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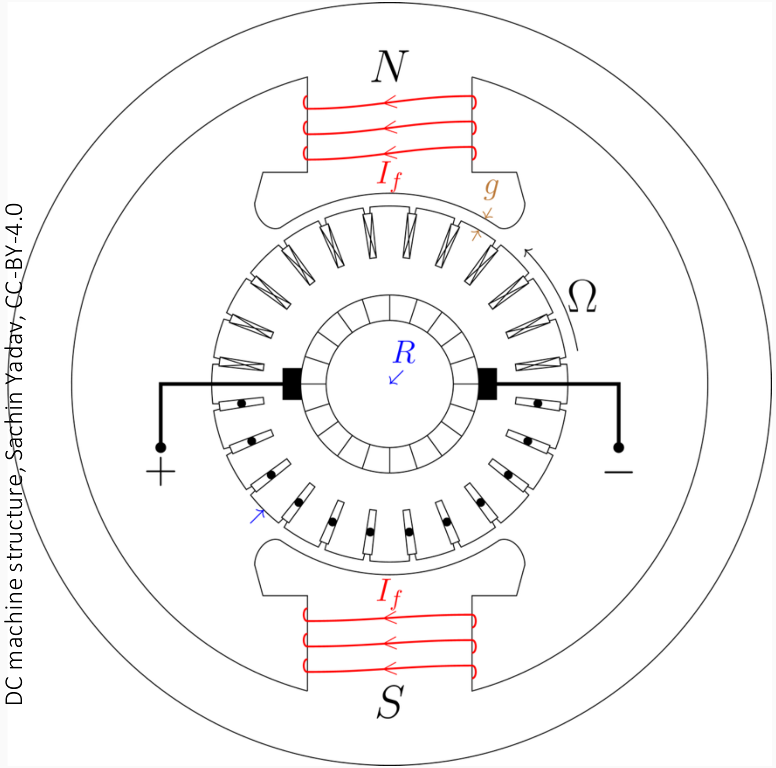
DC Motors

Structure, principle and models

Dr. Jianning Dong

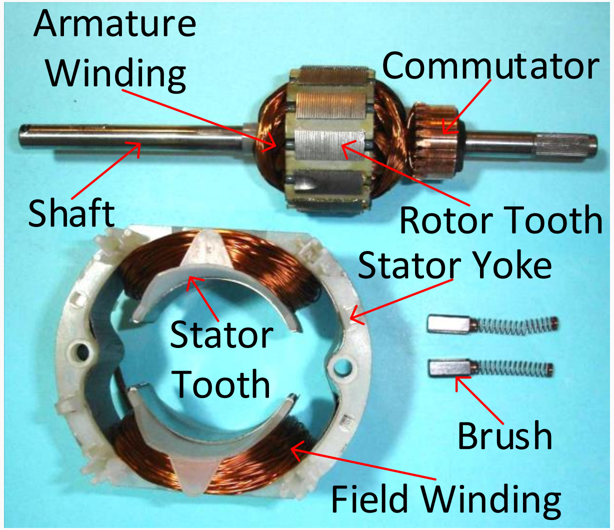


DC machine structure, Sachin Yadav, CC-BY-4.0

Lecture Outline

1. Structure
2. Operation principles
3. Equivalent circuit
4. Performance calculation
5. Dynamic model

How a DC motor is constructed?



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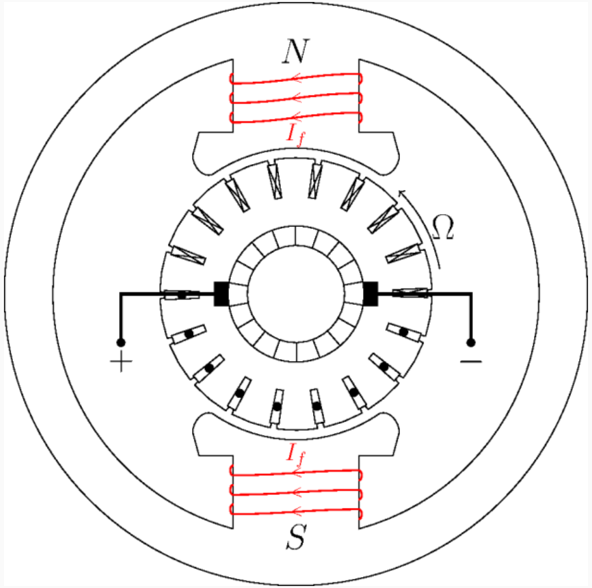

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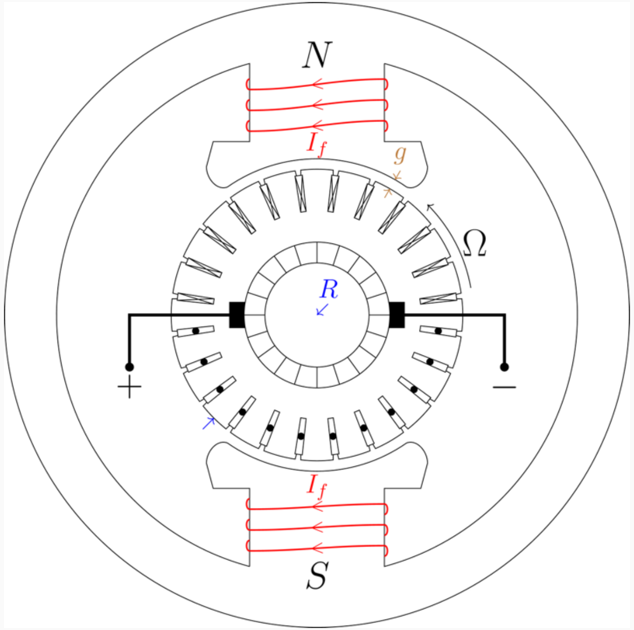
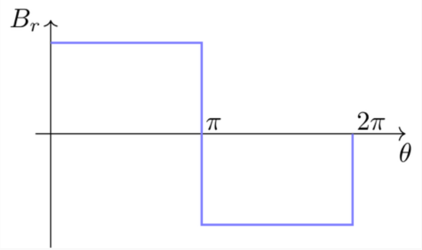
- **Field winding and magnetic core** (stator and rotor): source and path for magnetic field
- **Armature winding**: conductors to bear torque-producing current
- **Brush-commutators**: reverse current direction according to polarity (mechanical rectification)

How magnetic field is generated?

Operation principle: air-gap magnetic field

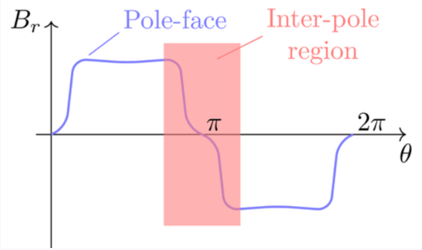


- Ideal air-gap magnetic field (from Ampére's Law)

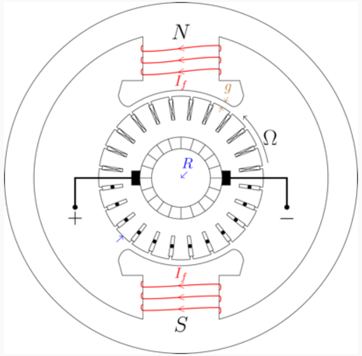


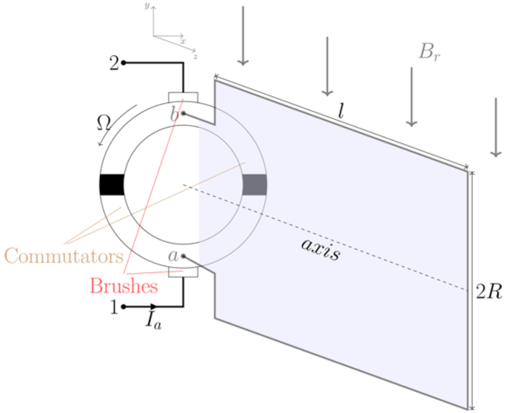
$$B_r = \mu_0 \frac{N I_f}{g}$$

- Real air-gap magnetic flux density considering inter-poles



Operation principle: induced voltage and force





- Consider a single loop of wire
  - Induced voltage on wire side

$$E = B_r l v = \pm B_r l \Omega R$$

  - Lorentz force on wire side

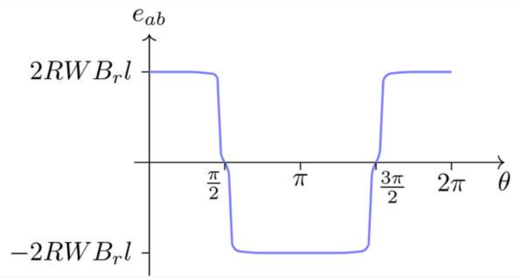
$$F = \pm B_r l I_a$$

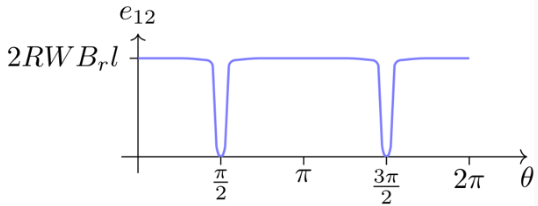
  - Total induced voltage at the brush terminal

$$E_t = 2\,|B_r l v| = 2 B_r l \Omega R$$

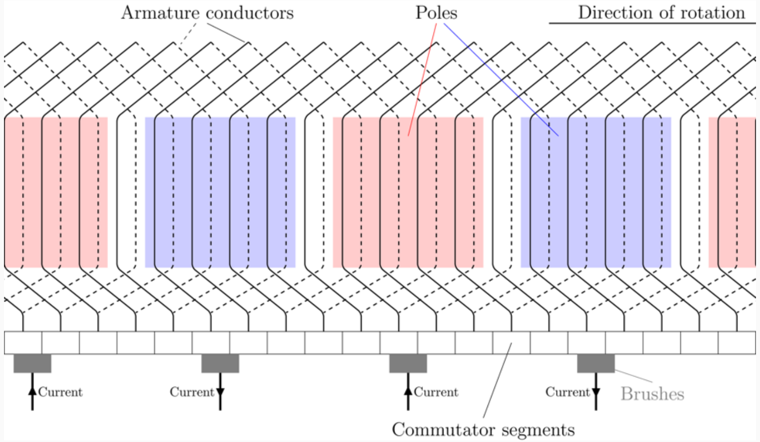
  - Total torque on one wire loop

$$T_t = 2\,|B_r l I_a|\,R = 2 B_r l I_a R$$





Operation principle: armature winding and brush-commutator



A "lap" winding featuring two parallel paths

Characterize a DC machine armature winding

- Number of active conductors underneath the poles C_a
- Number of current parallel paths m

For each active conductor

Back-emf and torque

$$E_{bc} = B_r l \Omega R$$
$$T_c = B_r l I_a R$$

Total induced back-emf and torque

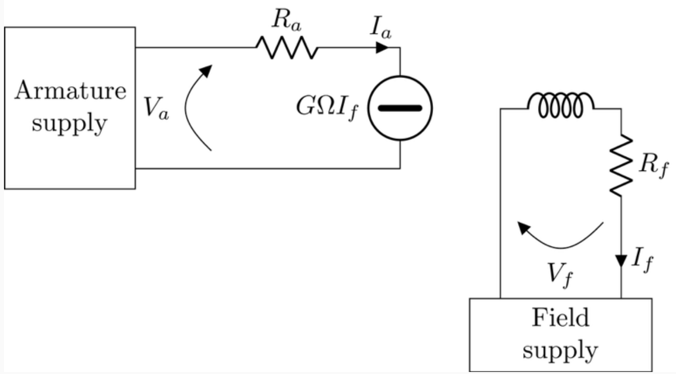
$$E_b = \frac{C_a}{m} B_r l \Omega R$$
$$T_e = \frac{C_a}{m} B_r l I_a R$$

Machine coefficient G

$$E_b = G I_f \Omega$$
$$T_e = G I_f I_a$$

How to calculate DC motor performance?

DC machine steady state performance: equivalent circuit



Back-emf and torque

$$E_b = G I_f \Omega$$
$$T_e = G I_f I_a$$

KVL armature circuit steady sate

$$V_a = R_a I_a + G\Omega I_f$$

Armature current steady sate

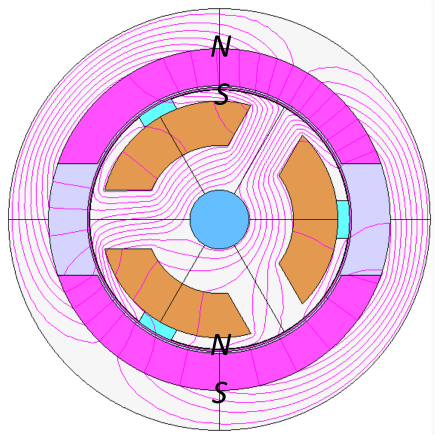
$$I_a = \frac{V_a - G\Omega I_f}{R_a}$$

Mechanical power output

$$P_{em} = T_e \Omega = E_b I_a$$

Another way to provide the magnetic field

Permanent magnet DC motor: an alternative way



Permanent magnet (PM) provides a fixed air-gap magnetic field

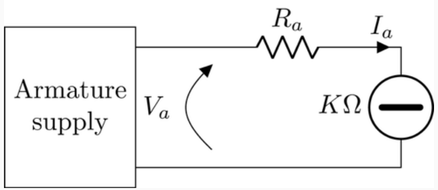
Stator

- Magnetic core and permanent magnets
- No field winding
- Field excited by permanent magnets

Rotor

- Armature winding
- Commutator and brushes

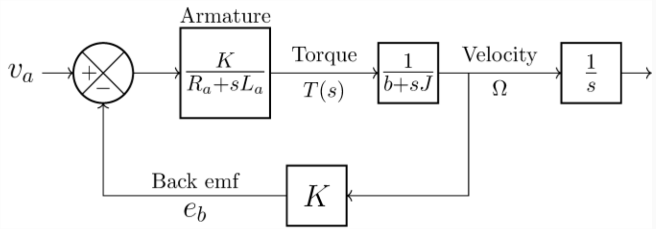
Equivalent circuit of PM DC machine



$$E_b = GI_f\Omega = K\Omega$$
$$T_e = GI_fI_a = KI_a$$

Dynamic model of DC motors

DC motor dynamics: described by ODEs and block diagrams



Block diagram describing dynamics of a DC machine

Armature voltage equation considering inductance

$$\begin{aligned} v_a &= R_a i_a + L_a \frac{\mathrm{d}i_a}{\mathrm{d}t} + e_b \\ &= R_a i_a + L_a \frac{\mathrm{d}i_a}{\mathrm{d}t} + K\Omega \end{aligned}$$

Torque equation

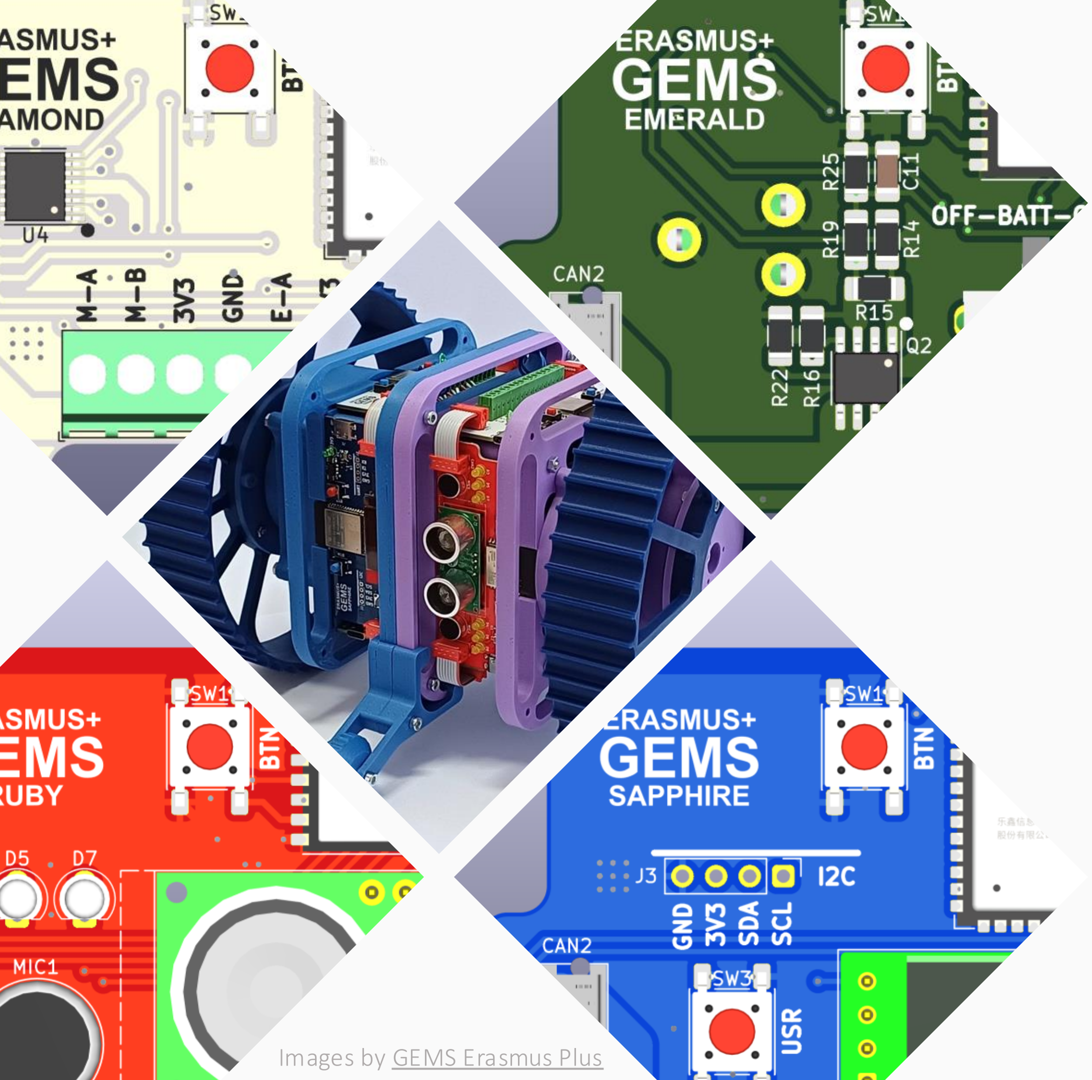
$$T = K i_a$$

Mechanical dynamics

$$T - T_L = J \frac{\mathrm{d}\Omega}{\mathrm{d}t} + b\Omega$$

Conclusions

- DC motor has linear torque/back-emf characteristics.
- Steady state performance analyzed based on equivalent circuit and Kirchhoff's Laws.
- Dynamics modelled by differential equations or transfer functions.



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