Vehicle Performance

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Lesson 2: Power sources

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

- T. Gillespie. « Fundamentals of vehicle Dynamics », 1992, Society of Automotive Engineers (SAE)
- J.Y. Wong. « Theory of Ground Vehicles ». John Wiley & sons. 1993 (2nd edition) 2001 (3rd edition).
- W.H. Hucho. « Aerodynamics of Road Vehicles ». 4th edition. SAE International. 1998.
- M. Eshani, Y. Gao & A. Emadi. Modern Electric, Hybrid Electric and Fuel Cell Vehicles. Fundamentals, Theory and Design. 2nd Edition. CRC Press.
- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)

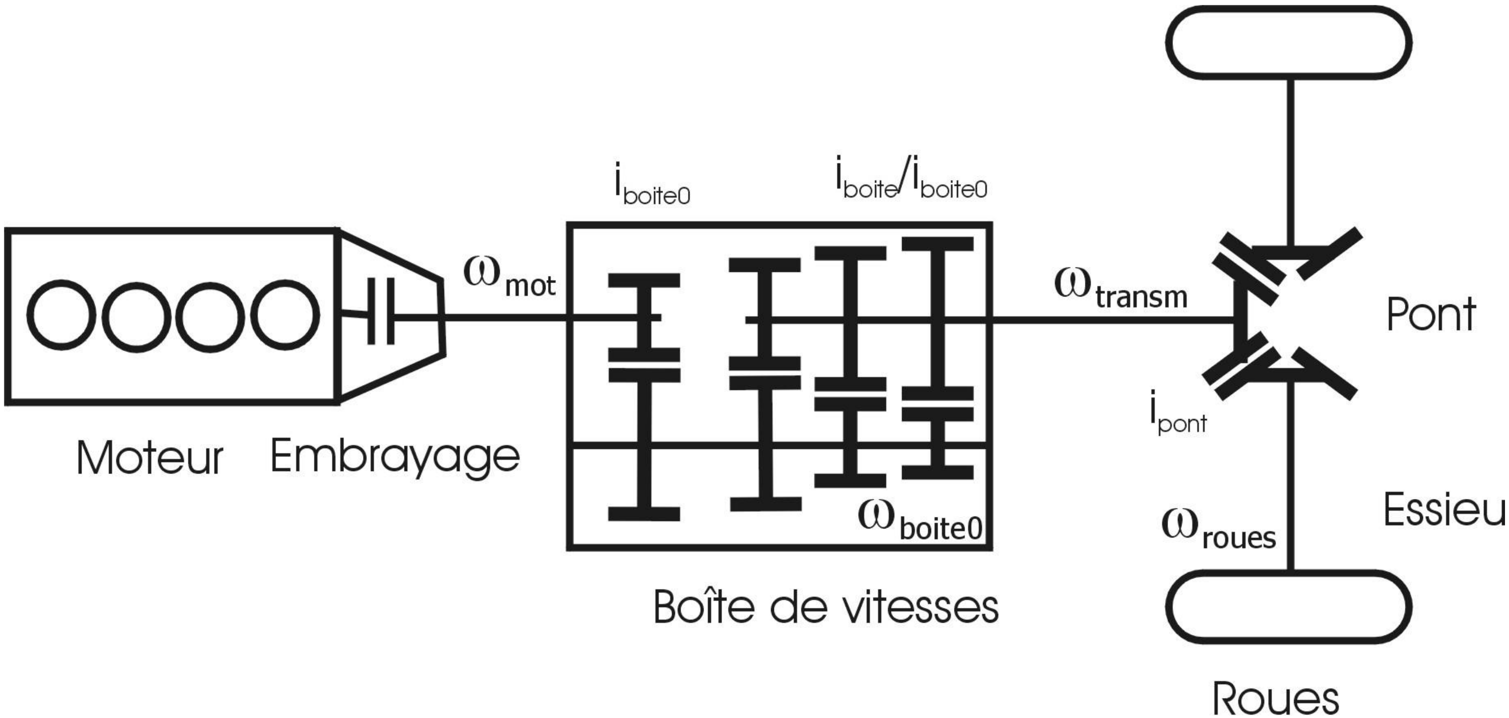
Introduction and Motivation

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…

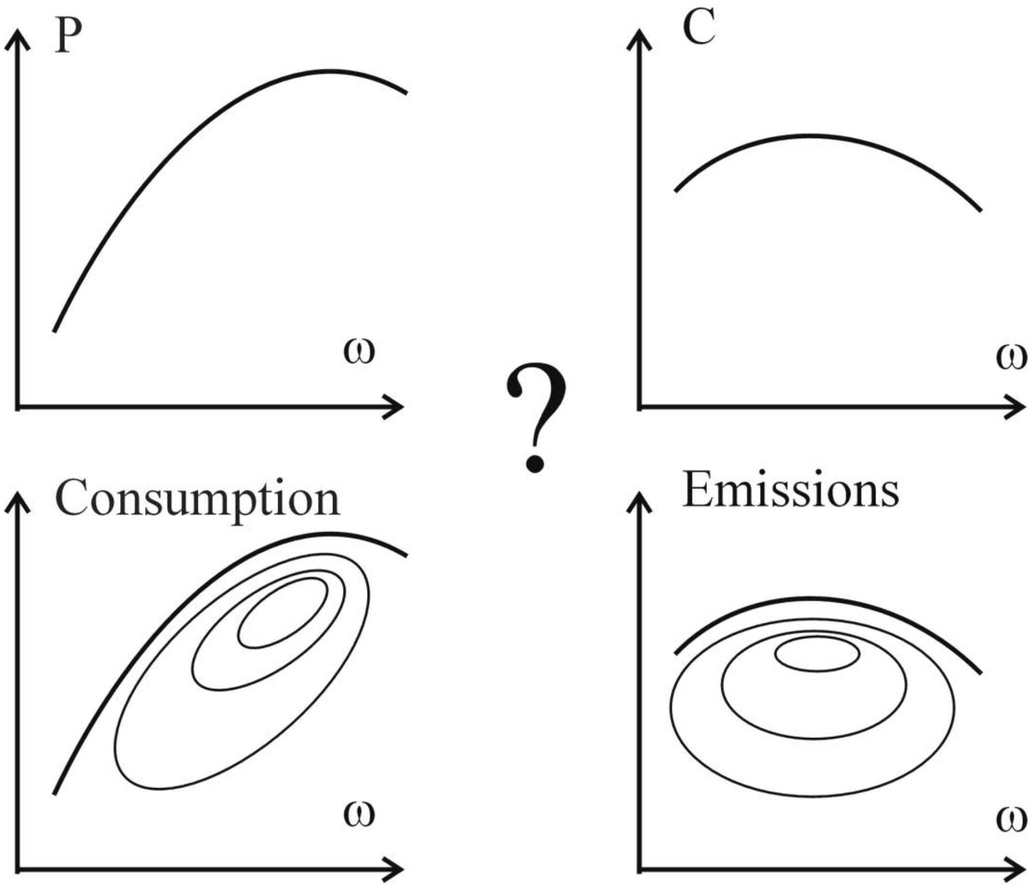
Motivation

- Vehicle model as a system made of components



Motivation

- Performance curves



Motivation

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

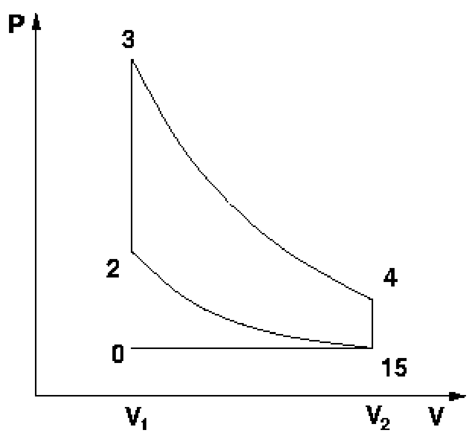
Piston engines

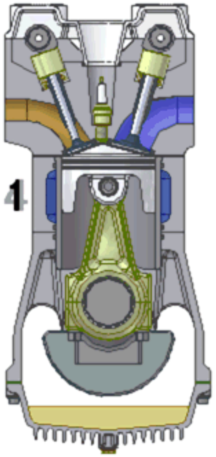
Piston engines

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

4 stroke engines: gasoline

- In 1862, Beau de Rochas developed an operation sequence that is still now the basis of any piston engine operations
- His cycle is the basis of the Otto's engine or spark ignited engine
- The 4-stroke engine requires to 2 crankshaft revolutions to accomplish one thermodynamic cycle, which means 4 stroke motions of the piston.



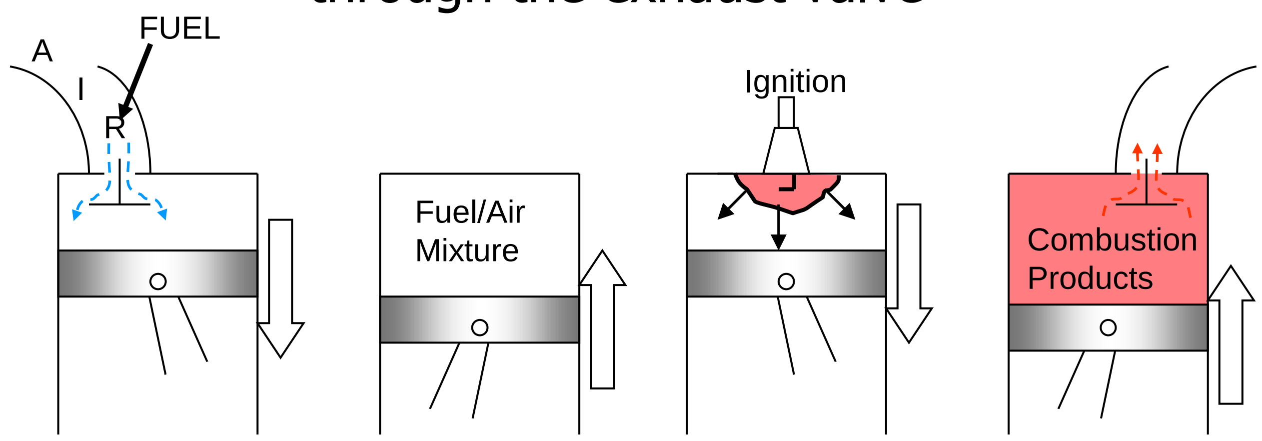


Beau de Rochas

Nikolaus Otto

4 stroke engines: gasoline

- Stroke 1: Fuel-air mixture introduced into cylinder through intake valve
- Stroke 2: Fuel-air mixture compressed
- Stroke 3: Combustion (roughly constant volume) occurs, and product gases expand producing work
- Stroke 4: Product gases are pushed out of the cylinder through the exhaust valve



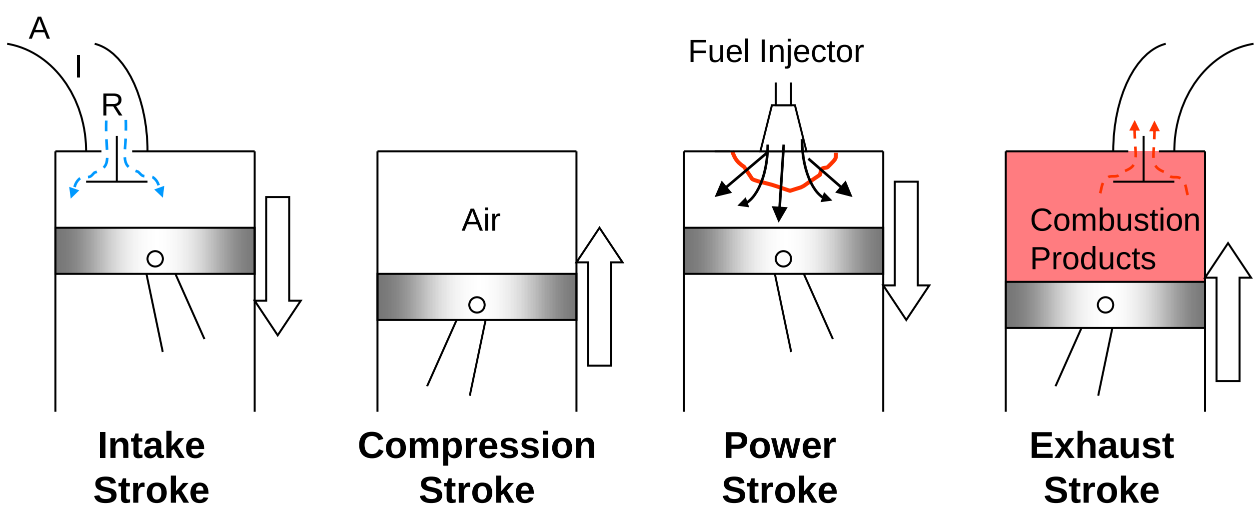
Intake Stroke **Compression Stroke** **Power Stroke** **Exhaust Stroke**

4 stroke engines: diesel

- The four stroke Compression Ignition (CI) Engine is generally denoted as the Diesel engine
- The cycle is similar to Otto’s one albeit that it requires a high compression ratio and a low dilution (air fuel) ratio.
- Air (alone) is admitted in the chamber and then compressed. The temperature / pressure condition rises the ignition point and then the fuel is injected at high pressure. It can inflame spontaneously.
- There is no need for a spark and so stoichiometric air fuel ratio is not necessary.

4 stroke engines: diesel

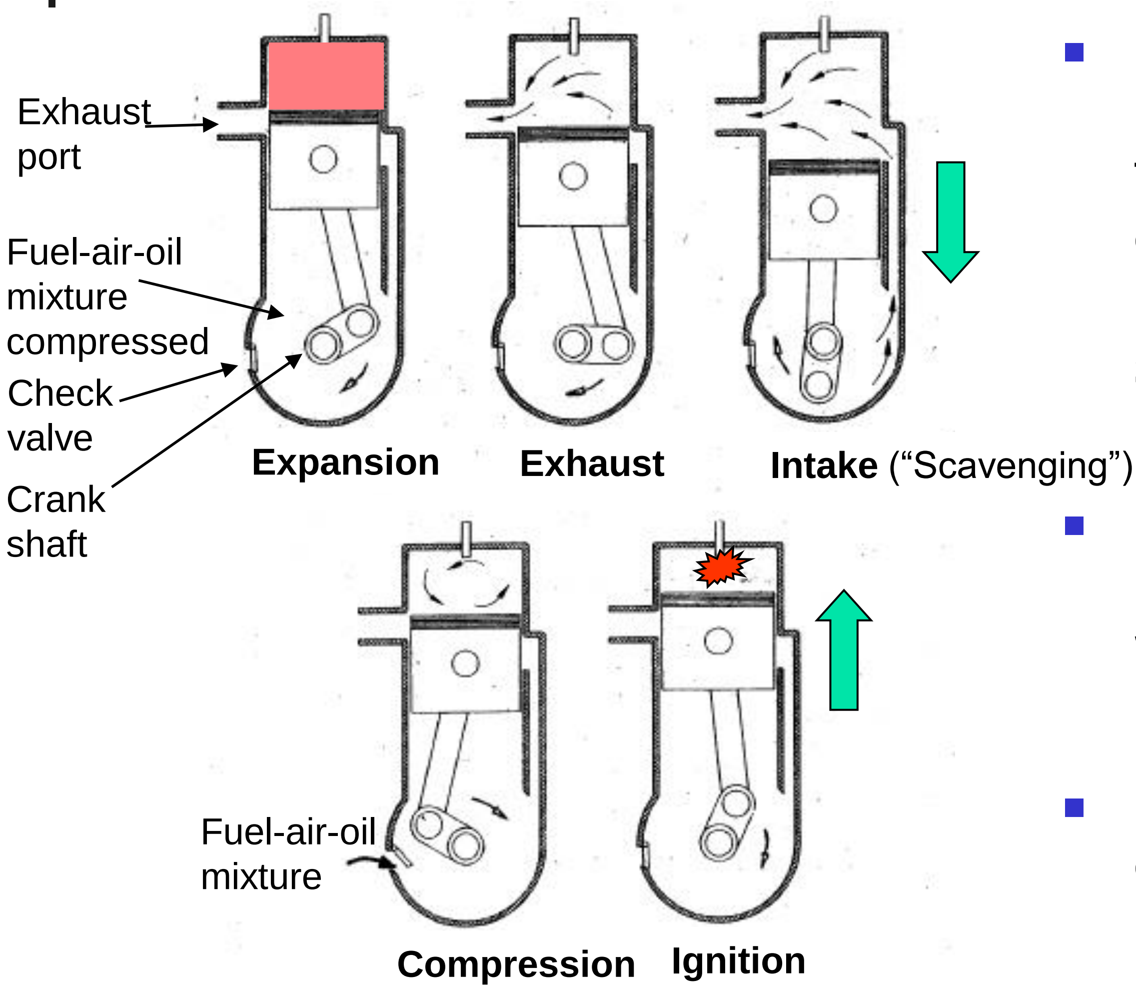
- Stroke 1: Air is introduced into cylinder through intake valve
- Stroke 2: Air is compressed
- Stroke 3: Combustion (roughly constant pressure) occurs and product gases expand doing work
- Stroke 4: Product gases are pushed out of the cylinder through the exhaust valve



2-stroke engines

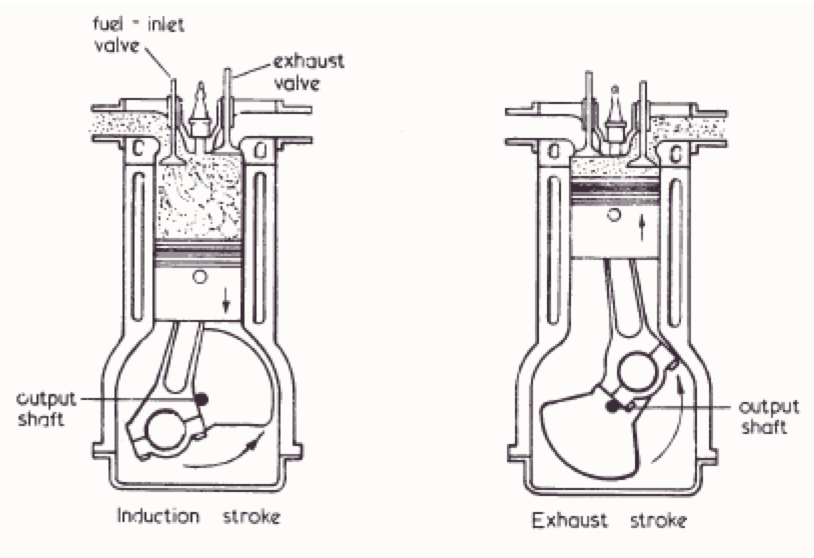
- Dugald Clerk invented the 2-stroke engine in 1878 in order to increase the power to weight ratio for an equal engine volume.
- The 2-stroke engines are also simpler with regards to the valve system
- The 2-stroke principle is applicable to both spark ignition engines and compression ignition engines. It is however more usual with spark ignition engines.
- The 2-stroke engine involves two strokes, and the cycle is carried out during one single crankshaft revolution.

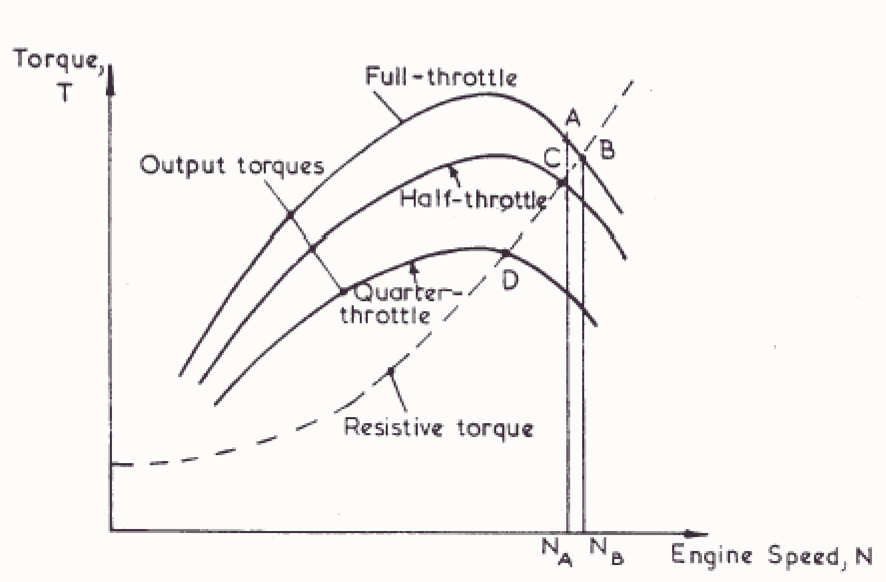
2-stroke engines



- Stroke 1: Fuel-air mixture is introduced into the cylinder and is then compressed, combustion initiated at the end of the stroke
- Stroke 2: Combustion products expand doing work and then exhausted
- Power delivered to the crankshaft on every revolution

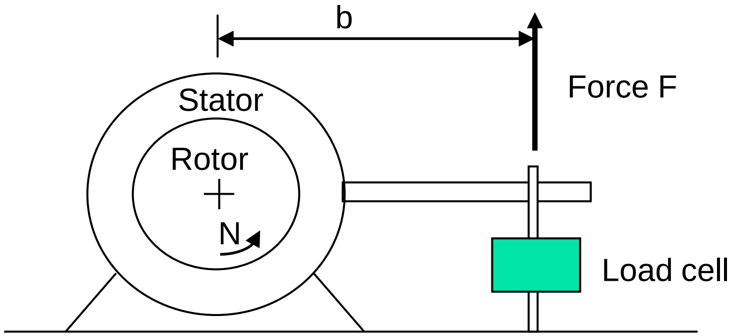
Torque-speed curves of ICE engines





Measure of torque and power developed by the engine

- The torque is measured on the output shaft mounted on the crankshaft using a dynamometer



- The torque C developed by the engine is given by

$$\mathcal{C} = F \cdot b \quad [\mathrm{J} = \mathrm{N.m}]$$

- The power absorbed by the brake is the product of the torque times the rotation speed N [tr/s]

$$\dot{W} = \mathcal{C} \cdot \omega = \mathcal{C} \cdot 2\pi \cdot \omega \quad [\mathrm{Watt} = \mathrm{N.m.rad/s}]$$

Measure of torque and power developed by the engine

- Torque is the ability of the engine to produce a work while power describes the rate at which it is able to develop that work.

- The term effective power, developed at the brake, is used to describe the power measured at the output shaft, which is the usable and transferable power to the load: $\dot{W}_b$

- The brake power is lower than the (indicated) power generated by the gas in the cylinders because of friction losses and parasitic loads of the auxiliaries (water and oil pumps, compressor...).

- The power produced in the cylinder by the working fluid is called the indicated power: $\dot{W}_i$

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:

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

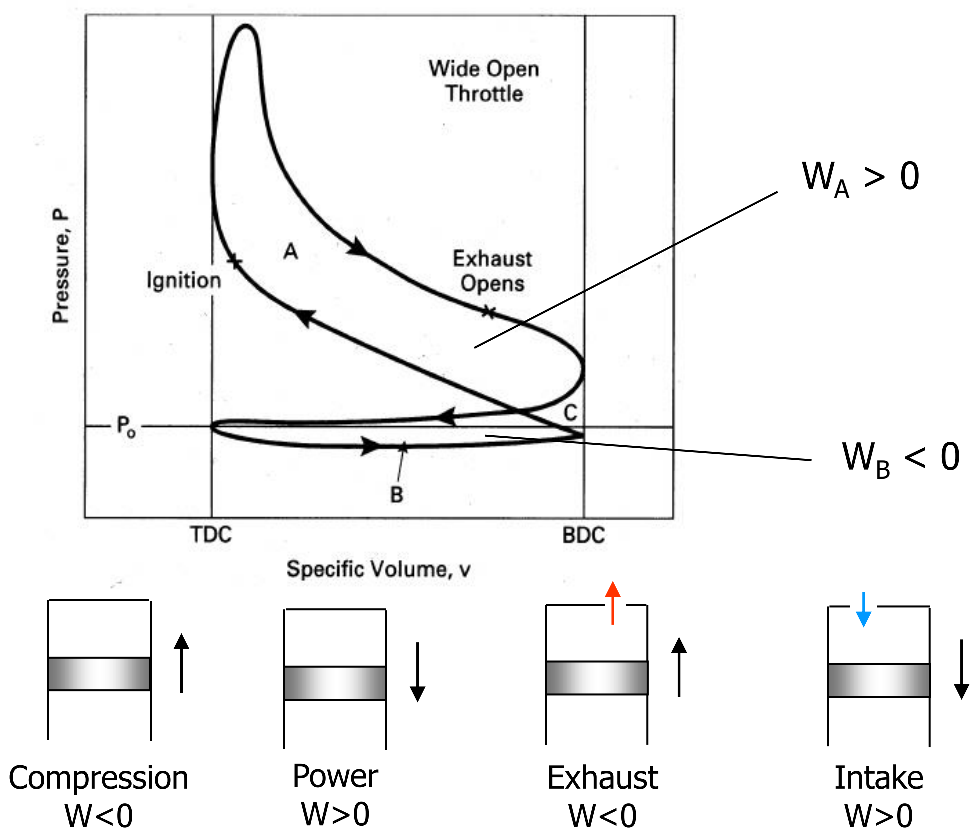
Engine mechanical efficiency

- 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.

Measure of indicated torque and power



- Given the cylinder pressure data over the operating cycle of the engine one can calculate the work done by the gas on the piston.
- This data is typically given as p vs V
- The <u>indicated work</u> per cycle is given by

$$W_i = \oint p\, dV$$

Measure of torque and power developed by the engine

- Indicated power is given by

$$\dot{W}_i = \frac{W_i \dot{N}}{n_R}$$

- where
  - N – crankshaft speed in rev/s
  - n_R – number of crank revolutions per cycle
    - = 2 for 4-stroke
    - = 1 for 2-stroke

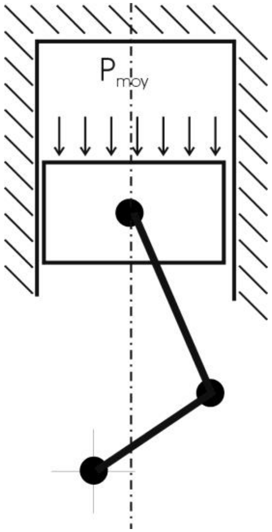
- Power can be increased by increasing:
  - the engine size, V_d
  - compression ratio, r_c
  - engine speed, N

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

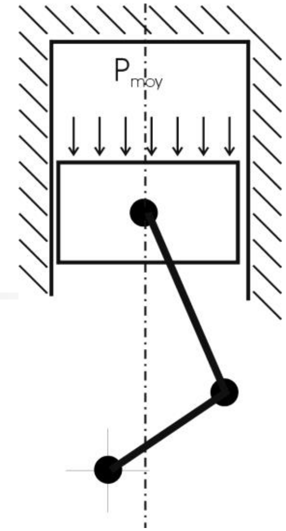
$$W_{1stroke}^{1cyl} = \text{imep}.\frac{\pi B^2}{4}.l = \text{imep}.V_{1cyl}$$



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

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

Mean effective pressure



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

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

- 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

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

- And the torque writes

$$C_i = \frac{\dot{W}_i}{\omega} = \mathrm{imep}\frac{V_d}{2.n_R.\pi}$$

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

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

- *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 weakly dependent of engine speed, N, and of 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

$$\text{bmep} = \frac{W_b}{V_d} = \frac{\dot{W}_b.n_R}{V_d.N} \quad \rightarrow \quad C_b = \frac{\dot{W}_i}{\omega} = \text{bmep}\frac{V_d}{2.n_R.\pi}$$

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

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%

Brake and indicated mean effective pressure

Vehicle	Engine type	Displ. (L)	Max Power (HP@rpm)	Max Torque (lb-ft@rpm)	BMEP at Max BT (bar)	BMEP at Rated BP (bar)
Mazda Protégé LX	L4	1.839	122@6000	117@4000	10.8	9.9
Honda Accord EX	L4	2.254	150@5700	152@4900	11.4	10.4
Mazda Millenia S	L4 Turbo	2.255	210@5300	210@3500	15.9	15.7
BMW 328i	L6	2.793	190@5300	206@3950	12.6	11.5
Ferrari F355 GTS	V8	3.496	375@8250	268@6000	13.1	11.6
Ferrari 456 GT	V12	5.474	436@6250	398@4500	12.4	11.4
Lamborghini Diablo VT	V12	5.707	492@7000	427@5200	12.7	11.0

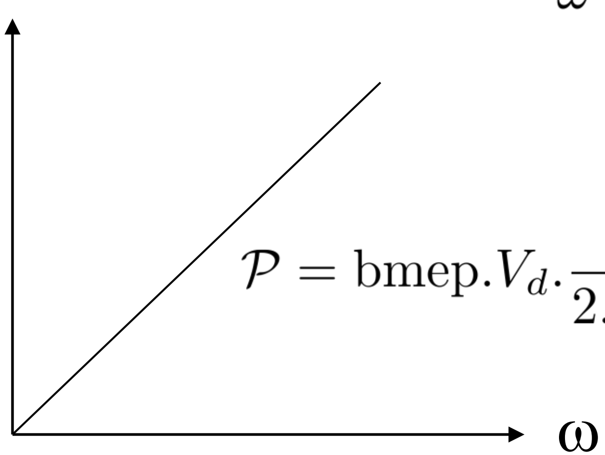
Torque speed curves of ICE

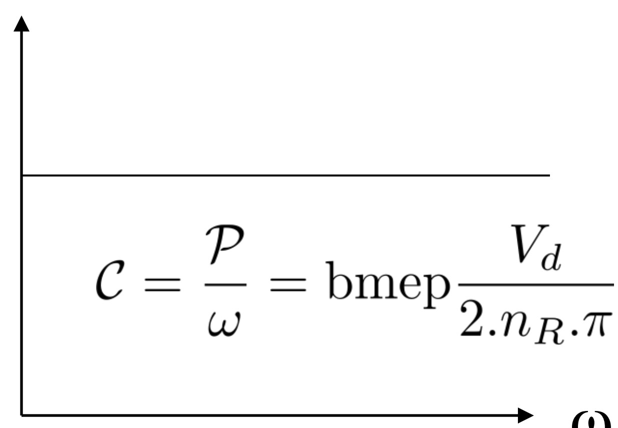
- It comes the power curves with respect to rotation speed:

$$\mathcal{P} = \dot{W}_b = \text{bmep}.V_d.\frac{\omega}{2.n_R\pi} = \text{bmep}.V_d.\frac{N}{n_R}$$

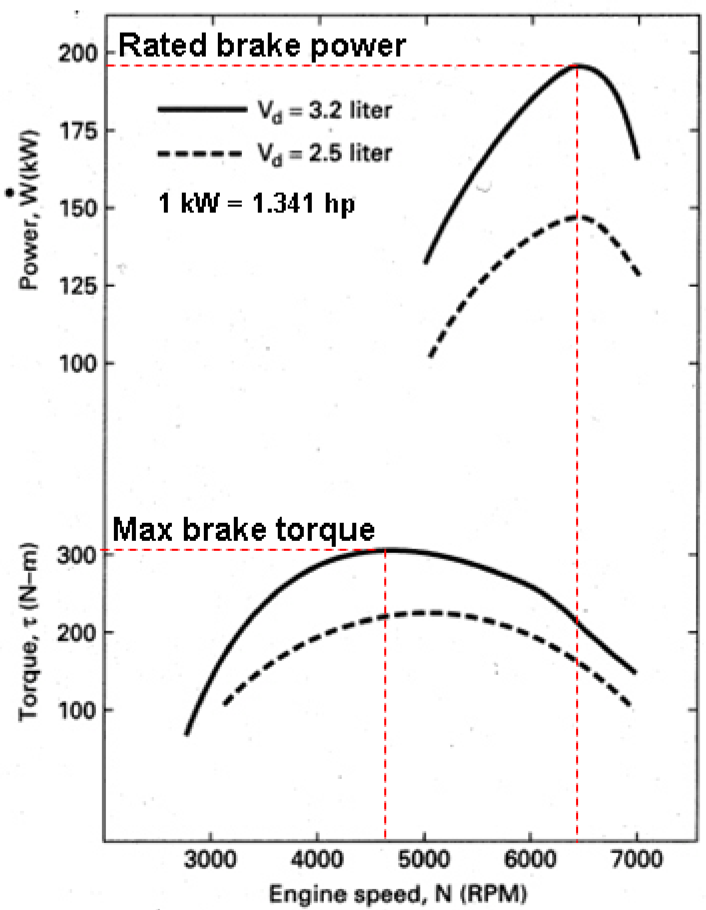
- The torque speed curve is

$$\mathcal{C} = \frac{\mathcal{P}}{\omega} = \text{bmep}\frac{V_d}{2.n_R.\pi}$$





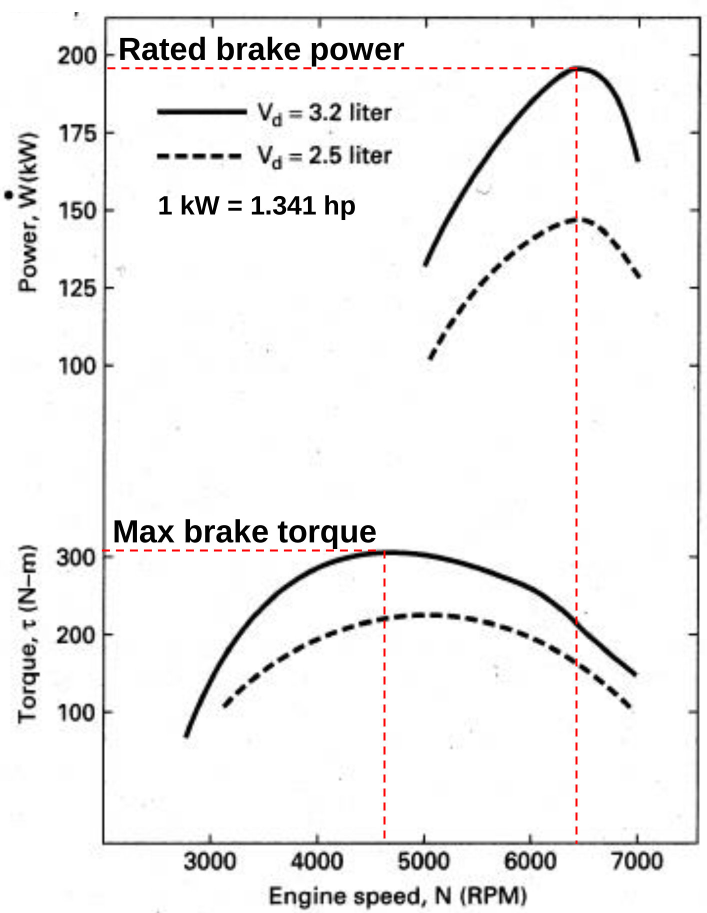
Power and torque as function of the rotation speed



- 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

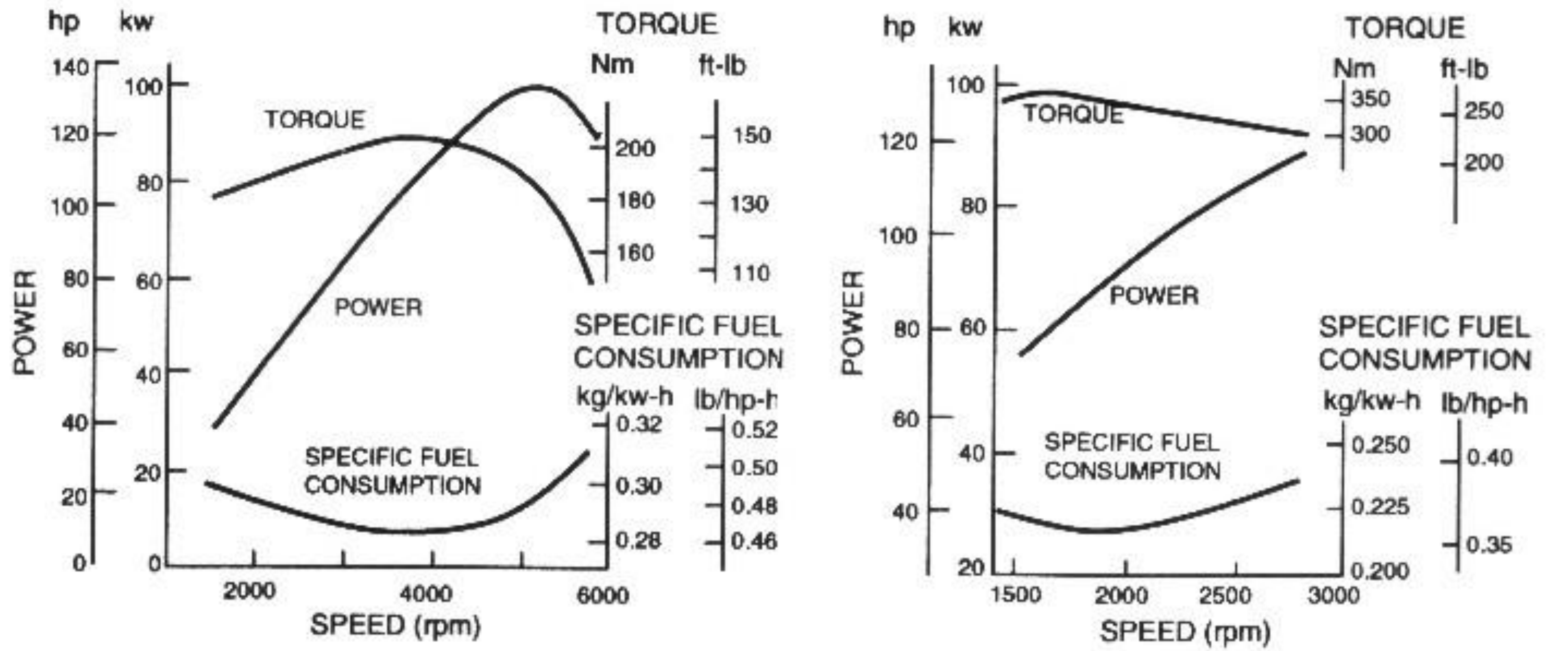
$$\dot{W}_b = \dot{W}_{i,g} - \dot{W}_f$$

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.

Piston engines characteristics



Gasoline Diesel

Gillespie, Fig. 2.1

Fuel consumption of thermal engines

- The specific fuel consumption of the engine is the mass of fuel that is used to develop a given work W:

$$\mathrm{bsfc} = \frac{m_f}{W_{mot}}$$

- Under variable operating conditions

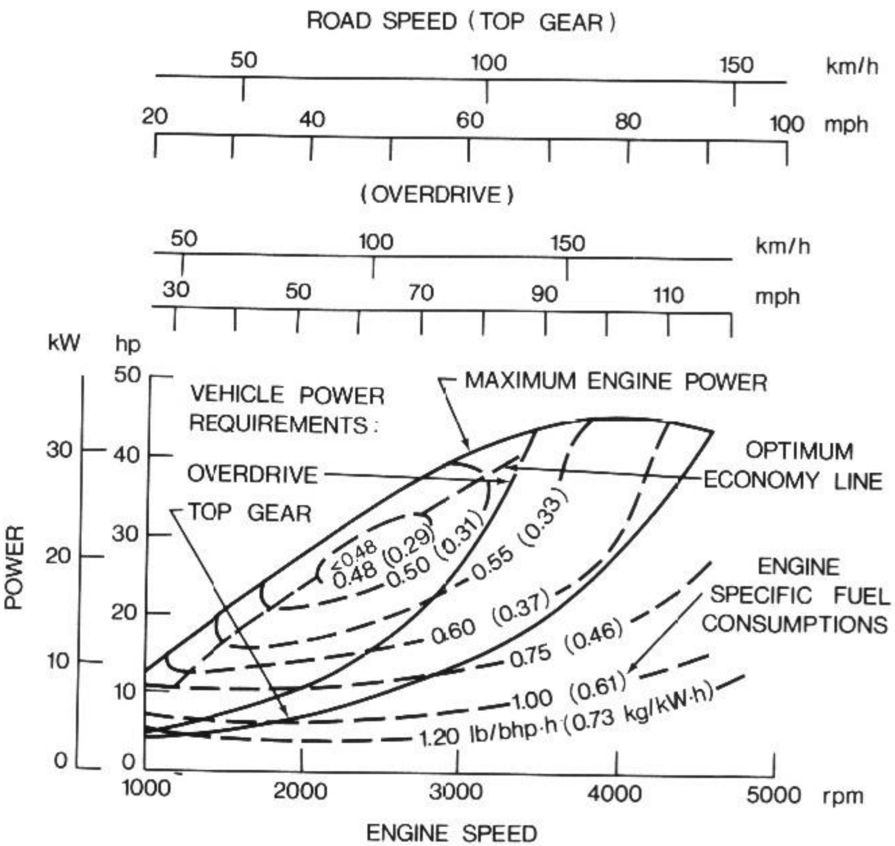
$$dW_{mot} = \dot{W}_{mot}\, dt$$

$$dm_f = \dot{m}_f\, dt$$

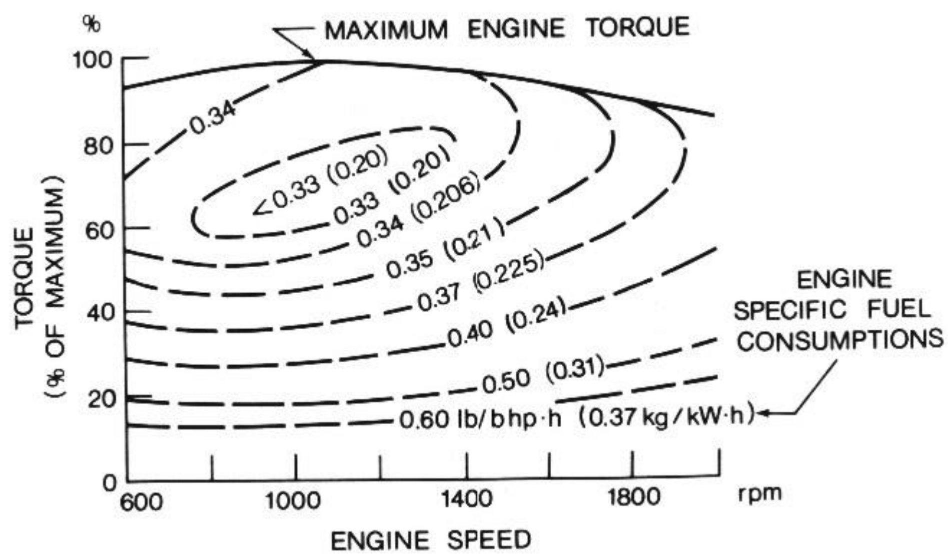
$$\mathrm{bsfc} = \frac{\dot{m}_f}{\dot{W}_{mot}}$$

- The fuel consumption depends on the operation point (power/torque/rotation speed)
- The fuel consumption is mapped on the power / torque curve diagram

Fuel consumption of thermal engines



Gazoline engine

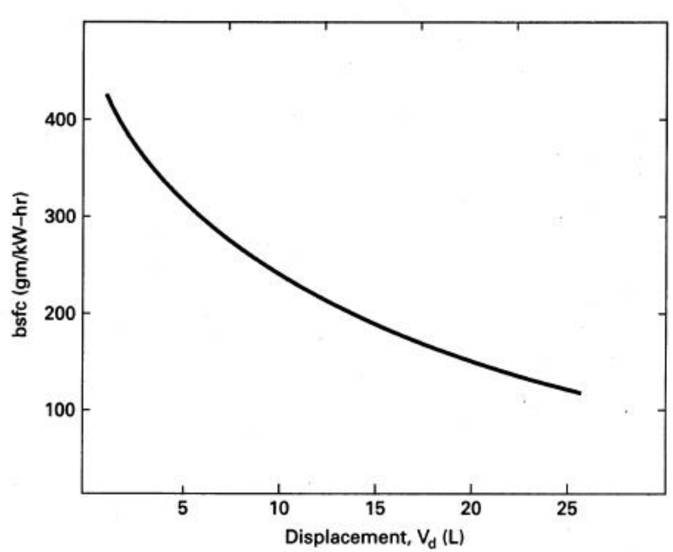


Diesel engine

Wong. Fig. 3.41 et 3.42

Brake Specific Fuel Consumption vs Engine Size

- Bsfc decreases with engine size due to reduced heat losses from gas to cylinder wall

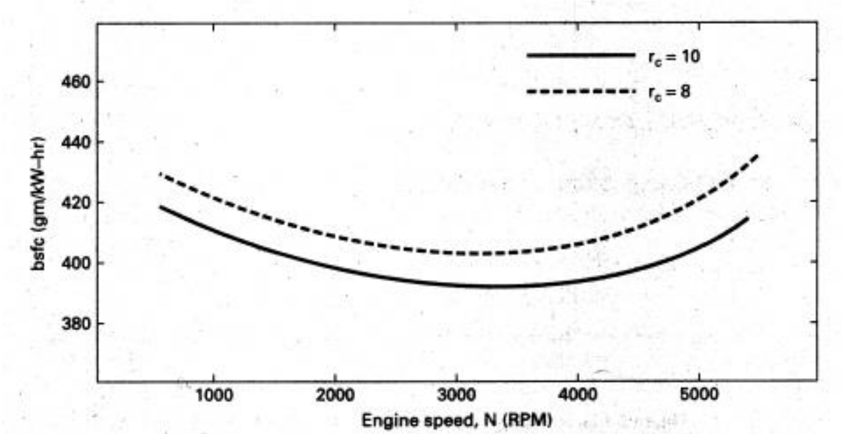


$$\frac{cylinder\ surface\ area}{cylinder\ volume} = \frac{2\pi rL}{\pi r^2 L} \propto \frac{1}{r}$$

- Note cylinder surface to volume ratio increases with bore diameter.

Brake Specific Fuel Consumption vs Engine Speed

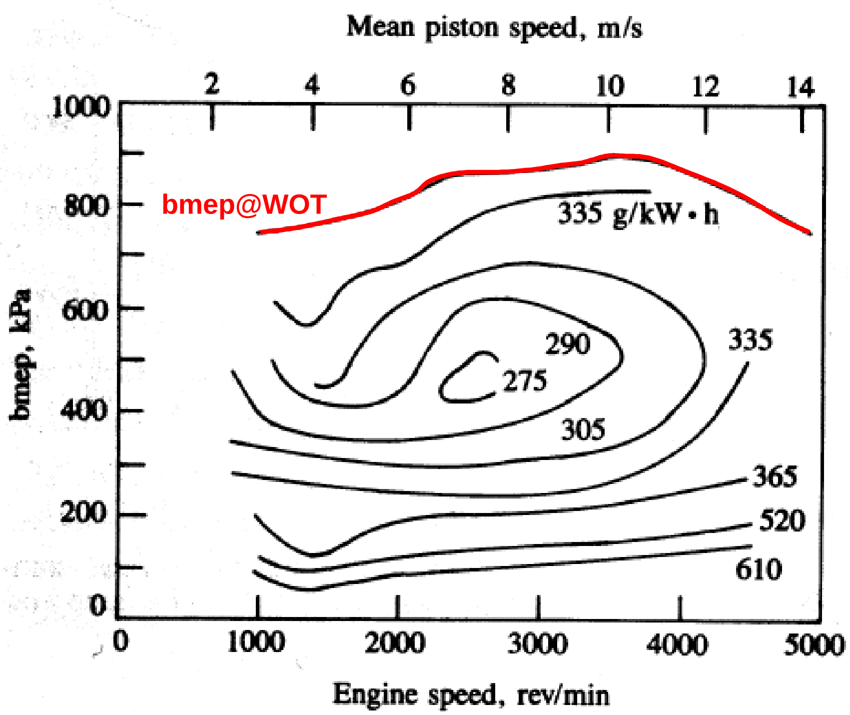
- There is a minimum in the bsfc versus engine speed curve



- At high rotation speeds, the bsfc increases due to increased friction i.e. smaller $\dot{W}_b$
- At lower speeds the bsfc increases due to the increasing time available for heat losses from the gas to the cylinder and piston wall, and thus a smaller $\dot{W}_i$
- Bsfc decreases with compression ratio due to higher thermal efficiency

Fuel consumption of thermal engines

- One often uses the fuel consumption mapping to illustrate the variability of the fuel consumption with the torque and the rotation speed.



$$bmep = \frac{2\pi \cdot C \cdot n_R}{V_d}$$

$$\dot{W}_b = (2\pi \cdot N) \cdot C$$

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b}$$

Fuel consumption of thermal engines

- It is also usual to use the energy efficiency of the plant, which is defined as the ratio between the mechanical output work and the input chemical energy associated to the mass of fuel with a given Lower Heat Value of the fuel LHV_{fuel}

$$\boxed{\eta_e = \frac{W_{mot}}{m_f \, \mathrm{LHV}_{fuel}}}$$

- That is

$$\boxed{\eta_e = \frac{\dot{W}_{mot}}{\dot{m}_f \, \mathrm{LHV}_{fuel}}}$$

Fuel consumption of thermal engines

- The efficiency and the fuel consumption are related to each other:

$$\eta_e = \frac{1}{\text{bsfc LHV}_{fuel}}$$

- Usual LHV

Fuel	LHV [kJ/kg]
Gasoline Super 95	42900
Diesel	42600
Ethanol	26900
Esther methylique of colza	37700
Dimethyl Ether	28430
Gepel Butagaz	46000
Natural gas	50000
Hydrogen	119930

Fuel consumption of thermal engines

- Nowadays, with the climate challenge, it is more usual to express the fuel consumption in terms of CO_2 emissions.

- Given the average chemical content of the fuel, it is possible to provide an equivalent conversion factor between one liter of fuel and the mass of CO_2 that is emitted when burning

Fuel	CO_2[g/liter] or [g/kg]
Gasoline Super 95	2392
Diesel	2640
LPG	1665
Natural gas (L)	2252
Natural gas (H)	2666

Fuel consumption of thermal engines

- Exercise:
  - A normalised fuel consumption of 5 litres per 100km of gasoline is equivalent to a CO_2 emission of
    5*2360 /100 = 118 gr CO_2/km
  - Target of 120 g of CO_2 per km is equivalent to
    - 120 *100/2360 = 5,08 l/100 km of gasoline
    - 120 *100/2730 = 4,39 l/100 km of Diesel

Emissions of pollutants

- With the growing importance of regulation of emissions, there is a great interest in assessing the four main pollutants emissions :
  - Nitrogen oxides (NOx),
  - Carbone monoxide (CO)
  - Unburnt hydrocarbons (HC),
  - Particulate matters (PM).

- Two kinds of measures are generally used to characterize the emission of pollutants:
  - Specific emissions (SE)
  - Emission Index (EI)

Emission rates

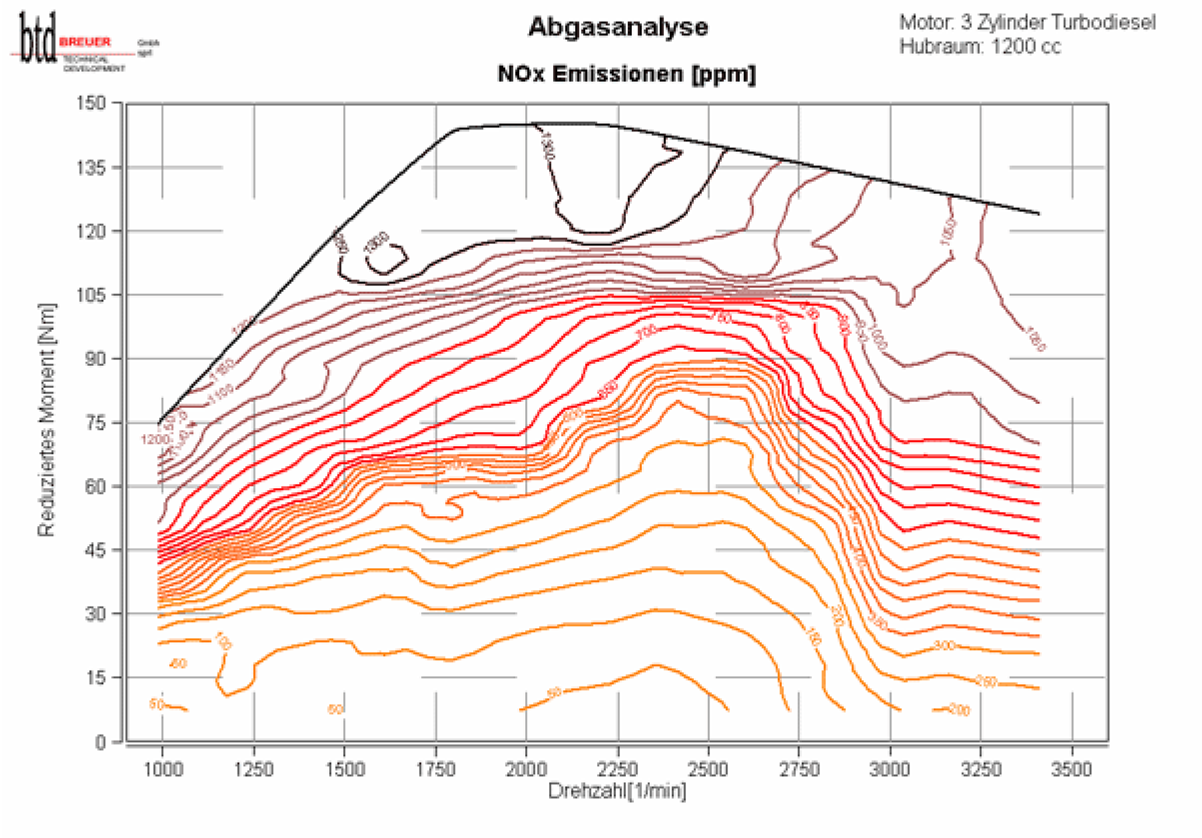
- Specific emissions

$$
\begin{aligned}
(SE)_{NOx} &= \dot{m}_{NOx}/\dot{W}_b \\
(SE)_{CO} &= \dot{m}_{CO}/\dot{W}_b \\
(SE)_{HC} &= \dot{m}_{HC}/\dot{W}_b \\
(SE)_{PM} &= \dot{m}_{PM}/\dot{W}_b
\end{aligned}
$$

- Emission index

$$
\begin{aligned}
(EI)_{NOx} &= \dot{m}_{NOx}/\dot{m}_f \\
(EI)_{CO} &= \dot{m}_{CO}/\dot{m}_f \\
(EI)_{HC} &= \dot{m}_{HC}/\dot{m}_f \\
(EI)_{PM} &= \dot{m}_{PM}/\dot{m}_f
\end{aligned}
$$

Piston engines characteristics: emission rates



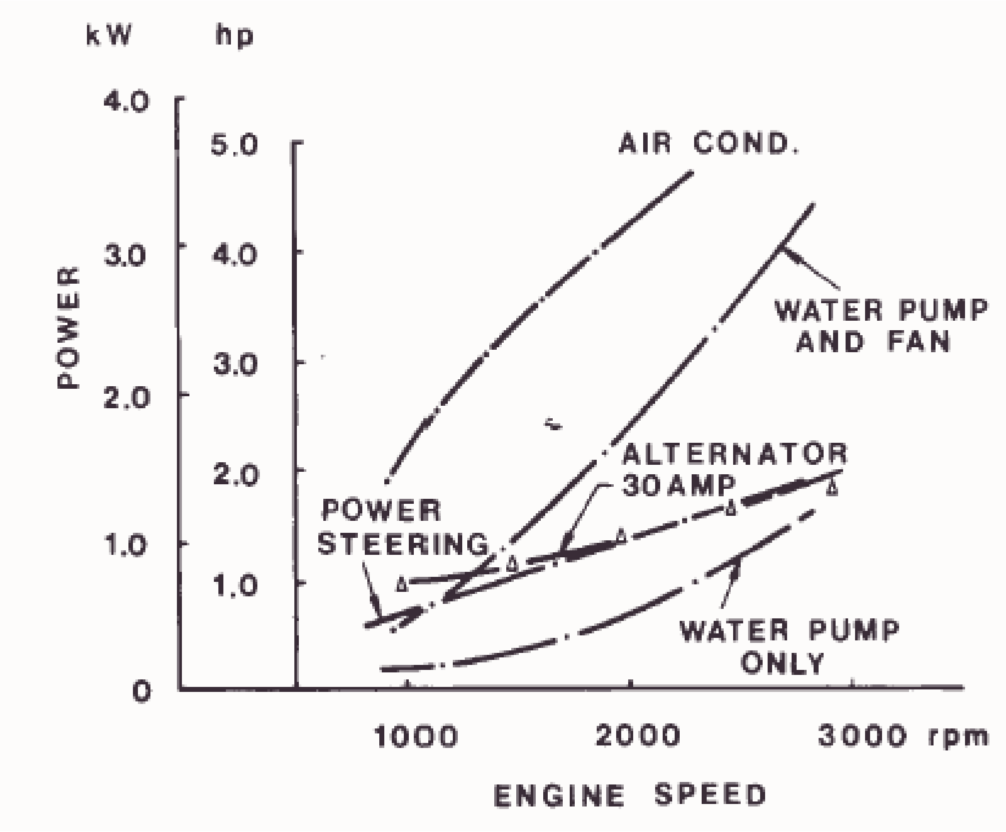
Standard performance curves of ICE

- 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:

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

- 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

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

- 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

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

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

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

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

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

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

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

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

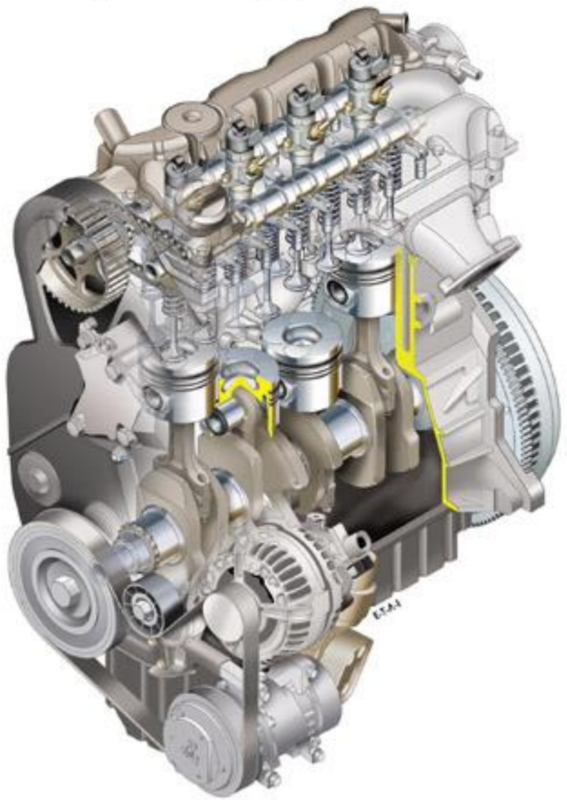
$$a_1 + 2\,a_2 + 3\,a_3 + 4\,a_4 = 0$$

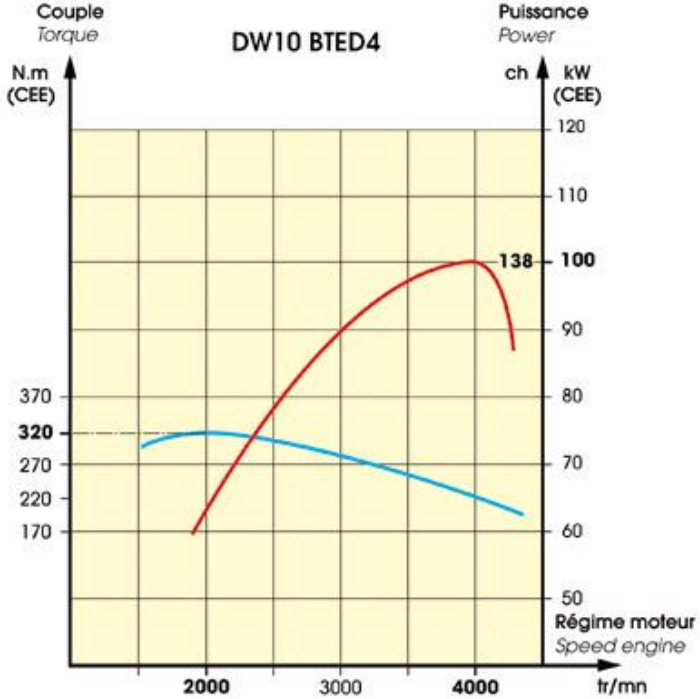
- Solve the linear system

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

Example: 2.0 HDI PSA engine

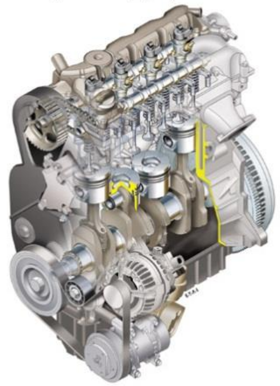
Moteur 2.0 HDi - 138 ch (DIN)
2.0 HDi engine - 138 hp (DIN)

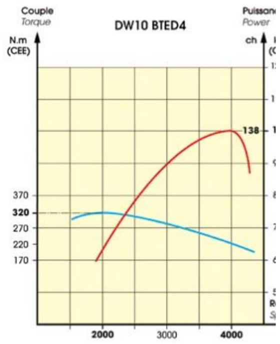


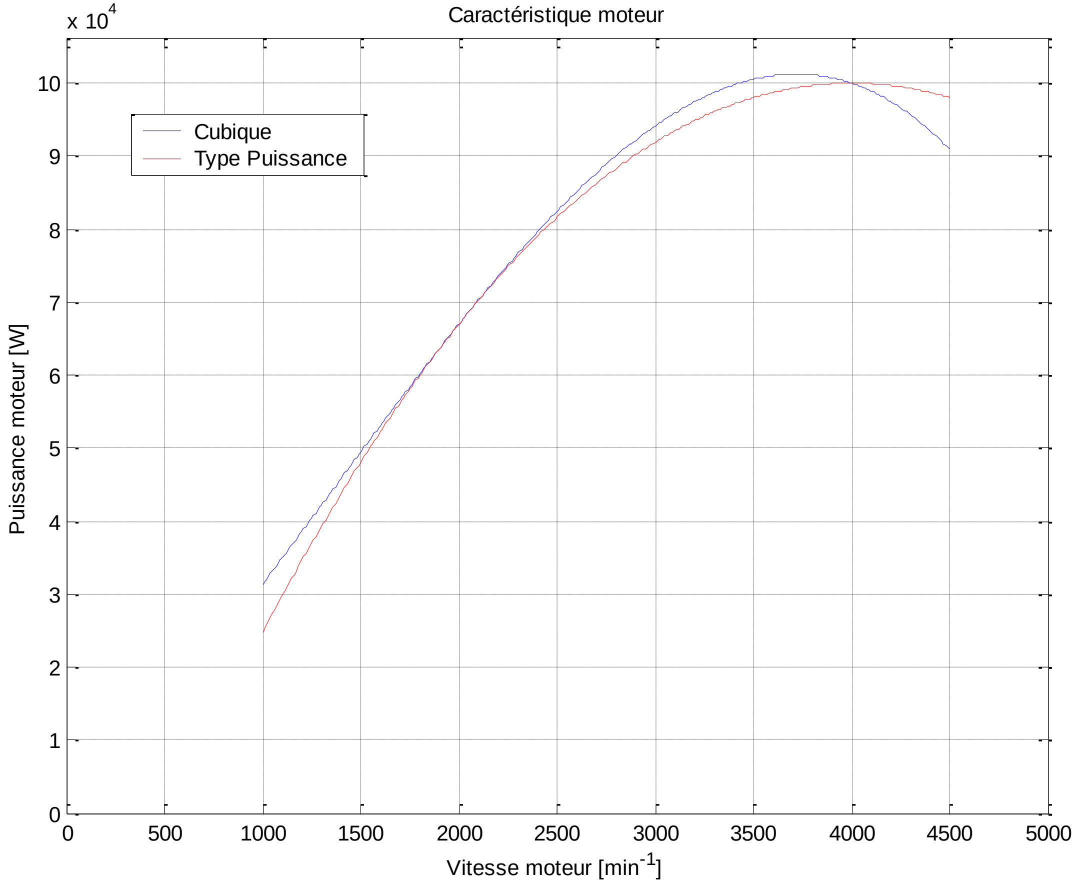


Example: 2.0 HDI PSA engine

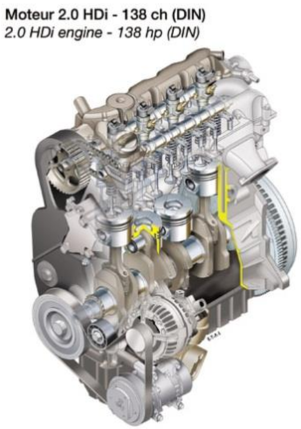
Moteur 2.0 HDi - 138 ch (DIN)
2.0 HDi engine - 138 hp (DIN)

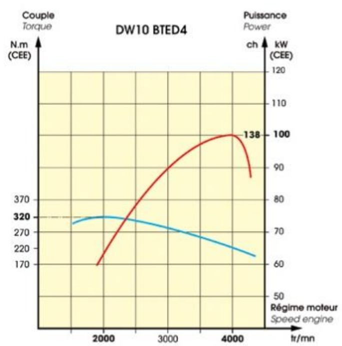


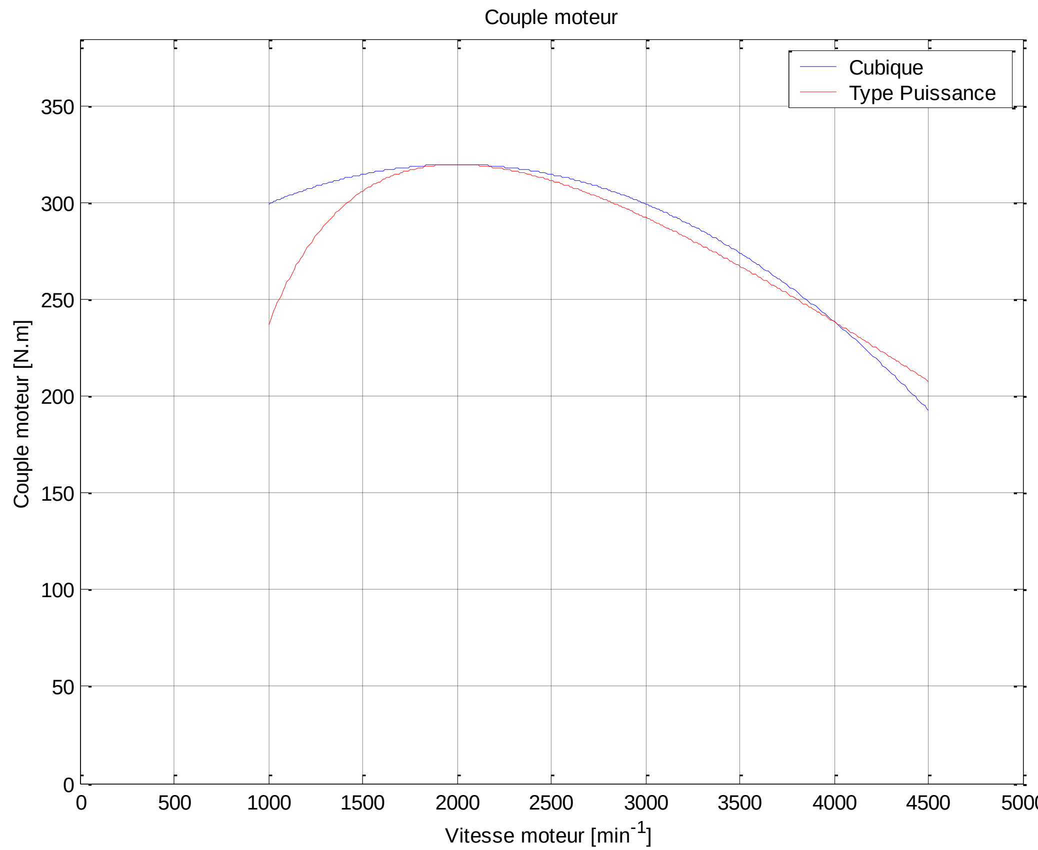




Example: 2.0 HDI PSA engine







Engine Universal Performance Map

- Golverk (SAE 941928) showed that a response surface with quadratic terms can represent with a sufficient accuracy the engine map

$$\text{bsfc} = a_1 + a_2 N + a_3 T + a_4 N^2 + a_5 N T + a_6 T^2$$

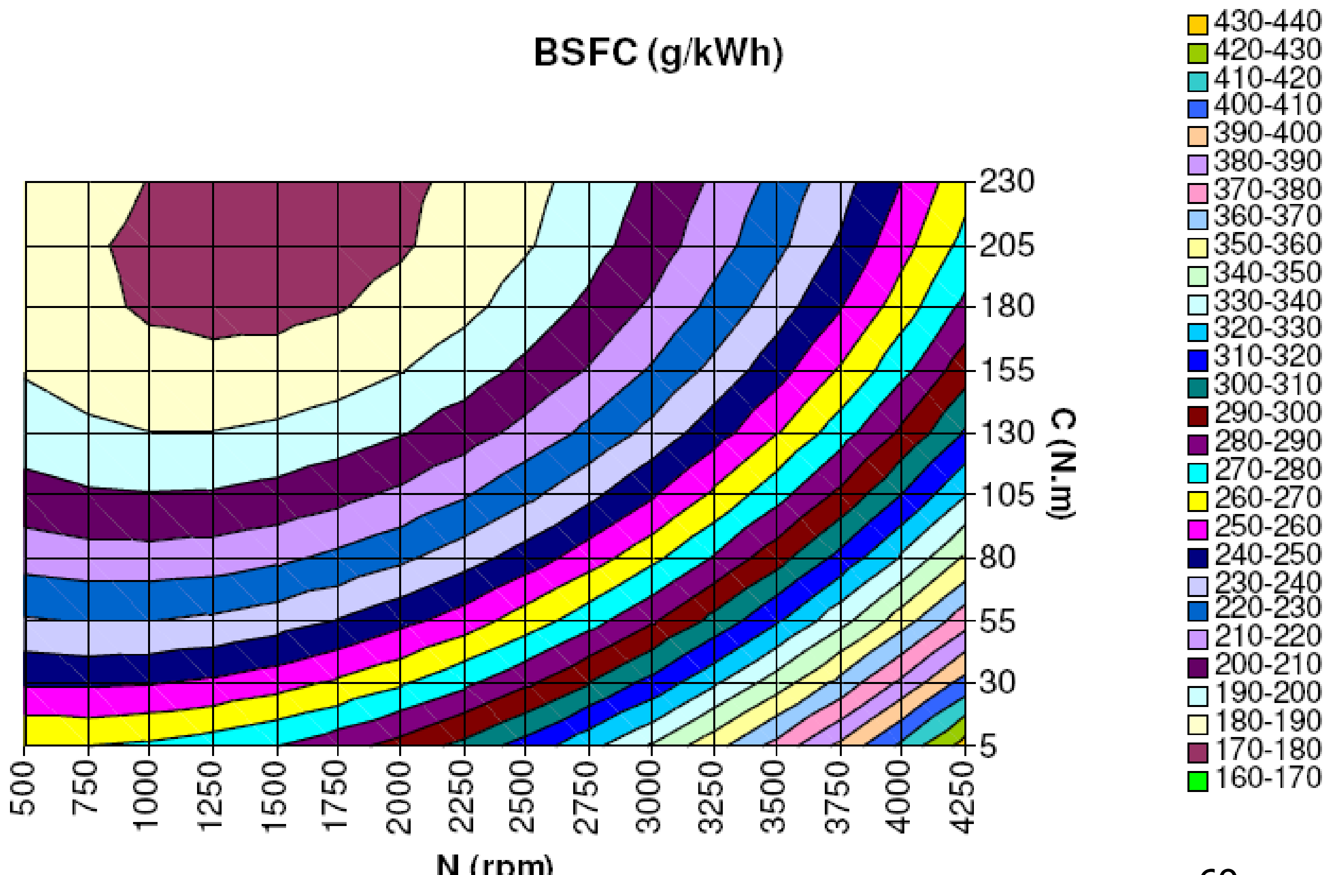
  - b_e [gr/kWh] the BFSC
  - T [Nm], the brake torque
  - N [rpm], the engine rotation speed
  - a_i: Empirical coefficients to be identified

Engine Universal Performance Map

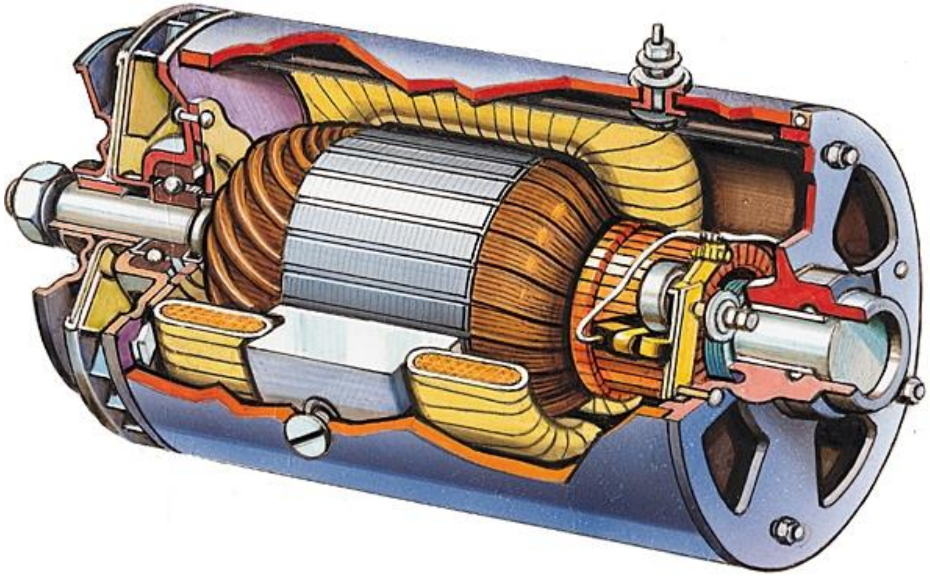
$$BSFC = A1 + A2 \cdot N + A3 \cdot C + A4 \cdot N^2 + A5 \cdot N \cdot C + A6 \cdot C^2$$

N	Speed (RPM)
C	(N.m)
BSFC (g / kWh)	

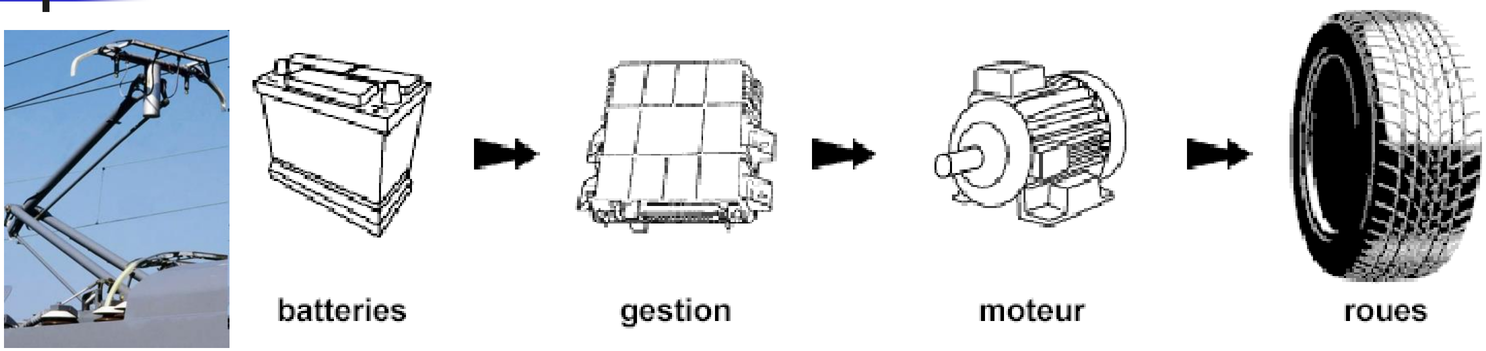
A1	278.65
A2	-0.01459011
A3	-0.87506231
A4	0.00001242
A5	-0.00010411
A6	0.00242572



Electric machines



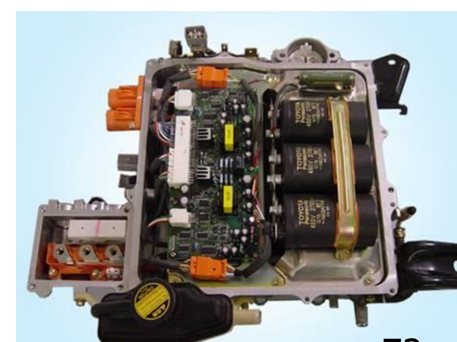
Electric vehicles



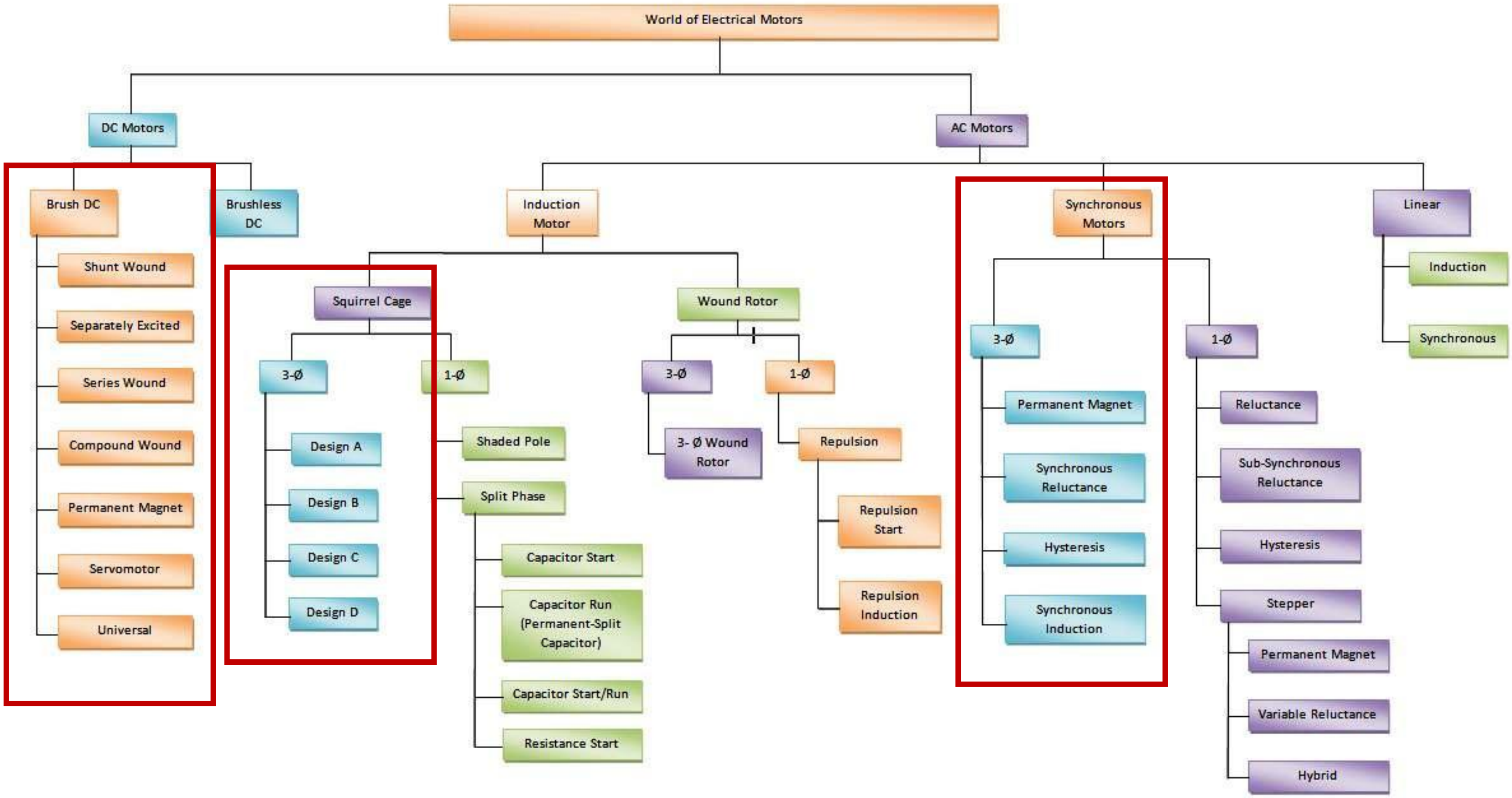
- Three main components of electric traction machines:
  - Electric machine itself;
  - The related power electronics: continuous management of voltage, current intensity, frequency of electrical energy supplying the electric machine depending on the driving request;
  - The command itself that is necessary to optimize the operation efficiency.

Electric powertrain

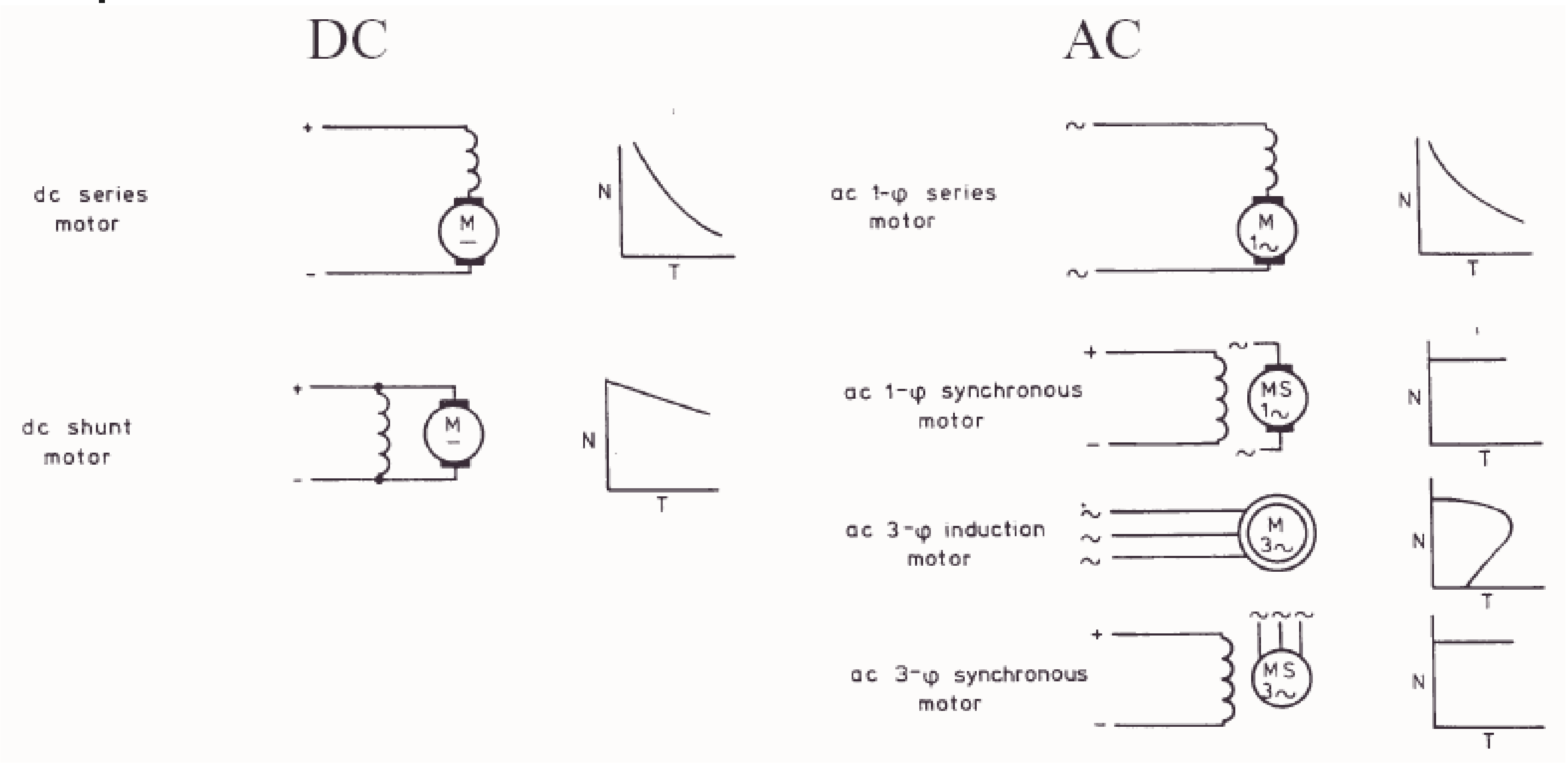
- E-Motors
  - DC shunt or series
  - AC asynchronous or synchronous machines with single phase or three phases supply
- Batteries:
  - Lead-acid
  - Nickel – Cadmium
  - Ni – MH (metal hydrides)
  - Li Ions
  - Supercaps
- Electronic power converters
  - Chopper
  - DC / DC converters
  - Inverter



Performance curves of electric machines



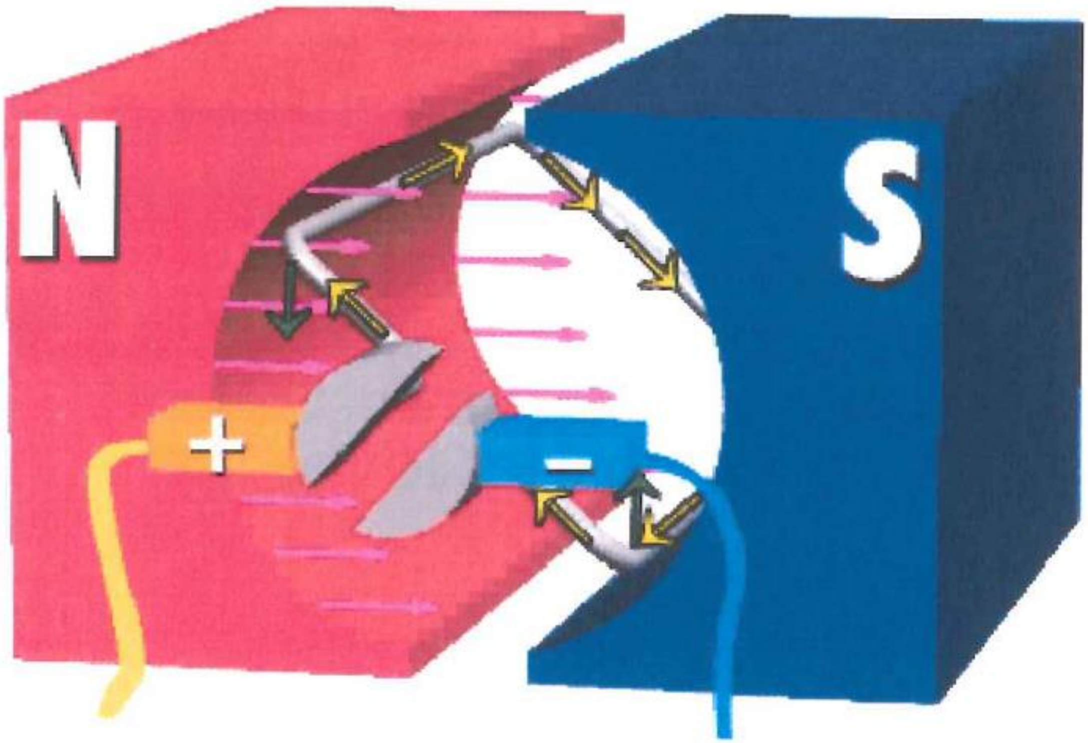
Performance curves of electric machines



DC electric motors

$$\vec{F} = i\,\vec{l} \times \vec{B}$$

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



Working principal of a DC motor

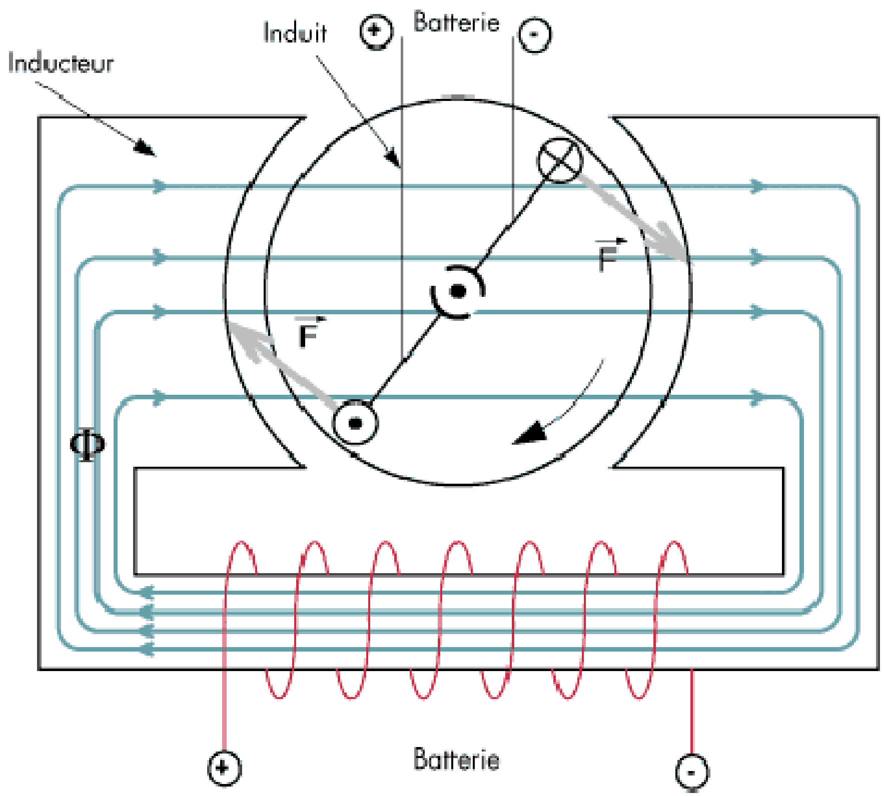
DC electric motors

Lorentz-Laplace force

$$\vec{F} = i\,\vec{l} \times \vec{B}$$

Torque on a current curl

$$T = B\,i\,L\,\cos\alpha$$

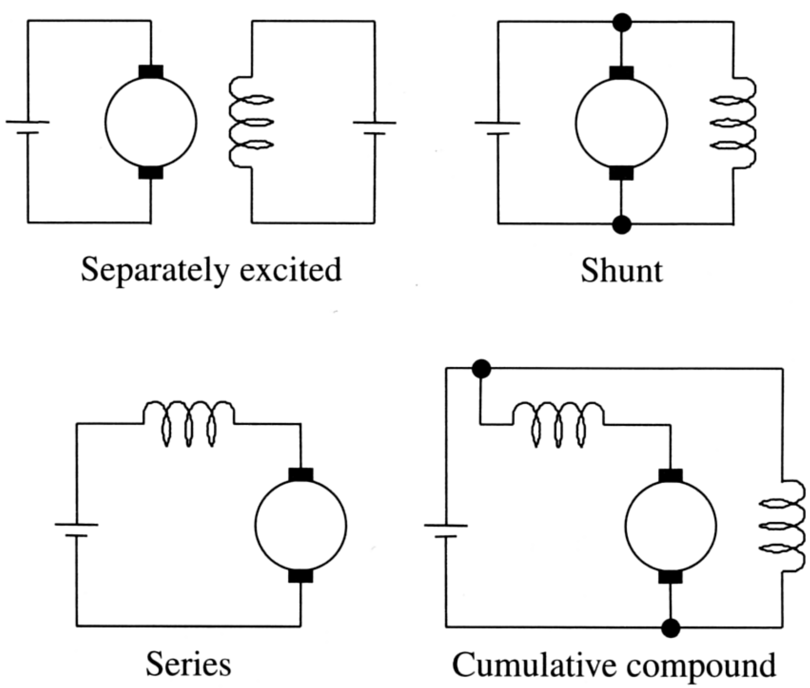


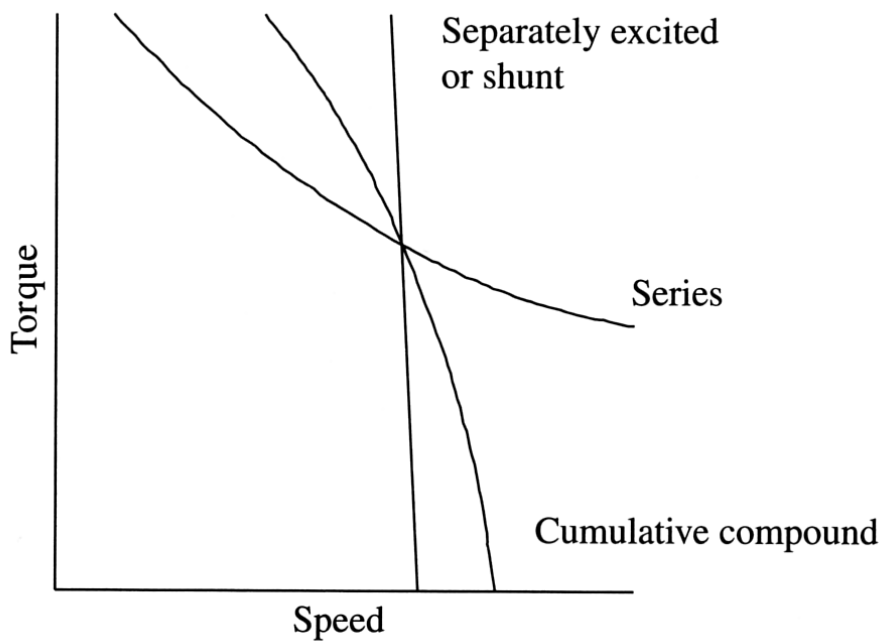
Counter electromotive force

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

Working principal of a DC motor

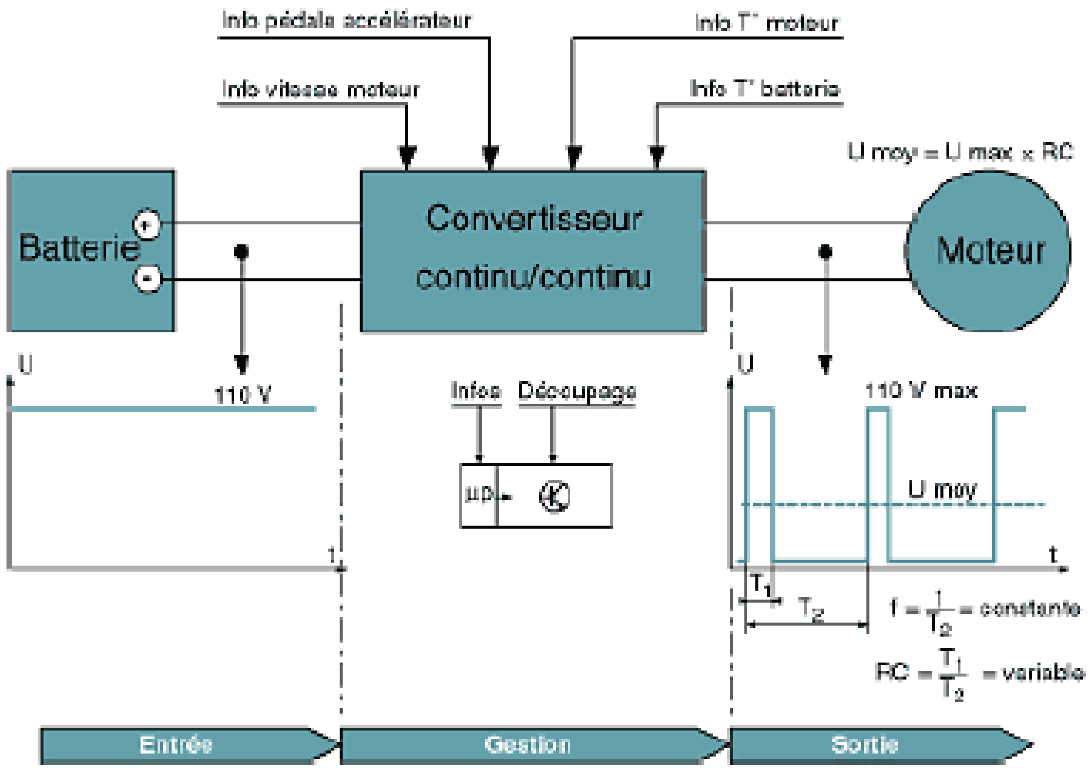
Performance curves of DC electric motors





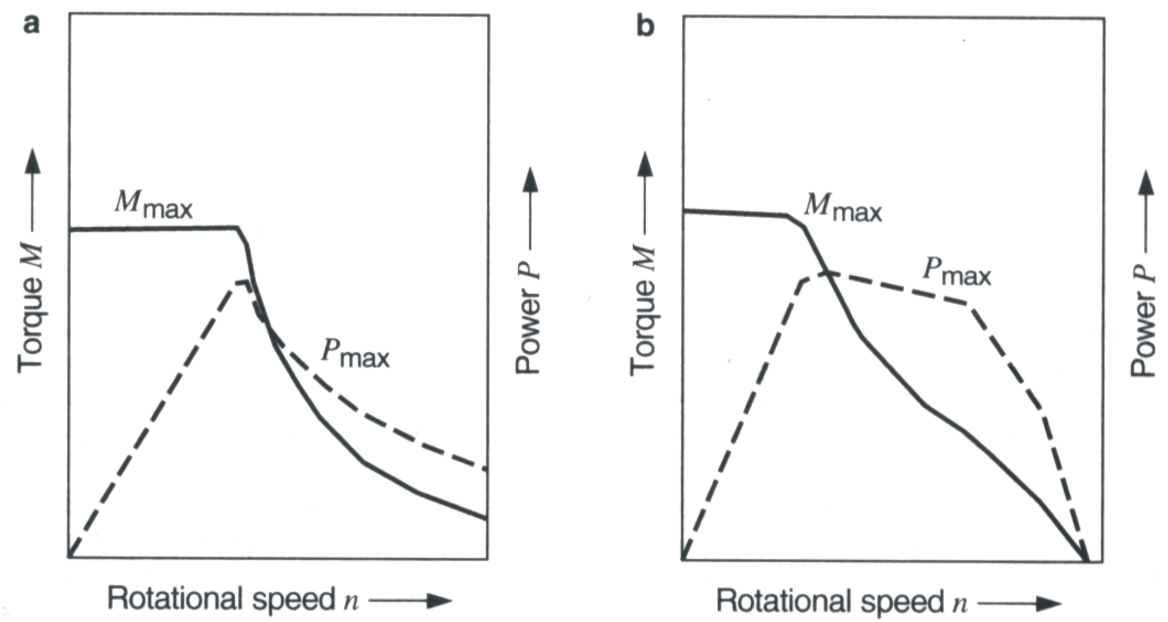
Types of DC machines and torque curves

Power electronic and control of DC machines



Working principle of a chopper

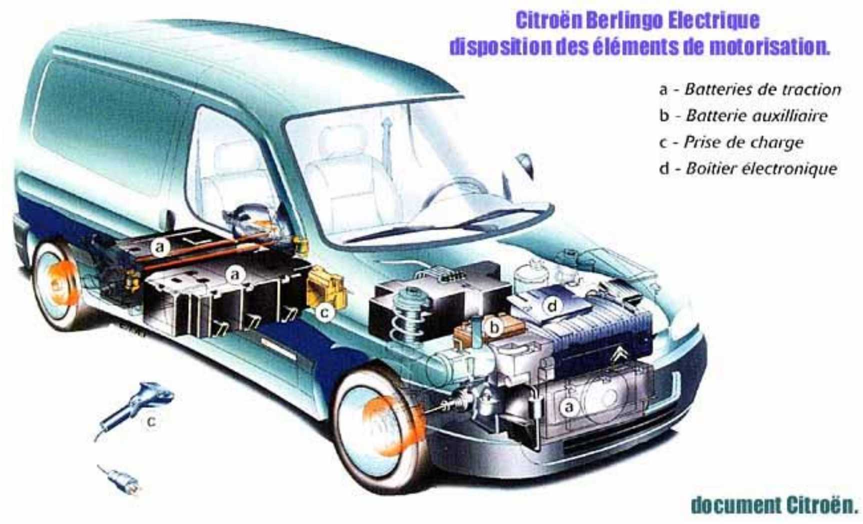
DC motor: series and separated excitation

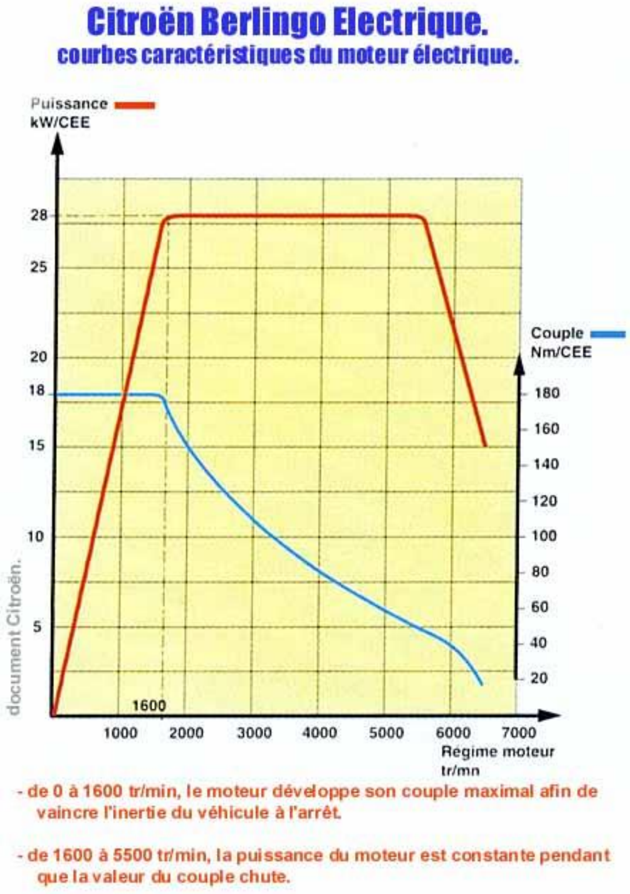


DC series motor

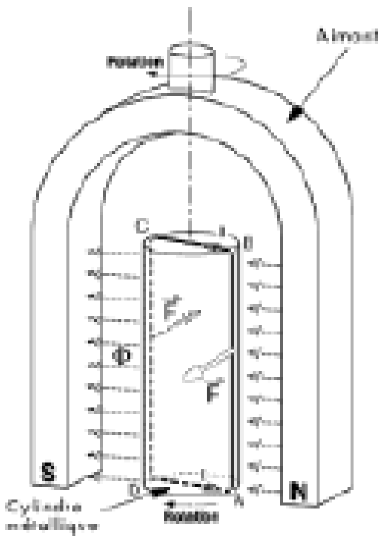
DC motor with separated excitation

DC electric machines

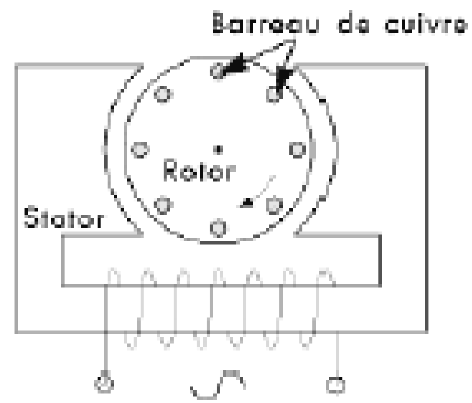




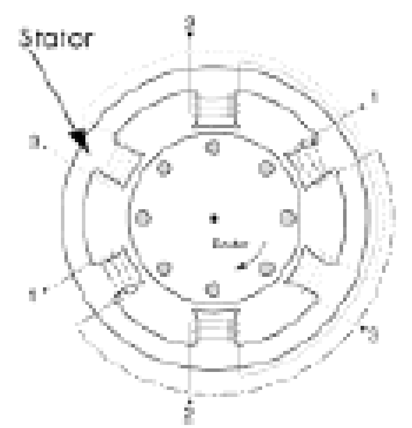
AC asynchronous electric motors



Working principle of AC asynchronous motors

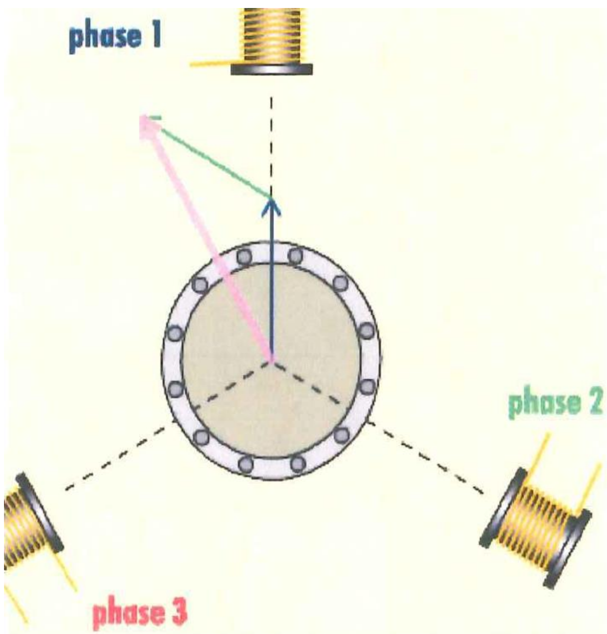


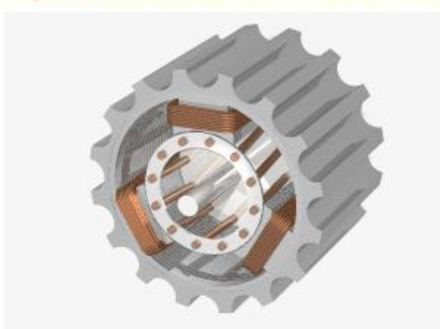
Moteur asynchrone monophasé



Moteur asynchrone triphasé (principe)

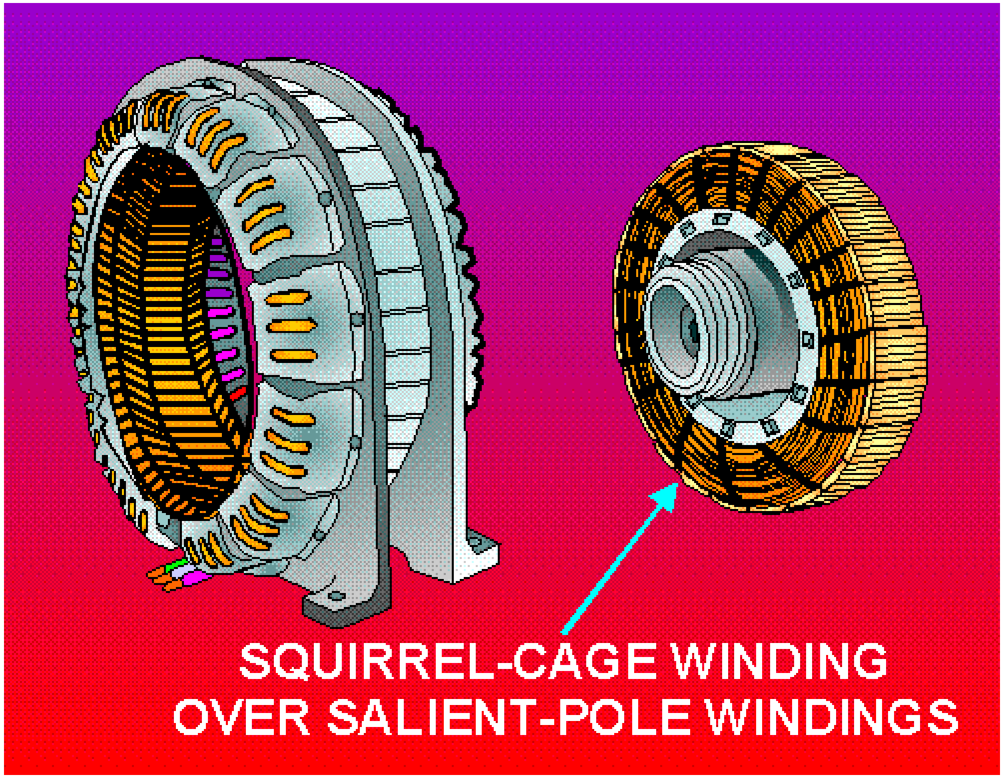
3-phase AC asynchronous motors

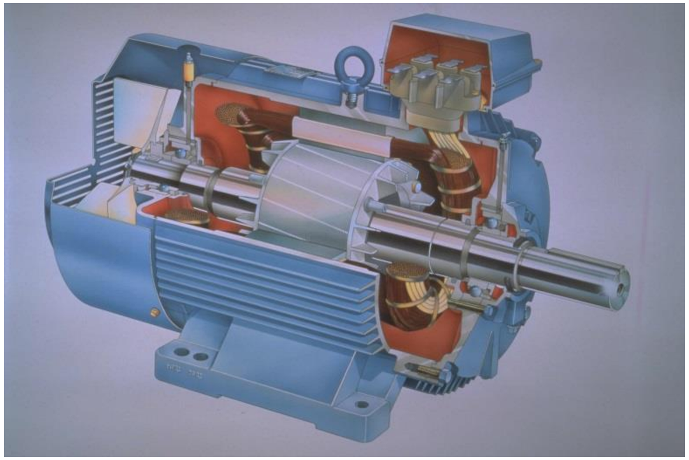




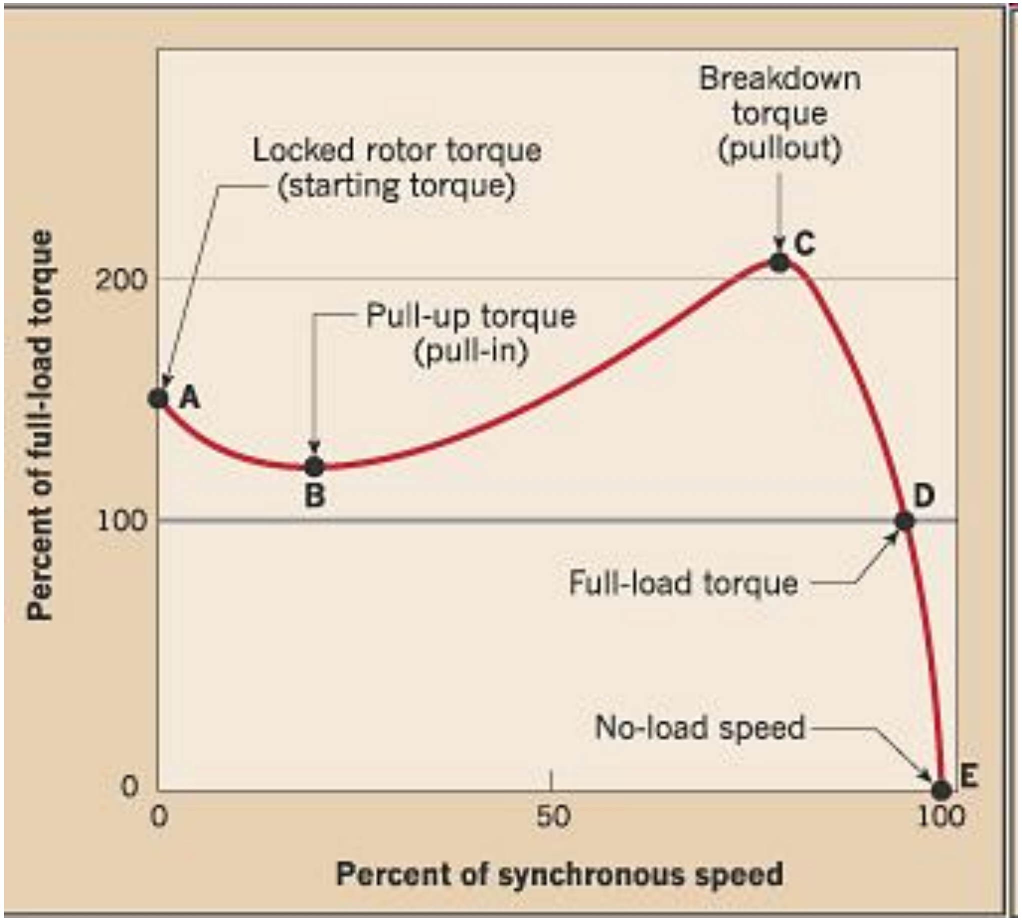
- Let's consider a 3-phase AC current system
- With the spatial shift of stator windings, one creates a rotating magnetic field whose rotation speed is given by external supply voltage frequency
- If the frequency of the 3-phase current system is controlled, one drives the e-motor rotation speed.
- The e-motor torque comes from the slippage between the rotation speeds of the stator magnetic field and the rotor ones. (Magnetic friction effect)
- By its nature, the efficiency of the induction motor is less than 100%

3-phase AC asynchronous motors

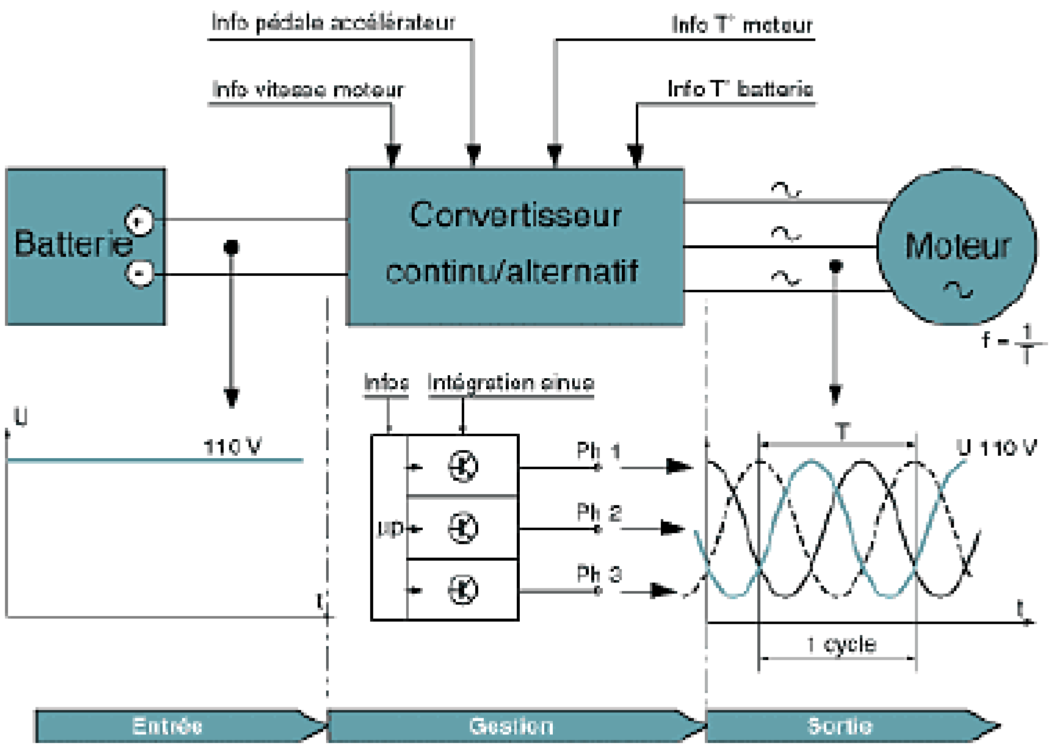




3-phase AC asynchronous motors

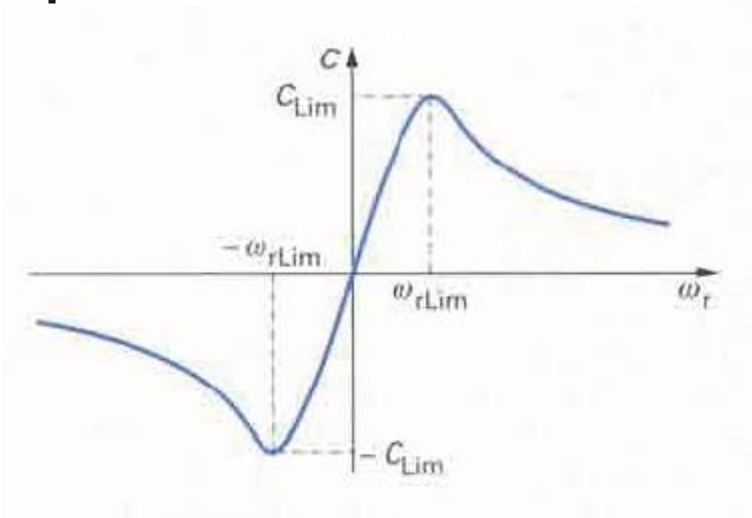


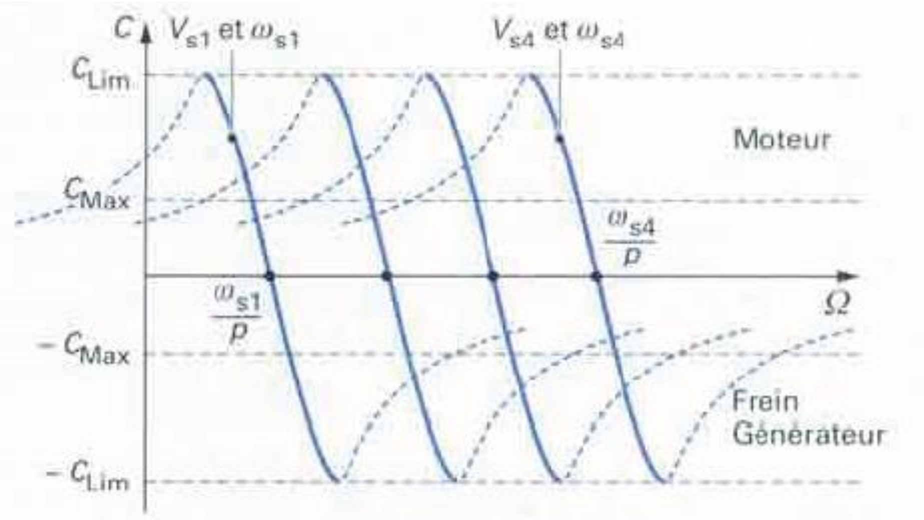
Power electronic and control of AC machines



Working principle of an inverter

AC Asynchronous motor

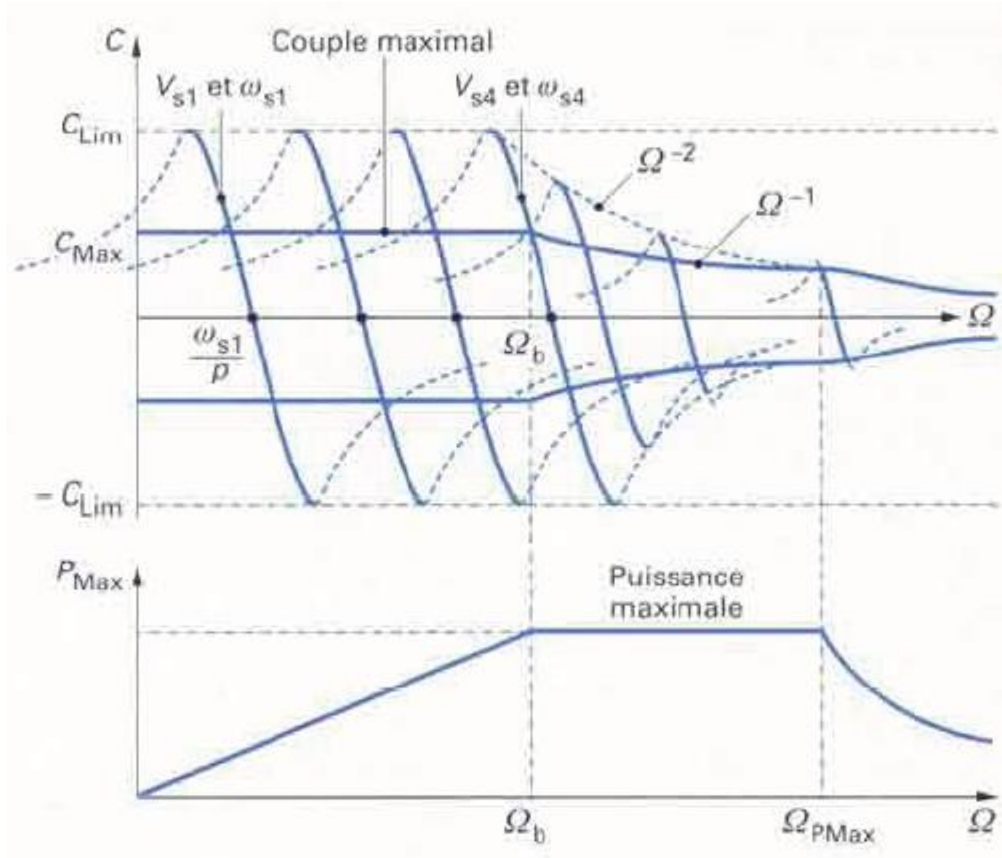




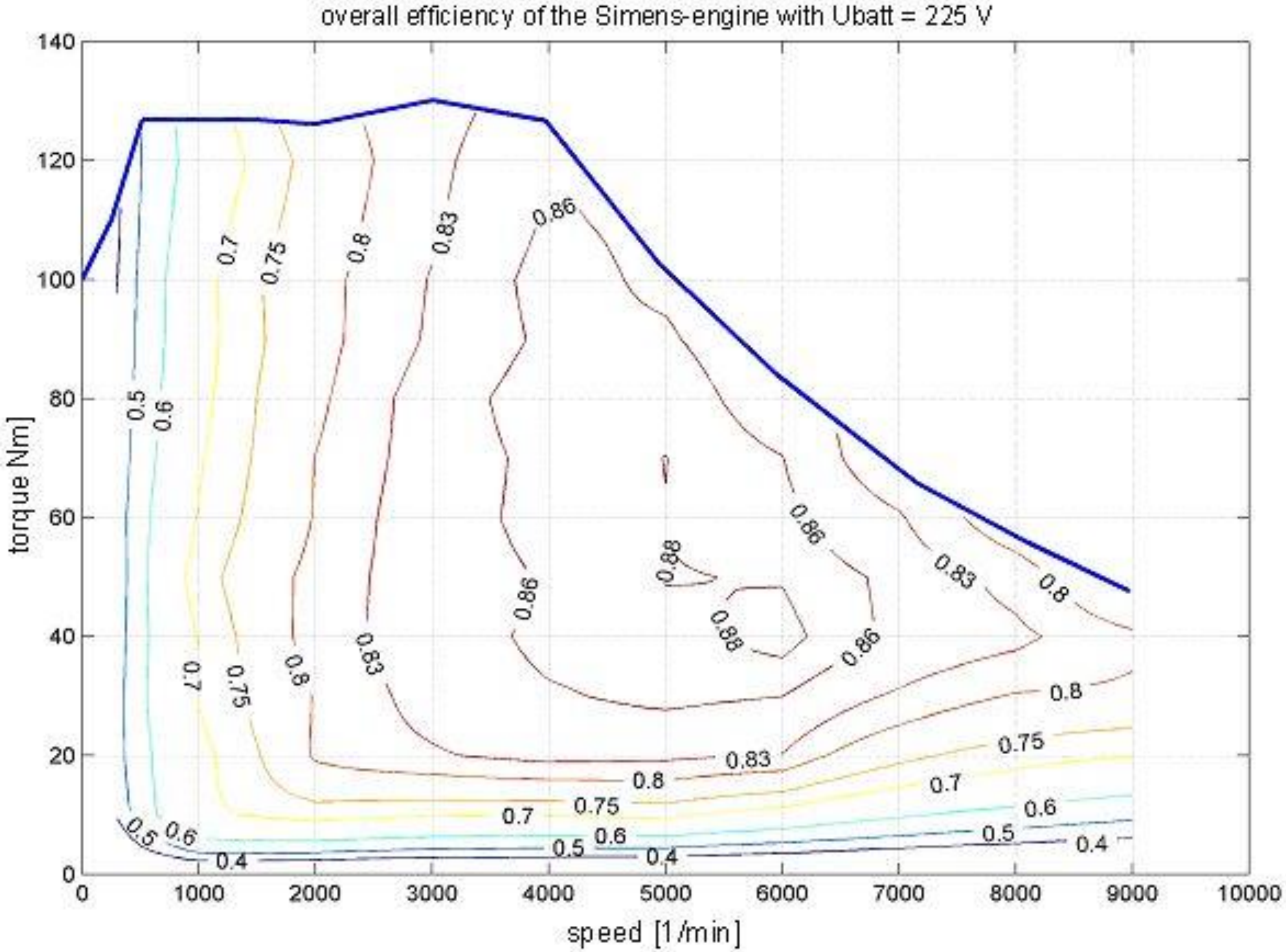
- Torque curve of AC asynchronous motor as a function of the slippage rotation speed
- Modification of torque curve of AC asynchronous motor when working at constant stator flux but variable frequency

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



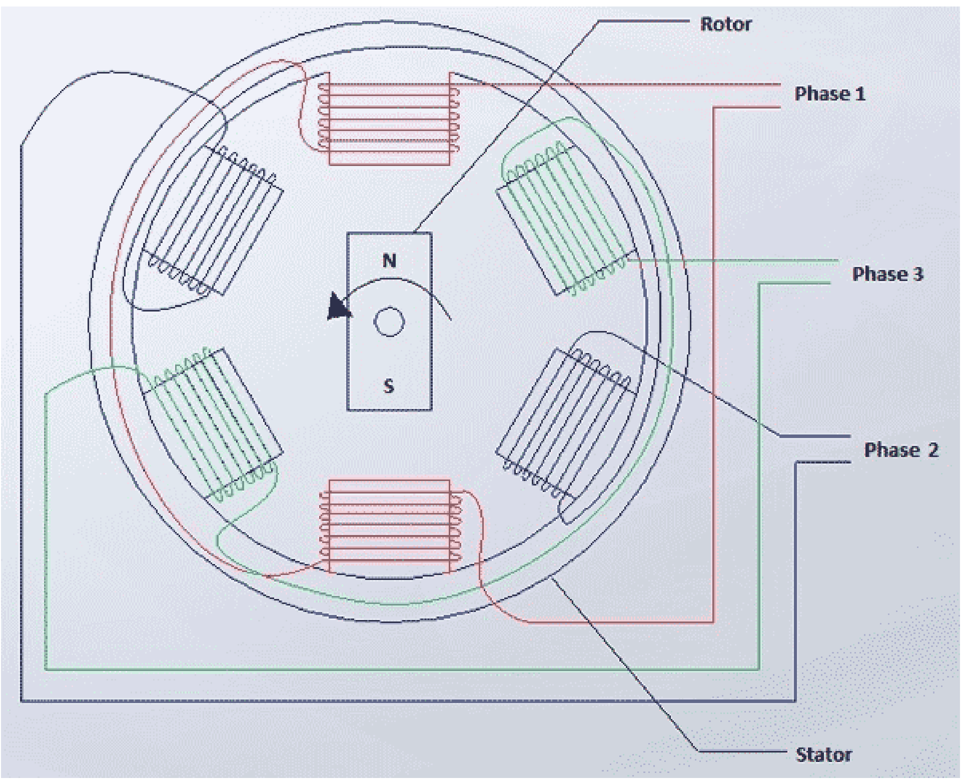
3-phase AC asynchronous motors



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
- Their command control laws are rather complex requiring a sophisticated power electronics
- Synchronous machines are also based on the principle of a rotating magnetic field generated by statoric 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 statoric magnetic field

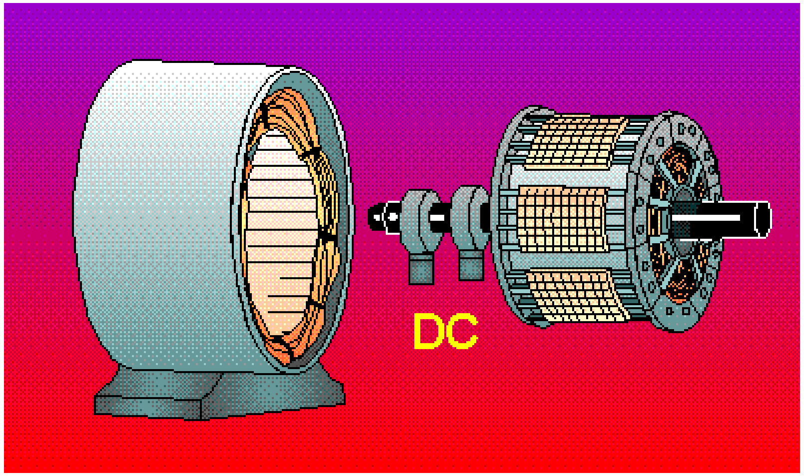
AC Synchronous motors



AC Synchronous motors

Generation of a rotor magnetic field

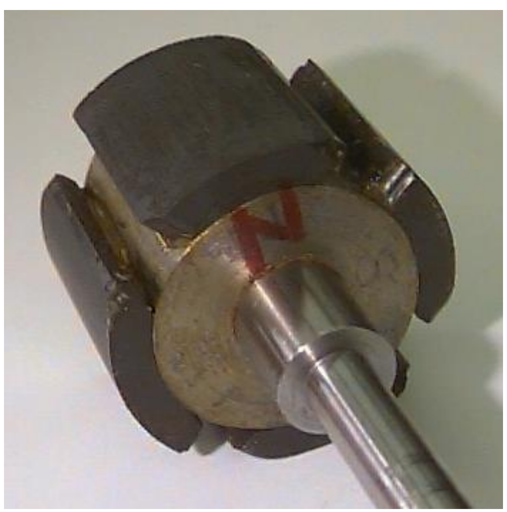
- Winding (synchronous machine with wound rotor)
  - Modulation of rotor field using a chopper (like a DC machine)
  - Enable the optimized control at high speed
  - Electric commutation with the brushes and the chopper
  - Extra cost and lower reliability



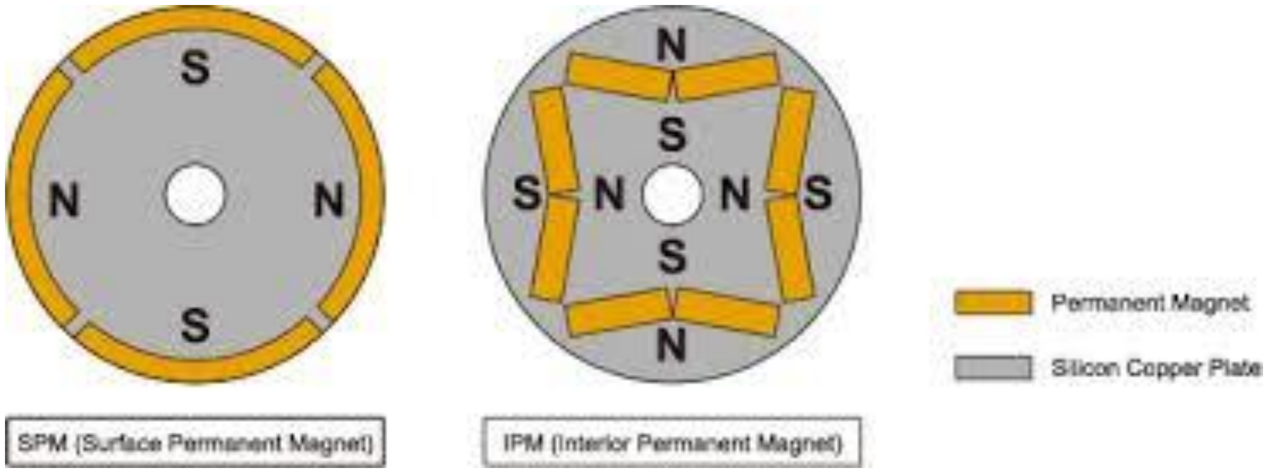
AC Synchronous motors

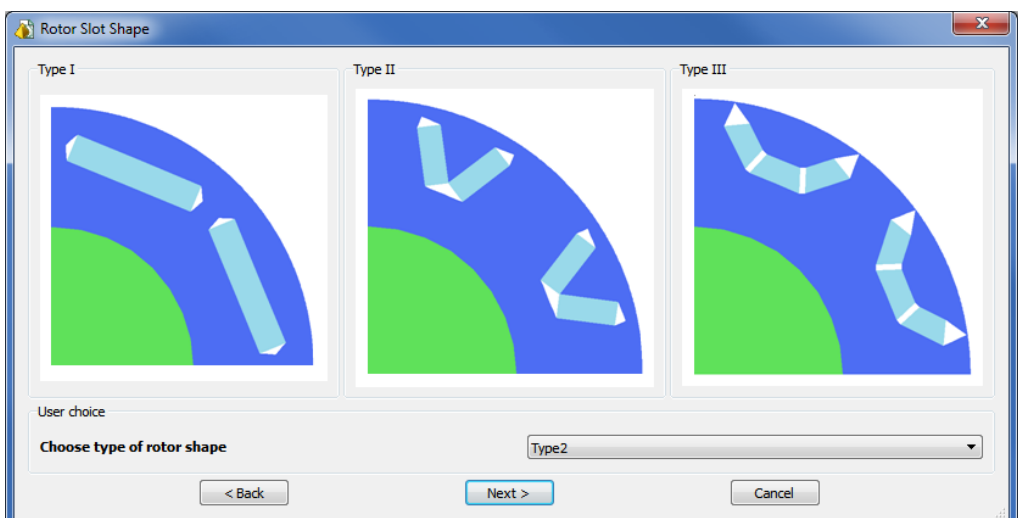
Generation of a rotor magnetic field

- Permanent magnets (Synchronous machine with permanent magnets)
  - High conversion efficiency
  - High energy density (3kW/kg) and volumetric energy
  - Reliability and maintenance operation similar to induction machine



AC Synchronous PM motors





AC Synchronous motors

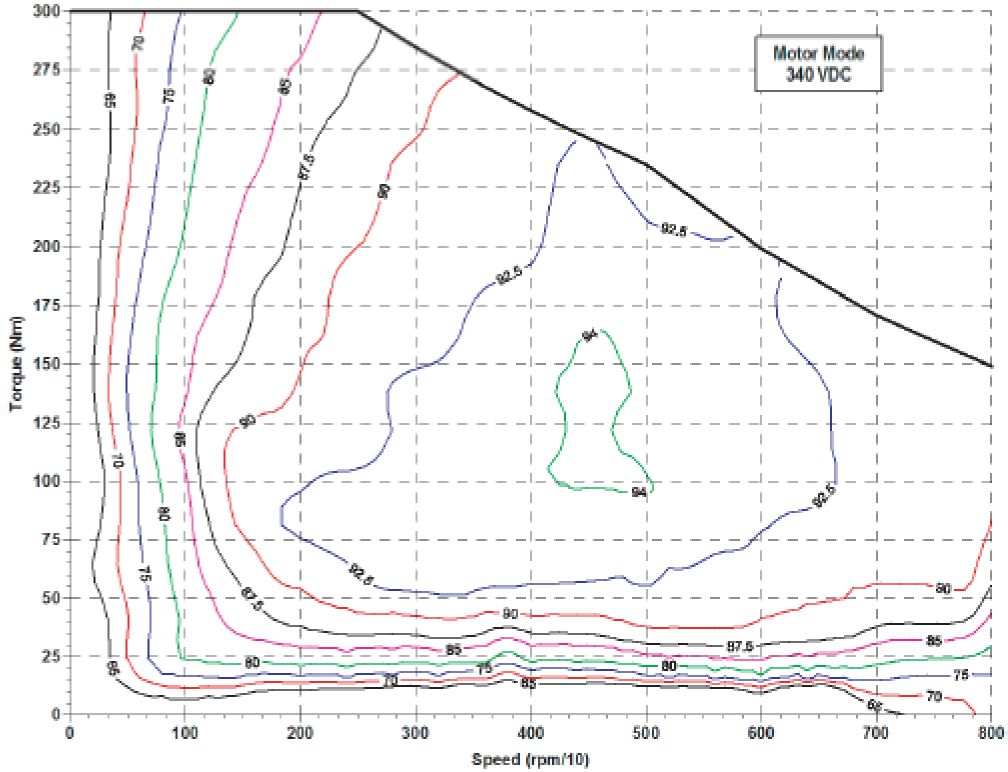
PM e-motors by UQM: PowerPhase 125

AC Synchronous PM motors

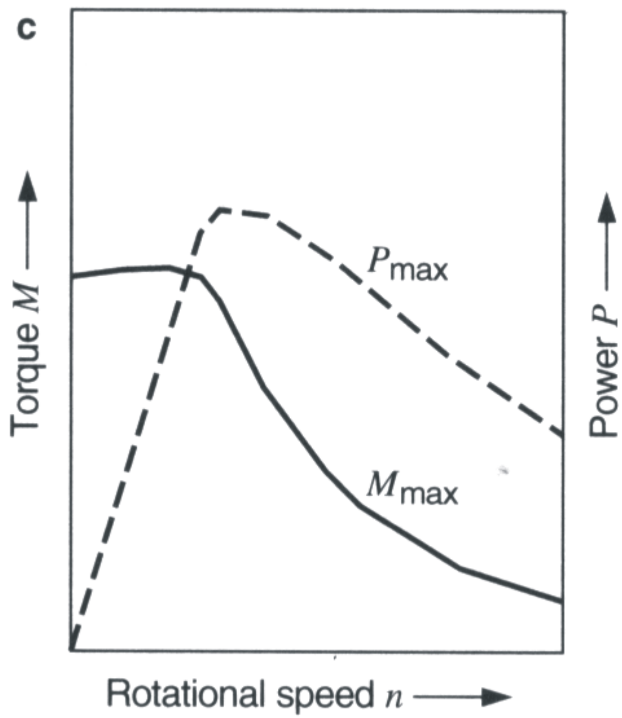
PowerPhase® 125

Motoring Efficiency Map

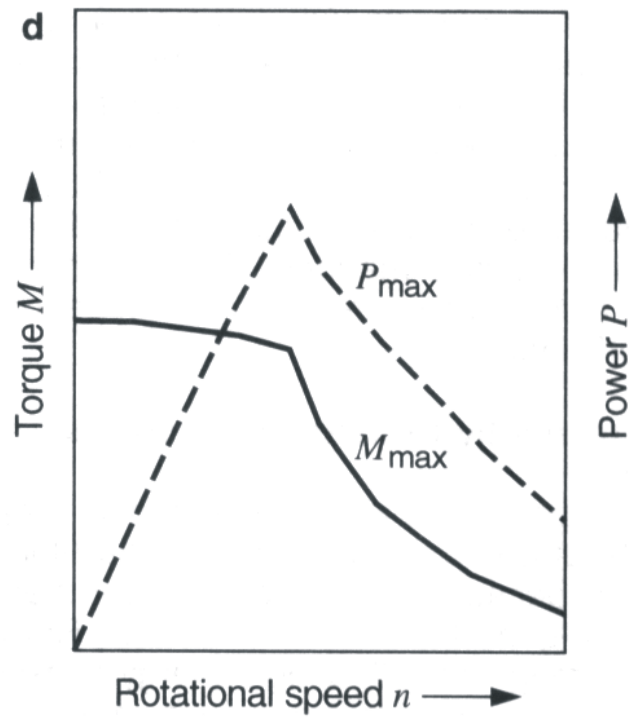
Includes controller and motor



AC motors: induction vs synchronous

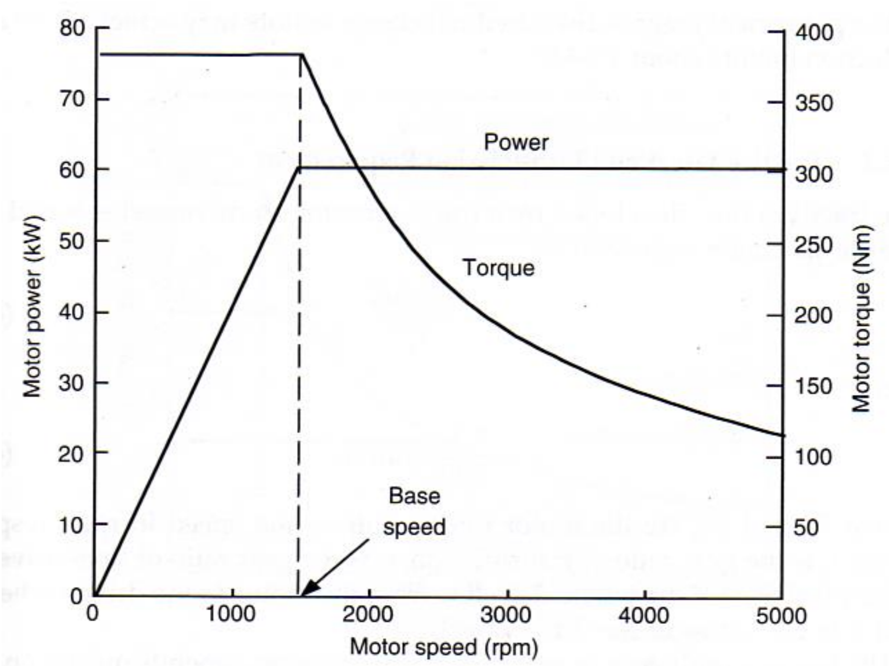


AC induction motor



AC synchronous motor

Traction motor characteristics



- At low speed: constant torque
  - Voltage supply increases with rotation speed through electronic converter while flux is kept constant

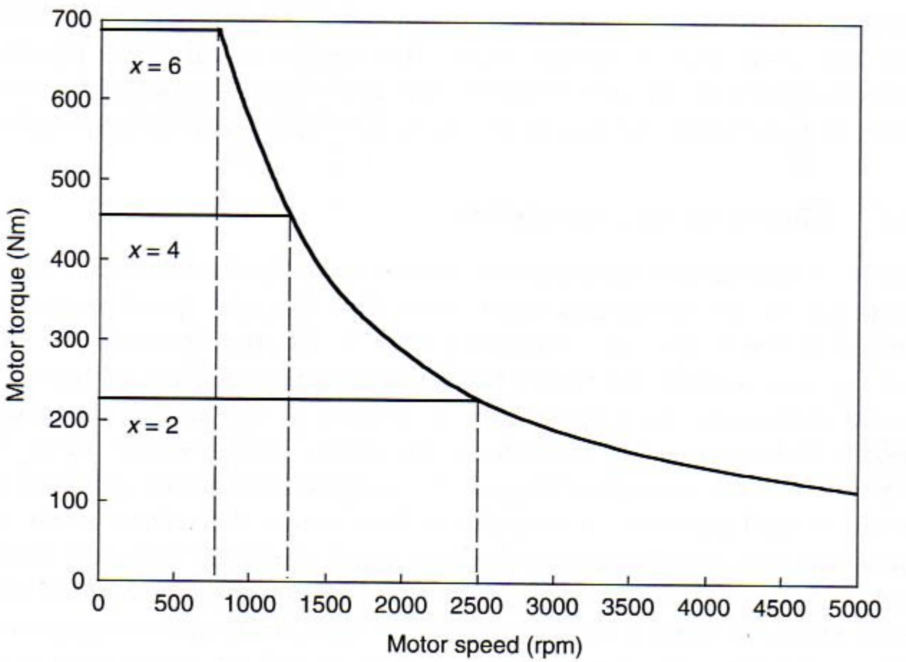
$$C = C^{MAX} \quad P = C^{MAX}\omega$$

- At high speed: constant power
  - Motor voltage is kept constant while flux is weakened, reduced hyperbolically with the rotation speed

$$C = P^{MAX}/\omega \quad P = P^{MAX}\omega$$

- Base speed: transition speed from constant torque to constant power regime $\omega_B = P^{MAX}/C^{MAX}$

Traction motor characteristics



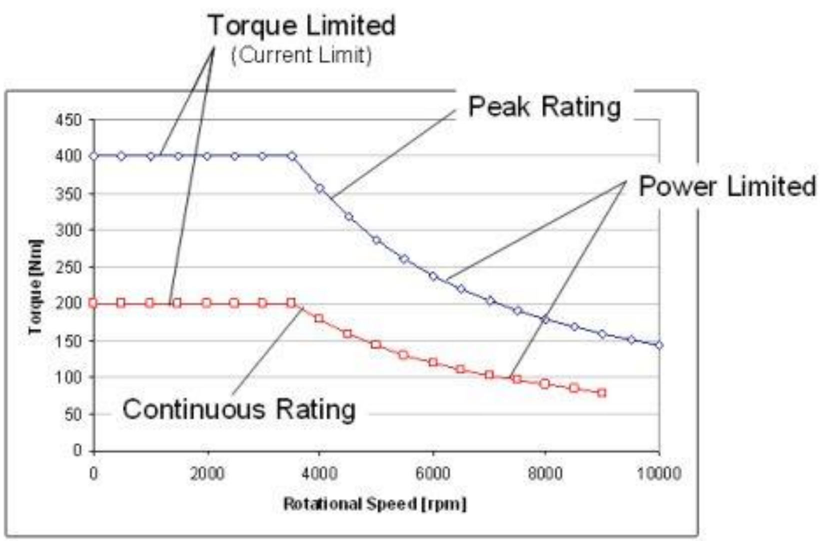
- Speed ratio x = ratio between the maximum rotation speed to base speed

$$X = \frac{\omega^{MAX}}{\omega_B}$$

  - X ~ 2 Permanent Magnet motors
  - X ~ 4 Induction motors
  - 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

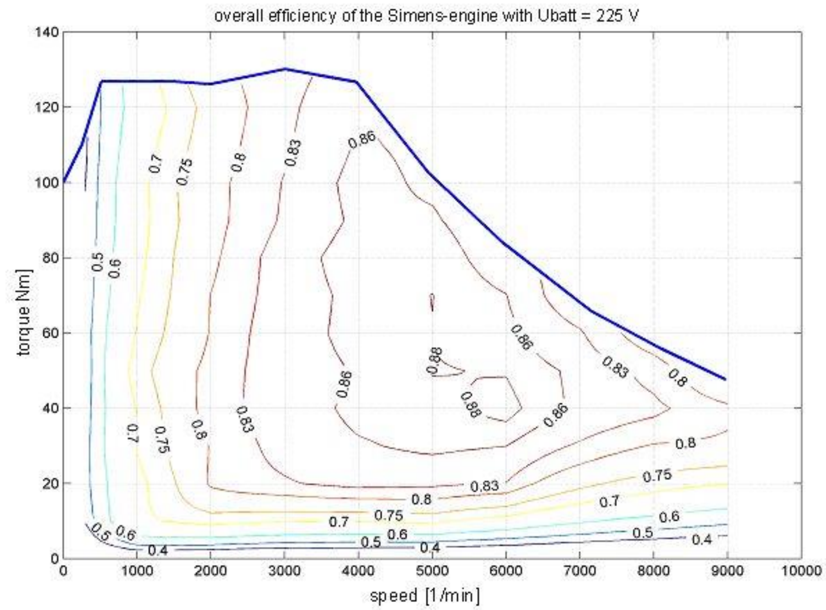


- Traction electric motors are able to sustain overcharging during a short period of time, typically 1 to 2 minutes.
- Overcharging factor depends of the electric motor technology but it can be up between 2 to 4.
- Thus one has also to distinguish the continuous power from the peak power (which is much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

Traction motor characteristics

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

$$\eta_e = \frac{\mathcal{P}_{meca}}{\mathcal{P}_{elec}}$$



- 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)