Power sources
Characteristics and modelling

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Outline

- MOTORIZATION CHARACTERISTICS
  - Piston engines
    - Working principles
    - Torque/Power vs rotation speed curves
    - Specific fuel consumption and emissions
    - Standard performance curves
    - Approximation of curves
    - Engine universal map
  - Electric machines
    - DC motors
    - AC motors: Induction machines and PM synchronous machines
    - Traction electric machines characteristic curves
    - Peak and continuous performance

References

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- J.Y. Wong. « Theory of Ground Vehicles ». John Wiley & sons. 1993 (2nd edition) 2001 (3rd edition).
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- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)

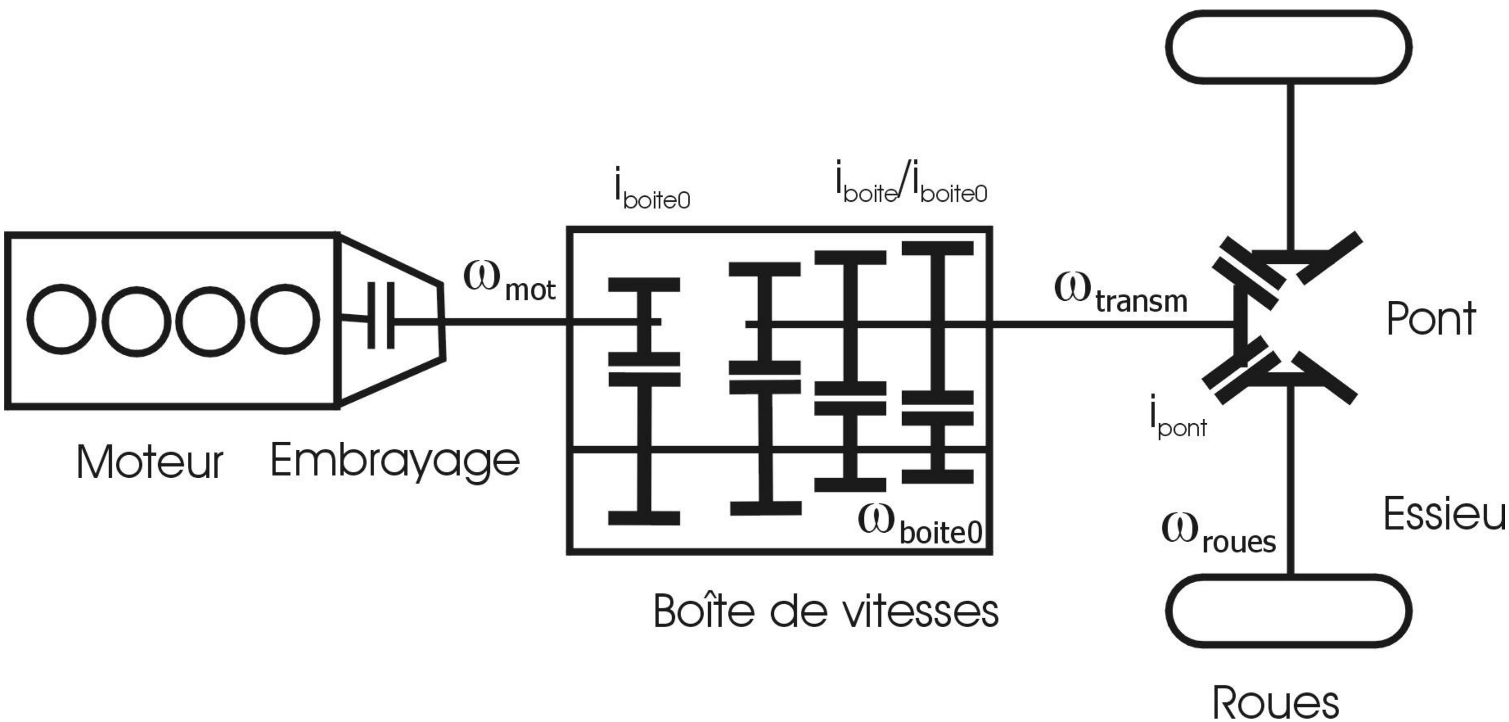
Introduction and Motivation

Motivation

- Motivation: modelling of power sources in order to carry out performance evaluation of the vehicle
- We generally work at the preliminary design stage
- Vehicle modelled as system
- Component and subsystem models
  - Characteristic curves: Torque / power vs rotation speed
  - Energy and fuel consumption in terms of torque and rotation speed
  - Emissions
  - Noise…

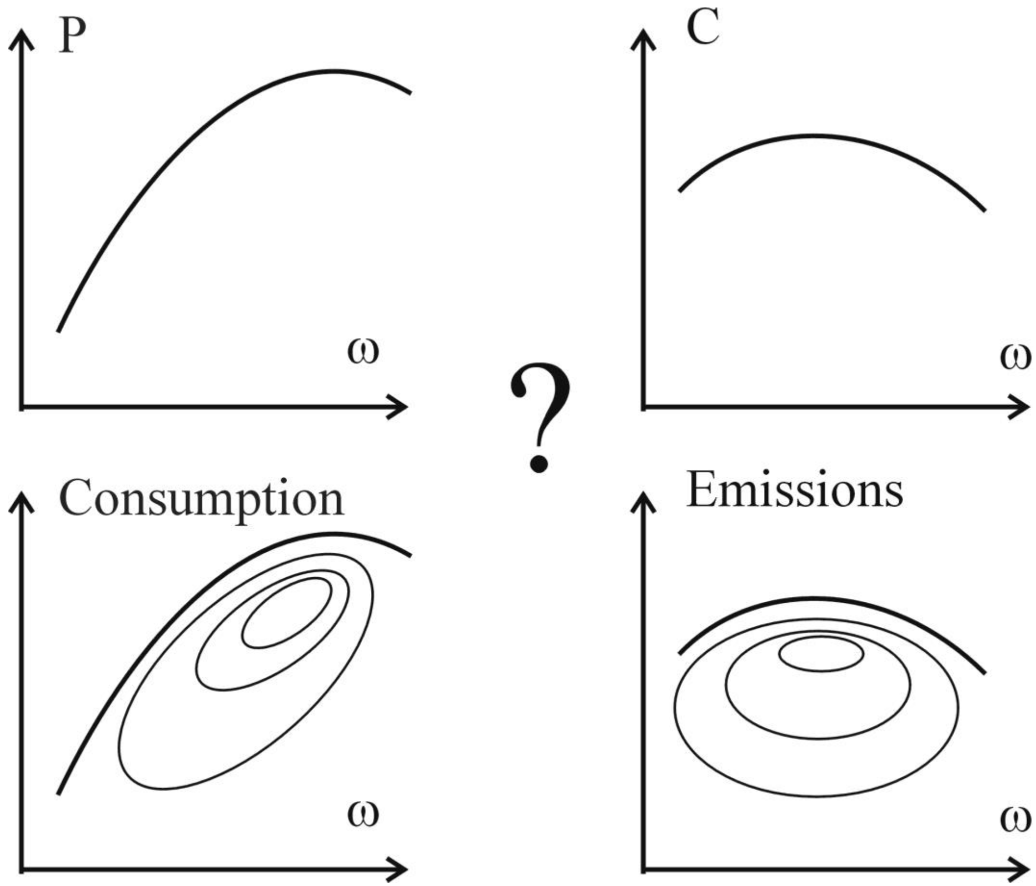
Motivation

- Vehicle model as a system made of components



Motivation

- Performance curves



Motivation

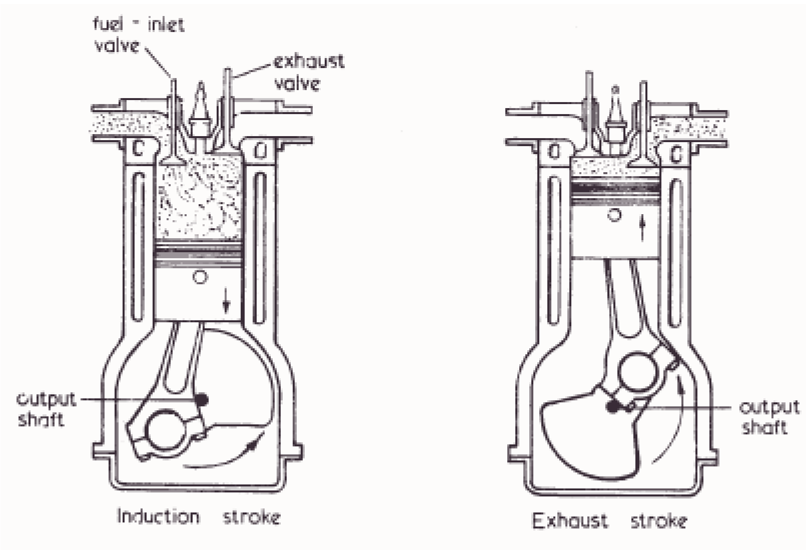
- In the preliminary design stage
  - Simplistic models: limited data
  - Steady state values
- Models can be refined as long as the project evolves
  - Internal variables
  - Experimental curves

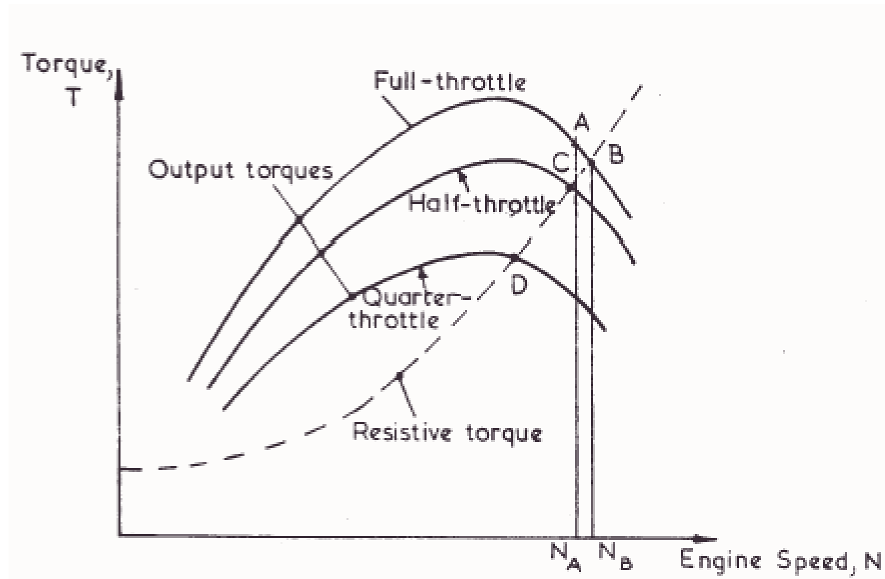
Piston engines

Piston engines

- One can distinguish several variants based on
  - Fuels:
    - Gasoline, Diesel, LPG, Natural gas, hydrogen (H_2), bio-fuels…
  - Thermodynamic cycles:
    - Otto : spark ignited engine: SI
    - Diesel : compression ignited engine: CI
  - Fuel injection system
    - direct vs indirect
    - Atmospheric vs turbocharged
  - Engine
    - 2 stroke vs 4 stroke
  - Operation:
    - Reciprocating vs rotary

Torque-speed curves of ICE engines





Indicated mean effective pressure

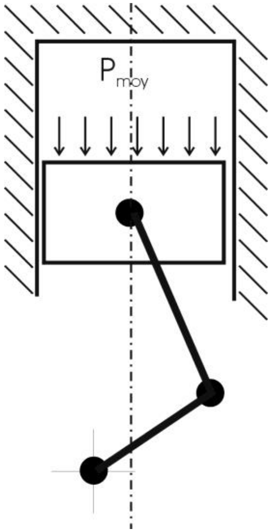
- The indicated mean effective pressure imep is a fictitious *constant* pressure that would produce the same work per cycle as if it acted on the piston during the power stroke

- The expression of the work done during the working stroke by one piston

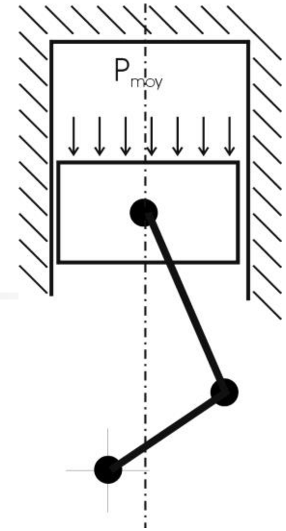
$$W_{1stroke}^{1cyl} = \mathrm{imep}.\frac{\pi B^2}{4}.l = \mathrm{imep}.V_{1cyl}$$

- The work of the n_{cyl} pistons over the cycle is:

$$W_{1stroke}^{ncyl} = \mathrm{imep}.V_{1cyl}.n_{cyl} = \mathrm{imep}.V_d$$



Indicated mean effective pressure



- The work of the n_{cyl} pistons over the cycle is:

$$W_{1stroke}^{ncyl} = \text{imep}.V_{1cyl}.n_{cyl} = \text{imep}.V_d$$

- For a 2*n_R-stroke engine the duration of the cycle is given by

$$t_{1stroke} = n_R.t_{1turn} = 2.n_R.\pi/\omega = n_R/N$$

N [turn/s] or w in [rad/s]

- Then power is given by

$$\dot{W} = \text{imep}.V_d.\frac{\omega}{2.n_R\pi} = \text{imep}.V_d.\frac{N}{n_R}$$

- And the torque writes

$$C = \frac{\dot{W}}{\omega} = \text{imep}\frac{V_d}{2.n_R.\pi}$$

Indicated mean effective pressure

- The indicated mean effective pressure imep is a fictitious *constant* pressure that would produce the same work per cycle as if it acted on the piston during the power stroke

$$\text{imep} = \frac{W_i}{V_d} = \frac{\dot{W}_i . n_R}{V_d . N} \quad \rightarrow \quad \dot{W}_i = \frac{\text{imep}.V_d.N}{n_R} = \frac{\text{imep}.A_p.\bar{U}_p}{2.n_R}$$

- *imep* does not strongly depend on engine speed.

- *imep* is a better parameter than torque to compare engines for design and output because it is independent of engine speed, N, and engine size, V_d.

Brake mean effective pressure

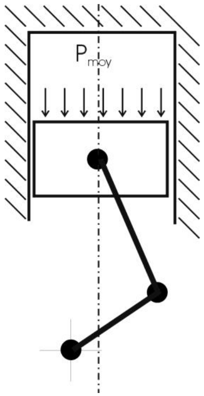
- The brake mean effective pressure (bmep) is defined similarly to the indicated mean effective pressure as a fictitious *constant* pressure that would produce the same brake work per cycle as if it acted on the piston during the power stroke

$$bmep = \frac{W_b}{V_d} = \frac{2\pi \cdot C \cdot n_R}{V_d} \quad \rightarrow \quad \mathrm{C} = \frac{bmep \cdot V_d}{2\pi \cdot n_R}$$

- If the power is quite dependent on the rotation speed, the torque remains less sensitive to the rotation since bmep is less dependent on the rotation speed.

Torque speed curves of ICE

- Suppose that the gas pressure is remaining constant along the power stroke, its work is given by:



$$\mathcal{W}_{1\,\mathrm{stroke}}^{1\mathrm{cyl}} = \mathrm{bmep}\,\frac{\pi B^2}{4}\,l = \mathrm{bmep}\,V_{1\mathrm{cyl}}$$

- The work of the n_{cyl} pistons over the cycle is:

$$\mathcal{W}_{1\,\mathrm{stroke}} = \mathrm{bmep}\,V_{1\mathrm{cyl}}\,n_{\mathrm{cyl}} = \mathrm{bmep}\,V_d$$

- For a 2*n_R-stroke engine the duration of the cycle is given by

$$t_{1\mathrm{stroke}} = t_{n_R}\,\mathrm{turn} = 2\,n_R\,\pi\;/\;\omega$$

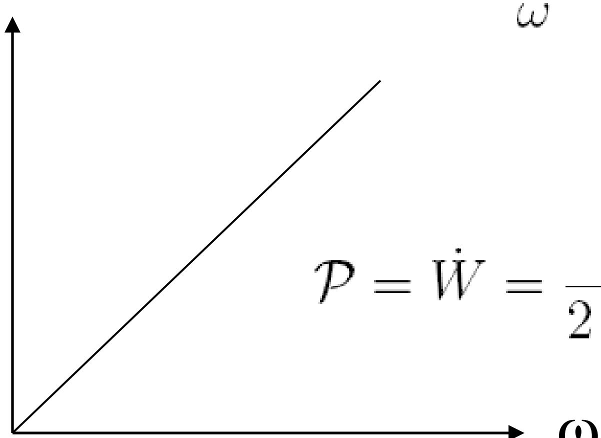
Torque speed curves of ICE

- It comes the power curves with respect to rotation speed:

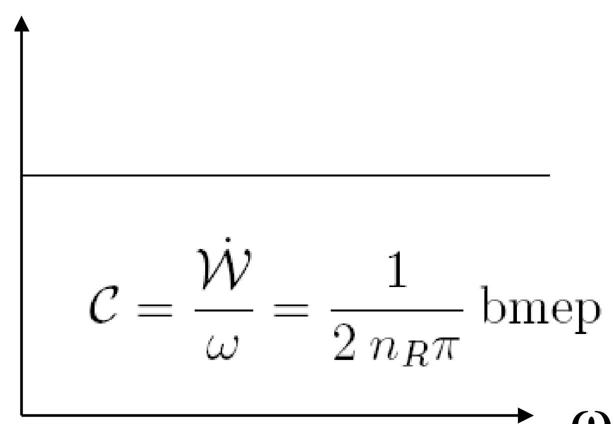
$$\mathcal{P} = \dot{W} = \frac{\omega}{2\, n_R \pi} \,\mathrm{bmep}\, V_d$$

- The torque speed curve is

$$\mathcal{C} = \frac{\dot{\mathcal{W}}}{\omega} = \frac{1}{2\, n_R \pi} \,\mathrm{bmep}\, V_d$$



$$\mathcal{P} = \dot{W} = \frac{\omega}{2\, n_R \pi} \,\mathrm{bmep}\, V_d$$



$$\mathcal{C} = \frac{\dot{\mathcal{W}}}{\omega} = \frac{1}{2\, n_R \pi} \,\mathrm{bmep}\, V_d$$

Engine mechanical efficiency

- A part of the thermodynamic work produced by the fluid is lost to overcome the engine frictions, the heat losses as well as the work to pump the gas in and out of the engine
- The friction power $\dot{W}_f$ is used to estimate as a whole the power dissipated by these losses:

$$\dot{W}_f = \dot{W}_{i,g} - \dot{W}_b$$

- The mechanical efficiency of the engine is defined accordingly as:

$$\eta_m = \frac{\dot{W}_b}{\dot{W}_{i,g}} = 1 - \frac{\dot{W}_f}{\dot{W}_{i,g}}$$

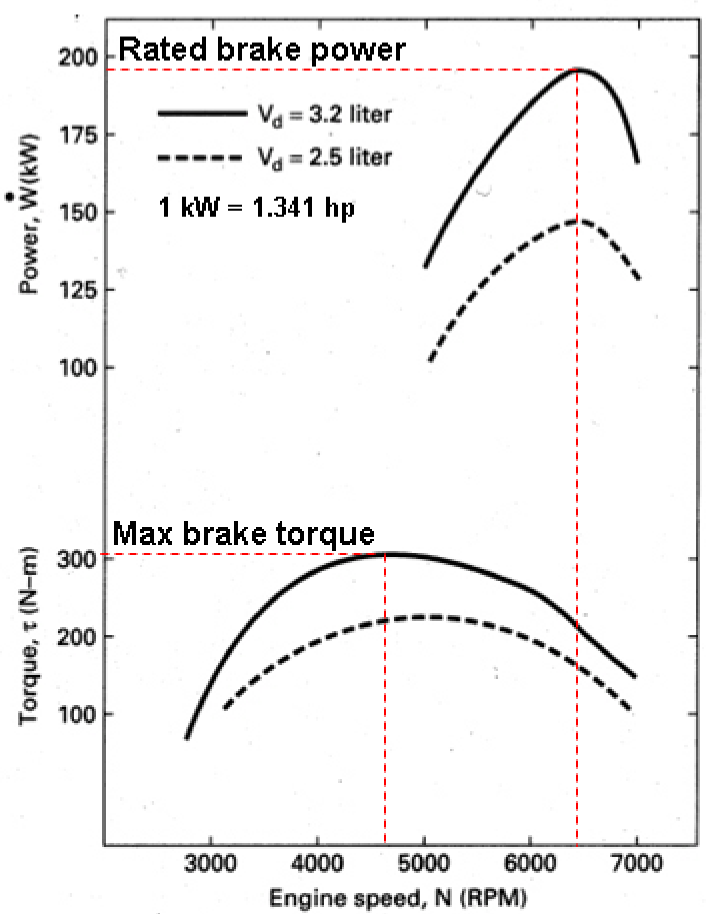
Engine mechanical efficiency

- The engine efficiency depends on the opening of the throttle valve, of the engine design and of course of the engine rotation speed

- Typical values of mechanical efficiency for car engines at full open throttle are:
  - 90% @ 2000 rpm and 75% @ max power regime

- Closing the throttle valve increases the pumping work and so reduces the work available at brake as well as reduces the mechanical efficiency. This efficiency drops at zero for idle regime.

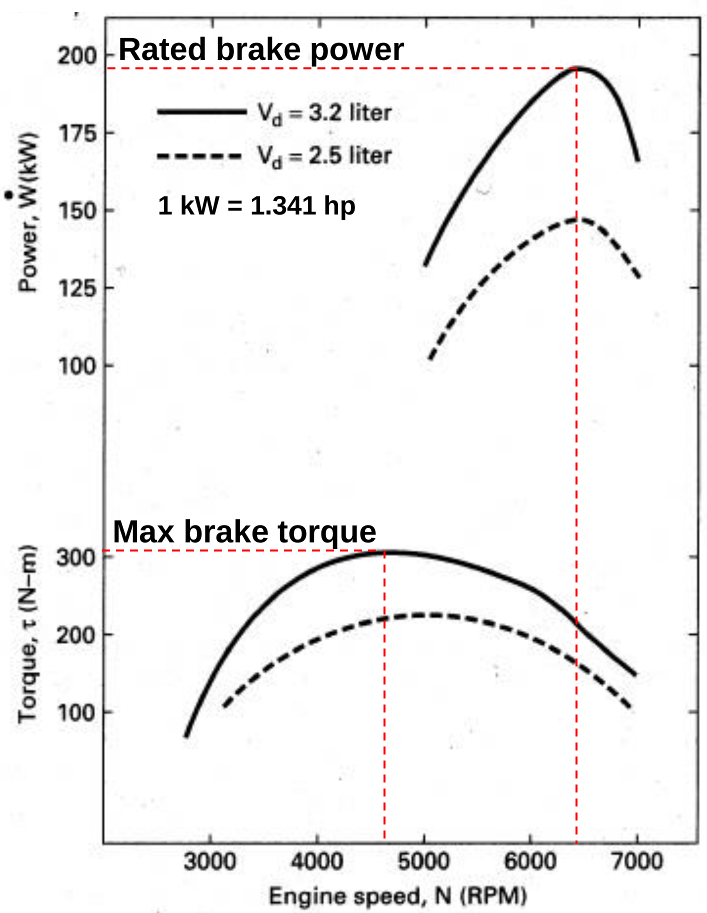
Power and torque as function of the rotation speed



- One observes that the power curve exhibits a maximum when engine rotation speed increases. This maximum power is called nominal power or rated power.
- The brake power increases as long as the torque does not drop too drastically.
- At high regimes, after nominal regime, the friction power increases a lot, and the brake power is finally decreasing

$$\dot{W}_b = \dot{W}_{i,g} - \dot{W}_f$$

Power and torque as function of the rotation speed



- At low regimes, the torque is reduced compared to maximum torque, because of heat losses increases between the gas and the piston or the cylinder sides since the time spent in the chamber becomes longer.

Brake and indicated mean effective pressure

- Order of magnitude of the brake mean effective pressure of modern engines:
  - Four-stroke engines:
    - Atmospheric
      - SI engine: 850 – 1050 kPa
      - CI engine: 700 – 900 kPa
    - Turbocharged
      - SI engine: 1250 - 1700 kPa
      - CI engine: 1000 - 1200 kPa
  - Two-stroke engines
    - SI engine : idem 4 stroke
    - Large 2-stroke diesel engines (e.g. boat) ~1600 kPa
  - Remark
    - Bmep is maximum at maximum torque and wide open throttle
    - At nominal power, the bmep is lower by 10 to 15%

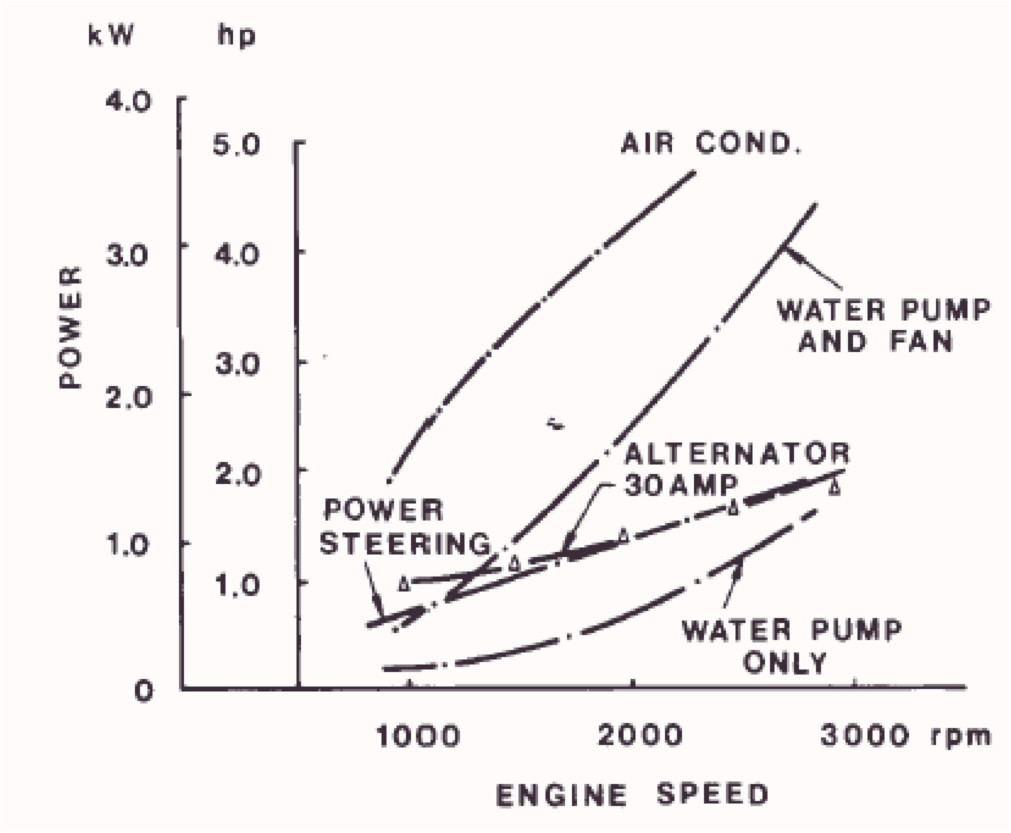
Standard performance curves of ICE

- Torque/power-curves provided by the manufacturer give the basic power of the engine.

- Basic power = performance with the required equipment to insure the normal engine operating conditions: ventilator, water pump, oil pump, exhaust pie, air filter.

- Pay attention to the multiplication of accessories and auxiliary equipments (air conditioned, steering wheel assistance, braking systems, electric generator) that reduce the power available at the wheels by a significant part.

Power consumption of auxiliaries



- The power consumption of the accessories is increasing and has a significant impact on the output power available for the propulsion especially for the small engines and the electric motors

Standard performances of ICE

- SAE (Society of Automotive Engineers, USA): the power of the engine without its auxiliaries, with parameters adapted to each regimes (ignition advance, carburetor). Ideal maximum power.
- DIN (Deutsche Industrie Normen) and CE. The engine has to provide the power necessary to operate all its needed auxiliaries while the parameter settings are the standard ones.
- CUNA. Italian system that is in between DIN and CAE: no accessories but standard settings.

Effect of atmospheric conditions

- The atmospheric conditions (temperature, pressure, hygrometry) affects the engine performances.

- Reference atmospheric conditions:
  - T_0=15.5°C = 520°R = 60°F
  - p_0= 101.32 kPa = 14.7 psi = 76 cm Hg

- Wong is referring to the correction formulae proposed by Taborek (1956):
  - p atmospheric pressure
  - p_v vapour pressure to account for the effect of the humidity
  - T the temperature (in °R) at admission pipe

Effect of atmospheric conditions

- For SI engines (gasoline)

$$\mathcal{P}(p,T) \;=\; \mathcal{P}_0\,\frac{p-p_v}{p_0}\,\sqrt{\frac{T_0}{T}}$$

- For CI engines (diesel) the effect of atmospheric pressures is more complex:

$$\mathcal{P}(p,T) \;=\; \mathcal{P}_0\,\frac{p-p_v}{p_0}\,\frac{T_0}{T}$$

- The atmospheric conditions may impact significantly the engine performances (Wong Fig. 3.24)

Effect of atmospheric conditions

- Norm EEC 80/1269 – ISO 1585 – JIS D 1001 – SAE J1349 for SI engines (gasoline)
- Standards conditions (temperature T_0= 298 K and dry air pressure p_0= 99 kPa)

$$A = 99/p_{PT}(\mathrm{kPa})$$
$$B = T(K)/298$$

- Corrected power

$$\boxed{\mathcal{P}_0 = A^{1.2}\, B^{0.6}\, \mathcal{P}}$$

Effect of atmospheric conditions

- Norm EEC 80/1269 – ISO 1585 – JIS D 1001 – SAE J1349 for CI engines (diesel)
- Standards conditions (temperature T_0= 298 K and dry air pressure p_0= 99 kPa)

$$A = 99/p_{PT}(\mathrm{kPa})$$
$$B = T(K)/298$$

- Corrected power

$$\boxed{\mathcal{P}_0 = A^{0.7}\, B^{1.5}\, \mathcal{P}}$$

Curve fitting of ICE characteristics

- Two families of curves
  - Fitting to a power function
  - Fitting of a polynomial

- Data
  - Nominal/rated (maximum) power

$$\mathcal{P}_1 = \mathcal{P}_{max}$$

$$\omega_1 = \omega_{nom}$$

  - Maximum torque

$$\mathcal{C}_2 = \mathcal{C}_{max}$$

$$\omega_2 = \omega_{C_{max}}$$

Power approximation

- One looks for a power function of the type

$$\boxed{\mathcal{P} \;=\; \mathcal{P}_1 - a\,|\omega - \omega_1|^b} \quad \text{with } b > 0$$

- Data

$$\mathcal{P}(\omega_1) = \mathcal{P}_1 = \mathcal{P}_{max} \qquad \omega = \omega_1$$

$$\mathcal{P}(\omega_2) = \mathcal{P}_2 = C_{max}\,\omega_{C_{max}} \qquad \omega = \omega_2$$

$$\left.\frac{d\,C}{d\omega}\right|_{\omega_2} \;=\; \left.\frac{d\,(\mathcal{P}/\omega)}{d\omega}\right|_{\omega_2} = 0$$

- We are going to show this yields

$$\boxed{a \;=\; \frac{\mathcal{P}_1 - \mathcal{P}_2}{|\omega_1 - \omega_2|^b}} \qquad \boxed{b \;=\; \frac{\frac{\omega_1}{\omega_2} - 1}{\frac{\mathcal{P}_1}{\mathcal{P}_2} - 1}}$$

Power approximation

- Maximum power in P_1: OK

- Maximum torque in ω_2:

$$\mathcal{P}(\omega_2) = \mathcal{P}_2 = C_{max}\, \omega_{C_{max}}$$

$$\left.\frac{d\,C}{d\omega}\right|_{\omega_2} = \left.\frac{d\,(\mathcal{P}/\omega)}{d\omega}\right|_{\omega_2} = 0$$

- Given (maximum) torque ω_2 :

$$\boxed{a = \frac{\mathcal{P}_1 - \mathcal{P}_2}{|\omega_1 - \omega_2|^b}} \qquad \mathcal{P} = \mathcal{P}_1 - (\mathcal{P}_1 - \mathcal{P}_2)\left|\frac{\omega_1 - \omega}{\omega_1 - \omega_2}\right|^b$$

Power approximation

- Maximum torque in ω_2:

$$\left.\frac{d\,C}{d\omega}\right|_{\omega_2} = \frac{\omega_2 \left.\frac{d\mathcal{P}}{d\omega}\right|_{\omega_2} - \mathcal{P}_2}{\omega_2^2} = 0 \qquad \mathcal{P}_2 = \omega_2 \left.\frac{d\mathcal{P}}{d\omega}\right|_{\omega_2}$$

- Derivative of the power

$$\left.\frac{d\mathcal{P}}{d\omega}\right|_{\omega_2} = -a\,b\,|\omega_1-\omega_2|^{b-1}\,\mathrm{sign}(\omega_1-\omega_2)\,(-1) = a\,b\,(\omega_1-\omega_2)^{b-1}$$

- Leads to the condition $\omega_1 > \omega_2$

$$\mathcal{P}_2 = \omega_2\;a\,b\,(\omega_1-\omega_2)^{b-1} = b\,\omega_2\,\frac{\mathcal{P}_1-\mathcal{P}_2}{\omega_1-\omega_2}$$

Power approximation

- Fitted exponent b

$$b = \frac{\frac{\omega_1}{\omega_2} - 1}{\frac{\mathcal{P}_1}{\mathcal{P}_2} - 1}$$

- Fitted approximation

$$\mathcal{P} = \mathcal{P}_1 - (\mathcal{P}_1 - \mathcal{P}2) \frac{|\omega_1 - \omega|^b}{|\omega_1 - \omega_2|^b}$$

$$\mathcal{C}(\omega) = \mathcal{P}(\omega)/\omega$$

- Under non dimension form

$$\frac{\mathcal{P}}{\mathcal{P}_1} = 1 - \left(1 - \frac{\mathcal{P}_2}{\mathcal{P}_1}\right) \left|\frac{1 - \frac{\omega}{\omega_1}}{1 - \frac{\omega_2}{\omega_1}}\right|^b$$

Power approximation

- Example: Peugeot engine XV3 943 cm³

$$\mathcal{P}_1 = 33,85\,kW \qquad n_1 = 6000\,tr/min$$
$$\mathcal{C}_2 = 67,81\,N.m \qquad n_2 = 3000\,tr/min$$

- One gets

$$\omega_1 = 628,30\,rad/s$$
$$\omega_2 = 314,15\,rad/s$$
$$\mathcal{P}_2 = \mathcal{C}_2\,\omega_2 = 21,30\,kW$$

$$\mathcal{P}_2/\mathcal{P}_1 = 0,6293$$
$$\omega_2/\omega_1 = 0,5$$

$$b = \frac{\frac{\omega_1}{\omega_2} - 1}{\frac{\mathcal{P}_1}{\mathcal{P}_2} - 1} = \frac{2-1}{1,5996-1} = 1,698$$

Power approximation

- Example: Peugeot engine XV3 943 cm³
- Inserting this value into the expression of the curvature coefficient a

$$a = \frac{\mathcal{P}_1 - \mathcal{P}_2}{|\omega_1 - \omega_2|^b} = \frac{33.85\,10^3 - 21,30\,10^3}{|628.30 - 314.14|^{1,698}} = 722.34\,10^{-3}$$

- Finally the expression of the power approximation of the power writes

$$\begin{aligned} \mathcal{P} &= \mathcal{P}_1 - a\,|\omega - \omega_1|^b \\ &= 33.85 \;-\; 722.34\,10^{-6}\,|628.30 - \omega|^{1.698}\;\;[\mathrm{kW}] \end{aligned}$$

Polynomial approximation

- Polynomial approximation
  - Power

$$\mathcal{P}(\omega) \simeq \sum_{i=0}^{n} a_i\, \omega^i$$

    - Or under non dimensional form

$$\mathcal{P}(\omega)/\mathcal{P}_{max} \simeq \sum_{i=0}^{n} a_i\, (\omega/\omega_{nom})^i$$

  - Torque

$$\mathcal{C}(\omega)/\mathcal{C}_1 \simeq \sum_{i=0}^{n} a_i\, (\omega^{i-1}/\omega_{nom}^i) \qquad \mathcal{C}_1 = \mathcal{P}_1/\omega_1$$

Polynomial approximation

- Polynomial approximation of order 3

$$\mathcal{P}(\omega)/\mathcal{P}_1 = a_0 + a_1\,(\omega/\omega_1) + a_2\,(\omega/\omega_1)^2 + a_3\,(\omega/\omega_1)^3$$

- Identification of the coefficients

$$\mathcal{P}(0) = 0 \qquad a_0 = 0$$

$$\mathcal{P}(\omega_1) = \mathcal{P}_{max} \qquad a_1 + a_2 + a_3 = 1$$

$$\mathcal{P}(\omega_2) = \mathcal{P}_2 = C_{max}\,\omega_{C_{max}} \qquad a_1\,n_2 + a_2\,n_2^2 + a_3\,n_2^3 = \mathcal{P}_2/\mathcal{P}_1$$

$$\left.\frac{d\,C}{d\omega}\right|_{\omega_2} = 0 \qquad a_2 + 2\,a_3\,n_2 = 0$$

$$n_2 = \frac{\omega_2}{\omega_1}$$

Polynomial approximation

- Polynomial approximation of order 3

$$\mathcal{P}(\omega)/\mathcal{P}_1 = a_0 + a_1\,(\omega/\omega_1) + a_2\,(\omega/\omega_1)^2 + a_3\,(\omega/\omega_1)^3$$

- Gives the coefficients

$$a_3 = \frac{\frac{\mathcal{P}_2}{\mathcal{P}_1} - \frac{\omega_2}{\omega 1}}{-\frac{\omega_2}{\omega_1} + 2\left(\frac{\omega_2}{\omega_1}\right)^2 - \left(\frac{\omega_2}{\omega_1}\right)^3} \qquad n_2 = \frac{\omega_2}{\omega_1}$$

$$a_2 = -2\,n_2\,a_3$$

$$a_1 = 1 + a_3(2n_2 - 1)$$

Polynomial approximation

- Polynomial approximation of order 4

$$\mathcal{P}(\omega)/\mathcal{P}_1 = a_0 + a_1\,(\omega/\omega_1) + a_2\,(\omega/\omega_1)^2 + a_3\,(\omega/\omega_1)^3 + a_4\,(\omega/\omega_1)^4$$

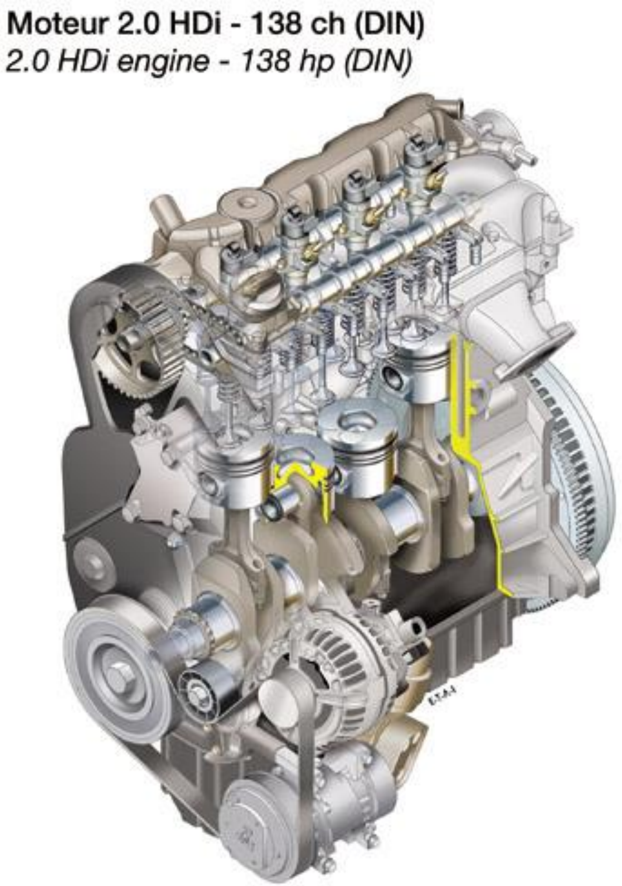
- Identification of the coefficient
  - Same as polynomial of order 3 + new condition on the maximum power in ω_1:

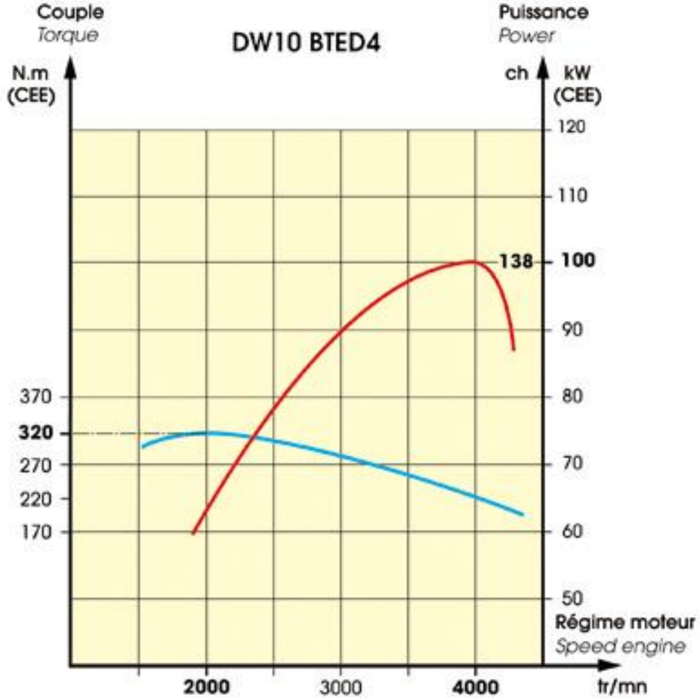
$$a_1 + 2\,a_2 + 3\,a_3 + 4\,a_4 = 0$$

- Solve the linear system

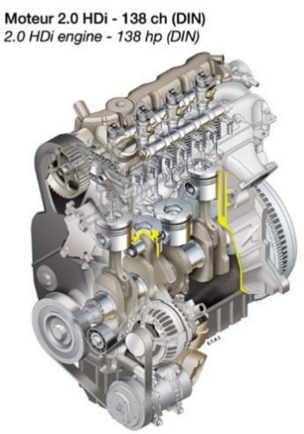
$$a_1 + a_2 + a_3 + a_4 = 1$$
$$a_1 + 2\,a_2 + 3\,a_3 + 4\,a_4 = 0$$
$$a_1\,n_2 + a_2\,n_2^2 + a_3\,n_2^3 + a_4\,n_2^4 = \mathcal{P}_2/\mathcal{P}_1$$
$$a_2 + 2\,a_3\,n_2 + 3\,a_4\,n_2^2 = 0$$

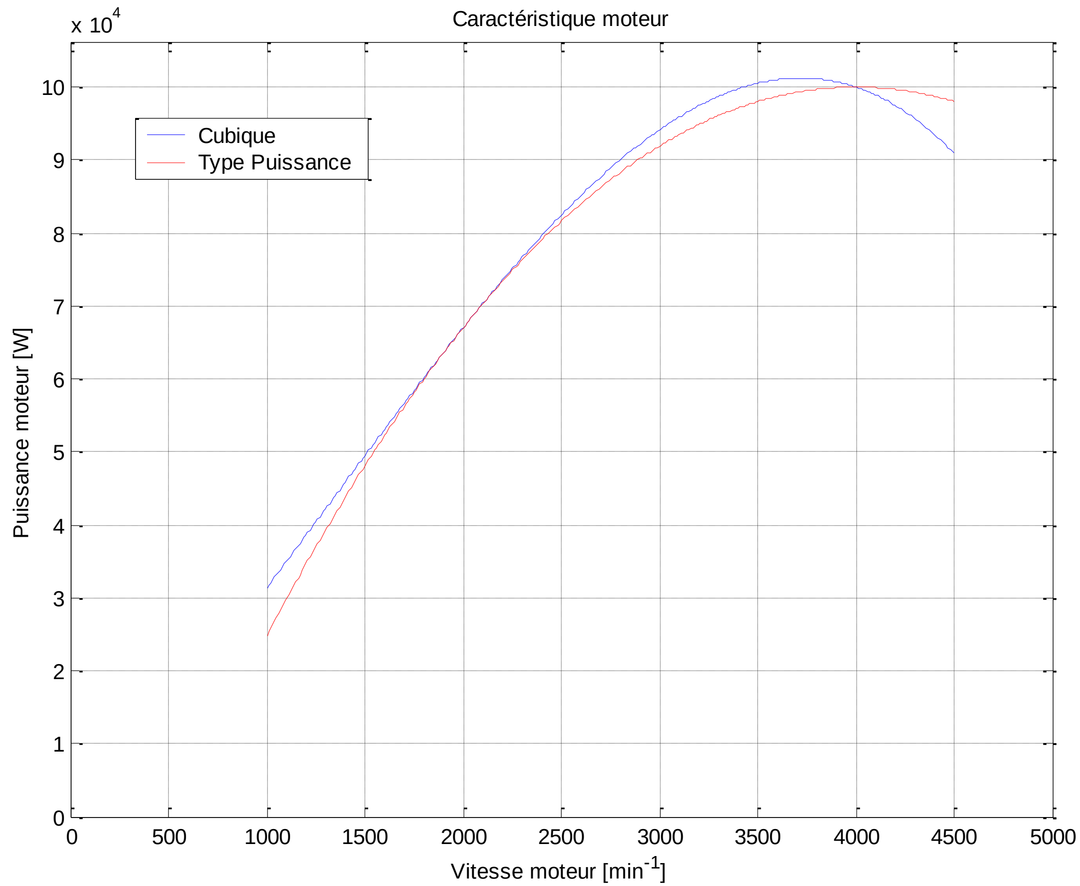
Example: 2.0 HDI PSA engine



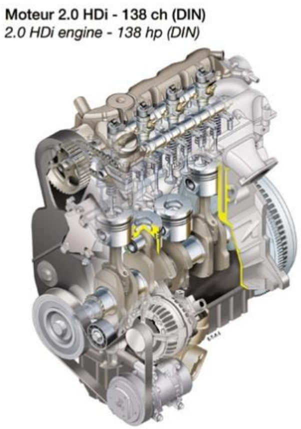


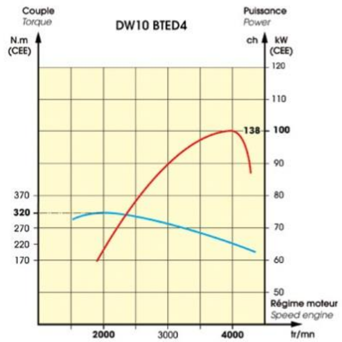
Example: 2.0 HDI PSA engine

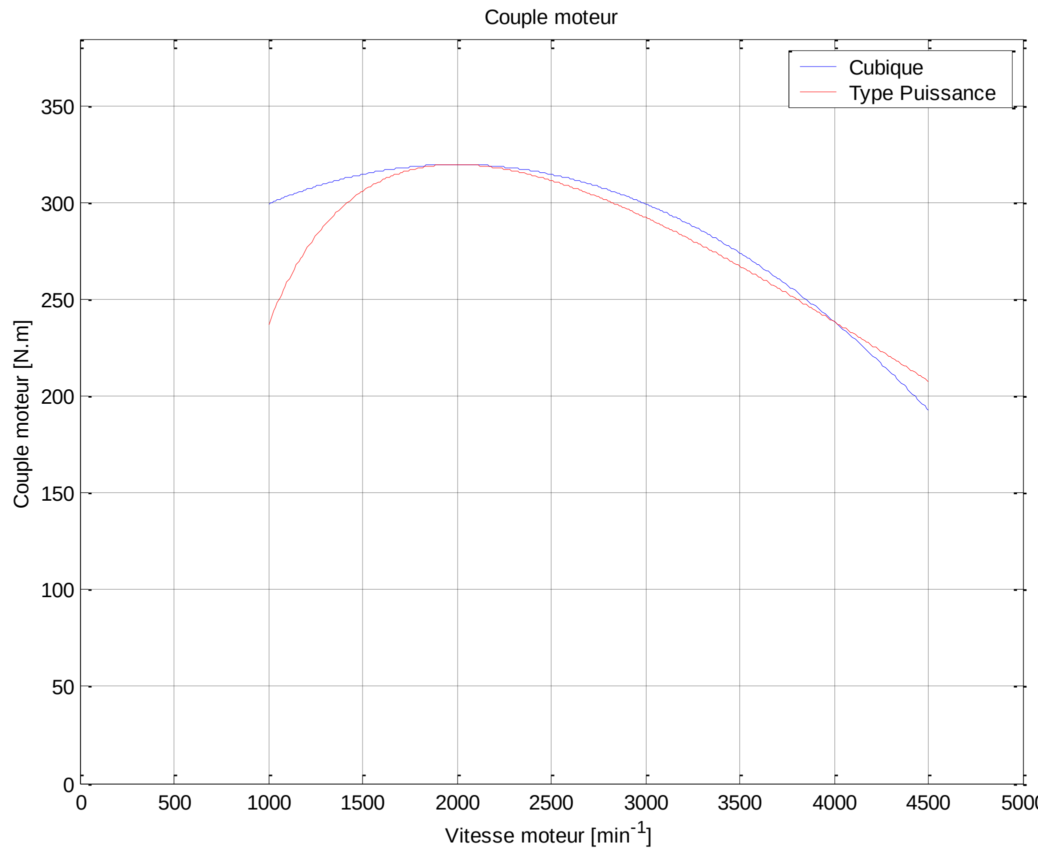




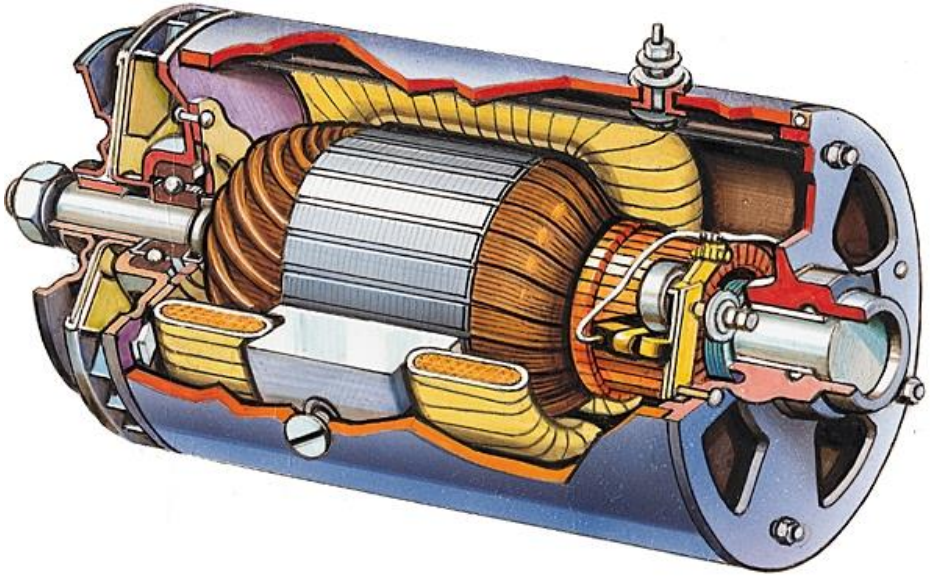
Example: 2.0 HDI PSA engine







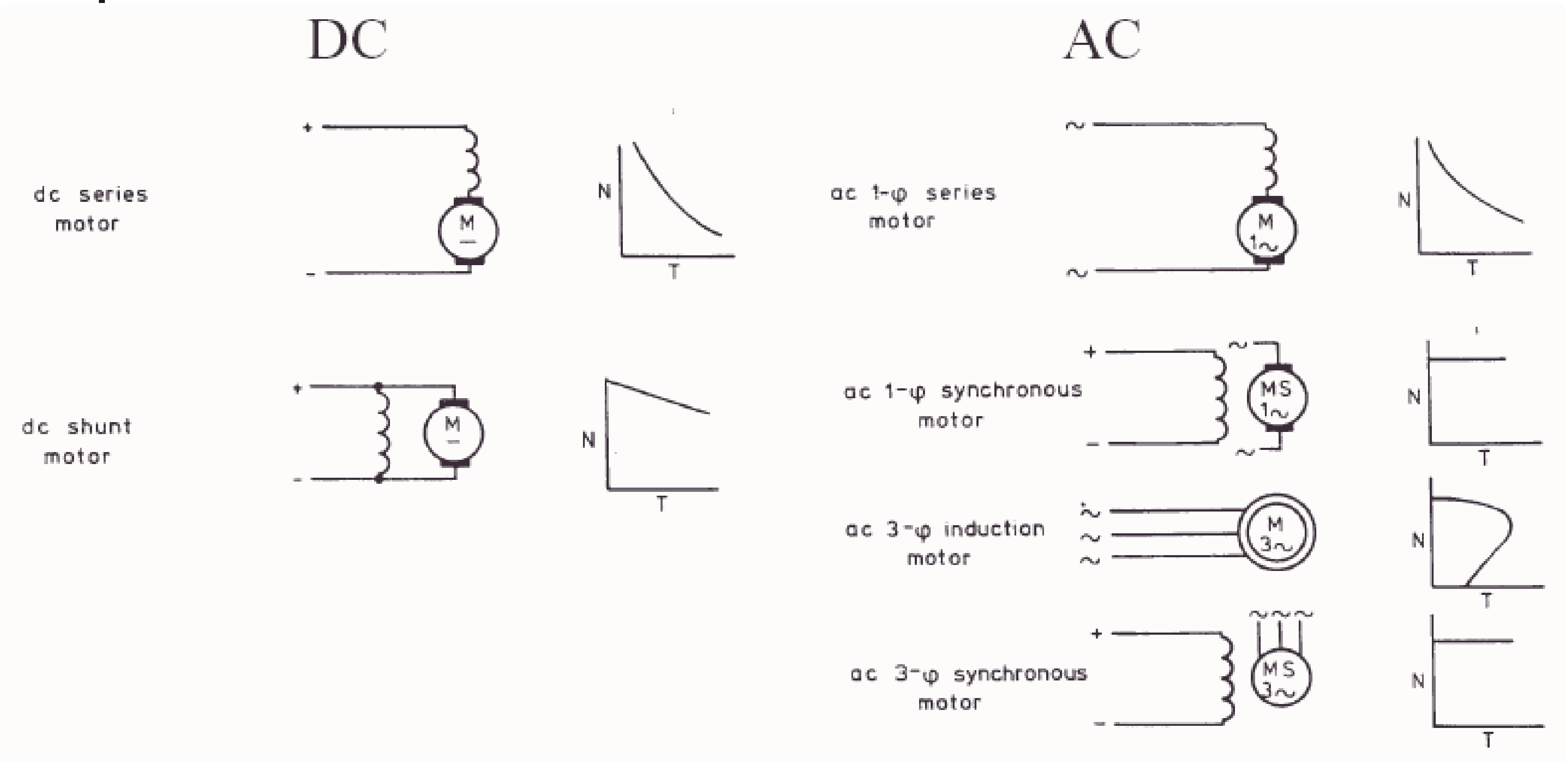
Electric machines



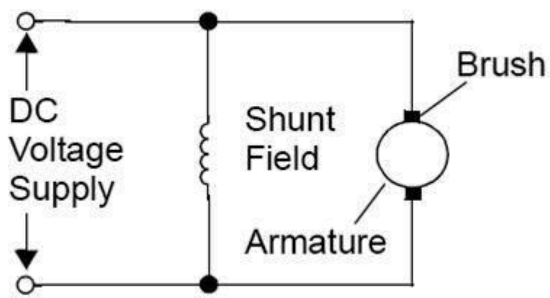
Introduction

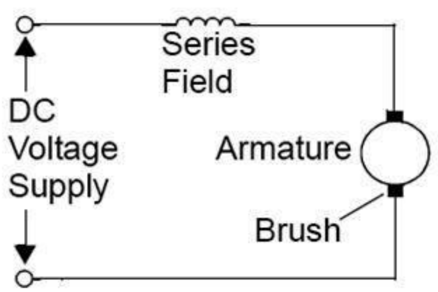
- This lecture introduces electric traction motors and their application to electric and hybrid electric powertains
- Three main components of electric traction machines:
  - Electric machine itself;
  - The related power electronics: continuous management of voltage, current intensity, frequency of electrical energy supplying the electric machine depending on the driving request;
  - The command itself that is necessary to optimize the operation efficiency.
- The powertrain architecture is treated in a separate lecture.

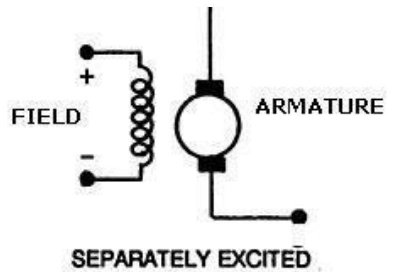
Performance curves of electric machines

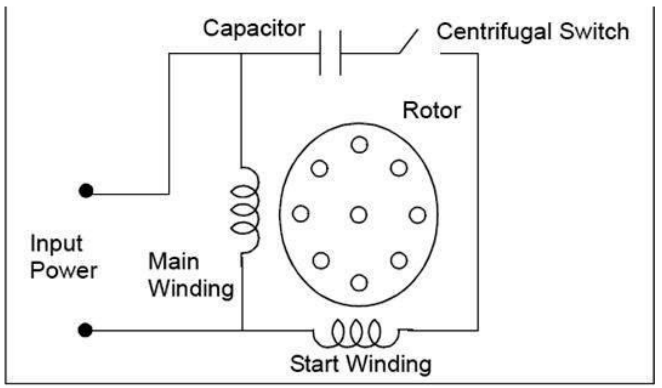


Performance curves of electric machines







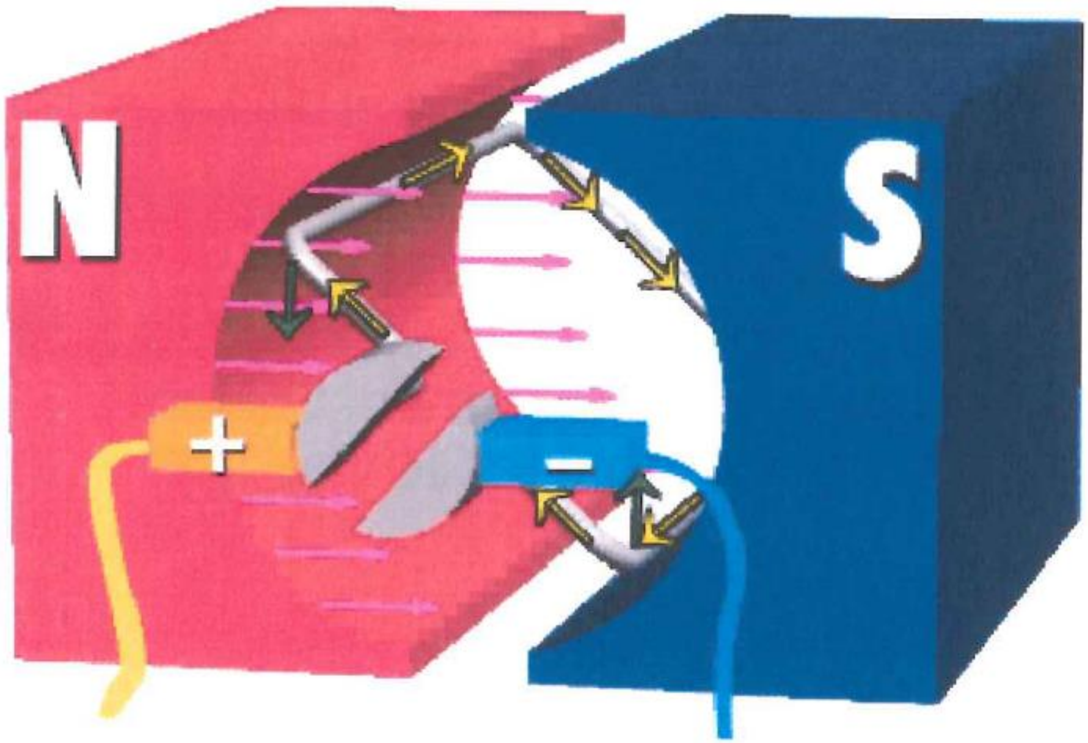


DC electric motors

$$\vec{F} = i\vec{dl} \times \vec{B}$$

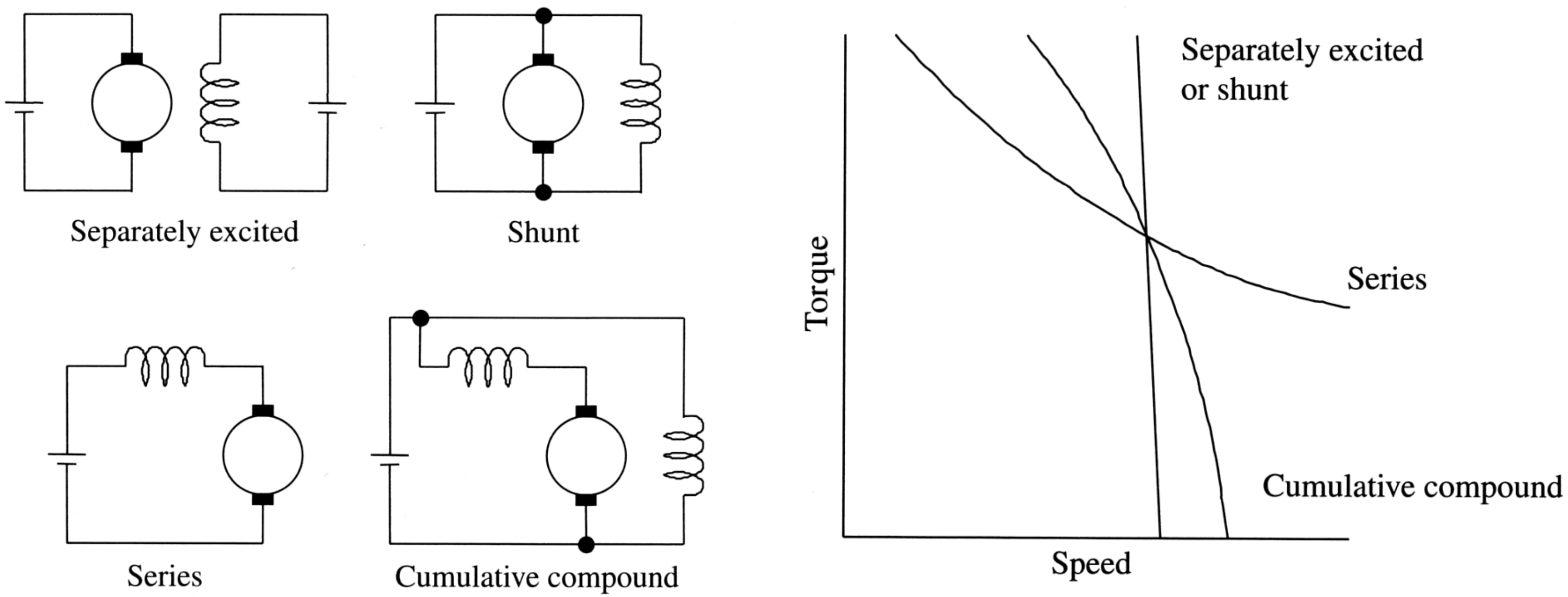
$$T = B\ I\ L\ \cos\alpha$$

$$E = -\frac{d\Phi}{dt} = -N\frac{d\phi}{dt}$$



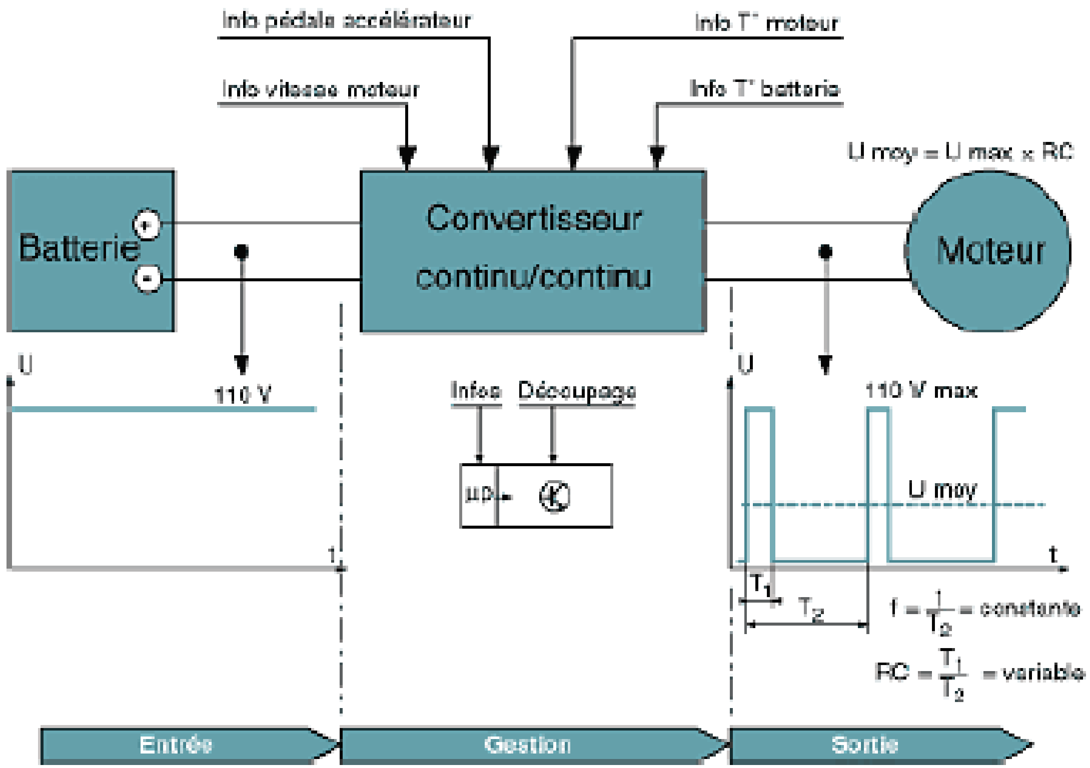
Working principle of a DC motor

DC electric motors



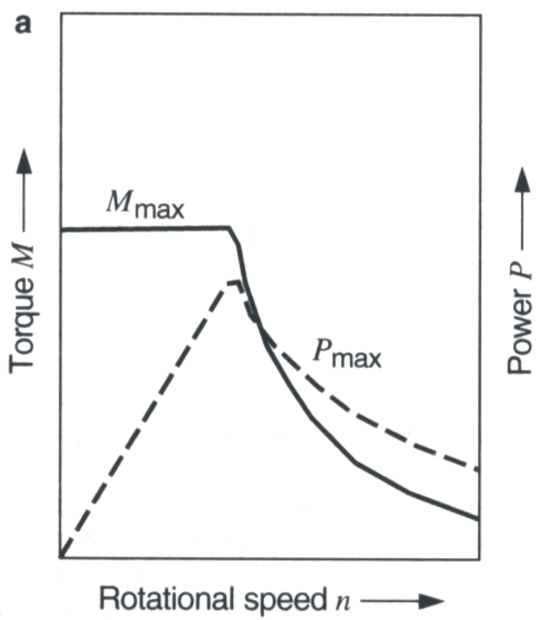
Types of DC machines and torque curves

Power electronic and control of DC machines

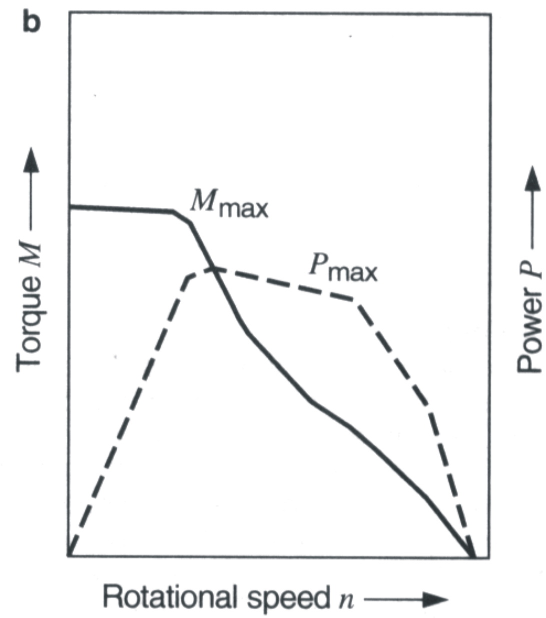


Working principle of a chopper

DC motor: series and separated excitation



DC series motor



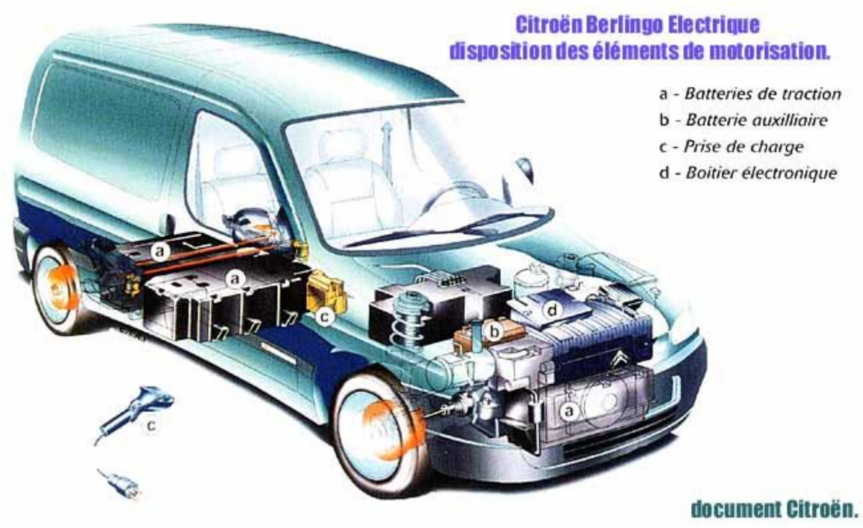
DC motor with separated excitation

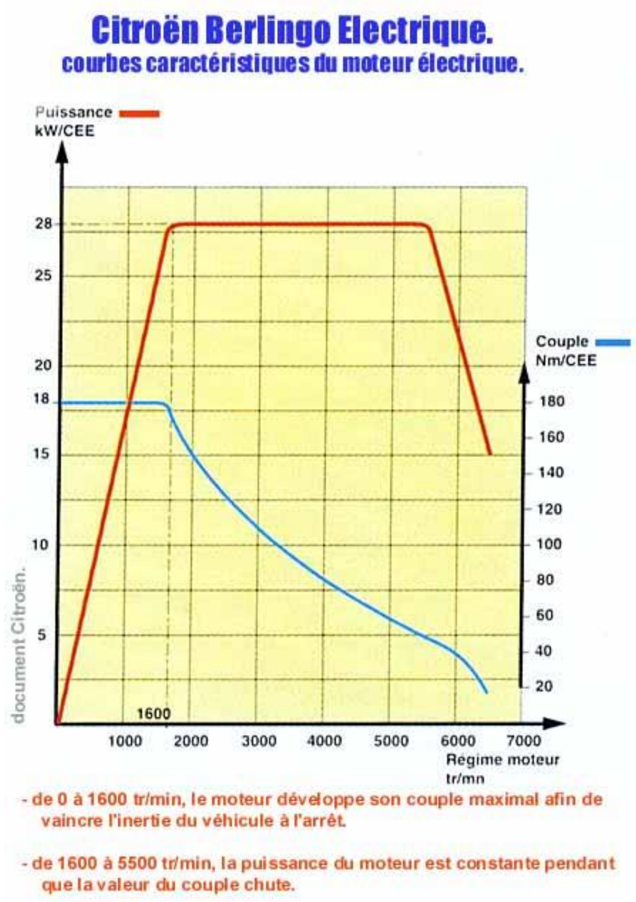
DC tractions motors

Peugeot 106 Electrique - EDF-GDF du Var
détail du raccordement véhicule - borne de recharge

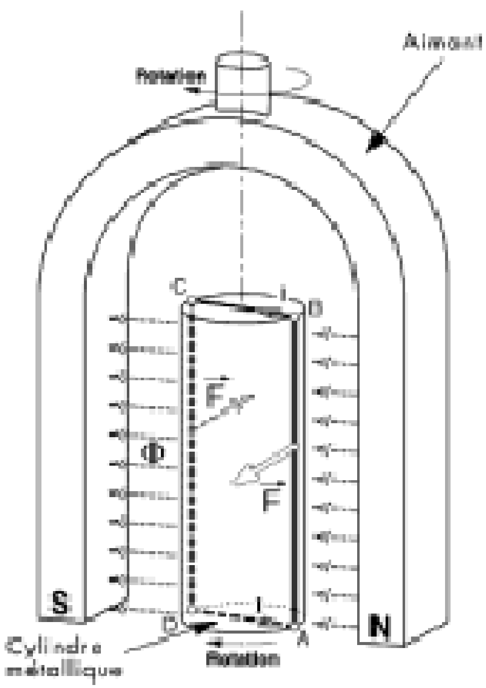
- Advantages of DC motors
  - Mature technology
  - Control of DC motor is well known: speed control from DC energy sources
    - Variable resistor → chopper (PWM)
  - Early usage of DC motors in vehicles based on DC series architecture: electric vehicles, tramways, etc.
- Disadvantages:
  - Brushes (carbon) must be replaced periodically: replacement after 3000 h of operation
  - Range of supply voltage is limited
  - Lower specific power
  - Medium energy efficiency (80-85%)
  - Rotor losses : very difficult to eliminate

DC electric machines



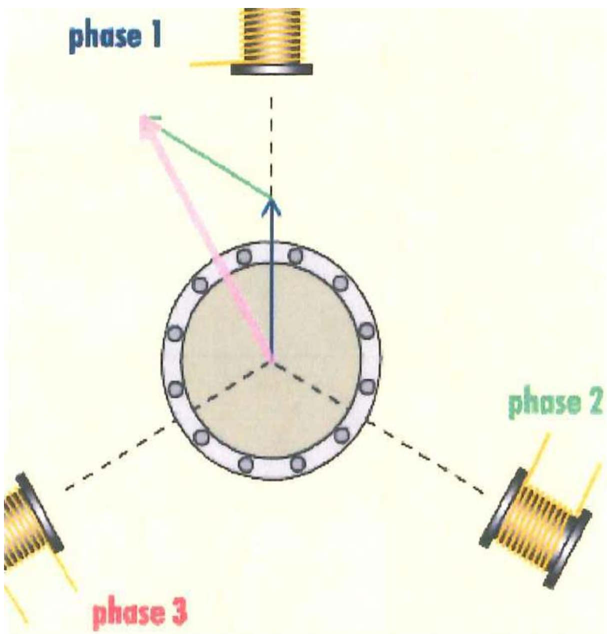


AC motor principles

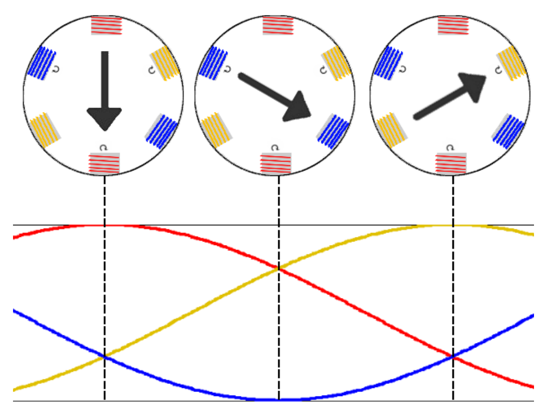


- A rotating magnet creates a rotating magnetic induction field that goes through a magnetic cylinder
- The edges of a metallic cylinder placed in the magnetic field behave like active wires. The induction currents are proportional to the flux variation
- Induction currents interact with the magnetic induction field to create Laplace forces producing a torque
- One observes that the cylinder follows the magnet rotation with a certain slippage.

3-phase AC asynchronous motors

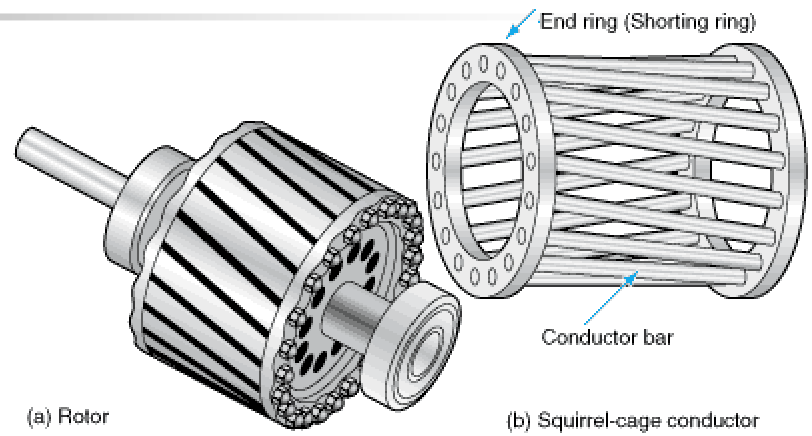


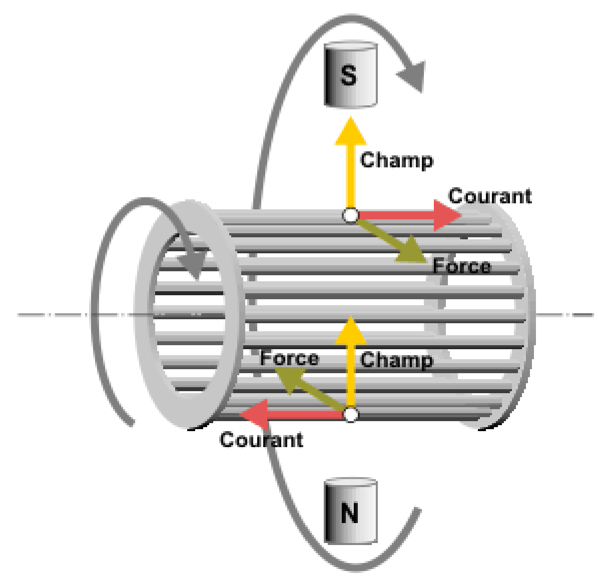
- The rotating permanent magnet can be replaced by the stator winding fed by a set of 3-phase AC currents
- With the 120° spatial shift of stator windings, one creates a rotating magnetic induction field, with a rotation speed given by external supply voltage frequency



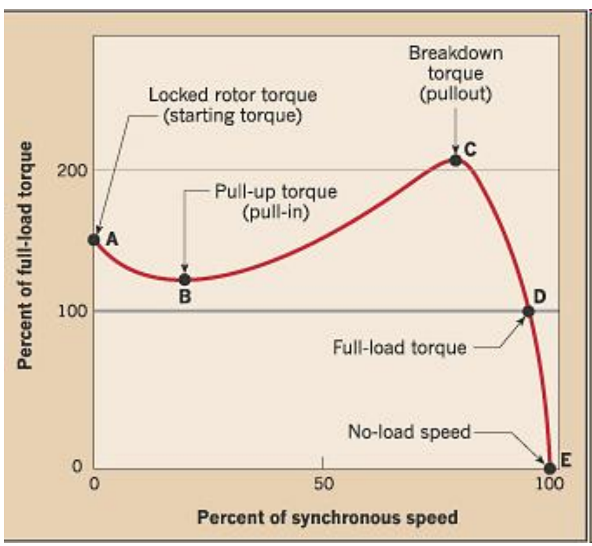
3-phase AC asynchronous motors

- The rotor is made of highly conducting metal rods (copper or aluminum) in short circuits to drive induction currents.
- The Laplace force due to induction field and the induced set of currents in the rotor yields a torque that makes the rotor spin.
- The rotation tends to reduce the slippage (difference of rotation speed) between the applied rotation induction field and the rotor speed.



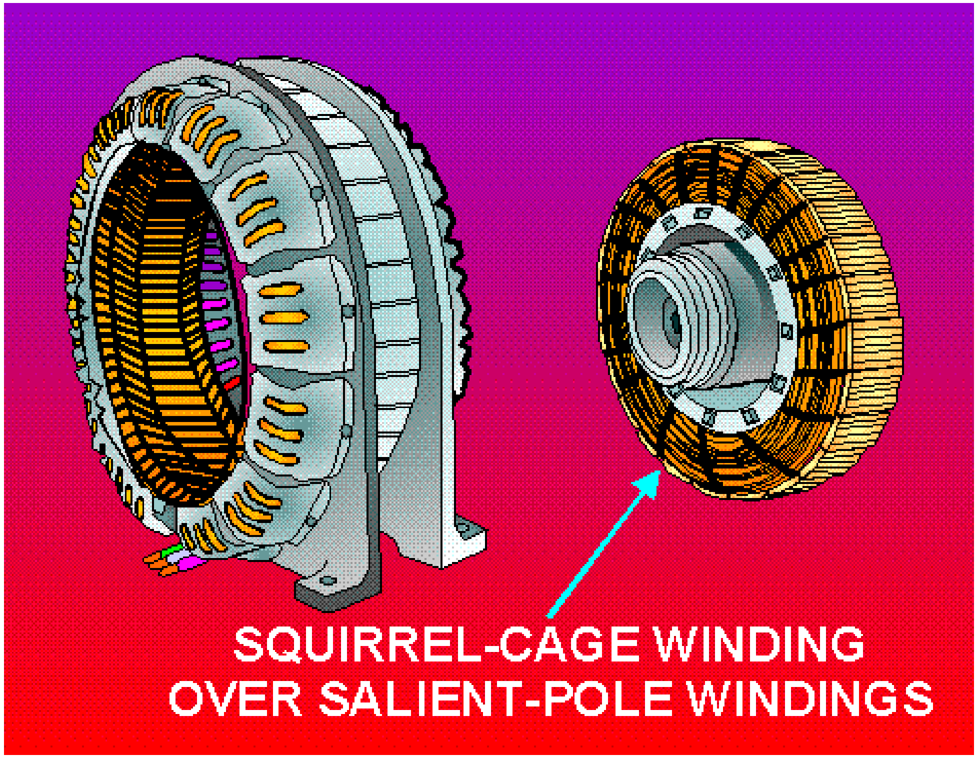


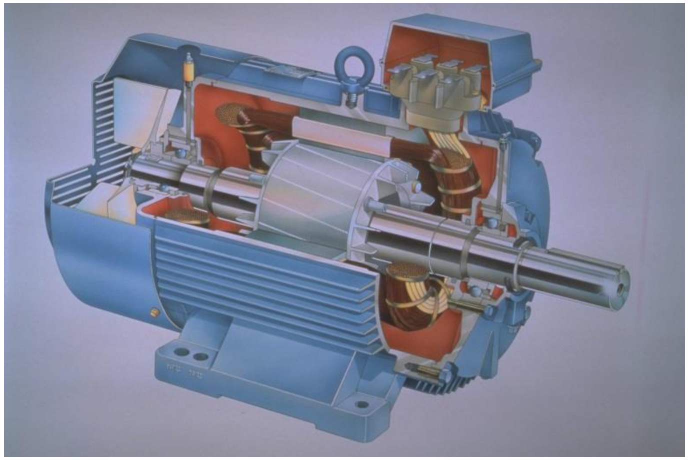
3-phase AC asynchronous motors



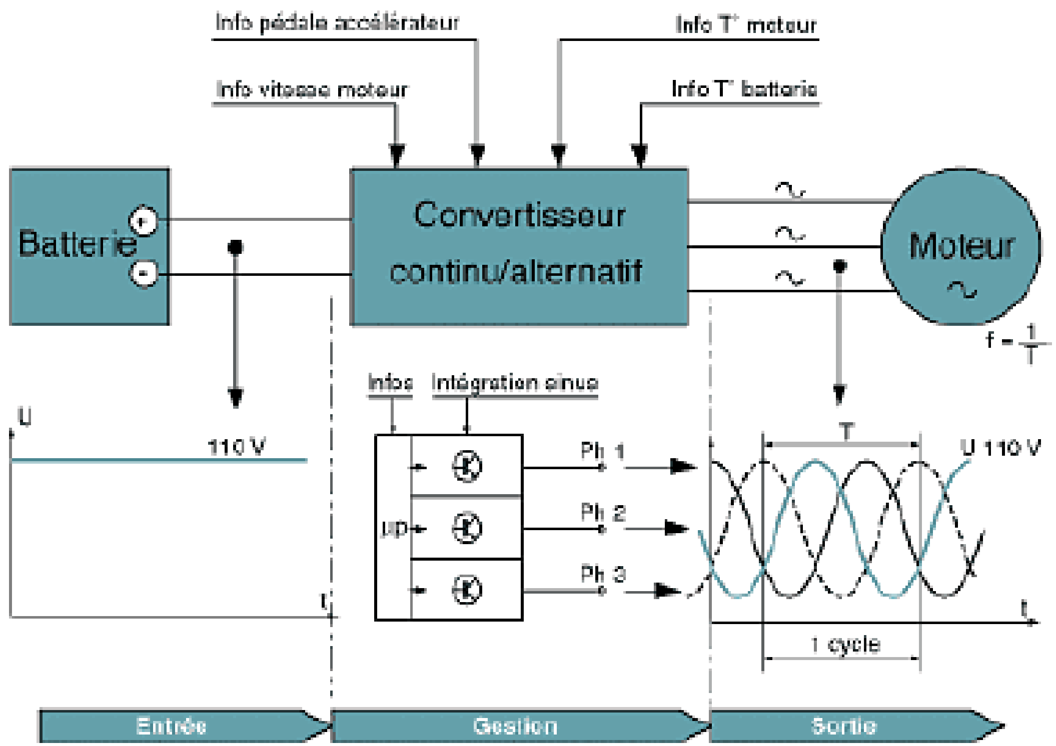
- The e-motor torque comes from the slippage between the rotation speeds of the stator magnetic field and the rotor ones. (Magnetic friction effect).
- If the frequency of the 3-phase current system is controlled, one drives the e-motor rotation speed.
- There are no brushes and no commutations
- Simple concept and simple manufacturing
- By its nature, the efficiency of the induction motor is less than 100%

3-phase AC asynchronous motors



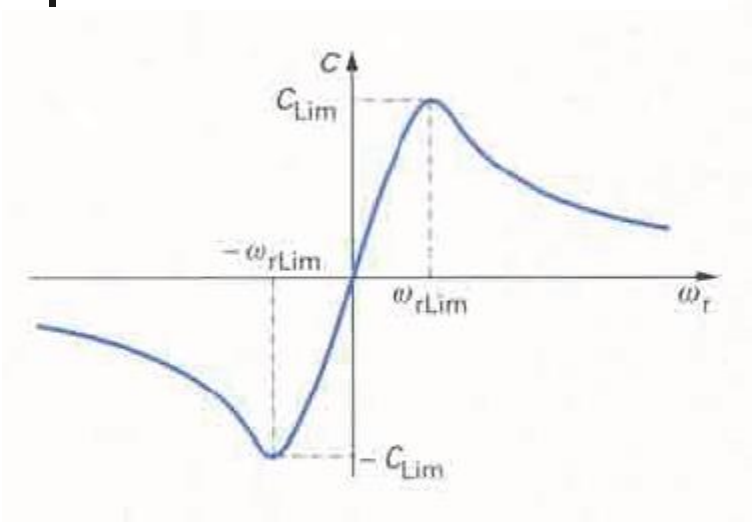


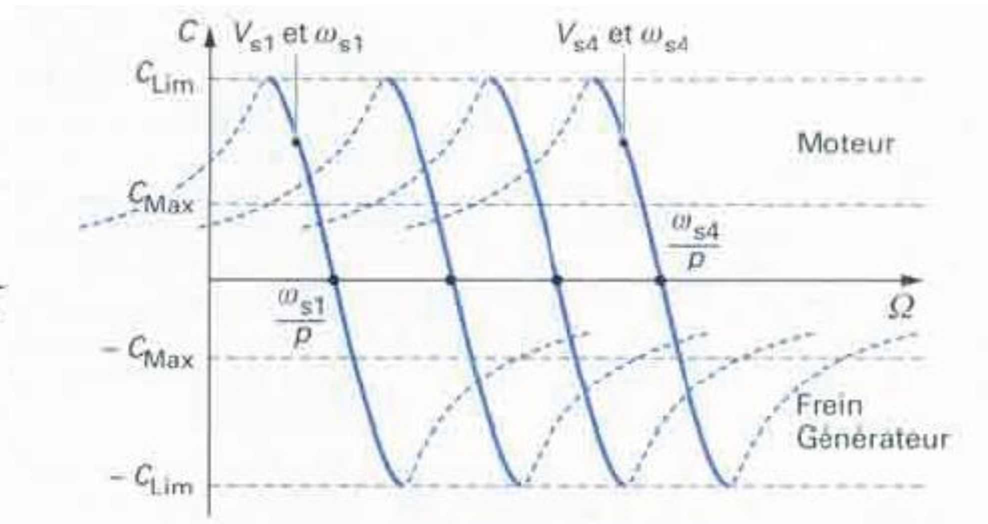
Power electronic and control of AC machines



Working principle of an inverter

AC Asynchronous motor

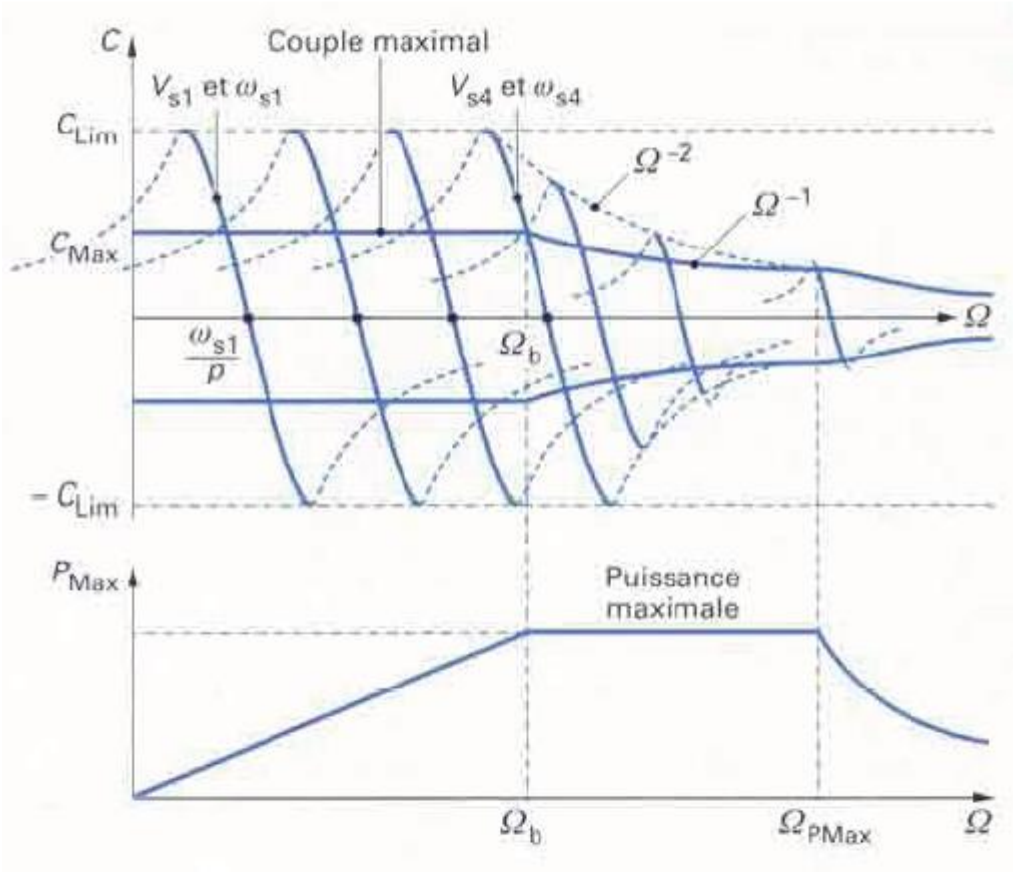




- Torque curve of AC asynchronous motor as a function of the slippage rotation speed
- If one works with a variable frequency induction voltage while keeping a constant stator flux, one modifies the torque curve of the AC induction motor

AC Asynchronous motor

- As for the separated excitation DC motors, the AC induction machines exhibit two regimes:
  - Constant max torque with a limitation of current
  - Constant power with reducing flux
  - Equivalent DC series operation



AC Asynchronous motor

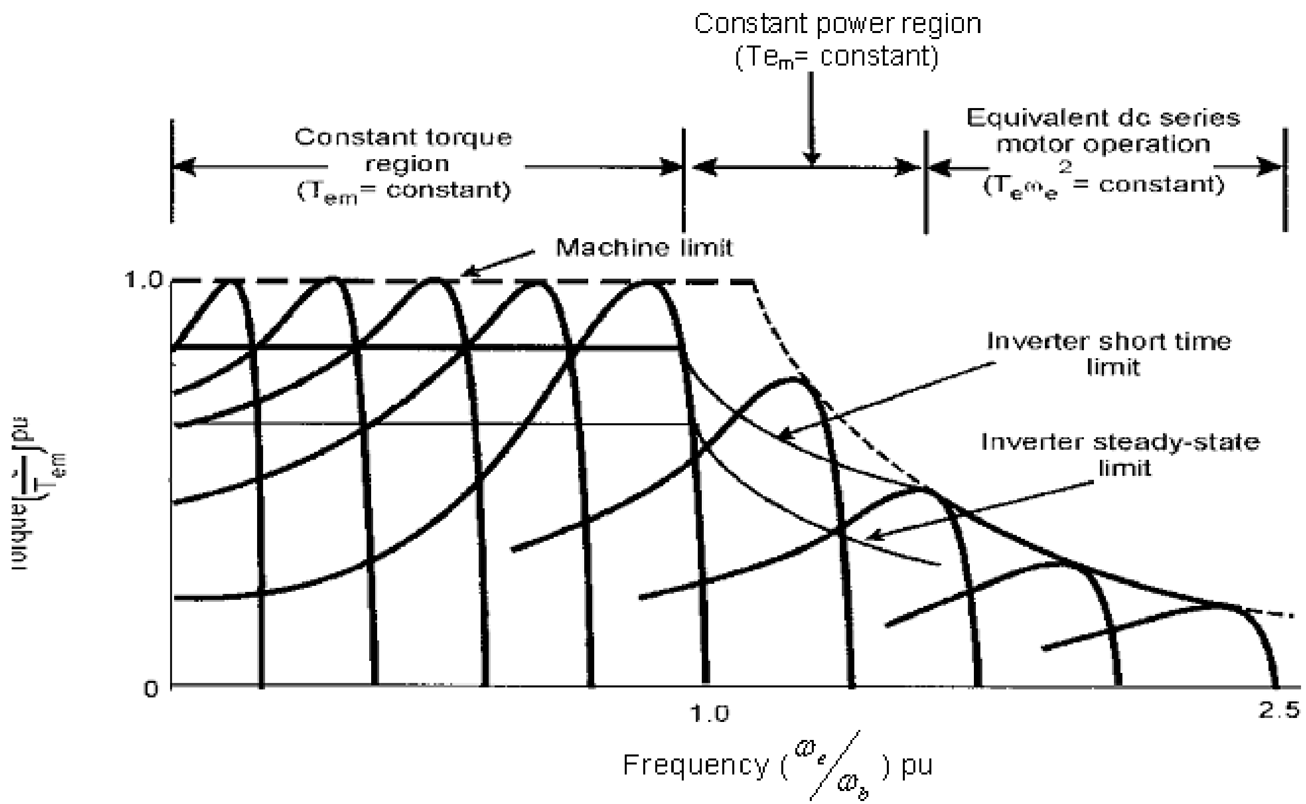
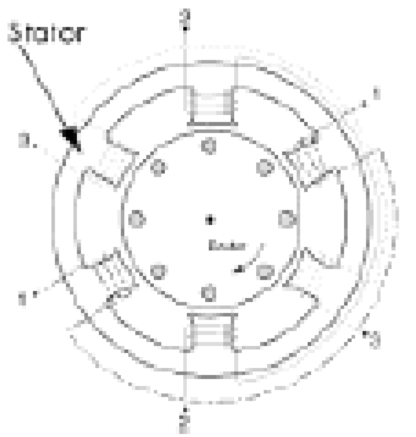
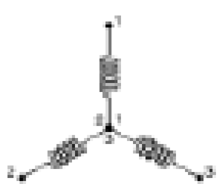


Fig-1.4 Torque-speed curves at variable voltage and variable frequency up to field-weakening region

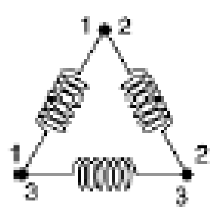
3-phase AC asynchronous motors



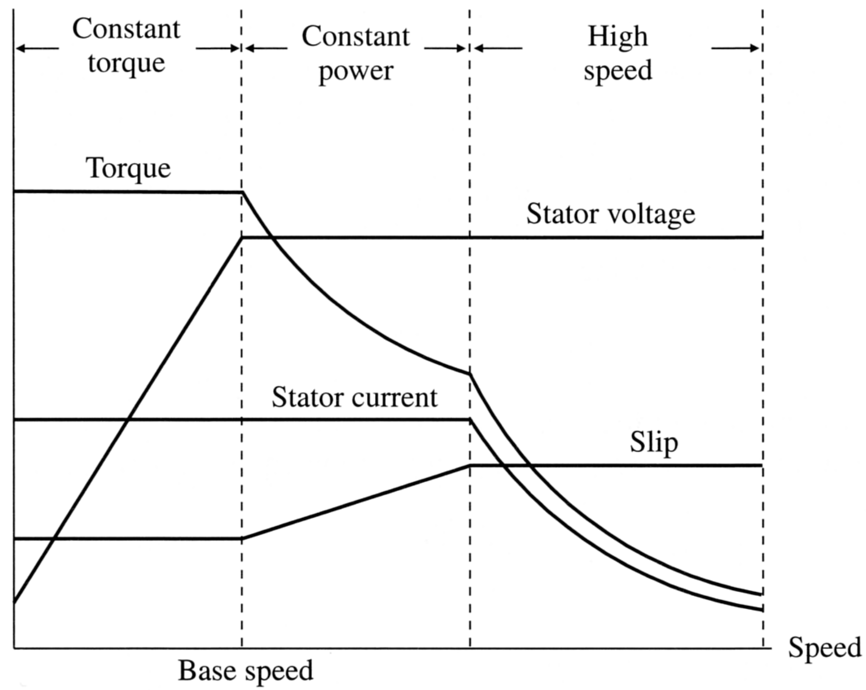
Moteur asynchrone triphasé (principe)



Montage étoile



Montage triangle



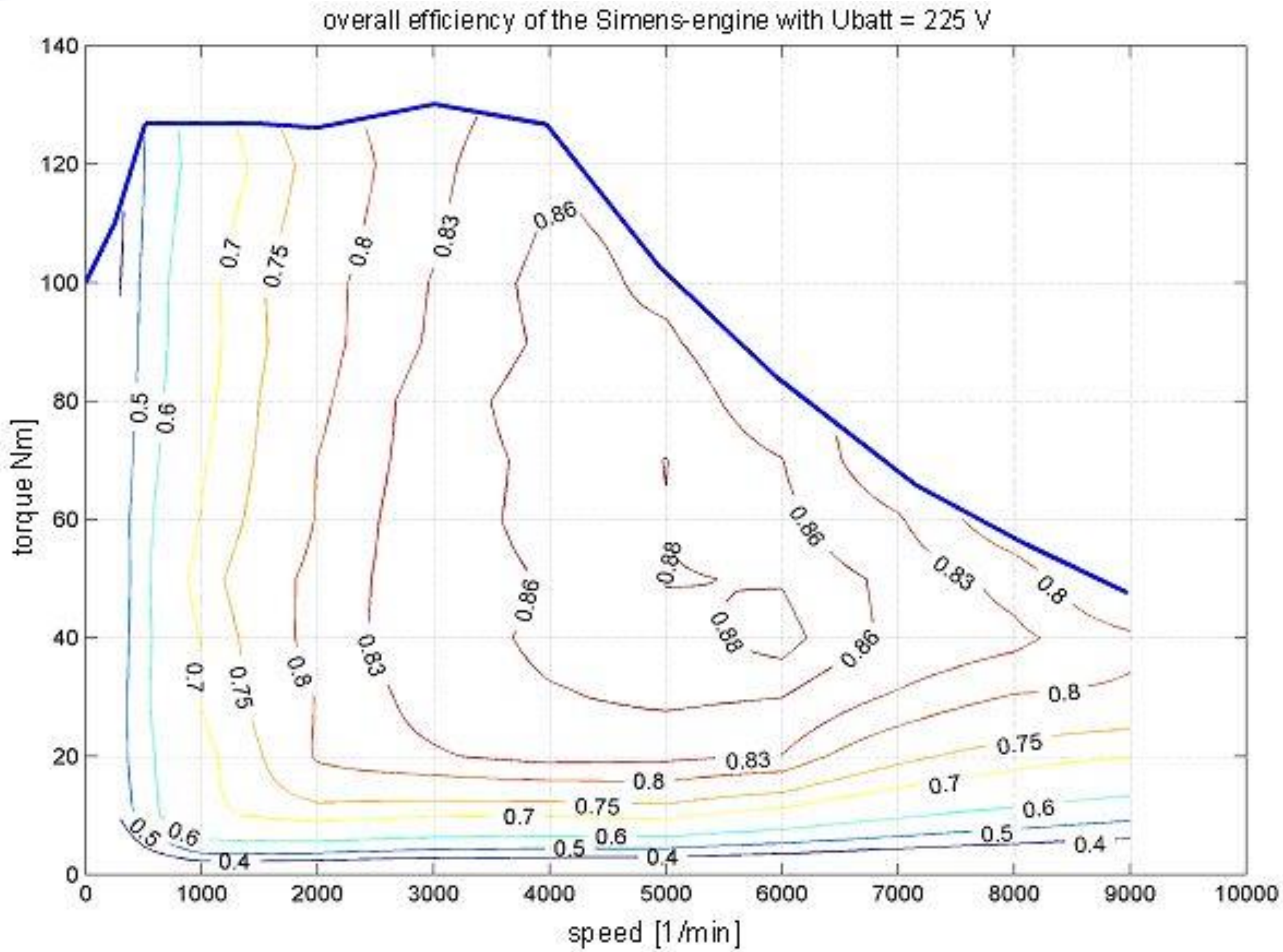
Model of torque-speed characteristics of AC asynchronous motors

3-phase AC asynchronous motors

- Advantages
  - Cost is lower (no permanent magnetic in the rotor)
  - Robustness (the swirl cage is mechanically robust, no brushes)
  - Specific power (kW/kg) is high
  - Thermal management can be made by external system (air or water cooled to reduced the rotor losses)
  - High rotation speed (15.000 to 18.000 rpm)
  - Excellent reliability and low maintenance effort

- Drawbacks
  - Efficiency is around 90% but lower than permanent magnets e-motors
  - Full control of induction motor requires a vector field command (I,V,f) which is complex and costly

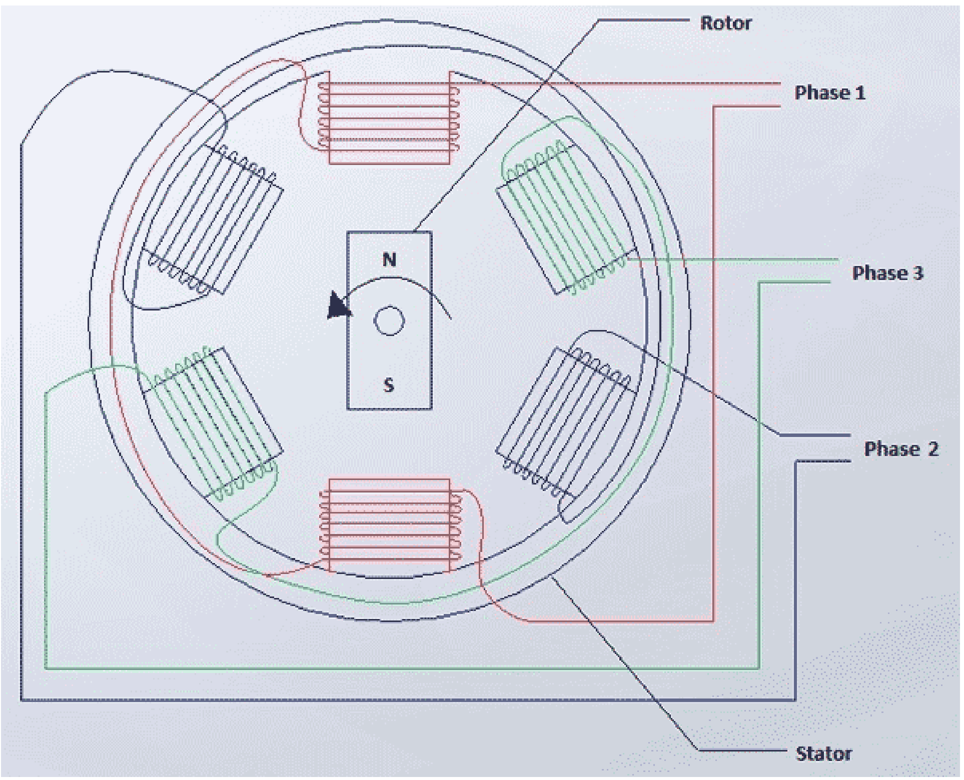
3-phase AC asynchronous motors



AC Synchronous motors

- Historically AC synchronous machines were used as generators
- More recently, synchronous machines have shown as the rising star of electric traction drives for passenger cars
- Synchronous machines are also based on the principle of a rotating magnetic field generated by stator windings
- Induction field at the rotor level can be created using two main principles
  - Winding like in DC motors with commutation
  - Permanent magnets
- Rotor spins at the same rotation speed as the external stator magnetic field
- Their command control laws are rather complex requiring a sophisticated power electronics

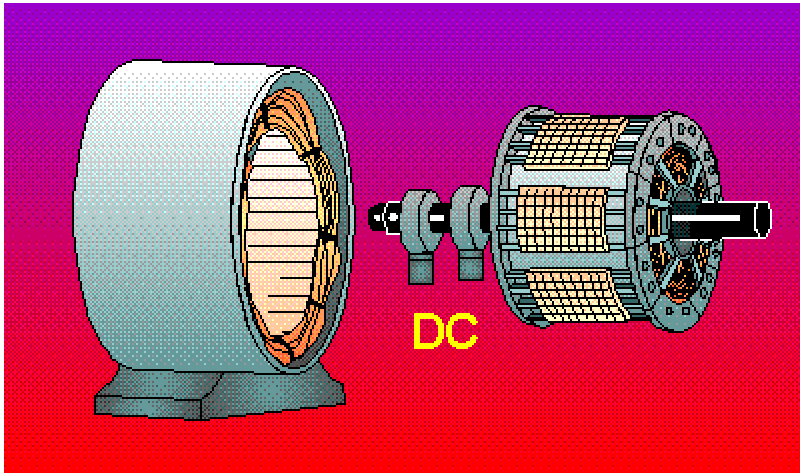
AC Synchronous motors



AC Synchronous motors

Generation of a rotor magnetic field

- Winding (synchronous machine with wound rotor)
  - Modulation of the rotor field using a chopper (like a DC machine)
  - Enables the optimized control at high speed
  - Electric commutation with the brushes and the chopper
  - Extra cost and lower reliability



AC Synchronous motors

Generation of a rotor magnetic field

- Permanent magnets (Synchronous machine with permanent magnets) to create the rotor flux
  - High conversion efficiency even at part load (> 90%)
  - High energy density (3kW/kg) and volumetric energy
  - Reliability and maintenance operations similar to induction machine

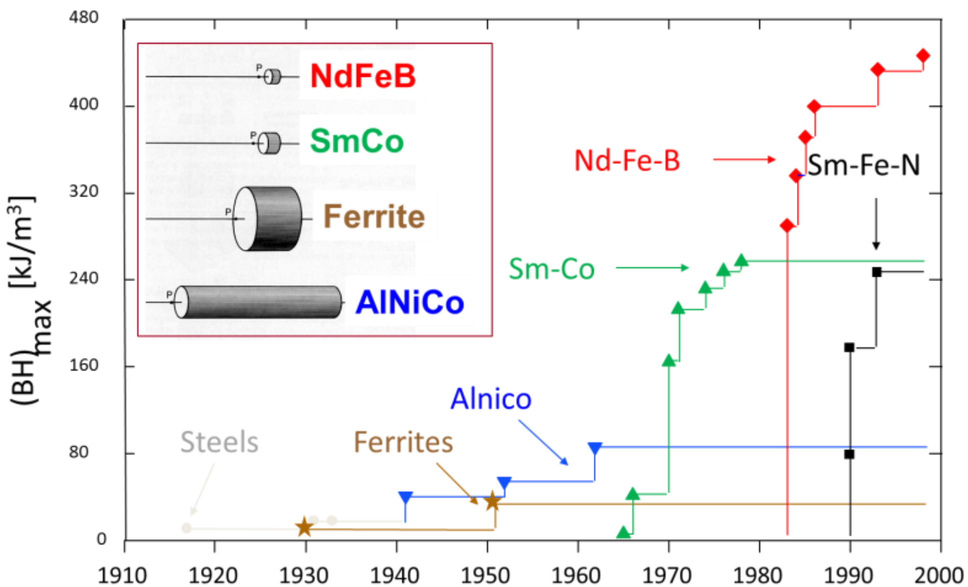
AC Synchronous motors

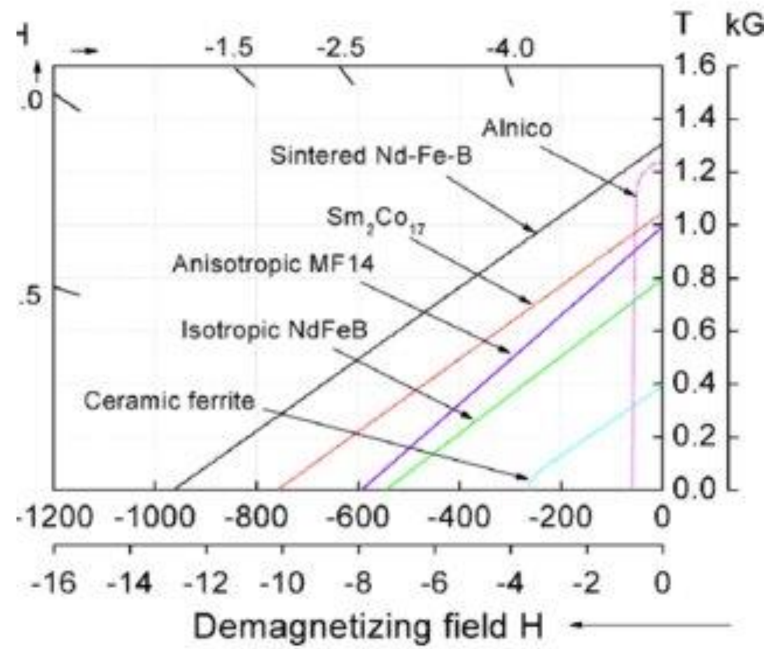
Generation of a rotor magnetic field

- Permanent magnets (Synchronous machine with permanent magnets)
  - Control is delicate: acceleration from rest, shocks at low rotation speed
  - It is possible to loose the permanent field in high flux operation and high temperature operations
  - Permanent magnets → rare earth: raw materials?
  - Examples:
    - Neodymium Fer Bore (NdFeB)
    - Samarium Cobalt (SmCo)
    - Aluminium, Nickel, Cobalt (AlNiCo)

AC Synchronous motors

- Permanent magnets materials





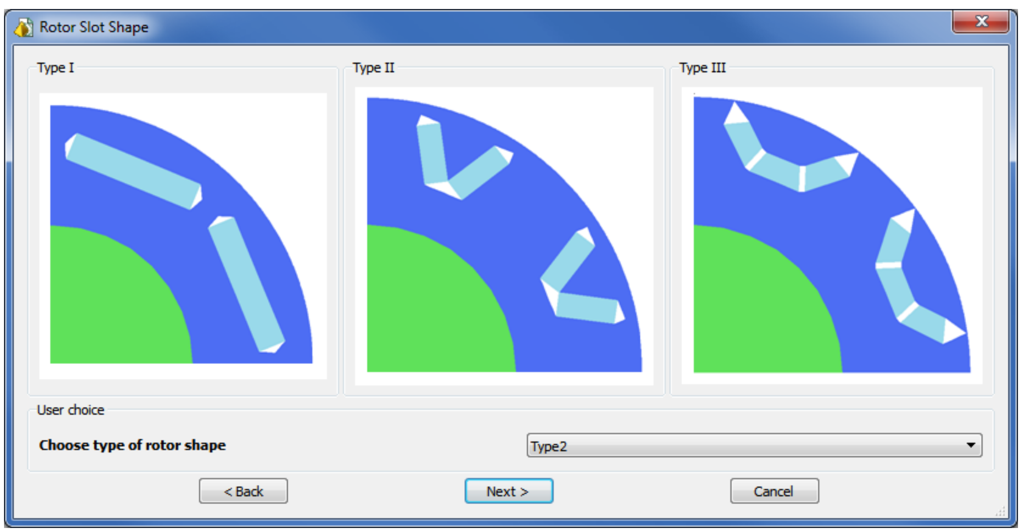
AC Synchronous motors

PM e-motors by UQM

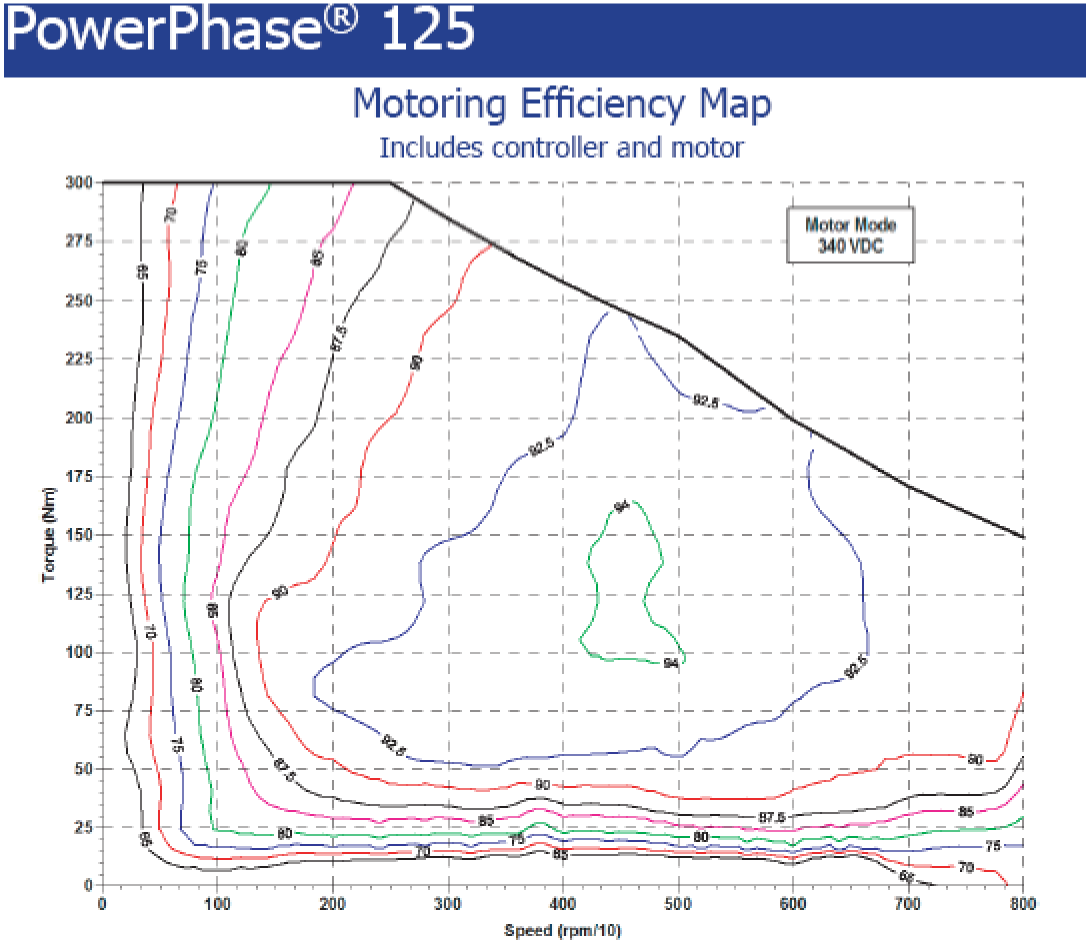
AC Synchronous PM motors

SPM (Surface Permanent Magnet)

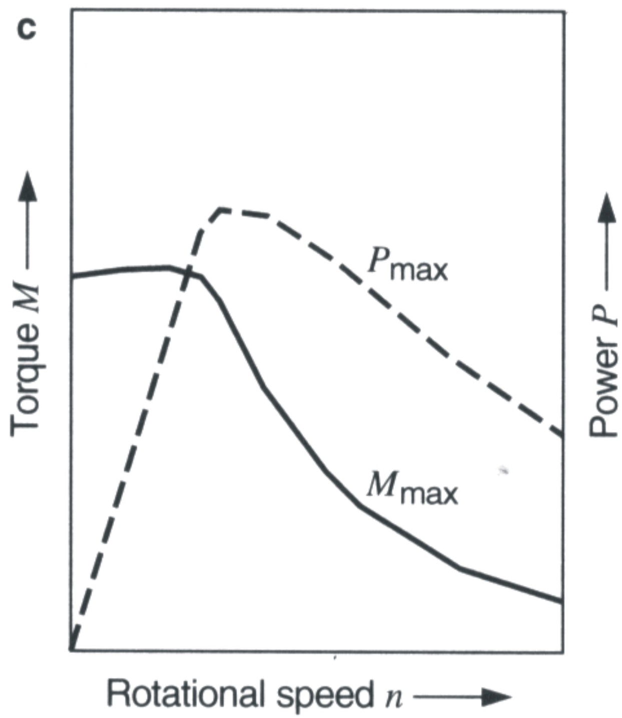
IPM (Interior Permanent Magnet)

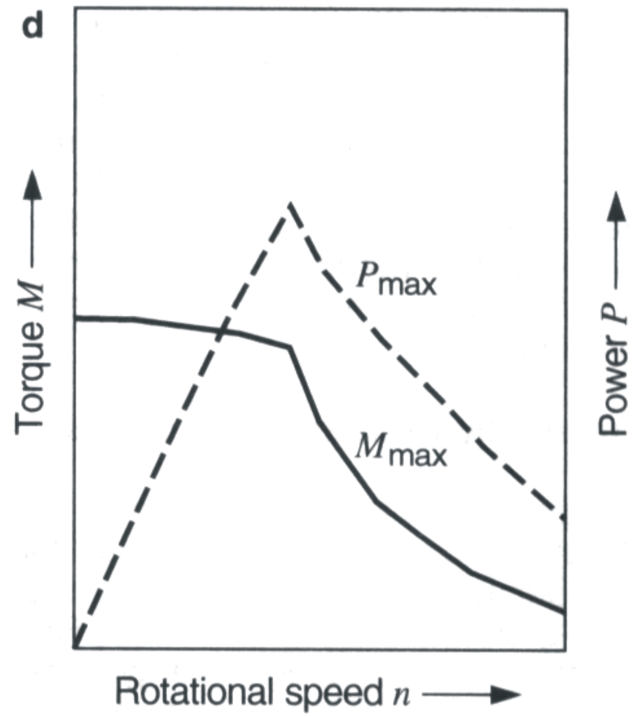


AC Synchronous PM motors



AC motors: induction vs synchronous

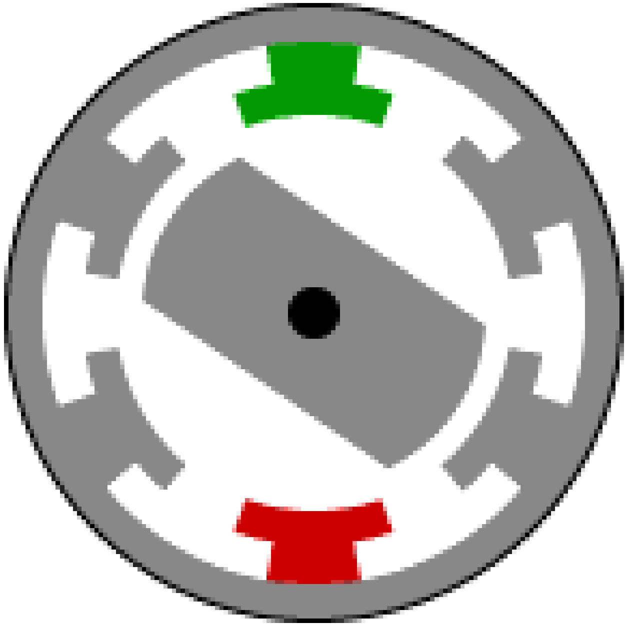


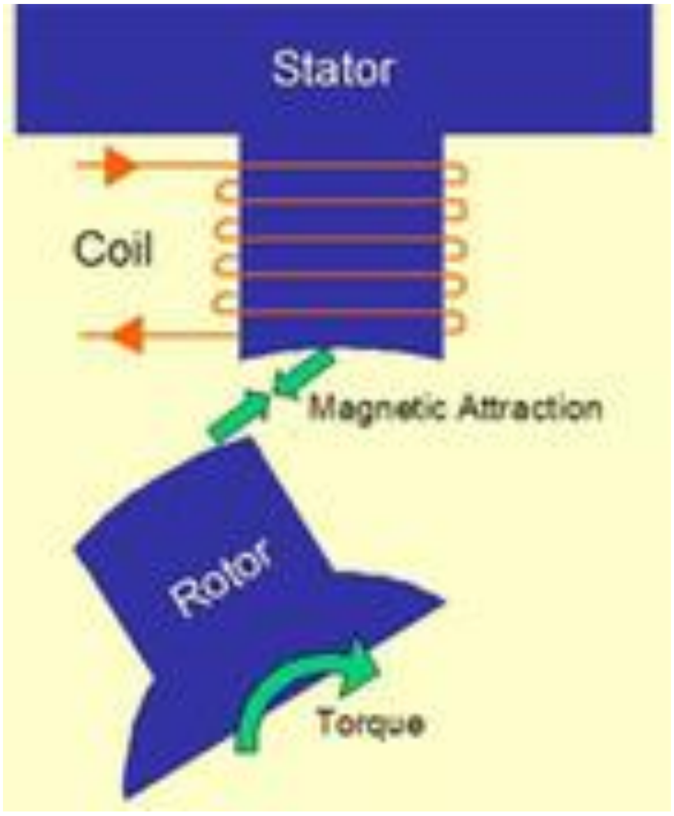


AC induction motor

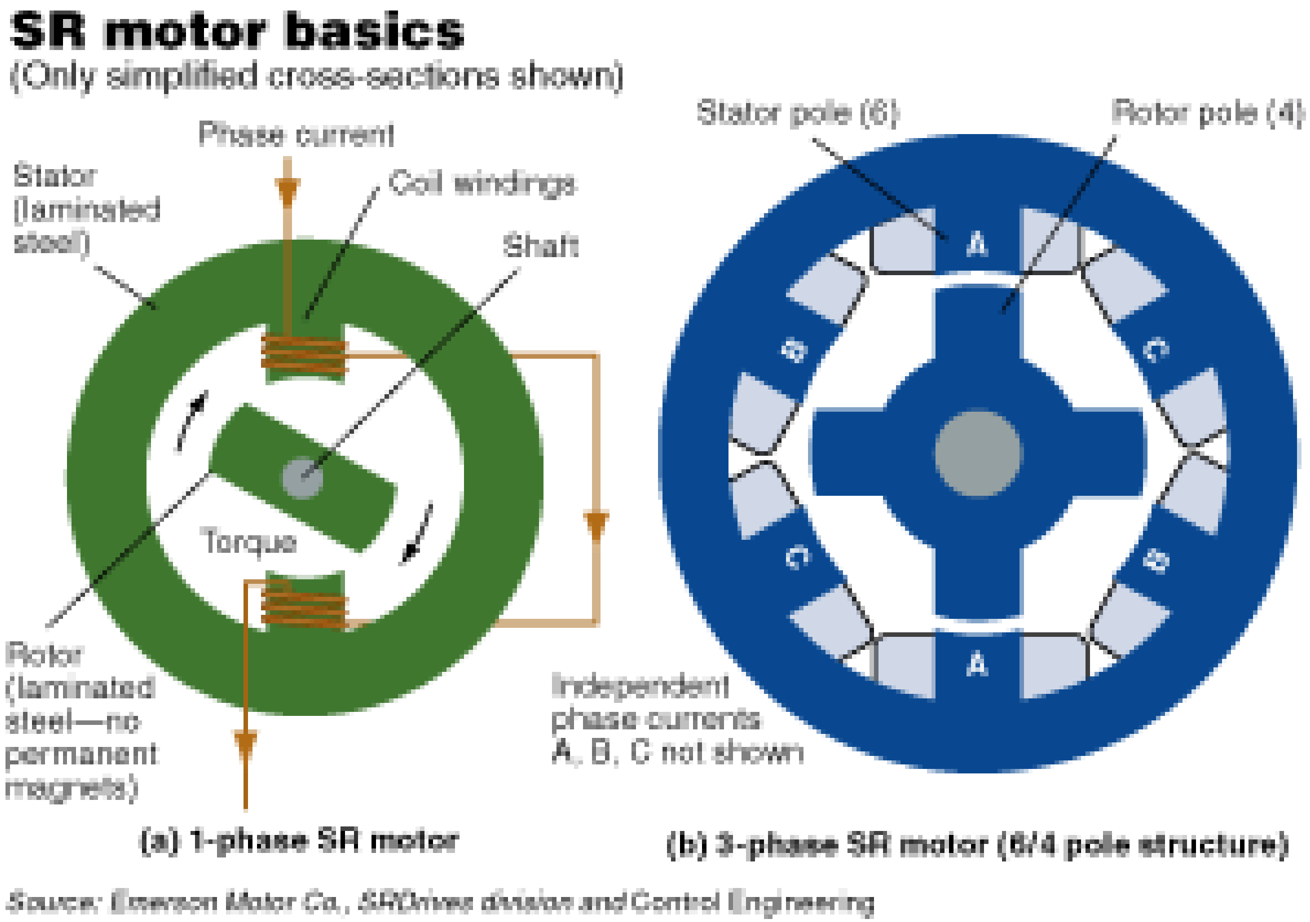
AC synchronous motor

Switched Reluctance e-Motors

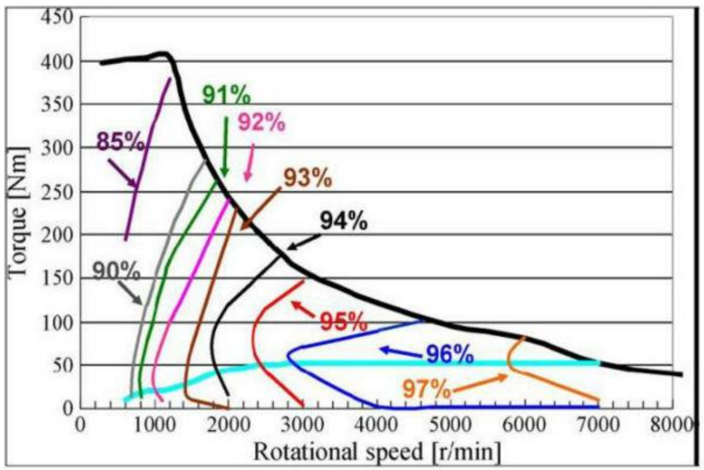


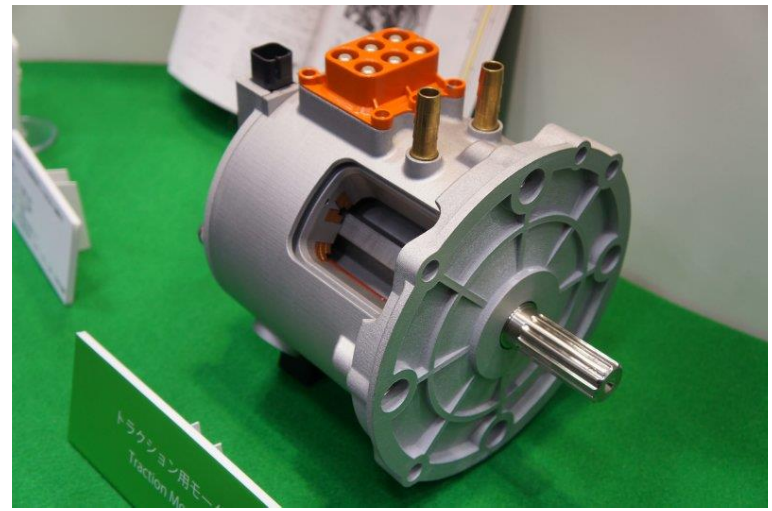


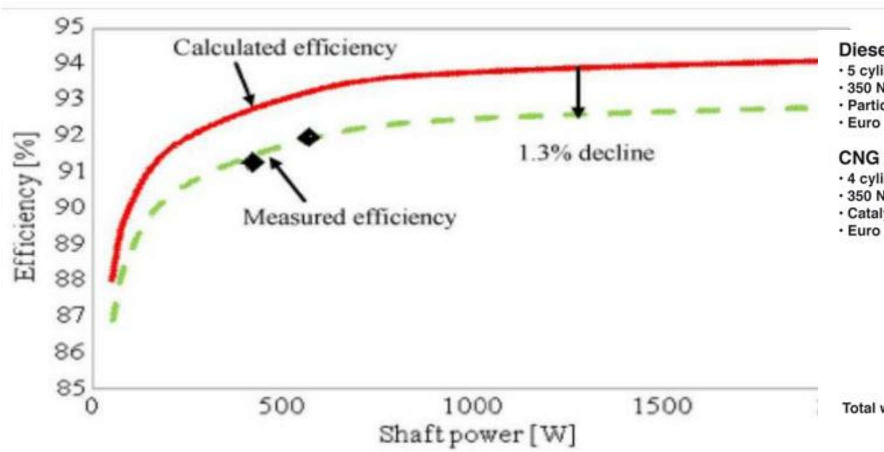
Switched Reluctance e-Motors

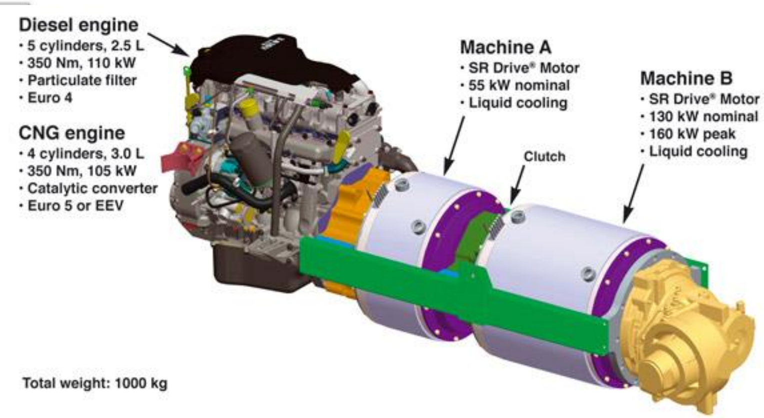


Switched Reluctance e-Motors

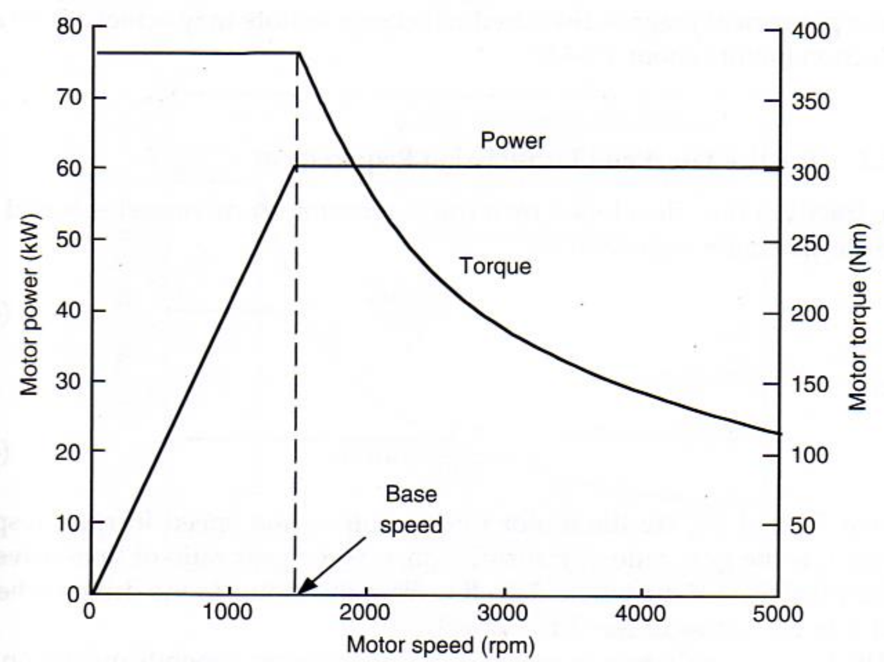






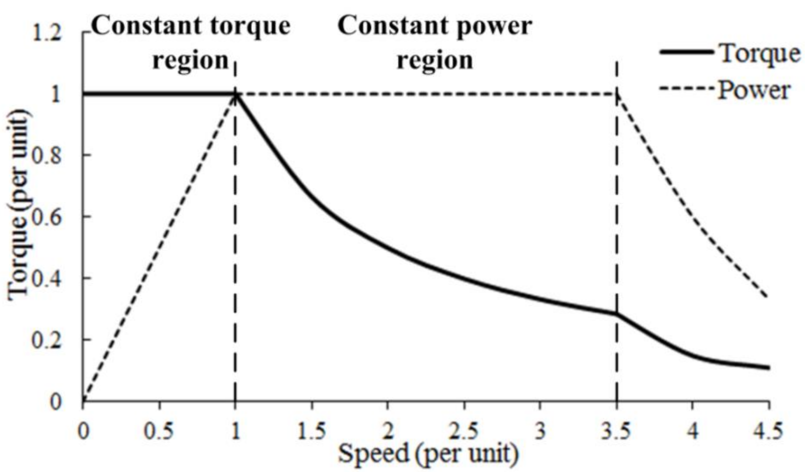


Traction motor characteristics



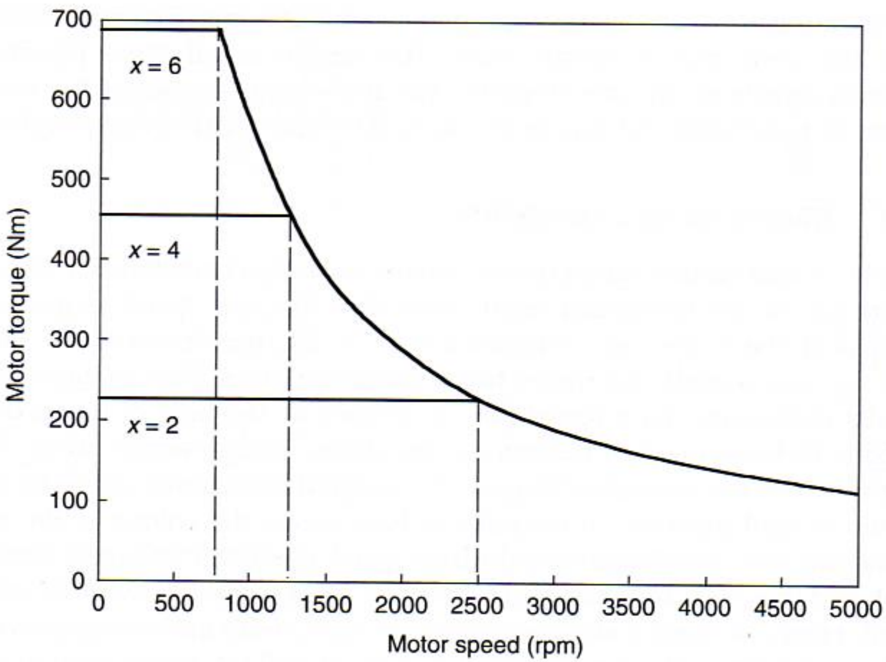
- At low speed: constant torque
  - Voltage supply increases with rotation speed through electronic converter while flux is kept constant
- At high speed: constant power
  - Motor voltage is kept constant while flux is weakened, reduced hyperbolically with the rotation speed
- Base speed: transition speed from constant torque to constant power regime

Traction motor characteristics



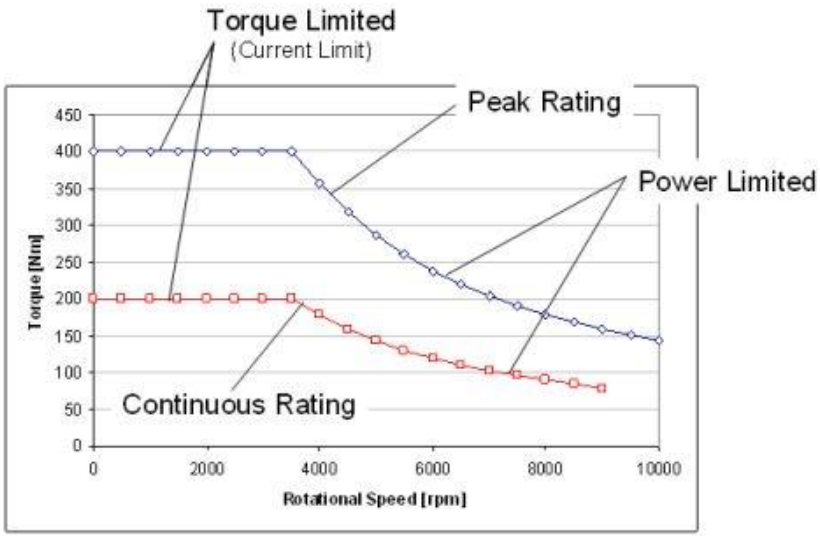
- Independently from the motor technology, the global performance of the combined motor and its power electronic system offer three regimes
  - In low regimes, the current is limited, and the torque is kept constant
  - Then, power remains constant, which means that the maximum torque is reduced as P/N
  - At very high speed: the max power regime can not be maintained and power drops. Generally, this part is not considered in the EV design.

Traction motor characteristics



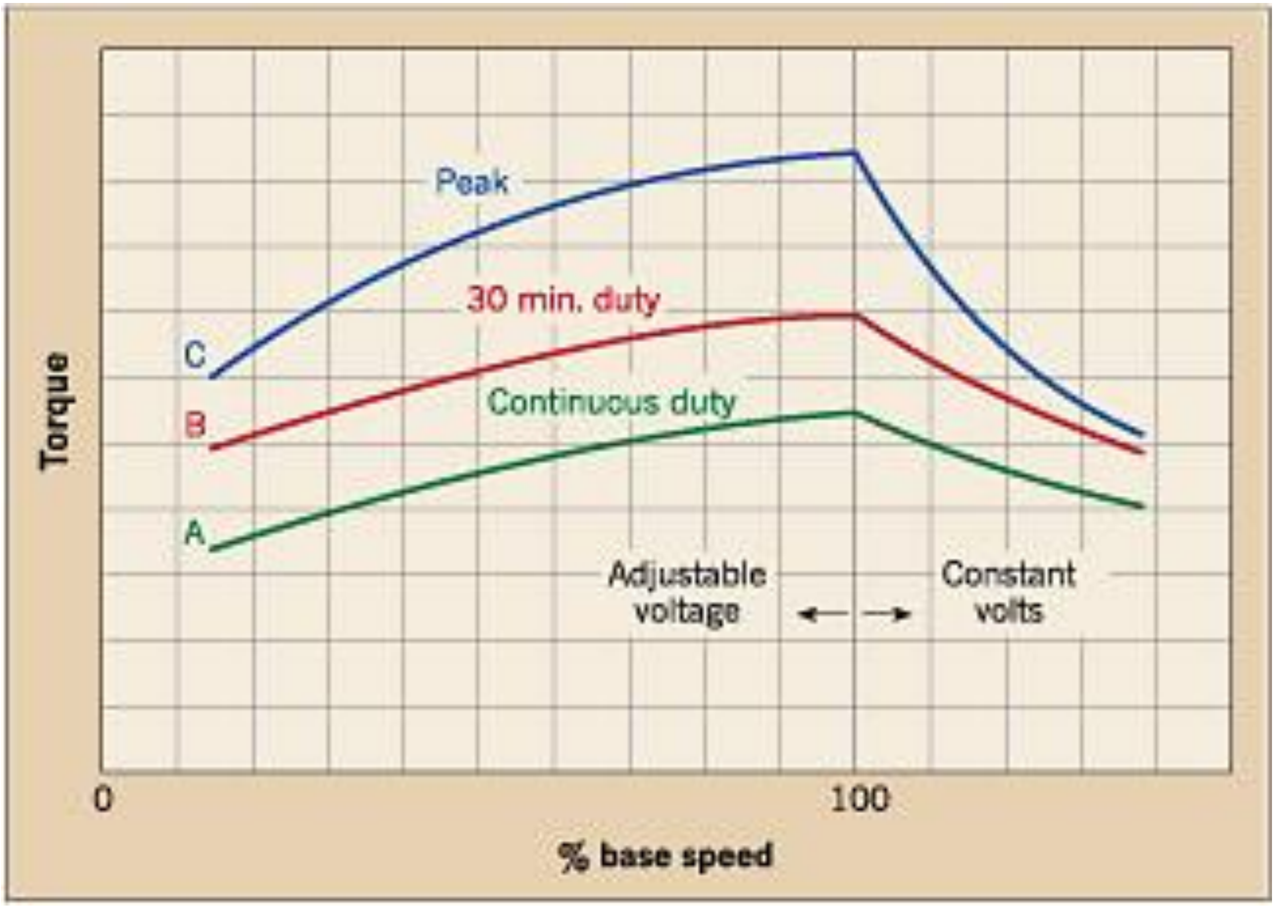
- Speed ratio x = ratio between the maximum rotation speed to base speed
  - X ~ 2 Permanent Magnet motors
  - X ~ 4 Induction Motors (IM)
  - X ~ 6 Switched Reluctance motors
- For a given power, a long constant power region (large x) gives rise to an important constant torque, and so high vehicle acceleration and large gradeability. Thus, the transmission can be simplified.

Traction motor characteristics



- Traction electric motors are able to sustain overcharging during a short period of time, typically 1 to 2 minutes.
- Overcharging factor depends on the electric motor technology but it can be as high as 2 to 4.
- Thus, one has also to distinguish the continuous power from the peak power (which is much higher)
- One can admit as a basic approximation that both regimes can be deduced from each other by constant scaling factor

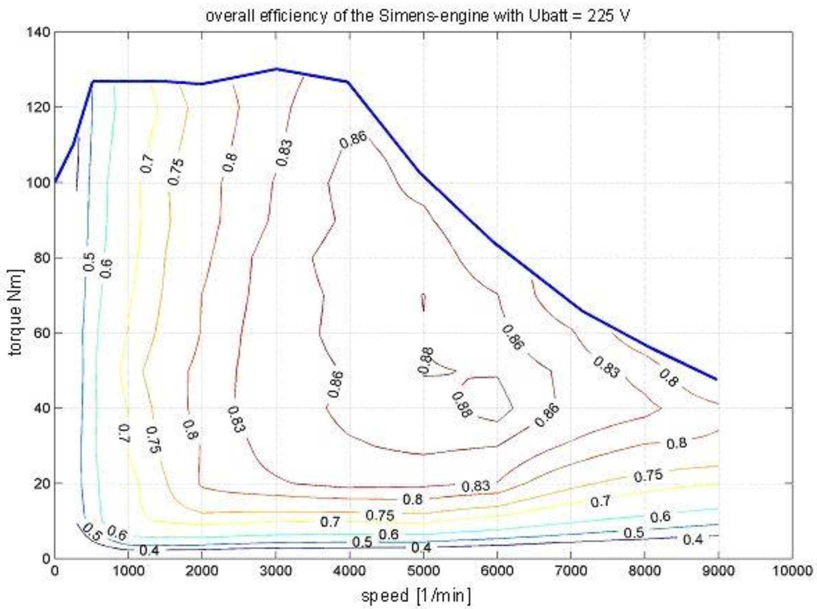
Continuous and peak regimes



Traction motor characteristics

- Electric machine efficiency of transformation of the electric power to mechanical power is dependent on the torque speed operating conditions

$$\eta_{e-M} = \frac{\mathcal{P}_{\mathrm{MECA}}}{\mathcal{P}_{\mathrm{ELEC}}}$$



- It can be mapped on the torque/power-speed space
- The efficiency mapping can be different when working as a motor (generally lower) than as a generator (often better)