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DEMec - Dep. of Mechanical Engineering
SAIC- Automation, Instrumentation and Control Section
Master in Mechanical Engineering

Electromechanical Systems

1st Year– 2nd Semester
2025-2026

Support documents to TP classes

Introduction
DC motors

Paulo Abreu

2026 Edition

Electromechanical Systems

Introduction
DC motors and BLDC motors

Paulo Abreu
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Dep. of Mechanical Engineering
2025-2026

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Contents

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Introduction

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Course Objectives

- To provide Knowledge and understanding of technological aspects in the field of **electromechanical drives**
- Present and develop a set of concepts and knowledge in the areas of
  - Electric drives and motor types
  - Mechanical transmission elements
  - Switching, control, and protection devices for electrical circuits and motors
  - Control and supervision equipment

Course Learning Outcomes (I)

At the end of the course, students will be proficient in:

- **System Identification:** identifying the structure and components of an electromechanical drive system
- **Operational Principles:** describing how various motors (DC, stepper, induction, and servo) work
- **Data Analysis:** performing a critical analysis of technical data from motor manufacturers
- **Specification:** analyzing and specifying switchgear components for protection and control

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Course Learning Outcomes (II)

At the end of the course, the students will be proficient in:

- **Mechanical Integration:** analyzing and specifying mechanical transmission elements (e.g., gearboxes, couplings)
- **Sensing Principles:** describing the functional principles of various sensors used in drive systems
- **Sensor Specification:** analyzing and specifying sensing elements for system integration
- **Power Electronics:** describing the working principle and characteristics of frequency inverters (VFDs)
- **System Synthesis:** analyzing and specifying overall solutions for electromechanical drive systems that meets specific industrial performance and efficiency standards

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Program

- Architecture of electromechanical drive systems
- Electrical Power Supply Systems
- Electric motors: DC motors, induction motors, stepper motors, and servo motors
- Mechanical transmission systems and sensing elements
- Electromechanical switchgear for protection and control
- Frequency inverters (VFD) and multi-axis motion controllers
- System Design & Implementation
  - Selection and sizing of actuators and transmissions, with a view to energy efficiency, and considering the current Standards and Regulations
  - Selection of power amplifiers (drives)
  - Parameterization and implementation of controllers

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Methodology and Assessment

- **Learning Approach**
  - TP classes for the presentation of concepts, technological information
    - One 1,5 h session per week (planned 13 classes)
  - PL classes, in the Laboratory of "Automatismos Industriais" (L004)
    - One 1,5 h session per week (planned 12 classes)
  - Autonomous Study
- **Evaluation**
  - Written exam: 100%
- **Registration of attendance in TP and PL classes**
  - The maximum number of absences is 25% of the effective classes in TP and PL

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SE and Moodle

- Use of Moodle platform:

https://sigarra.up.pt/feup/pt/moodle_portal.go_moodle_portal_up?p_codigo=209979

  - Share multimedia content
  - Share knowledge and support documents
  - Contribute to building and sharing information

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Bibliography

- Specific documents prepared for this curricular unit, to be available on Moodle, to support TP classes and PL classes

Complementary Bibliography

- Paul C. Krause, Oleg Wasynczuk; Electromechanical motion devices. ISBN: 0-07-035494-4
- Austin Hughes; Electric motors and drives. ISBN: 0-7506-4718-3

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Eletromechanical Systems (SE) Course Context

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SE: The Macro Context
Digitalization

- Key concepts
  - Digitalization / IoT / Digital Twins / Industry 4.0/ Industry 5.0
- Technologies supporting digitalization
  - Computer-based devices/communications/networks
  - Edge computing
  - Cloud-based data storage/ data processing
  - Artificial Intelligence / machine learning
  - 5G networks
- Need for Digital Enterprise at all levels/ Plant /City / Country

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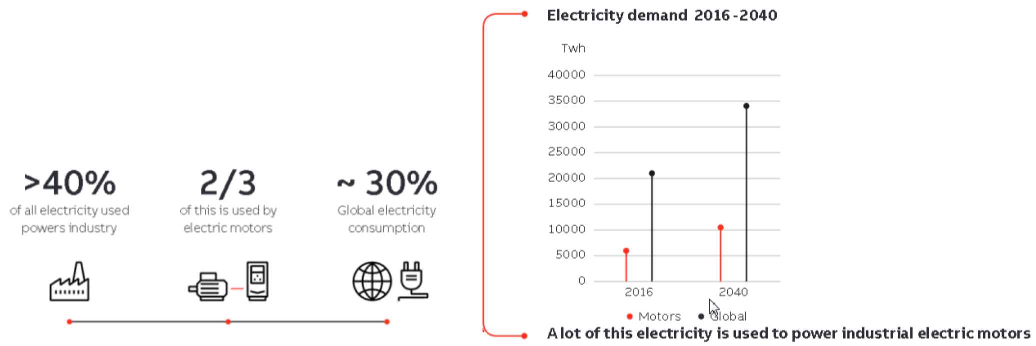
SE: The Macro Context
Global energy consumption and electrical motors



Sources: https://new.abb.com/drives/energy-efficiency
https://new.abb.com/motors-generators

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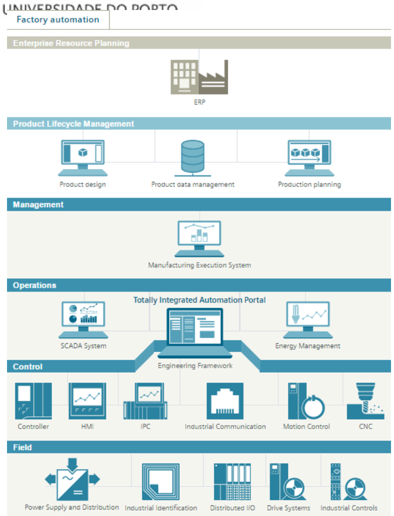
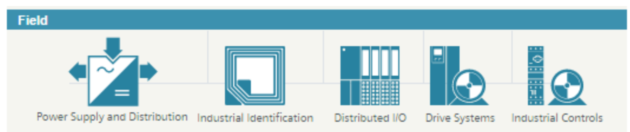
SE: The Macro Context
Factory Automation





SE main focus

www.industry.siemens.com

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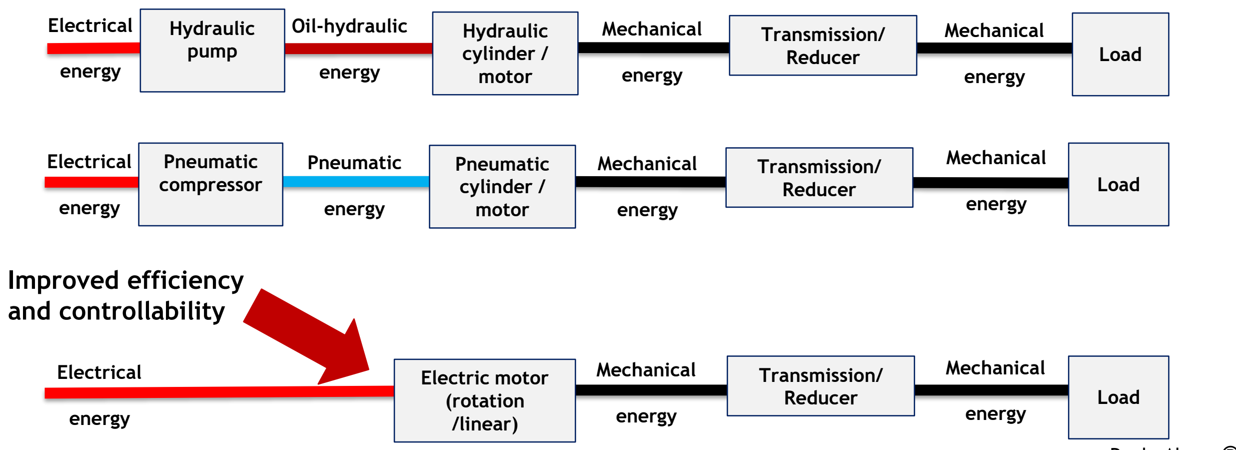
SE: The Macro Context
Power Drive Systems



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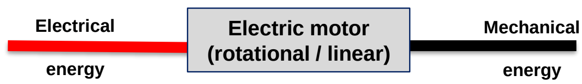
Electric motors

- Energy conversion device based on the principles of electromagnetism, specifically on the interaction between magnetic fields and electric currents



P_{ele} [W] = V [V] * I [A]

P_{mec} [W] = T [Nm] * ω [A] (rotational motion)
or
P_{mec} [W] = F [N] * v [m/s] (linear motion)

Efficiency = P_{mec} / P_{ele}

The efficiency of electric motors is typically very high, much superior to what can be achieved with pneumatic or hydraulic actuators

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Electric Motors classification
Working principle/source of energy

- Electric motors
  - Brushed Motors (*de escovas*)
    - DC motors
    - AC motors
    - Universal motor
  - Synchronous Motors (*síncronos*)
    - Single phase motors
      - Permanent magnets
      - Reluctance
      - Hysteresis motors
    - Three-phase motors
    - BLDC motors (brushless DC motors)
    - Stepper motors
  - Asynchronous Motors (*assíncronos*)
    - Single phase motors
      - Shadow poles
      - Capacitor start induction motors
    - Three-phase AC induction motors

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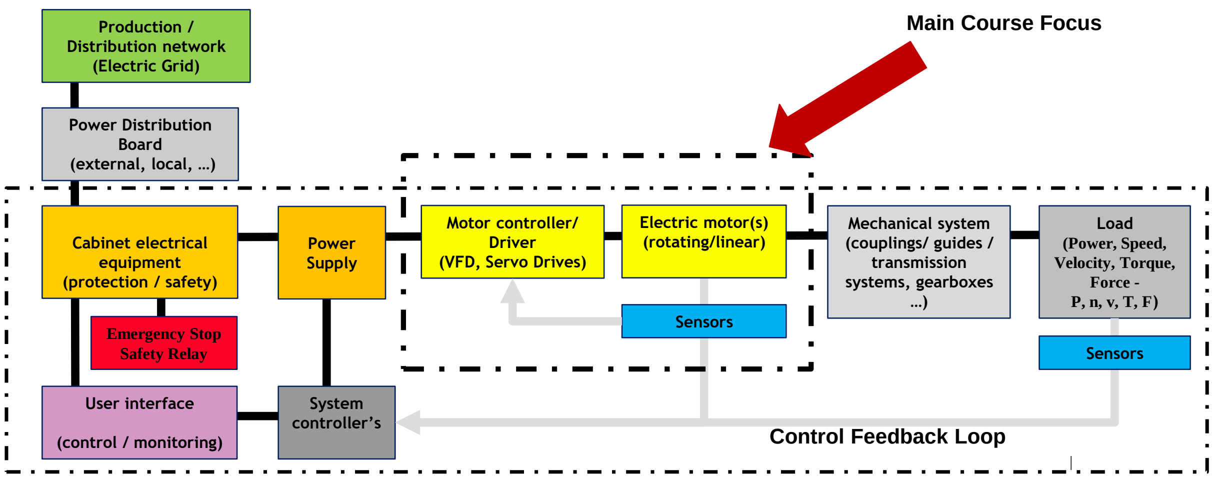
Electromechanical Drive System Architecture



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Electromechanical Drive Technologies

Drive Technologies

- Generators
- Electric Motors
  - Geared motors
  - Gear units/couplings
- Converters, inverters, drivers
- Low-voltage components (switchgear)

- Software tools for engineering and selection
- Digitalization in drive technologies

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Electromechanical Drive Technologies

Multiple types of electric motors + Multiple drives

- Very important choice of Motor + Drive
- High impact on energy efficiency
  - IEC/EN 60034-30-1:2014 Efficiency classes of **line-operated AC motor**(IE code, **IE1 to IE4**)
  - IEC 60034-30-2:2016 Efficiency classes of **variable speed AC motors**
  - IEC61800-9-2:2017 Energy efficiency indicators for **power drive systems** and **motor starters**
  - EU Ecodesign Regulation **EU 2019/1781**: requirements for **electric motors** and **variable speed drive** (to start in 2021 and 2023) (see also ABB info)

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Physics Fundamentals

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Electromagnetism and electric motors

The operation of all electric motors is predicated on the interaction between magnetic fields and electrical currents, governed by three fundamental **principles of electromagnetism**. These principles define how electrical energy is converted into mechanical work (rotational or linear) through magnetic coupling

- 1st Principle – Generation of **Magnetic Fields -** An electric current flowing through a conductor generates a surrounding magnetic field
- 2nd Principle – **Lorentz Force -** A current-carrying conductor placed within an external magnetic field experiences a mechanical force
- 3rd Principle – **Electromagnetic Induction -** (Generator/Back-EMF Action)
  An electrical circuit subjected to a varying magnetic flux (ϕ) will have an induced electromotive force (voltage) across its terminals

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Electromagnetism and electric motors
Generation of Magnetic Fields

- 1st principle: Generation of **Magnetic Fields** -an electric current flowing through a conductor generates a surrounding magnetic field
  - **Straight Conductor**: a current *i* flowing through a straight wire produces a magnetic field density B in concentric circles around the conductor.
  - **Mathematical Definition**: the magnetic flux density is defined by:

$$B = \frac{\mu}{2\pi \bullet r} \cdot \mathrm{i} \quad [\mathrm{T}]$$

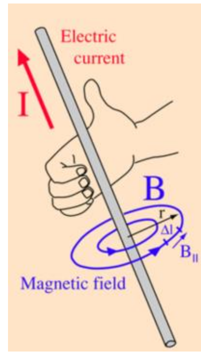
with $\mu = \mu_r \mu_0$ is the magnetic permeability of the material

with μ_r being the relative permeability and

μ_0 is the permeability in the vacuum, $(\mu_0 = 4\pi \cdot 10^{-7} \; [\mathrm{N/A^2}])$

For ferromagnetic materials, such as iron and nickel,

$\mu_r = 100...100000 [\mathrm{N/A^2}]$



http://hyperphysics.phy-astr.gsu.edu/hbase/index.html

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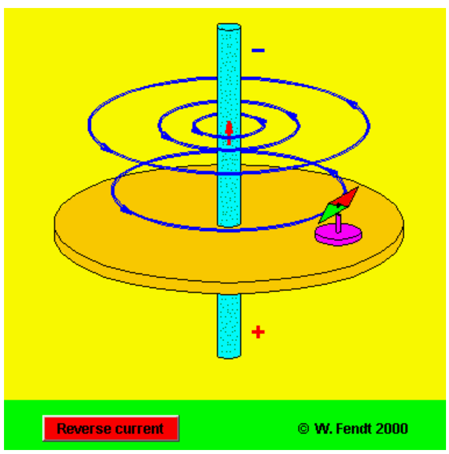
Electromagnetism and electric motors
Generation of Magnetic Fields

https://www.walter-fendt.de/html5/phen/magneticfieldwire_en.htm



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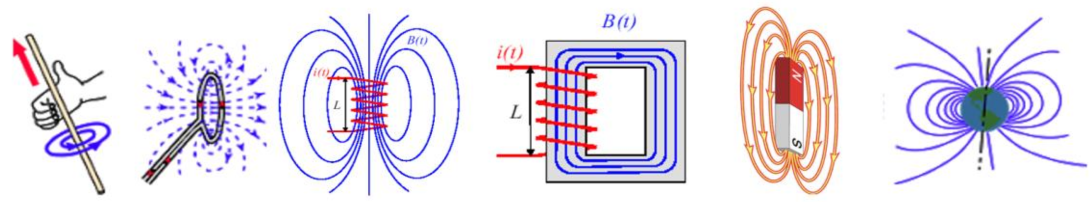
Electromagnetism and electric motors
Magnetic Fields

Sources of magnetic fields



Current in a wire | Current in a wire loop | Solenoid | Transformer | Permanent magnet | Earth

Electromagnetism and electric motors
Generation of Magnetic Fields

Solenoids and Coils: when a conductor is wound into a coil, the individual magnetic fields of each turn reinforce one another, creating a concentrated flux similar to a permanent magnet

If an electrical conductor, of length L, is wound in a coil, having N turns, then it will create a magnetic field inside of flux density B

$$\left\|\vec{B}\right\| = B = \mu \frac{N}{L} \cdot I$$

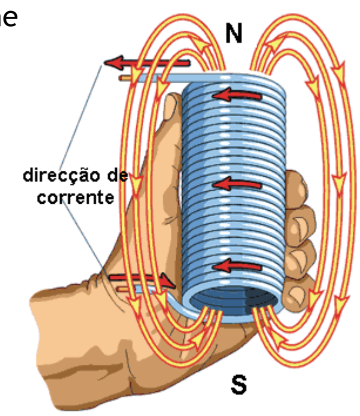
B: magnetic field density, [T] (Tesla)

μ: magnetic permeability of the environment [N/A^2]

N: number of turns [–]

L: lenght of conducter [m]

I: current [A]



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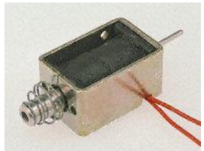
Electromagnetism and electric motors

Solenoids

- A solenoid is seen as an **electric actuator** that implements a **movement** (**linear** or **rotary**) of **limited amplitude**
  - It takes electrical energy as input and converts it into an electromagnetic field. This magnetic field exerts a magnetic force that attracts a moving ferromagnetic component, causing it to move



Linear Solenoid, momentary action, 240 V AC

Rotary Solenoid, DC, momentary action, rotation angle 45° or 95°

✓ The solenoid can be operated in a digital mode (in most cases) or in an analog mode.

✓ One of the most used applications of solenoids is in relays, contactors, and solenoid valves

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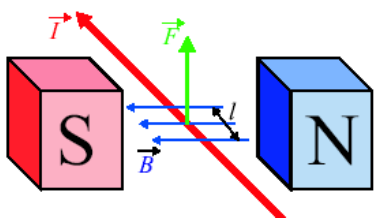
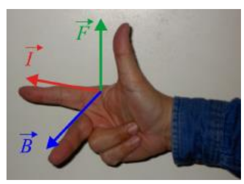
Electromagnetism and electric motors
Lorentz Force

- 2nd principle: Lorentz Force: a current-carrying conductor placed within an external magnetic field experiences a mechanical force
  - **Force Vector**: the force F is perpendicular to both the current *i* and the magnetic field B
  - **Mathematical Definition:**

$$\vec{F} = \left(\vec{i} \times \vec{B}\right) \cdot l \quad [\mathrm{N}]$$

$$F = (i \cdot B) \cdot \sin(\alpha) \cdot l \quad [\mathrm{N}]$$





Note:

- The Force is oriented according to the three-finger rule
- This principle is the primary driver for torque production in most industrial motors

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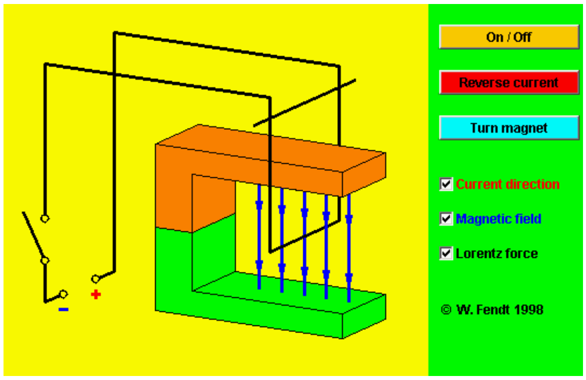
Electromagnetism and electric motors
Lorentz Force

2nd principle: Lorenz Force

$$\vec{F} = \left(\vec{i} \times \vec{B}\right) \cdot l \quad [N]$$



https://www.walter-fendt.de/html5/phen/lorentzforce_en.htm

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Electromagnetism and electric motors
Electromagnetic Induction

- 3rd principle: Electromagnetic Induction (Generator/Back-EMF Action)

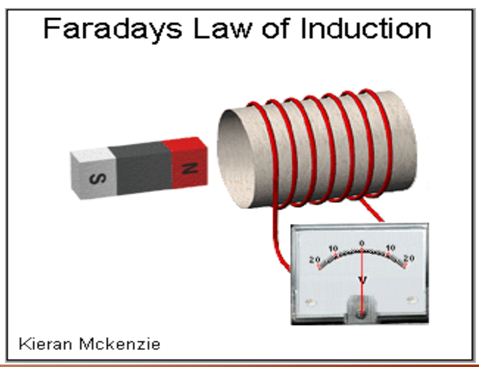
  An electrical circuit subjected to a varying magnetic flux (ϕ) will have an induced electromotive force (voltage) across its terminals

- **Faraday's Law**: the induced voltage (e) is proportional to the rate of change of magnetic flux **(ϕ)** linkage

  $$e = -N\frac{d\phi}{dt}$$ N - Number of Turns in the coil

- **Lenz's Law**: the polarity of the induced voltage is such that it creates a current whose magnetic field opposes the change in the original flux

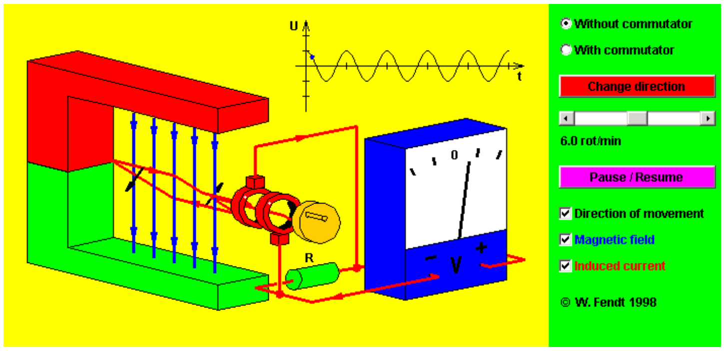
- **Significance in Motors**: in a running motor, this principle creates Back-EMF, which opposes the supply voltage and inherently regulates the motor's current and speed



Electromagnetism and electric motors
Electromagnetic Induction

Induced voltage direction

https://www.walter-fendt.de/html5/phen/generator_en.htm



The direction of the induced voltage is such that the electric current and the resulting electromagnetic forces tend, by their effect, to oppose the change in flux

Mechanisms of Torque and Force Production

The basic operating principle of all motors lies on the torque/force production due to the magnetic forces acting on the rotor/forcer, which translates into obtaining a rotational/linear movement

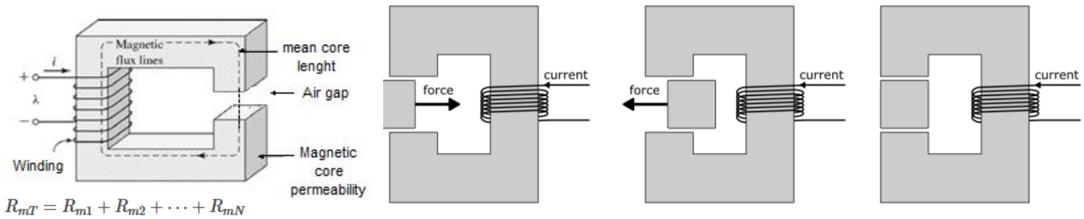
The torque/force production can be related to two different mechanisms:

- **Lorentz Force**: forces acting on current-carrying conductors within the rotor's magnetic circuit
- **Reluctance Force**: force generated by the tendency of a magnetic circuit to minimize its "magnetic resistance" or reluctance

Electromagnetism and electric motors
Relutance Force

The **reluctance force** is generated through a change of the magnetic resistance (magnetic reluctance) and not a force that acts on a current-carrying conductor.

This force tends to minimize the total reluctance (magnetic resistance) in a magnetic circuit



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Classification of Electric Motors
by Physical Operation

The diversity of motor types arises from how these fields are generated and interact with:

- **Energy Source**: DC (Direct Current) vs. AC (Alternating Current)
- **Field Generation:** permanent magnets vs. electromagnetic coils
- **Force/ Torque generation**: Lorenz force vs. Relutance force
- **Commutation Strategy**:
  - Mechanical Commutation (**Spatial Switching)**: used in brushed DC motors, where mechanical brushes change the current direction based on rotor position
  - Electronic Commutation (**Time/Electronic Switching)**: used in Brushless DC (BLDC), stepper, and servo motors, where controllers vary the field in time to maintain rotation

Note that in BLDC motors and servomotors, while the rotor's position triggers the switching, we classify it as **Timed/Electronic** because a microprocessor is actively deciding when to fire the power transistors based on a clock frequency

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Course Overview of Motor Topologies

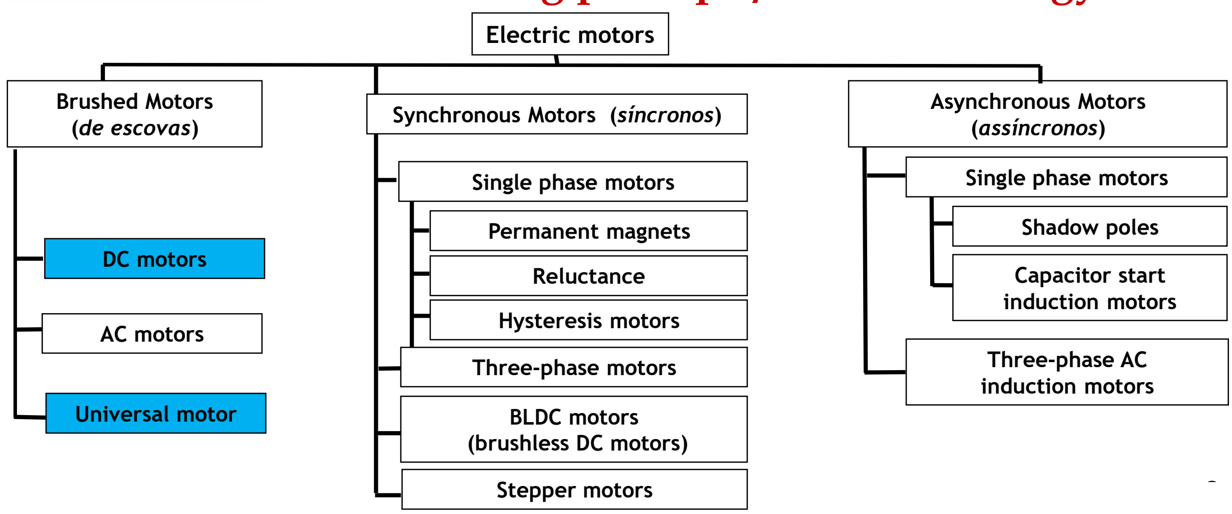
This course will specifically analyze the following technologies:

- DC Motors: Brushed configurations with permanent magnets or wound field coils.
- AC Motors: Focused on three-phase induction (asynchronous) machines.
- AC Syncronous motors
- Stepper motors: for discrete positioning and
- Servo motors for high-dynamic closed-loop control.Advanced

Variants:

- Brushless DC (BLDC), and Single-phase induction motors, Universal motors

Electric Motors classification Working principle/source of energy



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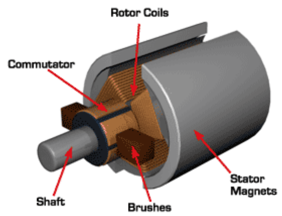
Brushed DC Motors



Core Components

- Stator (Field/Excitation): the stationary part. It provides the constant magnetic flux (Φ) via **Permanent Magnets** (PMDC) or **Field Coils** (Wound)
- Rotor (Armature/Induzido): the rotating assembly containing the armature windings
- Commutator & Brushes: the mechanical system responsible for **Spatial Switching**. Brushes (typically graphite) transfer current to the commutator segments (copper blades) to ensure the torque remains unidirectional as the rotor turns

✓interaction between magnetic fields by **spatial switching**

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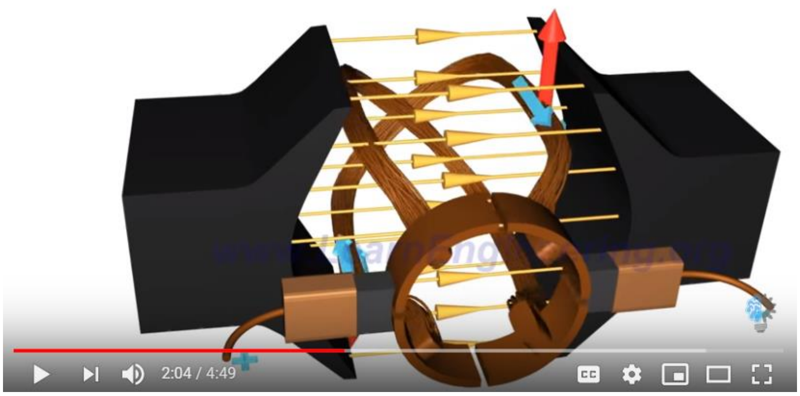
Brushed DC Motors



www.youtube.com/watch?v=LAtPHANEfQo

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Brushed DC Motors

Topology Classification

- **Permanent Magnet (PMDC):** linear characteristics; ideal for small, efficient applications
- **Series Wound:** field coils in series with the armature. High starting torque; speed drops significantly with load
- **Shunt (Parallel) Wound:** field coils in parallel. Nearly constant speed; ideal for conveyors
- **Separately Excited:** field and Armature powered independently. Offers the highest degree of control flexibility

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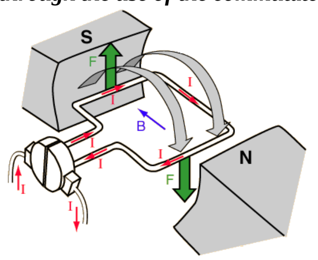
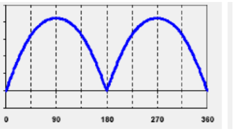
Permanent magnet DC motor: how it works

- Place a turn (loop), mounted on a support that allows it to have a rotational movement, in a fixed magnetic field, of flux density B
- Feed the turn with a current I, and torque will be generated, represented by the forces F
- The forces generated will make the coil rotate 90º, and it will be immobilized in this new position.
- If we later reverse the direction of the current in the loop, it will rotate an additional 90º and return to its initial position.

In a DC motor, the change of direction of the current is done through the use of the commutator



Resulting torque



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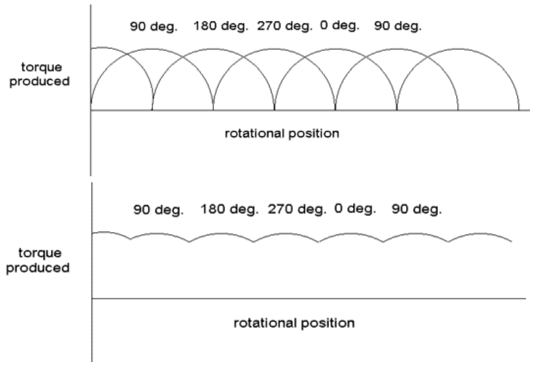
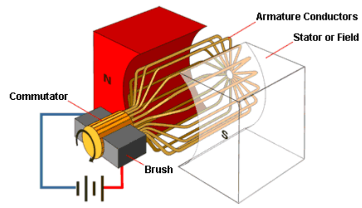
Permanent magnet DC motor: how it works

- Increasing the number of turns decreases the ripple of the torque obtained





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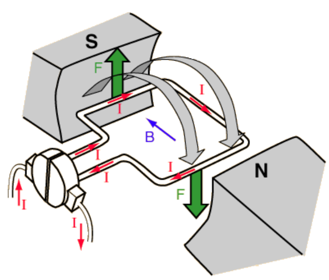
Permanent magnet DC motor: how it works

Counter-electromotive force (emf)

As the turn (loop) moves (rotates) within the fixed magnetic field, an electromotive force is generated, which translates into the induction of a current through the loop

This induced current is in the opposite direction to the current being supplied to the turn. Thus, the current flowing in the loop results from the difference between the supplied current and the induced current

This induction phenomenon is what makes a DC motor be used as a generator (mechanical energy is supplied and electrical energy is obtained)



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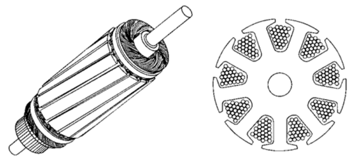
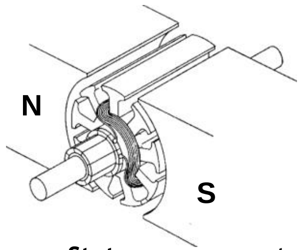
Permanent magnet DC motor: how it works

- In the simplified motor model shown, the rotor had fewer turns. In fact, in order to create a stronger magnetic field in the rotor, several turns are used, that is, the rotor is wound



Rotor



Stator: permanent magnet

Brushes

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Permanent magnet DC motor

Low voltage permanent magnet motor – TENV and TEFC

1/4 thru 1 Hp

Features:

- NEMA C-Face
- Class F insulation
- Double sealed ball bearings
- Top-mounted terminal studs for power connection on ratings 40-amps and up

Applications:

- Battery operation for portable pumps
- Fans
- Augers
- Winches
- Lifts

- **Modelo CDP3445**
  - Power 1 HP
  - Nominal velocity 1750 RPM
  - Armature 90 V
  - Current 10 A
  - Stator: permaent magnet

Mechanical characteristics

TENV – totally enclosed non ventilated

TEFC: Totally enclosed fan cooled

- NEMA 56 C- mounting frame
- sealed ball bearings

https://www.baldor.com/mvc/DownloadCenter/Files/9AKK108394

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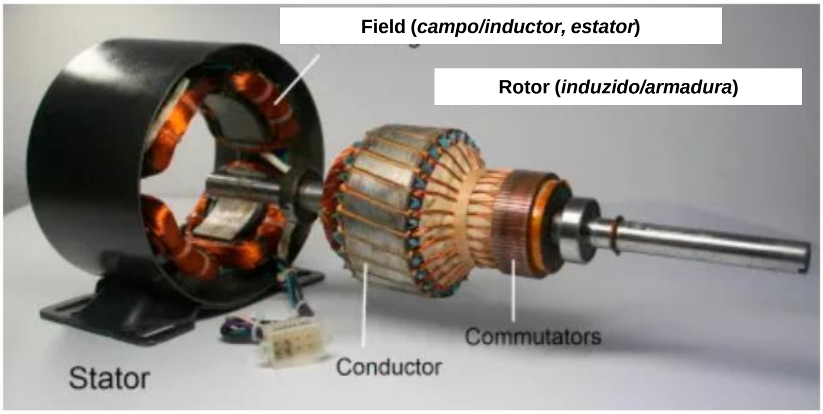
Wound DC motor



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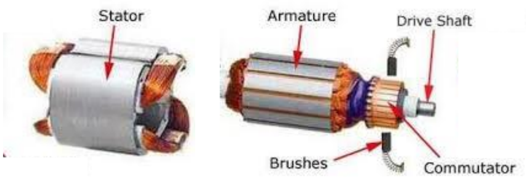
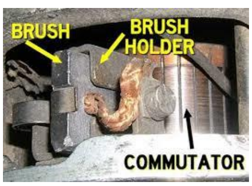
Wound DC motor



- Brushes:
  - Elements subject to wear
  - Brush replacement needed



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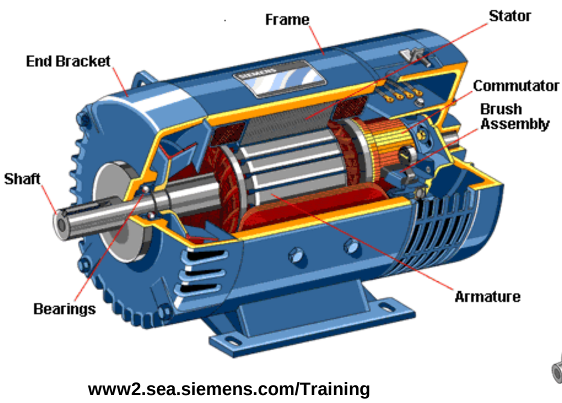
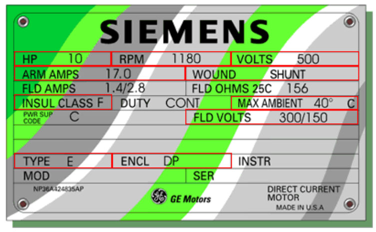
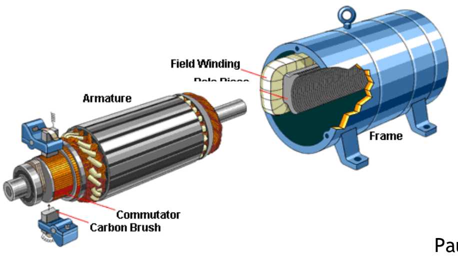
Wound DC motor



www2.sea.siemens.com/Training





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Wound DC motor (I)

Electromechanical Equations (Steady-State)

To analyze DC motors, we rely on two fundamental "bridge" equations that link the electrical and mechanical domains

1. The Voltage Equation (Kirchhoff's Law)

The total voltage supplied to the armature (V_a) must overcome the internal resistance (R_a) and the Back-EMF (E_a):

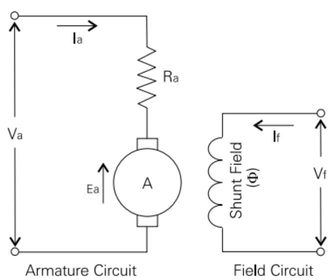
$V_a = E_a + I_a R_a$ where

V_a = apllied armature voltage [V]

E_a = Back EMF (counter electromotive force) [V]

I_a = armature current [A]

R_a = armature resistence [Ω]



2. The Back-EMF Equation

The Back-EMF is generated by the rotor conductors moving through the stator flux:

$E_a = K \cdot \Phi \cdot \omega_a$ where

K = Constructive motor constant [V/(Wb•rad/s)]

Φ = Magnetic Flux [Wb]

ω_a = Angular speed [rad/s]

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Armature Voltage Counter electromotive force

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Wound DC motor (II)

Electromechanical Equations (Steady-State)

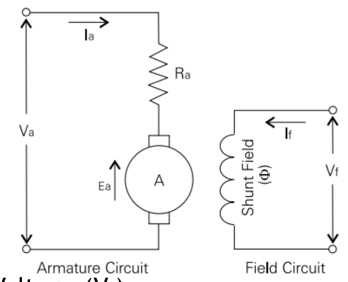
3. The Torque Equation

The interaction of the shunt and armature field flux produces torque. The mechanical torque (T) produced is directly proportional to the armature current:

$$T = K \bullet \Phi \bullet I_a$$

Note: In PMDC motors, k * Φ is often combined into a single constant k_t [Nm/A] (Torque Constant)

Combining the equations, $\omega_a = \dfrac{V_a - I_a R_a}{K \bullet \Phi}$



If the flux remains constant, the speed changes linearly with the armature Voltage (V_a)

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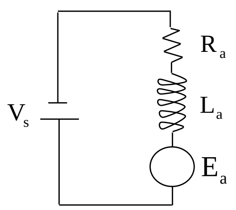
Permanent magnet DC motor

Motor equivalent circuit



$$E_a = K_e \bullet \omega_m$$
$$T_m = I_a \bullet K_T$$

- V_s motor supply voltage [V]
- I_a Armature current [A]
- R_a Armature resistence [Ω]
- E_a counter electromotive force [V]
- L_a inductance [H]
- ω_m motor speed [rad/s]
- K_e counter electromotive force constant [V/(rad/s)]
- K_T torque constant [Nm/A]
- T_m motor torque [Nm]

expressed in SI units $K_e \cong K_T$

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Permanent magnet DC motor

$$V_s = I_a R_a + E_b \quad = \quad I_a R_a + K_e \omega_m$$
$$= \frac{T_m}{K_T} R_a + K_e \omega_m$$
$$\omega_m = \frac{V_s}{K_e} - \frac{T_m R_a}{K_e K_T}$$

$$T_m = \frac{V_s}{R_a} K_T - \frac{\omega_m}{R_a} K_e K_T$$

when $\omega_m = 0$, the stall torque is given by

$$T_0 = \frac{V_s}{R_a} K_T$$

when $T_m = 0$,

the no-load speed is given by:

$$\omega_{m0} = \frac{V_s}{K_e}$$

Under dynamic conditions

$$T_m = K_T I_a(t) = T_{load}(t) + b\,\omega_m(t) + J\frac{d\omega_m(t)}{dt}$$
$$V_s = I_a(t) R_a + L_a \frac{dI_a(t)}{dt} + E_b$$
$$= I_a(t) R_a + L_a \frac{dI_a(t)}{dt} + K_e \omega_m(t)$$

T_{load} load torque [Nm]

b viscous friction torque constant

ω_m motor speed [rad/s]

J inertia seen by the motor [Nm/s^2]

L_a armature inductance [H]

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Performance Characteristics

The Torque-Speed Relationship

- By combining the equations above, we derive the linear relationship for a PMDC or Shunt motor:

$$\omega_a = \frac{V_a - I_a R_a}{K \bullet \Phi} = \frac{V_a}{K \bullet \Phi} - \frac{R_a}{(K \bullet \Phi)^2} \bullet T$$

- No-Load Speed (ω_0): the speed when torque is zero
- Stall Torque (T_s): the maximum torque produced when the motor is prevented from rotating (ω = 0). At this point, the current I_a is at its maximum: $I_{stall} = V_a / R_a$

Power and Efficiency

- Electrical Power (P_{ele}): $V_a * I_a$
- Converted Power (P_{conv}): $E * I_a = T * \omega_a$
- Mechanical Output (P_{out}): P_{conv} - P_{losses} (friction/windage)
- Efficiency (η): P_{out} / P_{ele}

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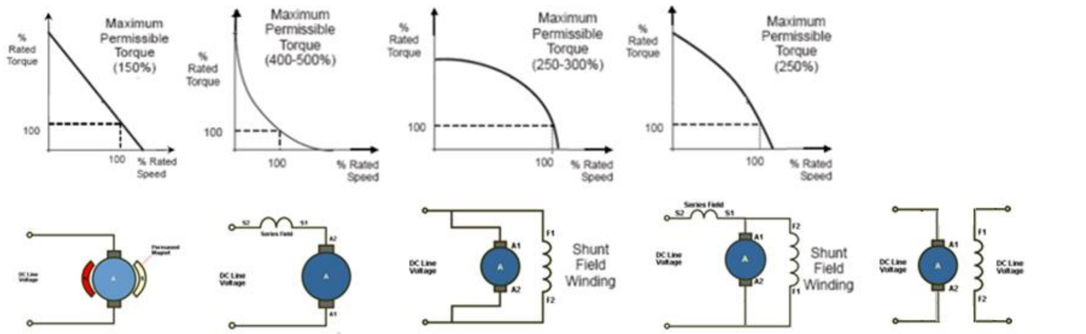
DC motors
Torque-speed curve



Permanent magnet DC motor | Series wound DC motor | Shunt (parallel) wound DC motor | Compound wound DC motor | Separately Excited DC motor (also referred as particular case of shunt)

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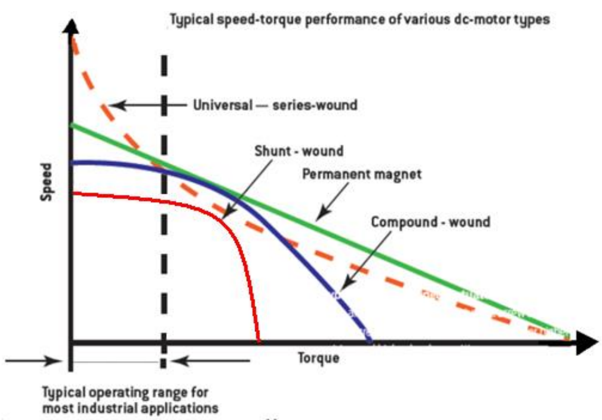
DC motors
Torque-speed curve comparison



https://www.designworldonline.com/a-new-look-at-an-old-motor/

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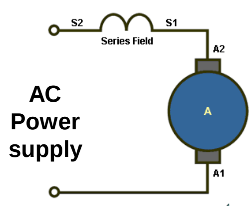
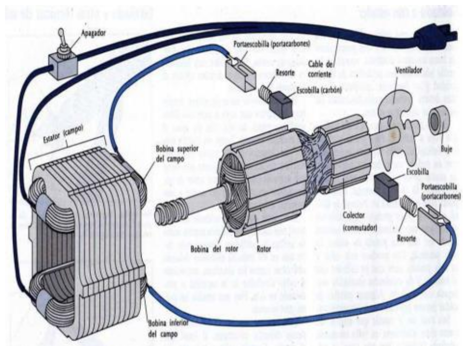
Universal Motor

- Similar to a series wound DC motor, but operating with an AC supply





http://maquinaseletricasi.blogspot.pt

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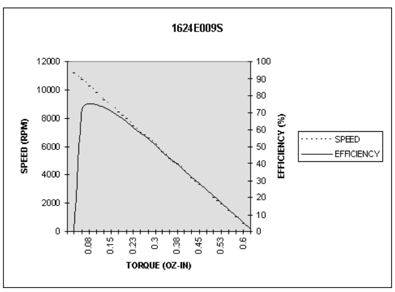
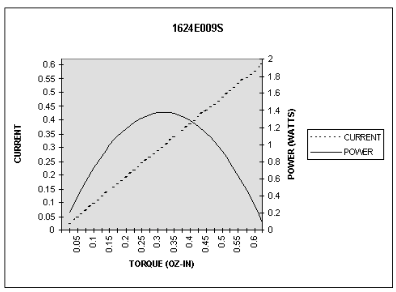
Permanent magnet DC motor

- Torque -speed and torque-current





http://www.micromo.com

- Power
  - P [W] = T [Nm] • w [rad/s]
  - P [W] = F [Nm] • v [m/s]

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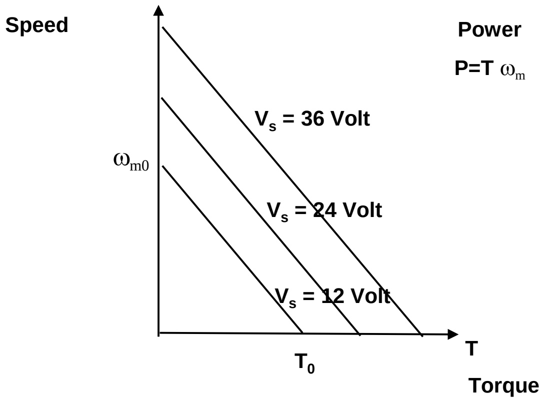
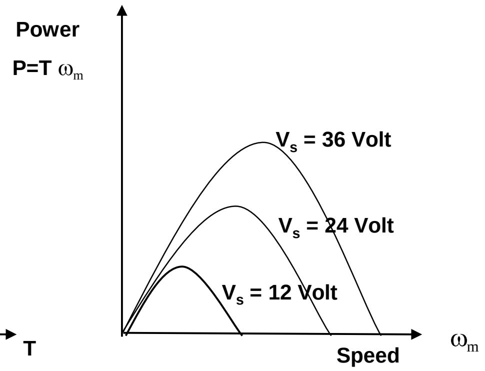
Permanent magnet DC motor

- Speed-Torque and Power-to-Speed Ratio





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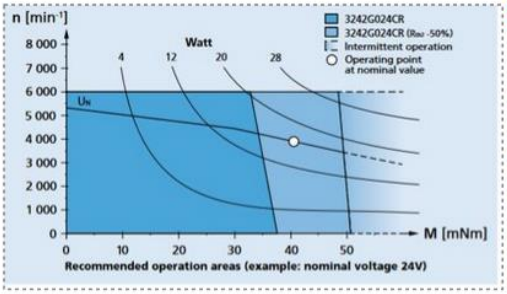
Permanent magnet DC motor

Permanent magnet DC motor

- Torque -speed curves
- Motor Series 3242 024CR

Faulhaber CR motors



Series 3242 ... CR

	Values at 22°C and nominal voltage	3242 G	024 CR
1	Nominal voltage	U_N	24
2	Terminal resistance	R	5
3	Efficiency, max.	$\eta_{max.}$	73
4	No-load speed	n_0	5 300
5	No-load current, typ. (with shaft ø 5 mm)	I_0	0,117
6	Stall torque	M_H	189
7	Friction torque	M_R	4,8
8	Speed constant	k_n	231
9	Back-EMF constant	k_E	4,33
10	Torque constant	k_M	41,3
11	Current constant	k_I	0,024
12	Slope of n-M curve	$\Delta n/\Delta M$	28
13	Rotor inductance	L	540
14	Mechanical time constant	τ_m	7,5
15	Rotor inertia	J	26
16	Angular acceleration	$\alpha_{max.}$	74

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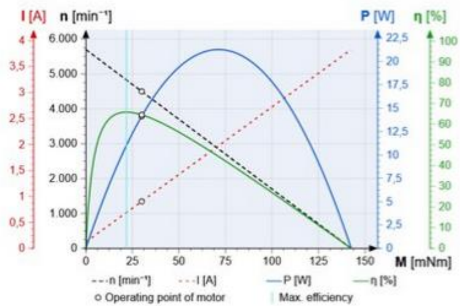
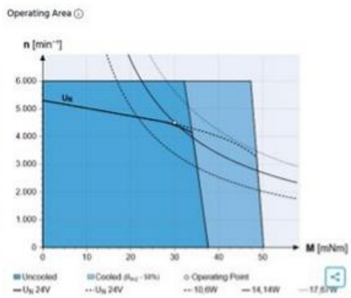
Permanent magnet DC motor

- Speed-torque and current-torque curves
- Motor Series 3242 024CR

Faulhaber CR motors





Example for load requirements:
30 mNm,
4500 rpm

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Permanent magnet DC motor

- Faulhaber CR motors
- Motor Series 3242 024CR

Possible compatible drivers from Faulhaber

- Motion controller Series MC 5005 S, V3.0, 4-Quadrant PWM, with RS232, CANopen or EtherCAT interface; supply voltage:12 ... 50 V DC. Max. continuous output current: 5 A. Max. peak output current: 15 A

- Speed controller, Series SC5004 P, 4-Quadrant PWM configurable via PC. Supply voltage:6 ... 50 V DC. Max. continuous output current: 4 A. Max. peak output current: 8 A

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Control Strategies for DC motors

Speed and torque can be controlled through three primary methods:

- **Armature Voltage Control** (V_a): most common; varies speed while keeping torque capability constant. Usually implemented via PWM (Pulse Width Modulation)
- **Field Cont**rol (Φ): reducing field current increases speed but reduces torque (Field Weakening)
- **Armature Resistance Control** (R_a): using external rheostats; inefficient and rarely used in modern systems
- **Speed-torque tradeoff**: involves adjusting the load on the motor to control the speed and torque (for example: increasing the load, decreases the speed but increases torque)

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Selection Criteria for Dc motors
Generic considerations

When specifying a motor from suppliers like ABB, Crouzet, or Maxon, consider:

- Duty Cycle: S1 (Continuous) vs. S3 (Intermittent)
- Thermal Limits: the motor's ability to dissipate heat generated by I_a^2 * R_a losses
- Dynamic Response: high torque-to-inertia ratio for rapid acceleration

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Selection Criteria for a permanent magnet DC motor

1. Thermal limitation: the motor must be able to dissipate the thermal power generated in the rotor winding $P_{thermal}$ [W]= I^2 [A] x R_a [W]

2. The current in the motor determines the torque produced I_a[A] = T [Nm] / K_T [Nm/A]

3. If the load torque is constant, the motor speed only depends on the supply voltage

4. Power is the product of speed and torque. Maximum power is obtained at the operating point which corresponds to half the no-load speed and half the torque ("stall torque"). Rarely does a motor operate at full power due to thermal limitations

5. Normally, a motor should run at 90% of "no-load speed" and at 10%-30% of "stall torque"

6. If it is necessary to use a reduction gear, the motor must be selected for the minimum operating speed, choosing a motor with an operating voltage higher than the supply voltage available for operation

7. Other factors to consider include motor size and weight, operating environment, mechanical loads, and service life

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Selection Criteria for a permanent magnet DC motor

Efficiency

- The maximum efficiency of a permanent magnet DC motor is typically achieved when the motor develops approximately 10% of its starting torque ("stall torque"). Thus, if a particular application requires very high efficiency, the motor must be selected with a starting torque 10 times the required operating torque

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Permanent magnet DC motor
Motor parameters

Common specifications
- Power (mechanical) [W]
- Nominal voltage [V]
- No-load speed [rpm]
- No-load current [A]
- Stall torque (torque @ 0 speed) [Nm]
- Friction torque [Nm]
- Speed constant [rpm/V]
- Back-EMF constant [V/rpm]
- Torque constant [Nm/A]
- Terminal resistance [ohm]
- Rotor inductance [mH]
- Efficiency [%]
- Maximum speed and current permissible
- Continuous maximum current

- Mechanical specifications
- Mechanical time constant [ms]
  The time required for the motor to reach a speed of 63% of its final no-load speed, from standstill
- Rotor inertia [Nm/s^2]
  - Thermal resistances [°C/W]
  - Rth1 corresponds to the thermal resistance between the winding and housing
  - Rth2 corresponds to the thermal resistance between the housing and the ambient air
- Thermal time constant
- Operating temperature range
- Maximum rotor temperature[°c]
- Shaft bearings / Shaft load max.
- Shaft diameter [mm]
- Shaft play (axial e radial) [mm]
- Motor weight[g]

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Permanent magnet DC motor

- Benefits
  - Relatively simple power electronics
  - Easy speed and torque control
  - Low complexity and cost driver
- Disadvantages
  - The collector is the weak point (wear requires replacement)
  - Poorly withstands currents above the rated current
  - Heating problems

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DC Motors

Use of DC motors

- Wide range of use and applications
  - Small motors: appliances, power tools, low-power applications
  - Medium-sized motors: pumps, fans, conveyors
  - Large power motors: cranes, industrial machines, electric traction

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DC Motors

Available large range of DC motors, from multiple vendors

- Permanent Magnet DC motors
  - DC micro-motors from Faulhaber (www.faulhaber.com), power 0.5 W/0.17mNm up to 160 W/224 mNm, supply voltage 1.5 V a 48V, dimensions ∅6 up to ∅ 38 mm, length 15 up to 90 mm, no load speed up to 20000 rpm
- Wounded DC motors
  - From WEG (www.weg.net), power up to 10,000 kW, supply voltage 100 up to 1000V, dimensions frame IEC 90 up to 1800
  - From Siemens Series SimoticDC (www.siemens.com), power from 30 kW up to 16,000kW, supply voltage up to 810 V, torque up to 44500Nm, speed up to 3600 rpm

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DC Motors

Suppliers of DC motors

- Small DC motors
  - Faulhaber: https://www.faulhaber.com/en/
  - Portescap: https://www.portescap.com/
  - Maxon: https://www.maxongroup.com/en

- Small-medium DC motors
  - Crouzet https://www.crouzet.com/products/dc-motors
  - ABB/Baldor https://www.baldor.com/brands/baldor-reliance/products/dc-motors/permanent-magnet

- Large DC motors
  - Simomotor https://www.simomotor.com.cn/dc-motor/
  - ABB https://www.baldor.com/brands/baldor-reliance/products/dc-motors/integral-hp-and-rpm-iii

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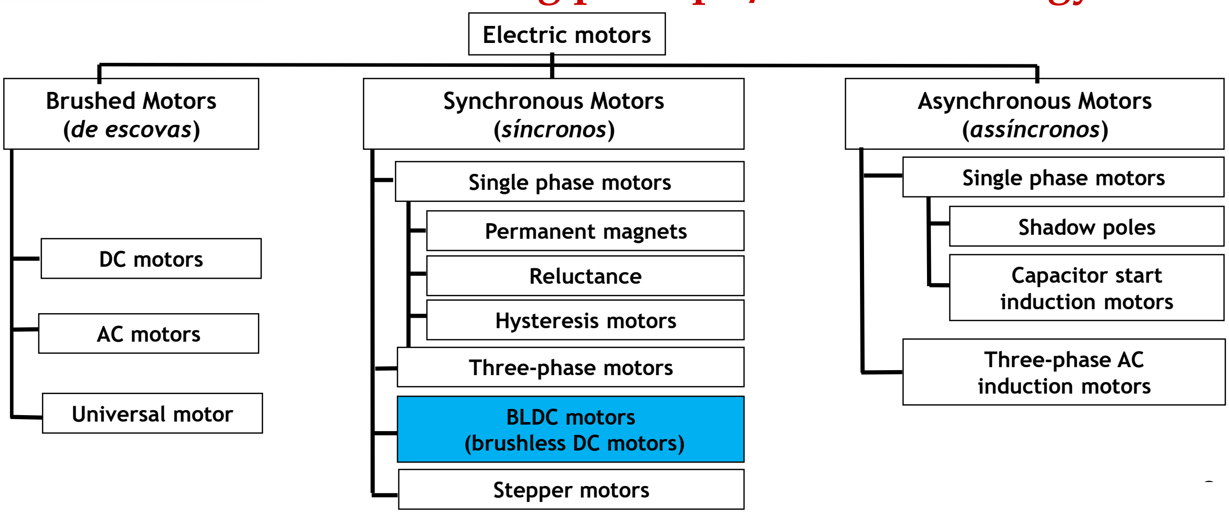
Electric Motors classification
Working principle/source of energy



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BLDC Motors

The Brushless DC (BLDC) motor is a Permanent Magnet Synchronous Motor (PMSM) designed to provide the performance characteristics of a conventional brushed DC motor but without the mechanical limitations of brushes and commutators

In a BLDC system, the traditional roles are reversed:

- **The Rotor:** contains permanent magnets (moving part)
- **The Stator:** contains the electromagnetic windings (stationary part)
- **Commutation:** performed electronically via an external or integrated **Driver**, rather than mechanically via brushes

BLDC Motors
Key Technical Features

Unlike brushed motors, BLDC motors require a dedicated electronic drive circuit to operate. Their primary advantages include:

- **Operational Longevity**: no brush wear or carbon dust accumulation
- **High Power Density**: compact size relative to torque output
- **High Efficiency**: lower thermal losses in the rotor and no voltage drop across brushes
- **Low Electromagnetic Interference** (EMI): n electrical arcing/sparks

BLDC Motors
Key Technical Features

- The BLDC motor needs a **Driver**
  - The Driver uses the rotor position signal to apply a voltage to the stator windings. This motor uses electronic commutation
  - The Driver can be external or, in particular cases, integrated into the motor
  - The rotor position detector can use a low resolution or high resolution devices
- The BLDC (brushless DC) motor combines characteristics of AC motors (brushless structure) and DC motors (current and voltage are respectively proportional to torque and rotating speed)
- The BLDC motor has a wide range of applications, from home appliances, computer fans, to automobiles

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BLDC Motors
The Principle of Electronic Commutation

The core challenge in a BLDC motor is knowing when to energize the stator coils to maintain continuous rotation. This is achieved through a closed-loop feedback system.

- Rotor Position Detection
  - To synchronize the stator's magnetic field with the rotor's position, the driver must receive feedback. This is typically achieved using:
    - **Hall Effect S**ensors: usually three sensors that detect the magnetic poles of the rotor*low resolution detection)
    - **High-Resolution Encoders**: used in advanced servo applications for precise position and velocity control
- Commutation

  The driver uses the rotor position data and translates to power the stator coils:
  - **Block Commutation**: the driver uses a six-step switching sequence (standard operation) to energize two out of the three phases at any given time
  - **Field-Oriented Control** (FOC): advanced drivers can use sinusoidal currents for smoother torque and higher efficiency

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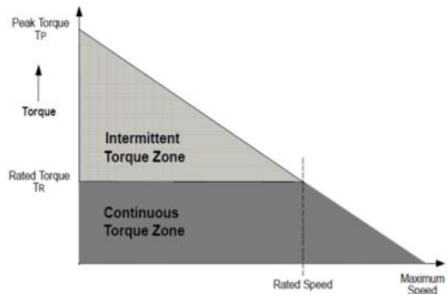
BLDC Motors
Torque-Speed Relationship

The **torque-speed curve** of a BLDC motor is remarkably similar to that of a permanent magnet brushed DC motor

- **Speed Control:** adjusted by varying the average DC voltage applied to the windings using **Pulse Width Modulation (PWM)**
- **Linearity:** the relationship between torque and current, and between speed and voltage, remains largely linear

Operating Zones

- **Continuous Torque Zone:** the range where the motor can operate indefinitely without overheating
- **Intermittent Torque Zone:** high-torque peaks allowed for short durations (e.g., during acceleration) limited by the thermal constraints of the windings



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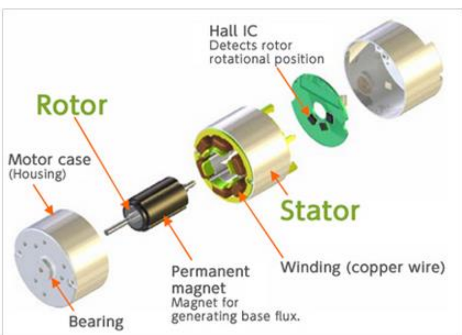
BLDC Motors
Inner rotor type

Inner rotor type (rotor inside the stator)



Advantages
- Rotor with a small moment of inertia
- High dynamic response
- High heat dissipation, as the coils are located on the outside

Disadvantages
- Reduced output torque
- Magnets can be damaged by centrifugal force

https://www.nidec.com/en/technology/capability/brushless/

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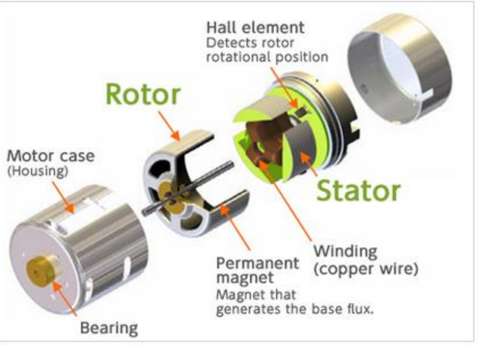
BLDC Motors
Outer rotor type

Outer rotor type (rotor outside the stator)



Advantages
- easy to achieve high torque
- easy to achieve a stable speed
- Easy to create a structural base with the stator coil (coil directly installed on the printed circuit board)

Disadvantages
- the rotor is large (higher moment of inertia)

https://www.nidec.com/en/technology/capability/brushless/

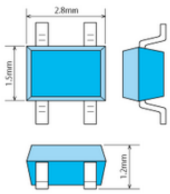
BLDC Motors

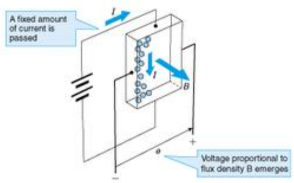
Maxon BLDC motor in 3D and AR

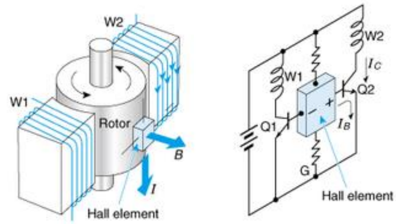
Maxon link

BLDC Motors

Detection of rotor position: use of Hall sensors







(a) Hall element placed near side surface of the rotor. (b) Hall element connected to winding.

Simplest principle of switching the current that flows through a brushless motor by the use of a Hall sensor and transistors

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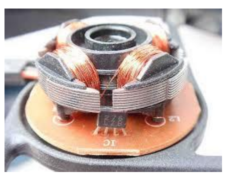
BLDC Motors

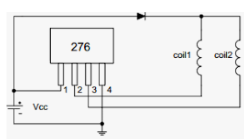
- Example of a BLDC motor used in a computer fan



Dc motor 12 V, 0.24 A

BLDC Motor

- **Rotor** mounted in the exterior of the stator (rotor: permanent magnet)
- **Stator** with 2 windings (two pairs of poles)
- **Integrated driver**: AH266IC with Hall sensor and transistor driver for block commutation of stator windings



- Video: https://www.youtube.com/watch?v=bCEiOnuODac

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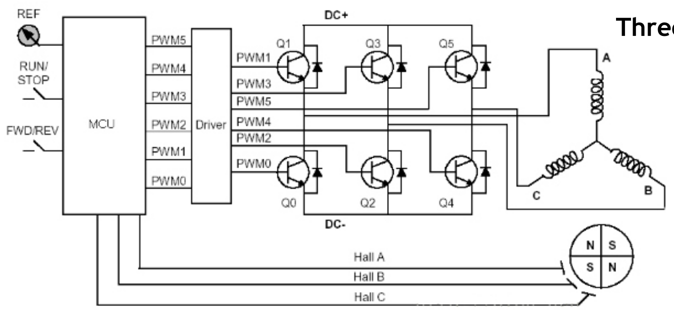
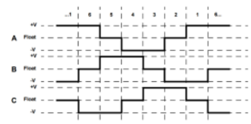
BLDC Motors
Block Commutation

- BLDC motor drive circuit



Three phase motor



Video maxon

https://www.bldcmotor.org/brushless-dc-motor-drive-circuit.html

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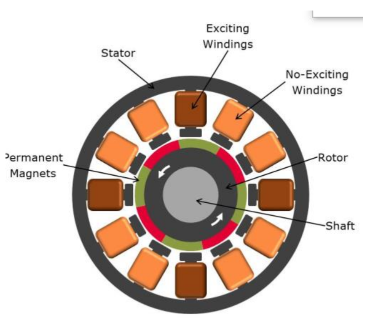
BLDC motors

- Some BLDC motors can be fitted with high-resolution rotor position detectors (encoders) and, with sophisticated drivers, with field-oriented control (FOC), enabling torque, velocity, and position control. This type of control is similar to the one used with servomotors



Inner rotor / outer stator BLDC motor schematic (position detector not shown)

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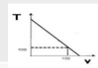
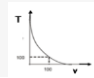
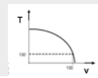
Motor comparison

Designation	Power source	Stator	Rotor	Other key components	Driver	Type of commutation	Torque/speed curve
Permanent magnet DC motor	DC	Permanent magnet	Wounded	Commutator and brushes	Direct on line starter or use of PWM driver	Mechanical	
Universal motor/ DC serial motor	AC single phase or DC	Wounded	Wounded	Commutator and brushes	Direct on line starter or use of PWM driver	Mechanical	
DC shunt motor	DC	Wounded	Wounded	Commutator and brushes	Direct on line starter or use of PWM driver	Mechanical	
BLDC motor (brushless)	DC	Coil	Permanent magnet	Detection of rotor position (low resolution)	Need a driver (can be embedded with the motor)	Electronic	

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