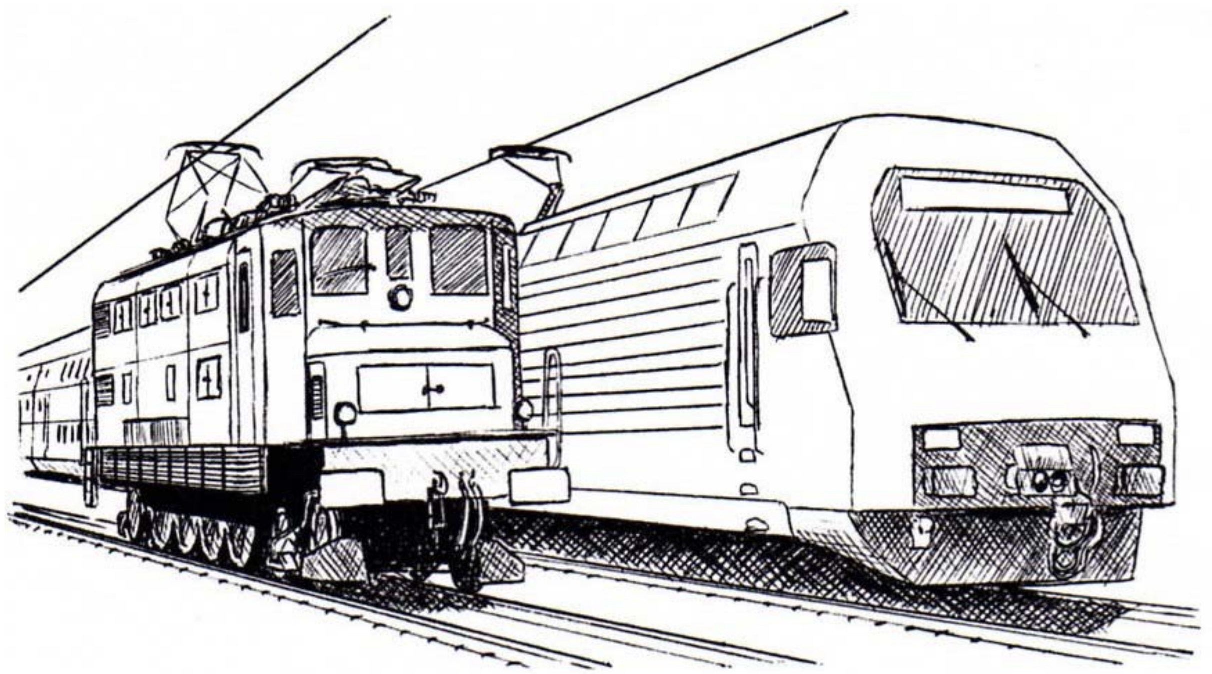
Railway Technology



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1.1 Introduction

Railways still existed for a long time when electric traction appeared. But this last offered a further expansion until which one we know today:

- Upgrade of train payload.
- More speed and acceleration to reduce travel time.

Compared to steam locomotive, and now diesel locomotive of same weight, the electric locomotive offers not only more nominal power, but can also deliver shortly a higher power – de 50 % à 100 % – more than nominal one. This property justifies the heavy costs of electrification, when the traffic increases on a line. Diesel is let on low traffic lines.

1.2 Introduction to second edition

Since the first edition (1995), some technologies get a large expansion and some other disappeared totally (in new built vehicles).

The *mass transit* and the *high speed trains* knew an unsuspected growth. Also *heavy freight* has increased activity,

The part of railway transport will probably grow in the next years, because the road saturations and the climate heating.

1.3 Introduction à l'édition en ligne

In this edition, the main place is put on the actual and new solutions. Some older a shortly mention for following reasons:

- The life of a railway vehicle is long enough so that "obsolete" technologies can be found on daily commercial service.
- The technological-historical knowledge can be useful to understand some actual choices.

Compared to printed version, the electronic one uses the same figures and equations numbering. This summary invites to buy the full book by PPUR.

1.4 The locomotive: an energy-converter.

The function of an *electric* locomotive is to convert electric energy on mechanic energy. This conversion varies during time. We prefer to talk about power conversion.

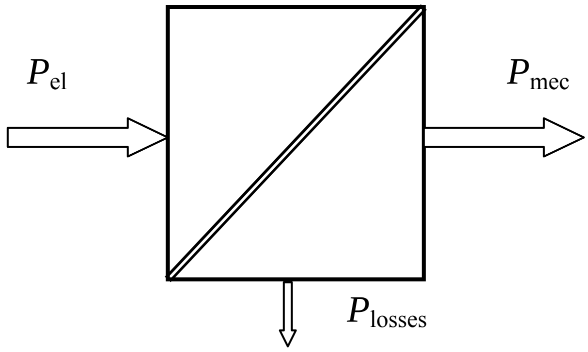


Fig. 1.1 Power conversion.

Conversion acts on three steps.

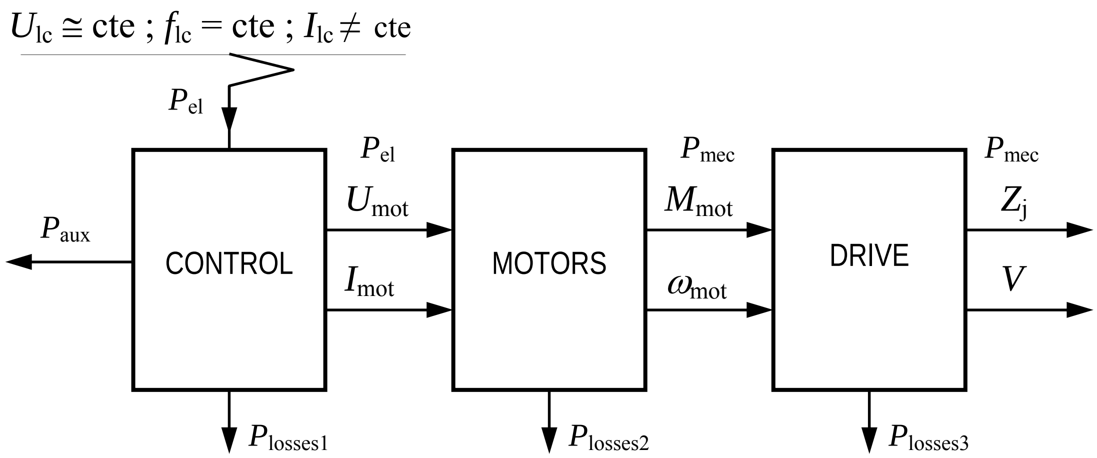


Fig. 1.2 Flows and powers in a locomotive on traction mode.

On electric brake, a reverse conversion is operated.

1.5 Locomotive building: a multidisciplinary task.

The design, building and operation of an electric locomotive need different technologies (Fig. 1.3). Multidisciplinary organization is necessary from the beginning, in order to optimize the vehicle.

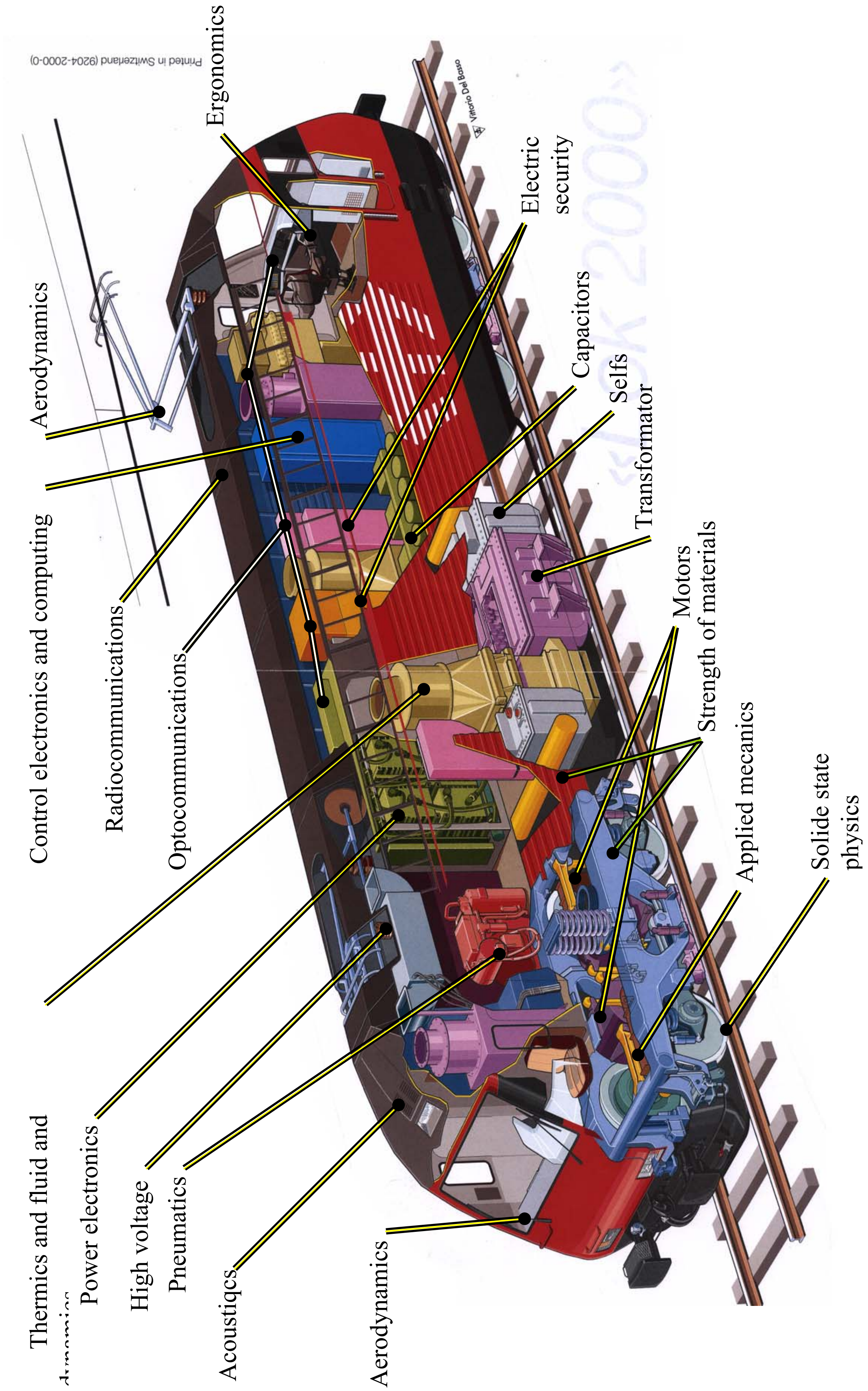


Fig. 1.3 A locomotive and the applied s technologies.

2.1 Interdependance of development

Railway and electric traction history is closely linked with the electro-technic development rhythms, in particular transformers, motors and semiconductors. Fashion, politic or strategic choices also influenced notably the evolution of electric traction.

On electrifications, technologically strong solutions were implemented until ones with higher efficiency fond a sufficient reliability. After this, the last were used for new realizations as shown figure 2.1.

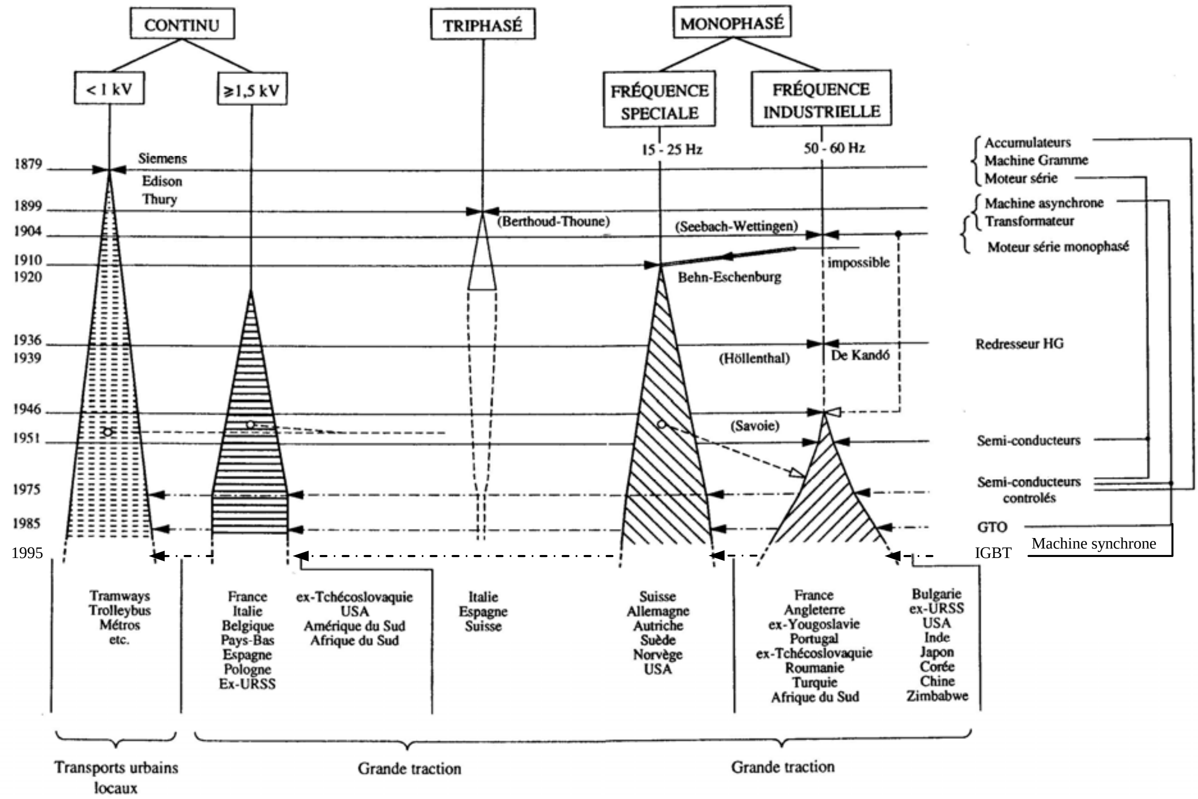


Fig. 2.1 Evolution of Systems.

2.2 Today's epoch

Today, only two systems are yet in full expansion: single phase with industry frequency for *great traction* and DC at low voltage for *mass transit*. Some infrastructures built long time ago with choices which will be different today; they are regularly used, and for long. As examples, the DC and AC at special frequency are only used on great traction because their replacements were too expansive.

Something is new in vehicle design. For three quarters of the century, the electric designer had quickly estimated the weight of electric part necessary to obtain the requested performances of the vehicle. The mechanical designer had to find the building solution in order not to exceed the maximal axle load. Mechanic and electric part were often built by different factories, perhaps by two independent divisions in the same company. Each partner had the challenge, not to exceed the designed weight. From seventies, the electronic assistance for the driver took its place at the side of both electric and mechanic parts. At millenary's change, a revolution went. Locomotives and trains are globally designed, researching optimization of a final product including computers – electro-technics – mechanics. The developments in detail are supervised by a general designer who defines precise specifications for each equipment, and the interface between them… and their builders. The power supply of network and the track geometry are included in design procedure. With so a method, the weight and costs can be optimized in comparison with barely older vehicles of same function (Examples: *185* de Bombardier, *Citadis* de Alstom, *Flirt* de Stadler, *ICE3* de Siemens).

3.1 General equations

The train movement is essentially a mobile of mass *m* with a single degree liberty. It's described by a scalar Newton-equation.

$$\sum_{i=1}^{n} F_{\mathrm{i}} = m^{*}\, a \qquad (3.1)$$

Forces produced in the train: forces from motors or from mechanical brake and the forces undergone by the trains: proper frictions and localized forces (slope, frictions in tunnels or curves).

The proper frictions have three parts: a constant, a part proportional to the speed and a part proportional to the square of speed.

$$F_{\mathrm{f}} = A + Bv + Cv^{2} \quad [\mathrm{N}] \qquad (3.5)$$

Please take care if numeric values are given for speeds in [m/s] in [mph] or in [km/h]. The curves on the figures 3.3 to 3.4 are quoted in forces relatives to train weight. Note that the hauled trains have different curves than locomotives, which open the way in the air.

1 UIC car about 1960 (SNCF, CFF, DB, FS)
2 Corail car 1975 (SNCF), Eurofima 1980 (DB, FS, ÖBB, …) or VUIV 1985 (CFF)
3 Light car 1940 (CFF)
3 adding 20 [N/t] BOB car on rack section.

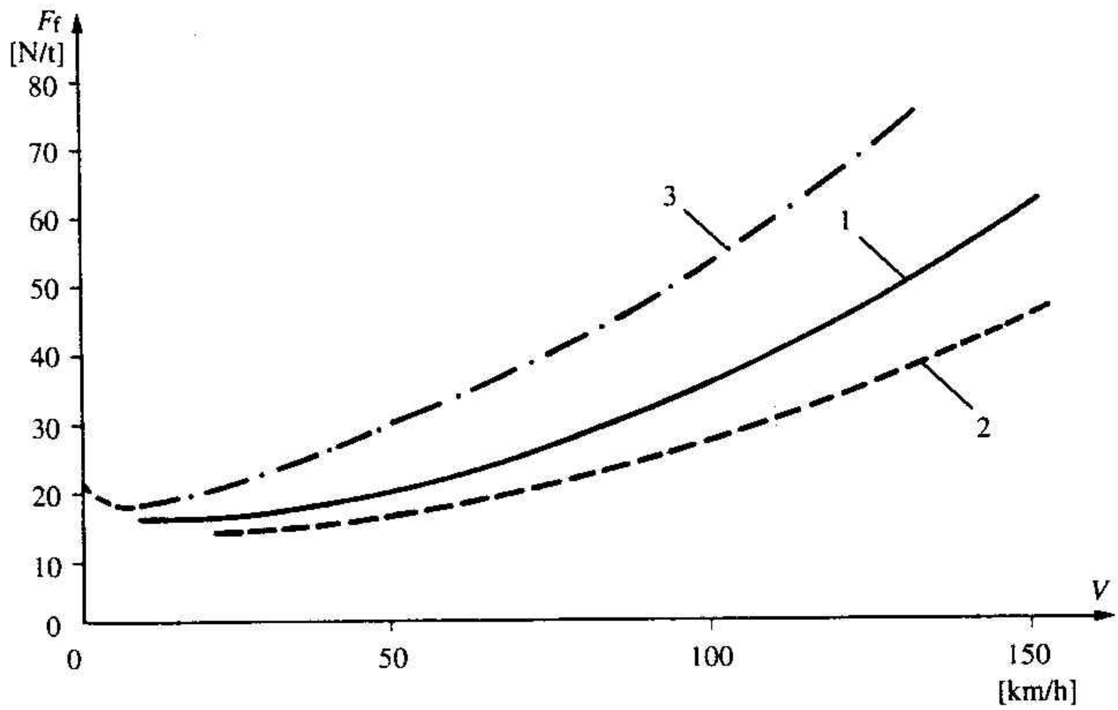


Fig. 3.4 Movement resistance for passenger trains.

1 locomotive Ae 6/6 (CFF): CoCo of 120 t
2 locomotive 9001 (SNCF): BB of 80t
3 locomotive 6001 (SNCF): CC of 120 t
4 locomotives Am 4/6 (CFF) : 1BoBo1 of 93 t, Re 460 (CFF) : BoBo of 84 t (———)
5 locomotive 2D2 (PO)
6 locomotive BBB (FS)
7 locomotive Re 4/4 II (CFF) : BoBo of 80 t
8 locomotive Re 6/6 (CFF) : BoBoBo of 120 t
9 motor-car BOB on rack
10 motor-car BOB on adherence
11 articulated motor-car TSOL or Stadtbahn B

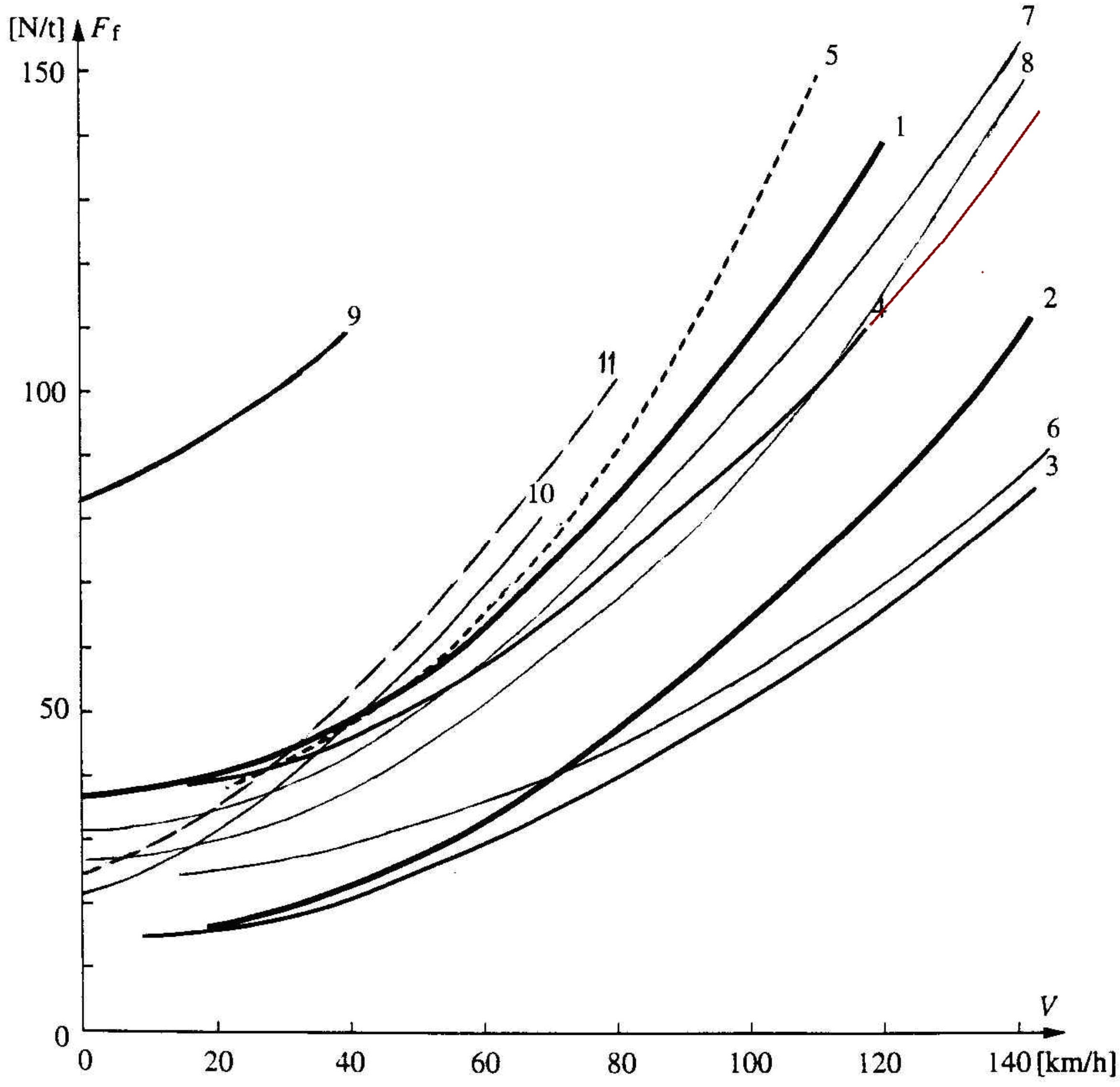


Fig. 3.3 Movement resistance of motor vehicles.

The freight trains have different characteristic, because the different forms end the non-flat wall increase the aerodynamic frictions with turbulences.

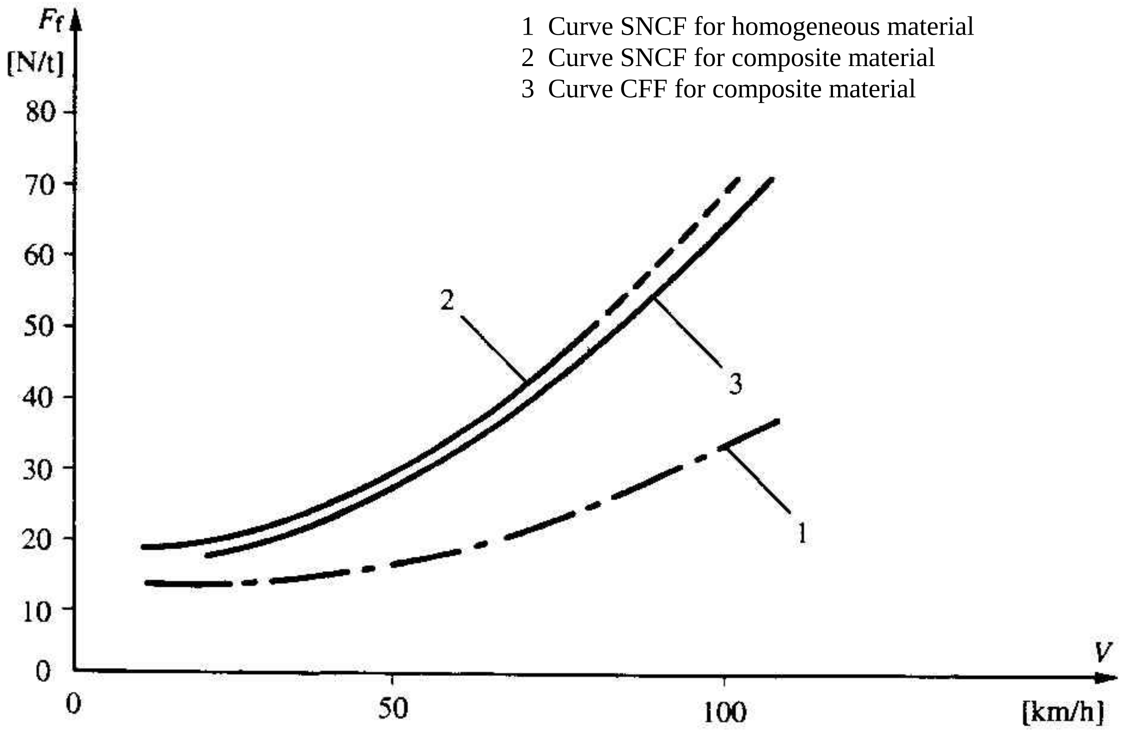


Fig. 3.5 Movement resistance for freight trains.

On a slope, the movement resistance is obtained by multiplication of the train weight and the pent *i* of the track, given en per mille in the tables. Note that angle sinus is replaced by angle tangent, which is good until about 120 ‰.

$$F_{\mathrm{d}} = m\, g\, i\, 10^{-3} \quad [\mathrm{kN}] \tag{3.12}$$

If the mass is measured in kilograms and not in tons, the force is obtained in [N].

The additional friction force F_c in curve is limited on certain segments of the way, where the curve radius is small.

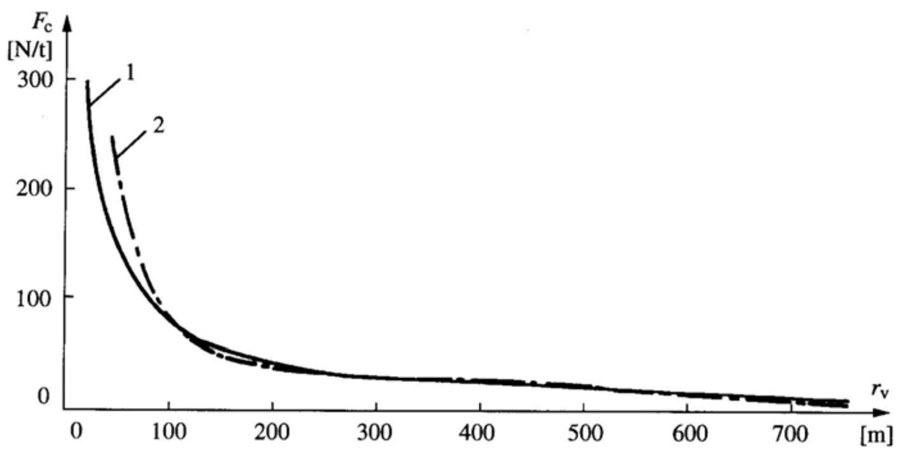


Fig. 3.10 Additional movement in curves on standard gauge.

For the additional friction force in tunnel, the value « Cv^2 » of the equation (3.5) is doubled in a double-tracks tunnel and tripled in a single-track tunnel. This takes care of the piston effect in the tube of tunnel.

For the train acceleration (3.1), note the weight mass has to be increased by the effect of rotating masses – wheels, cog wheels, motor rotors – which causes an apparent increased mass, symbolized by the factor ξ.

$$m^* = \xi\, m \qquad (3.22b)$$

Vehicles		ξ
Complete train	for adhesion	1,06 à 1,10
Cars and wagons		1,02 à 1,04
Empty cars		1,05 à 1,12
Motor-cars		1,08 à 1,14
Locomotives		1,15 à 1,30
Cars	for rack	1,05 à 1,10
Motor-cars		1,30 à 2,50
Locomotives		1,50 à 3,50

Fig. 3.13 Coefficient of rotating masses.

The traction effort $Z = F_{in}$ is computed from the torque M_m at motor shaft, the gear ratio k_G , the wheel radius r_e and the gear efficiency η_G (see chap. 5).

$$Z = \eta_G \frac{M_m}{k_G r_e} 10^{-3} \quad [\text{kN}] \qquad (3.17)$$

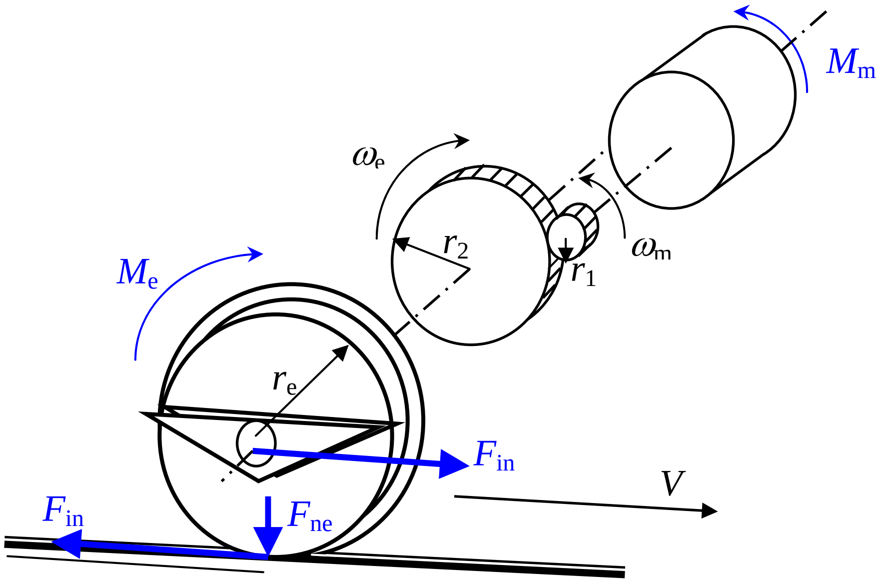


Fig. 3.12 & 3.14 From rotation to translation, on adhesion.

Because of the adhesion conditions of steel wheels on steel rails, the traction effort and braking effort are limited. The limit depends on the adhesion's factor μ_r and the force F_{ne} of the axle perpendicularly to rail surface. In a first approximation, the force can be considered as a quarter of the weight a four-wheel locomotive, but it is not a constant in reason of the dynamic of bogies and body and their suspensions, when a tractive effort at the coupling and the efforts at wheel rims cause a rotation torque. The adhesion's factor depends on the translation speed of the vehicle and the gliding speed of wheel on rails, from empiric laws described on figures 3.15 and 3.17.

$$Z < \mu_r F_{ne} \quad [\text{kN}] \qquad (3.24b)$$

If the condition (3.24b) is not respected, the concerned axle begins to glide: This movement will increase if the driver ore an anti-gliding device does not reduce strongly and quickly the motor torque.

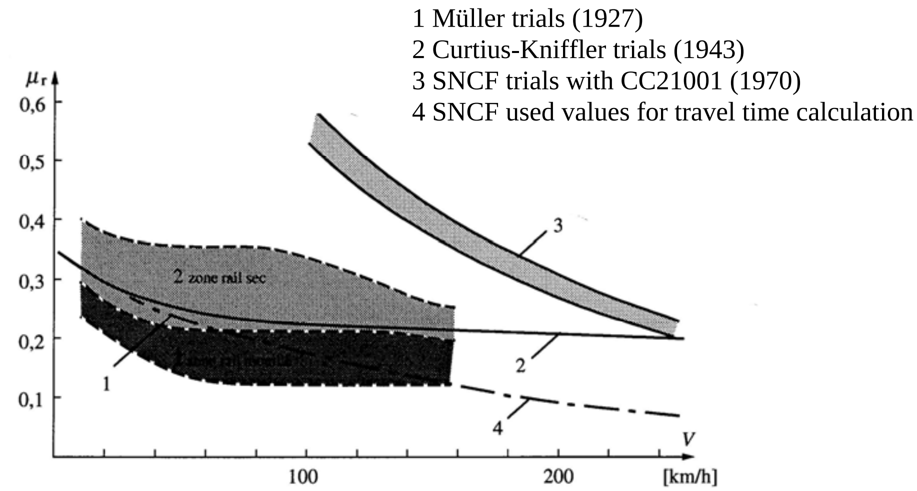


Fig. 3.15 Adhesion factor in function of the translation speed.

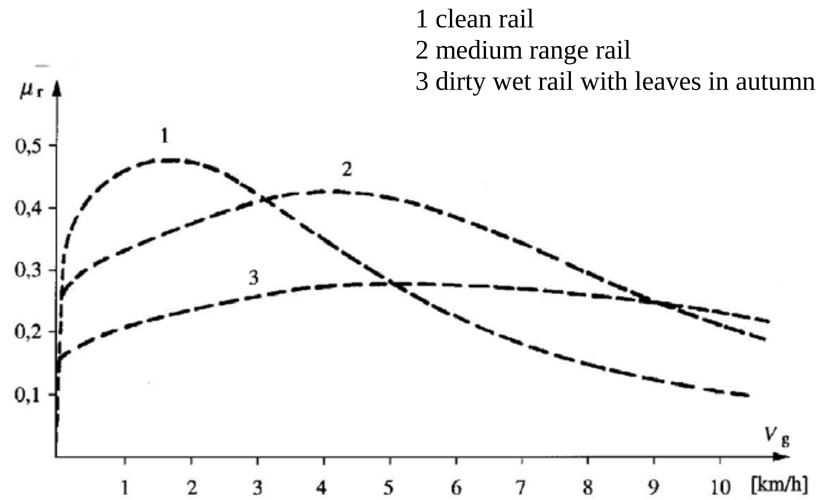


Fig. 3.17 Adhesion factor in function of the gliding speed.

The adhesion factor of a rubber tire on a roadway – metro or trolleybus – is quite double as a steel wheel on steel rail, between 0,55 and 0,62 depending of the surface type.

The necessary efforts Z maximal are at start.

$$Z = m * a + F_{\text{d}} + F_{\text{f}} \tag{3.1b}$$

The SNCF uses an empiric method to estimate effort, with a modified ramp i_{corr}.

$$Z = m\ g\ i_{\text{corr}}\ 10^{-3} \quad [\text{kN}] \tag{3.12b}$$

As example, the values are given for a freight train for an acceleration of 0,03 [m/s^2] :

$$\begin{aligned} i_{\text{corr}} &= 1{,}225\ (i + 2{,}2) && \text{if} \quad i \geq 7\ [‰] \\ i_{\text{corr}} &= 4{,}35 + i && \text{if} \quad i < 7\ [‰] \end{aligned} \tag{3.14b}$$

The *coupling effort* F_{att} is the effort at wheels rims, minus the necessary effort used for the traction engine itself.

$$F_{\text{att}} = Z - (m_{\text{loc}} * a + F_{\text{d\_loc}} + F_{\text{f\_loc}}) \tag{3.44}$$

The « UIC » coupling is built for a minimal breaking force of 850 kN. From this value, railway operators uses security margin and give a service limit (SNCF : 360 kN, CFF : 650 kN). Reinforced screw coupling exist (limit at 1350 kN) with same geometry as standard coupling. With an automatic coupling, the limit reaches 1500 kN.

The limits of adherence or of coupling have to be carefully observed at star.

4.1 DC-Motor

The collector motor, or DC-motor, as guaranteed the expansion of electric traction from the origin to a recent past: the end of 20th century. Supplied from a DC-current contact line, its work point is adjusted by a rheostat R_{rh} – which acts on voltage – and a shunt R_{sh} – which acts on the excitation – with a variable ohmic value. The excitation is mostly in series with the armature.

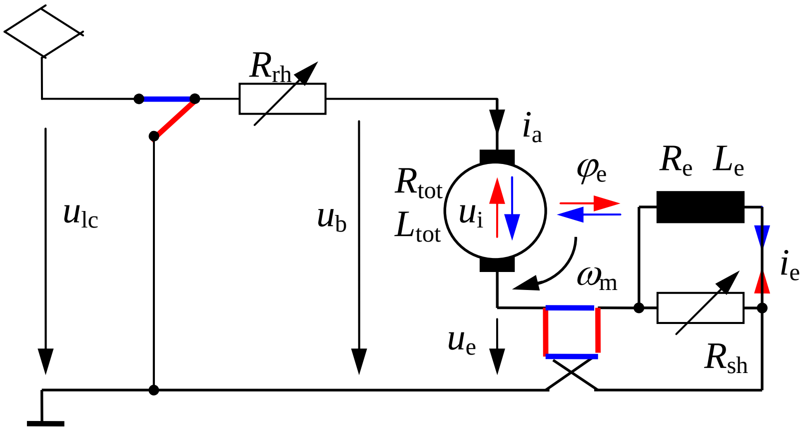


Fig. 4.4 Motor series in traction.
Fig. 4.9 DC-Motor: rheostatic braking with series excitation.

The internal equations are written below, neglecting leakage inductances in the motor. The motor constant is C_m, N_p is the number of whorls per pole and p the number of pole pairs. The total flow is Ψ_e and the gap flow φ_e.

$$\Psi_e = 2pN_p\phi_e \tag{4.3}$$

$$u_i = C_m\phi_e\omega_m \tag{4.4}$$

$$M_m = C_m\phi_e i_a \tag{4.5}$$

The dynamic equation shows the dependence of motor– with inertia (proper and herited) J – on the external torque M_{ex}. The rotation speed is ω_m.

$$\frac{d\omega_m}{dt} = \frac{1}{J}(M_m - M_{ex}) \tag{4.7}$$

In traction, the electric mesh equations can be written.

$$\frac{di_a}{dt} = \frac{1}{L_{tot}}(u_{lc} - R_{rh}i_a - R_{tot}i_a - u_i - R_{sh}(i_a - i_e)) \tag{4.8}$$

$$\frac{d\Psi_e}{dt} = R_{sh}i_a - (R_{sh} + R_e)i_e \tag{4.9}$$

In braking mode, only (4.8) has to be fitted: u_{lc} is zero and sign from u_i has to be changed. The three contactors allow select the coupling in traction (blue) or braking (red) in one sense of drive. In the other sense of drive the positions of both excitation contactors are exchanged: braking (blue) and traction (red), but the rule of contactor on the power supply side remains the same (AOMC: BDeh 4/4).

The characteristics for different ohmic values can be designed. Because the number of values is not very high, the working point variations go stepwise.

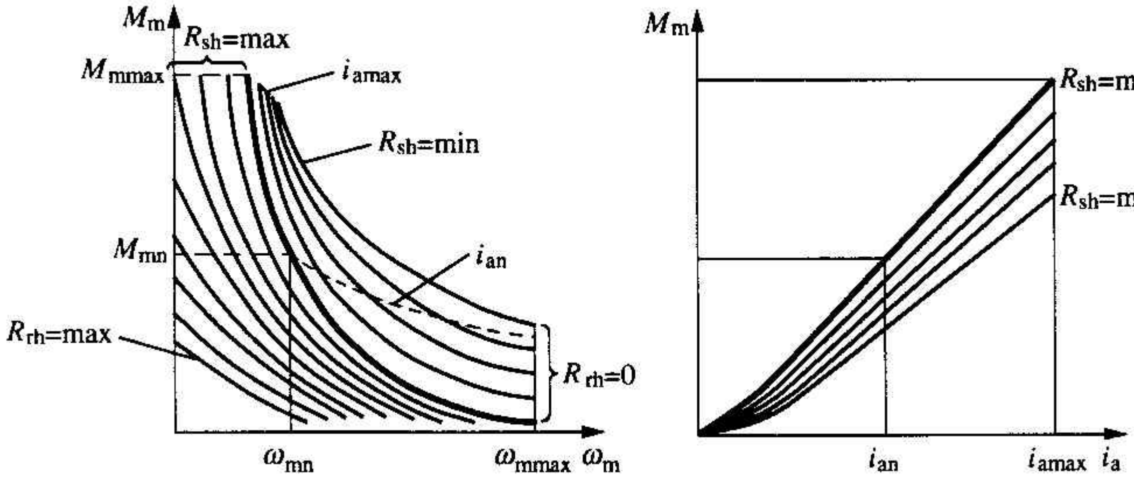


Fig. 4.6 Motor series in traction: torque characteristics versus current and speed.

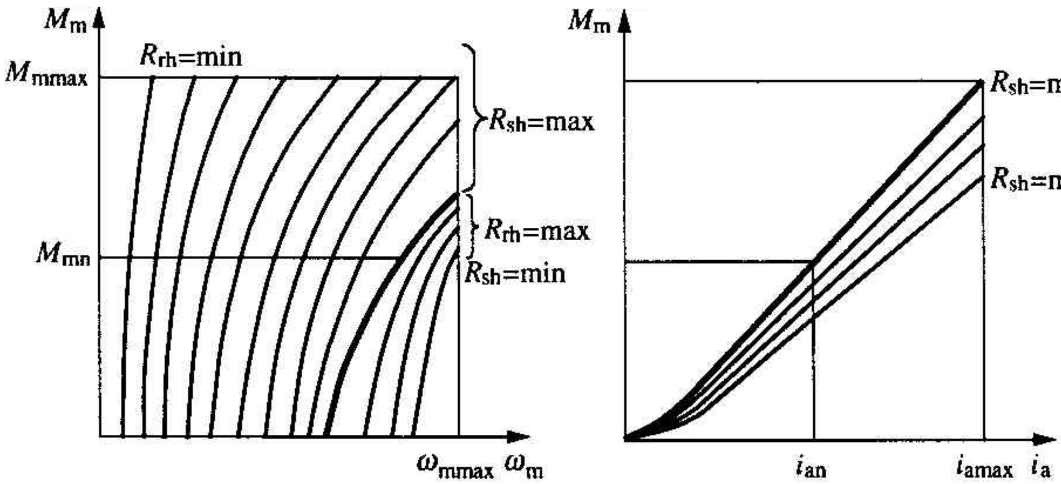


Fig. 4.11 Motor series in braking: torque characteristics versus current and speed.

On rheostatic braking, it can also be chosen separate excitation u_e, given from battery (SNCF: CC 6500), or from a generator moved by a motor, which is supplied from contact line (CFF: RAe TEE II).

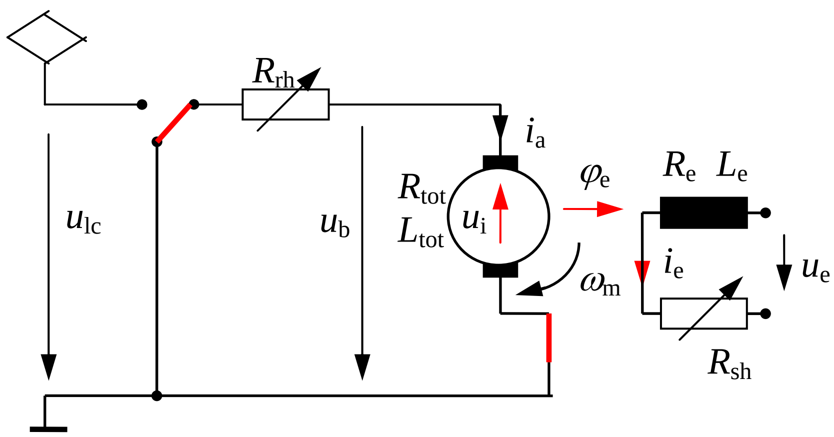


Fig. 4.13 DC-motor: rheostatic braking with separate excitation.

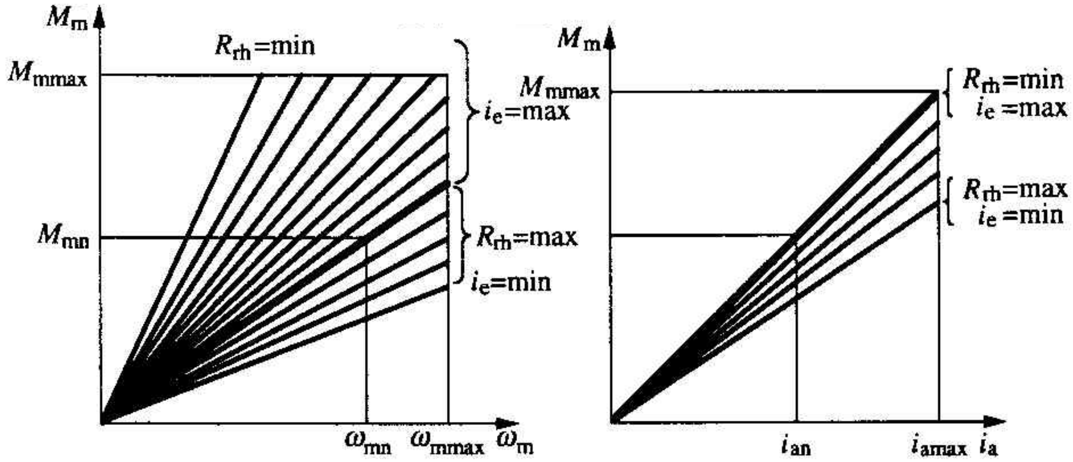


Fig. 4.15 DC-motor: rheostatic braking with separate excitation: torque characteristics.

Instead of take away (cinetic or potential) braking energy in a resistor, it can be injected on contact line: this is regenerative braking.

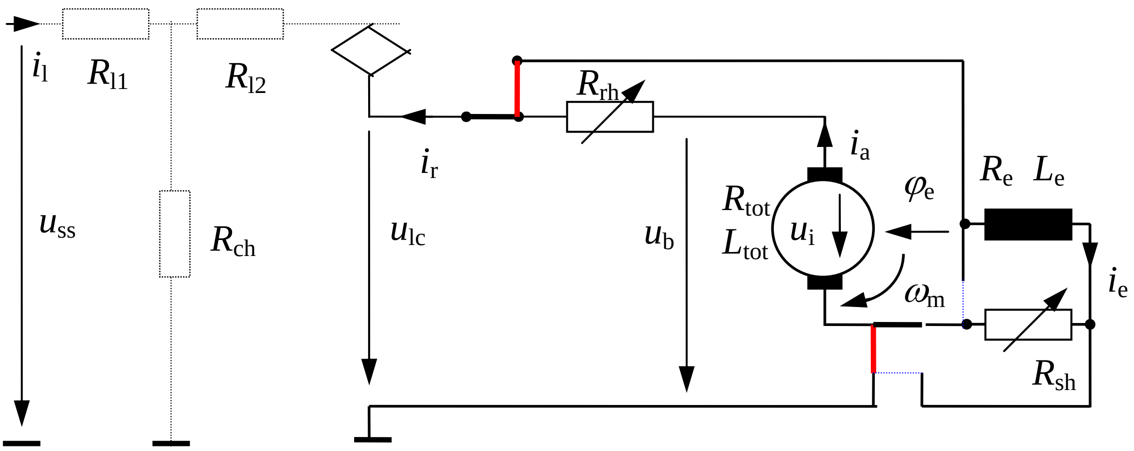


Fig. 4.17 DC-motor with separate excitation: principle of regenerative braking.

In traction the red contactors are open and the blue dotted are closed.

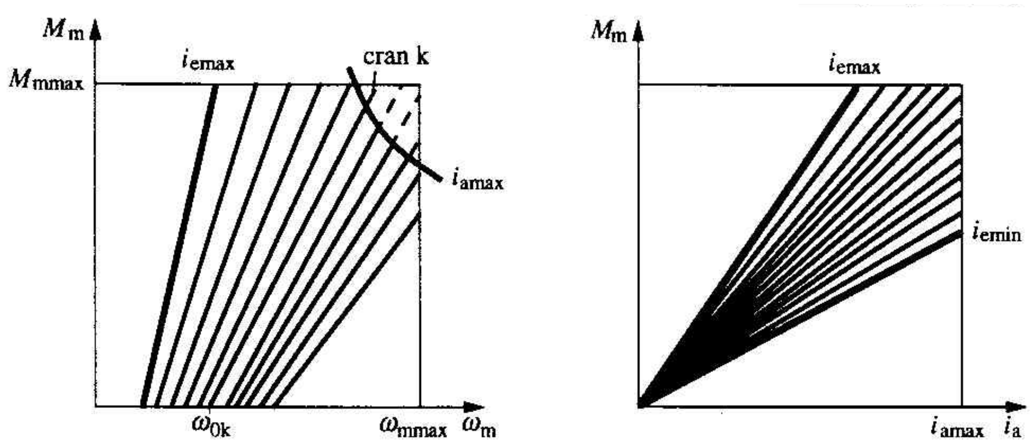


Fig. 4.19 DC-motor: regenerative braking with separate excitation: torque characteristics.

It is clear that in all points where the ohmic value of rheostat is not zero, one part of the energy from contact line is lost in heat in the resistor.

In order to increase the working point where the rheostat is zero (efficency 100 % in the motor control devices), contactors are installed to allow different motor arrangement in series or in parallel. It is possible to install contactors to allow transitions series-parallel without loss of tractive effort.

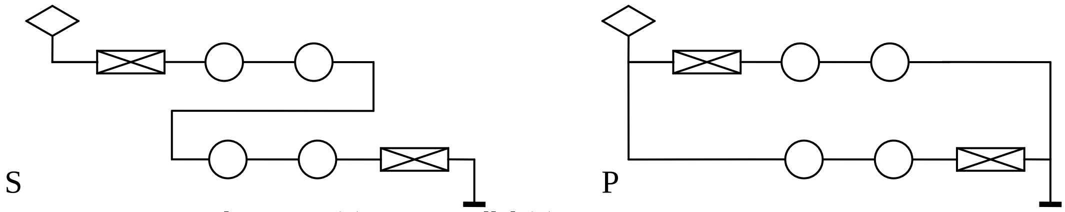


Fig 4.21B motors arranged in series (S) ou en parallel (P).

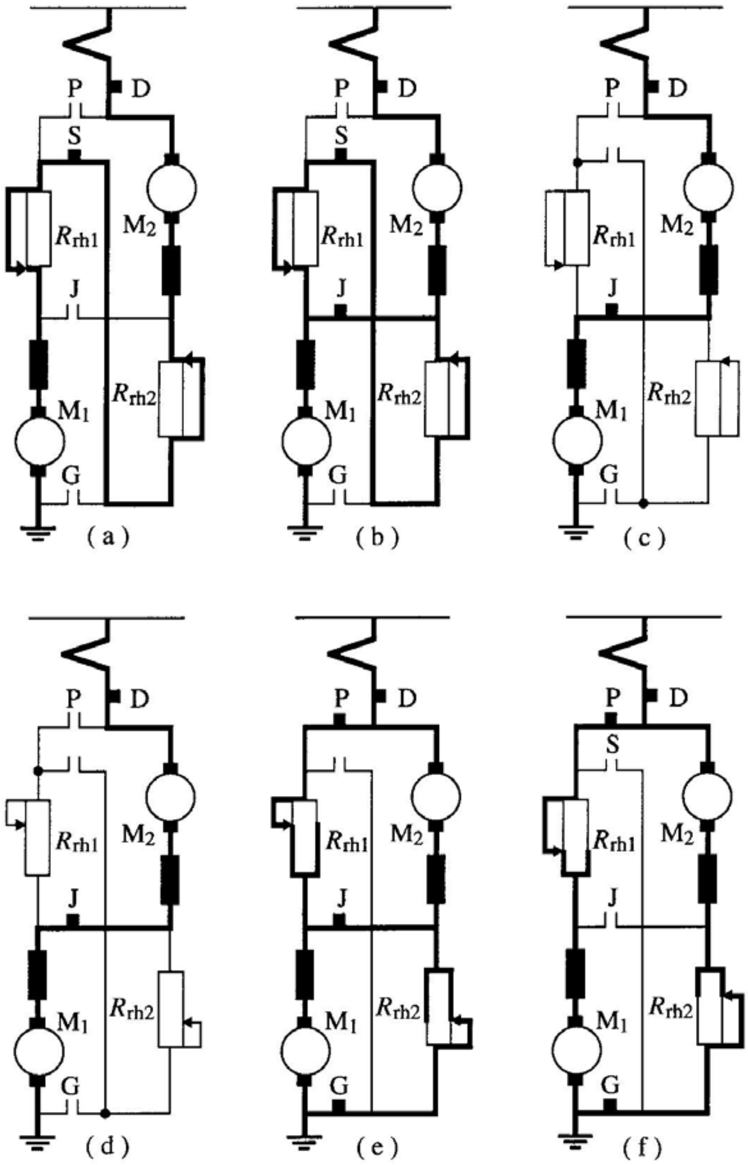


Fig. 4.22 Sequence from steps in a series-parallel transition with bridge-method (BOB : ABeh 4/4 II).

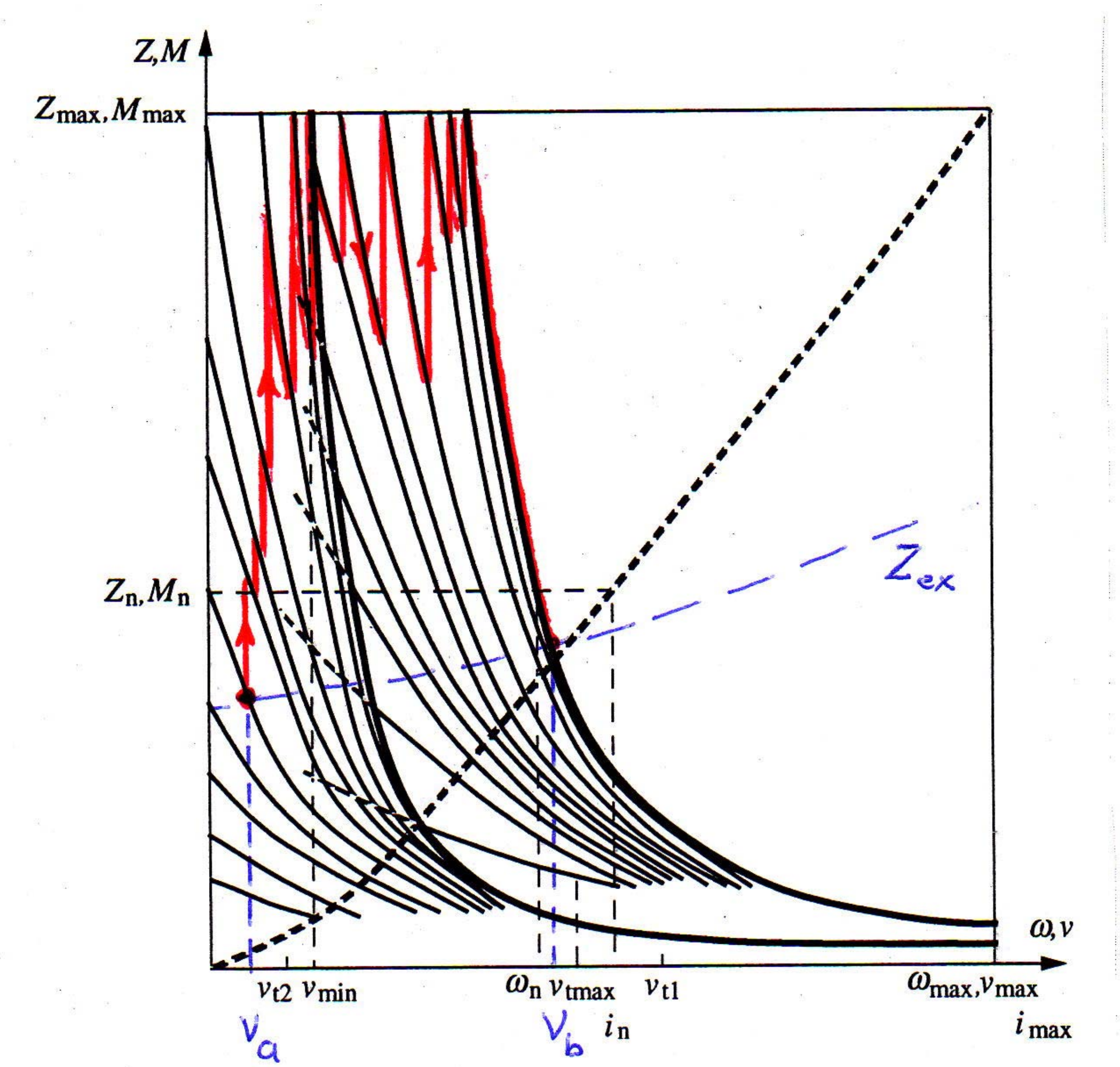


Fig. 4.21 Characteristics of motors en series (S) or in parallel (P).

Fig. 4.27 Acceleration from V_a to V_b, with the maximal traction effort: trajectory of work points.

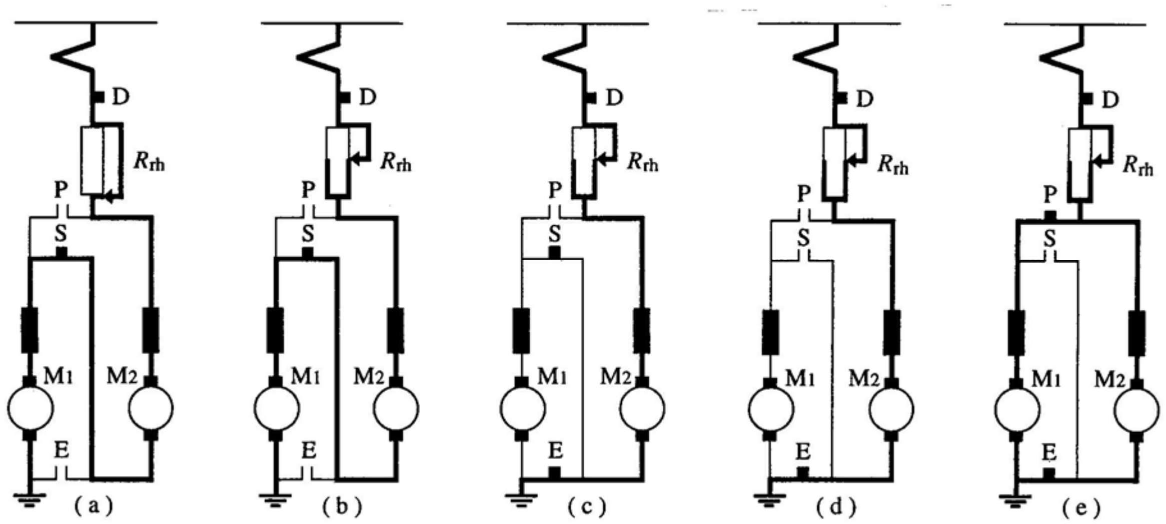


Fig. 4.23 Sequence ot steps in a transition with short-circuit-method(RhB : ABe 4/4).

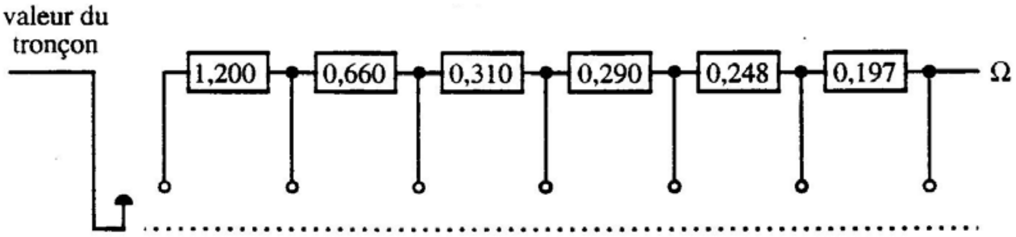


Fig. 4.34 Example of graduator at direct-current. (SNCF : Z2, rheostat # 1).

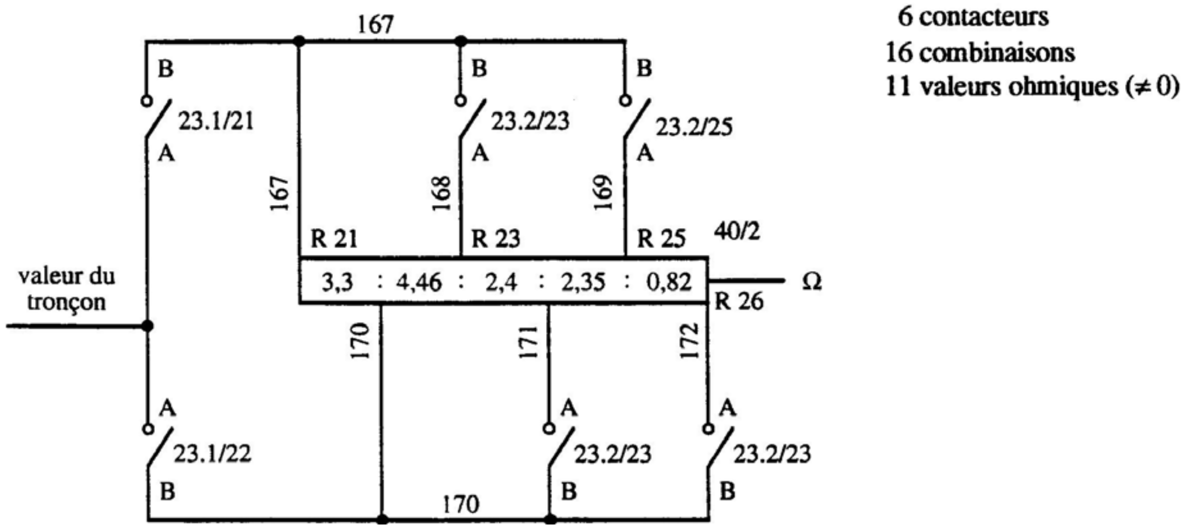


Fig. 4.35 Example of rheostat with contactors. (BOB : ABeh 4/4 III, rheostat # 2).

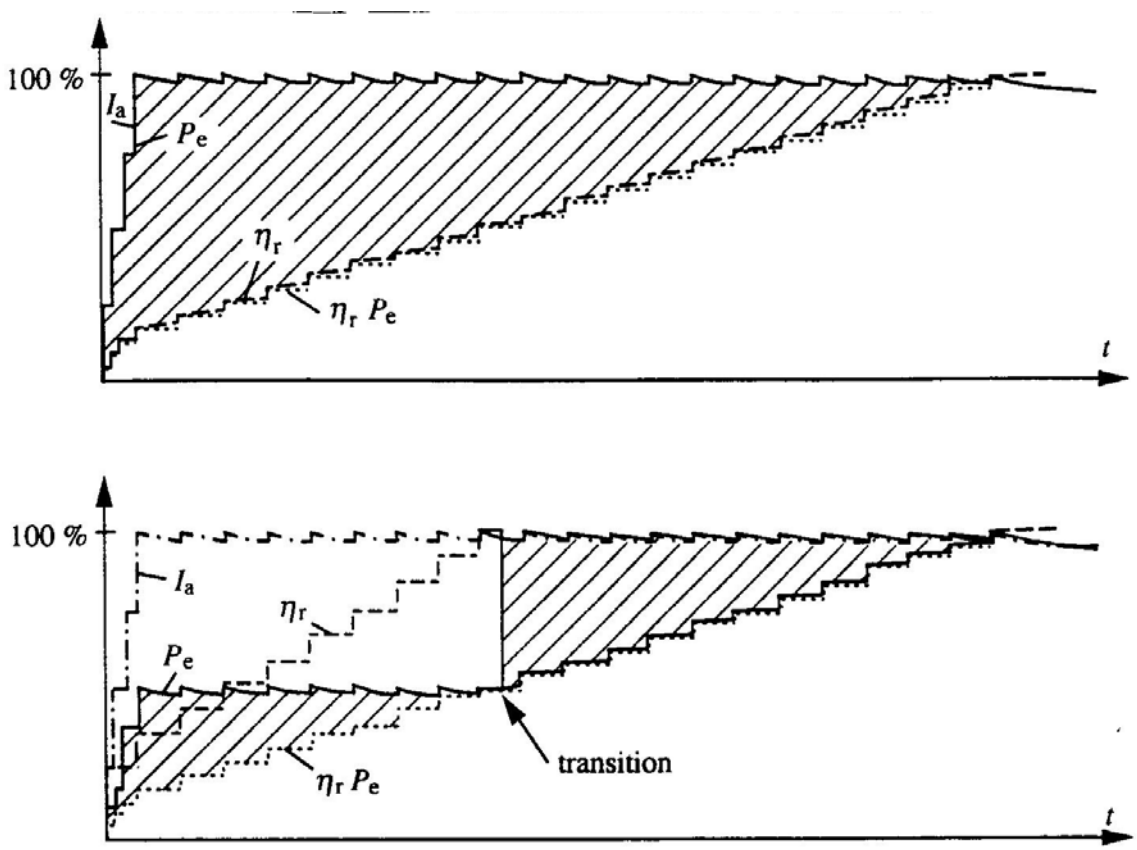


Fig. 4.36 Train start-up : losses in the starting rheostat: single coupling (up) and series-parallel (down)

4.2 Direct Motor

The commutator motor was the masterpiece of electric traction from the beginning until the end of the 20th century. It can be supplied from a single phase contact-line, the working point is adjusted by a transformer, which gives its voltage across. The excitation is mostly in series with the armature. This is a DC-motor *direct*ly supplied by a sinus voltage, giving its name *direct-motor*. This sinus voltage requires special fitting, which were developed by Behn-Eschenburg near 1905.

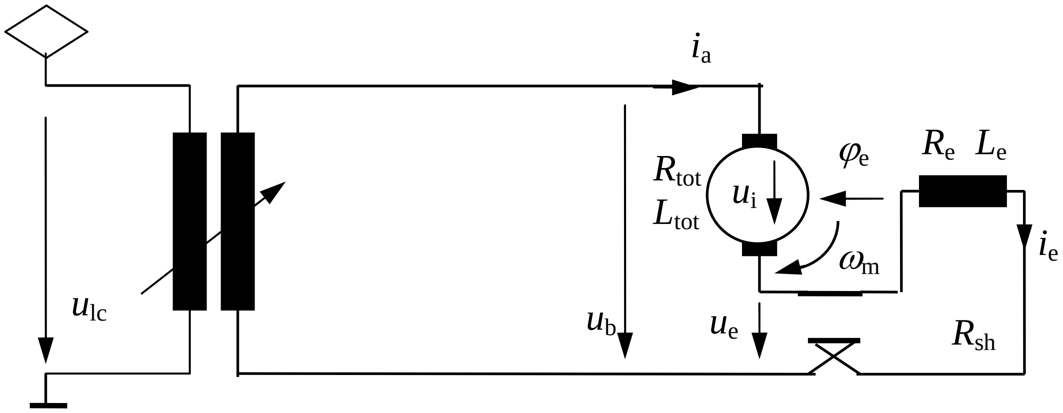


Fig. 4.42 Series motor in traction.

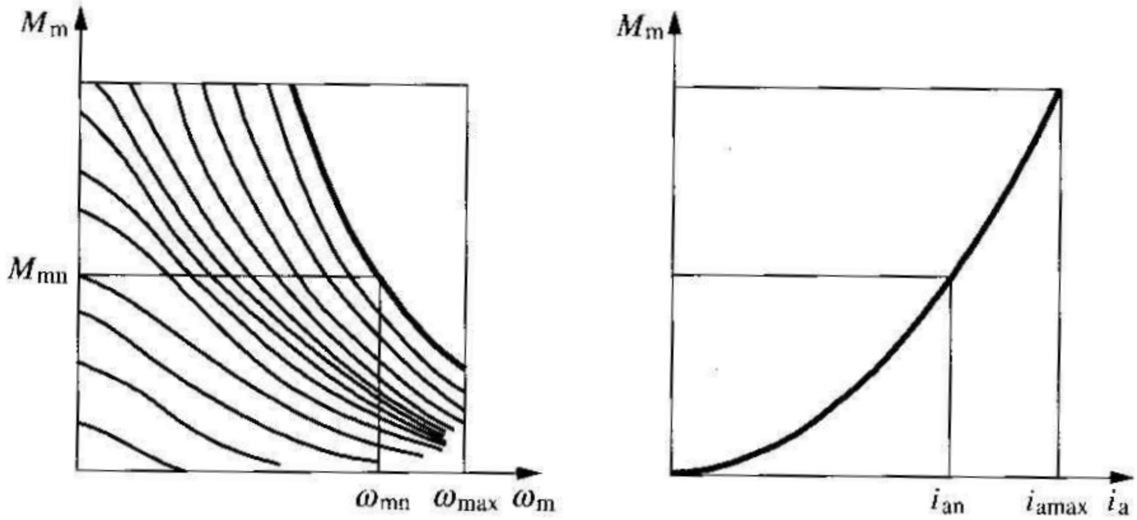


Fig. 4.44 Direct motor in traction: torque characteristics versus current and speed.

At section 4.1, the *commutation winding* was not mentioned; it allows to compensate the commutation voltage u_k which appears between two adjacent collector blades (see Traité d'Electricité, vol. X, § 8.6.4), this winding accelerate the return to zero of the current in the abandoned winding by the brushes on the collector. This winding did not exist on the first motor at the early beginning of electric traction.

$$u_k = L_\sigma \frac{di_a}{dt} \tag{4.19}$$

On single phase motors appears a transformation voltage u_{tm}.

$$u_{tm} = 4{,}44\, \phi_e\ f_{lc}\ N \tag{4.18}$$

To compensate these both voltages, an ohmic shunt R_c is put in parallel to the commutation winding. The *compensation winding* L_{comp} compensate partially la chute de tension the inductive voltage drop in the motor.

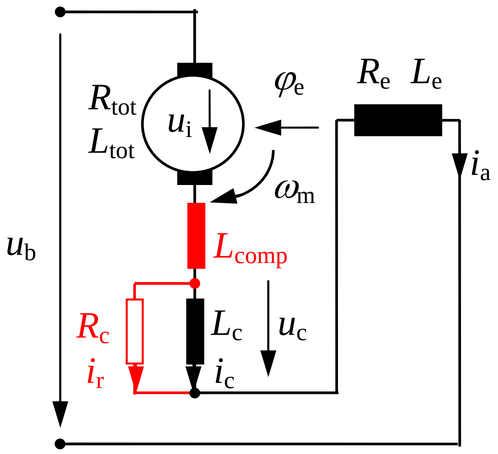


Fig. 4.37 Windings in single-phase motor.

A vector diagram of motor show the voltage u_c on the commutation winding and both ainsi voltages u_k et u_{tm} : the effect of ohmic du shunt is clear.

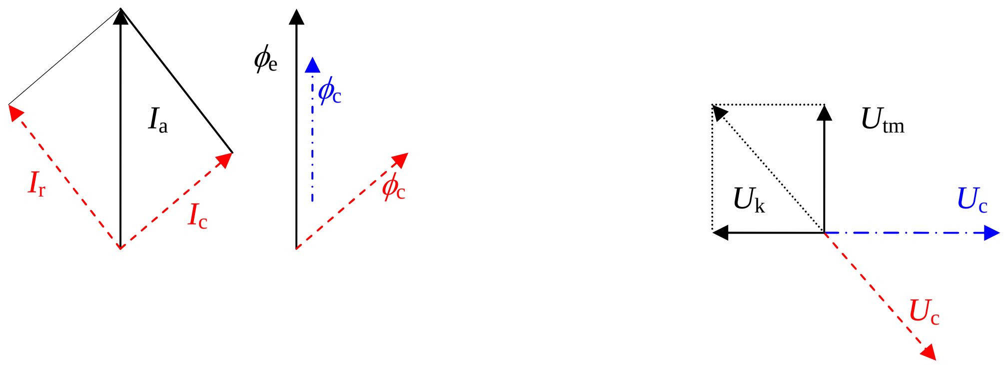


Fig. 4.38 & 4.39 Commutation in single-phase motor without and with ohmic shunt.

Without ohmic shunt, only one component – u_k – of collector voltage is compensated. The derivative of current in rotor winding depends on the speed, the compensation is only good at the speed where shunt calculation were done; in other speeds, it remains a residual voltage u_f.

Fig. 4.40 Commutation in single-phase motor at low or nominal speed.

In braking modes, not all wiring diagrams are studied in this summary, but only two examples: one in rheostatic and one in regenerative. Excitation energy can be supplied by an embedded converter (BLS : Ae 4/4).

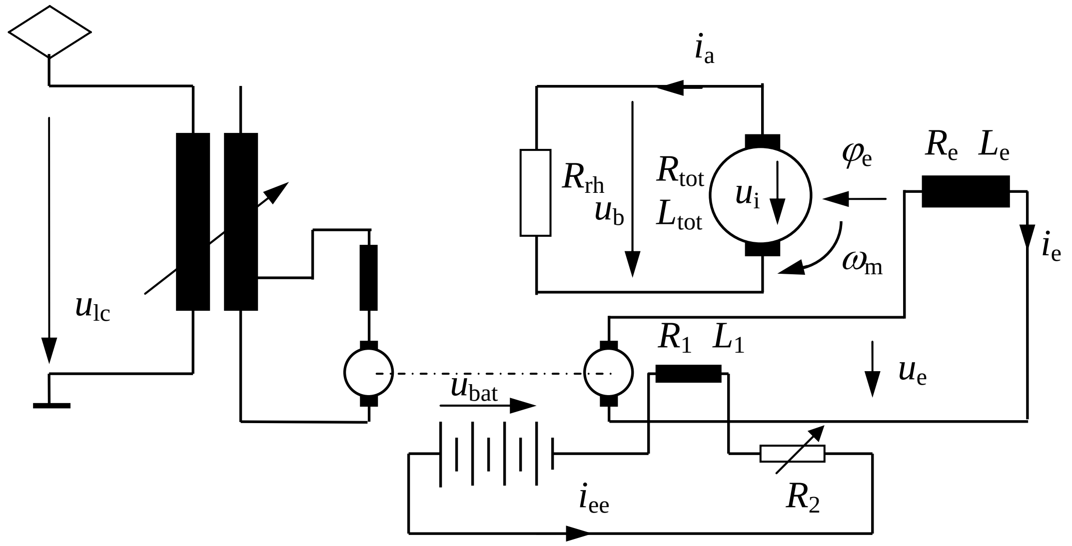


Fig. 4.46 & 4.48 Rheostatic braking at DC-excitation: diagram with generator group.

The excitation current i_{ee} in exciting machine is low, the resistance R_2 is built for continuous variation and not with steps.

One of traction motors can be used as generator to supply the others (DB:150). The diagram is similar but the « exciting machine» is driven by the axle.

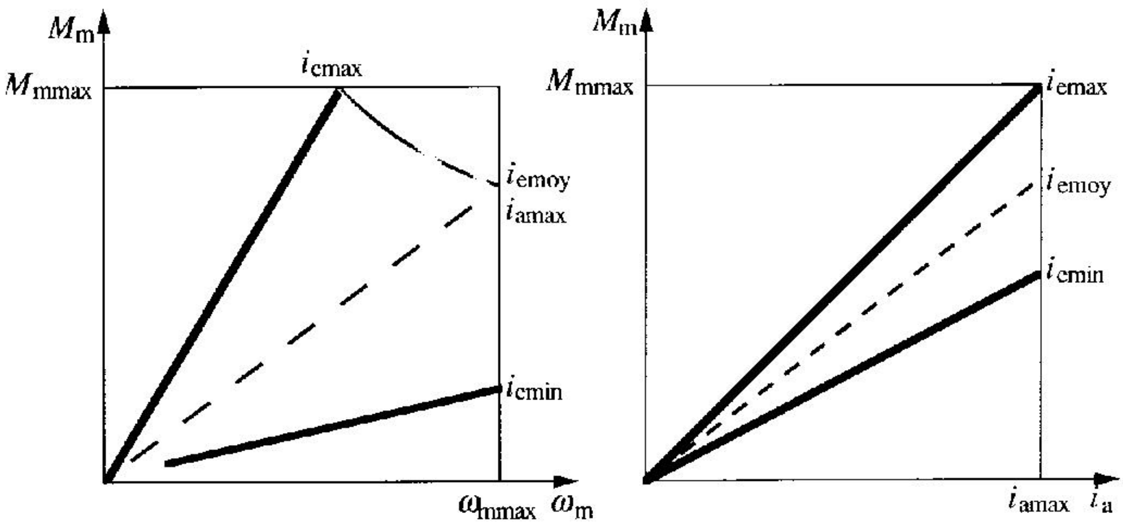


Fig. 4.50 Rheostatic braking at DC-excitation: characteristics.

Instead of take away the braking energy in a resistor it can be injected on supply network. The ultimate version Behn-Eschenburg-principle is the excitation by one of traction motors (CFF : Re 4/4 II).

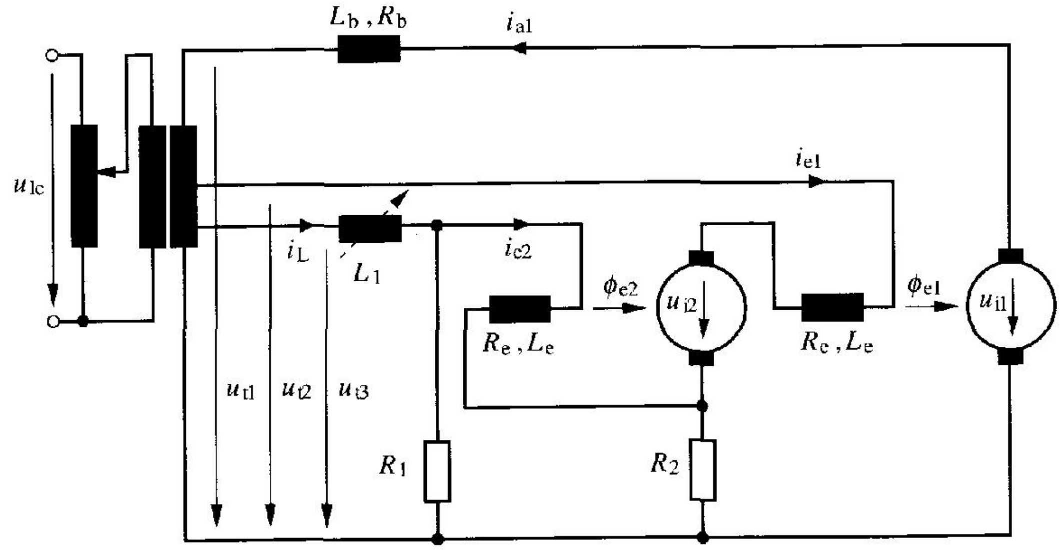


Fig. 4.59 Regenerative braking with separate excitation: diagram with excitation motor.

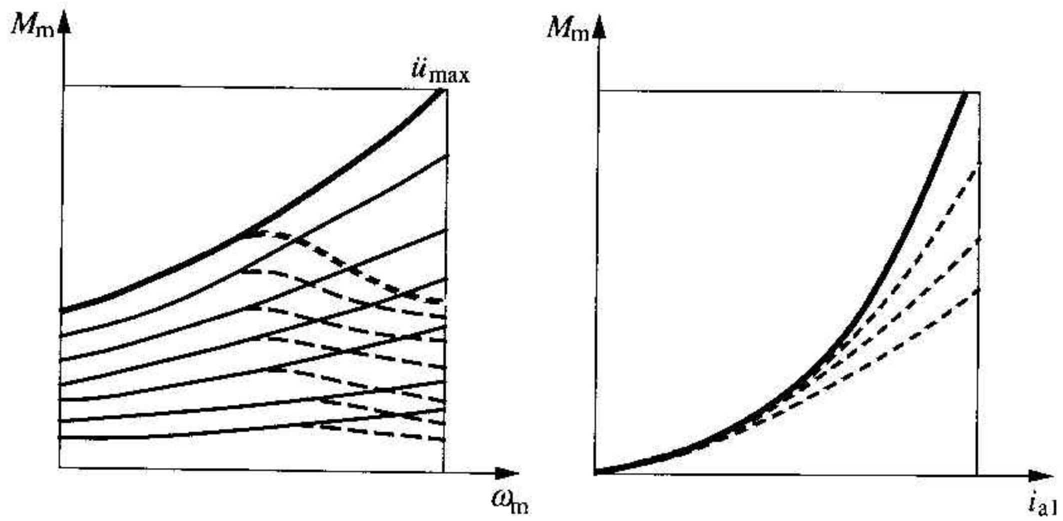


Fig. 4.61 Regenerative braking with separate excitation: characteristics.

The power ratio of this diagram is very low.

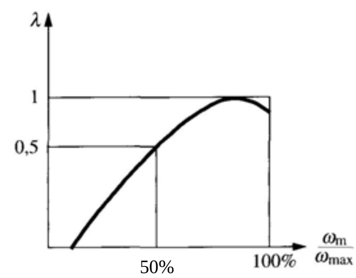


Fig. 4.62 Power ratio for braking with excitation motor.

The last conceived series of locomotives with direct motors were delivered from 1972 (CFF: Re 6/6) et 1974 (DB : 155). Last built units went in service in the middle of eighties (CFF : Re 4/4 II et DB : 155).

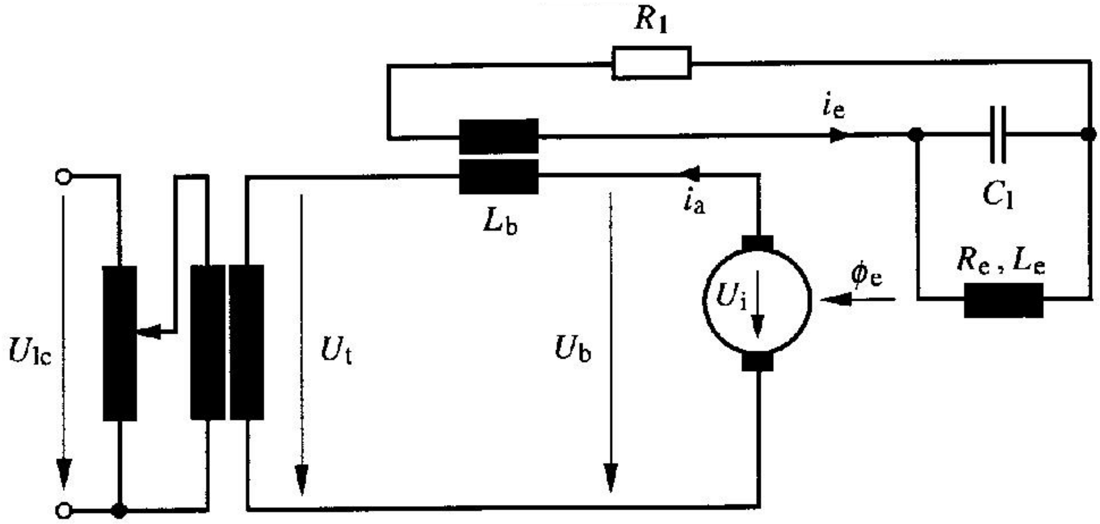


Fig. 4.63 Main circuit diagram for braking with resonance circuit.

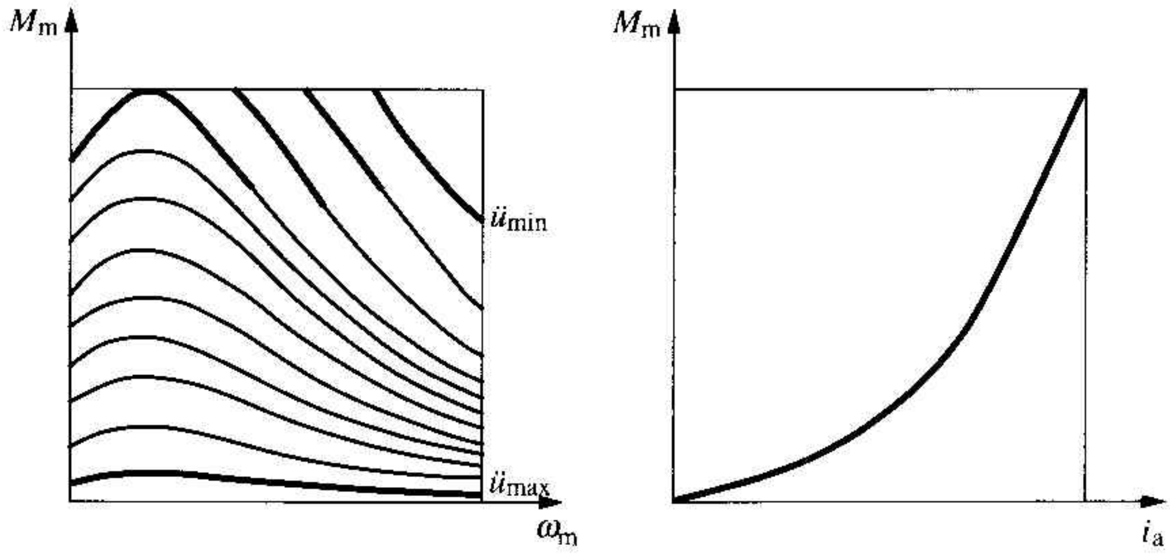


Fig. 4.65 Torque characteristics for braking with resonance circuit.

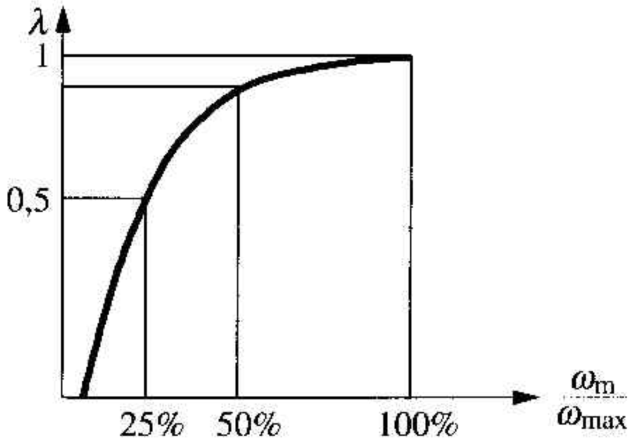


Fig. 4.66 Power ratio for braking with resonance circuit.

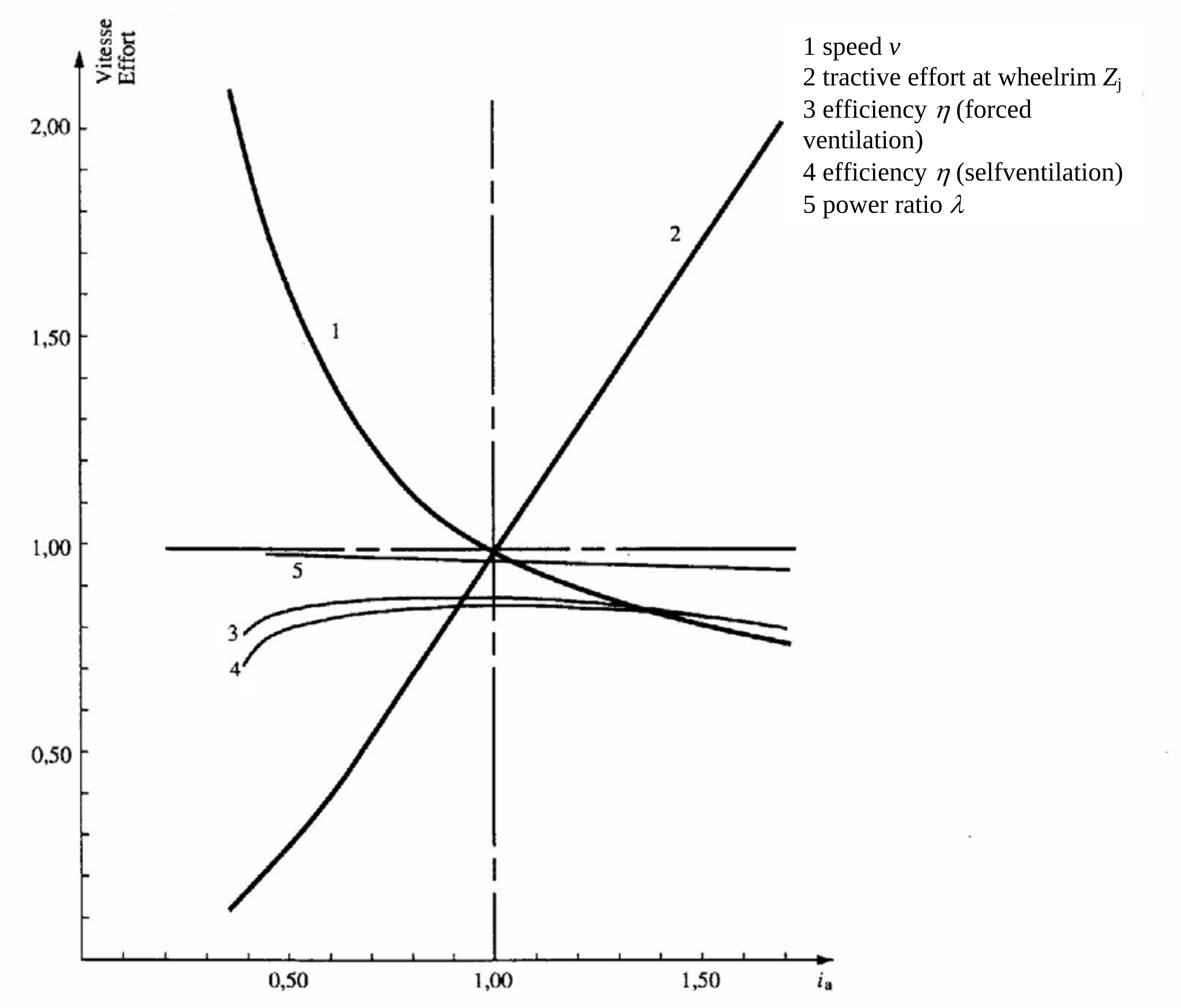


Fig. 4.67 Typical functions for a direct motor at test bank.

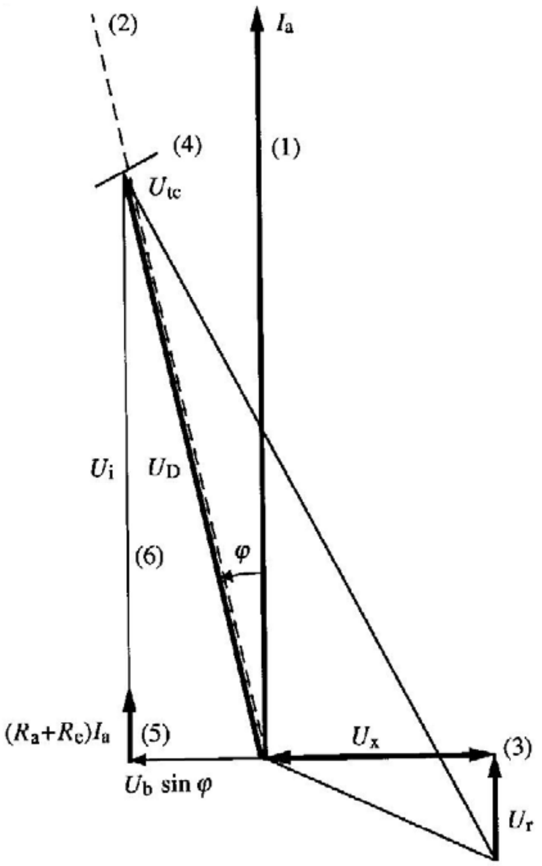


Fig. 4.71 Vector diagram of a motor at nominal work-point.

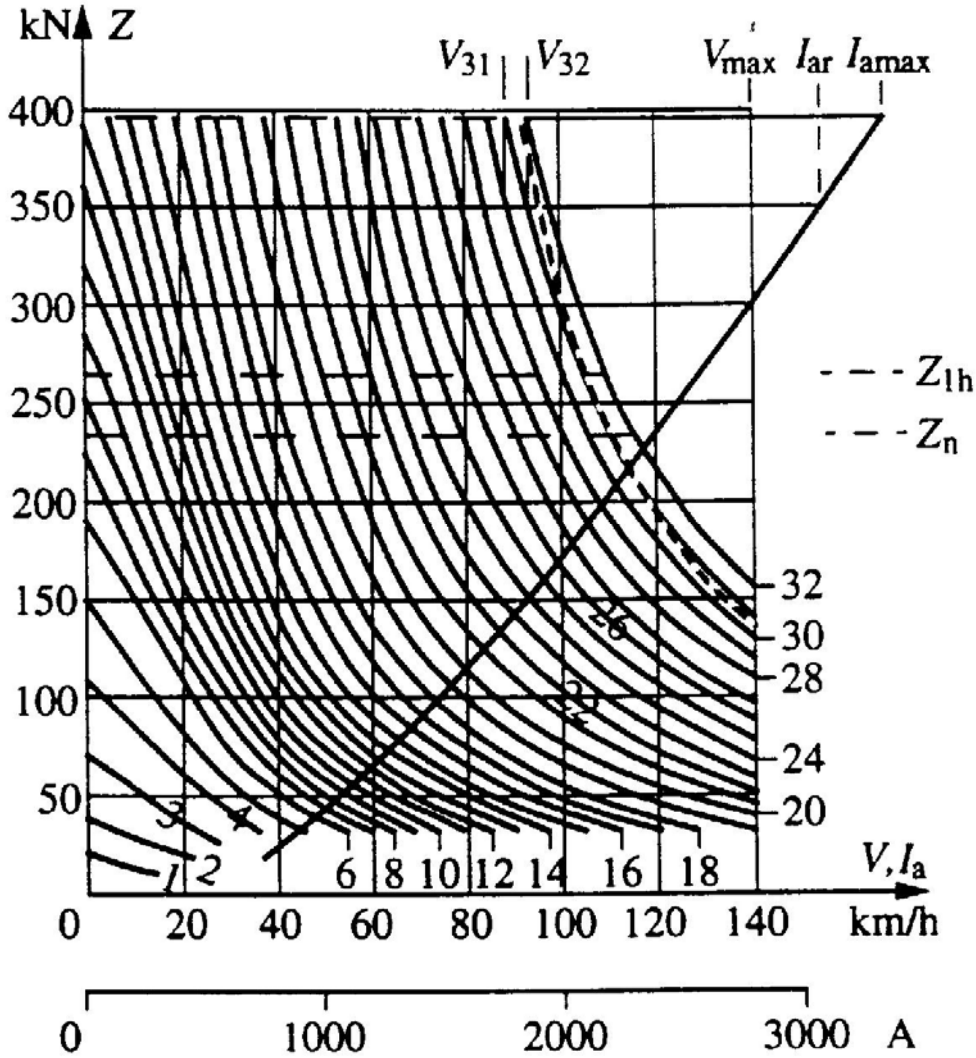


Fig. 4.72 Typical characteristics of a motor vehicle with direct motors.

Steps Stufen Crans	Voltage Spannung Tension
0	0
a	28
1	50
2	70
3	89
4	109
5	129
6	143
7	153
8	163
9	173
10	183
11	192
12	202
13	216
14	231
15	245
16	260
17	279
18	297
19	316
20	339
21	363
22	386
23	409
24	433
25	456
26	479
27	502

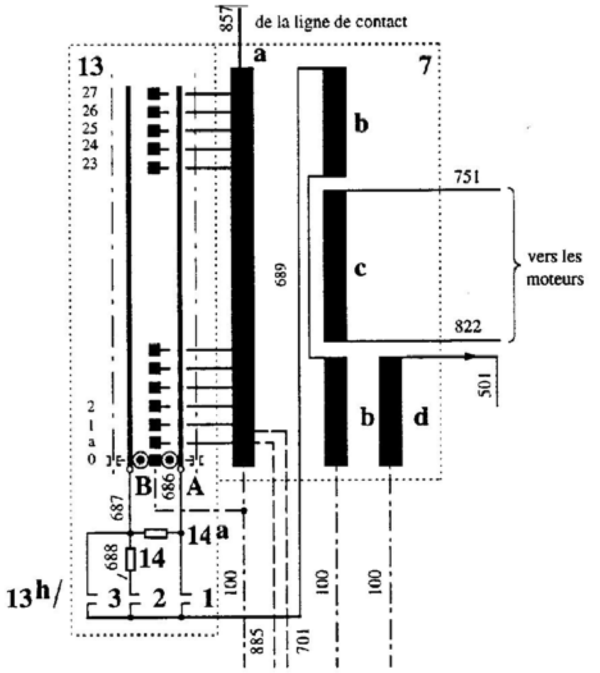


Fig. 4.74 High voltage tap changer : locomotive CFF Ae 6/6 : 6 motors in parallel for 4300 kW.

Steps Stufen Crans	Voltage Spannung Tension	Switches Schützen Contacteurs																
		1	2	3	4	5	6	7	8	9	……	27	28	29	30	31	32	33
0	0																	
1	100	●		●														
2	140	●		●	●	●	●											
3	140	●	●	●	●	●	●											
4	167		●	●	●	●	●	●										
5	193			●	●	●	●	●	●									
6	220				●	●	●	●	●	●								
7	247					●	●	●	●	●								
8	273						●	●	●	●								
9	300							●	●	●								
10	330								●	●								
11	360									●								
12	390																	
13	427																	
14	463																	
15	500																	
16	543																	
17	587																	
18	630																	
19	677																	
20	723																	
21	770											●						
22	817											●	●					
23	863											●	●	●				
24	910											●	●	●	●			
25	957											●	●	●	●	●		
26	1003											●	●	●	●	●	●	
27	1050												●	●	●	●	●	●

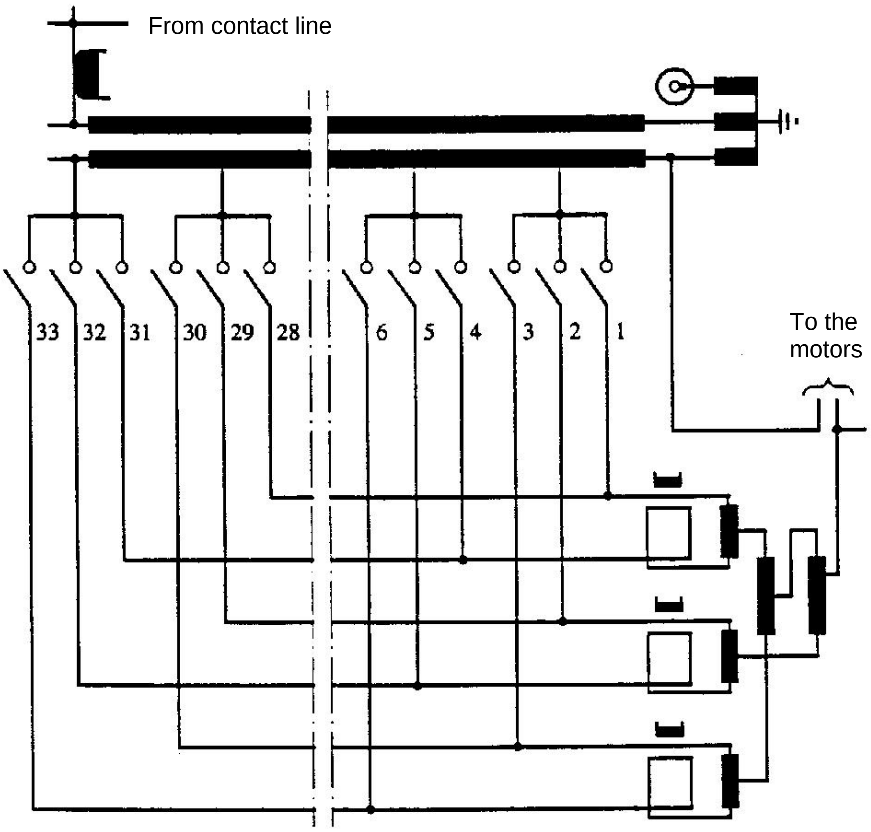


Fig. 4.75 Low voltage contactors: 1/3 of a locomotive SJ Dm3: 2 motors en series for 2400 kW.

4.3 DC-Motor: chopper control

On an inductive load, a pulsed voltage u_d may be applied by a swich *CS*. The mean value of voltage u_b at load is the product of duty ration and supply voltage u_{lc}. A diode D_r dite called "free wheel" allows the flow of inductive current when the switch is open. An input filter LC is computed from chopper frequency to limit current ripples in the electric network. The switch is realized as *static switch* with semiconductors.

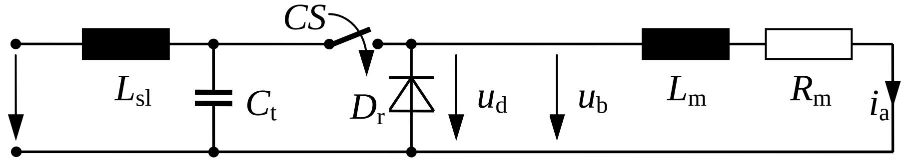


Fig. 4.77 Principle of chopper.

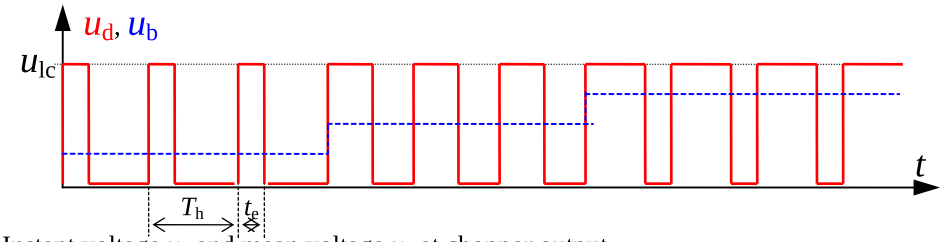


Fig 4.78 Instant voltage u_d and mean voltage u_b at chopper output.

$$u_b = u_{lc} \frac{t_e}{T_h} \tag{4.43}$$

The DC-motor is powered from contact line through a chopper. Its work-point is adjusted by the duty ratio, without discontinuities. The static switch *CS* is mounted with thyristors, self and capacitors, and more recently by one GTO or one IGBT, following the technology progress between the seventies and now, at frequencies varying from 400 Hz to 2 kHz. A recent power circuit diagram is presented below. The power flow inversion is obtained her by inversion of armature current. In the first realized vehicles, one single chopper was used for traction and braking. The topology of power circuit diagram was changed by electromechanical switches, only changed at zero-current. In modern technology, the CS and its antiparallel diode is often encapsulated in one single device.

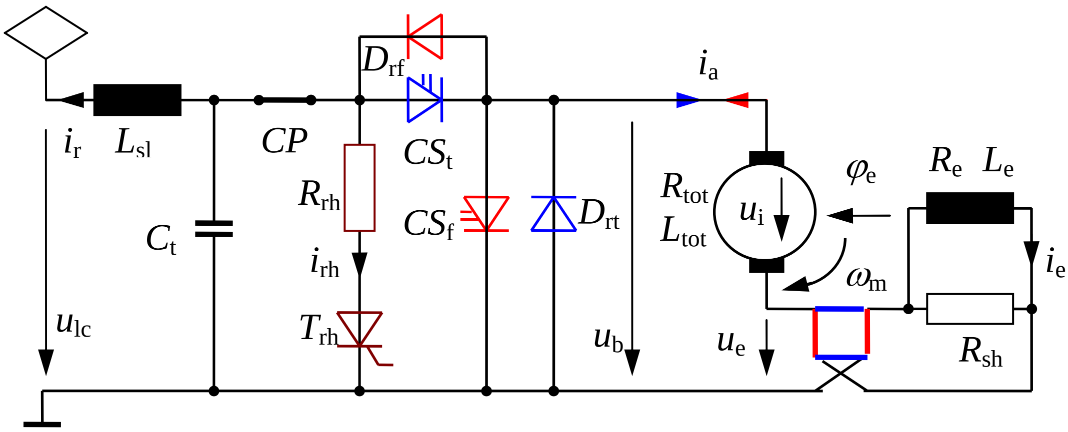


Fig. 4.76 DC-motor and chopper: traction.
Fig. 4.82 DC-motor and chopper: regenerative braking with series excitation.
Fig. 4.88A DC-motor and chopper: rheostatic braking with series excitation.

The resistor R_{sh} deviates about 2 % of mean armature current out of the excitation, but most of the pulsing part of current flow through the circuit without inductance: this limits the pulsing part of motor torque. The regenerative braking is done by the switch CS_f and the regenerative diode D_{rf}. If the network cannot receive the full braking power, the surplus is destroyed in the fix resistor R_{rh} through the thyristor T_{rh}: it is often called combined braking. On full rheostatic braking (characteristics 4.90A), the main switch CP is open and the static switch CS_f pulse on the rheostat to adjust its equivalent ohmic value, an electromechanical switch take place of T_{rh}.

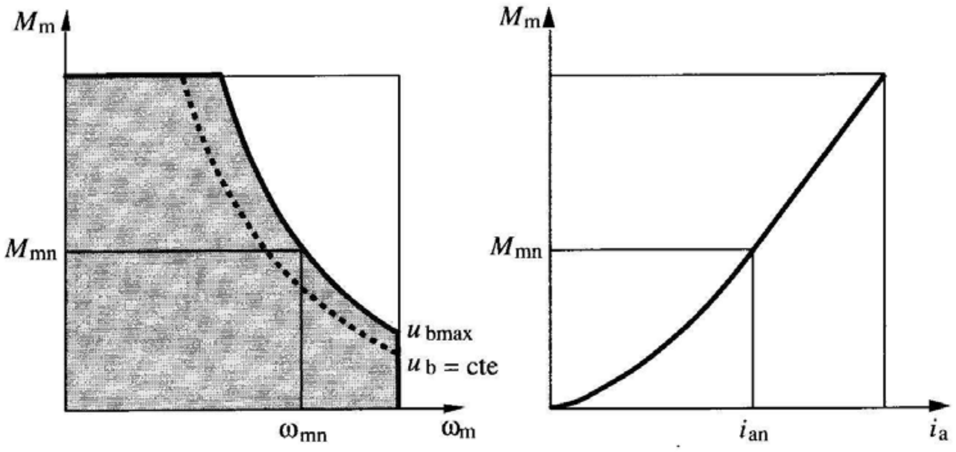


Fig. 4.79 DC-motor and chopper: traction characteristics.

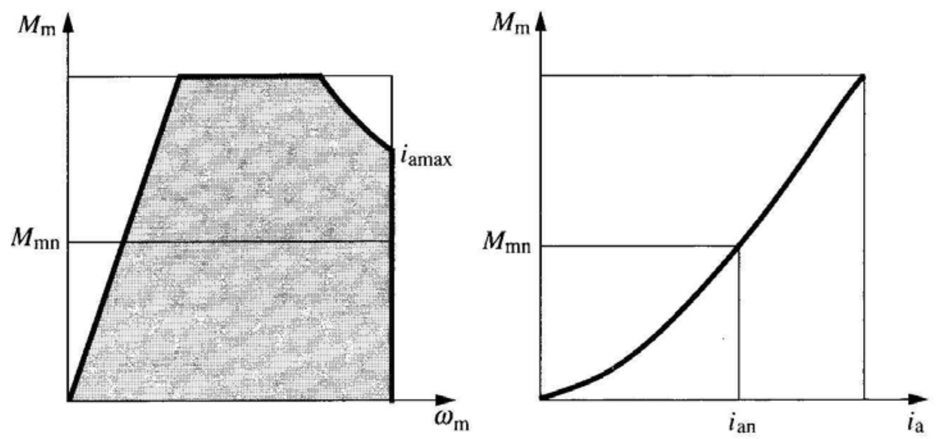


Fig. 4.85 DC-motor and chopper: regenerative braking characteristics with series excitation.

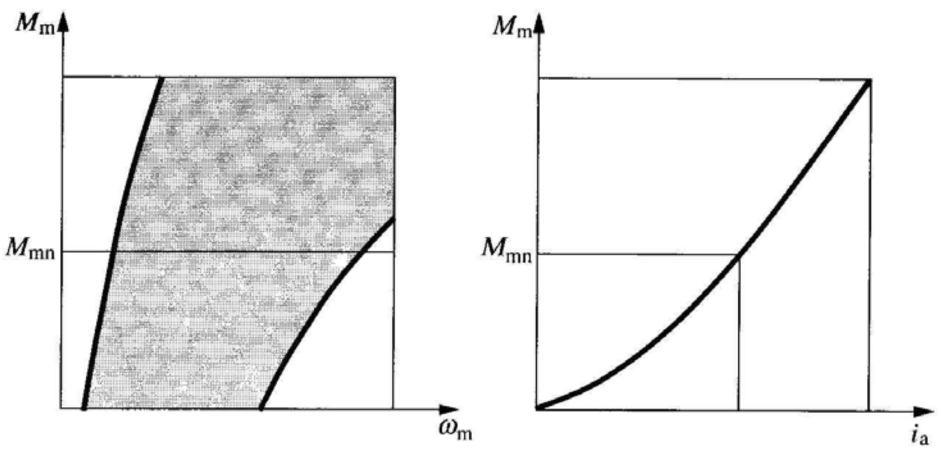


Fig. 4.90A DC-motor and chopper: rheostatic braking characteristics with series excitation.

The power flow inversion can also be obtained her by inversion of voltage. In this case, the same static switch operates in traction and braking: the switch CF is open in braking mode (Semaly : Metro A, Üstra : 6000, SZU : Be 4/4). Here also, the thyristor T_{rh} carries only the part of energy which cannot be regenerated.

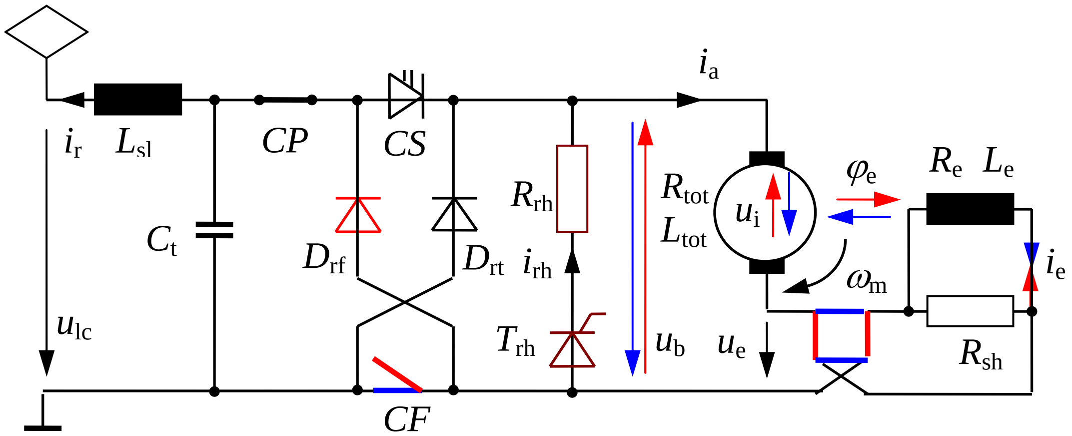


Fig. 4.87A DC-motor and chopper: traction.
Fig. 4.87B DC-motor and chopper: regenerative braking with series excitation.
Fig. 4.88A DC-motor and chopper: rheostatic braking with series excitation.

The characteristics are the same (fig. 4.79, 4.85 et 4.90A).

In some cases, the excitation is separate by a specific static switch CS_e. If this is controlled in order that the excitation current follows the armature current until full opening of main switch CS_t, it is named *series-picture-moteur*. When CS_t is full open, the excitation current can be decreased to have a reduced field, the working space of motor is so increased (MOB: GDe 4/4). In combined braking, the thyristor T_{rh} is controlled to eliminate only the part of braking energy which cannot send back to the supply network. In full rheostatic braking, the switch CS_f est inactive (or not installed), CP is open and an electromechanical switch often take place of T_{rh}. Braking point is controlled by CS_e.

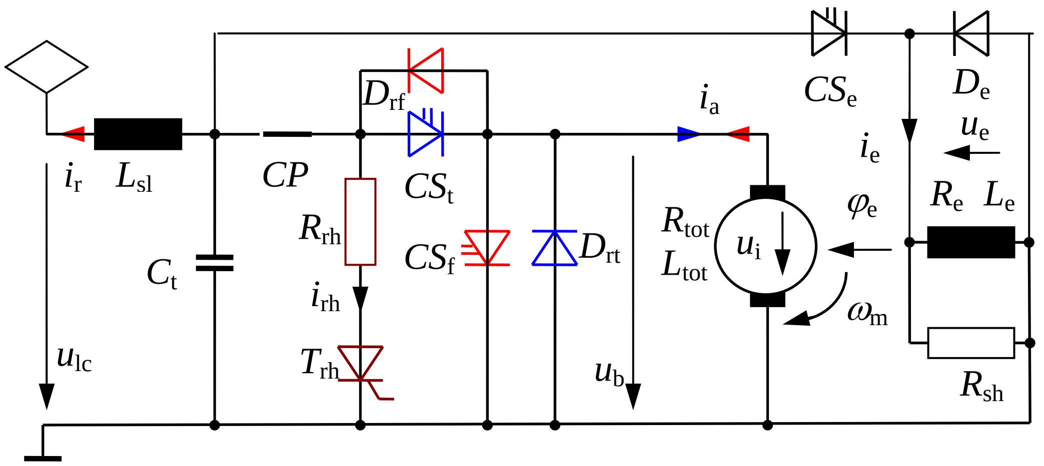


Fig. 4.95 DC-motor and chopper: traction at separate excitation.
Fig. 4.86A DC-motor and chopper: regenerative braking with separate excitation.
Fig. 4.88C DC-motor and chopper: rheostatic braking with separate excitation.

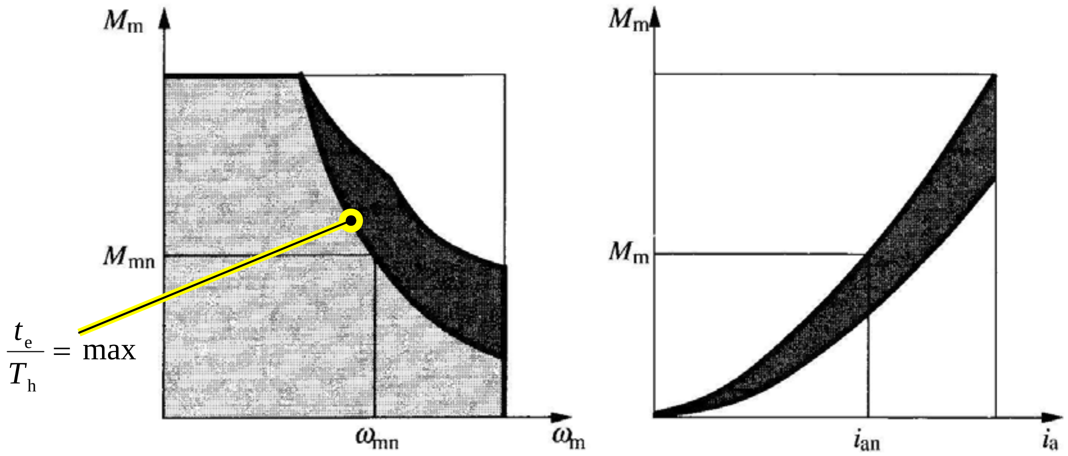


Fig. 4.97 DC-motor and chopper: traction characteristics at separate excitation: « series picture ».

There are also controls principles of CS_e at constant current for all the space where the main switch is controlled. The excitation current is reduced when CS_t is full open to increase working space at high speed (SJ: Rc4)

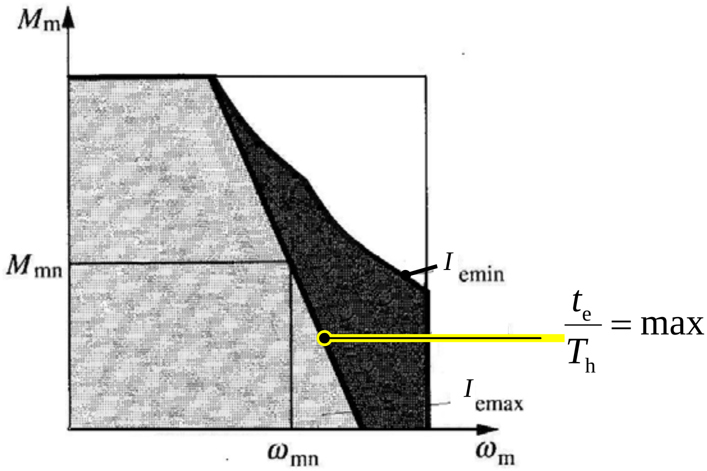


Fig. 4.97A DC-motor and chopper: traction characteristics at separate constant excitation.

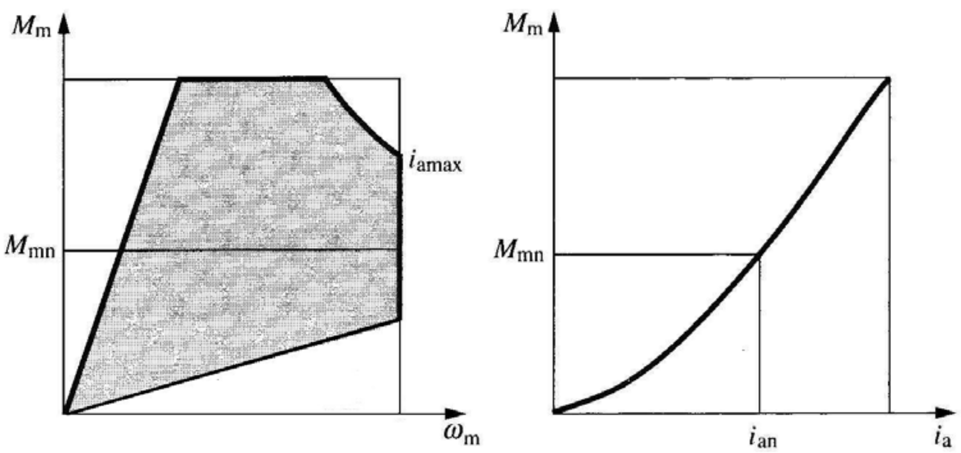


Fig. 4.90C DC-motor and chopper: rheostatic braking characteristics at separate excitation.

In regenerative braking with separate excitation, characteristic is shown at figure 4.85.

With series excitation, the field can be reduced by the thyristor T_{sh} and the diode D_{sh} (SNCF: BB 7200). The thyristor T_{sh} is switched on when the main switch CS_t carries current, deviating armature current out of the excitation circuit. By stopping conduction in CS_t, T_{sh} is automatically switched off.

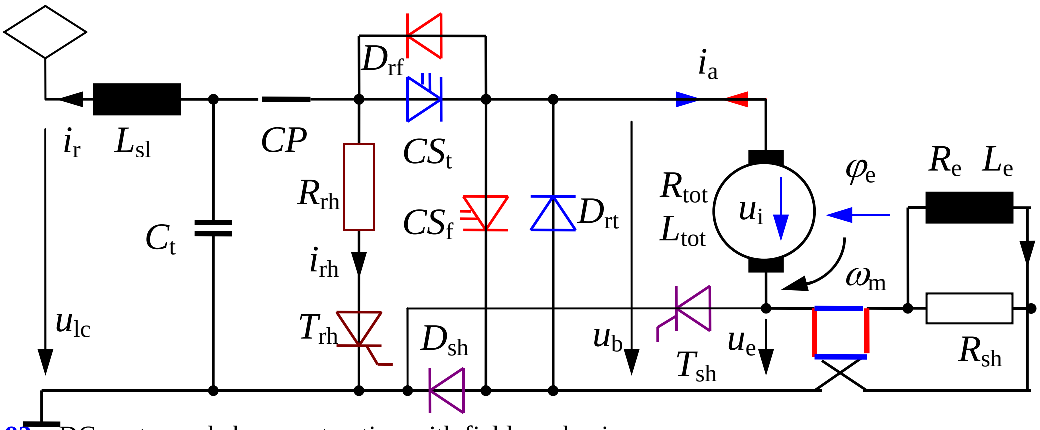


Fig. 4.93 DC-motor and chopper: traction with field weakening.

The characteristics are at figure 4.97.

In opposite with rheostatic control, the chopper control doesn't loss energy in a resistance, the efficiency is better. Losses in commutation and conduction in the semi-conductors are not to be neglected. Modern chopper have an efficiency near 98 % in all the working space, also at full opening. The efficiency of first choppers (1970 – 1980) was under 95 %. We know that an electric motor, computed for a nominal power, can be used for a greater power during a short time. This opportunity is largely used on locomotives with direct motors or with rheostatic control. The junctions of semi-conductors have short thermical time constant and a momentary overload – parts of milliseconds yet – induces a heat increasing and destroys the component. The chopper has to be computed for the maximal power of the vehicle and not for the nominal power of the motors.

On rheostatic braking, shunt excitation was also used: energy for excitation is taken from battery at beginning, and in deviation from rheostat when the current flows (CSD : 363).

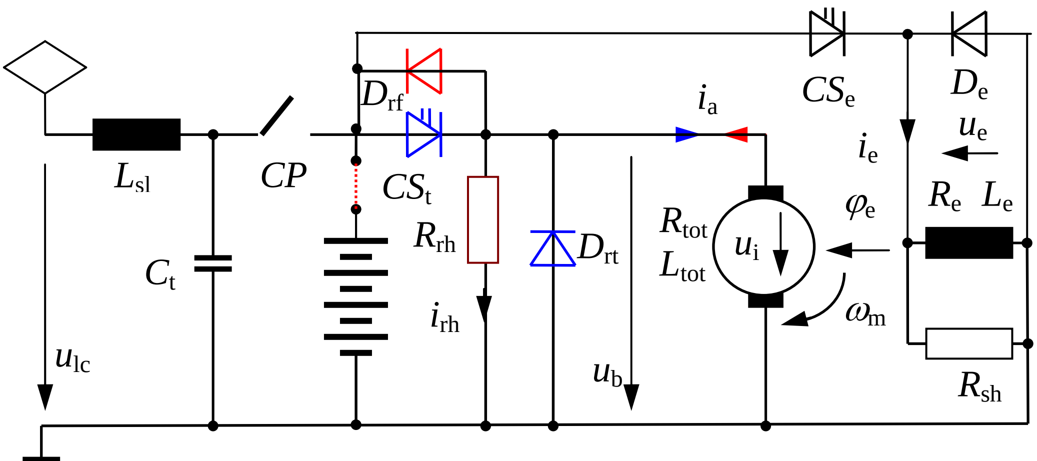


Fig. 4.95 DC-motor and chopper: traction at separate excitation.
Fig. 4.88B DC-motor and chopper: rheostatic braking with shunt excitation.

The characteristic is the same as with separate excitation (fig. 4.90C).

The automatic field weakening was also used. In comparison with controlled field weakening (fig. 4.93), the control is simplified: only the main switch is controlled. The excitation is produced by the armature current when the main switch CS_t is blocked. If this time is short, it is not sufficient to have a full excitation and it comes to field weakening.

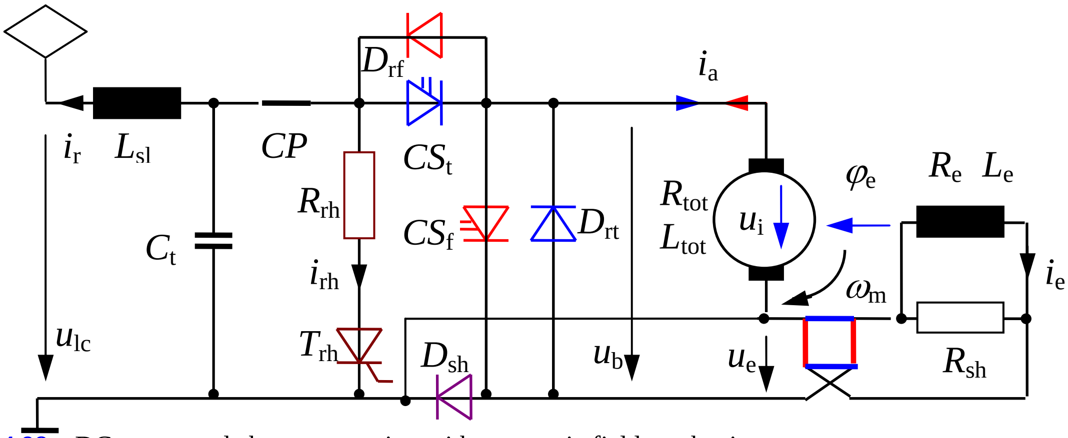


Fig. 4.98 DC-motor and chopper: traction with automatic field weakening.

The characteristic is similar as figure 4.97, but the limit between full field and weakened field is very fuzzy (NStCM : Be 4/4). In this case, the limit of full open switch is the external curve of the characteristic.

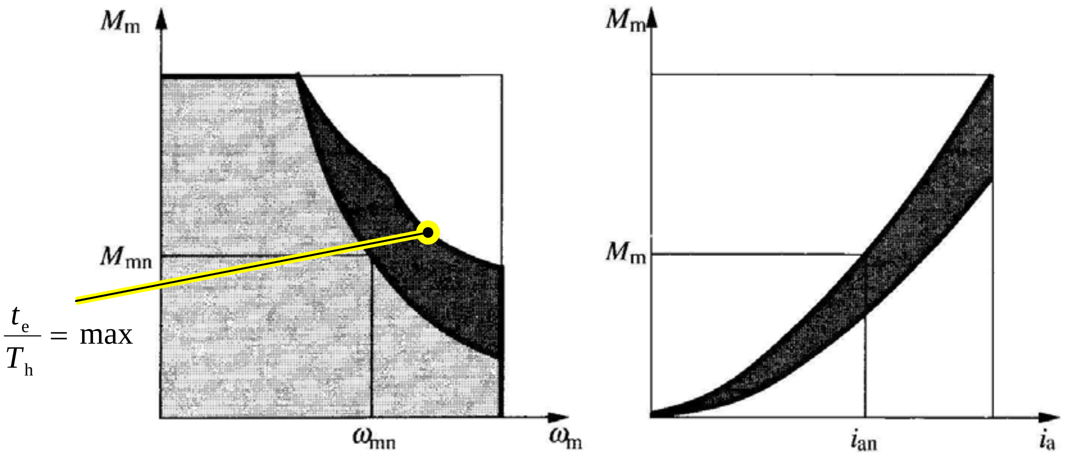


Fig. 4.97C DC-motor and chopper: characteristics in traction with automatic field weakening.

To limit the current ripple caused by the chopper, the elementary choppers to drive the current are not simply mounted in parallel but interlaced. (SNCF : BB 7200).

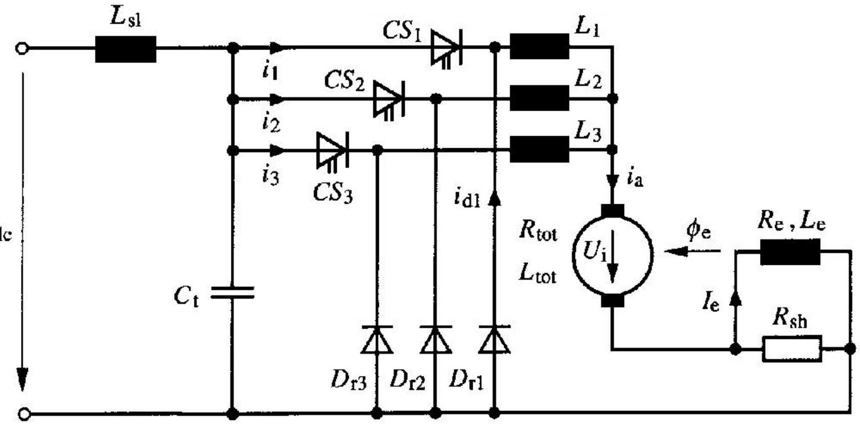


Fig. 4.102 Principle of the interlaced choppers.

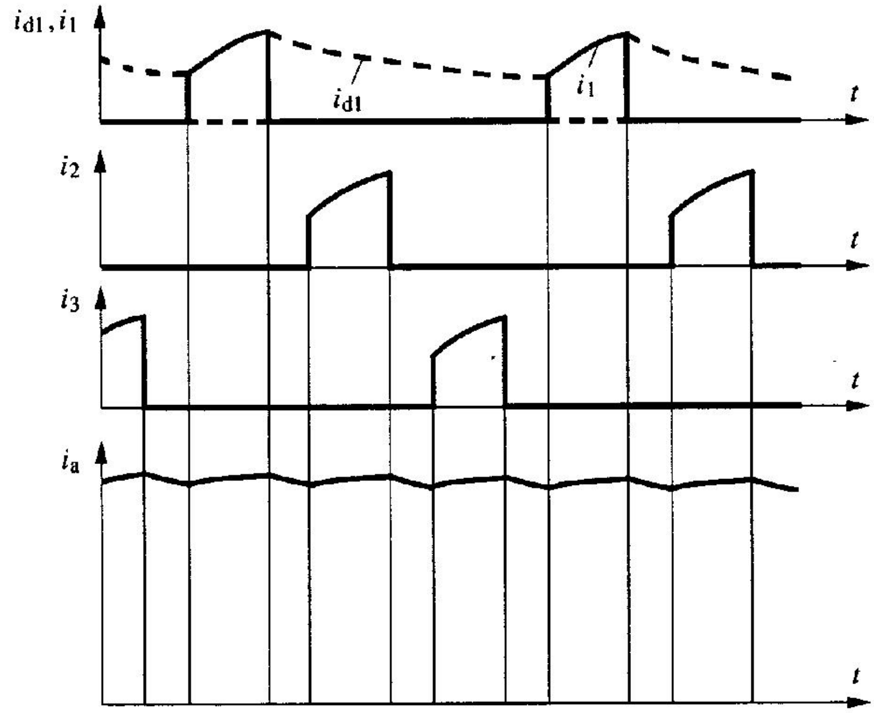


Fig. 4.103 Currents in the motor and in interlaced choppers.

The Vernier-chopper allows to reduce the torque-step at start-up with the minimal duty ratio. (SNCB : 27).

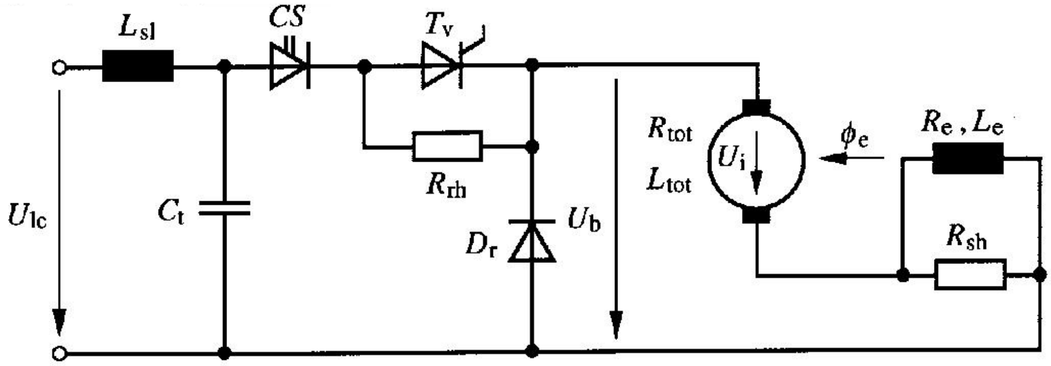


Fig. 4.104 Principle of Vernier-chopper.

If a vehicle rolls the most of time in the weakened field area, hybrid control was some time used: rheostatic control for the armature and separate excitation with series picture bay a chopper.

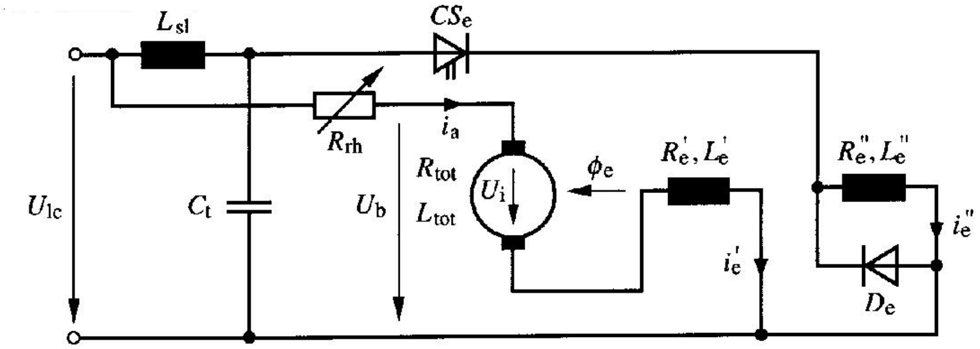


Fig. 4.105 Hybrid control: principle in traction (JNR : 215).

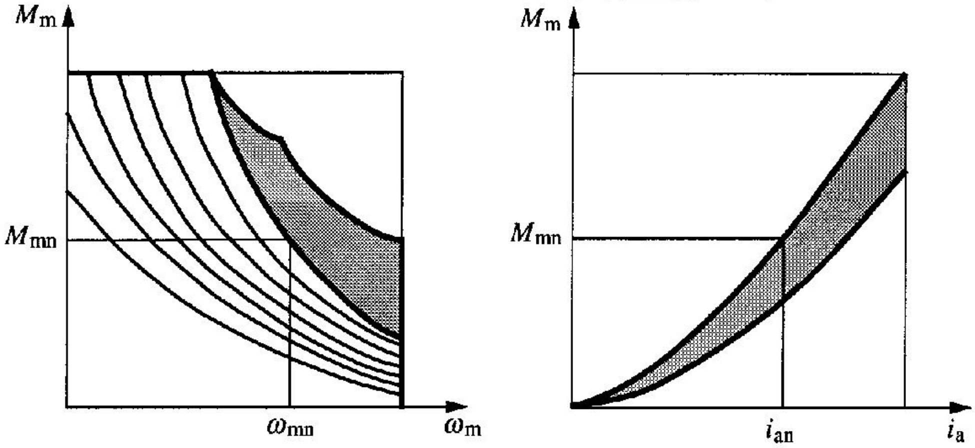


Fig. 4.106 Hybrid control: characteristics in traction.

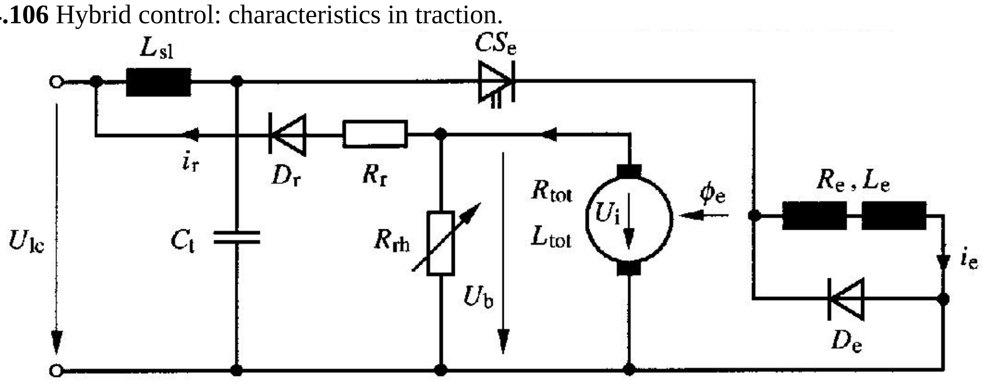


Fig. 4.108 Hybrid control: principle in braking (BOB: ABeh 4/4 II).

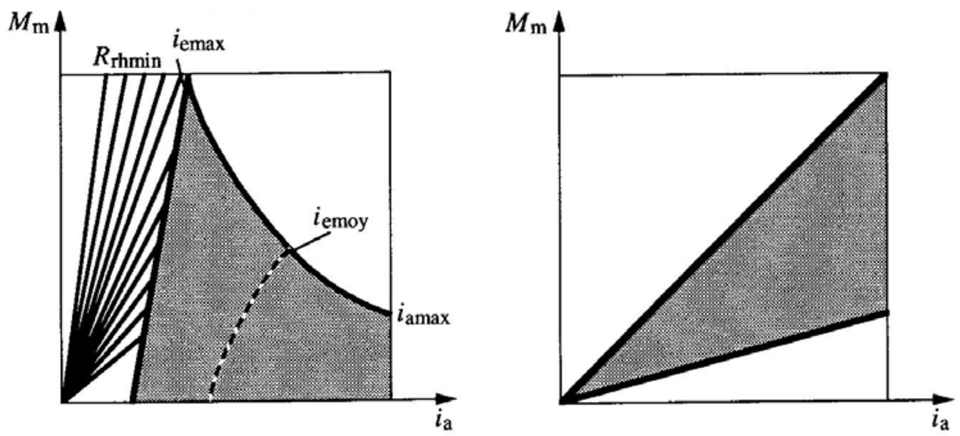


Fig. 4.111 Hybrid control: characteristics in braking.

Drive computing

The traction motors are computed for the current at continuous work point (●, with a limit in blue dot-dashed line) or nominal current. Motors can be overloaded during a limited time, using the thermic inertia of metellic parts, without overheating of the most delicate parts (red hatching on the diagram). More the work point is distant from the coninuous regime, shorter is the time to reach the maximal heating of components.

At maximal duty ratio (~100%) of the chopper, the motors are at the limit of full field **(**- - - -). The voltage at motors group is approximately this of contact line. It is quasi constant. The equations are written for an established work point:

$$U_{lc} = k_m I_a V - R_a I_a \qquad Z = k_t I_a - I_0$$

$$Z = k_t \frac{U_{lc}}{k_m V - R_a} - I_0$$

At weakened field, the effort characteristic is a little lower (in green).

For the semiconductors devices, chopper in this case, ther is not thermic inertia. The chopper has to be computed for the maximal power. (♦ - - ♦).

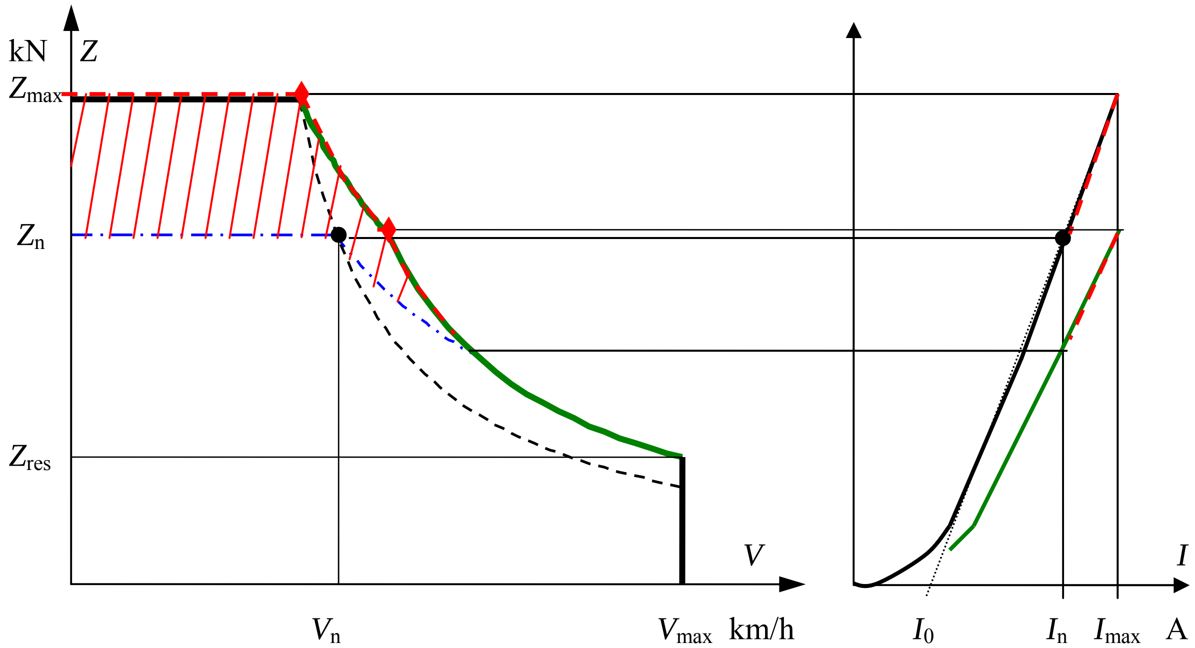


Fig. 4.97B Charactristics for a series motor supplied by a chopper.

4.4 DC-Motor with rectifier

The DC-motor can be supplied from a single-phase contact line through a rectifier, push-pull or diode bridge. The motor is very similar as which one controlled by chopper, without all sophisticated devices in direct motor. In the first built vehicles, the rectifier is fixed and the voltage is controlled by a tapped transformer (BLS: Re 4/4, SNCF: BB 16500). In braking, the rectifier provides the excitation voltage – lower than voltage in traction – and the motor armature gives current to a fixed braking resistance (CFR: 060-EA).

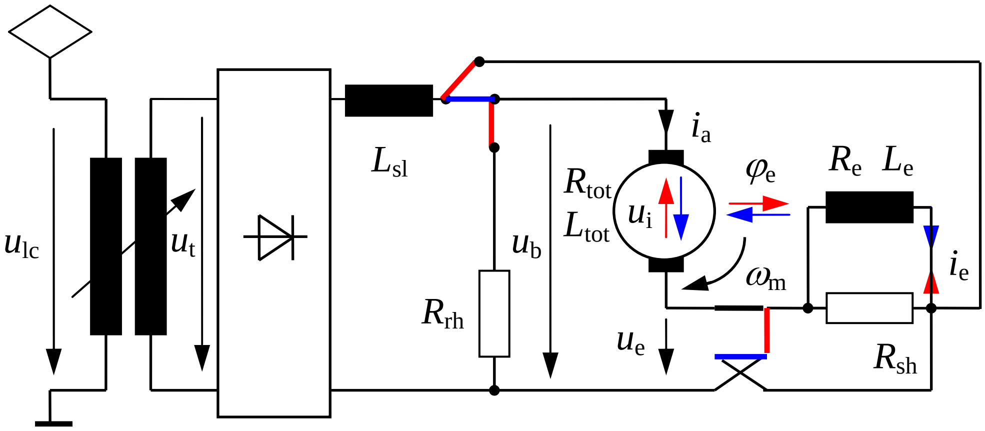


Fig. 4.112 DC-motor with rectifier: traction.
Fig. 4.119 DC-motor with rectifier: rheostatic braking with separate excitation.

The current in the transformer is in phase with the voltage and in approximately rectangular form if the motor inductivity is high. The characteristics deformation at low speed is not present as on a direct motor.

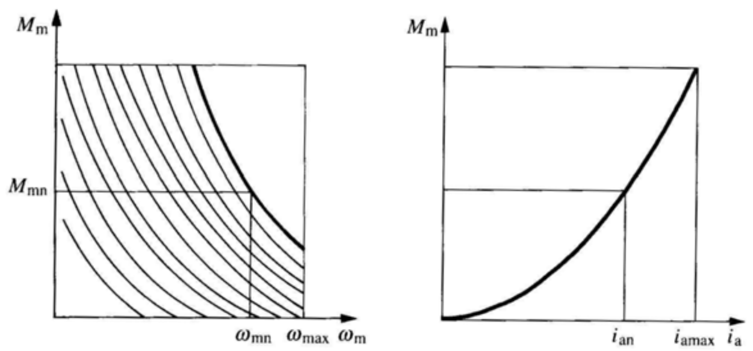


Fig. 4.118 DC-motor with rectifier in traction: characteristics versus current and speed.

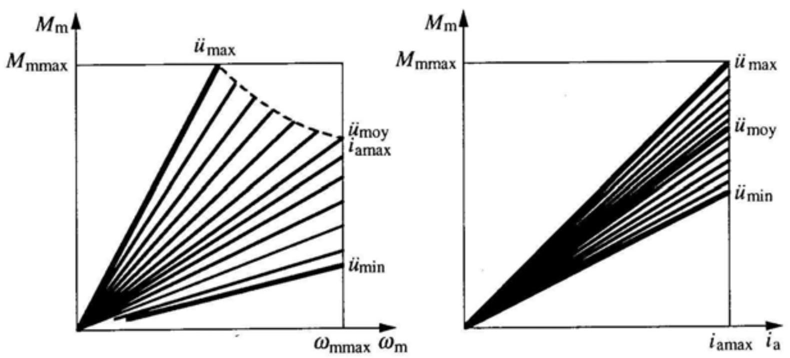


Fig. 4.121 DC-motor with rectifier in rheostatic braking: characteristics versus current and speed.

The development of semi–conductors allowed to build controlled rectifiers, the output voltage is determined by the opening angle of thyristors. The work-point can be changed without discontinuity. The bridge can be full-controlled (CFF Ee 3/3 16502) or half-controlled (SNCF CC 21000). Le rapport du transformateur est alors fixe. En freinage, le redresseur règle le courant d'excitation (RAG : EA1000).

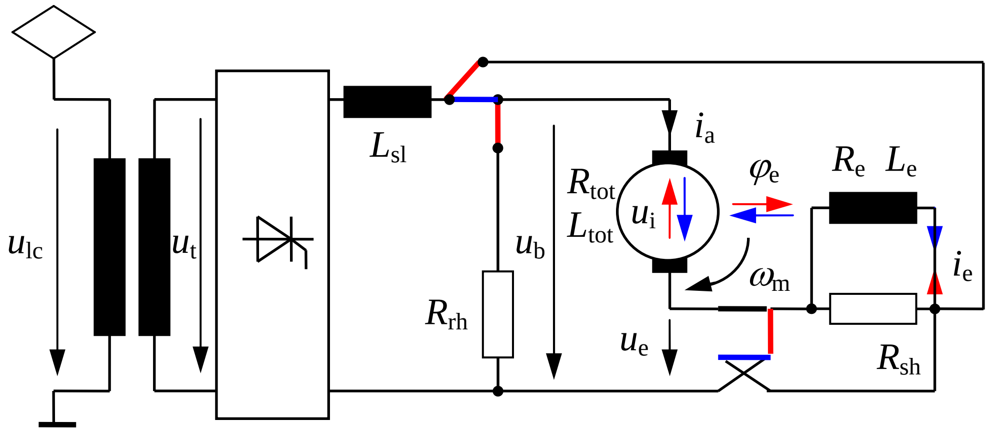


Fig. 4.122 DC-motor with controlled rectifier: traction.
Fig. 4.133 DC-motor with controlled rectifier: rheostatic braking with separate excitation.

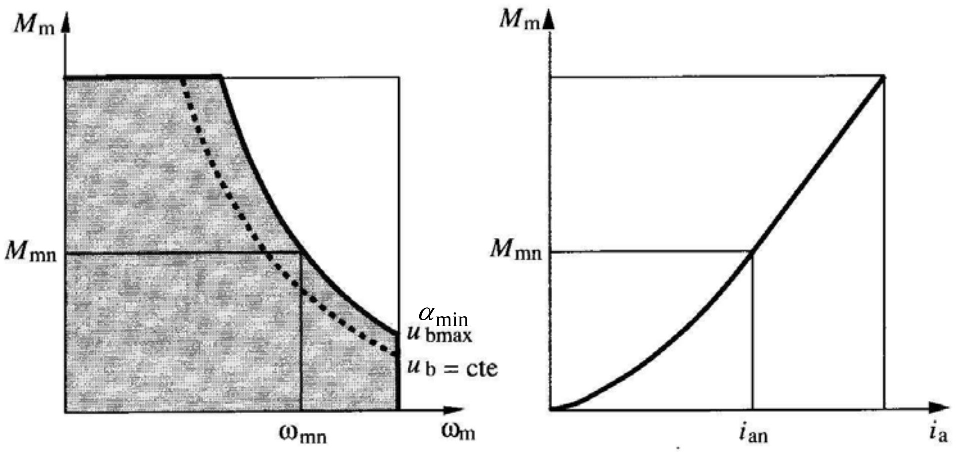


Fig. 4.129 DC-motor with controlled rectifier in traction: characteristics versus current and speed.

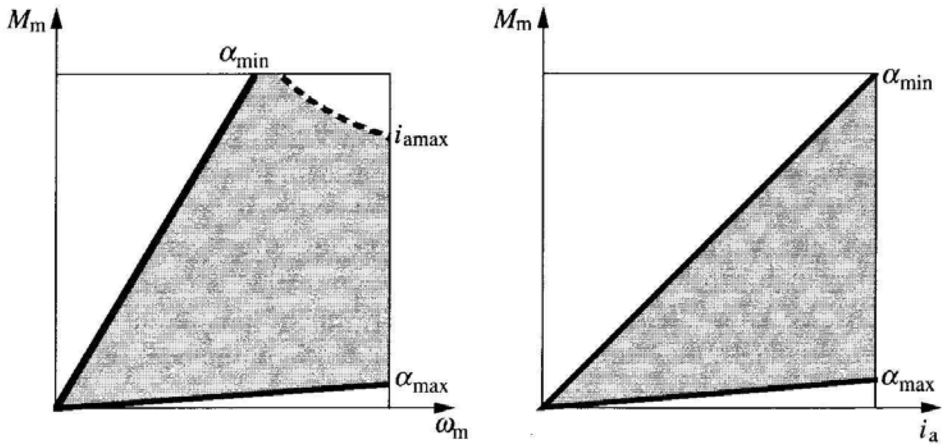


Fig. 4.136 DC-motor with controlled rectifier in rheostatic braking: characteristics versus current and speed.

The simple rectifiers as used in the first vehicles are shown below. More complex mounting will be presented further, with the target to reduce reactive power and harmonics in the contact line.

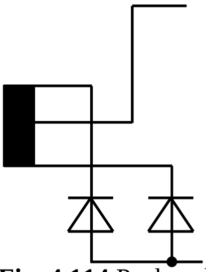


Fig. 4.114 Push-pull.

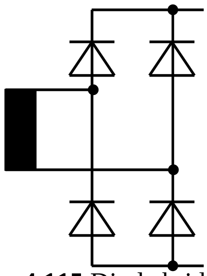


Fig. 4.115 Diode bridge.

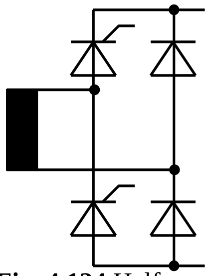


Fig. 4.124 Half-controlled.

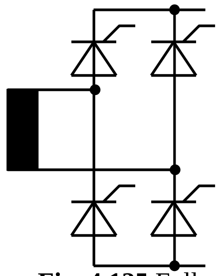


Fig. 4.125 Full-controlled.

A full-controlled bridge can drive a regenerative braking. (CFF : Ee 3/3 II).

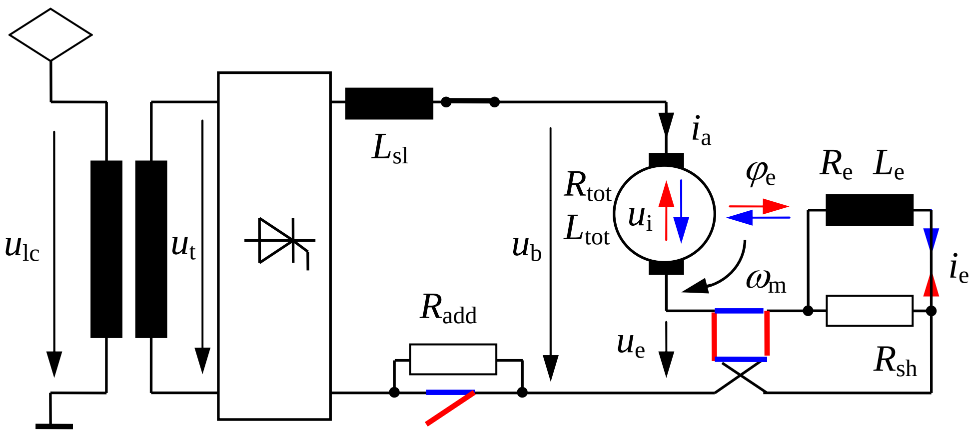


Fig. 4.122 DC-motor with controlled rectifier: traction.
Fig. 4.130 DC-motor with controlled rectifier: regeneration braking with series excitation.

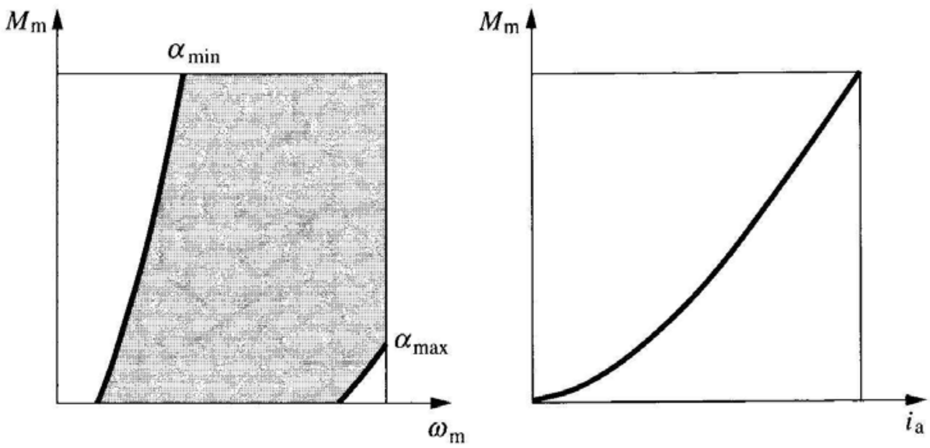


Fig. 4.132 DC-motor with controlled rectifier in regenerative braking: characteristics versus current and speed.

To limit the effects on supply network, bridges in cascade were adopted with two levels (Fig. 4.139), 3 levels (Fig. 4.139A) or 4 levels (Fig. 4.140). In these solutions, the control of par triggering angle is only present on one (bridge I), the other are blocked or full opened. As for motors supplied from continuous voltage, the field weakening can be used to extend their working area. (Fig. 4.142). One solution uses auxiliary thyristors T_{sh} which are triggered during the conducting phase of the main bridge.

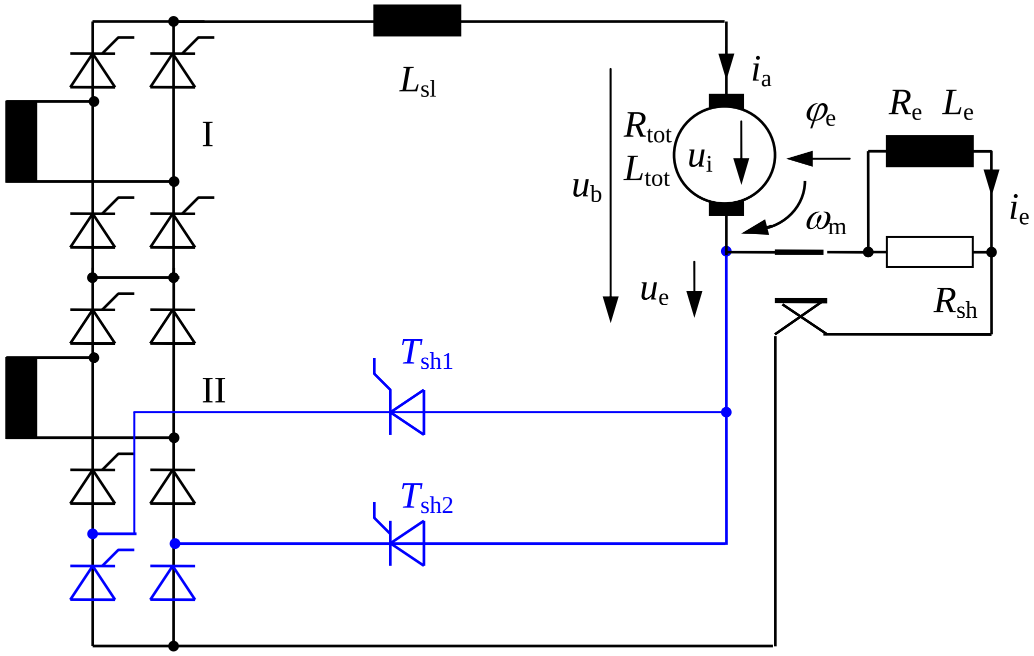


Fig. 4.139 Two bridges in cascade.
Fig. 4.142 Two bridges in cascade with field weakening (SNCF : BB 15000).

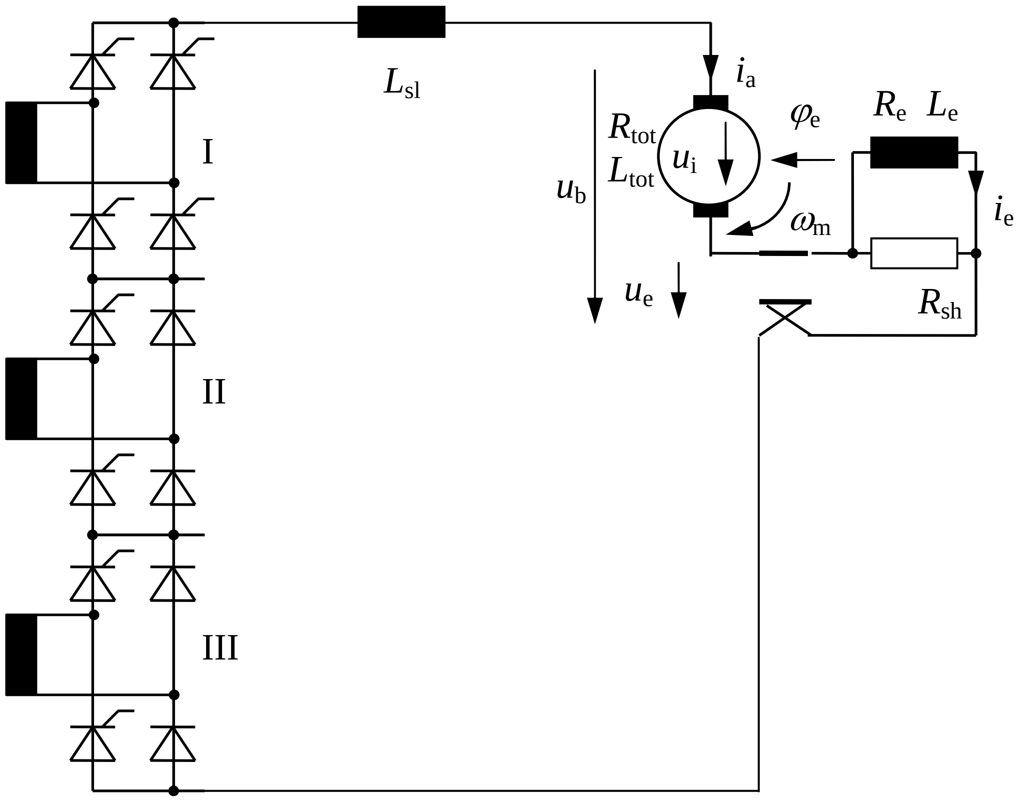


Fig. 4.139 A Three bridges in cascade. (SJ : Rc 1).

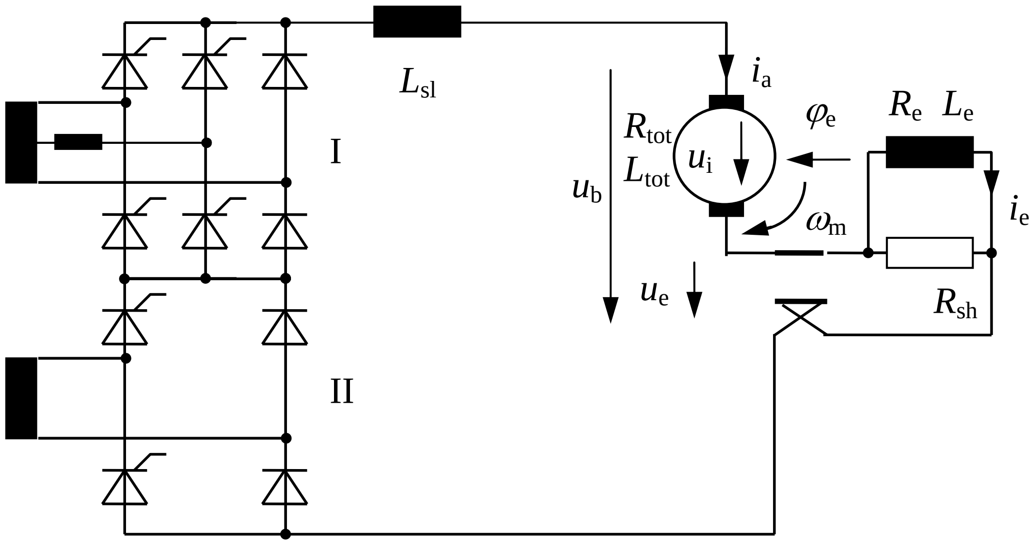


Fig. 4.140 Four bridges in economical mounting (ÖBB : 1044).

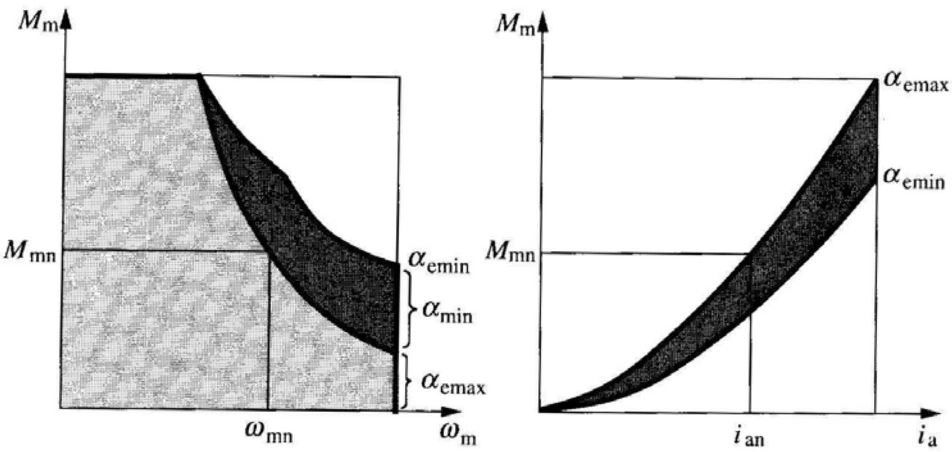


Fig. 4.143 Characteristics in traction with field weakening.

In traction and in braking, separate excitation can be provided by a dedicated secondary of transformer and another rectifier (Fig. 4.145). The excitation rectifier can be controlled (II) in order that the current i_e which produces field follows armature current until full opening of main bridge (I), in this case, it is called simulated-series-motor (RhB : Be 4/4). The torque characteristic is presented above (Fig. 4.143). With the same circuit, a constant induction current can be chosen until full opening of main bridge (SJ : X1) (Fig. 4.143A, p. 4.4-7). In both cases, the field weakening is obtained by increasing of triggering angle at bridge II. In braking, the main bridge I is controlled as inverter and the bridge II controls the excitation current to maintain a sufficient induced voltage at low speed.

The motor can also have two excitation windings: one in series and the other powered by a separate bridge. It is called *compound excitation* (CFF : RBDe 4/4). At minimal field, only the series winding receives the armature current, the bridge II is blocked (fig. 4.148, p. 4.4-10).

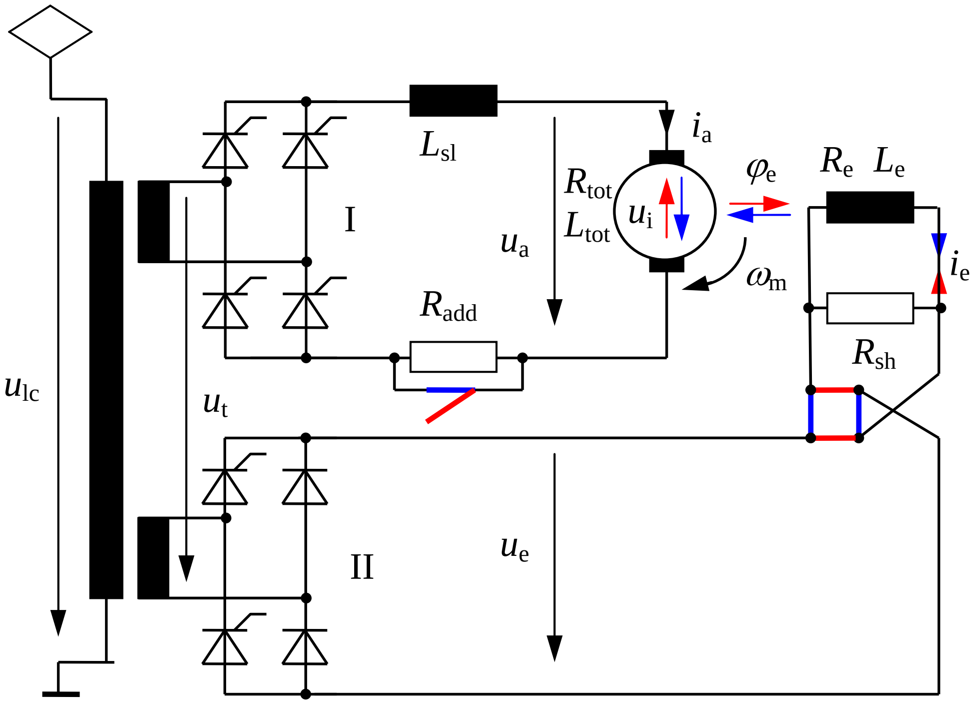


Fig. 4.145 DC-motor with controlled rectifier with separate excitation: in traction and in regeneration braking.

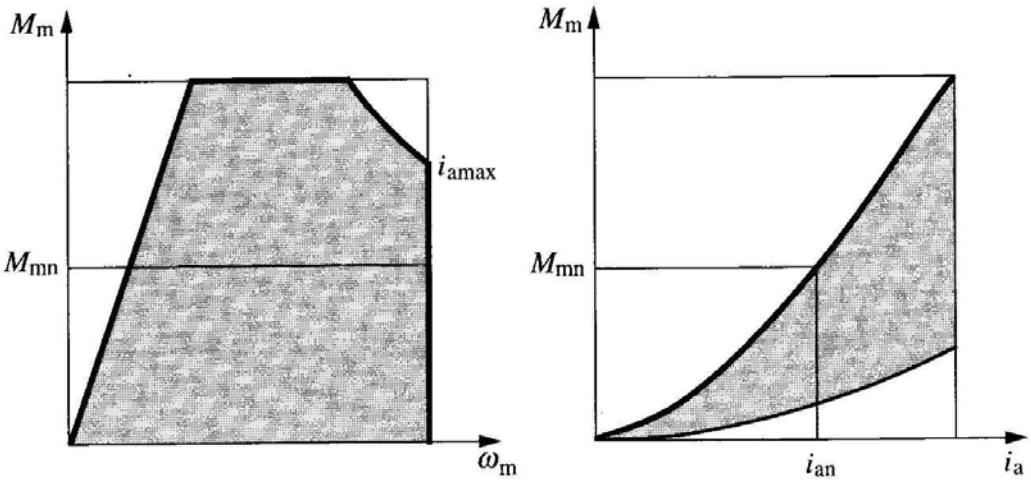


Fig. 4.147 DC-motor with controlled rectifier with separate excitation: characteristics versus current and speed.

The rectifier, as the chopper (sect.4.3) has to be computed for the maximal motor power and not the nominal power (see p. 4.4-11).

If the separate-excitation current is constant, traction characteristics are quite different.

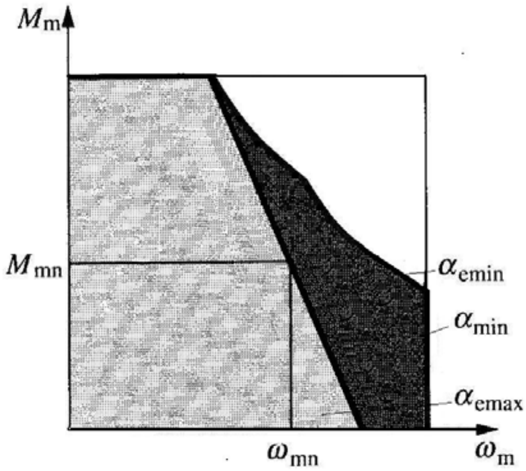


Fig. 4.143A Characteristics in traction with field weakening.: separate excitation.

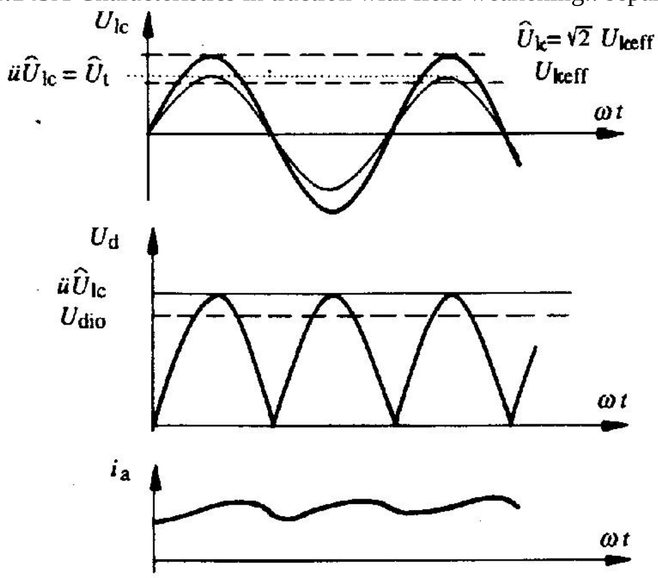


Fig. 4.113 DC-motor with diode rectifier: motor current and voltages.

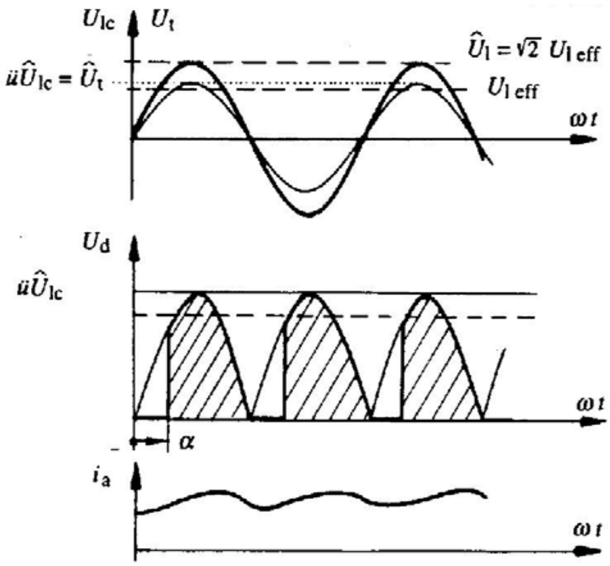


Fig. 4.123 DC-motor with controlled rectifier: motor current and voltages.

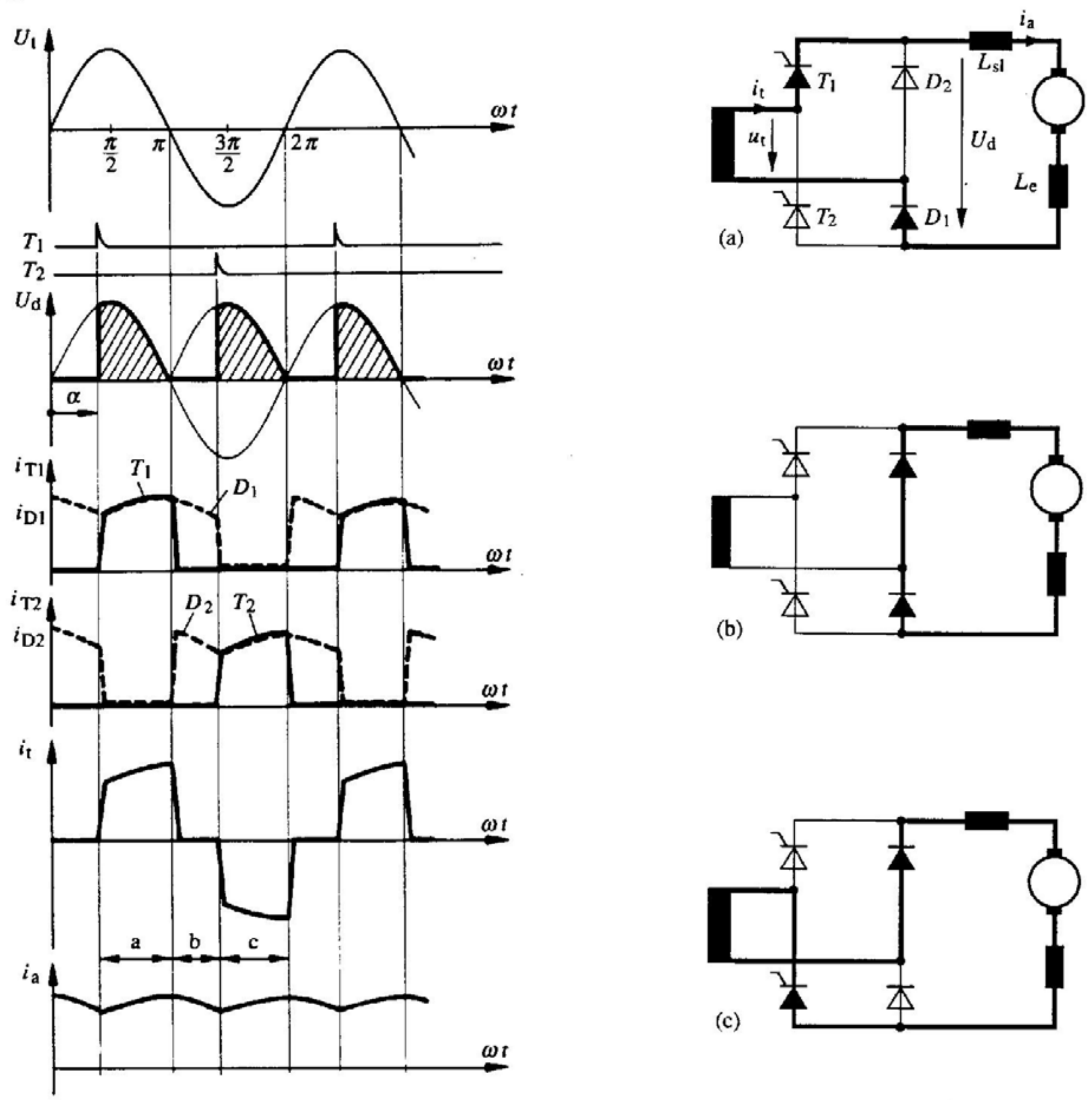


Fig. 4.126 DC-motor with controlled rectifier: currents and voltages.

It is clear to see the phase-shift between the voltage u_t at transformer secondary and the current i_t across this winding. This causes transit of reactive power in contact line and railway power supply network, with losses and temperature rises. More complex mountings (fig.4.140) were used to limit these problems, by reducing reactive power with a ratio of 4 for the same active power (fig. 4.141).

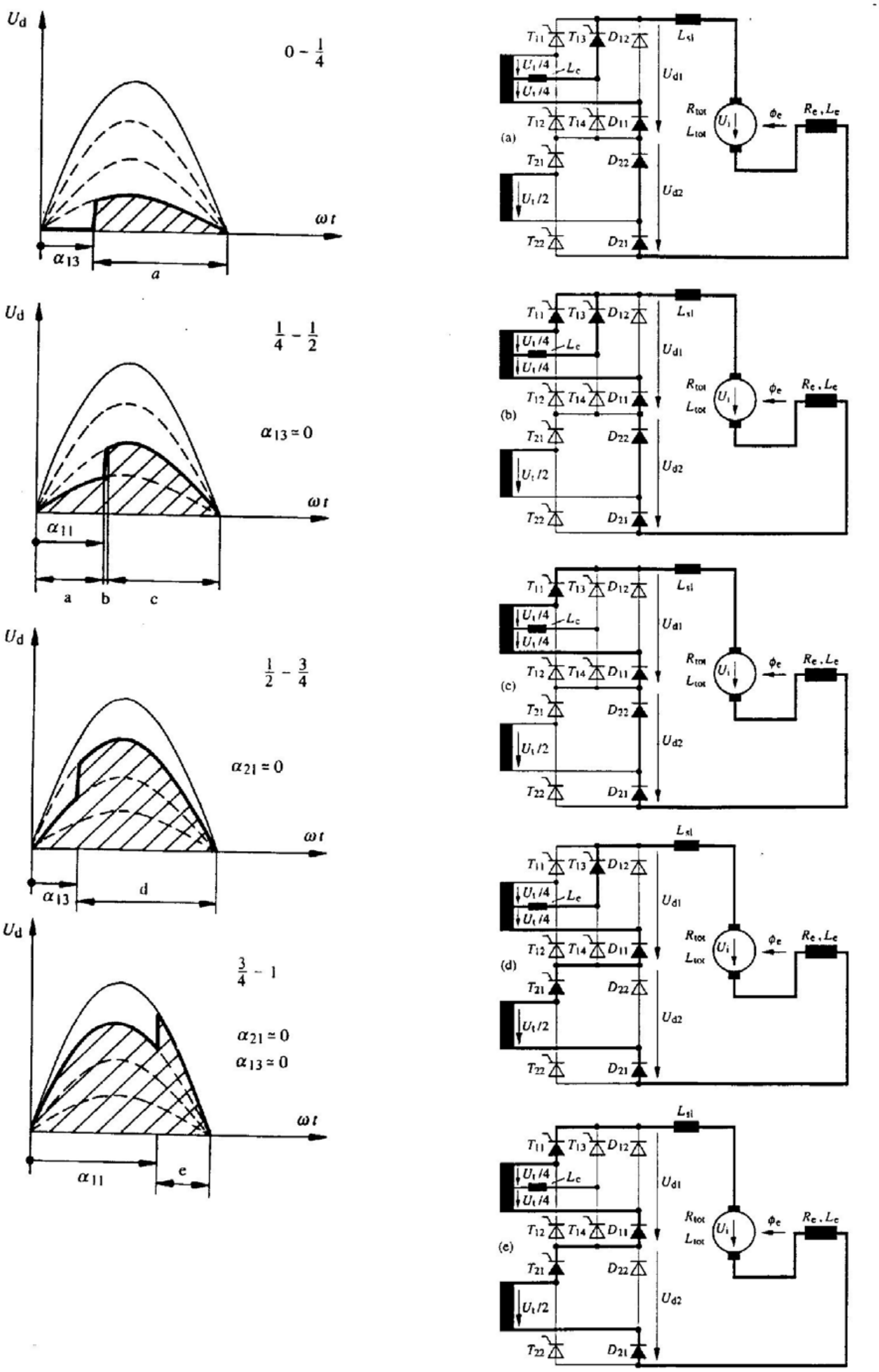


Fig. 4.141 DC-motor with “4-step” controlled rectifier : currents and voltages.

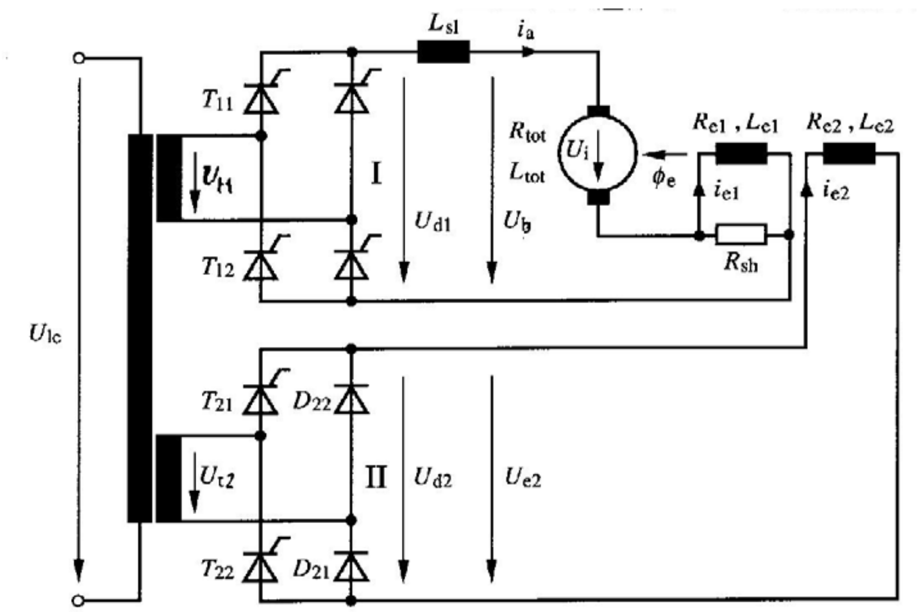


Fig. 4.148 DC-motor with controlled rectifier in compound excitation.

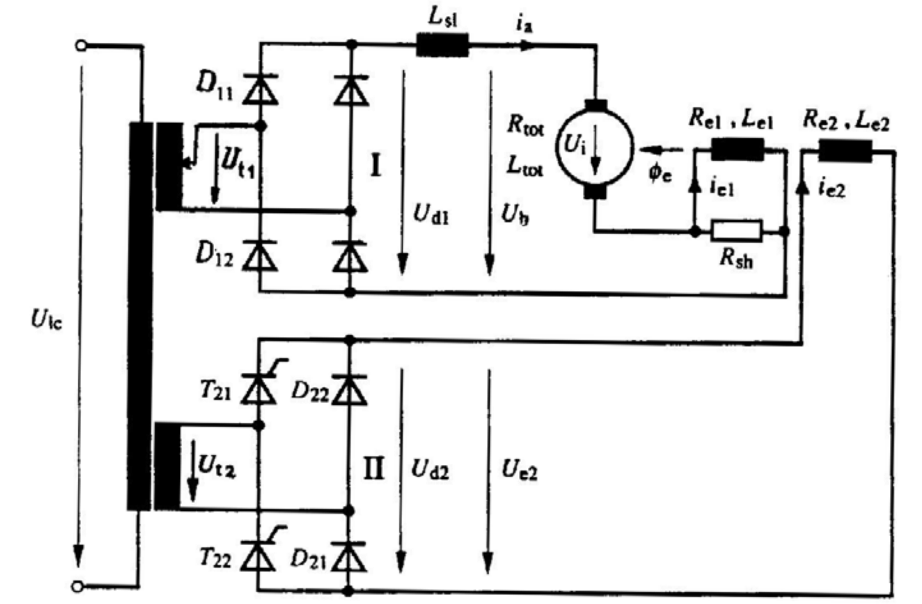


Fig. 4.148A DC-motor with controlled rectifier in compound excitation: hybrid control.

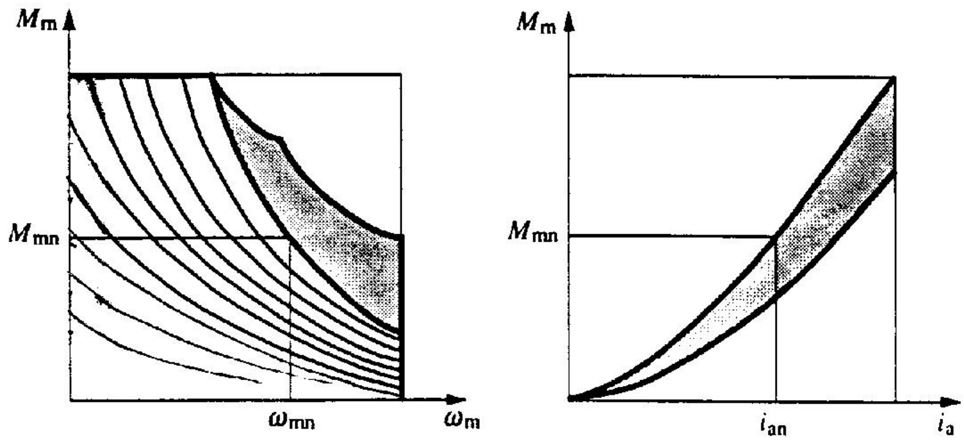


Fig. 4.148B DC-motor with compound excitation: hybrid control, characteristics.

Drive computing

The traction motors are computed for the current at continuous work point (●, with a limit in blue dot-dashed line) or nominal current. Motors can be overloaded during a limited time, using the thermic inertia of metellic parts, without overheating of the most delicate parts (red hatching on the diagram). More the work point is distant from the continuous regime, shorter is the time to reach the maximal heating of components.

At the higher transformation ratio, the motors are on the last full-field step **(** - - - -). The across voltage at motor group is defined by the transformer secondary and the diode rectifier: U_d. Voltage is about constant, but not exactly, beecause the transformer is not an ideal voltage-source and has its own losses. The characteristc at constant voltage is only available at builder's test bank (— ·· — ·· —):

$$U_\mathrm{d} = k_\mathrm{m} I_\mathrm{a} V - R_\mathrm{a} I_\mathrm{a} \qquad Z = k_\mathrm{t} I_\mathrm{a} - I_0 \qquad Z = k_\mathrm{t} \frac{U_\mathrm{d}}{k_\mathrm{m} V - R_\mathrm{a}} - I_0$$

At weakened field, the torque characteristic versus current is a little lower and shifted right versus speed (in green on characteristics).

In drives with current converter (controlled rectifier), the full-field limit **(**- - - -) tie in the minimal trigerring angle (~ 0°) of the main rectifier. For the semiconductors devices, chopper in this case, ther is not thermic inertia. The converter has to be computed for the maximal power. (♦ - - ♦).

In most of case, the motor vehicle rolls under its continuous work-point. With the great thermical inertia of the transformer, it can be computed for a lower nominal power as the sum of motor nominal powers. Exception: commuter trains.

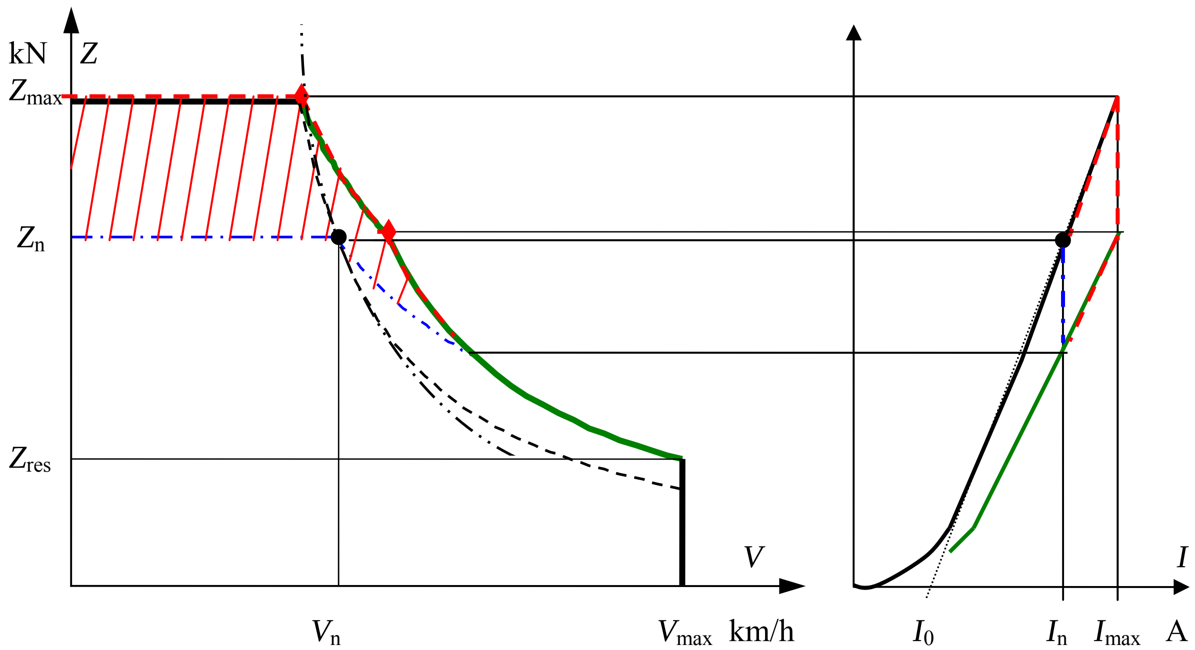


Fig. 4.143B Characteristics for series motor s powered through rectifier.

4.5 Induction motor

Induction motor is very easy to build, in comparison with DC-motor. Only the development of power electronics allows the general use of induction motors in electric traction, by the creation of three-phase voltage systems at variable frequency from a continuous voltage: contact line or intermediate circuit. At figure 4.164, a principle-drawing is presented: this example uses voltage-link, as usual since 1990. Each arm contains two static switches which pulse the u_d voltage to build a sinus-voltage (and harmonics). To avoid to high harmonics, the pulsing frequency must be 20 times the higher frequency of three-phase system. In the first generations of AC-AC converters, current-link converters were used and inverter with sequential phase control. For DC-AC converters, it was necessary to install a chopper between contact line and DC-current-link. The development of one arm – framed in dash-dotted green line at figure 4.164 – will be explained further at figure 4.167.

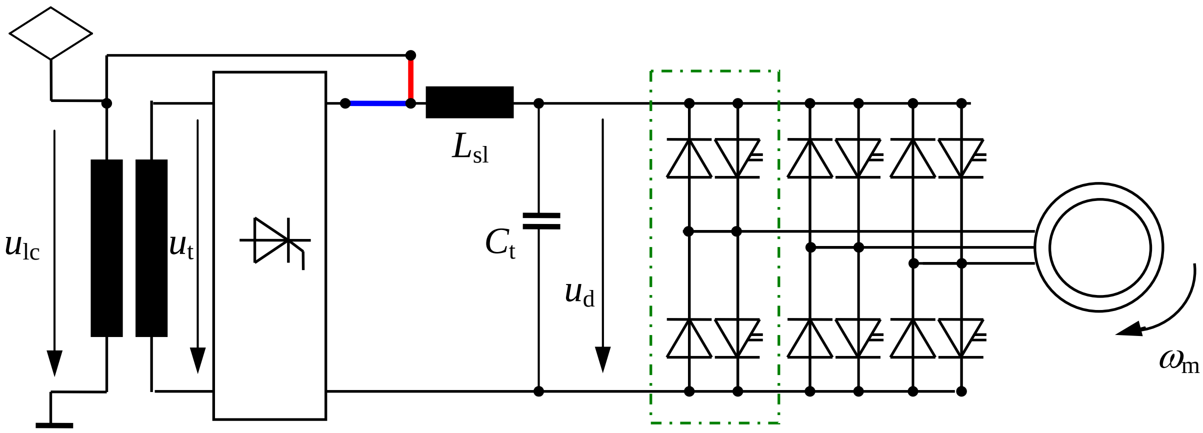


Fig. 4.164A Induction motor and three-phase converter for DC- or AC-contact line. Principle drawing.

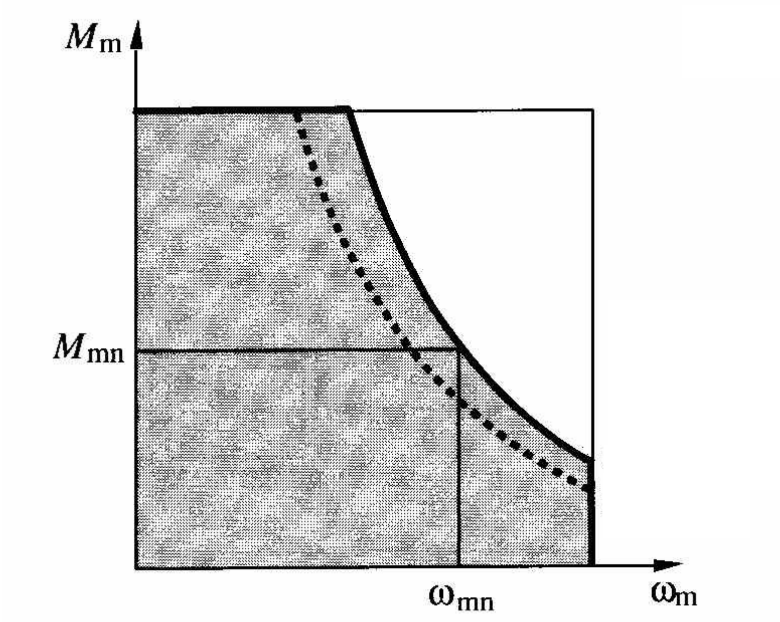


Fig. 4.164B Induction motor and three-phase converter: characteristics versus speed.

Induction motor is not only easier to build as DC-motor – no commutator – but its power is higher at the same mass. In addition, it does not need switches to change from traction to braking:

- If the motor-converter frequency is higher as induction machine speed, the machine works in motor and the converter in inverter.
- If the motor-converter frequency is lower as induction machine speed, the machine works in generator and the converter in rectifier.

On a single-phase line, for regenerative braking, the single-phase bridge at contact line side has to be able to work in inverter. For rheostatic braking, the schema has to be completed by a resistance and a static switch to convert on board the braking power in thermic power.

At time of classical thyristors, they needed a special swich-off circuit with thyristor, self and capacitors. With GTO, which can be switched off by a negative voltage on their gate, the arms were simplified. With the increasing of blocking voltage and conduction current in GTO development, simplification could go on. The IGBT follow the same progress, but later. They were used only recently for high power. Their control needs lower power as GTO and their conduction and commutation losses are lower. In opposition of GTO, their parallel mounting is very easy.

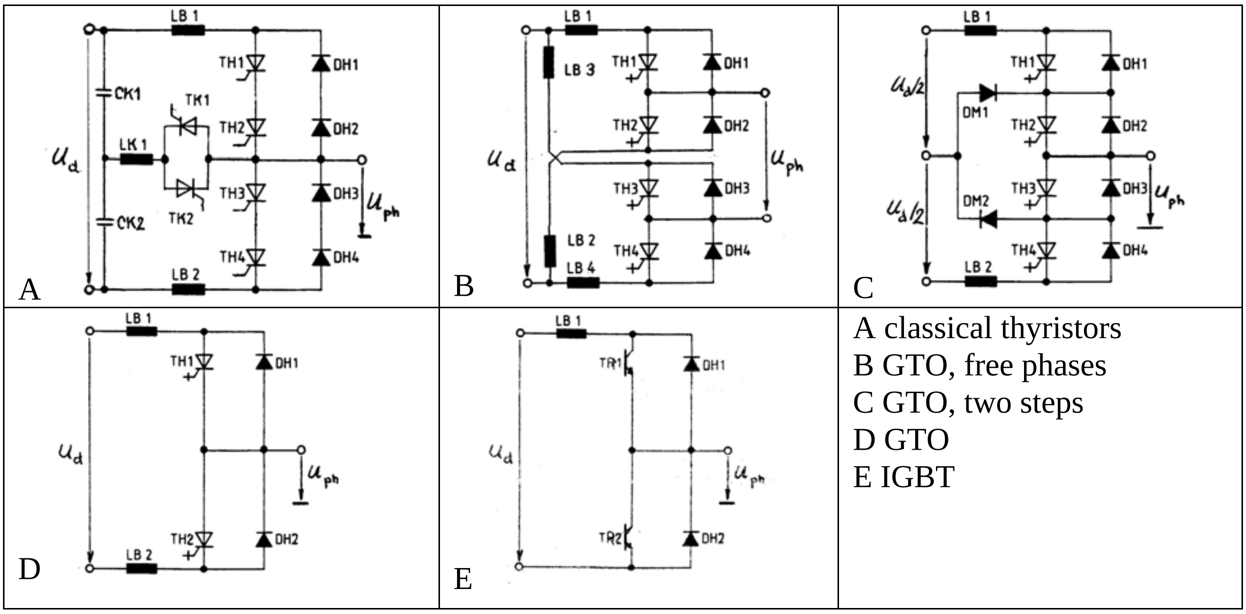
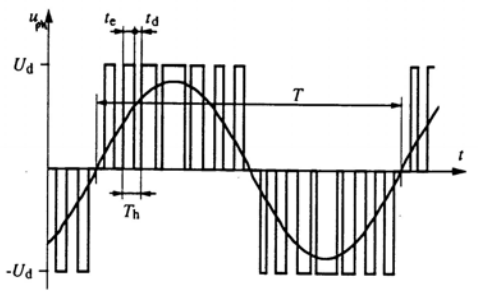
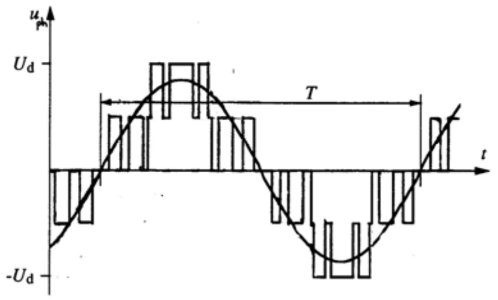


Fig. 4.167 Architectures of inverters arms.

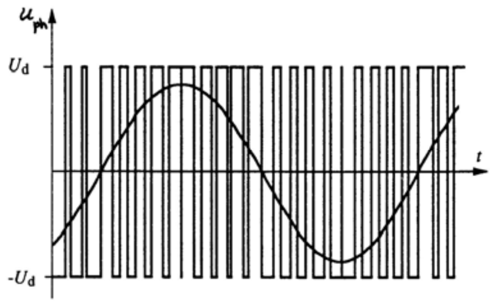
The arm control has also changed in function of the switch-time of semi-conductors. The single-pole control is today used by all industries.



U



U2



B

B Bipolar
U Single-pole
U2 Single-pole with two levels

Fig. 4.168 Inverter arm-control.

Arm	A	B	C	D	E
Diodes	8	4	6	2	2
Semi–conductors	18 Thy	4 GTO	4 GTO	2 GTO	2 IGBT
Selfs	4	4	2	1	1
Capacitors	2	0	0	0	0
Control	B	B	U2	U	U
Power [MW]	0,3 – 0,5	0,5	0,4 – 1	0,3 – 0,9	0,5 – 0,9
Year of beginning	1979	1987	1990	1992	(1997) 2004
Examples	DB : 120 NSB: El17 DSB: EA3000	BT: Re 456 CFF: Re 450	CFF: Re 460 ÖBB : 1822 FS: ETR500	BLS: Re 465 SNCF : BB 36000 DB : 185	(ABB: 12X) DB : 185.2 SNCF : BB 447000

Fig. 4.168 & 4.167 Examples : inverters arms.

The first installations used controller with sequential phase control, where classical thyristors were used without forced quenching device. It needs DC-current-link.

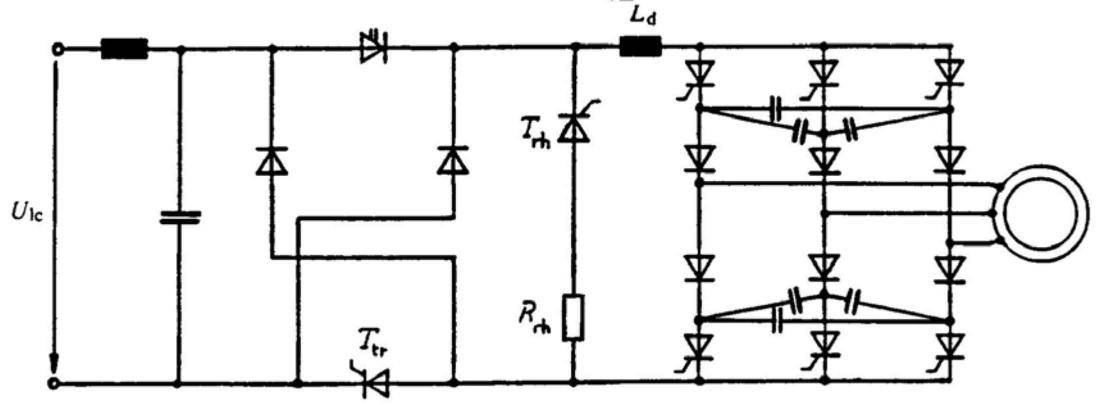


Fig. 4.165 Bidirectionnal I-converter for DC contact line (SNCF : Z20500).

Actually (2005), the more frequent form is the U-converter, with DC-voltage-link. Under DC line, the three-phase converter can be directly connected to line, with a LC-filter. The arms of single-phase bridge are identical as ones of the three-phase bridge (Fig. 4.167D).

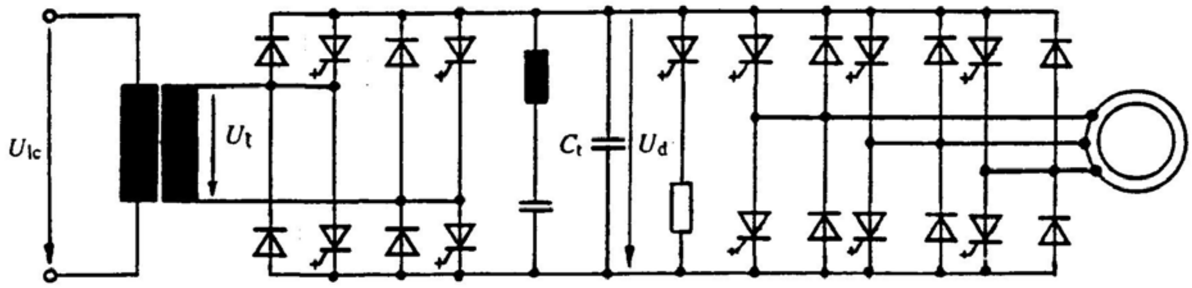
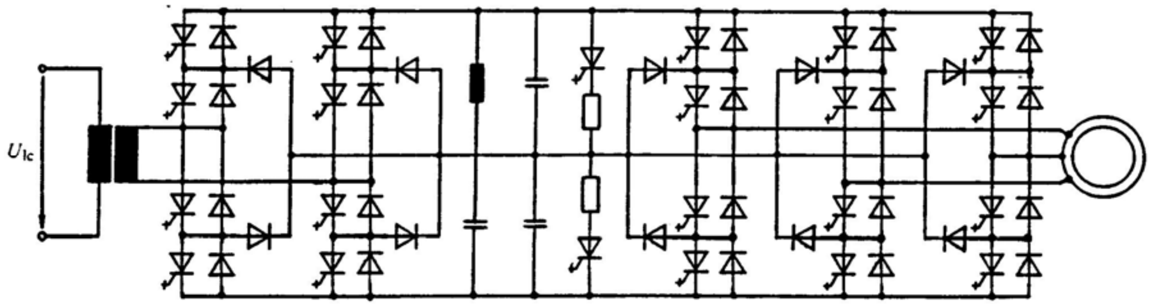
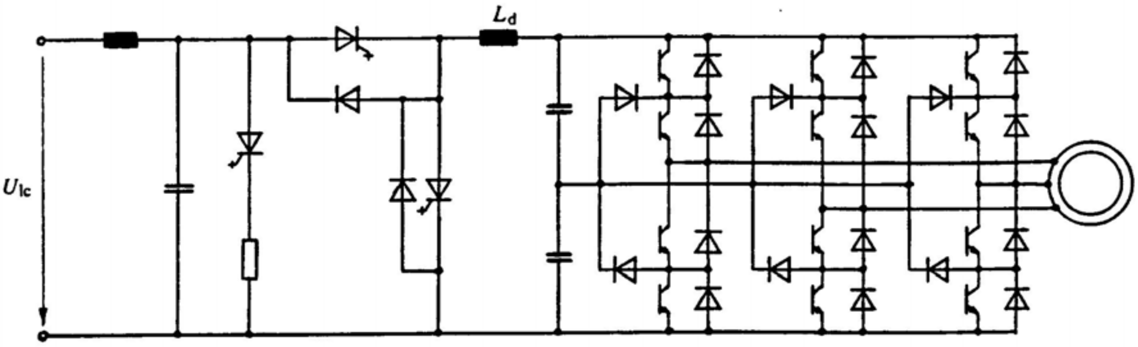


Fig. 4.166A Bidirectionnal U-converter for AC contact line (BLS : Re 465).

During development phase an intermediate circuit with middle point was also used. At this time, the blocking voltage of available GTOs or IGBTs was not sufficient to have a simple arm with the requested power.



C



D

Fig. 4.166 C Bidirectionnal U-converter with GTO for AC contact line GTO (CFF : Re 460).
D Bidirectionnal U-converter with IGBT for DC contact line (JNR : 207).

The evolution in semi-conductors goes in direction to operate schema 4.166A with IGBT. So converter has same performances as ones with GTO with higher efficiency and lower weight.

The converters at network side were at the beginning the same as ones used for DC-motors. They are actually pulsing converters (20 times network frequency) similar as motor converters. The line- and motor-converters in the same locomotive have often exchangeable arms: same spare parts are to be stored. In multi-current vehicles, the line-converter can be configured as step-down chopper to operate under 3 kV= (CFF: Re 484: multi-current version of DB 185.2) in other, a 3,8 kV voltage-link was chosen, which can be directly supplied from 3 kV= (SNCF: BB 447000).

Drive computing

The traction motors are computed for the current at continuous work-point (in blue dot-dashed line) or nominal current. Motors can be overloaded during a limited time, using the thermic inertia of metellic parts, without overheating of the most delicate parts (red hatching on the diagram). More the work point is distant from the continuous regime, shorter is the time to reach the maximal heating of components.

The work-point is adjusted by the voltage and the frequency of the three-phase system. The speed is mostly adjusted by the frequency and the torque by the voltage or the slip.

For the semiconductors devices, chopper in this case, ther is not thermic inertia. The converter has to be computed for the maximal power. (♦ - - ♦).

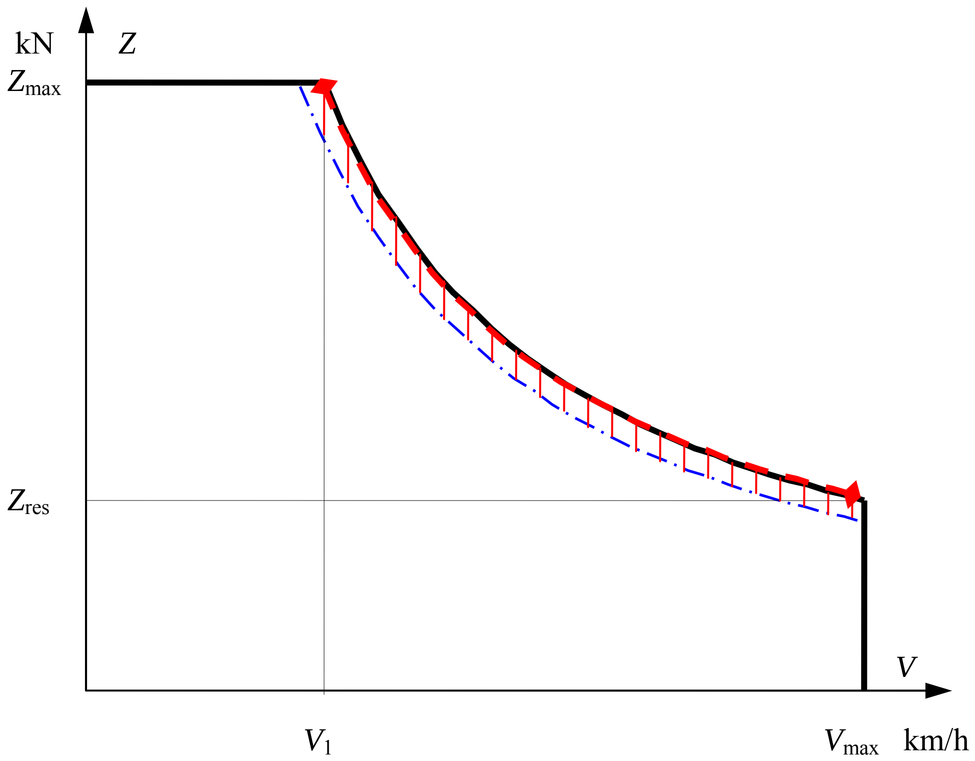


Fig. 4.164C Characteristics for an induction motor supplied by a three-phase inverter.

4.6 Synchronous motor

At the beginning of the 21th century, the synchronous motor seems to have a good future as traction motor. With the permanent magnets which produce a high magnetic density, synchronous motors can be built lighter and more compact as induction motors of same power. The construction of such motors succeeds with the development of rare-earth-magnets reinforced by fibers. Their price is now higher as induction motors. The three-phase converters are very similar as converters for induction motors (Transpôle : VAL 208, BCT : H40LF). This drive was first used for city transit but is also chosen for high speed trains (Japan and France NTV: *Italo*).

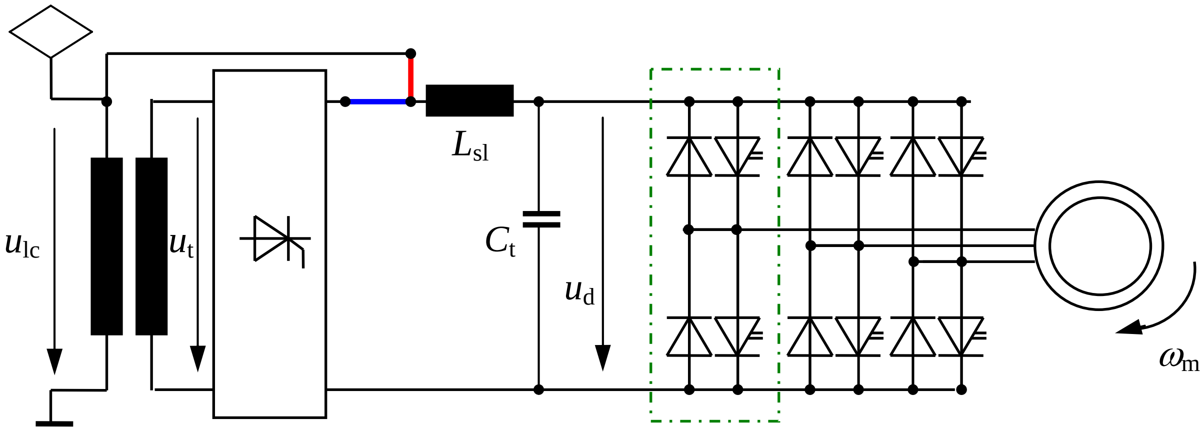


Fig. 4.178A Permanent magnet synchronous motor and a three-phase converter for DC- or AC-line. Schema of principle.

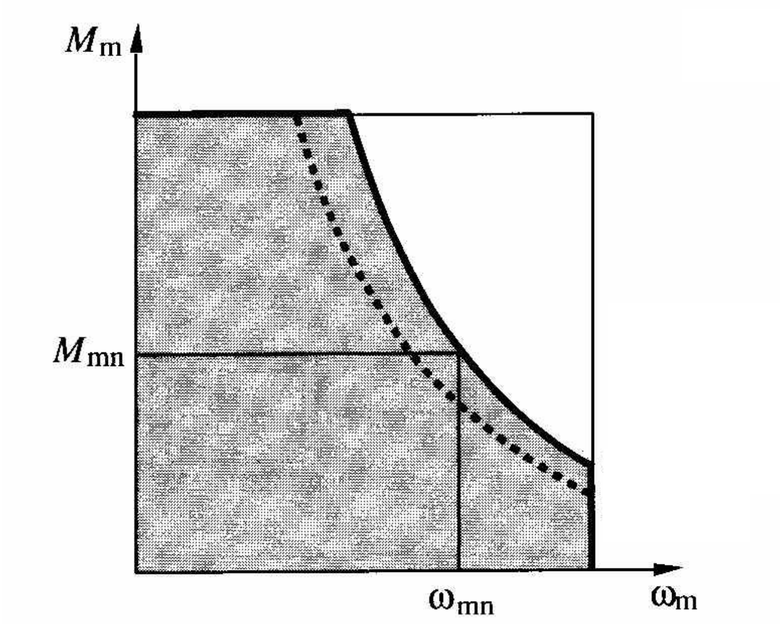


Fig. 4.180A Synchronous motor and three-phase converter: characteristics versus speed.

Synchronous motors with wired rotor were used before, with the need of contact rings to supply the rotor windings through a chopper or a rectifier. In these first constructions, three-phase converters were used, with natural commutation. They were controlled by the rotor position measured by two methods. They are called *self-controlled synchronous motors*. The group converter-motor is powered from contact line through a chopper or a converter as a

DC-motor (SNCF : BB 26000 or TGV-A). This drive is also named *DC-motor with static commutator* or *brushless DC-motor*.

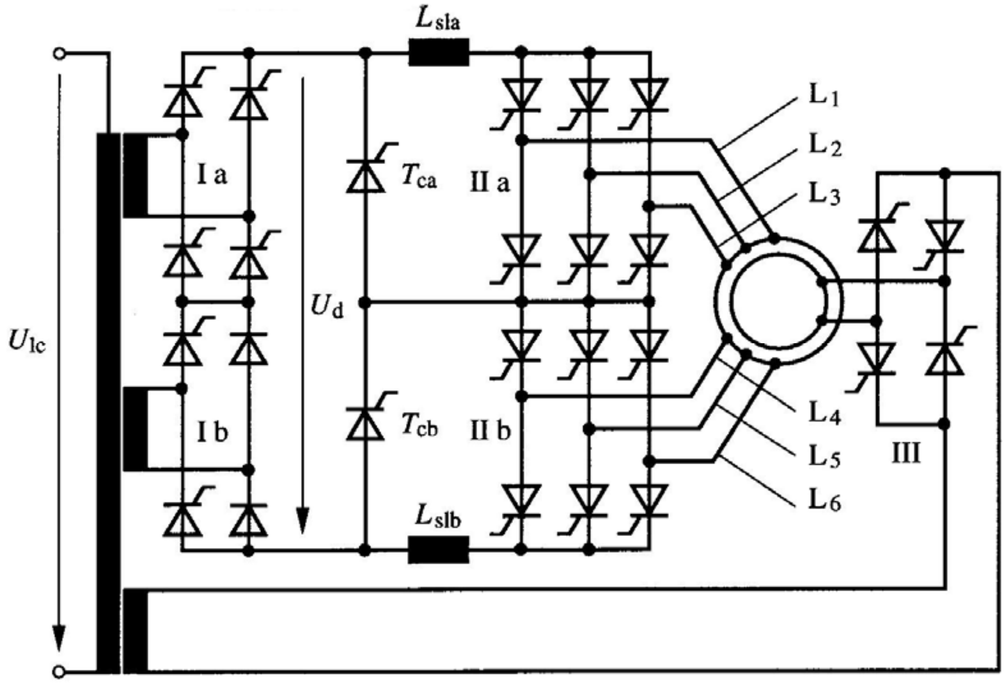


Fig. 4.179 Self-controlled synchronous motor: schema of principle: traction and regenerative braking (SNCF: BB 10004).

The area B is obtained by the triggering angle of bridge I, the C area by field weakening on bridge III. La zone B est obtenue par réglage de l'angle d'allumage du pont I, la zone C est obtenue par affaiblissement du champ sur le pont III. At very low speed, in area A, the switch-off in arms of converter II are obtained by the thyristors T_c, the induced voltage is not high enough to naturally switch off the arm.

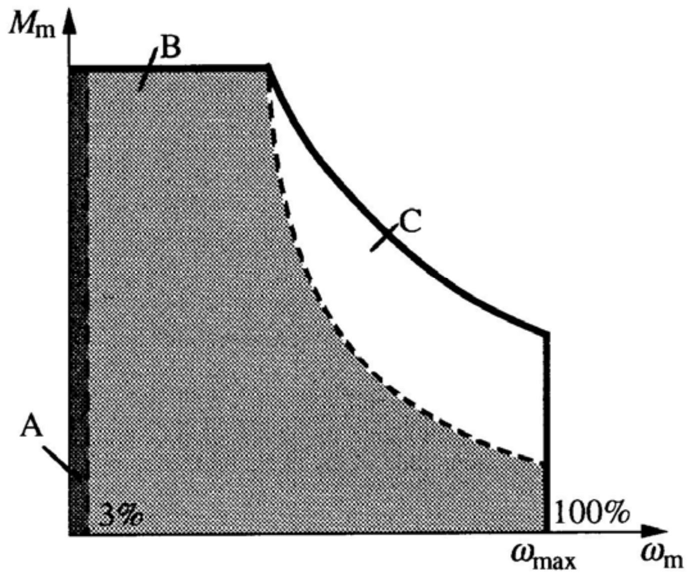


Fig. 4.180 Self-controlled synchronous motor: characteristics versus speed.

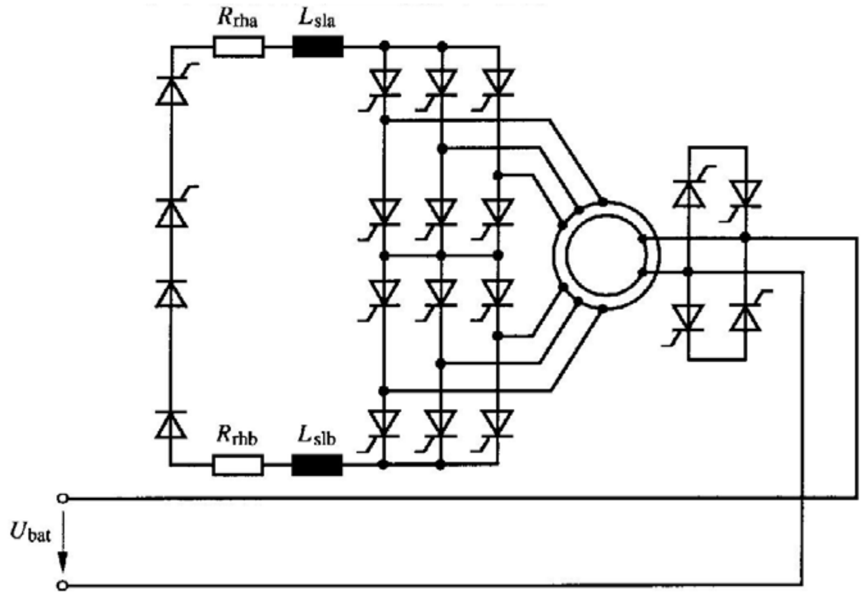


Fig. 4.182 Self-controlled synchronous motor: rheostatic braking (SNCF : BB 10004).

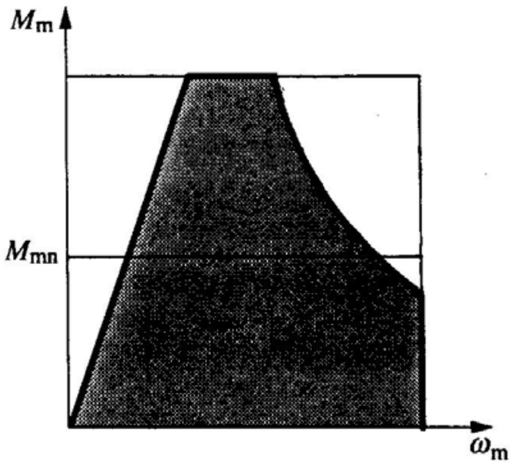


Fig. 4.183 Self-controlled synchronous motor: characteristic in braking versus speed.

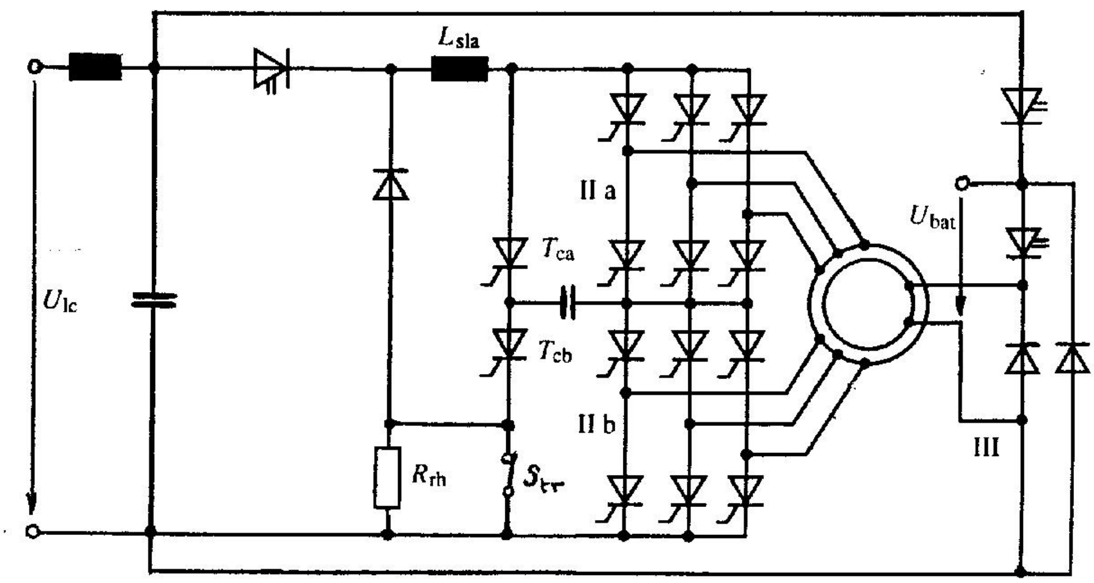


Fig. 4.179A Self-controlled synchronous motor, DC line: traction and rheostatic braking (SNCF: BB 26000).

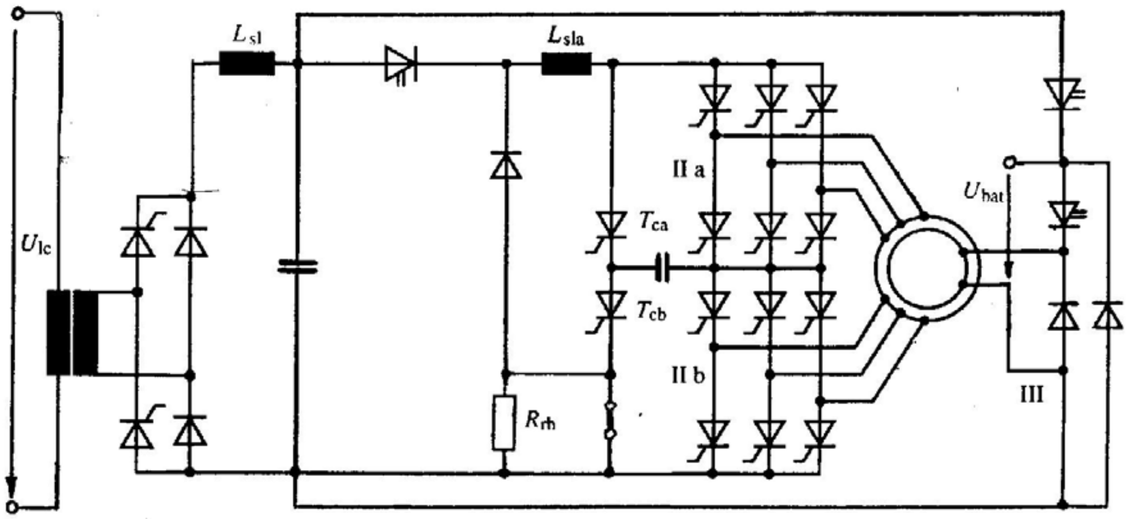


Fig. 4.179B Self-controlled synchronous motor, DC line: traction and rheostatic braking (SNCF: BB 26000).

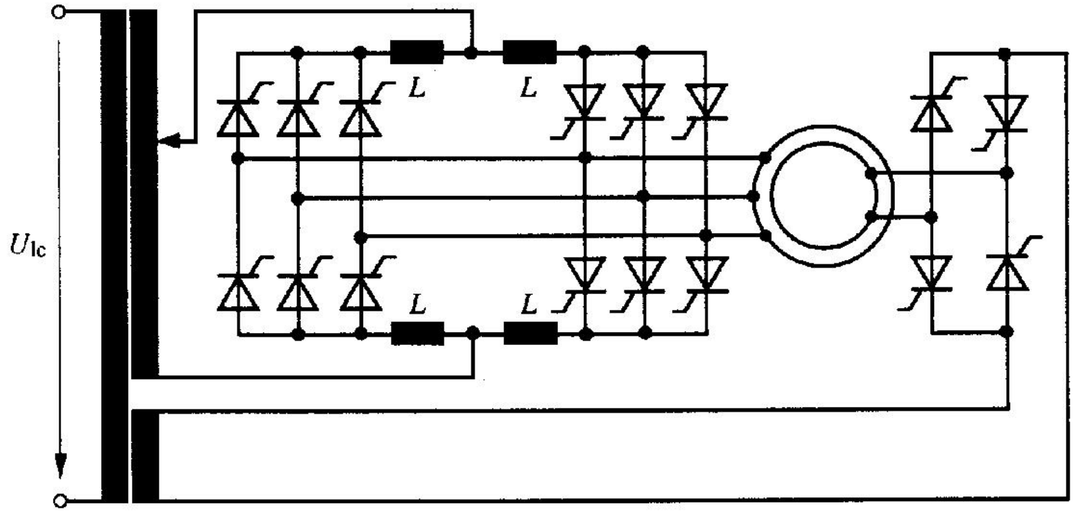


Fig. 4.186 Synchronous motor and direct frequency converter (SZD: VL80V).

4.9 Thermo-electric Drive

4.9.1 Principle

The traction motors of a thermo-electric vehicle do not receive electric energy from a contact line, but from an embedded generator group. This generator converts chemical energy of a fuel in electric energy.

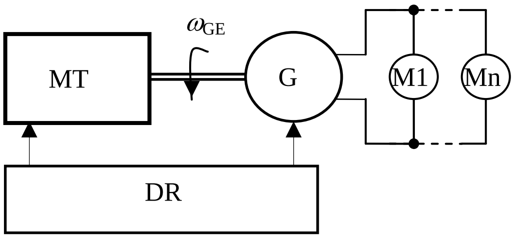


Fig. 4.203A Thermo-electric drive: principle.

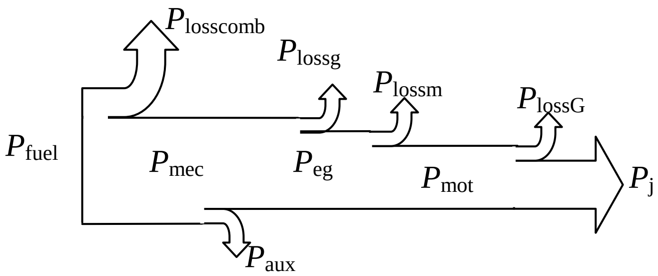


Fig. 4.203B Thermo-electric drive: power flows (arrows widths are not on scale).

The drive counts four steps:

- One thermic machine MT receives a power as fuel flow q and converts it in mechanical power with an efficiency η_{MT}.
- One generator G converts mechanical power in electrical power with an efficiency η_g. The mechanical power as to supply power for auxiliary devices, control device DR and excitation for generator.
- The traction motors convert electrical power in rotating mechanical power with an efficiency η_{mot}.
- The gearing and the wheels convert rotating mechanical power in translation mechanical power at wheelrims with an efficiency η_G.

With all these efficiencies, the effective power at wheelrims P_j do not exceeds 30 % of power in the injected fuel.

$$P_{méc} = \omega_{GE} \; M_{MT} \tag{4.100}$$

$$P_{méc} = \eta_{MT} \; e_{carb} \; q \tag{4.101}$$

$$P_{é} = \eta_g \; (P_{méc} - P_{aux}) \tag{4.102}$$

$$P_{mot} = \eta_{mot} \; P_{é} \tag{4.103}$$

$$P_j = \eta_G \; P_{mot} \tag{4.104}$$

The thermic machine is often a diesel motor (f. ex GTW 2/6 of Stadler) and rarely a gas turbine (Amtrak : JetTrain, SNCF : TGV001). The efficiency of diesel motor depends on its work-point. Modern control devices chose the motor work-point in order to optimize the efficiency for the asked power for traction and auxiliaries (curve AC on figure 4.205). In the traction vehicles for passenger trains, the generator group has to provide *hotel power* (heating or air conditioning, lighting…).

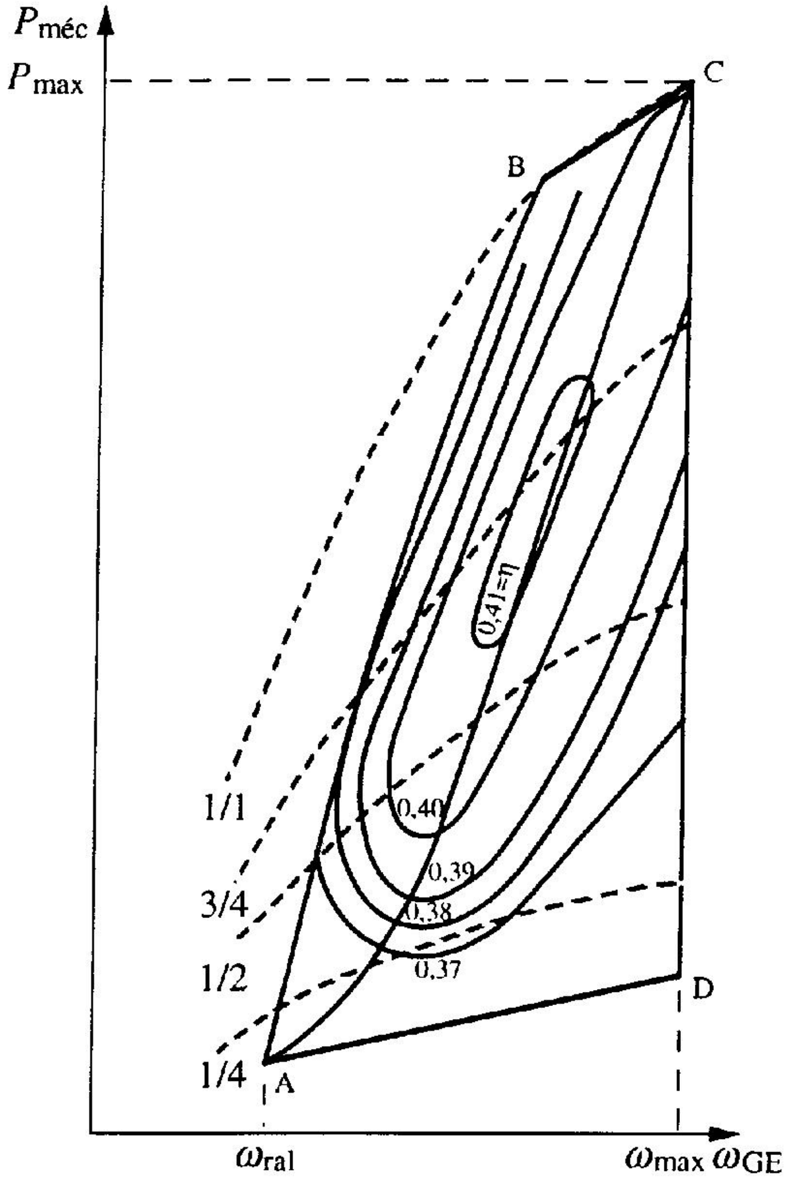


Fig. 4. 205 Efficiency of diesel motor on power-speed characteristic.

The curve AD is the lower limit to avoid the fouling of diesel motor, the curve AB is the upper limit to avoid too much smoke rejection and the curve BC corresponds at the full opening of fuel injectors. The diesel motor efficiency not exceeds much 40 %, and only for power between half and three quarters of maximal power.

Unlike on pure electric vehicles, the traction motors cannot be used other their continuous power, because total power is limited by the generator group, this gives a really stretched traction characteristic (fig.4.215) typical on diesel traction vehicles. The maximal effort decreases at low speed yet and the residual effort at maximal speed is very low.

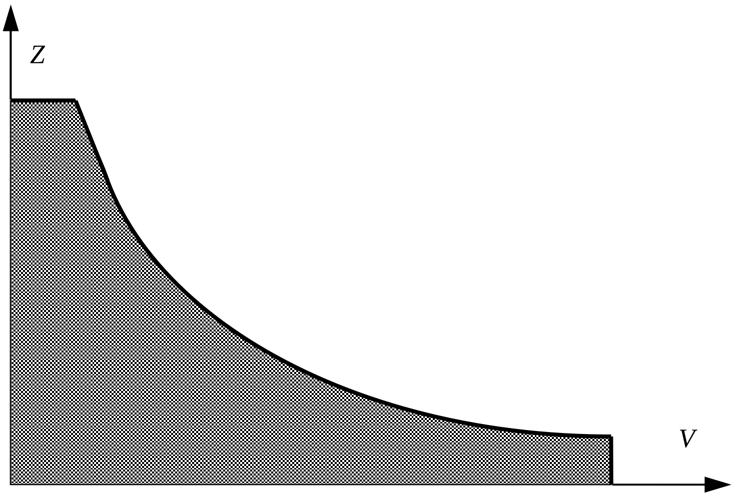


Fig. 4.215 Diesel-electric drive: characteristic traction versus speed.

Generator knew three steps of development:

1. At the beginning, it was a commutator with three excitation windings: series, shunt et separate. The work-point was adjusted by excitation current furnished by a battery and amplified by a dedicated machine moved by the thermic motor (leaflet 8.10.1, fig. 4.207). Other variants were also applied.
2. From the end of the sixties, a synchronous machine was used, followed by a three-phase diode rectifier. Le point de fonctionnement est ajusté par le courant rotorique fourni par une machine d'excitation (leaflet 8.10.5, fig. 4.218).
3. From about 2000, some vehicles use an induction alternator followed by a controlled three-phase rectifier. The work-point is adjusted by the difference between generator-frequency and converter-frequency on rectifier mode (fig. 4.227). With this design, it is possible to stop fuel injection in the diesel motor in braking mode, the induction machine works in motor to move diesel motors and its chilling and lubricating pumps; the three-phase bridge works on inverter mode.

The traction motors were at the beginning commutator motors with series excitation, as in pure electric traction. They were connected in parallel at the generator terminals (collector- or synchronous with rectifier). From the beginning of eighties, there were induction motors powered through three-phase inverters at variable frequency (fiche 8.10.3).

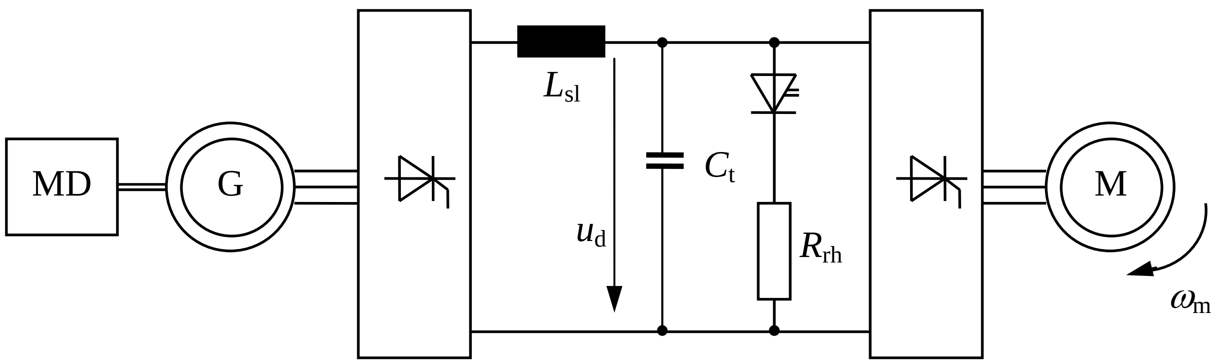


Fig. 4.227 Diesel-electric drive: transmission induction–continuous–induction.

In fuel-cell, the conversion form fuel (Hydrogen) power to electric power do not requires intermediate mechanical power. The electric power is produced at low voltage with high current; this requires a sep-up chopper to supply intermediate DC-circuit.

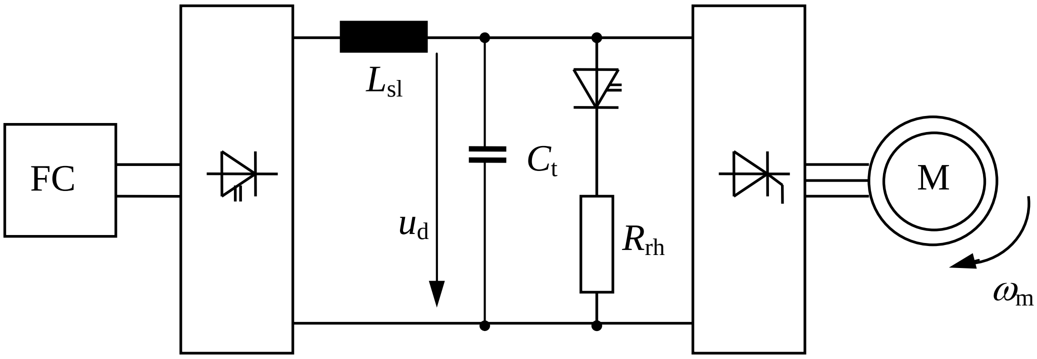


Fig. 4.228 Fuel-cell drive: transmission continuous–continuous–synchronous.

Some advantages and disadvantages of this drive regarding diesel-electric are listed below (2005). This can change in the next years.

- Higher efficiency (70 % instead of 30 %).
- Exhaust is water steam.
- Fuel storage clearly more difficult.
- More complex filling stations.
- More important place request.
- Higher acquisition price.
- More maintenance.
- Lower availability.

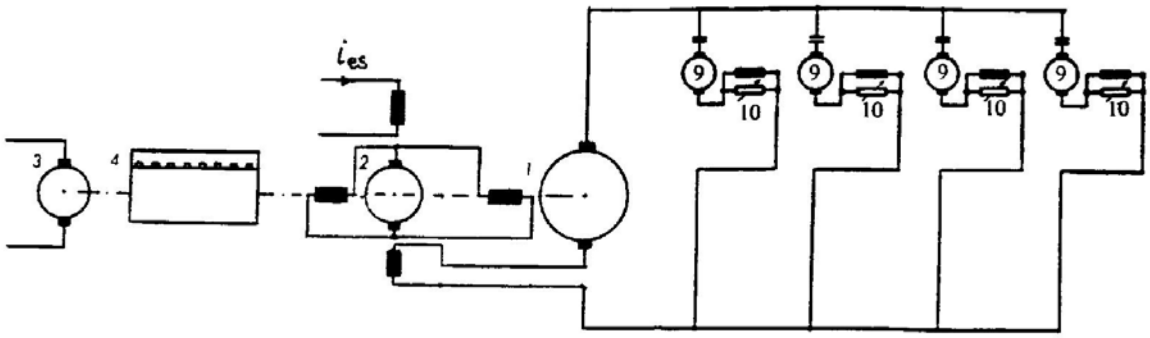


Fig. 4.207 Thermo-electric drive: DC-generator.

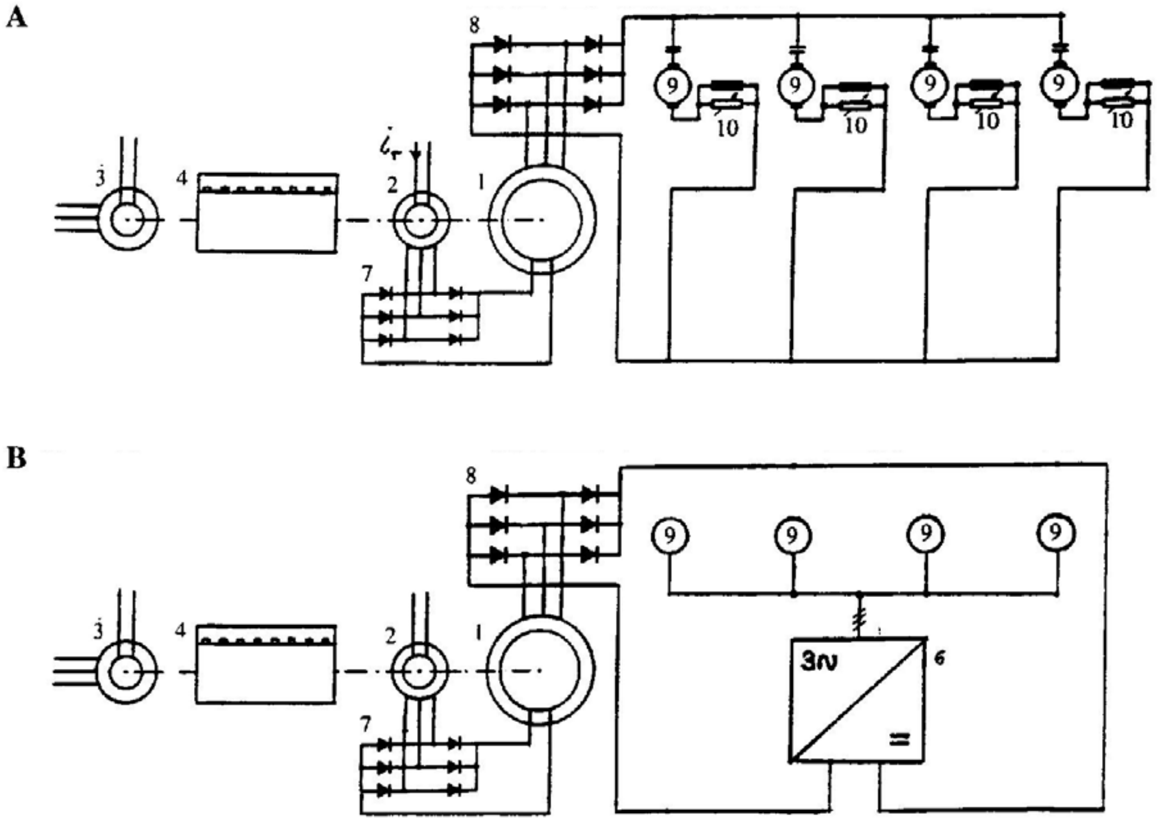


Fig. 4.218 Thermo-electric drive: synchron alternator with rectifier
A Commutator motors.
B Induction motors and inverter.

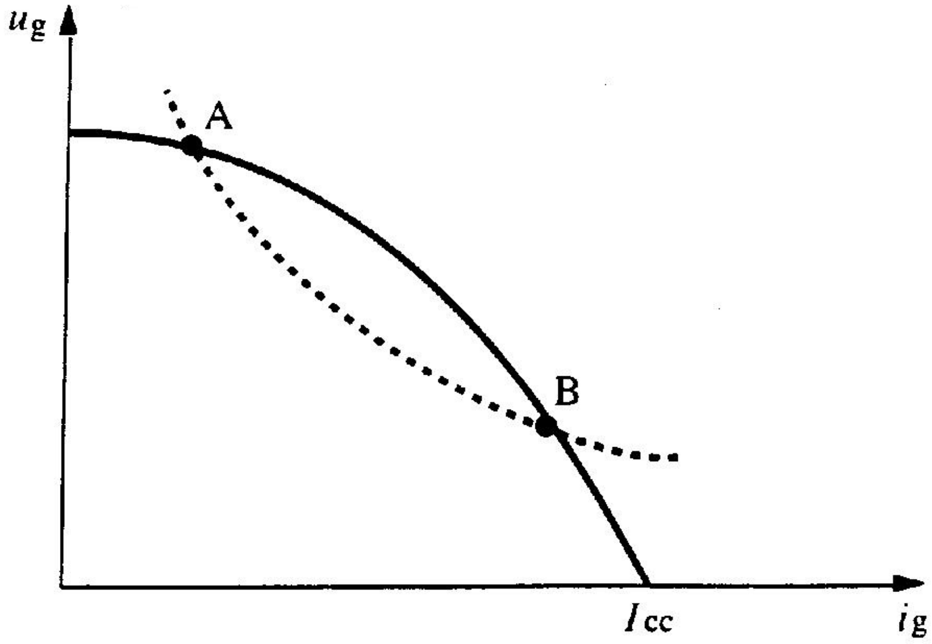


Fig. 4.221 Maximal output characteristic of an alternator.

The dotted curve AB shows the power limit of diesel motor.

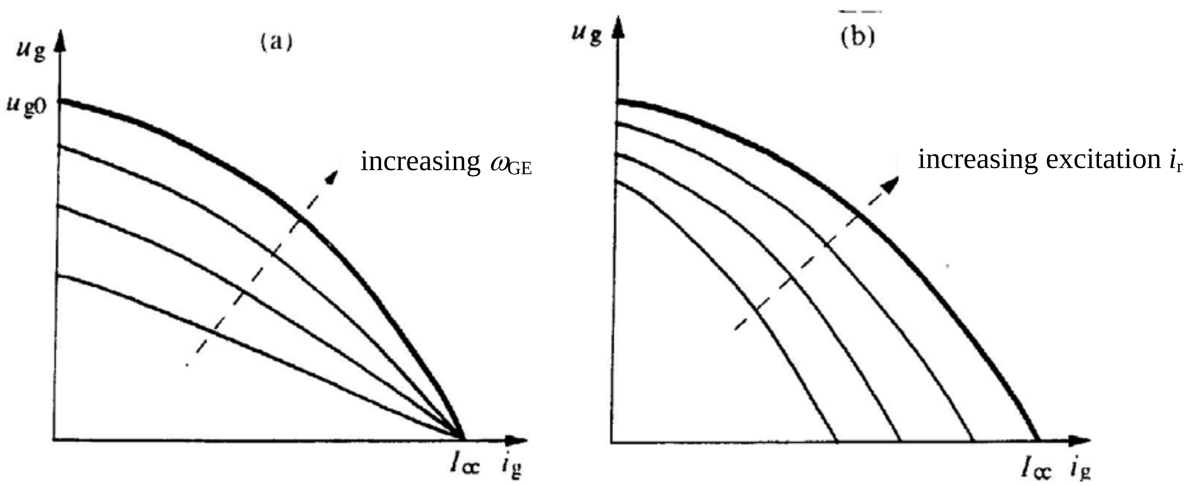


Fig. 4.222 Output characteristics of an alternator:

a For different values of group speed at constant excitation.

b For different values of excitation at constant group speed.

Comparison electric – thermo-electric

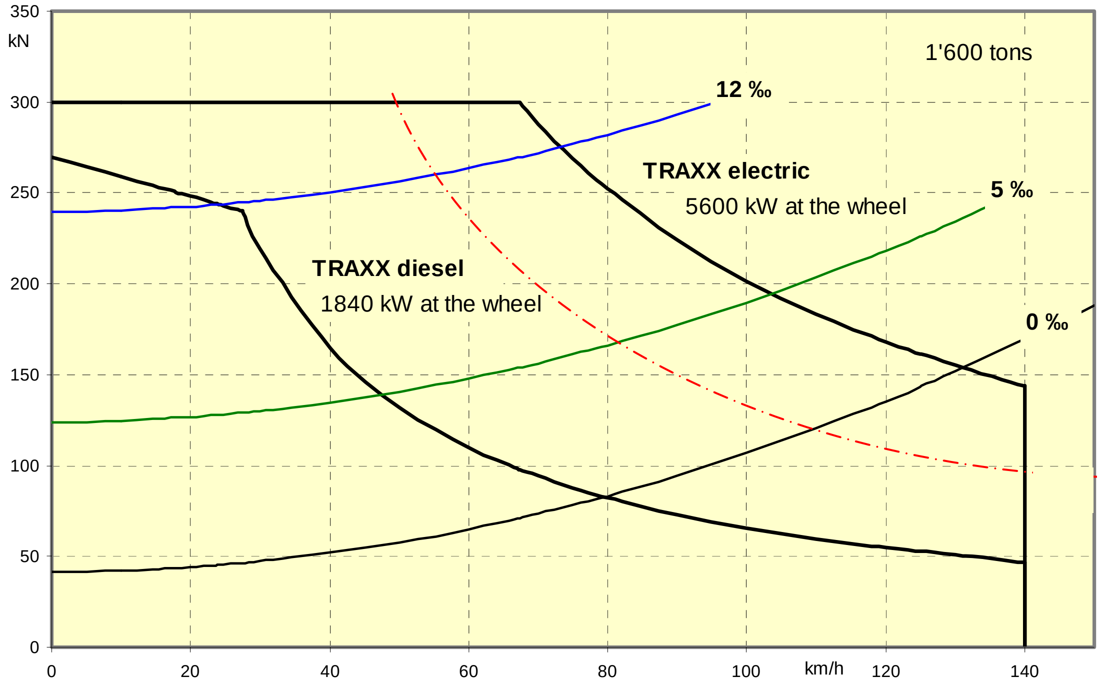


Fig. 4. 229 Locomotives of same weight and same design: electric and diesel (*doc. Bombardier*).

If a diesel-electric motor vehicle is compared with a pure-electric, we see that the performances in continuous regime are higher for an electric locomotive which can develop 4,2 MW (red curve in dash-dotted line) than a diesel-electric limited at 1,84 MW by the power of its diesel motor (2,2 MW). In addition, an electric locomotive can be asked for a higher power during a short time (black curve: about 10 minutes). A 82 tons locomotive can develop 5600 kW but a diesel-electric one only 1840 kW.

The multiple-unit service is more frequent with diesel. The acceleration is lower with trains in diesel-electric traction.

Train power supply (HEP)

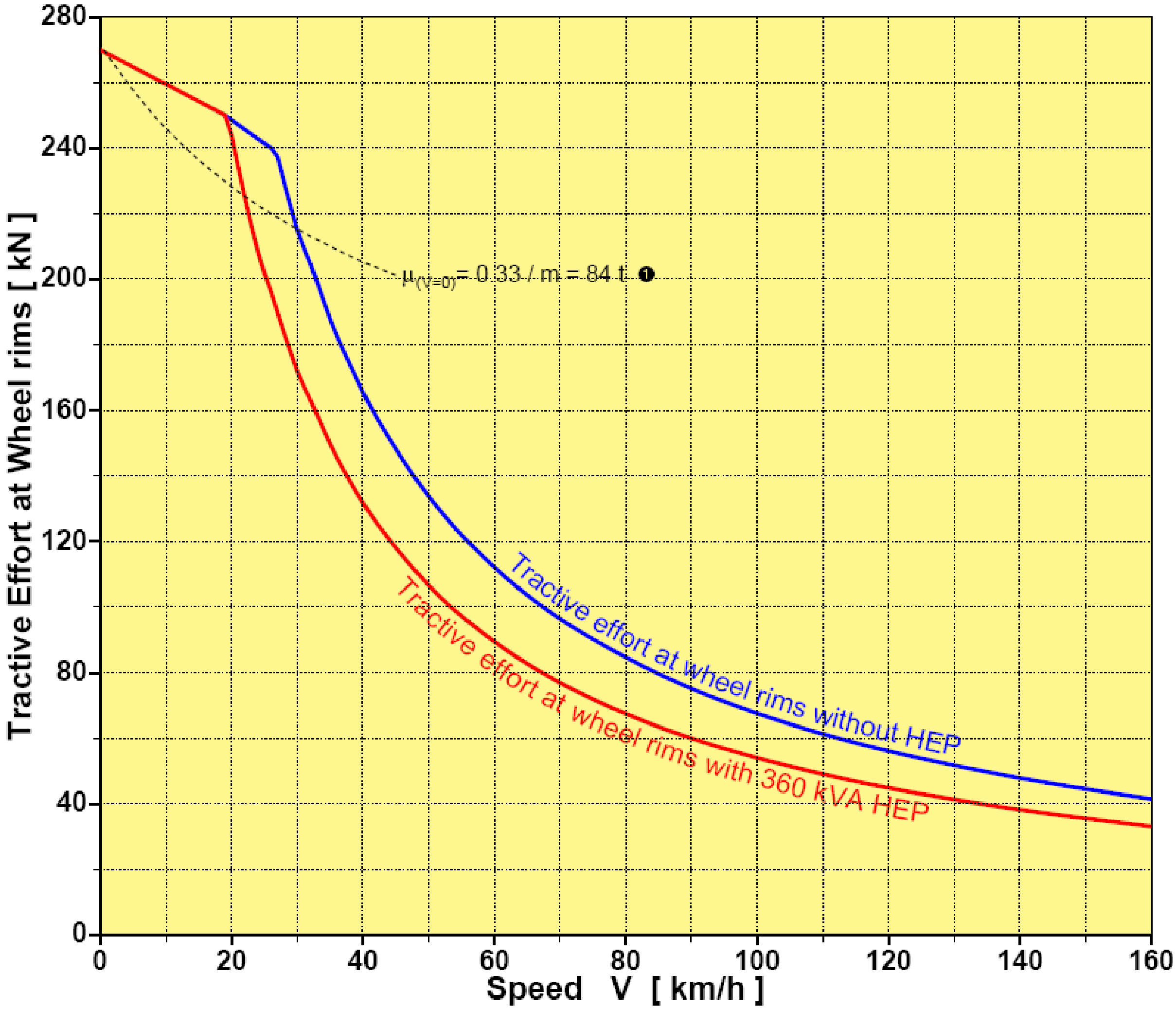


Fig. 4.230 Characteristic of effort: diesel locomotive with and without train power supply (doc. *Bombardier*).

If a diesel locomotive pulls a passenger train, the diesel motor has also to give power for the train. This power cannot be used for traction (red curve)! On a short ramp, the train driver can switch-off the HEP on the train – which has temporarily no more air conditioning – in order to use the full diesel power for the traction.

5.1 Mechanic drives

The mechanic drive, or gear, have to transmit at the driving wheel the torque developed by the traction motors.

Between the body of traction vehicle, its bogie frame and the axle boxes, some suspension devices are to be found. Motors are generally fixed on bogie frame or at body ground. Motors are called full-suspended if all their weight is on frame or semi-suspended if a part of weight is directly laid on the axle. The mechanical drive has to hold relatives movements between motor axis and axle axis. If the motors are fixed under body, the mechanical drive has also do hold relative movements between body and bogie, which needs telescopic cardan shaft (TGV, ICN).

The mechanic drive follows two targets:

- For a defined power output, a motor which turns fast is smaller and lighter than a slow motor. The drive contains a gear box between speeds of motor ω_m and axle ω_e.

$$\omega_e = k_G \omega_m \tag{5.1}$$

- To provide that shocks encountered by wheels (passing on rail joints or switches) go until the motors the drive contains also elastic elements.

The suspension of motors also contribute to track longevity: the track received shocks only with the mass of axles and not axle and motor. Drives can be classified in three classes, from the quality of its suspension:

- Class 1: Nose suspended motors are fixed on one side at frame with silent-blocs and on the over side at axle with bearings. They are not full-suspended (N1 – N3). The *gearless* drives and the planetary gears are also in this class.
- Class 2: The cardan shaft is put between motor shaft and the gear. It is installed inner of motor tubular shaft (*BBC with discs*, *Sécheron with blades*, *ASEA*, *Sumitomo*). The motor is fixed on frame of bogie or vehicle. The great cog-wheel is fixed on the axle (B1, B2, B6, B8, K1, K4, K5).
- Class 3: The cardan shaft is put between axle and the gear. This shaft is a tube around the axle (*Jaquemin*, *BBC with rubber joint*, *Alstom*, *Kaelble-Gmeinder*) (K2, B3, B4, B7). Drives with free shaft are also put in this class (B5, K3).

The figure 5.0 presents a more complete inventory of different solutions.

The mechanical power of motors is not fully transmitted at wheel rim, but with an efficiency η_G comprised between 0,95 and 0,99.

$$P_j = \eta_G P_{mot} \tag{5.4}$$

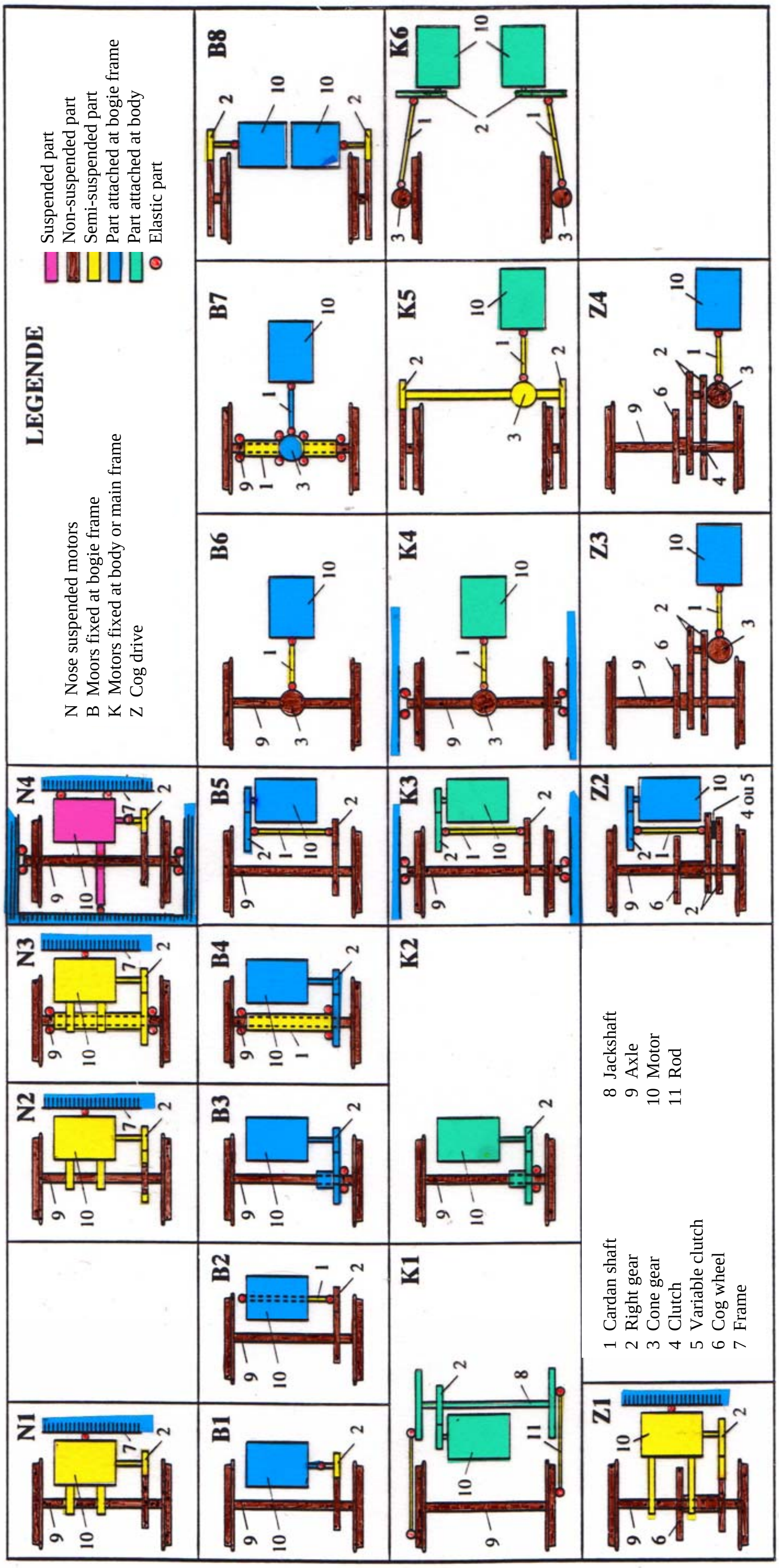
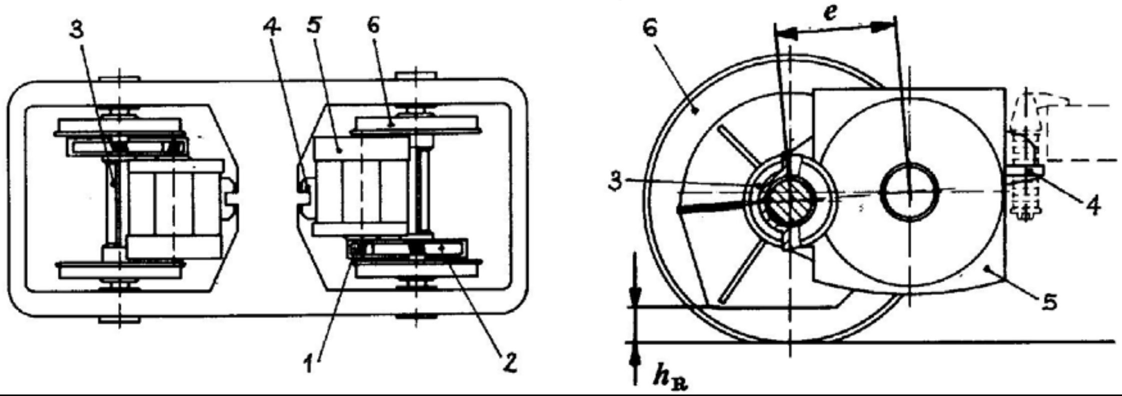


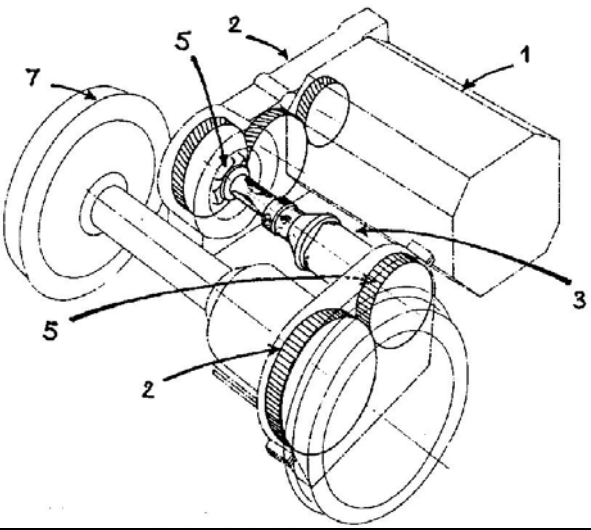
Fig. 5.0 Applications of transmissions.

5.2 – 5.6 Chosen examples



1 pinion	5 motor
2 cog wheel	6 axle
3 bearing	e meshing distance
4 fixation at frame (nose)	h_R space under carter

Fig. 5.2 Nose-suspended motor.



1 motor (fixed under body)	5 cardan
2 right gear	7 axle
3 slide shaft	

Fig. 5.30A Transmission TGV.

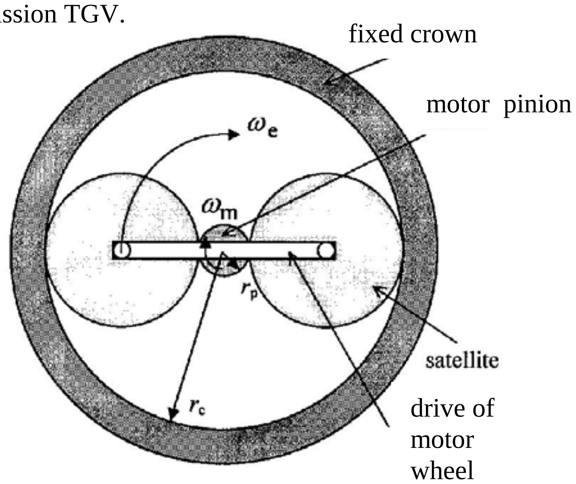
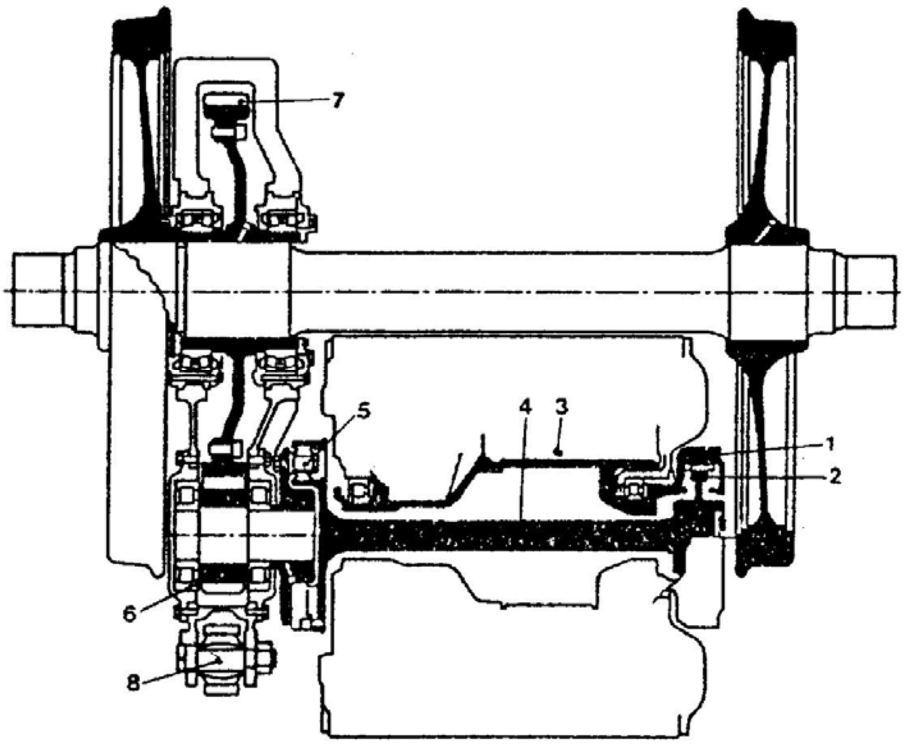
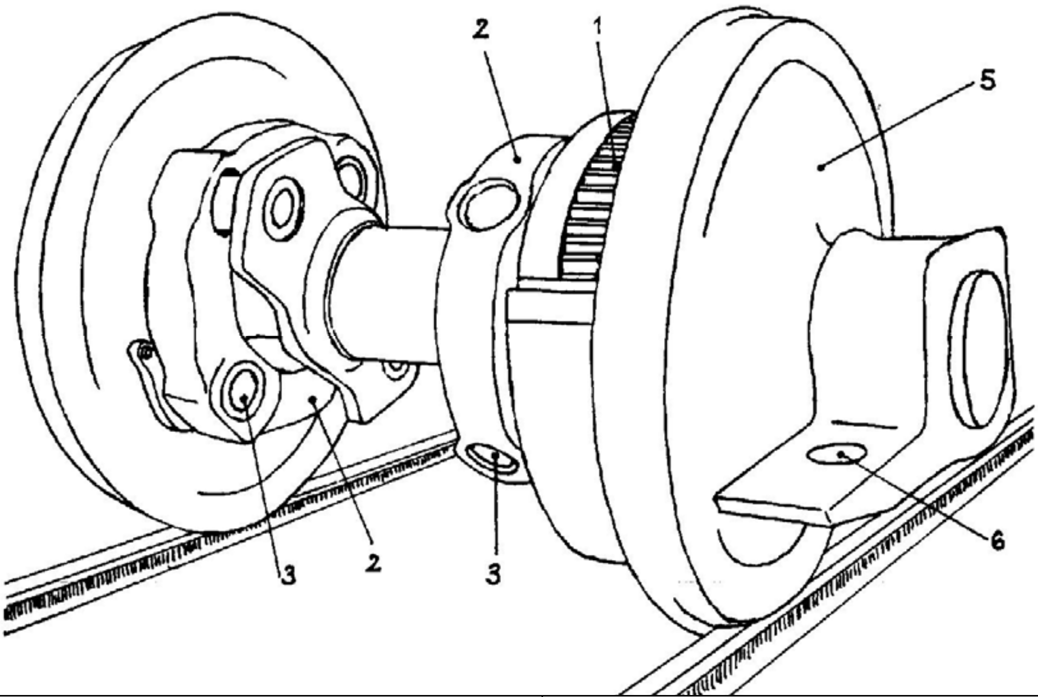


Fig. 5.32A Planetary gear.



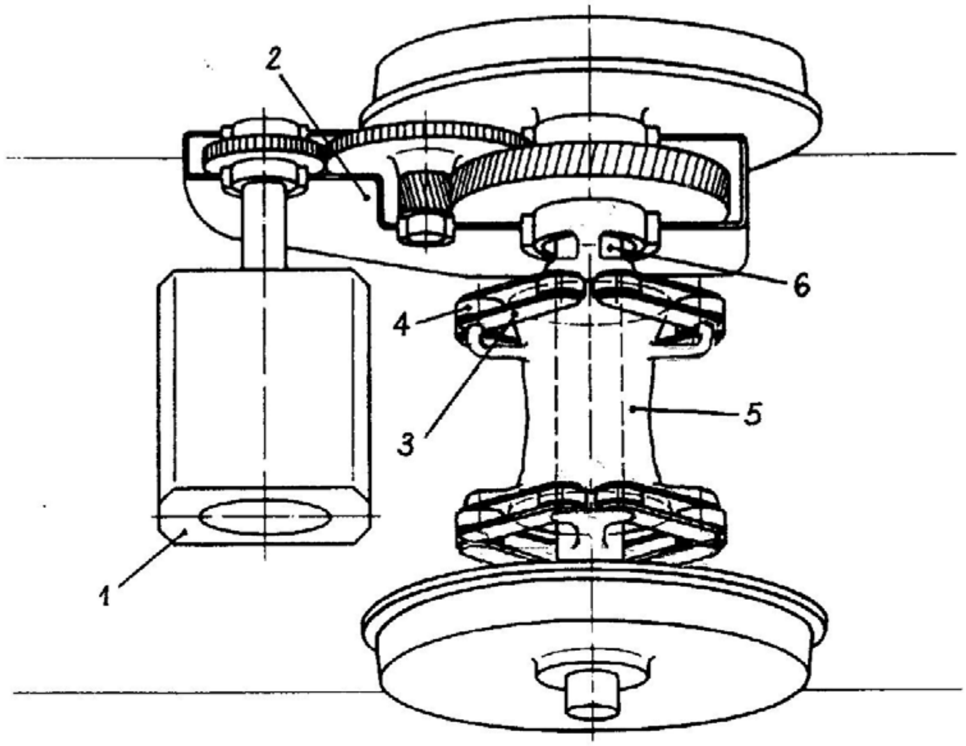
1 cog coupling in oilbox	5 cardan with rubber joints
2 pinion	6 pinion of gear
3 hollow rotor	7 great cog wheel of gear
4 torsion shaft	8 nose suspension of the carter

Fig. 5.23 Transmission *ASEA*.



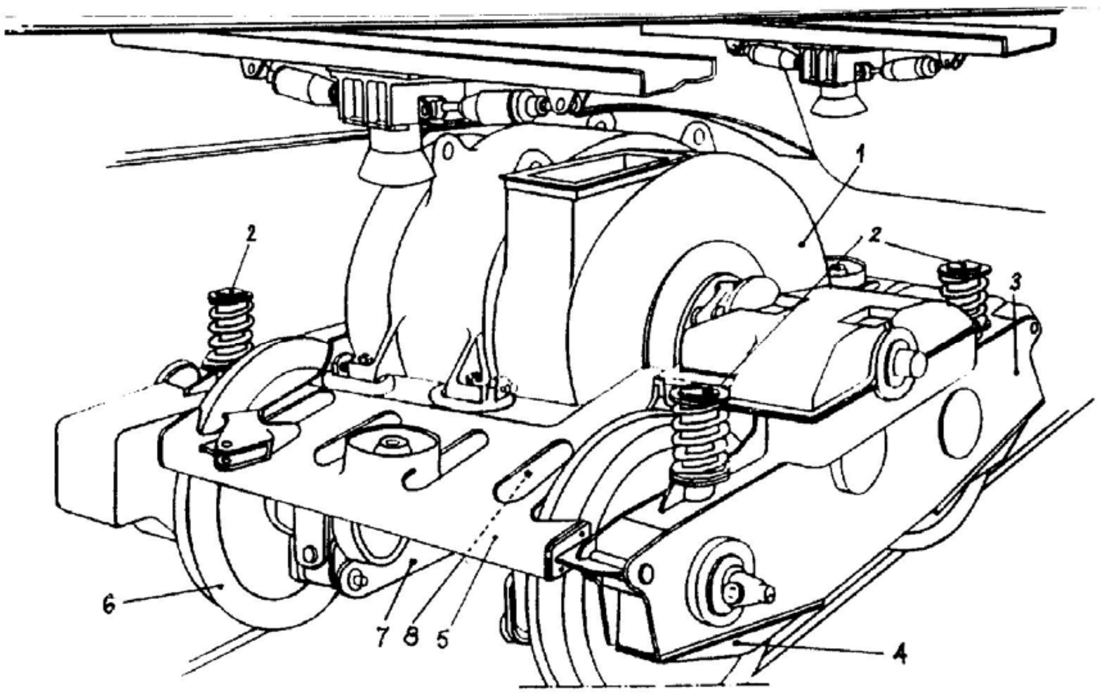
1 great cog wheel of gear	4 hollow shaft
2 ring	5 axle
3 patella	6 place of primary suspension

Fig. 5.24 Transmission *Jacquemin*.



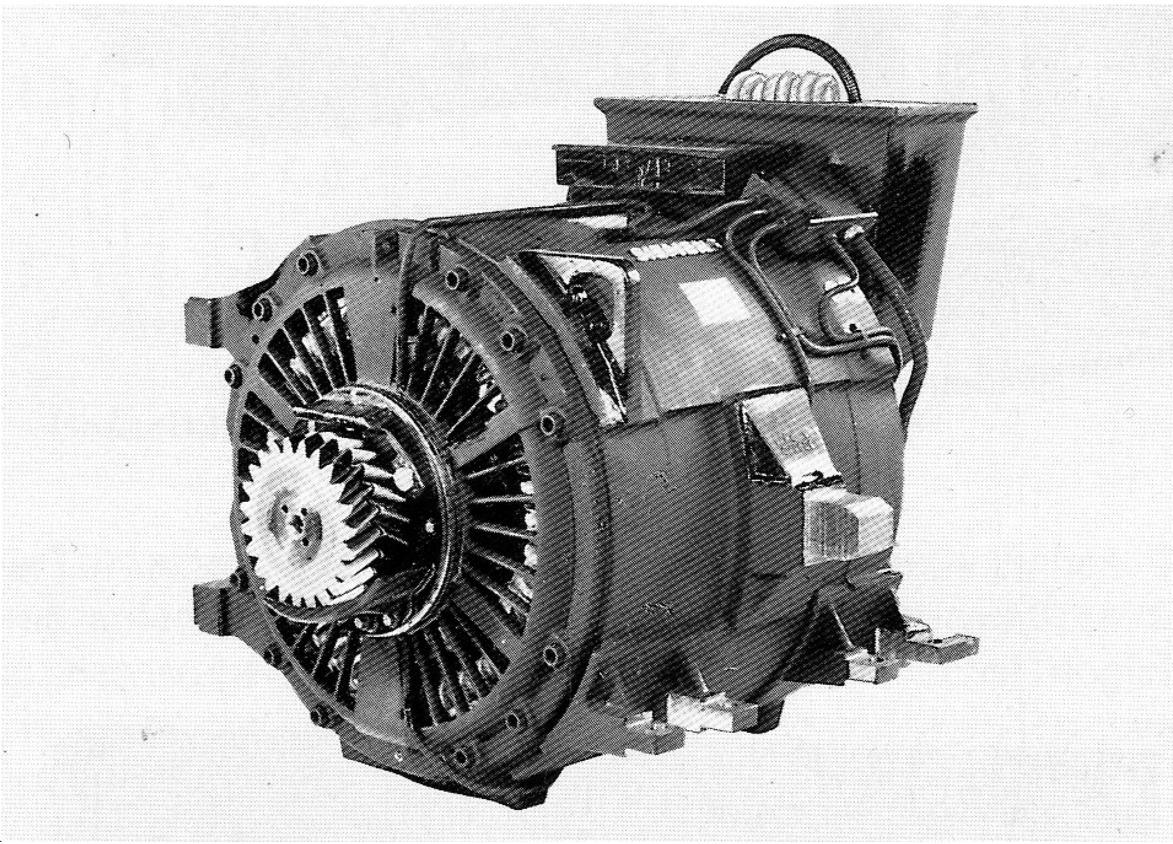
1 motor	4 rubber joint
2 gear	5 hollow shaft
3 rods	6 axle shaft

Fig. 5.25 Articulated transmission with rubber joints (*ABB, BBC, Hurth, Kaelble-Gmeinder, Krauss-Maffei)*.

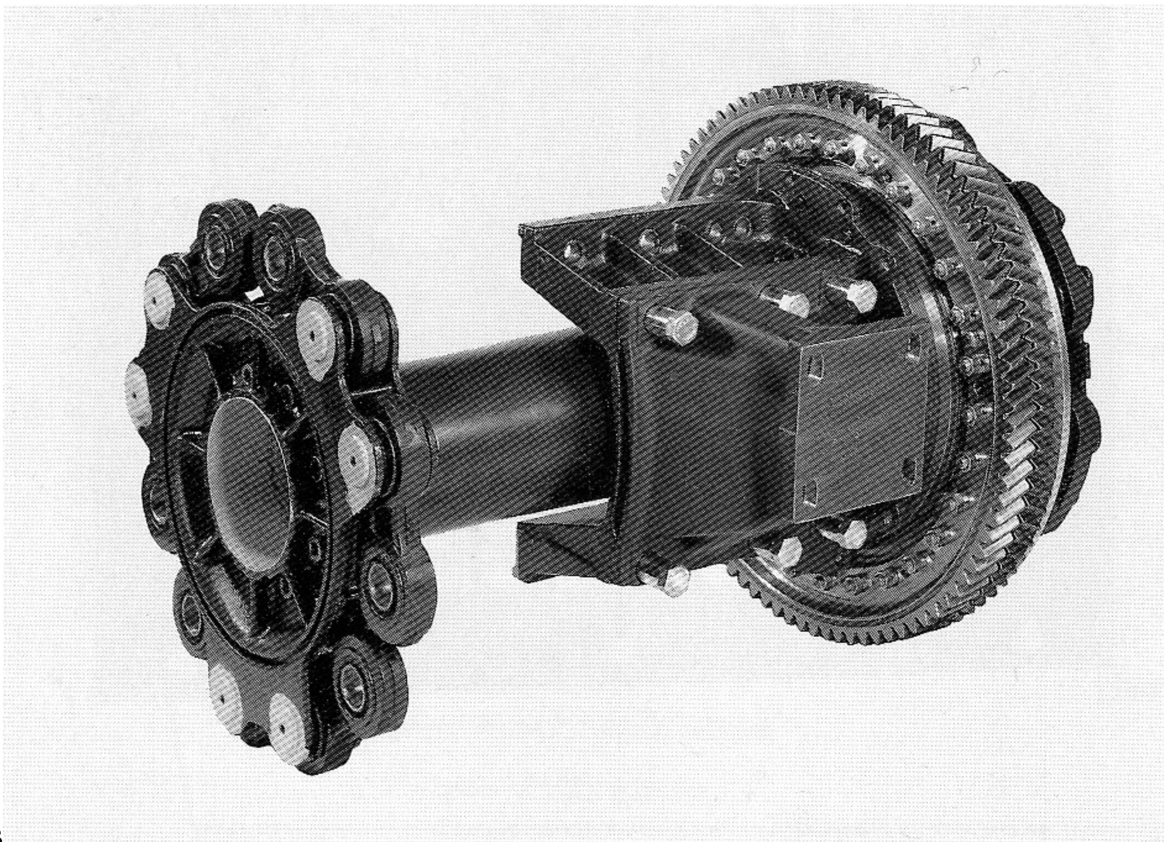


1 motor	5 bogie frame
2 secondary suspension	6 axle
3 carter of gear	7 axle boxes joined by spars
4 dancing ring	8 primary suspension

Fig. 5.27 Single-motor bogie (SNCF: BB 8500).



A



B

A Motor and pinion. On the right, fixing at the center crossing of the bogie frame.
B Great cog wheel, hollow shaft and rod cardan. On the right, fixing at the external crossing of the bogie frame.

Fig. 5.35 Example of hollow shaft: *Krauss-Maffei*.

5.8 Calculation of mechanic transmissions

The mechanic drive, or transmission, has the target to transmit at motor wheels the torque of traction motors: the dimension of gear cogs and of the shafts must be calculated in function of maximal tractive effort, plus a margin. Do not forget that fixations and silent-blocs must hold out, also after aging.

The most difficult part of the calculation is on another place: this is an oscillating system with multiples inertia joined with torsion shafts. The complexity of systems growths with the class number (see page 5-1.1). For a system of class 3, the number of freedom degrees can reach 20. Depending of the rolling speed, some mechanical resonance frequencies can be found. If more, one of these frequencies is an integer multiple of an electrical frequency caused by the network or the harmonics of converter, some majors problems are encountered. The science of mechanic engineer is to survey that these resonance frequencies would not be excited in normal operating conditions, in particular with an adequate choice of elasticity factor of each part.

In the calculation of dimension of the gear cog, the number of contact points has to be constant, to provide the generation of vibrations.

At certain speed, a runout of wheels – one or two tenth of millimeters – can generate vibrations which excite a resonance in the mechanic structure.

5.9 Cog-rack Transmissions

For the climbing of steep ramps, the adhesion is not sufficient to insure the traction and some cog wheels, meshing on a rack, are installed.

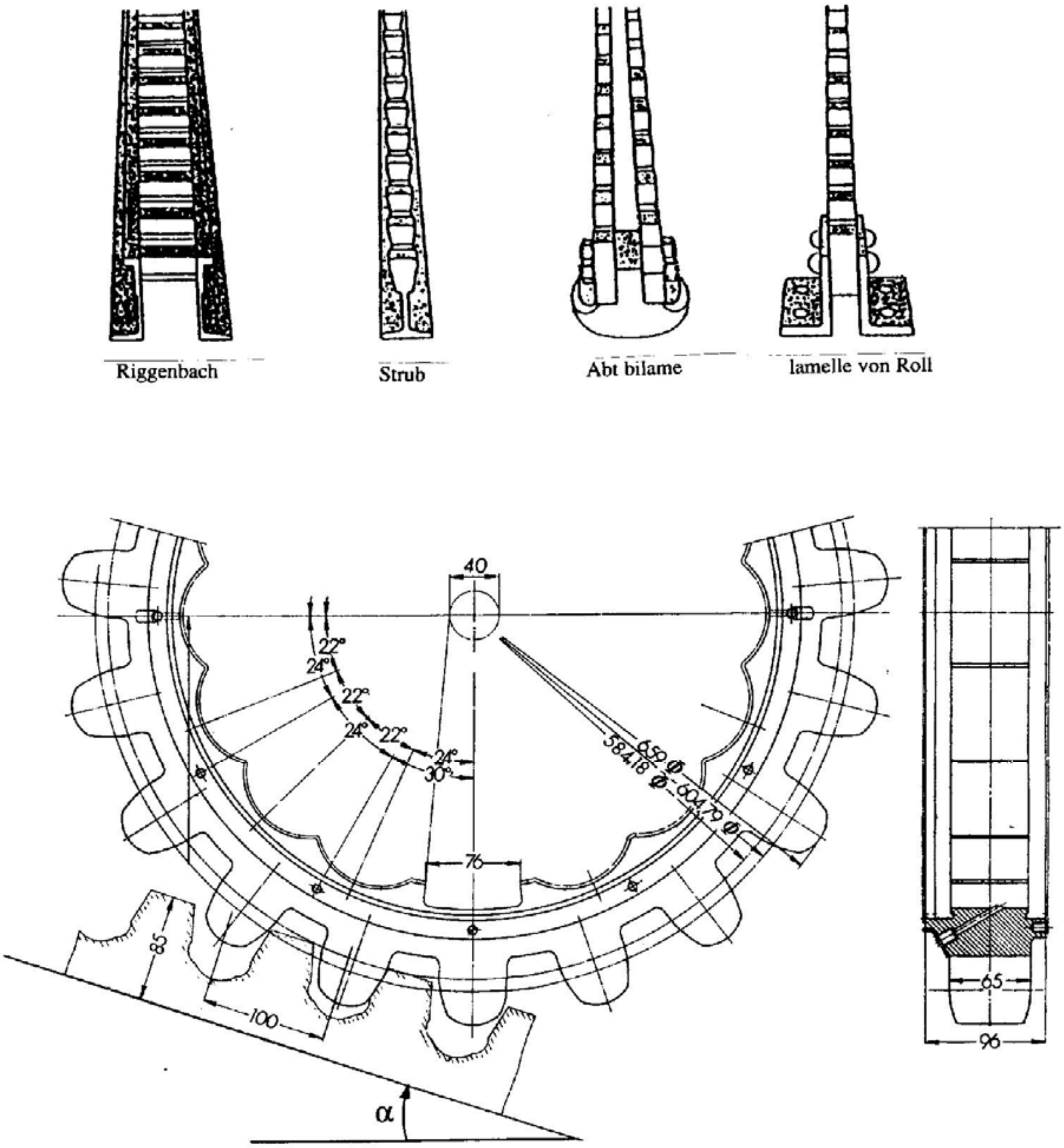


Fig. 5.36 Cog wheel and rack.

6.1 Auxiliaries

If the electric and mechanic drives are preferably studied, it is totally false to neglect the auxiliary devices which are necessary for the operation of traction.

When using energy from contact line (or diesel motor), the auxiliaries have to execute two types of missions:

1. Provide services necessary to a good operation of traction equipment and a good circulation of train, including the brakes.
2. Provide power to comfort equipment for the passengers (lights, heating – air conditioning, doors movements, etc.).

The first type is essentially studied, which is necessary for all the train.

On traction engine is often parked with down-placed pantographs. It is necessary to hold energy on board to prepare the engine until the pantograph will be pressed on contact line and the main circuit breaker will be closed. This energy is stored on an accumulator which is charged through a dedicated device from contact line. On an autonomous engine, the stored energy must start the diesel motor.

The train braking must be guaranteed all times. Generally, pneumatic energy is used (vacuum or air). The compressor, or the vacuum pump, has to guarantee a full availability of this pneumatic energy.

At last, the cooling and the lubrication of all devices of the traction drive have to be done surely. The motors of fans et pumps must be functional at all contact line voltages (standard: from –30 % to +20 % of nominal value).

In the modern vehicles (from about 1990), a board static converter produces a three-phase network at constant frequency (for ex. 400V 50 Hz) from the intermediate circuit à continuous voltage of the electric drive. Often, two static converters are installed, to guarantee a certain redundancy to cover the essential functions in case of failure of one. This 3-phase network allow to choice industrial components in place of specially developed ones.

In older vehicles, some complex and ingenious solution were found to insure security and availability.

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8.1 Presentation

In order to illustrate theory chapters in an attractive manner, some concrete examples of vehicles built around the world are presented. Each example has the form of a four-page technical leaflet.

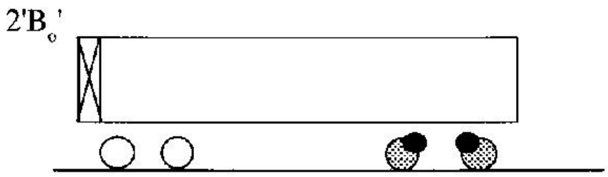
First page give a general presentation:

- Type of vehicle.
- Axle’s arrangement.
- Railway company.
- Picture or drawing.
- Symbolic representation of equipment.
- Year of building.
- Main technical data.

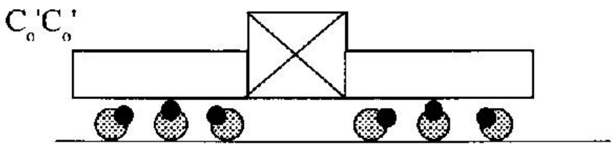
The second page gives a description of the vehicle, including the mention of similar series. References on theoretical part or articles are proposed for supplementary study.

Last two pages show effort diagrams versus speed, power-circuit diagram and vehicle diagram.

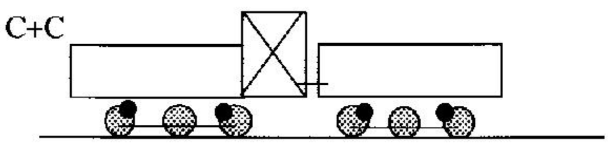
For axle arrangement, UIC conventions are used. As supplementary, index « i » is used for individual drive on wheels, without axis between them, in a similar way as index « o » is used for individual drive of axles in the same bogie or the same body.



Single-body vehicle on two two-axles bogies. Only one is motorised.
Example : Power-car BT BDe 2/4



Single-body vehicle on two three-axles bogies.
Example : Locomotive SBB Ee 6/6 II

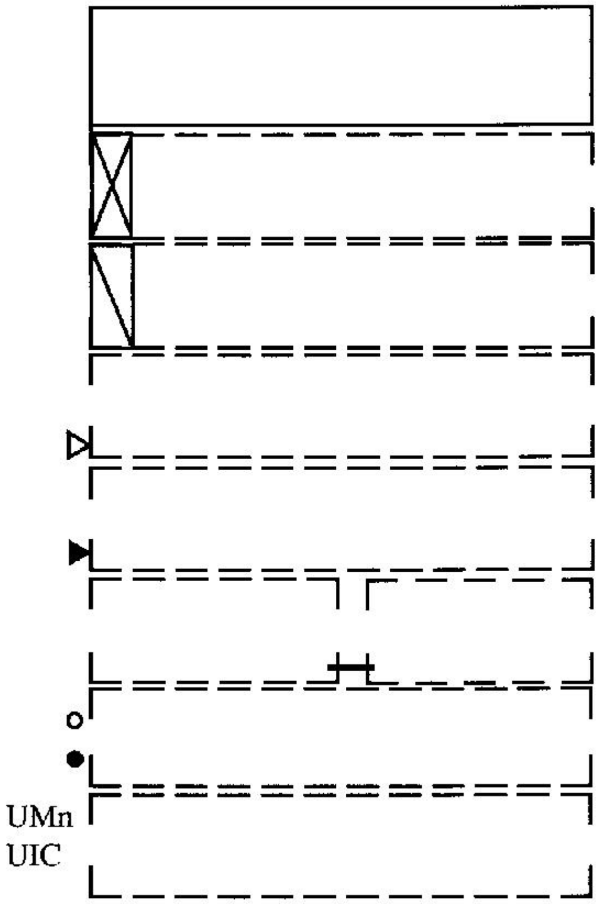


Vehicle on two bodies, each one on three coupled axles.
Example : Locomotive SBB Eem 6/6

Fig. 8.2 Examples of vehicle designations.

Leaflets are classified from the type of power supply.

For the symbolic representation, some simple symbols allow a quick understanding of the equipment.



Body

Complete driving cab.

Partial driving cab.

Automatic coupling.

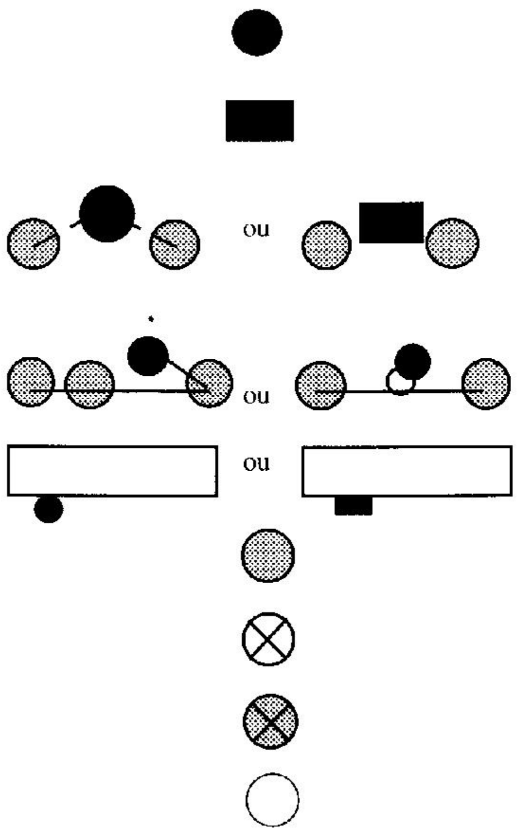
Automatic coupling with electrical connexions.

Permanent coupling, only separable in workshops.

Connecting – for energy
Cables – for control

MU until *n* units
UIC control line

Fig. 8.3 Symbols : bodies and connexions.



Transversal traction motor

Longitudinal traction motor

Monomotor bogie

Rod drive

Underfloor motor

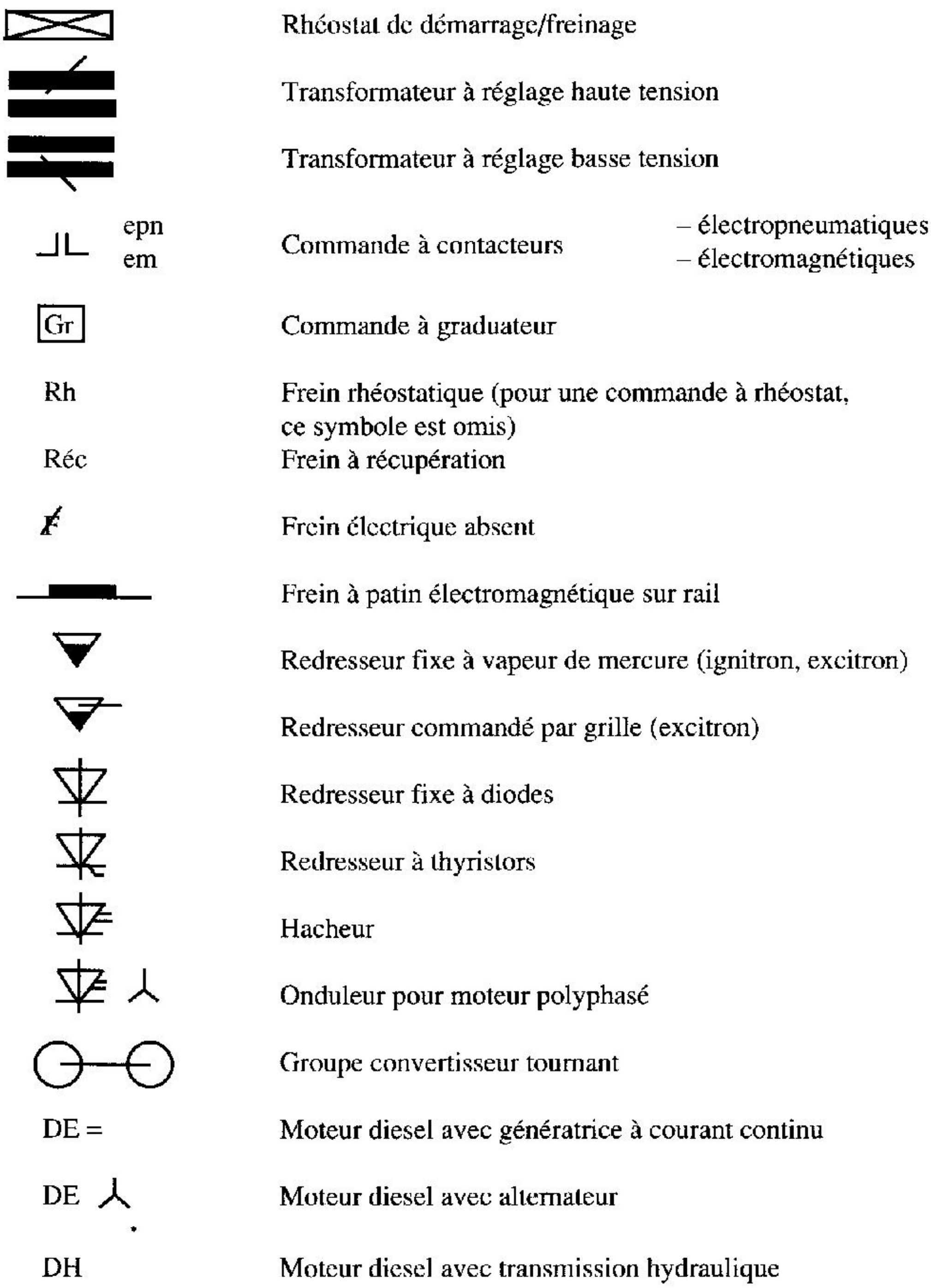
Adhesion drive

Rack drive

Combined rack- and adhesion drive

Carrying axle

Fig. 8.4 Symbols : motors and axles.



Symbole	Désignation	
	Rhéostat de démarrage/freinage	
	Transformateur à réglage haute tension	
	Transformateur à réglage basse tension	
epn em	Commande à contacteurs	– électropneumatiques – électromagnétiques
Gr	Commande à graduateur	
Rh	Frein rhéostatique (pour une commande à rhéostat, ce symbole est omis)	
Réc	Frein à récupération	
	Frein électrique absent	
	Frein à patin électromagnétique sur rail	
	Redresseur fixe à vapeur de mercure (ignitron, excitron)	
	Redresseur commandé par grille (excitron)	
	Redresseur fixe à diodes	
	Redresseur à thyristors	
	Hacheur	
	Onduleur pour moteur polyphasé	
	Groupe convertisseur tournant	
DE =	Moteur diesel avec génératrice à courant continu	
DE	Moteur diesel avec alternateur	
DH	Moteur diesel avec transmission hydraulique	

Fig. 8.5 Symbols : electric equipement.

pna	frein pneumatique à air comprimé	
pnv	frein pneumatique à vide	
hy	frein hydraulique	
epna	frein électropneumatique	
rub	frein à ruban	inépuisables
ress	frein à ressort	inépuisables
cli	frein à cliquet	inépuisables
(T)	frein électrique à courant de Foucault («Telma»)	

Fig. 8.6 Symbols : mechanical brakes.

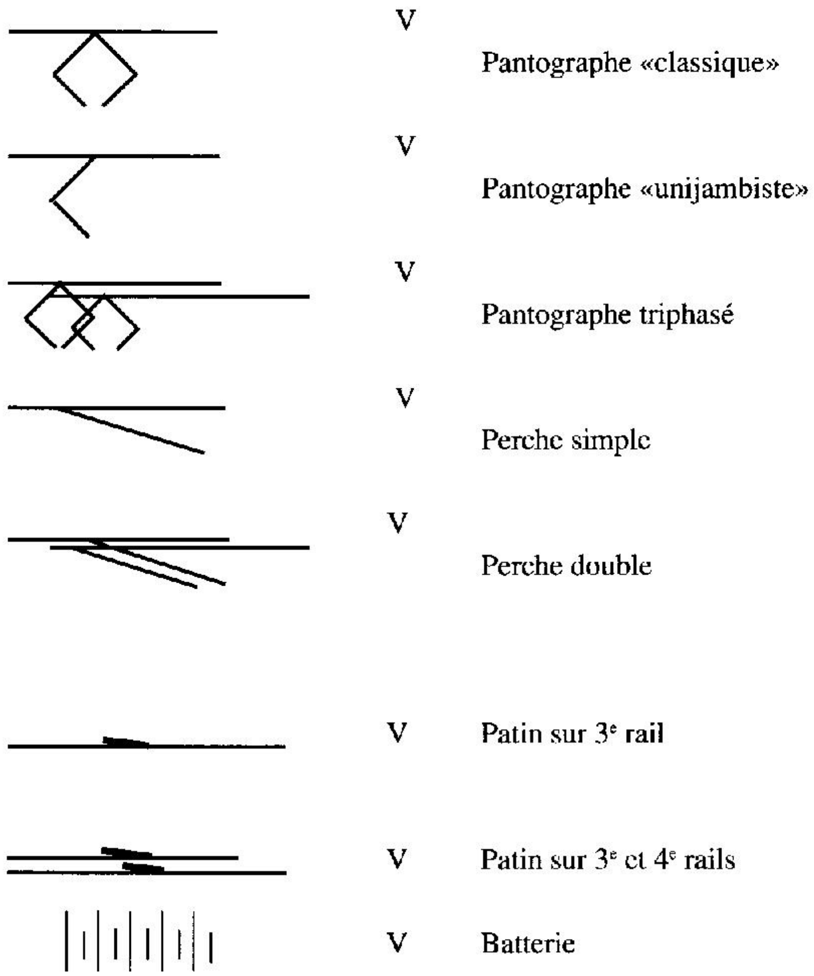


Fig. 8.7 Symbols : collection of current.

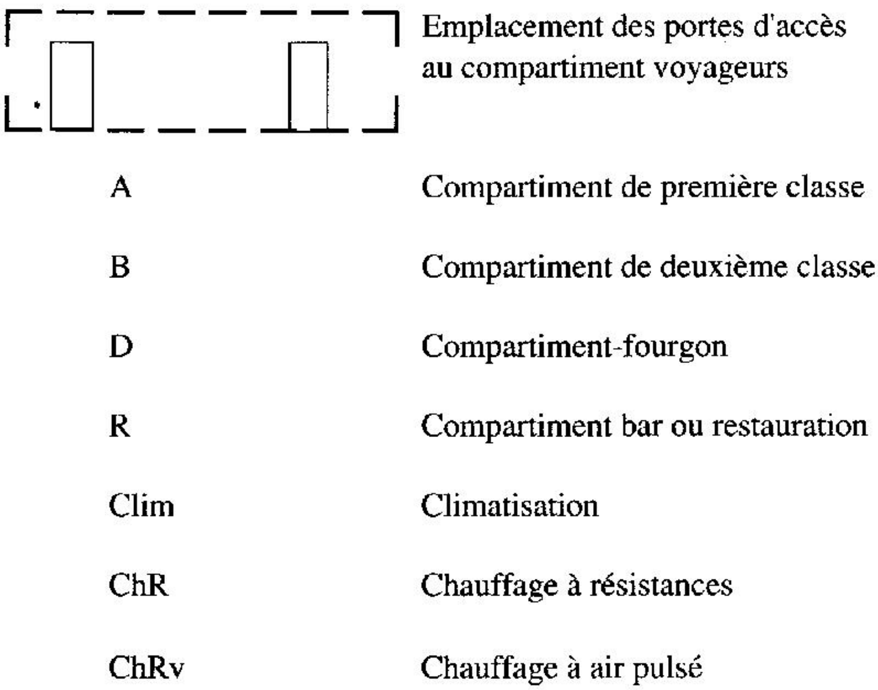


Fig. 8.8 Symbols railcars and EMUs.

9.1 Track technology

The track forms system from which four main components assume the necessary function for the final transport target: the rail, the sleepers, the ballast and the platform.

The rail is a steel bar in three parts; the rail trace is the upper face of the head, who permits the wheel rolling.

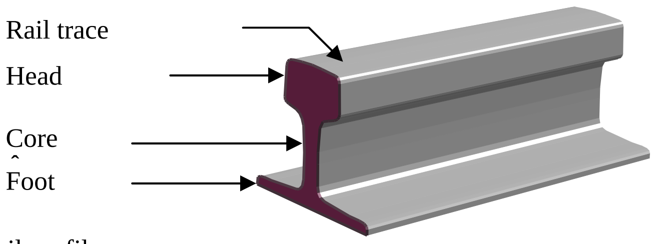


Fig. 9.2 Rail profil.

The sleepers not only guarantee the constant rail spacing, but also transmit at ballast the length rails constraints and their transversal, longitudinal or vertical forces. It exist a great number of rail fixing systems on the sleepers; the recent type fixings do not allow the longitudinal rail gliding.

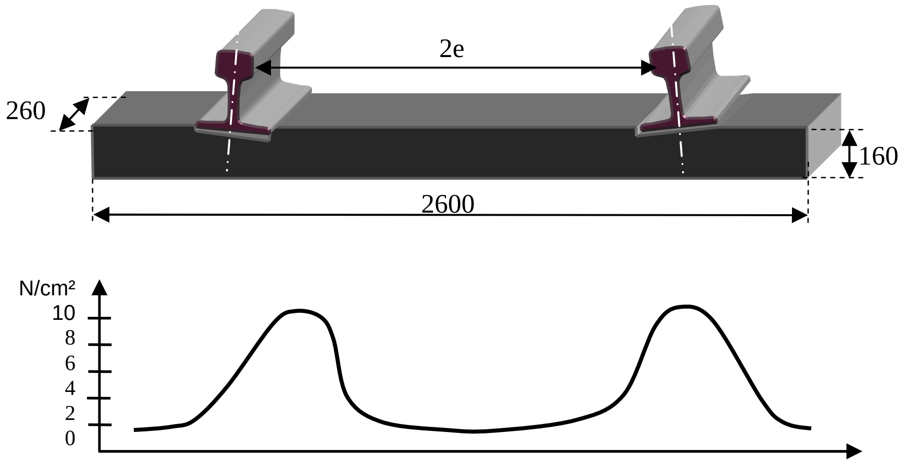


Fig. 9.6 Constraint distribution on a sleeper.

The platform fixes the trace and assures the flow of precipitations and the ballast hold the sleepers in all directions.

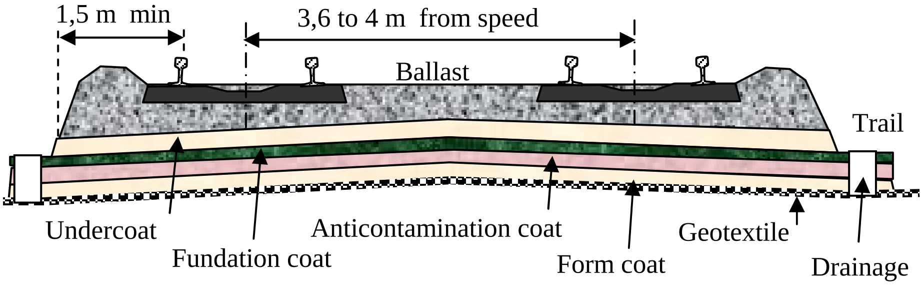


Fig. 9.10 Crossprofil of the track.

In curve, the track laying provides a superelevation in sort the composition of forces would be – if possible – perpendicular of the track plan by a circulation at the expected speed on this line. The superelevation is limited by the risk of switching inside the curve at the start of a train stopped in the curve. By insufficient superelevation, the force moment on the body risk to induce the switching outside the curve. The body pendulation allows reaching a force perpendicular to the floor for passengers, accepting a light insufficient superelevation for vehicle on le rail. This allows a higher speed without passengers comfort reduction, without approaching derailment limits described in this section and the next one.

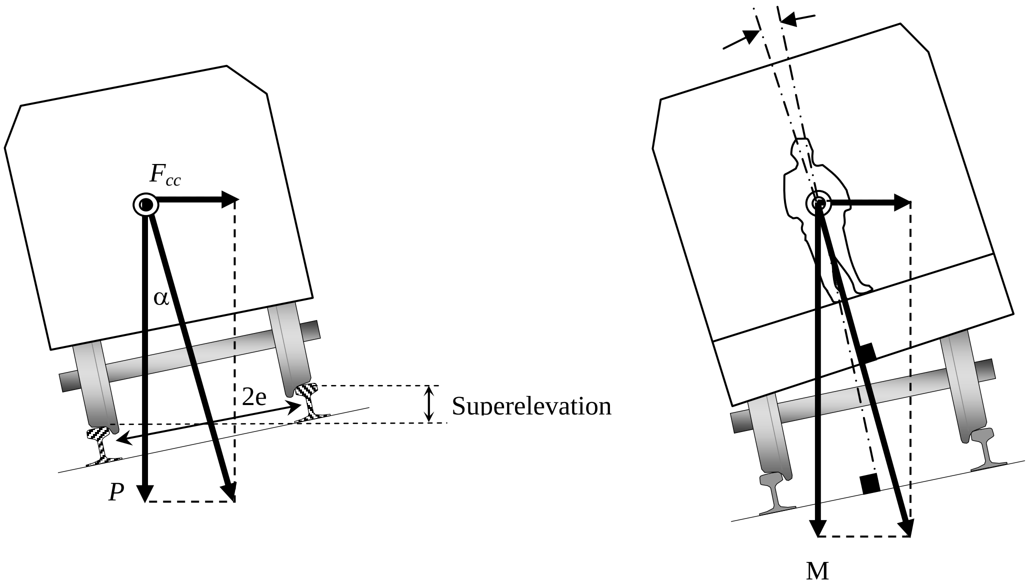


Fig. 9.16 Forces in curve and superelevation.

9.2 Circulations on rails

The dicon of the plan of wheel rolling band to the plan of rail trace guarantee the centering of the axle on the track in sort that the flange touch almost never the internal face of rail head. It assumes the function of a « automatic differential» which permit, in curve, the rolling of each wheel on a different diameter, corresponding to distinct way lengths.

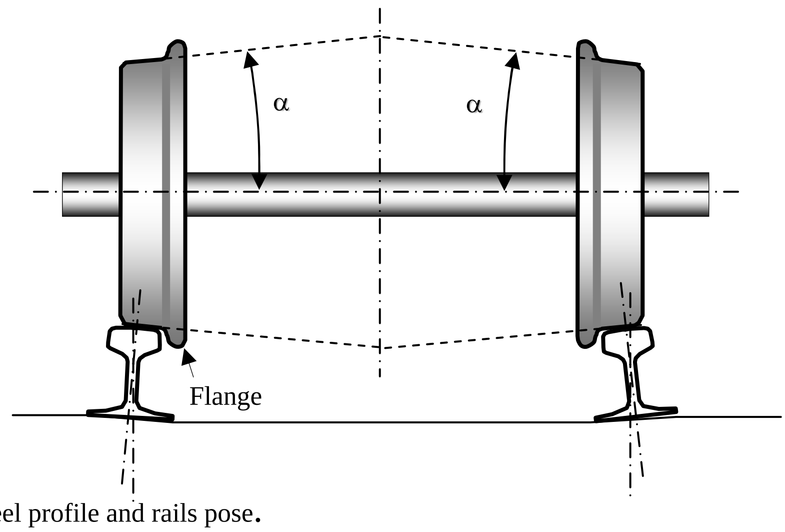


Fig. 9.24 Wheel profile and rails pose.

The speed on curve has to be limited to avoid that the force component induces the flange rise on the rail trace, ending on a derailment. In practice, the centrifugal force Y must not exceed 150 % of the weight Q.

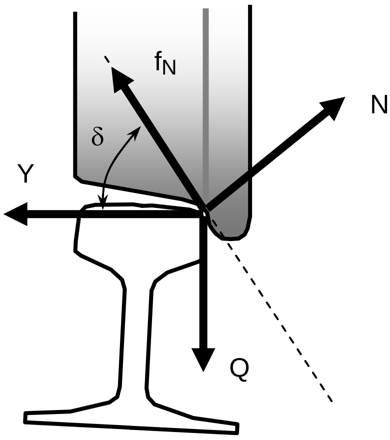


Fig. 9.30 Efforts at derailment.

In general, the axles are not aligned with the track curvature direction. Grouped on bogies, the axles form an angle with the radial direction, increasing the risk of flange rise on the head.

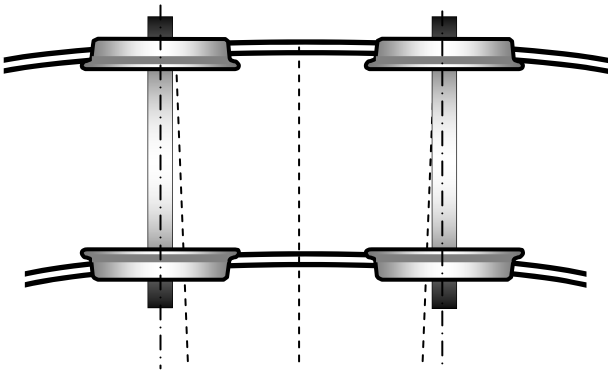


Fig. 9.31 Bogie in curve.

The Prud'homme limit has to be mention, exceeded if the centrifugal force Y cannot be contained by the sleeper pressure on the ballast.

The usury of wheel profiles compromises the good running of vehicles, on alignment and on curve and needs a regular reprofiling.

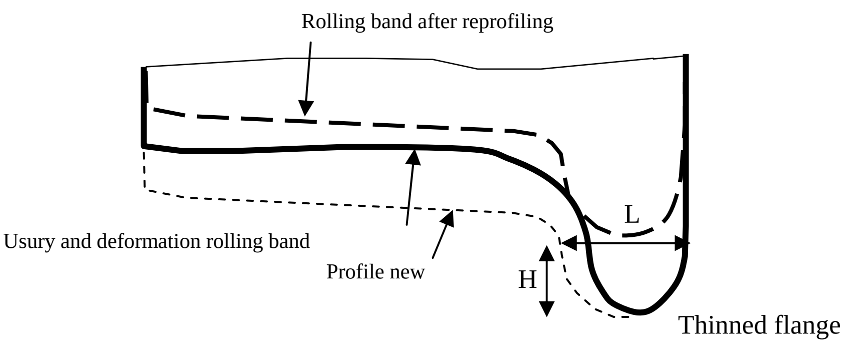


Figure 9.33 – Usury of wheel.

9.3 Switches

The principle of flange wheels, rolling on a pair of steel rails, induces the necessity of complex devices for route changes. The essential pieces are mobile blades, which guide the flanges, and the gaps necessary for the way, and are a missing for the other way. Passing the gap, the wheel « falls» and hits the next rail or the hearth's point.

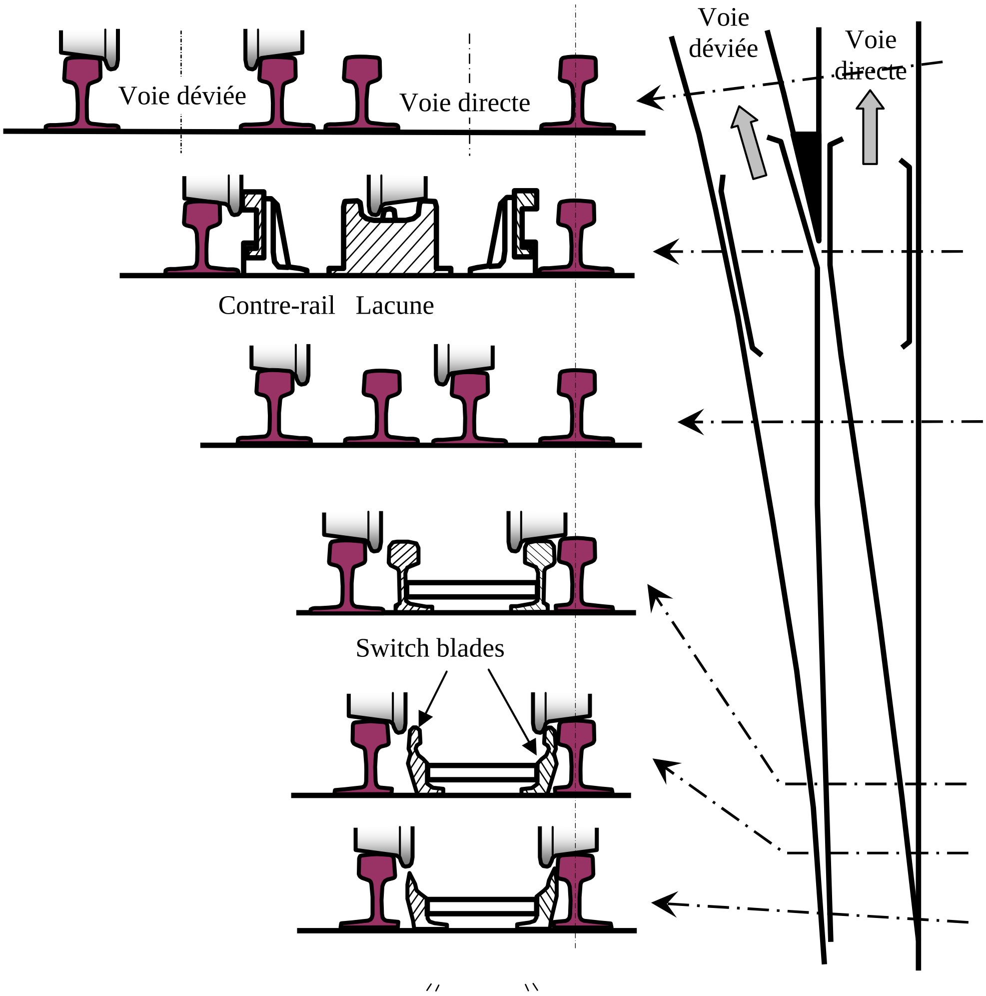


Fig. 9.37 Kinematics at switch passing.

9.4 Special tracks

As mentioned at section 5.9, the traction can be transmitted through a cogwheel on a rack. With one exception (Santos-Jundiai) the rack is installed high on track center to permit the passing of cogwheel above the rail trace at a switch.

9.5 Contactless tracks

They are very complicated systems of magnetic guiding and sustentation for « light», vehicles, incompatible with classical railway.

9.6 Gauge

The fixed obstacles along the track must let a free place greater than vehicle dimension, including a place for imprecisions of track installation and lateral movements in curves or due at vehicle suspensions.

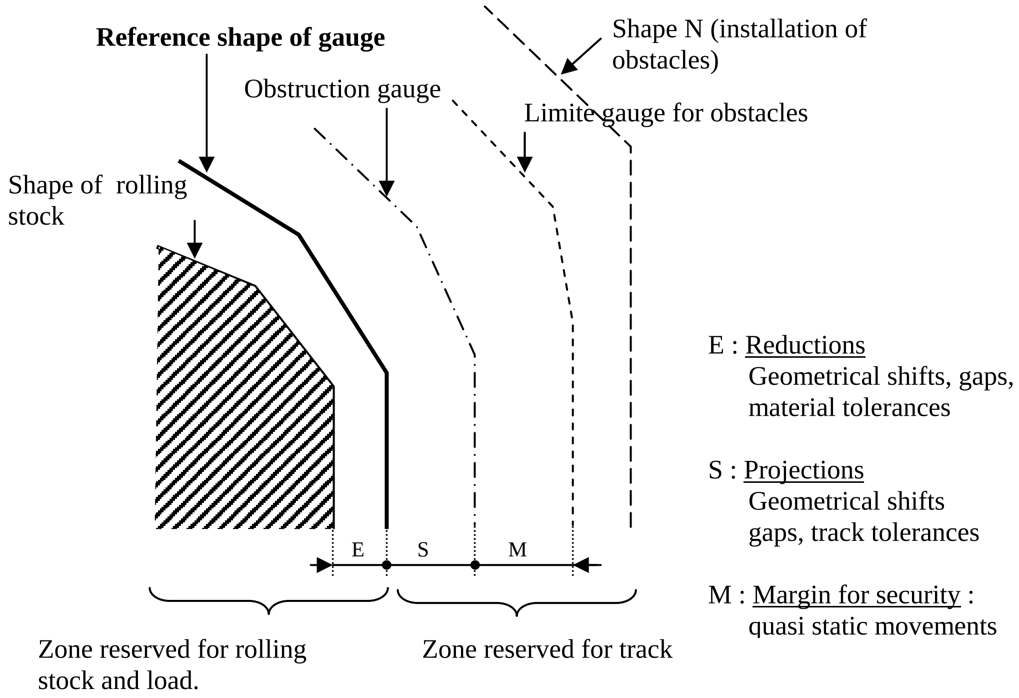


Fig. 9. 52 Marges de sécurité des gabarits

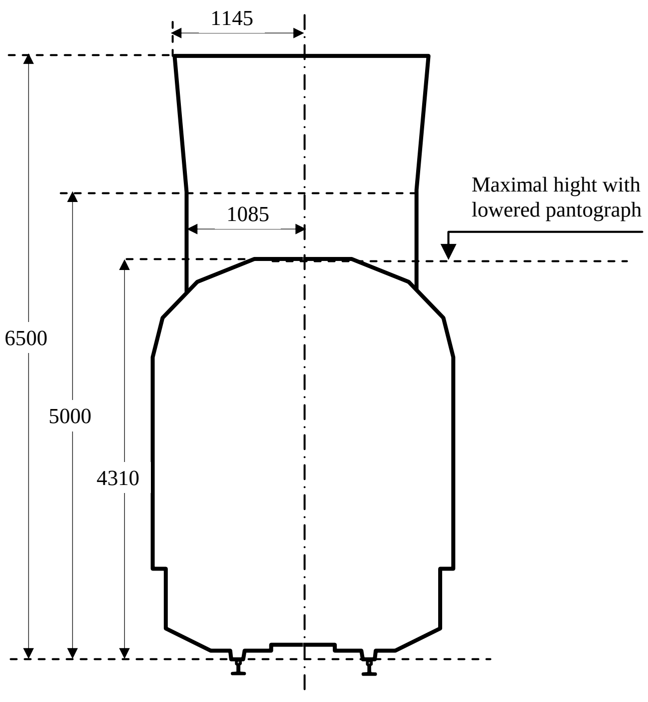


Fig. 9. 54 Example of gauge for electric vehicle (aerial line)

10.1 Dynamic Topology

The complete system is composed of a deformable circuit between the energy supply by the sub-station and the train. The sub-station supplies energy at a voltage level adapted at the use possibility for a traction engine, it receive it at other characteristics, adapted at transport, from production site.

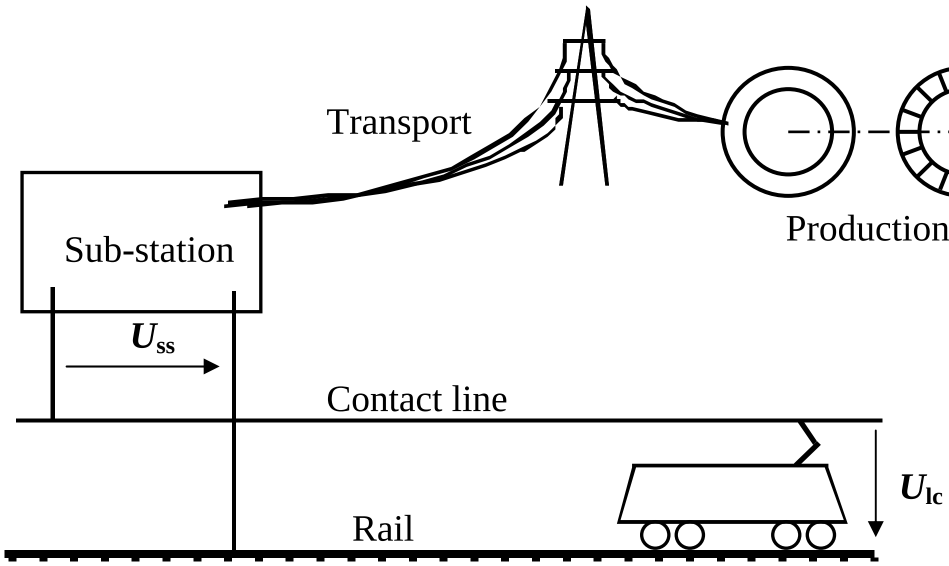


Fig. 10.3 Schematic disposition of electric traction.

10.2 Traction circuit constitution

The traction circuit is composed of two very different conductors:

1. The contact line isolated from supports, with a well known characteristics at construction.
2. The rails and surrounding field where current is divided on undetermined manner.

However, it is possible to draw a simplified schema considering all impedances.

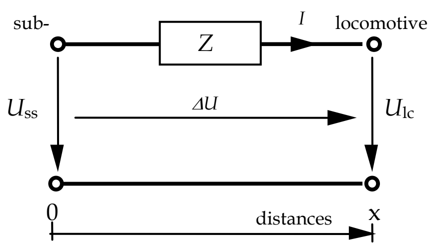


Fig 10.4 Traction circuit: simplified schema.

As impedance *Z*, for a specified type of construction, depends on distance, it is often spoken of linear impedance. Typical values of contact lines have been calculated for tracks with standard traffic; for ground conductor, mean values were chosen. Please note that the track construction needs careful dispositions in order to guarantee the electric continuity in sort of the main part of current passes through rails.

	Linear impedance [Ω/km]	
	Single track	Double track
1,5 kV=	0,07	0,05
3 kV=	0,08	0,06
15 kV 16,7 Hz	0,08 + *j* 0,13	0,05 + *j* 0,08
25 kV 50 Hz	0,13 + *j* 0,35	0,09 + *j* 0,21

Fig. 10.10 Linear impedances for typical lines.

The voltage effectively usable by the traction engine is one delivered by the sub-station, from which the voltage drop is subtracted. This voltage drop depends on the distance from the sub-station and from the intensity of the current asked by the traction engine. Not all lines are supplied by a single sub-station, but in particular indirect current, one section of length *d* can be supplied at both ends.

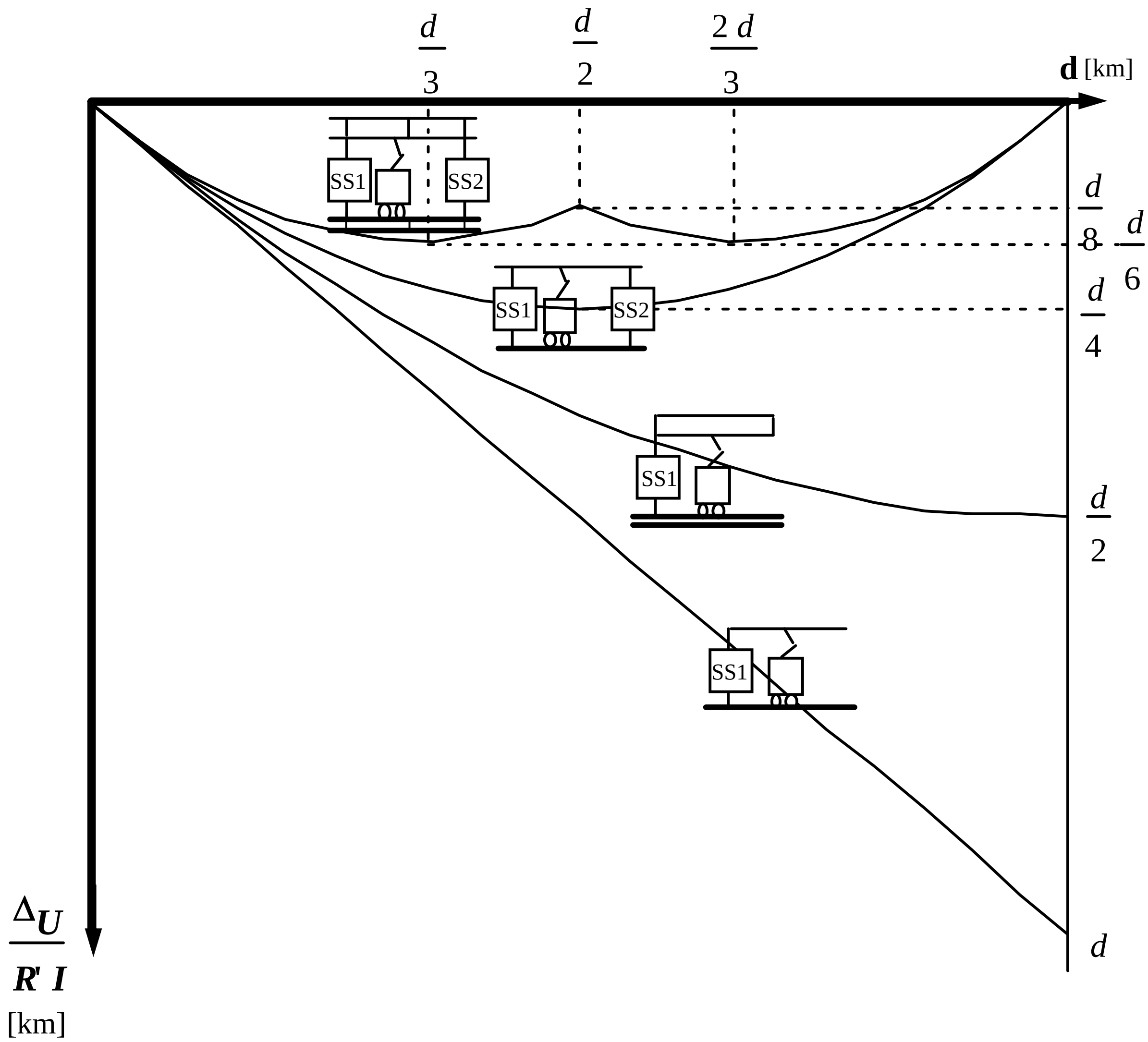


Fig. 10.17 Relatives tension drops on line.

10.2 Constitution

The sub-stations and the contact line are linked by contactors, to permit different structures of traction circuit. If the parallel coupling of direct-current sub-stations don't get problems, in single-phase, the parallel coupling is only possible if both sub-stations have exactly the same phase.

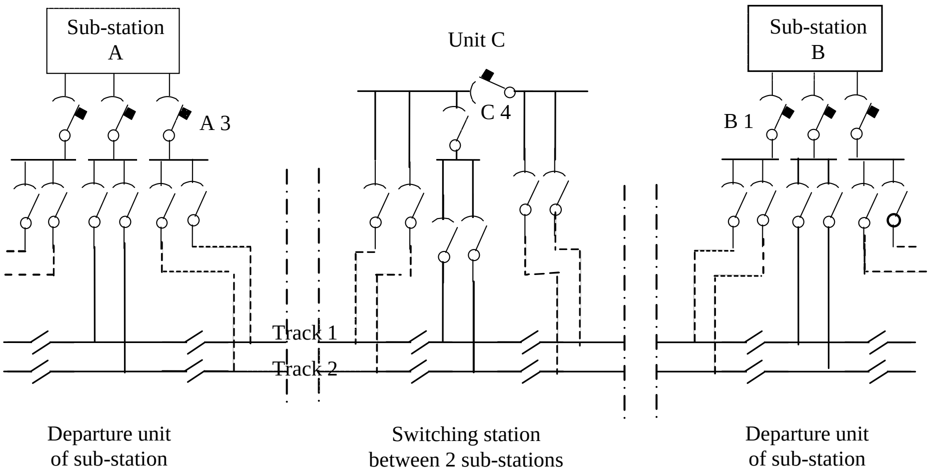


Fig. 10.46 Coupling of two sub-stations

To reduce the linear impedance in single-phase, a dual voltage in chosen in many times, with autotransformers in line.

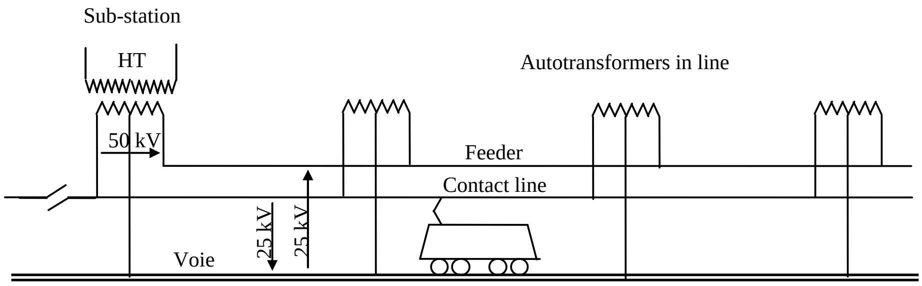


Figure 10.48 Double single-phase power supply.

	Distances between sub-stations [km]	Power per sub-station [MVA]
Direct current 1500 V	8 to 14	3 to 12
Single-phase 16,7 Hz 15 kV	30 to 60	10 to 30
Single-phase 50 Hz 25 kV	30 to 60	10 to 30
Single-phase 50 Hz 2 x 25 kV	40 to 90	30 to 60

Tableau 10.52 Intervals and powers of sub-stations depending of systems

The transformer defines the nominal power what furnish a sub-station, it can be overlade for a short time (for ex. 200%*P_n during 2 minutes). For direct-current sub-stations, the overload will be limited by the maximal current of the rectifier.

10.3 Power supply

The single-phase contact lines are supplied from the general three-phase grid (fig. 10.52a) through sub-stations three-phase – single-phase who step down voltage. Care is taken on the best load equilibrium of the three phases on the general grid by the sub-stations who follow each over on a line.

The direct-current contact lines are also supplied from the general three-phase grid (fig. 10.52c) through sub-stations transformer and three-phase rectifier. At the beginning of electric traction, it were found direct current power plant who supply directly the contact line.

The single-phase contact lines at special frequency can be supplied from a single-phase grid and single-phase power plants (fig. 10.52b) through sub-stations with single-phase transformers, or from the general three-phase grid (fig. 10.52d) through frequency converter sub-stations or par through a combination of both modes.

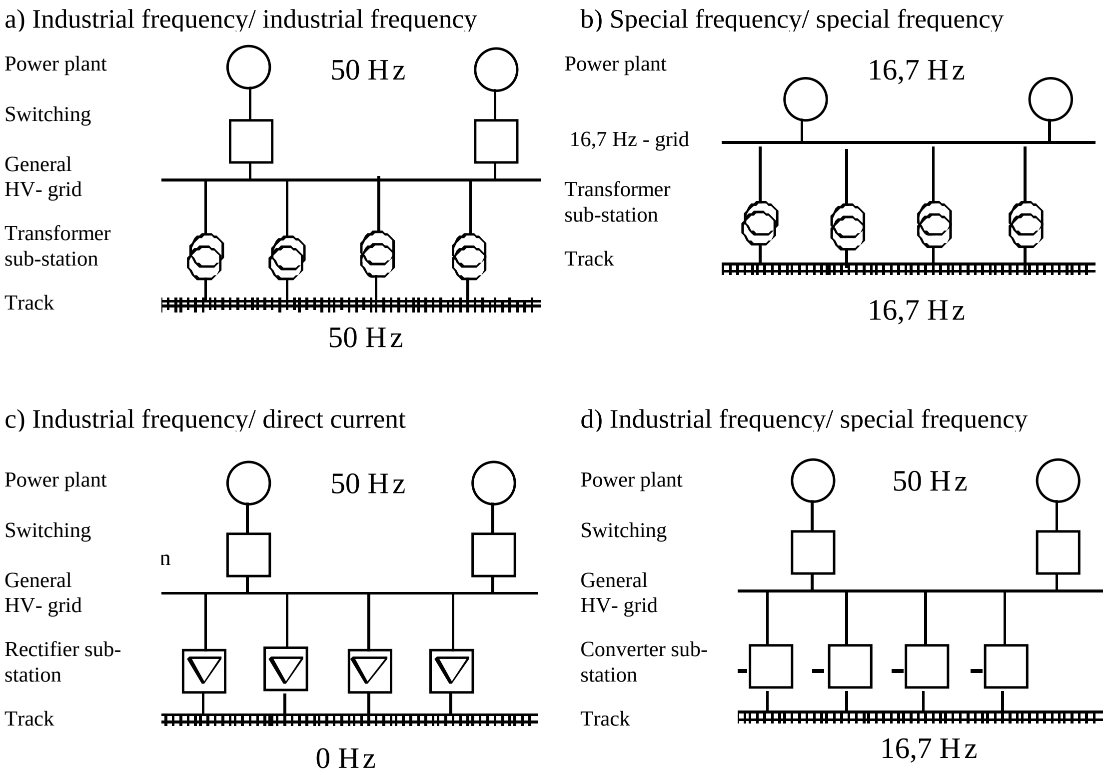


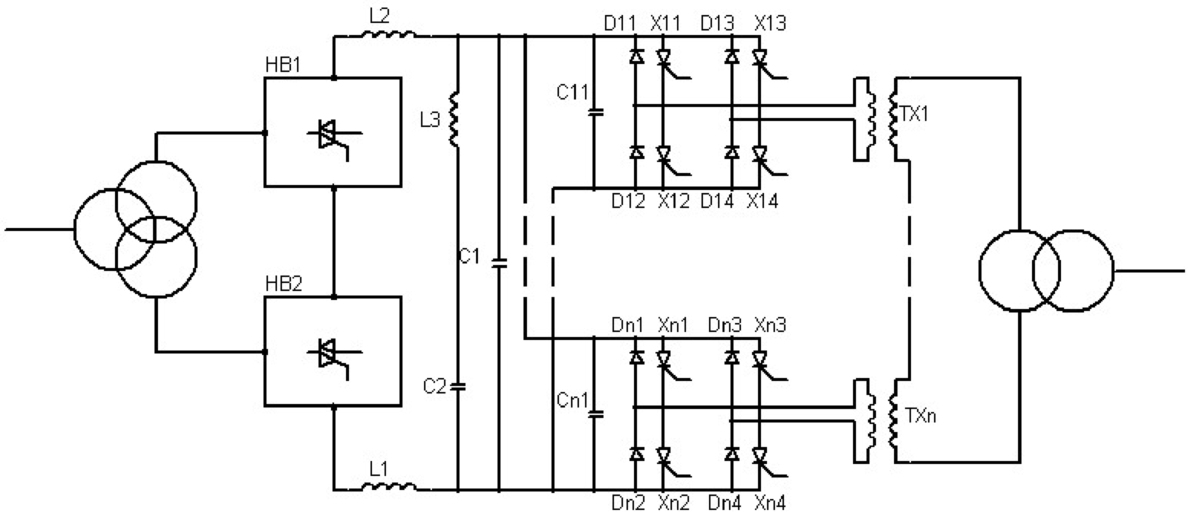
Fig. 10.53 Different power supply possibility.

For frequency conversion, rotating converters were first used: rigid for special frequency without own production, weak for ones with an own supply. Now, static frequency converters are used, with intermediate continuous voltage circuit (U-converter). So on three-phase side as on single-phase side, elementary converters are installed in cascade, in order to guarantee a low harmonic factor from chopper frequency. First implementations used GTO (CFF: Giubiasco) [122]. The recent realizations use IGCT (DB: Bremen) [123] who permitted less conduction losses, – 25 % , a reduction in a factor 5 to 6 of the gate-unit power and commutation time reduced in factor 6 to 8. These commutation times are similar as ones of IGBT, who have greater conduction losses. The structure of a IGCT is comparable at one of a IGBT of same range, this permit quantity gain in the productions costs.

These equipments are reversible.

Such equipments are also thought between three-phase 50 Hz and single-phase 50 Hz [147]. For a moderate buying cost supplement compared to simple transformers, the using costs are reduced:

- No penalties to pay at the energy supplier for consumption asymmetry.
- Harmonics absorbed through filters on the intermediate circuit.
- Reactive power furnished by the intermediate circuit.
- Voltage level is controlled at upper allowed value if sub-station supply power and at lower one if it absorb power.



Transformer 3-phase 50 Hz **Converters** **Intermediate circuit** **Converters in parallel** **Transformers at serie secondaries** **Transfo. 16.7 Hz**

Fig. 10.62 Static frequency converter.

For the direct-current lines power supply, rotating machines and mercury rectifiers are no more used today. In general, single-direction diode rectifiers are used.

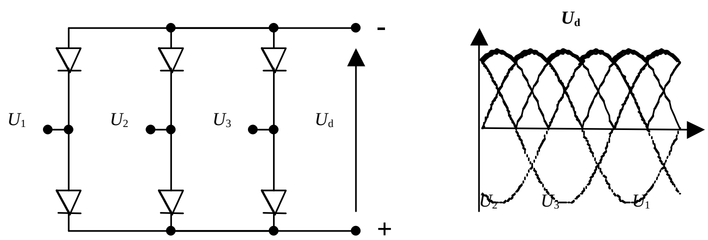


Fig.10.64 Three-phase rectifier.

In single-phase, we have seen than linear impedance is complex (fig. 10.10). This causes that the available voltage for the traction engine is lower than at sub-station output, but it is also shifted in phase (fig.10.69a). In place of reducing sub-station intervals, with great costs, capacitor rack can be implemented on line, in series with contact line (RhB, NSB, fig. 10.69b) or in parallel SNCF, fig. 10.69c). Not only the voltage at contact line is better, but also the reactive power, who is supplied by the sub-station is lower: the phase difference φ_{ss} between voltage U_{ss} at sub-station and the furnished current I is lower.

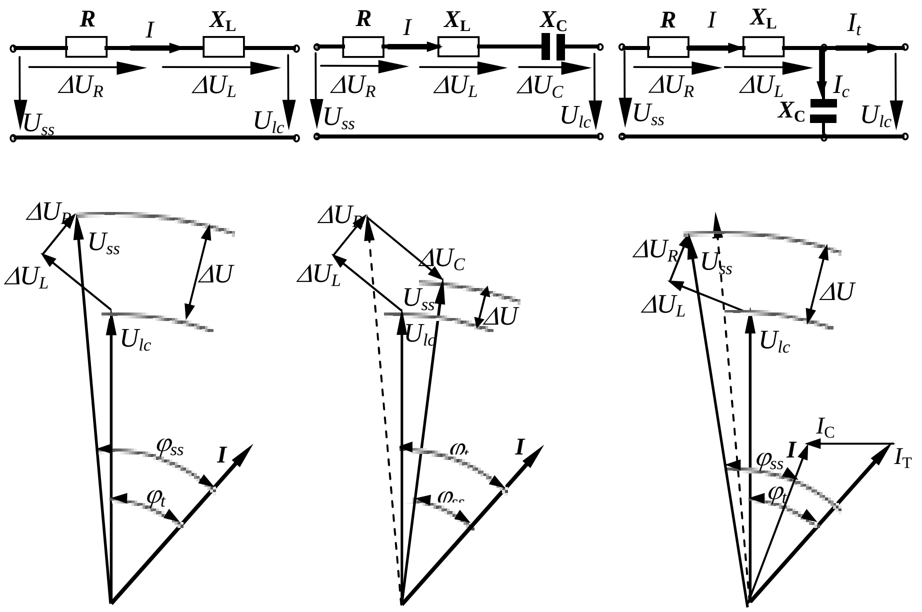


Fig. 10.69 Voltage drop compensation on single-phase by capacitor.

Better than using passive components who helps only on certain parts of lines for certain load cases, we use today static voltage compensators (SVC) who combine batteries of selfs et capacitors with semiconductors controlled by a software who survey in real time voltages and currents at contact line. The impedance value can be adapted at the real load condition at contact line.

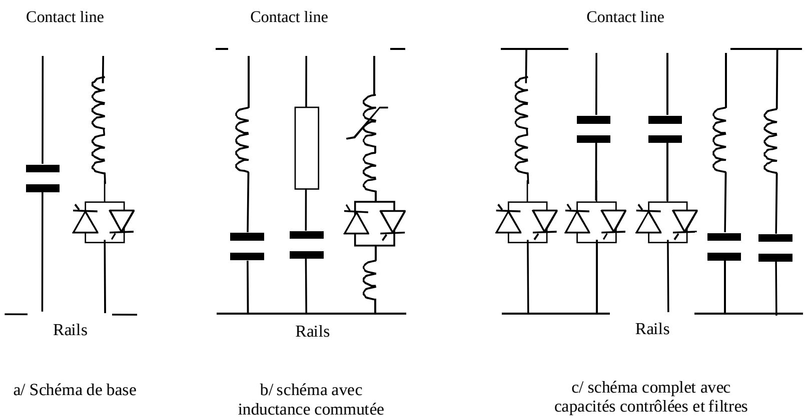


Fig. 10.71 Static voltage compensators for reactive power.

The direct-current sub-stations are considered as real voltage sources adjusted for U_0, with an internal resistance R_i and conceived for a nominal current I_{ssn}. They may be shortly overloaded.

$$U_{ss} = U_0 - R_i \cdot I_{ss} \qquad (10.75)$$

$$I_{ss2h} = 1{,}5 \cdot I_{ssn} \qquad I_{ss1min} = 3 \cdot I_{ssn} \qquad (10.76)$$

In single-phase, internal impedance has to be considered. They may be shortly overloaded.

$$I_{ss15min} = 1{,}5 \cdot I_{ssn} \qquad I_{ss5min} = 2 \cdot I_{ssn} \qquad (10.77)$$

10.5 The influence of motor vehicle and its master.

The effet of the current asked by the traction engine on the voltage at contact line was seen at section 10.2. According to UIC instructions, variations are admitted on contact line between –30 % and +20 % around nominal voltage.

In modern vehicles controlled by computers, these instructions are integrated in the program to prevent any current request if the voltage is at minimal value and any current injection when it is at maximal value. Around the nominal value the maximal power is allowed and the power requested by the driver is applied on equipment.

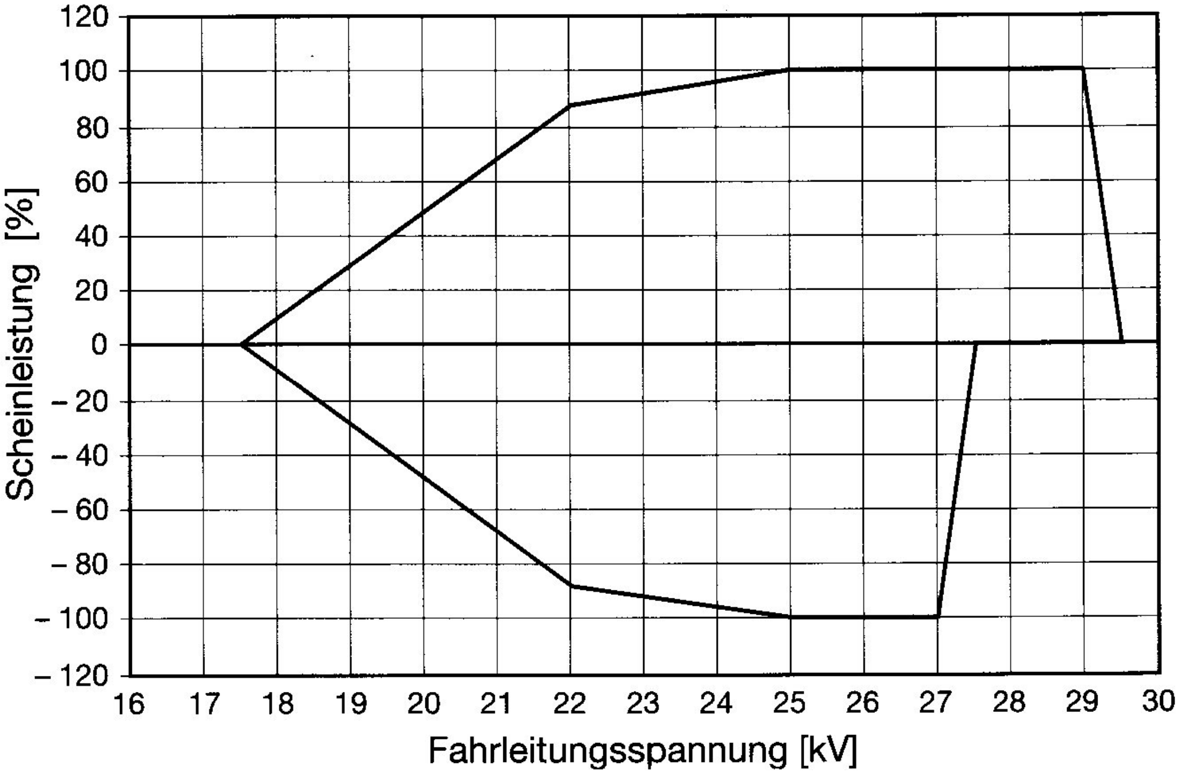


Fig. 10.83 Limitation of power in function of the voltage at contact line, example at 25 kV.

The figure 10.83 presents an example, this is only a principle: the form is established in function of the network features where the engine has to circulate. The limitation has to be applied progressively: function without discontinuity. For a direct current line, the principle is the same. It is sure to have sufficient power for auxiliaries (in particular brake devices, see chap. 6) unless the voltage has totally disappeared.

For a single phase line, it must be acted on the power factor to remain inner the limits. Around the nominal value, a factor of 1 is chosen, or a reactive power of 0 %. This can only be obtained with modern pulsation inverters on the network side, where the power factor is adjustable.

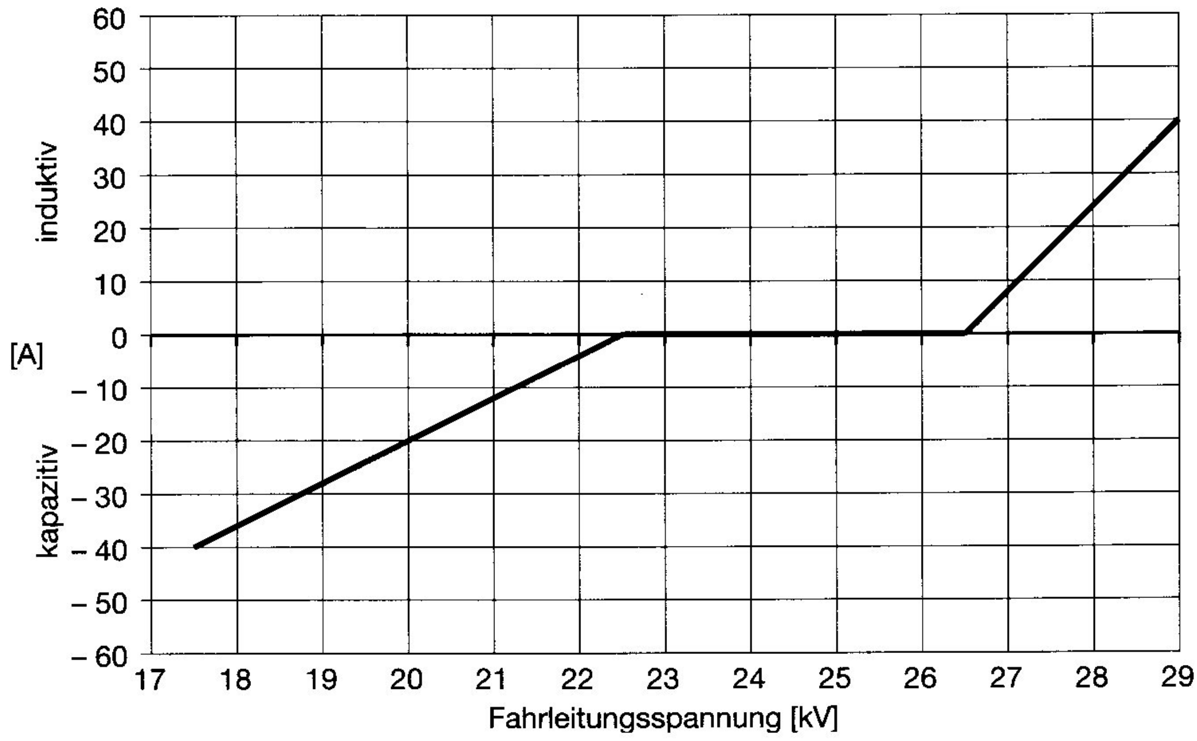


Fig 10.84 Imposition of reactive power in function of the voltage at contact line, example at 25 kV.

11.1 General

The electric energy supply on a railway line needs two conductors on a single phase[1] or direct current. (sect. 9.6) On of them is constituted by the rails; the second, isolated from rails can be :
- « aerial », above the vehicle ;
- ground fixed, lateral or on track center (not shown).

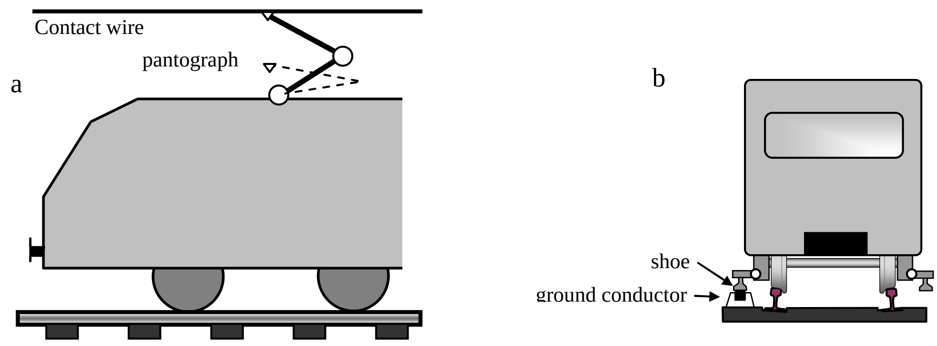


Fig. 11.1 Aerial and lateral current catch.

11.2 Dynamics

The aerial line is formed by a copper-wire, strained between isolators carried by masts.

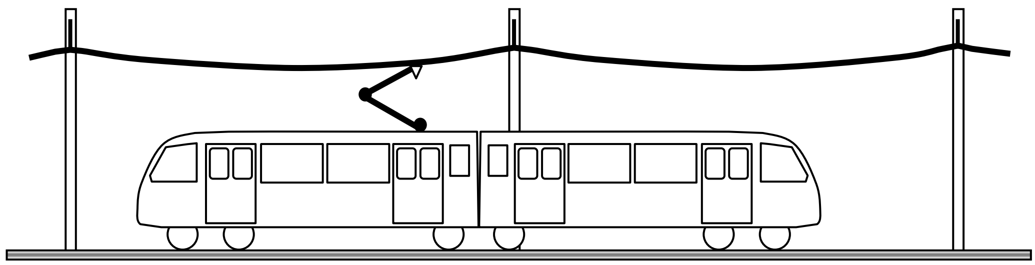


Fig. 11.3 Aerial contact line

At more than a certain speed, 60 km/h approximately, the capture quality needs a wire height above rail as regular as possible. This goes to eliminate the natural arrow of chain. Three solutions are possible:
- multiply the number of supports in order that the wire strength permit to neglect the arrow between supports. Solution incompatible from economical sight, and also the aesthetical one.
- increase the wire section until the wire strength permit to neglect the arrow between supports. In some cases – tunnels as example – this solution is used and called « rigid wire ».
- introduce intermediate supports, called « pendulum », between the contact wire and a carrier cable fixed on mast by isolators. This association is largely used and is called « catenary suspension » shown on fig 12.4.

[1] Three conductors are necessary for a three-phase power supply, as in Italy until sixties.

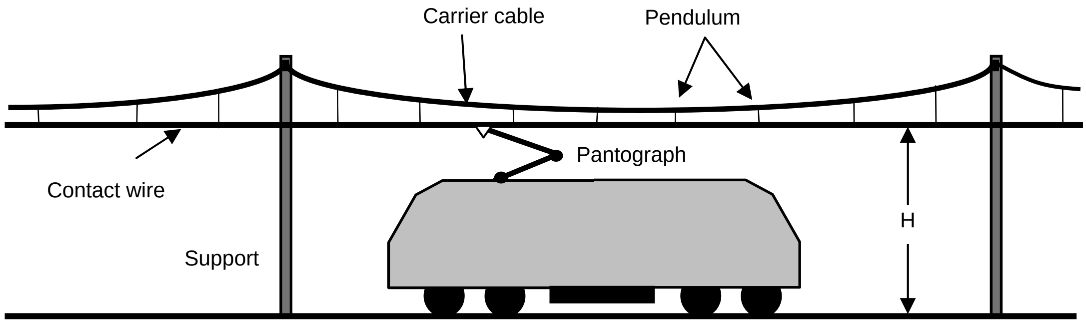


Fig. 11.4 Principle schema of a contact line with catenary suspension.

11.3 Pair: contact line – pantograph

From the good adequacy between dynamics properties of pantograph and contact wire depend the good current capture and the life cycle of the contact wire and contact shoe. The pantograph has to press with sufficient force to get a permanent contact to the wire, without cause a too big rising, with the risk to lose contact after the next fixation point.

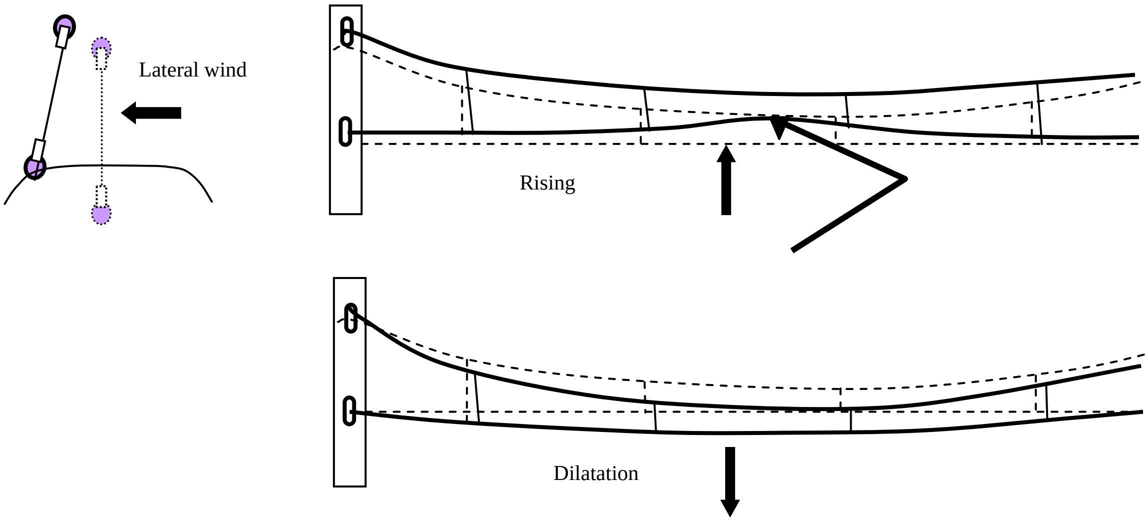


Fig. 11.5 Factors influencing the dynamic behavior of the contact line.

11.4 Technology

The circular section of the contact wire has two grooves for suspension claws (fig 11.9). From the voltage supply and the requested power, the wire section varies between 107 mm² and 150 mm². Section can be cylindrical or receive a flat at its bottom to increase the contact surface between it and the shoe.

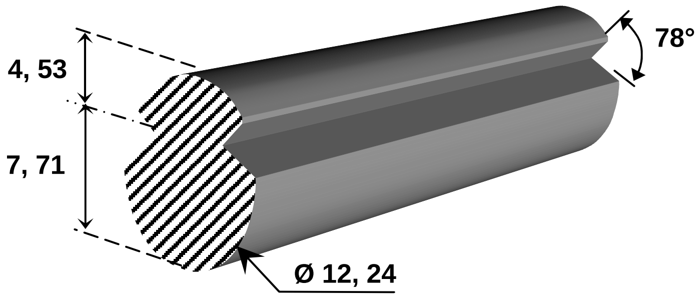


Fig. 11.9 Example of contact wire

The carrier cable has to hold the mechanical strain, it is fixed at supports by isolators. To reduce the electric resistance of the line, the contact wire and the carrier cable are connected in parallel, regularly by copper shunts, or by each pendulum, called *connecting pendulum*. The catenary is specified by its « equivalent copper » section noted in mm². The different electrification systems use specific construction modes, depending from the transported current intensity.

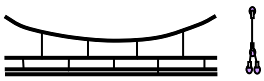
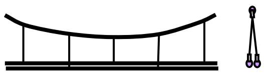
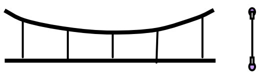
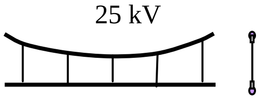
Contact line	Carrier	Contact wire	Equivalent copper section	Weight on linear meter
« tramway » 		Hard copper 107 mm²	107 mm²	1,52 kg
1500 V compound 	Principal : bronze - Sn 116 mm² Auxiliaire : 143 mm²	Hard copper 2 × 150 mm²	480 mm²	5,309 kg
3000 V simple 	Copper 120 mm²	Hard copper 2 × 100 mm²	320 mm²	2,85 kg
15 kV 	Steel-copper 92 mm²	Copper 1 × 107 mm²	189 mm²	1,85 kg
25 kV 	Al + steel 36 mm²	copper – Mg (or Sn) 1 × 150 mm²	147 mm²	1,334 kg

Tableau 11.12 – Main characteristics of some catenary types.

In plan view, the contact line installation needs a zig-zag from the center of track, to vary during the time the contact point on the contact shoe. A constant point would lead the sawing of the shoe.

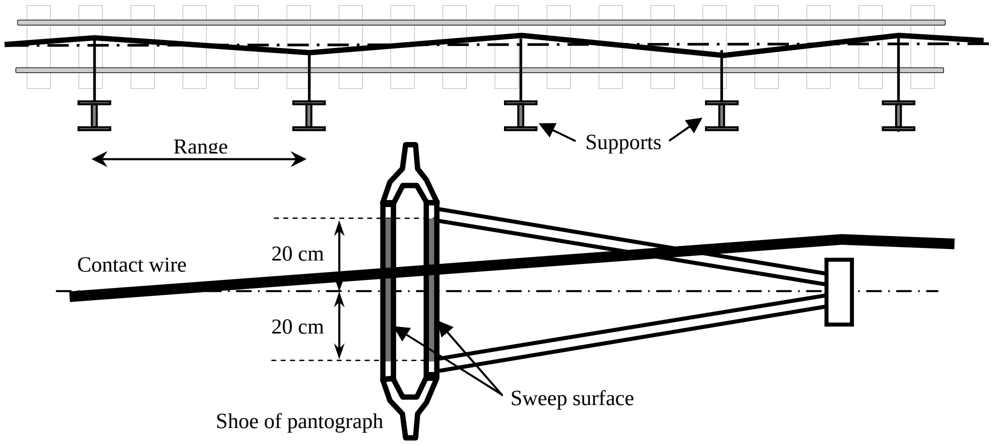
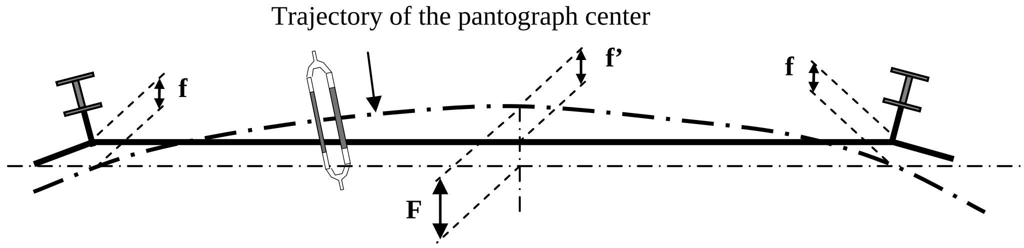


Fig. 11.14 Periodical misalignement on a right line.

In curves, the supports spacing must be compatible with the shoe width, including the possible transversal movements.



F : curve arrow in the middle of range = $a^2/8R$
f : misalignment at support
f' : misalignment in the middle of range

Fig.11.15 Curve misalignment

11.5 Current catching devices

Today, the current catching is done by « lights » pantographs.

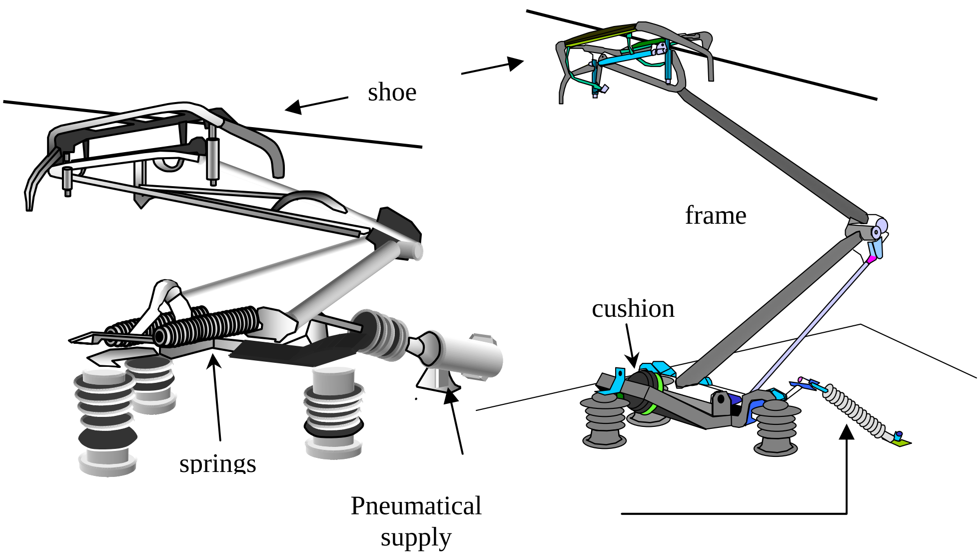


Fig. 11.28 – Two examples of pantographs

12.1 Security installations

12.1.1 Motivations

At the moment when more than one single train rolled on a network, it was necessary to define a method to avoid route conflicts between trains and to reduce the accident risk. First step was realized with visual signals, giving information at drivers if they can continue their route or not. This imposes a strict respect of signal and dispositions by the train personals. This ask also a strict choice of signal images – closed or open – by the ground personals who have to know if a way is free or not: it's the principle of *cantonment*. Signals had to present an image without ambiguity. They were first realized with mobile elements, then with colored lights.

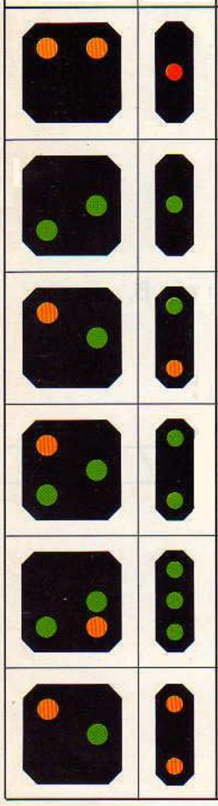
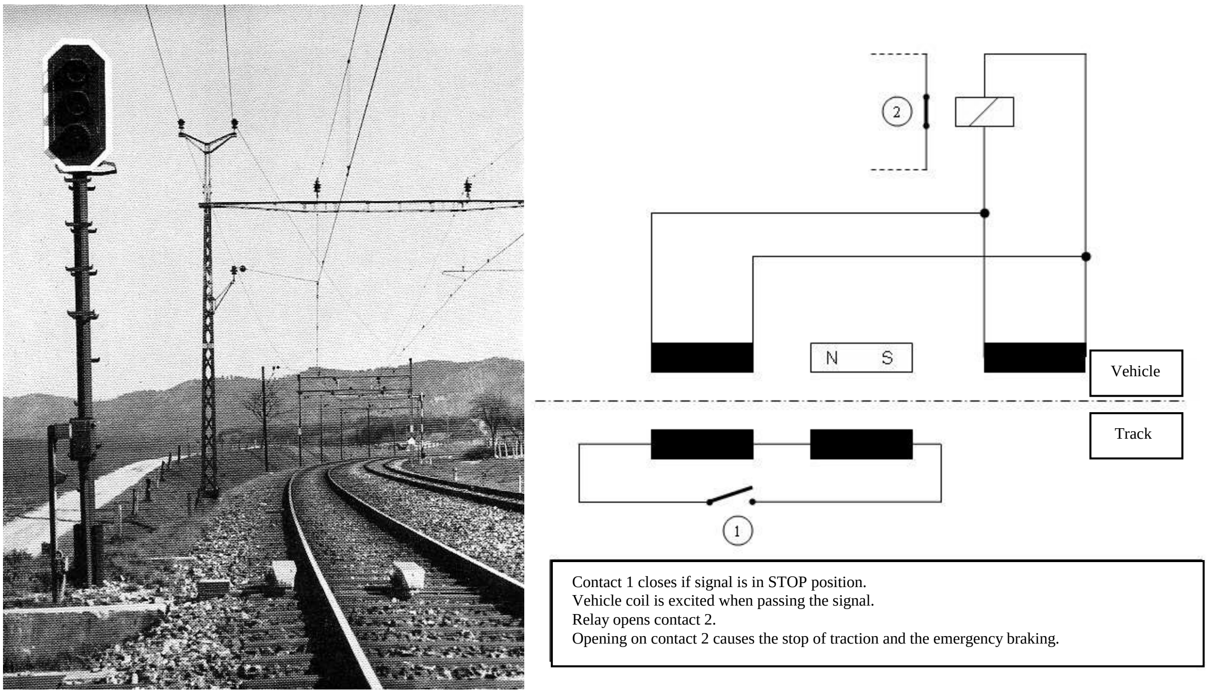


Image of signal avanced	Image of signal main	Image	Signification:
		–	Stop before main signal
		1	Way at the maximal speed mentioned on the timetable.
		2	Way at 40 km/h, if the timetable don't mention a lower speed.
		3	Way at 65 km/h (R-trains) or 60 km/h (other trains). If the timetable mention a speed in a circle or a square, this last is available.
		5	Way at 95 km/h (R-trains) or 90 km/h (other trains).
		6	Way at 40 km/h: – From the next switch. – For the next track section. Next signal will be a stop.

Fig. 12.1 – Example of light signals: Switzerland about 1970.

12.1.2 Base developments

Accidents due to human failures had brought a second step: a floor device coupled with a signal give an emergency stop order to the train if it passes a closed signal after an error of the driver: the tractive effort is stopped and the main pipe of the brake is opened, causes a braking. To avoid errors of the ground personals, a system prevents the train access on a track section where another train is yet on the way: it is called *block system*. Most of railways are on this second step, with various sophistication levels. Principles are quite the same on all national networks, but are incompatibles between them, for historical reasons.



A Device at the track. **B** Functional principle.

Fig. 12.2 – Example of a supervision device for signal passing: *Signum*.

The systems in different networks are not totally safe: for example, the distance between signal and dangerous point is sometimes shorter than the emergency braking distance and do not avoid collision if the *incorrect* train runs at maximal allowed speed. Such systems can be classified in two categories: contact devices and induction devices. The increase of speeds induces the needs of advanced signals giving information at the driver if the next signal is closed or not; the sight distance became shorter than braking distance. In some cases, two steps of advanced signals were built. For high speed, trains were equipped with repetition of signals on driver's desk, in order to give enough time to read surely the signal.

12.1.3 Recent developments

The traffic growth and the gaps in different systems induced a third step at the end of the XXth century: an exchange of coded messages takes place at some points between track and train. The message is defined by image of the protection signal and the local topology. From received information: allowed speed at a defined distance, the computer calculates the limit profile for stop or deceleration, including the train parameters memorized at the beginning of the journey. This system allows also the supervision of the maximal speed. At the main signal, a message is sent to the board computer when the signals opens, giving the new allowed speed. In case of profile overtaking, the computers order an emergency braking. It is guaranteed that the train stops – by the driver or the computer – before the closed signal or will not arrived too fast on a section limited in speed. In different countries were built different systems with different technical solution not compatibles between them.

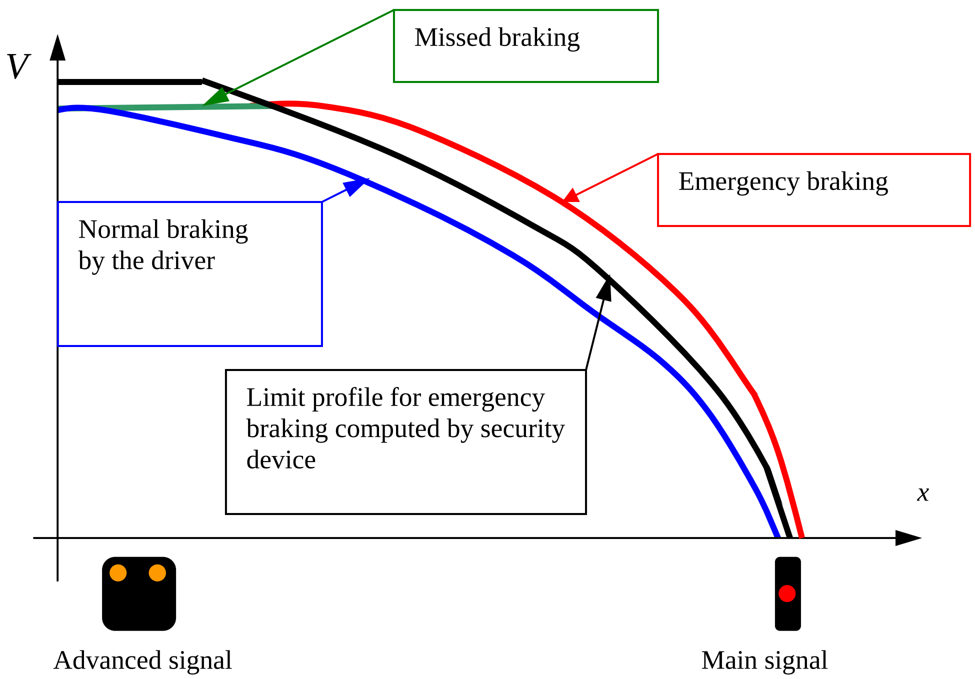


Fig. 12.3 – Real- and computed speed profiles.

A fourth step is on the way: an European standardization of ground-train transmission (wave type and dialogue protocol) with a larger function of speed monitoring, including the option of full automatic drive (ETCS : *European Train Control System*). At redaction time, such lines are in service, for passenger- freight- or mixed traffic. With such a system, the protected sections are not absolutely connected with the ground, but could be gliding defined by the preceding train: this system is called *mobile cantonment*. In this case, the ground signal can be avoided. The availability of ground-train dialog has to be guaranteed full time, the train position have to be known exactly so by the mobile computer than by the traffic control. The speed sensor on the axle axis give a sufficient precise measure for speed control but not for positioning, were accumulation of little errors could induce a malfunction. Satellite positioning will be used (GPS, Galileo) or at least sufficient points to reset the exact position on the embedded computer.

12.1.4 Interoperability

The will to operate locomotives and trains on diverse railway networks induce the installation of many security devices under the floor. It's difficult to find enough space for all and one unused must not disturb other embedded or ground devices.

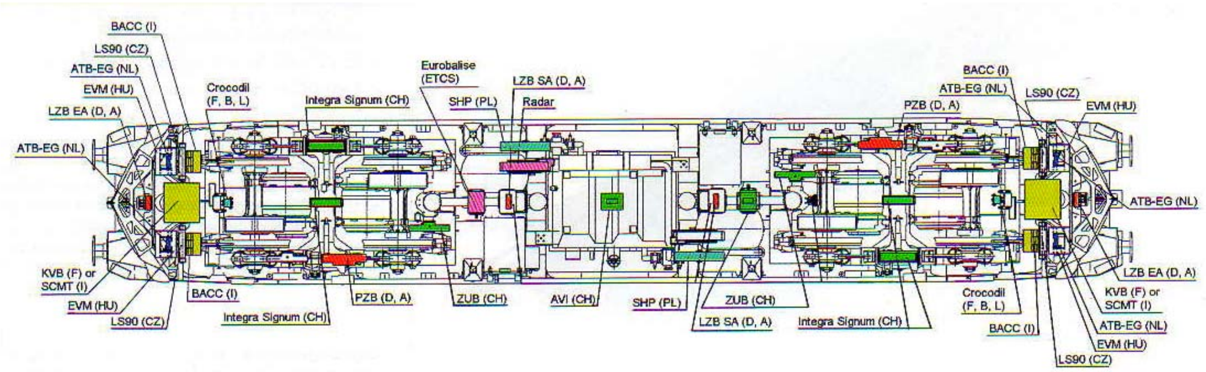


Fig. 12.4 – Security devices under a four-axle locomotive.