Design of Electric Motors

Sakthivadivel.D, Bosch

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Design of Electric Motors
Contents

Electric Motors - Basics
Electromagnetic basics

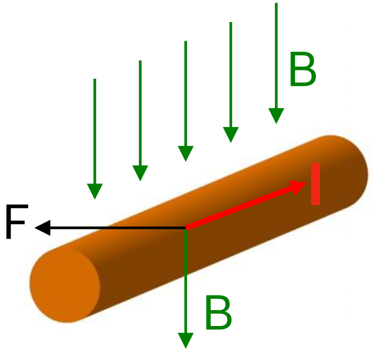
Lorenz Force

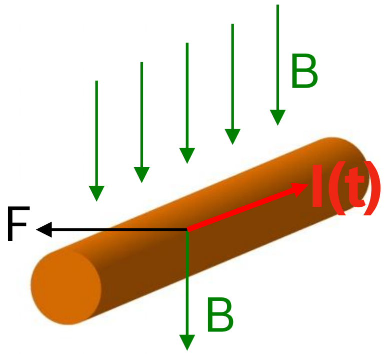
➔ Force acting on a current-carrying conductor in a magnetic field (" Lorentz force ")

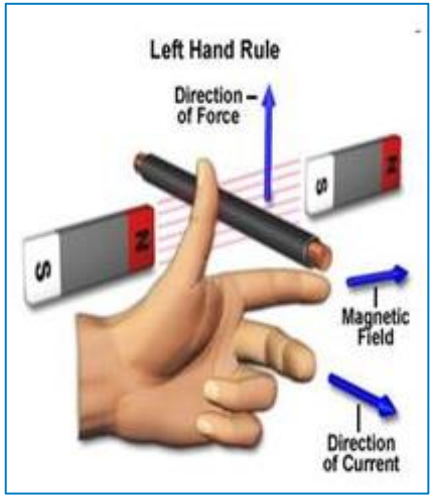
Force $F = B \times \mathbf{I}$

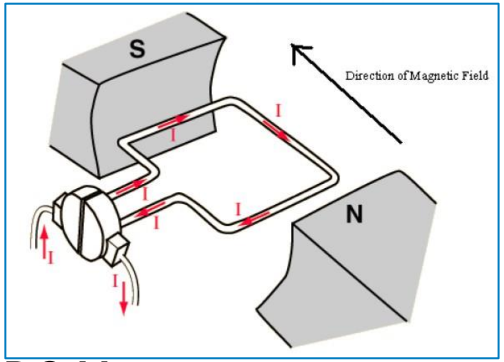
B…Magnetic Flux density and

$\mathbf{I}$…Current

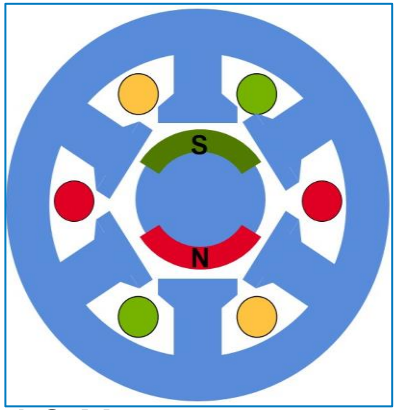








DC Motor



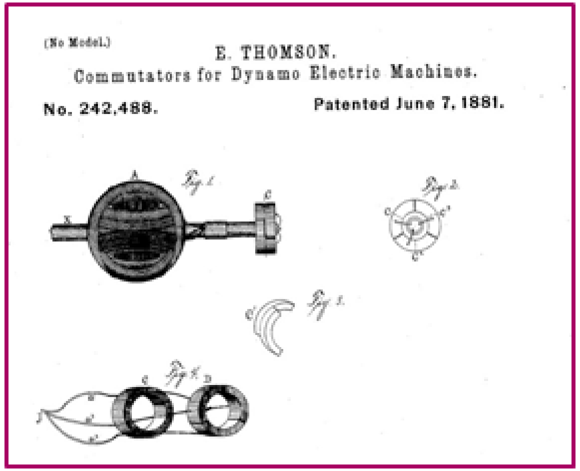
AC Motor

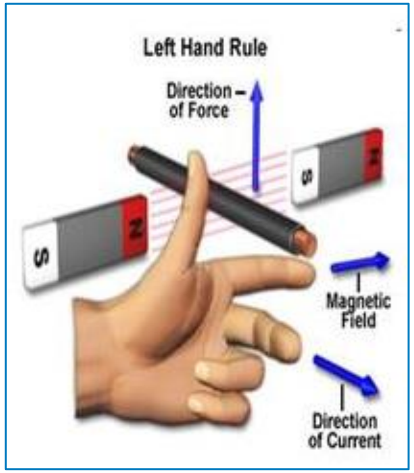
Electric Motors - Basics

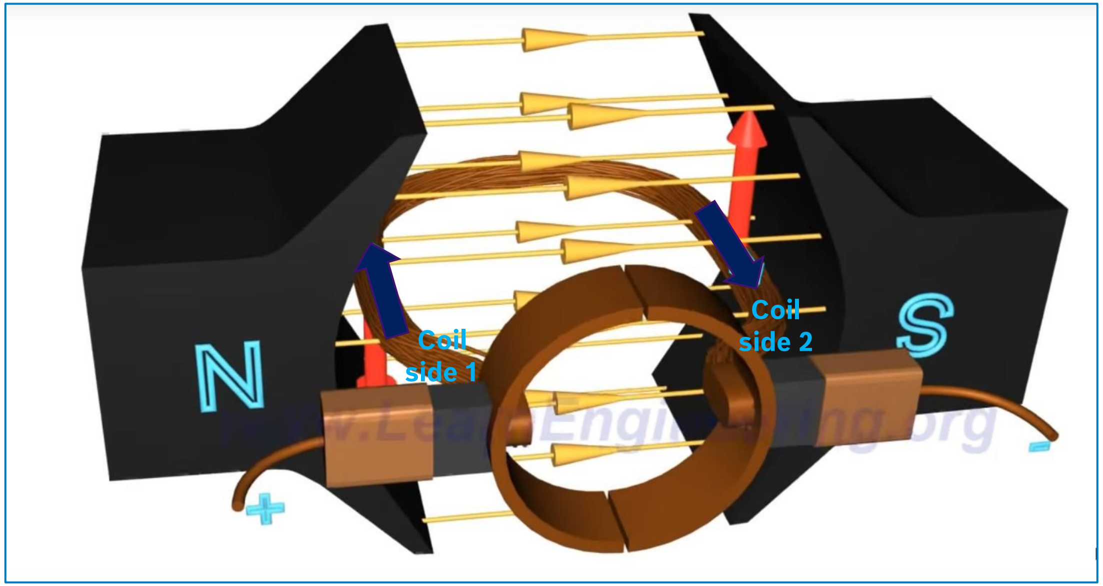
Electromagnetic basics

Commutation

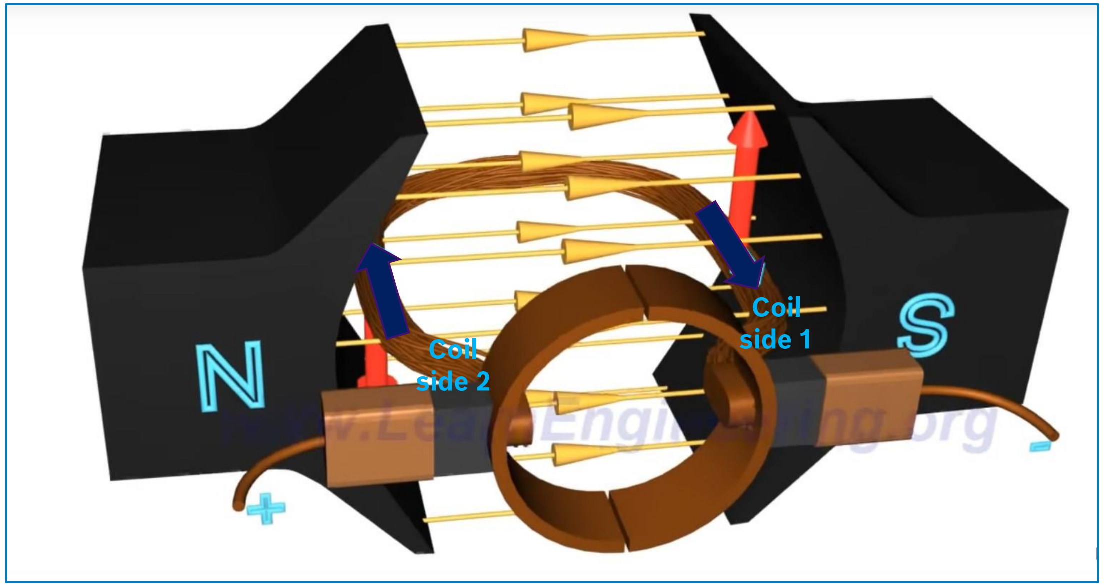
DC Motor







Intial Position



After one rotation of coil

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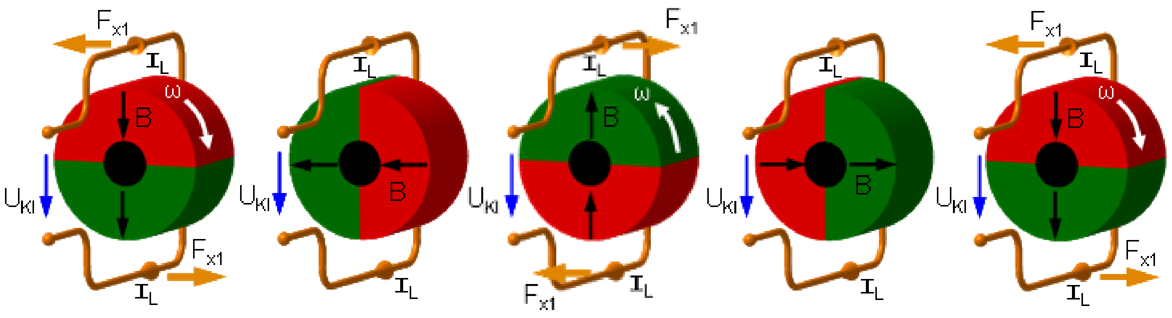
Electric Motors - Basics
Electromagnetic basics
Commutation

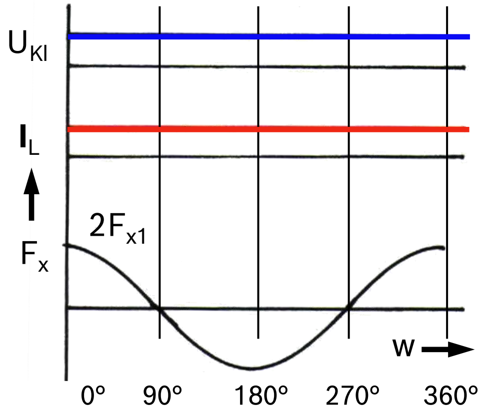
➔ Force action 2-pole - 1-phase machine "

AC Motor

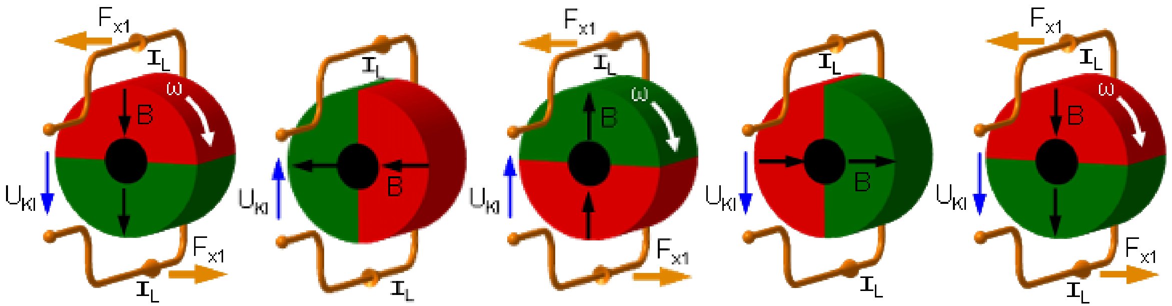


w = 0° 90° 180° 270° 360°

Current direction I_L = constant

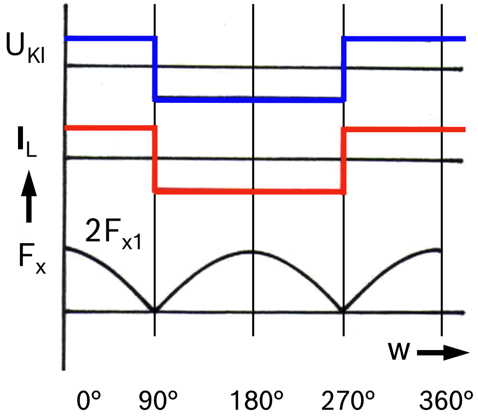


max. Sums force 2 F_{x1}



w = 0° 90° 180° 270° 360°

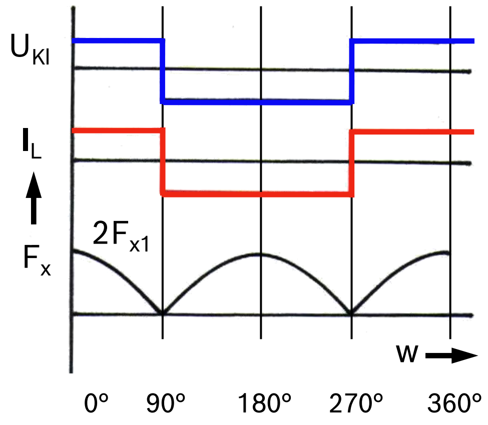
Current direction I_L adjusted = rotor position



Electric Motors - Basics
Electromagnetic basics
Commutation

→ Object of the commutation

It provides right switching of currents across phases in order to rotate the motor.



→ Types of commuatation

Mechanical Commutation
DC motor

Electronic Commutation
EC-Motor (PMSM/BLDC)

Commutator and brushes / accessories

The electromagnetic circuit
Iron / copper / Magnet

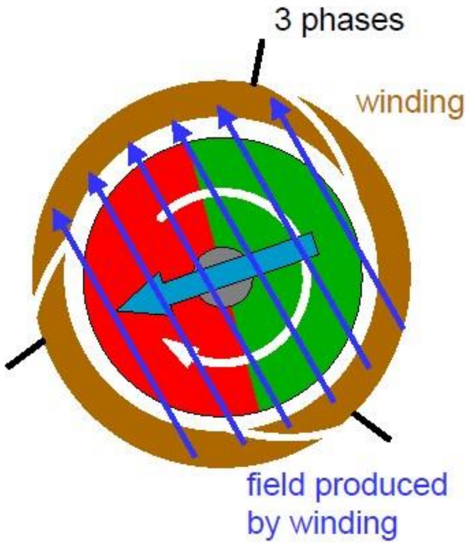
Electronic Switches / Accessories

Concept related differences

Electric Motors - Basics
Electromagnetic basics

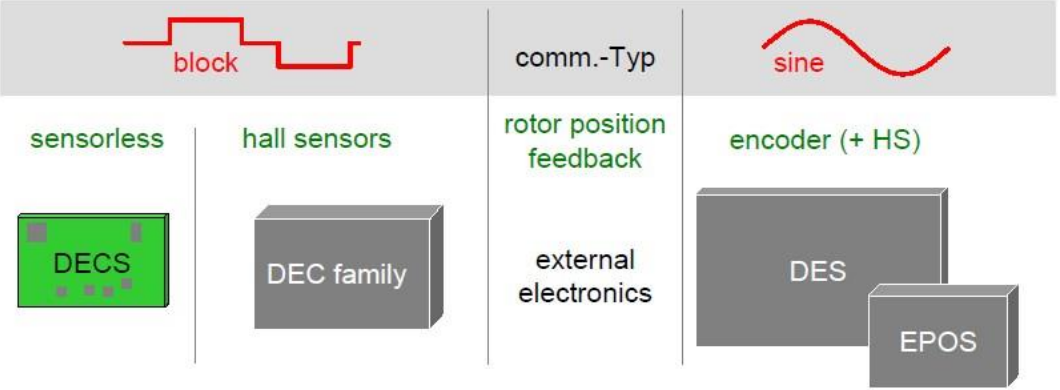
Interaction of rotor and stator

- current distribution in phases
  - 3 phases
  - 6 possible current distributions
  - 6 winding magnetic field directions rotated by 60°
  - commutation every 60°



Electronic commutations systems

- common goal: Applying the current to get the maximum torque
- perpendicular magnetic field orientation of
  - rotor (permanent magnet)
  - and stator (winding)
- knowledge of rotor position with respect to winding



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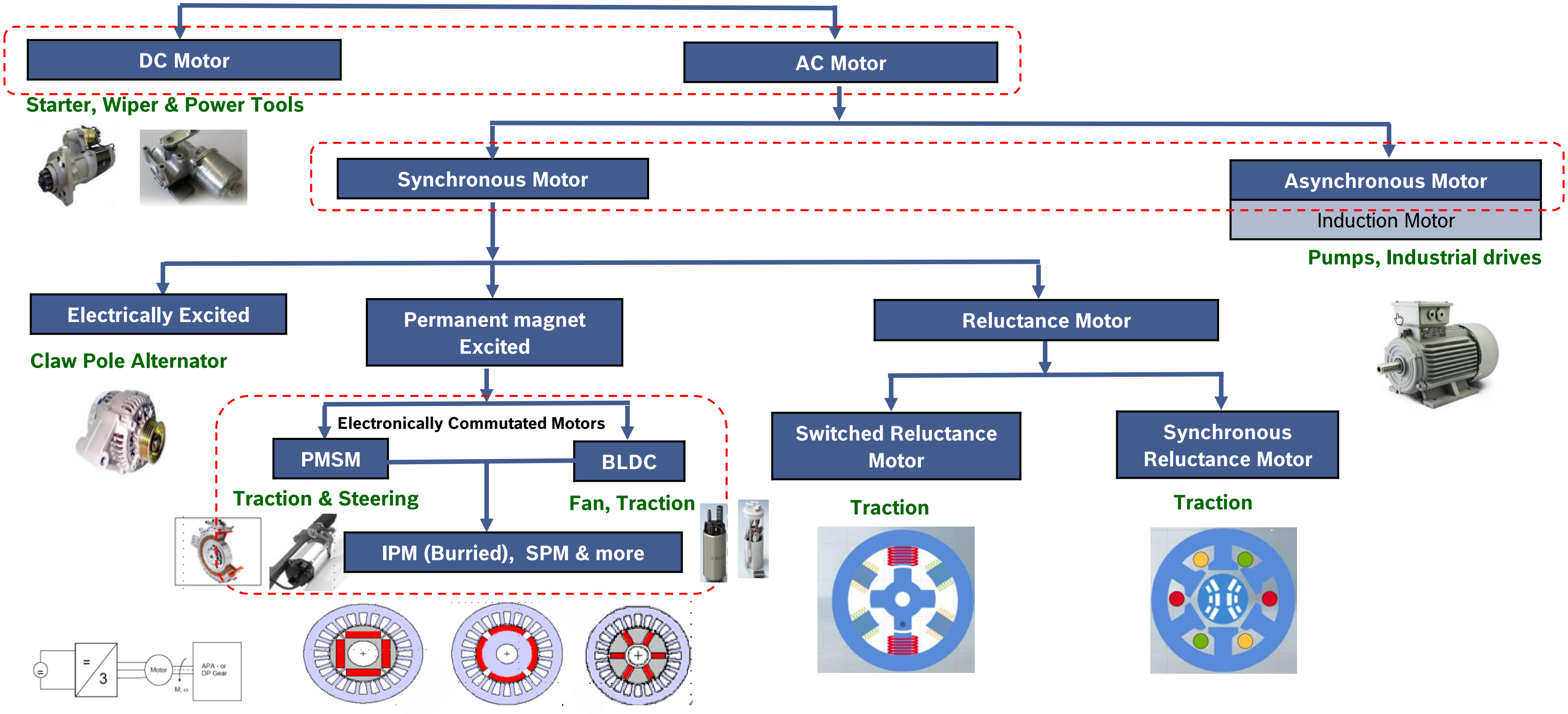
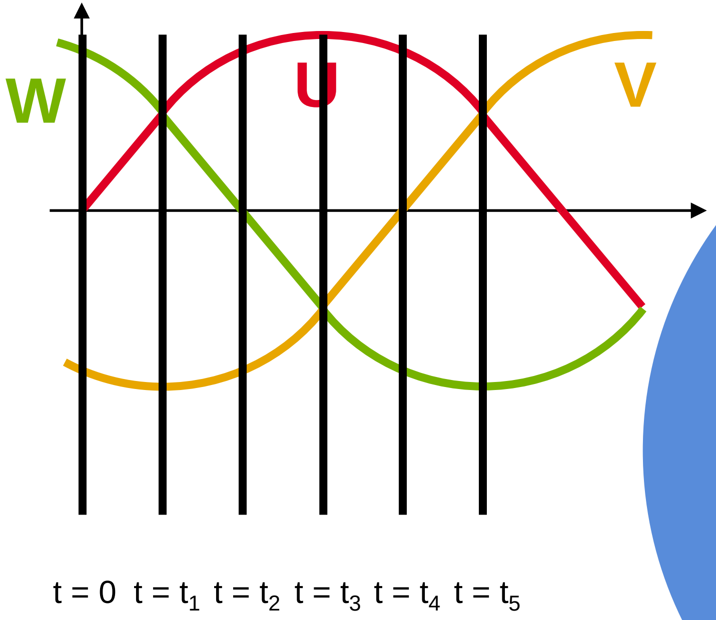
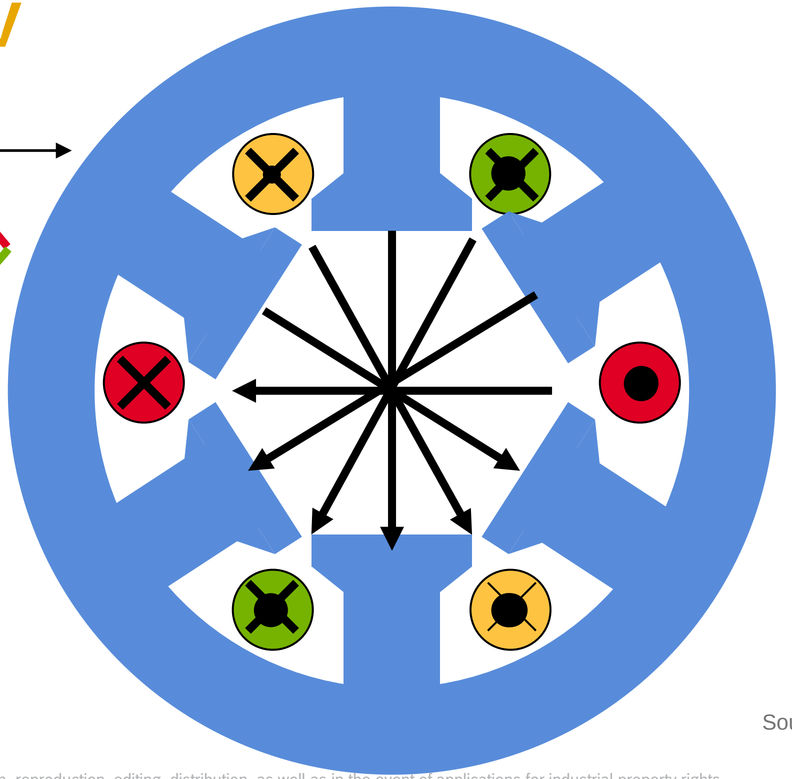
Electric Motors - Basics
Motors Overview



Electric Motors - Basics
Permanent Magnet Excited Synchronous Machine (PMSM)

➔ Three phase windings are shifted spatially by 120° and fed by three temporally shifted (120°) phase currents.



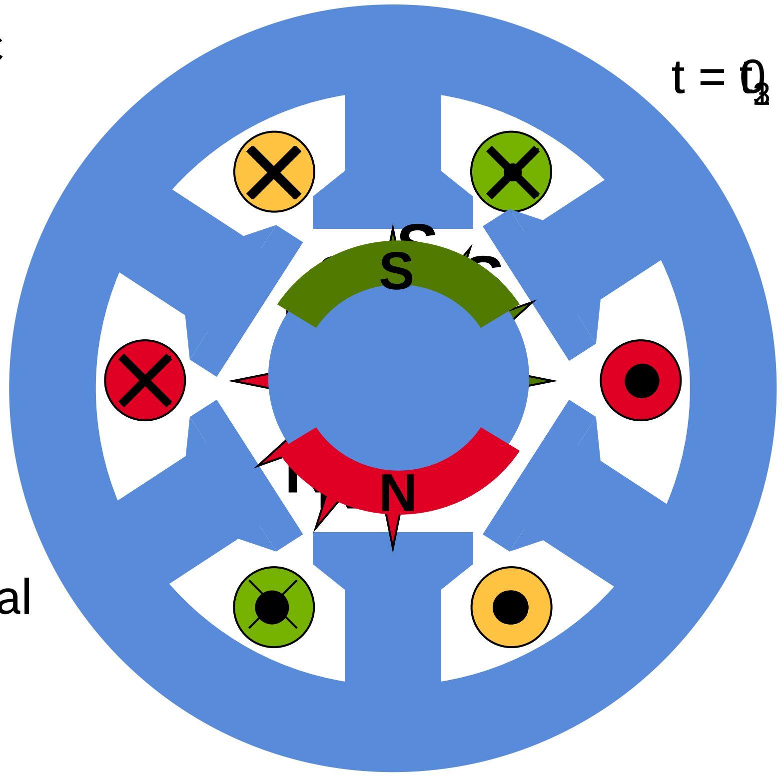


Rotating Stator Field

Source: CR/ARE3-Rt

Electric Motors - Basics
Permanent Magnet Excited Synchronous Machine (PMSM)

- Thought experiment: magnetic needle located in the stator
- Magnetic needle will align with magnetic field
- When magnetic field moves, magnetic needle will move along



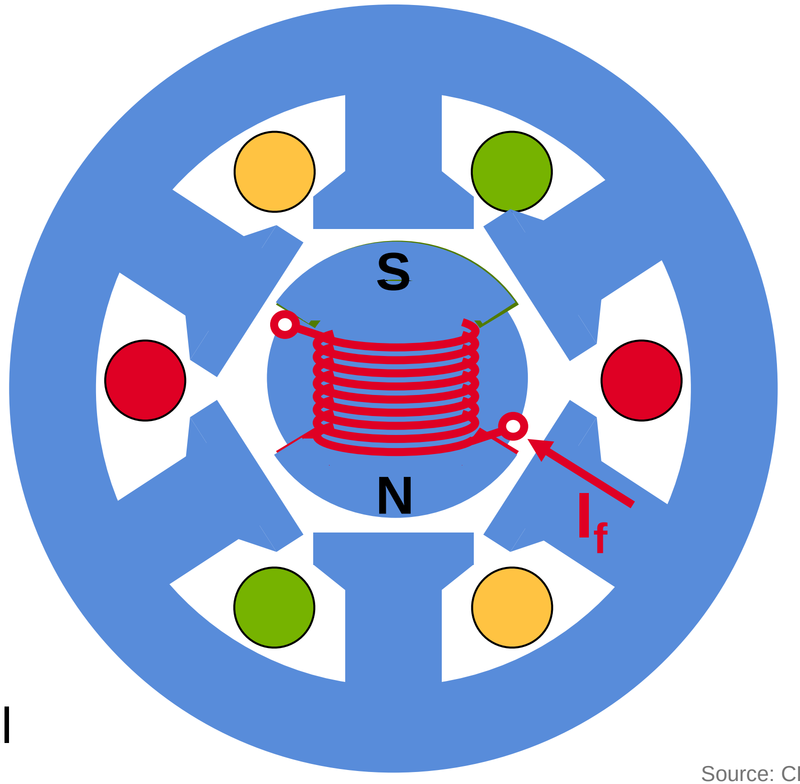
→ Real machines have rotor with permanent magnets instead of magnetic needle

→ Control unit needs rotor position signal for torque control

Source: CR/ARE3-Rt

Electric Motors - Basics
Electrically Excited Synchronous Machine (ESM)

- Permanent magnet replaced by electromagnet
- Same functional principle as PSM

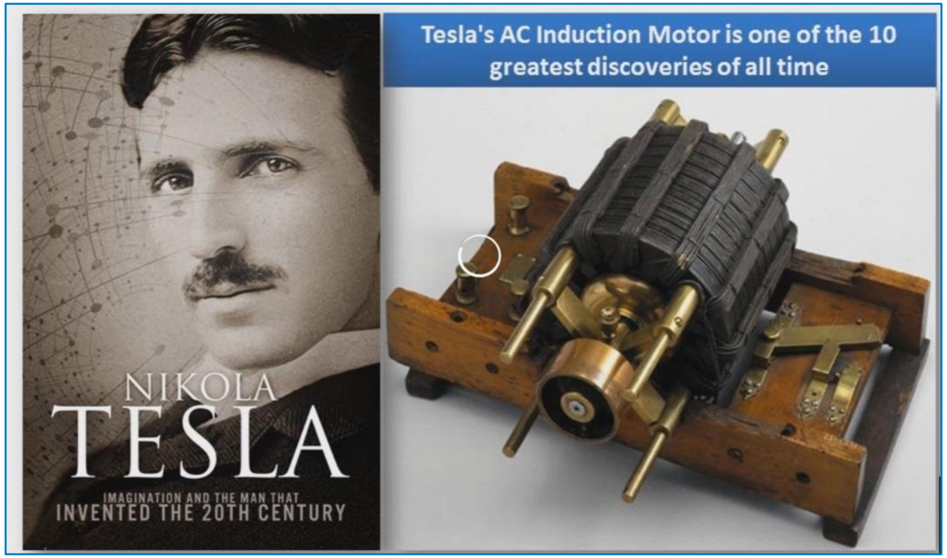


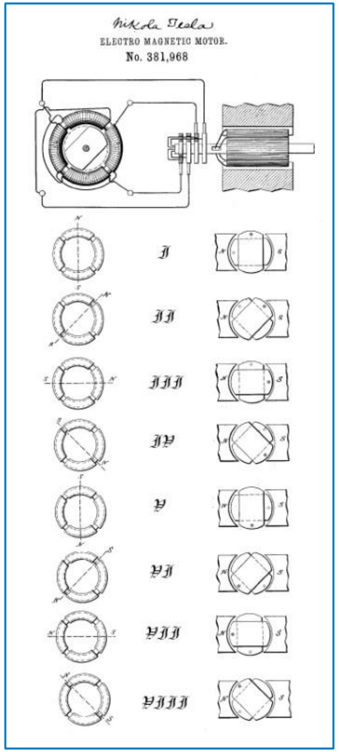
Source: CR/ARE3-Rt

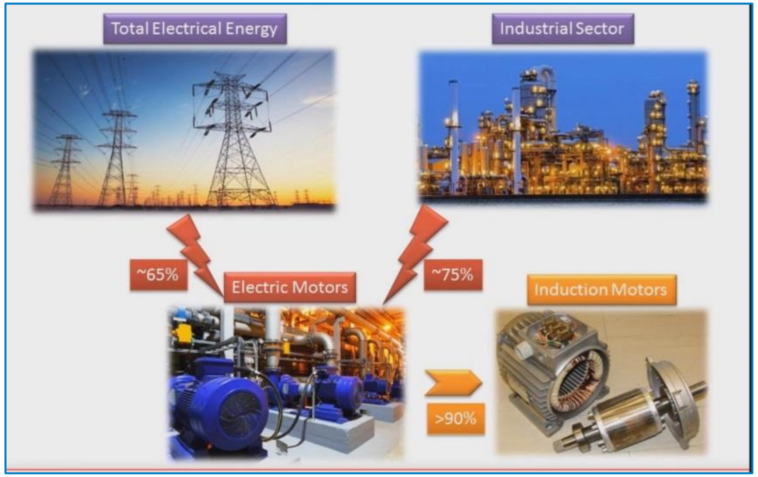
- Advantage:
  - Rotor magnet field can be controlled by field excitation current I_f
- Challenge:
  - Feed rotating rotor winding with DC-current
- Control unit needs rotor position signal for torque control

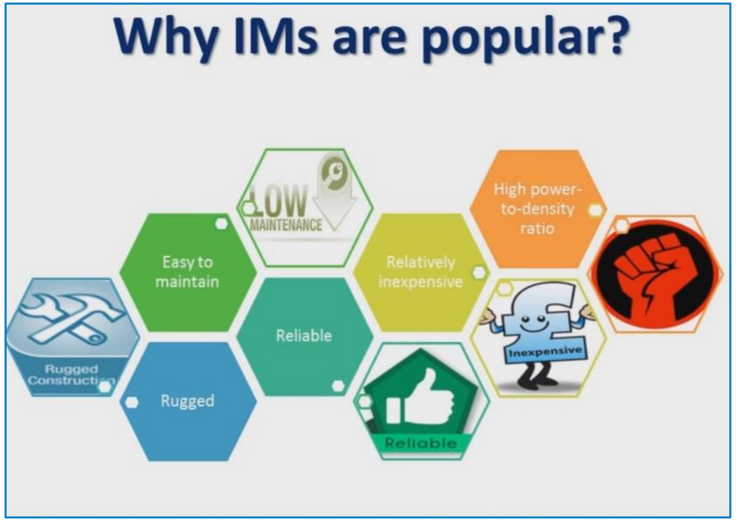
Electric Motors - Basics
Induction / Asynchronous Machine

Which Motor Type is Used Everywhere?









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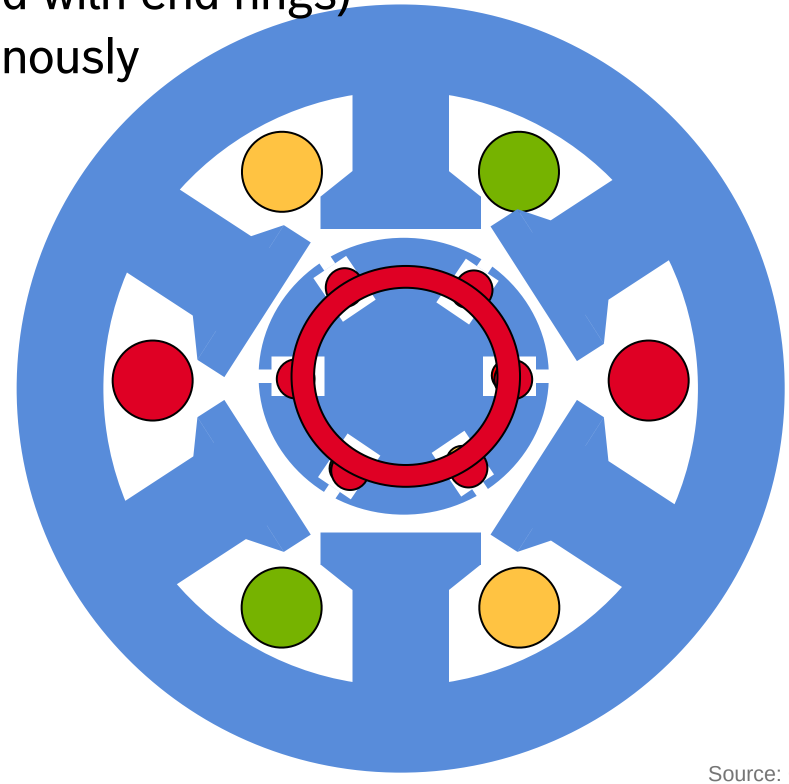
Electric Motors - Basics
Induction / Asynchronous Machine

- Rotor contains multi-phase-winding or…

➔ …cage (slots with bars, short circuited with end rings)
➔ If rotor and stator field rotate synchronously
$\rightarrow$ No induced voltage
$\rightarrow$ No rotor current
$\rightarrow$ No torque

➔ Rotor cage and stator field need slip (speed difference) to generate torque. → „Asynchronous machine“



Source: CR/ARE3-Rt

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Electric Motors - Basics
Electromagnetic basics
Traction Motor Types

What is the type of motor used in Tesla Model 3?

Tesla Model 3 Motor — Everything I've Been Able To Learn About It (Welcome To The Machine)

Twitter | LinkedIn | Facebook

March 11th, 2018 by Steve Bakker

to know why. What's going on? What motor did the company use instead? But Tesla's not talkin'. OK, they're talking a little bit. We were warned of upcoming changes back in 2015 when Tesla's Chief Technology Officer, J.B. Straubel, informed us that the Model 3 would come with "*a new motor technology*." We also got tipped off in late 2017 when an EPA document surfaced indicating that the Model 3 was using … a permanent magnet motor. Double wow. This was confirmed earlier this year when an article in *Charged* quoted Tesla's Chief Motor Designer, Konstantinos Laskaris, characterizing the new motor like this: "So, as you know, our Model 3 has a permanent magnet machine now. This is because for the

best of my knowledge hasn't been explained publicly before. The guy seems to really know his stuff. I engaged Ingineerix in the video's comments section, where he revealed that the car has a "Switched Reluctance motor, using permanent magnets." Ingineerix went on to say, "Tesla calls it a PMSRM, Permanent Magnet Switched Reluctance Motor. It's a new type, and very hard to get right, but Tesla did it!"

MOTOR	
Variant	P2
Construction	3 Phase AC Induction Motors
Power	19kW @ 3500 r/min
Torque	70Nm @ 1050 r/min
Controller	600 Amp

TESLA Roadster (USA)

TECHNISCHE UNIVERSITÄT DARMSTADT

- Lithium-ion-battery:
  6381 cells = 11 series modules
  1 module = 9 series component
  1 component = 69 parallel cells
- Max. torque 271 Nm
- Max. power 185 kW
- Sports vehicle
- 1.2 tons empty weight
- 0 … 100 km/h in 4 seconds
- max. 200 km/h (125 mph)
- max. motor speed: 13000/min
- Squirrel cage induction machine
- Price: 110.000 USD

- Range: 392 km in combined EPA-test cycle with 45 kWh battery energy
- 3.5 h charging time
- Lifespan 500 cycles: 500 x 392 = 200000 km

Tesla Roadster (Source: http://www.teslamotors.com/)

Lightning GT (UK)

TECHNISCHE UNIVERSITÄT DARMSTADT

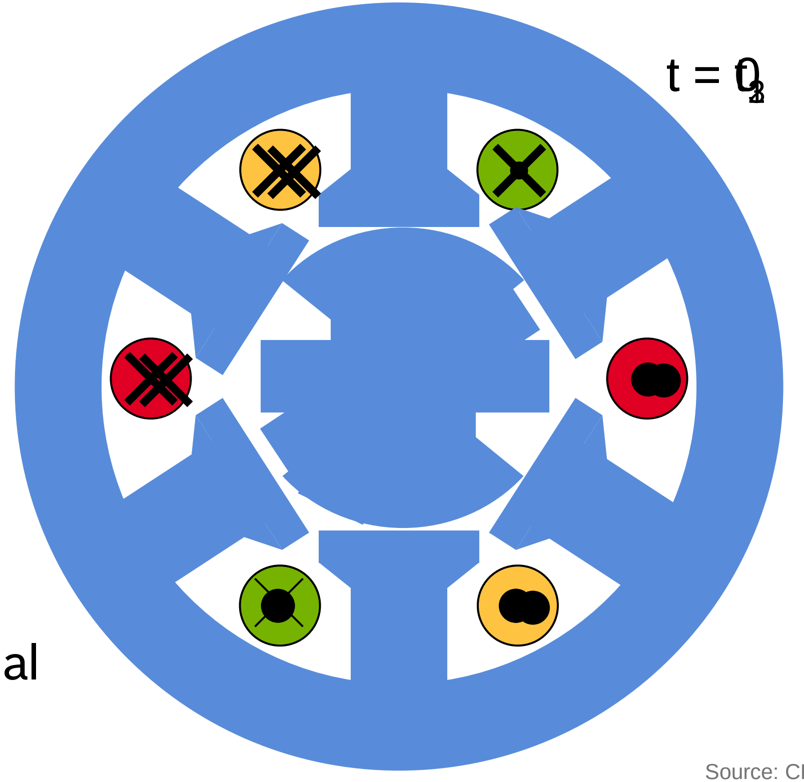
- Lithium-ion-batteries: (*AltairNano*: „NanoSafe“)
  Nano-titanat-technology instead of graphite
- Max. power 552 kW
- Sports vehicle
- Carbon fiber-Kevlar-composite chassis
- 0 … 100 km/h in 4 seconds
- Max. 210 km/h
- 4 PM-synchronous motors as brushless-DC hub motors (P_N = 120 kW each Motor),

- Range: 415 km with fully charged battery
- 10 min. quick-charge: 155 km range
- Lifespan: after 15000 cycles: 85% of new-capacity

MOTOR	
Variant	C2
Construction	3 Phase AC Induction motor
Power (kW)	31 kW (41 HP) @ 4000 r/min
Torque (Nm)	91 Nm @ 3000 r/min
Controller	550 A

Electric Motors - Basics
Reluctance Machine (RM)

- A magnetic steel bar inserted in the stator follows the rotating stator field.
- „Magnetic conductivity“ (permeance) of the bar differs in d- and q-axis

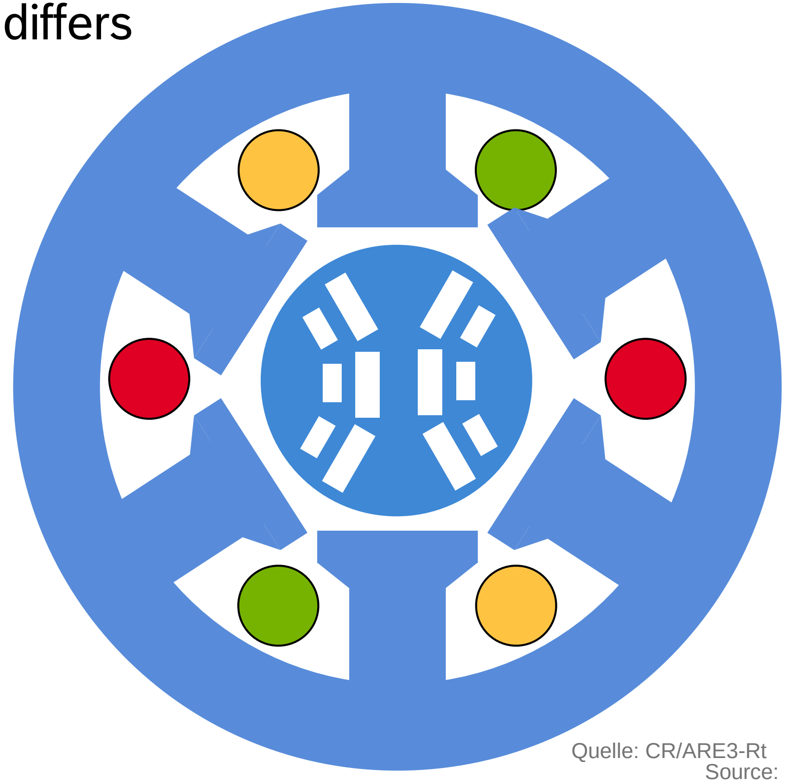


➔ Real shape of a reluctance rotor
➔ Control unit needs rotor position signal for torque control

Source: CR/ARE3-Rt

Electric Motors - Basics
Synchronous Reluctance Machine (SynRM)

- Special type of reluctance machine
- Cylindric rotor with air gaps
- “Magnetic conductivity“ (permeance) differs in d- and q-axis
- Stator winding fed with sinusoidal currents



Quelle: CR/ARE3-Rt
Source: CR/ARE3-Rt

- Advantage:
  - Simple rotor design
- Challenges:
  - Mechanical speed strength
  - Torque & power density

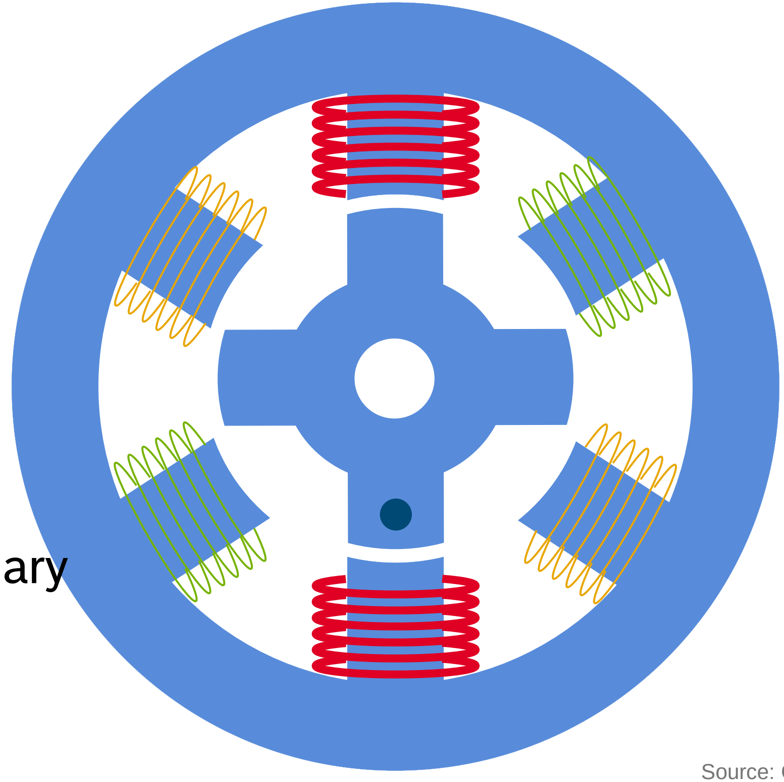
Electric Motors - Basics
Switched Reluctance Machine (SRM)

- Special type of reluctance machine

➔ Coil currents switched on and off according to spatial shift
→ Rotating field

➔ Advantage:
  - ➔ Simple design

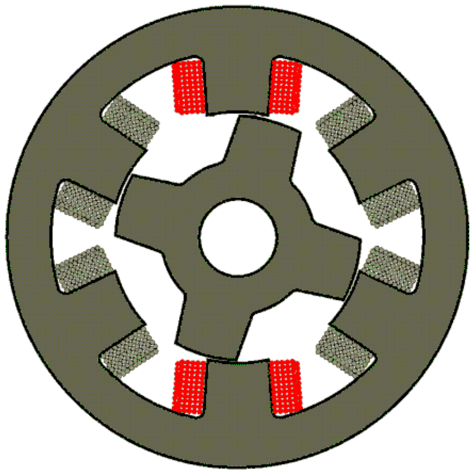
➔ Challenges:
  - ➔ Noise generation
  - ➔ Special power electronics necessary

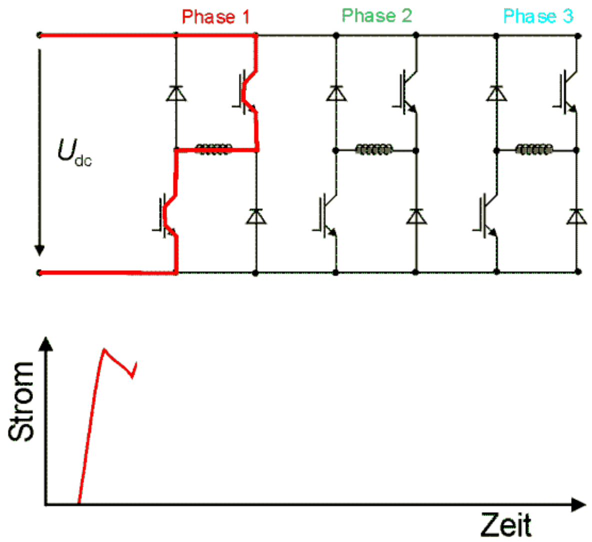


Source: CR/ARE3-Rt

Electric Motors - Basics
Switched Reluctance Machine (SRM)

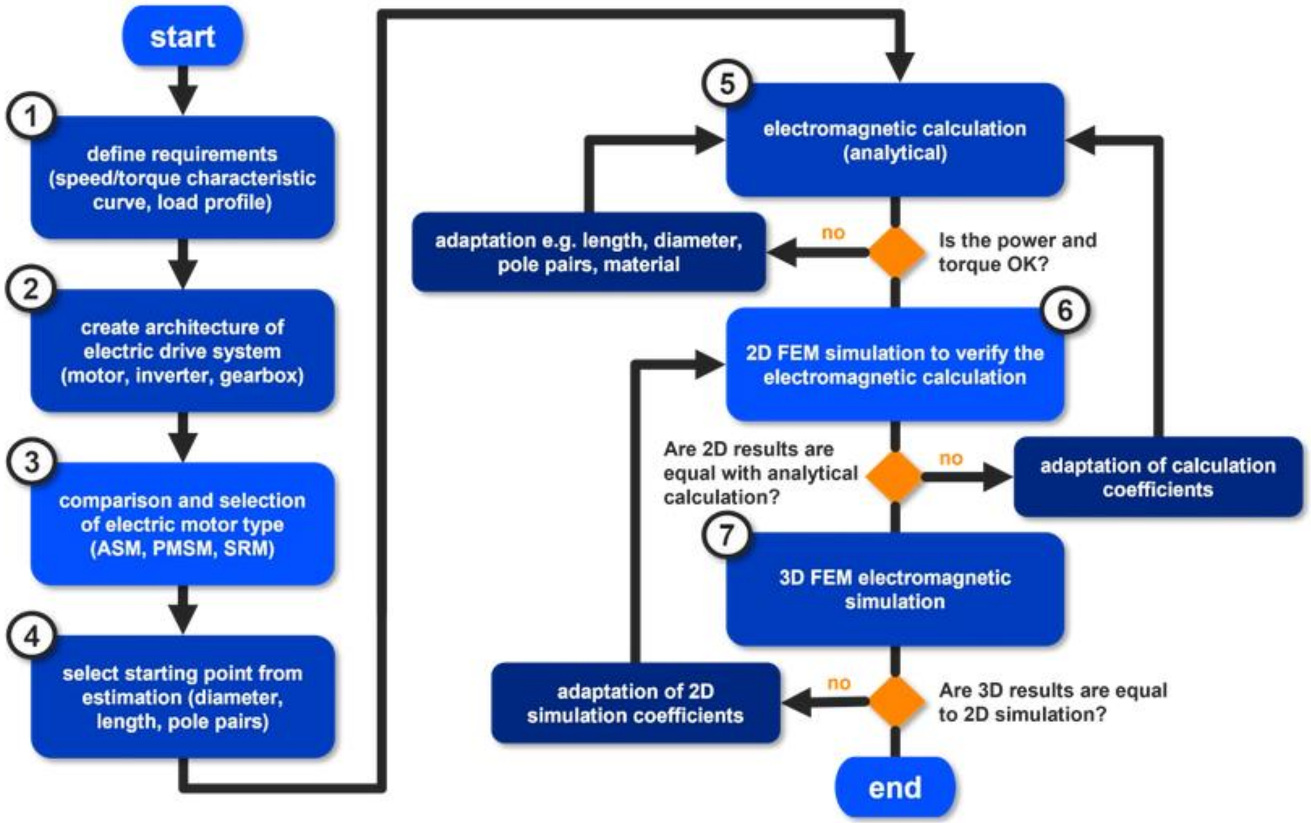
- Special power electronics necessary





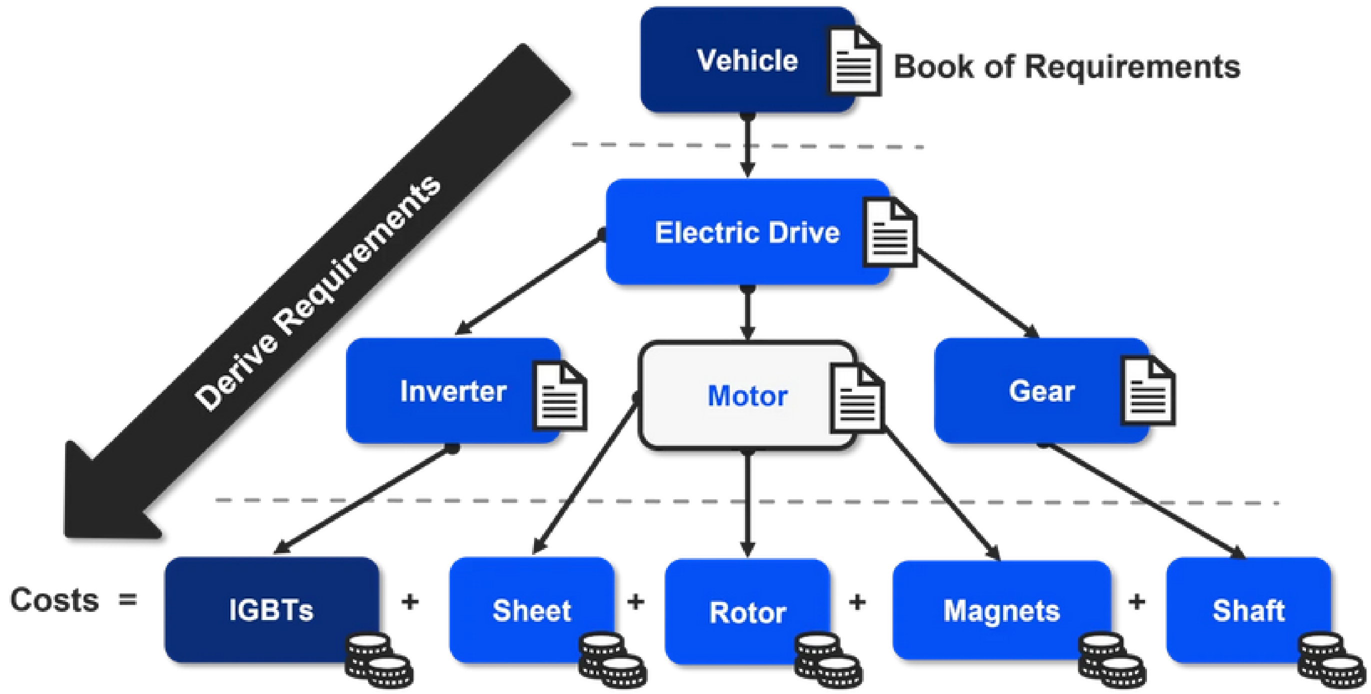
Source: CR/ARE3-Rt

Design of Electric Motors
Design Process



electric motor design and development process

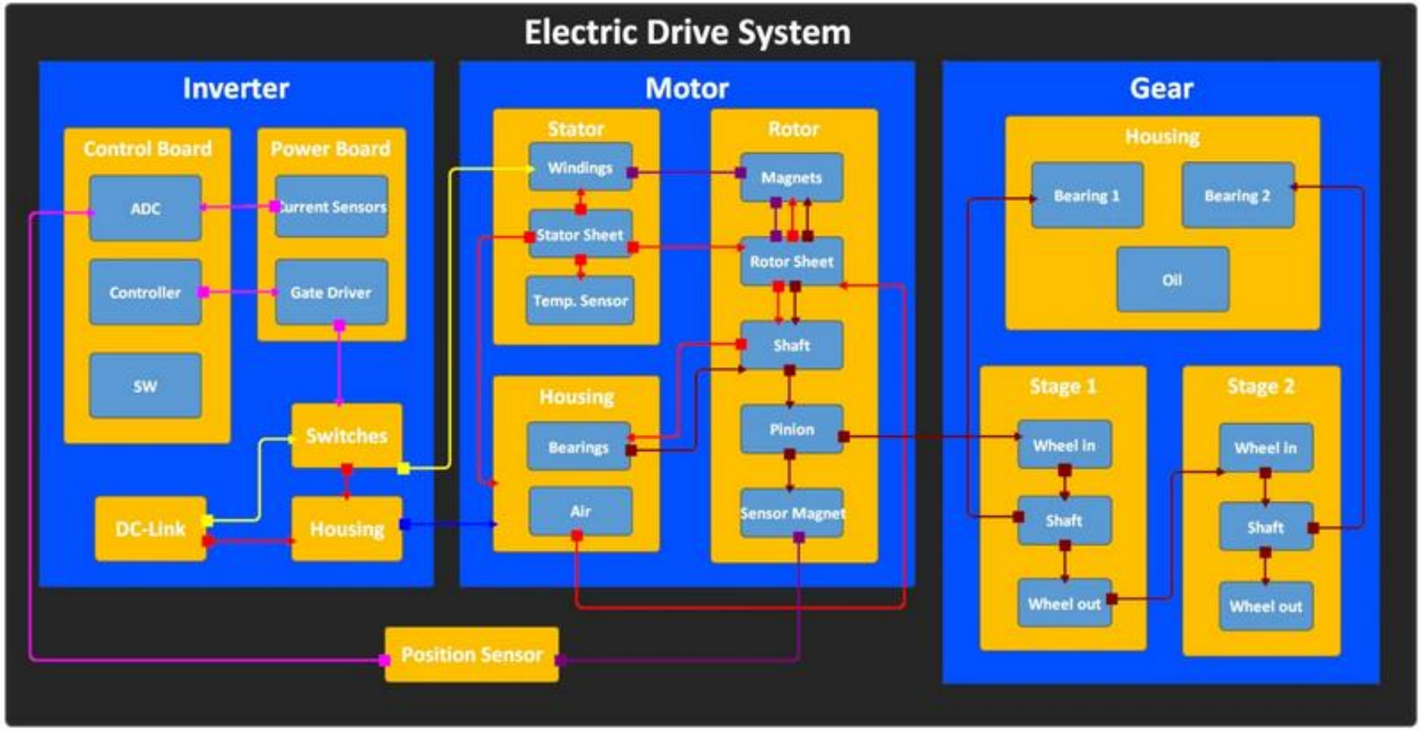
Design of Electric Motors
Defining Requirements



derive electric motor requirements

Main Requirements:
Torque and speed
Peak & Continuous power
Efficiency
Cost
NVH
Dimension Constraints (if any)
Outer Diameter
Stack Length

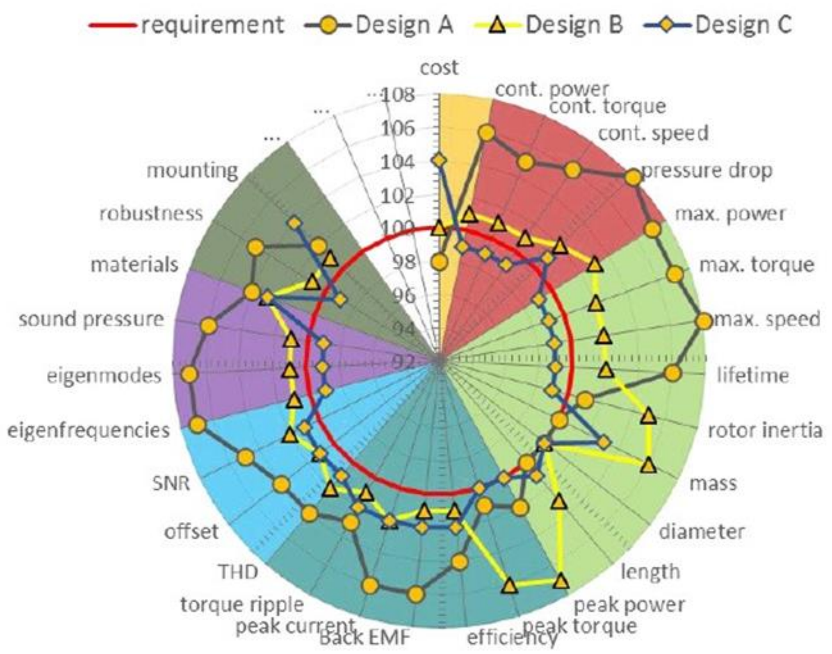
Design of Electric Motors
Defining System (Electrical Drive) Architecture



architecture of electric motor drive system

Design of Electric Motors
Selection of Electric Motor Type and Comparison

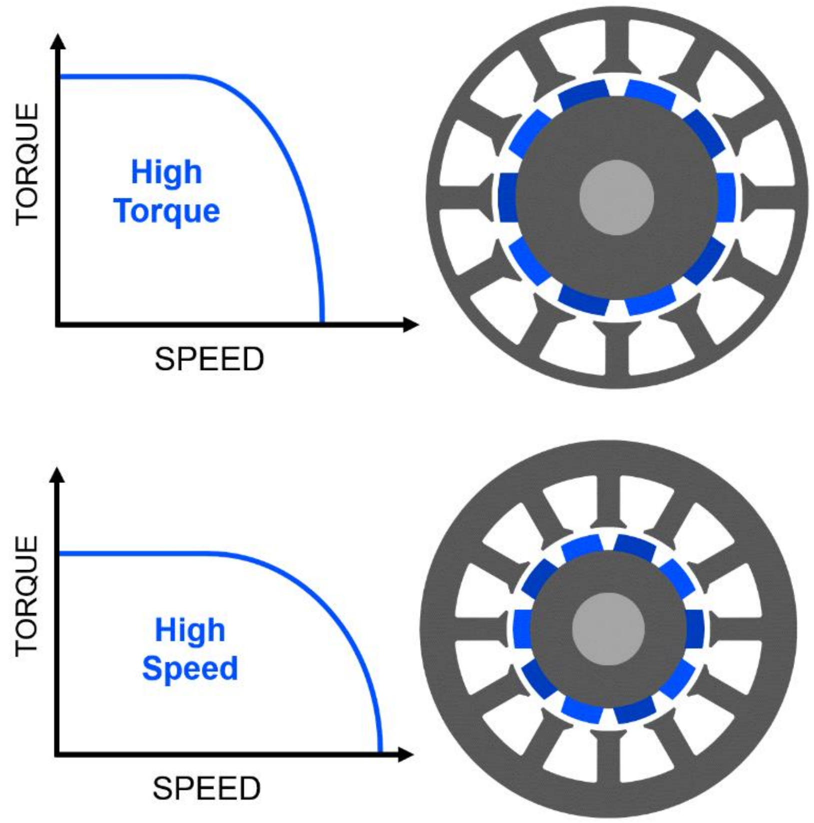
- Requirements and performance indicators in different domains
  - Cost
  - Thermal
  - Mechanical
  - EMAG
  - Control
  - NVH
  - Environment
  - tbc



- Radar chart
  - Dimensionless representation
  - Requirements as 100 % reference (outside red circle = requirement fulfilled)
  - All information in one single chart
  - Easy comparison of several designs

In the preselection what type of electric motor is the best for the specific application. Each electric motor has its advantages and disadvantages.

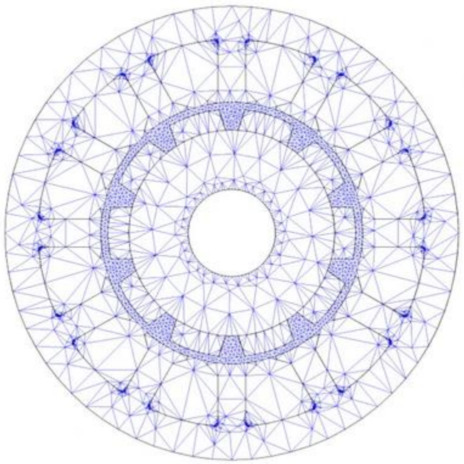
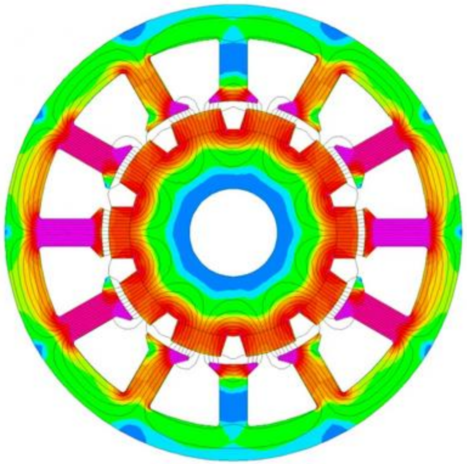
Design of Electric Motors
Analytical Electromagnetic Motor Design Calculation



Analytical software tools are used for the design and calculation. Input into the software are the parameters like diameter, length and voltage of the electric motor. The motor design software then calculates the torque and speed analytically using an equation. This also takes only a few seconds until you have a result.
However, the analytical calculation has a big problem and that is the accuracy of the result of speed, torque and efficiency.

Example tool:
- Ansys RMxprt
- Jmag Express

Design of Electric Motors
2D FEM Electric Motor Simulation

2D means that the motor is divided into many small pieces in the two dimensions X and Y. The smaller these pieces are, the more accurate the result will be. The smaller you make these pieces, the more accurate the result of the simulation will be, but this will also require more computing time. The results can then be used to improve the parameters in the analytical calculation.
So why should you even take the step back into an analytical calculation again? In a two-dimensional simulation, only exactly one load point is usually calculated, i.e. the efficiency at exactly one speed/torque point. This usually takes several minutes to hours, so it makes more sense to calculate an efficiency map analytically, with adapted parameters from the 2D simulation.

3D FEM Electric Motor Simulation

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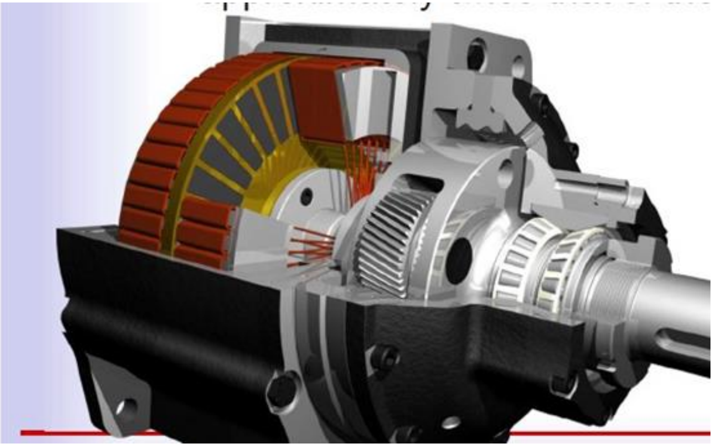
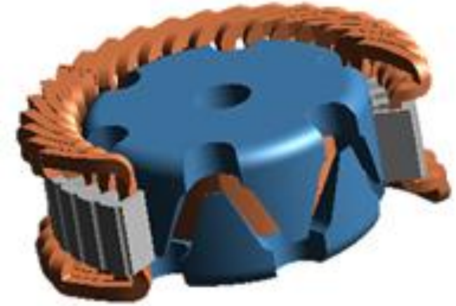
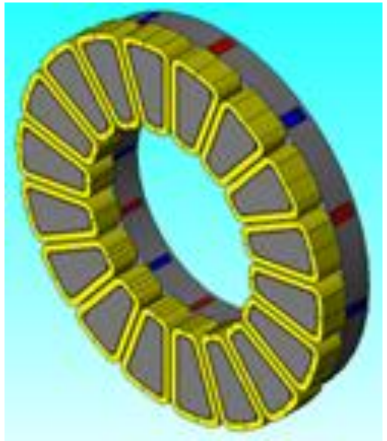
Design of Electric Motors
3D FEM Electric Motor Simulation



When and why do you also need a 3D simulation? Well, 2D simulation assumes that the structure is repeated in the Z-direction. But if you look at the electric motor from above, for example, this is not the case at the top and bottom ends of an electric motor. Stray fluxes can occur at the top and bottom ends of the motor, and one should estimate how large their influences are. For very short electric motors, the influence of stray fluxes can be large. Therefore, the results of the 3D simulation should be used again in the 2D simulation.
Because the calculation of an electric motor characteristic curve in a 3D simulation would require too much computing capacity and time. Another example where 3D simulations are needed are

- axial flux motors where the electromagnetic field changes in all 3 dimensions.
- In very long electric motors, bending vibrations of the shaft can occur, causing the distance between rotor and stator to change over the length. This distance is also called air gap and its change has of course influence on the torque and its course.
- Claw pole alternators





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Design of Electric Motors
Simulations Overview for Motor Design