quad v_a = r_a i_a + K_v \omega_0$

$T_e = K_v i_a \rightarrow T$ control

$\omega_r = \frac{v_a - i_a r_a}{K_v} = \frac{v_a}{K_v} - \frac{r_a}{K_v^2} T_e \rightarrow$ speed control



Separate



PM

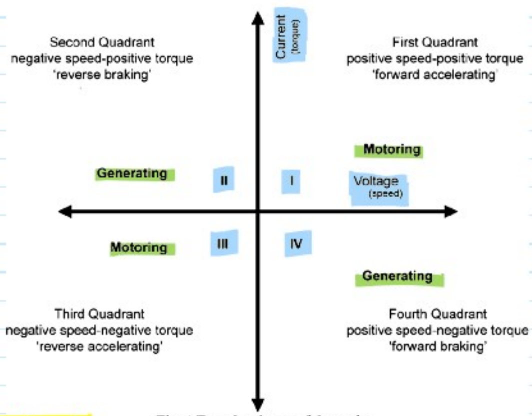
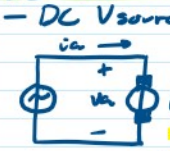


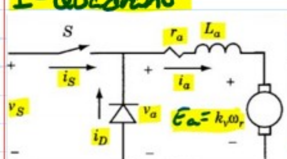
Fig. 1 Four Quadrants of Operation

DC – DC Converters for DC – Motors

- DC V_{source}, avg V_{out} controlled

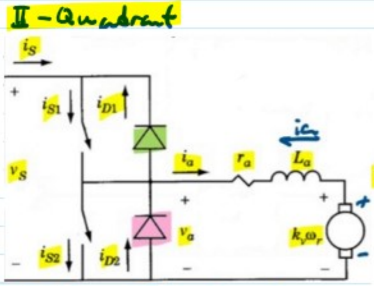


I-Quadrant



PWM: $S \rightarrow \neg S$

II-Quadrant

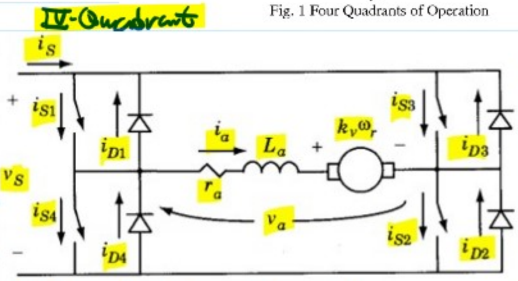


$S_1, D_2 \rightarrow$ I Quadrant

$S_2, D_1 \rightarrow$ II Quadrant

PWM: $S_1 = \neg S_2$ or $\neg S_1 = S_2$

IV-Quadrant



PWM: $S_1 = S_2 = \neg S_3 = \neg S_4$