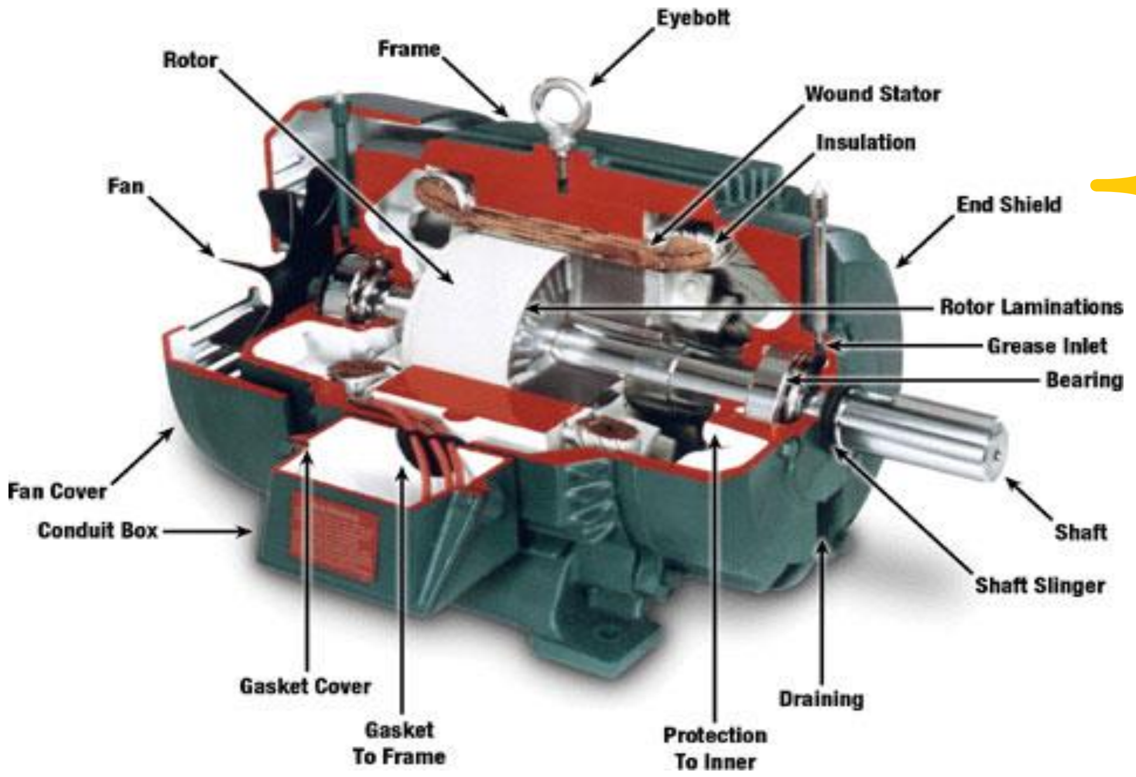
Electrical Drives I

Week 2: **SPEED-TORQUE** characteristics of Electric motors

DC Motor

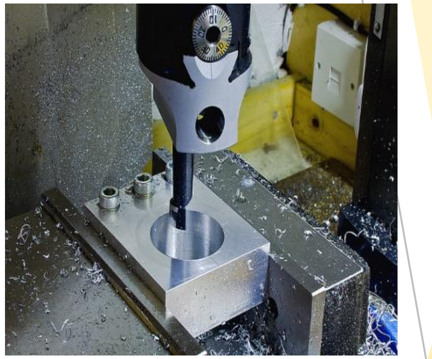
- Very popular due to its simple operation and control
- High starting torque and that’s why its is used in traction applications
- Used in a large number of applications and power tools used at home, such as saws and blenders.

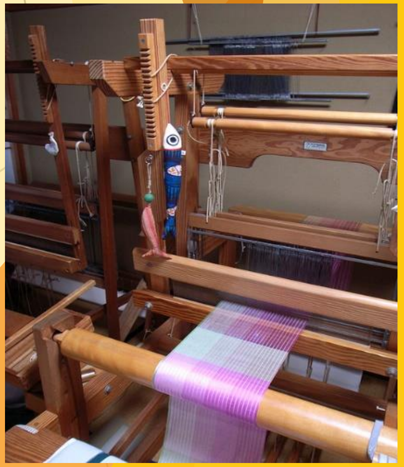
DC Motor: 1- Construction



Armature circuits

Field circuits





DC Machine – Theory of Operation

- **Field winding** - on stator pole
  - i_f produces ϕ_f
- **Armature winding** –on rotor
  - i_a produces ϕ_a
- ϕ_f and ϕ_a mutually **perpendicular**
  - **maximum torque**
- Rotor rotates clockwise
- For **unidirectional torque and rotation**
  - i_a must be **same polarity** under each field pole
  - achieved **using commutators and brushes**

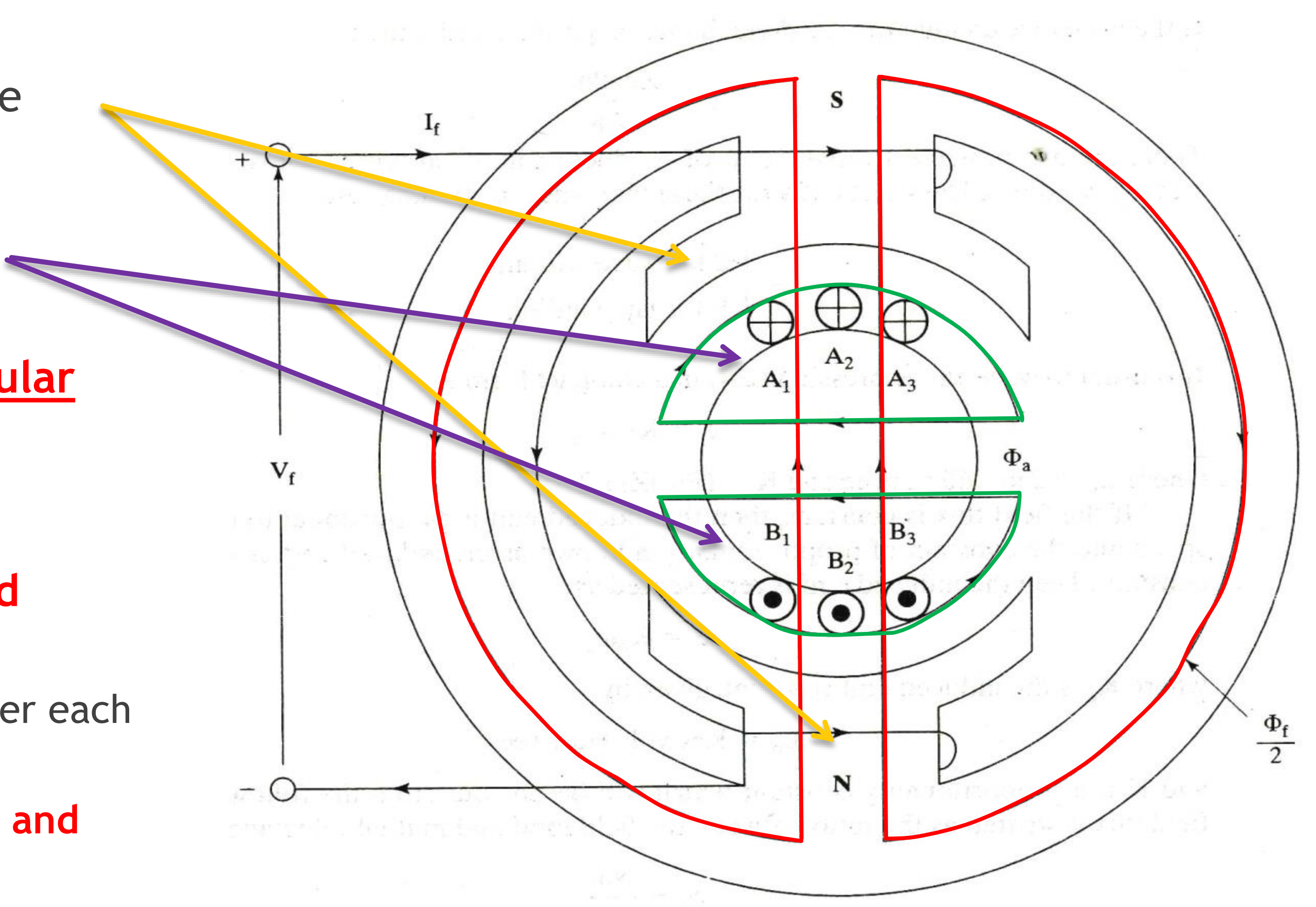
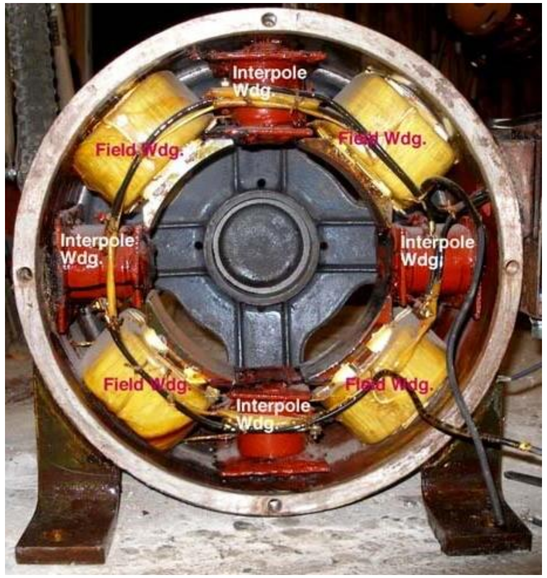


Figure 2.1 Schematic representation of a dc machine

1- DC Motor: Construction

Field circuits



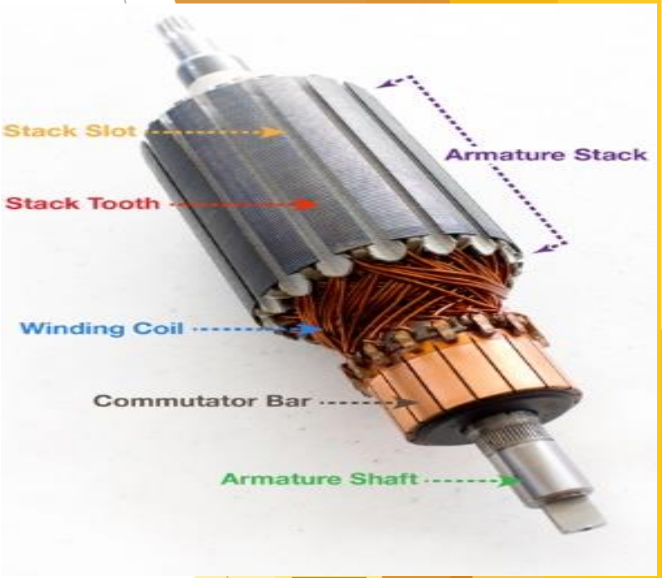
“Electric magnet” fed from a dc power supply **OR** is a permanent magnet (small machines)

Brushes

Brushes are mounted on the stator and are stationary but are in contact with the rotating commutator segments. Allows the commutator seg. to connect to an external dc source

Winding and commutator are mounted on the rotor shaft and they “rotate”.

Armature circuit and commutator

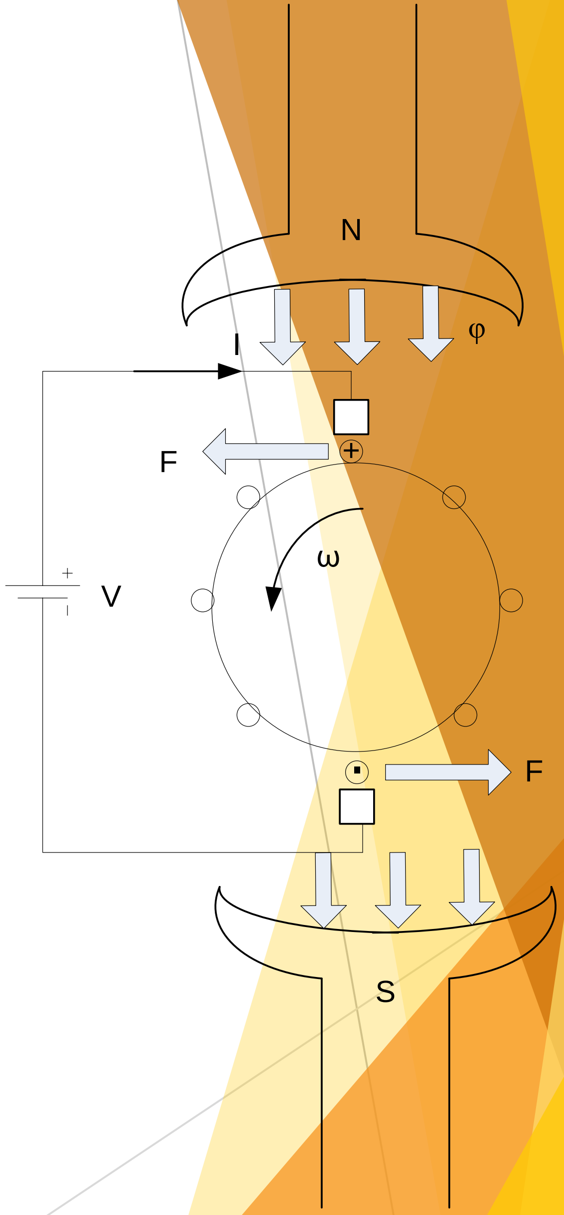


Rotor windings are composed of several coils, each two terminals are connected to the commutator. Commutator seg. are electrically isolated from each other

DC Motor: 1- Theory of Operation:

How dc motor works

- Stator filed produces flux ϕ from N pole to S poles.
- Brushes touch the terminal of the rotor coil under the pole.
- When brushes are connected to an external dc source of potential V, current I enters the rotor coil under the N pole and exits from the terminal that is under the S pole.
- **Rotor current + stator flux= force F** on coil (Lorentz force). This force will produce **torque T** that rotates the armature counterclockwise.
- Then the coil carrying current moves away from the brush and is disconnected from the external source and the next coil moves under the brush and the theory repeats itself.
- The force F is continuously produce and the motor keeps rotating.
- Commutator and brush “switch” the coils mechanically.



Operation of typical DC machine

DC Motor: 3- Important rules:

Some limitations:

- High maintenance (commutators & brushes)
- Expensive
- Speed limitations
- Sparking

DC Motor: 4- Connections:

- DC machine
  - Separately excited
  - Self excited
    - Series
    - Shunt
    - Compound
  - Permanent magnet

DC Motor: 4- Connections:

1. **Separately Excited:**
    - field is composed of large N with small cross section wire.
    - Designed to stand high voltage of motor. Armature and field have separate sources
    - ***Independent control of i_f (ϕ_f) and i_a (T)***

2. **Shunt:**
    - field is composed of large N with small cross section wire (same as separately excited).
    - Field is connected in parallel to armature
    - Common source is used
    - ***Variable-voltage operation complex. Coupling of ϕ_f (i_f) and T (i_a) production***

3. **Series:**
    - field is composed of small N with large cross section wire
    - Designed to stand high current of motor
    - Armature and field connected in series
    - ***Variable-voltage operation complex. Coupling of ϕ_f (i_f) and T (i_a) production***

DC Motor: 4- Connections:

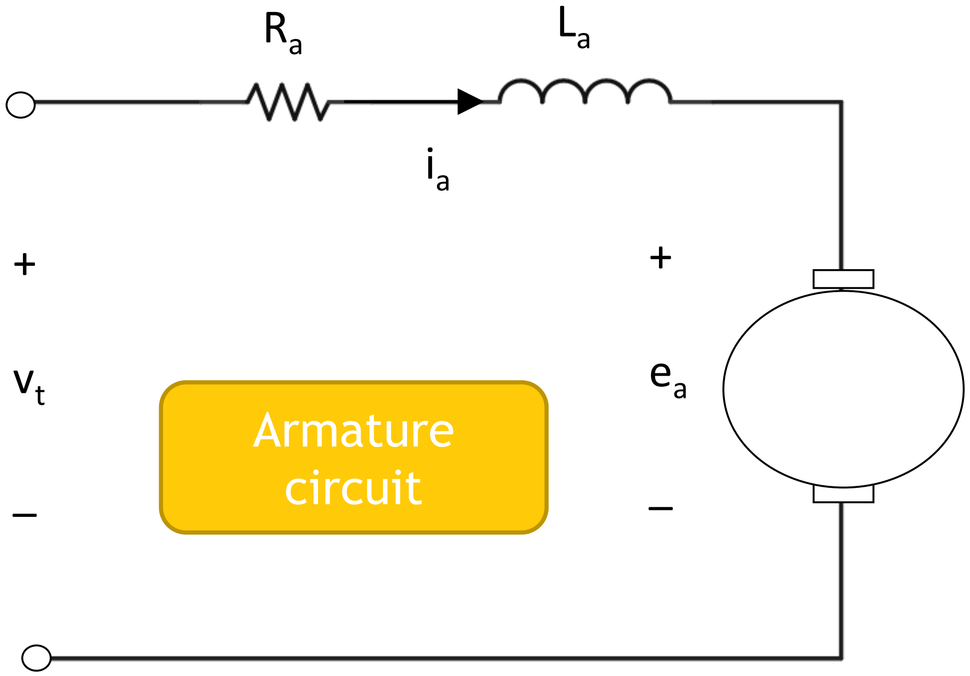
4. Compound:

- Combines best feature of series and shunt, Series – high starting torque and Shunt’s – no load operation

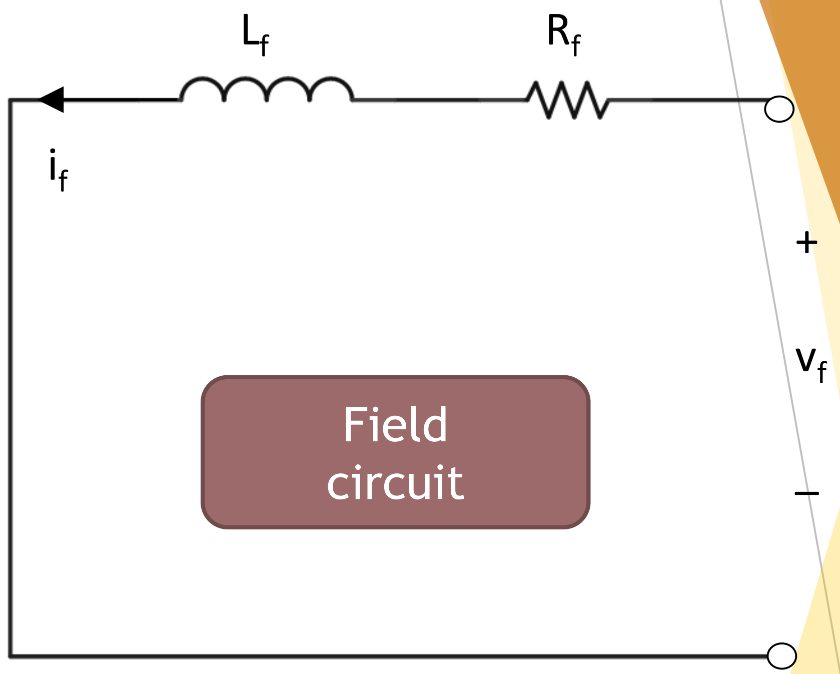
5. Permanent Magnet

- Field provided by magnets
- Less heat
  - No field winding resistive losses
- Compact
- Armature similar to separately excited machine
- Disadvantages:
  - Can’t increase flux
  - Risk of demagnetization due to armature reaction

a- Separately Excited DC motor:



$$v_t = R_a i_a + L_a \frac{di_a}{dt} + e_a$$

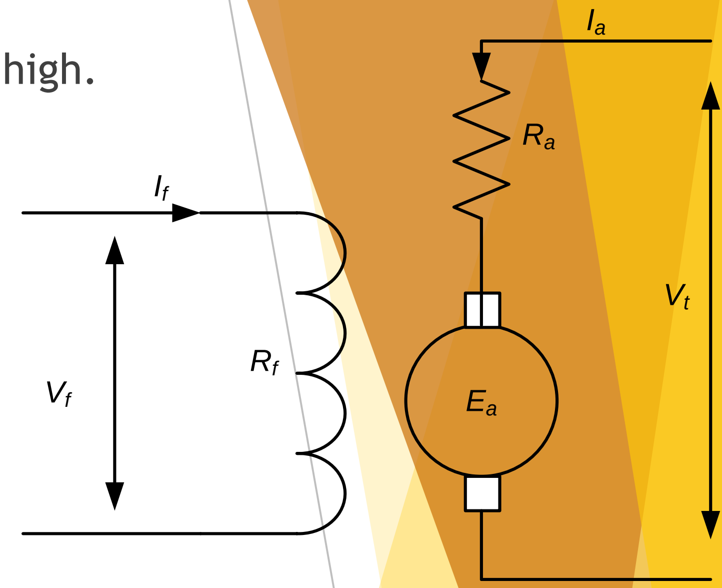


$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

a- Separately Excited DC motor: Field and armature

- Field is excited from separate DC source, V_f. Field resistance and inductance is high. Inductance has no impact at steady state.
- The field current can be calculated as:

$$\boxed{I_f = \frac{V_f}{R_f}}$$



Separately excited DC machine

- Small motor's field could be a permanent magnet and in this case, the field current might not be adjusted.
- External source is connected to armature V_t to provide the electric energy needed to drive the load.
- Relative to the field, the armature carries a much higher current than that of the field. The armature resistance R_a is smaller than R_f.
- Field current is usually between 1%-10% of rated armature current. The field and armature voltages are usually the same magnitude.
- The emf E_a and current I_a are related as:

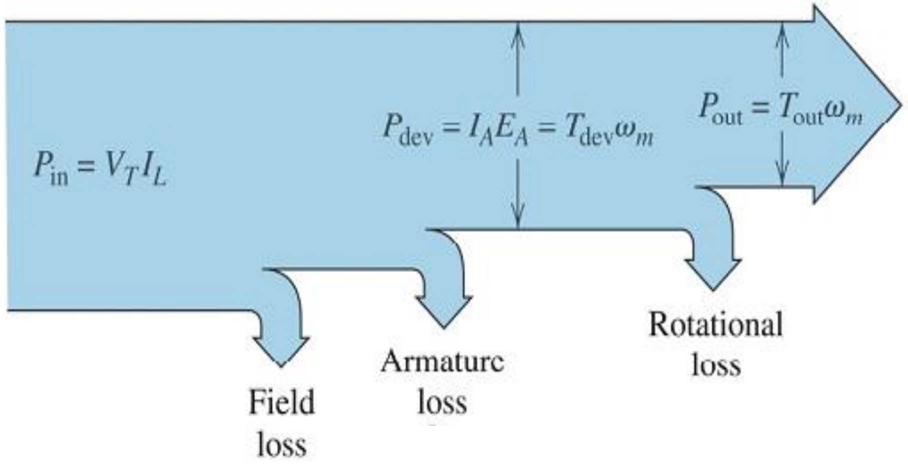
$$\boxed{I_a = \frac{V_t - E_a}{R_a}}$$

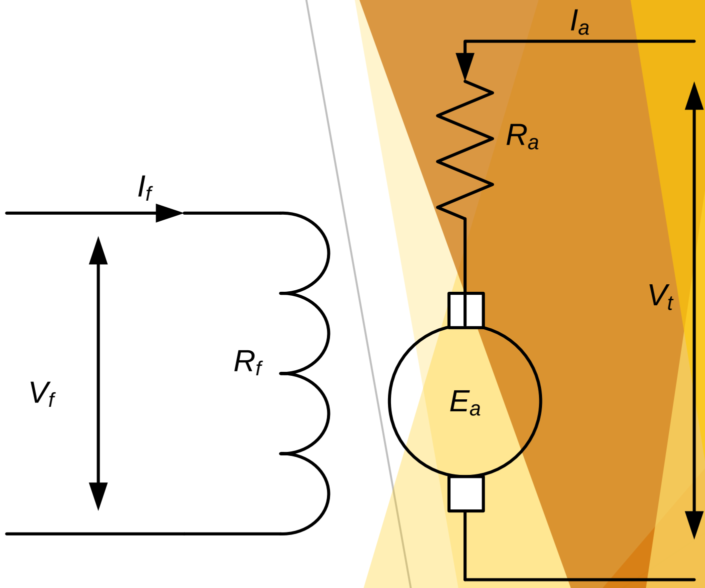
a- Separately Excited DC motor: Developed Power

- The developed power, P_d is given by:

$$\boxed{P_d = E_a I_a = T_d \omega}$$

- The developed power P_d is also equal to the output power consumed by the load plus the rotational losses (friction and windage).
- Similarly, the developed torque, T_d is equal to the load torque plus the rotational torque.





Separately excited DC machine

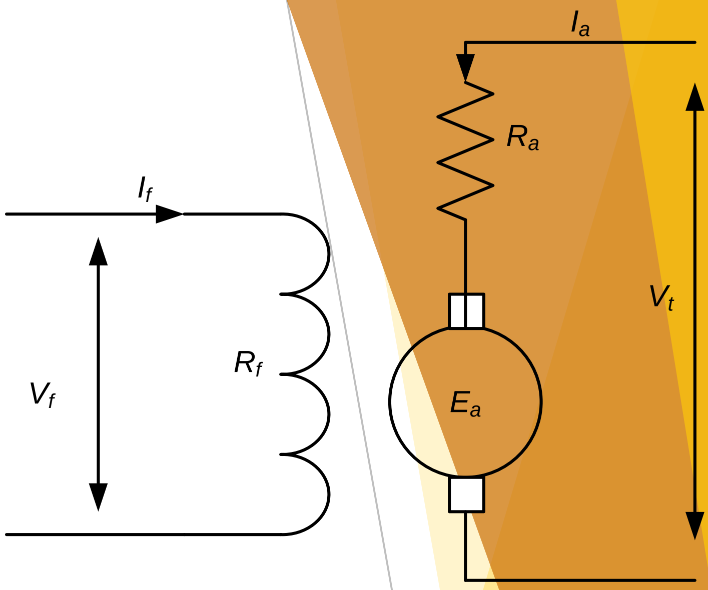
i- Separately Excited DC motor:

- Using the torque expression instead of force, and using angular speed instead of v, E_a and T_d can be written as:

$$\boxed{E_a = \phi\ P\ \frac{n}{60}\ \text{x}\ \frac{Z}{a}}$$

$$\boxed{T_d = \phi\ P\ \frac{I_a}{2\pi}\ \text{x}\ \frac{Z}{a}}$$

$$\boxed{\begin{aligned} E_a &= k\varphi\omega \\ T_d &= k\varphi I_a \end{aligned}}$$



Separately excited DC machine

Speed - torque equation is thus:

$$\boxed{T_d = k\varphi \frac{V_t - E_a}{R_a}}$$

i_a= armature conductor current
E= induced emf in conductor
Φ= flux (proportional to field current)
K= constant dependent on machine (poles, parallel paths, number of conductors)

a- Separately Excited DC motor:

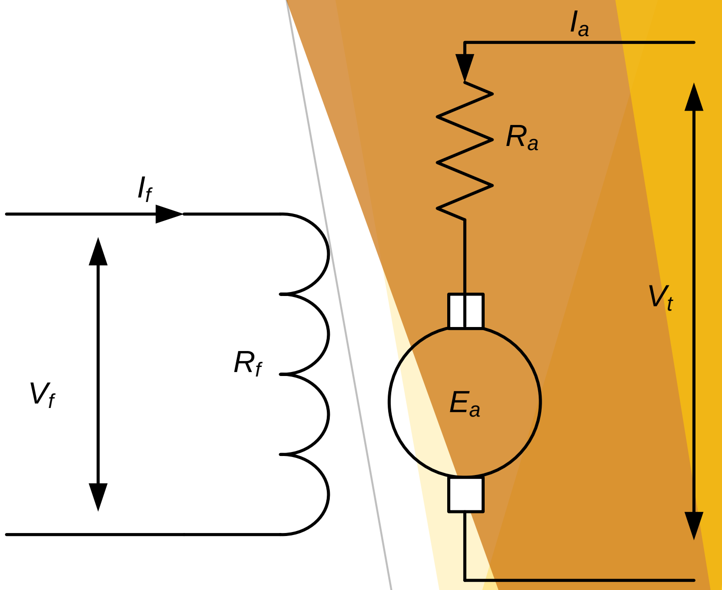
$$\boxed{T_d = k\varphi \frac{V_t - E_a}{R_a}}$$

- By substituting E_a and re-writing:

$$\boxed{T_d = k\varphi \frac{V_t - k\varphi\omega}{R_a}}$$

- Thus ω can be re written as:

$$\boxed{\omega = \frac{V_t}{k\varphi} - \frac{R_a}{(k\varphi)^2} T_d}$$



Separately excited DC machine

B: magnetic flux density
l= length of conductor
i_a= armature conductor current
E= induced emf in conductor
Φ= flux (proportional to field current)
K= constant dependent on machine (poles, parallel paths, number of conductors)

a- Separately Excited DC motor:

$$\boxed{\omega = \frac{V_t}{k\varphi} - \frac{R_a}{(k\varphi)^2}T_d}$$

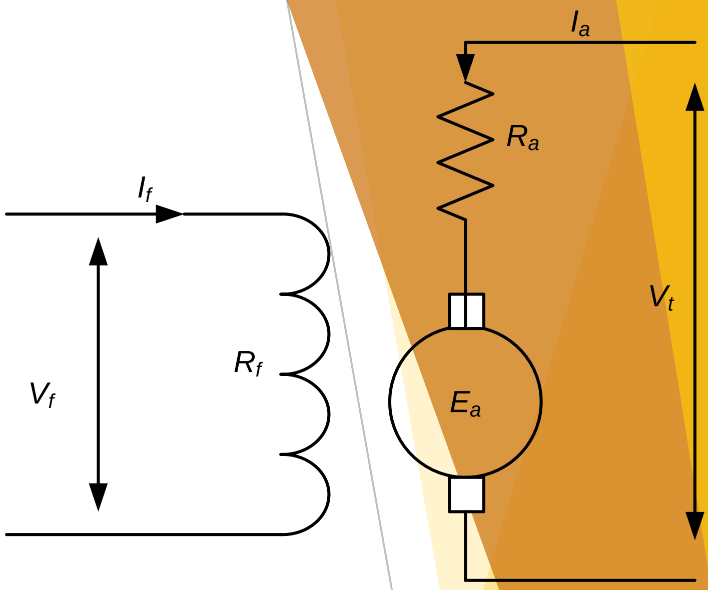
- The speed- current equation can be obtained if $\frac{T_d}{k\varphi}$ is replaced by I_a:

$$\boxed{\omega = \frac{V_t}{k\varphi} - \frac{R_a I_a}{k\varphi}}$$

- If the mechanical losses are ignored, the developed torque T_d is equal to the shaft torque, and the no-load armature current is equal to zero. Hence the no-load speed can be calculated using any of the above ω equations by setting the no-load current and load torque equal to zero:

No -load speed

$$\boxed{\omega_0 = \frac{V_t}{k\varphi}}$$



Separately excited DC machine

B: magnetic flux density
l= length of conductor
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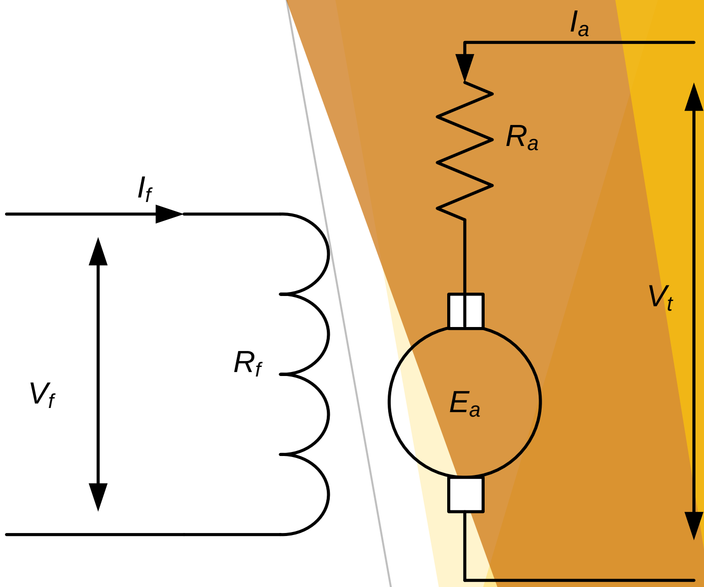
E= induced emf in conductor
Φ= flux (proportional to field current)
K= constant dependent on machine (poles, parallel paths, number of conductors)

a- Separately Excited DC motor:

- In reality, the mass of the drive system and the rotational losses are the base load of the motor. Thus $\omega_0$is smaller than the value obtained by the equation of ω_0 and the equation gives an approximated approach.
- At steady state, the developed torque T_d is equal to load torque T_m. At the given load torque T_m, the speed of the motor drops by an amount of $\Delta\omega$ that is equal to the second term of equation



Separately excited DC machine

$$\because \omega = \frac{V_t}{k\varphi} - \frac{R_a}{(k\varphi)^2}T_d$$

$$\omega_0 = \frac{V_t}{k\varphi}$$

$$\therefore \Delta\omega = \frac{R_a}{(k\varphi)^2}T_m$$

- Expressing the speed using the no-load and speed drop:

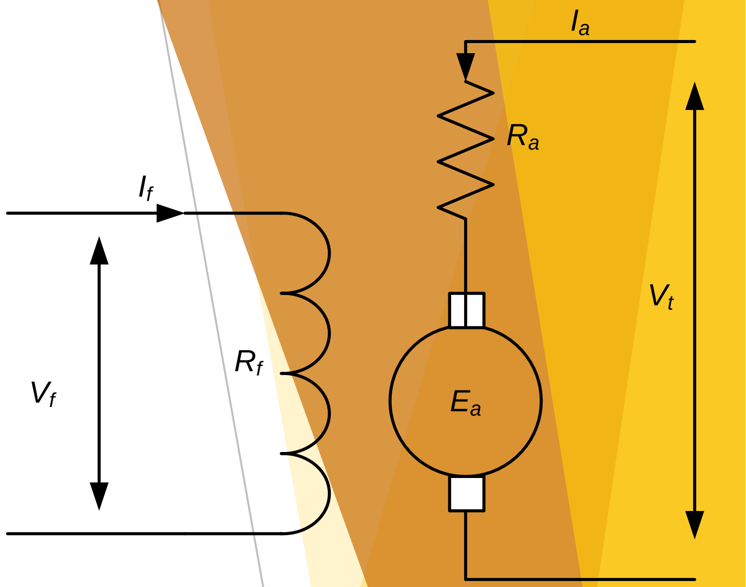
$$\omega = \omega_0 - \Delta\omega$$

a- Separately Excited DC motor:

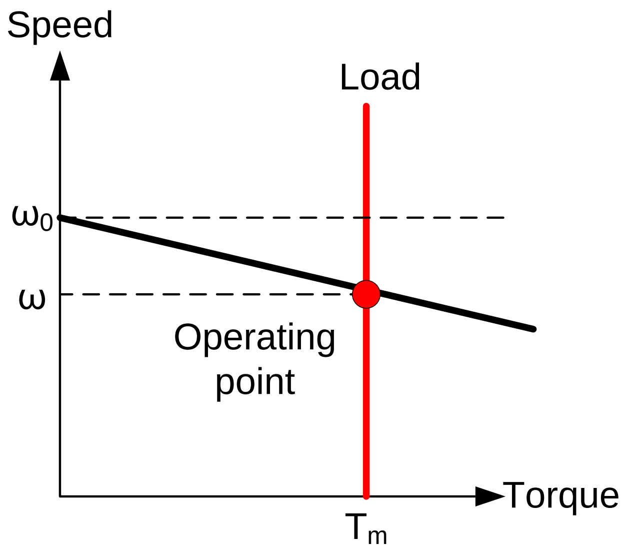
- For large motors (larger than 10 hp), R_a is very small because the armature carries higher current and the cross section of the wire must be large. For these motors, $\Delta\omega$ is very small. The motors are considered as a constant speed machine

$$\boxed{\because \omega = \frac{V_t}{k\varphi} - \frac{R_a}{(k\varphi)^2} T_m}$$

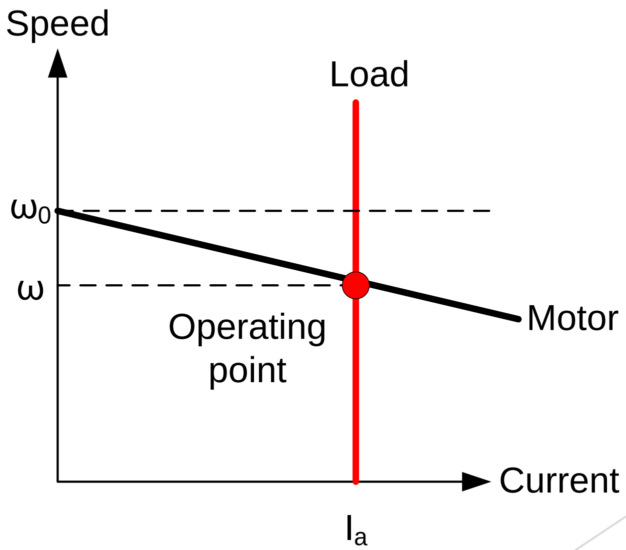
$$\boxed{\omega = \omega_0 - \Delta\omega}$$



Separately excited DC machine



Torques - speed characteristics Separately excited



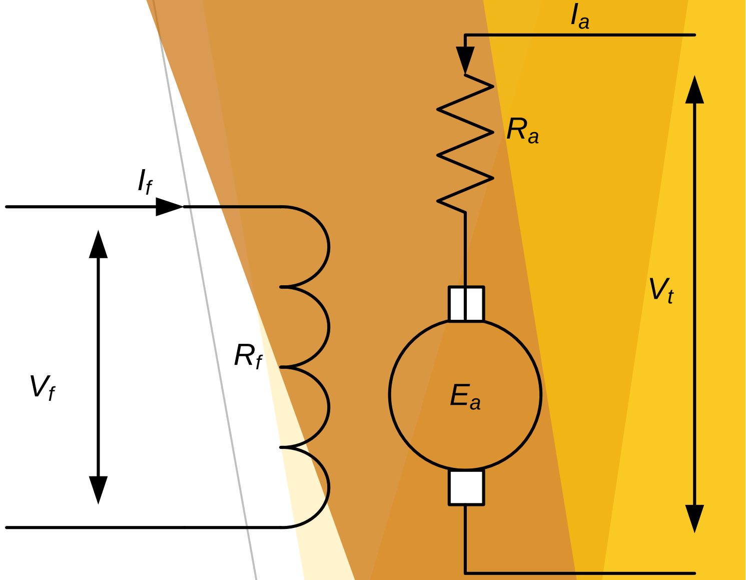
Speed- current characteristics Separately excited

a- Separately Excited DC motor: STARTING

- The developed torque at starting, T_{st} and the starting armature current I_{st} can be calculated using:

$$\omega = \frac{V_t}{k\varphi} - \frac{R_a}{(k\varphi)^2} T_d$$

$$\omega = \frac{V_t}{k\varphi} - \frac{R_a I_a}{k\varphi}$$



Separately excited DC machine

- And by setting the motor speed to zero,

Describes the starting behavior of a separately excited machine

$$T_{st} = k\varphi \frac{V_t}{R_a}$$

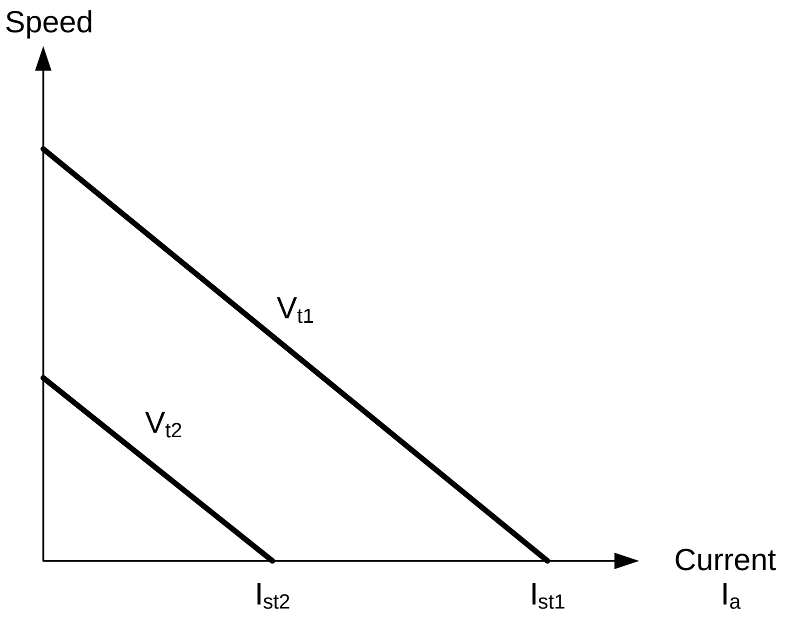
$$I_{st} = \frac{V_t}{R_a}$$

- Since Ra is very small, the starting torque is very large at rated voltage.
- VERY useful with motor starting at heavy loads.
- Be careful of large currents as it may affect windings.
- Large currents may cause high losses which when accumulated over time can melt insulation and cause short circuit

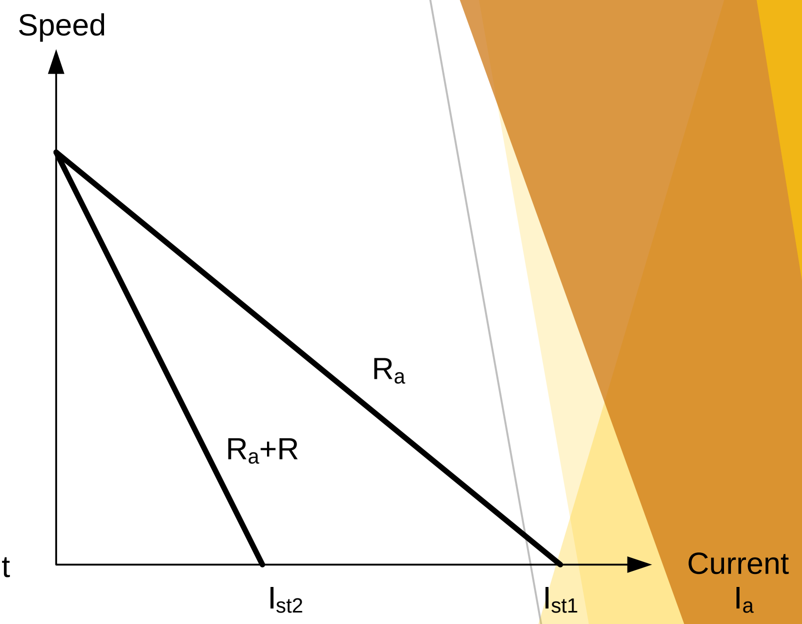
Starting of Separately Excited DC Motor: STARTING

$$T_{st} = k\varphi \frac{V_t}{R_a}$$

$$I_{st} = \boxed{\frac{V_t}{R_a}}$$



Terminal voltage reduction



Armature resistance insertion

- Starting is a TRANSIET condition, and could be limited by either:
  - reducing the terminal voltage during the starting to reduce the starting current, but consequently the starting torque will be reduced
  - Inserting a high resistance (or inductance) in starting. Resistance option will increase losses.
  - With terminal voltage reduction, the starting current is reduced AND also the no load speed is reduced. The slope is unchanged
  - With resistance insertion, slope is changed BUT the no load speed is unchanged.