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.

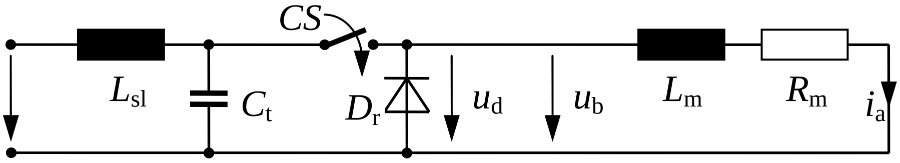

Fig. 4.77 Principle of chopper.

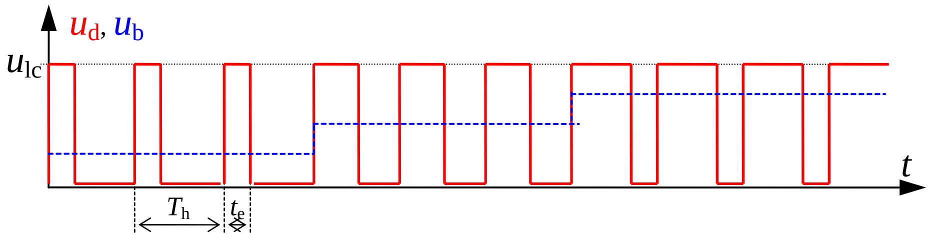

Fig 4.78 Instant voltage u_d and mean voltage u_b at chopper output.

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

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.

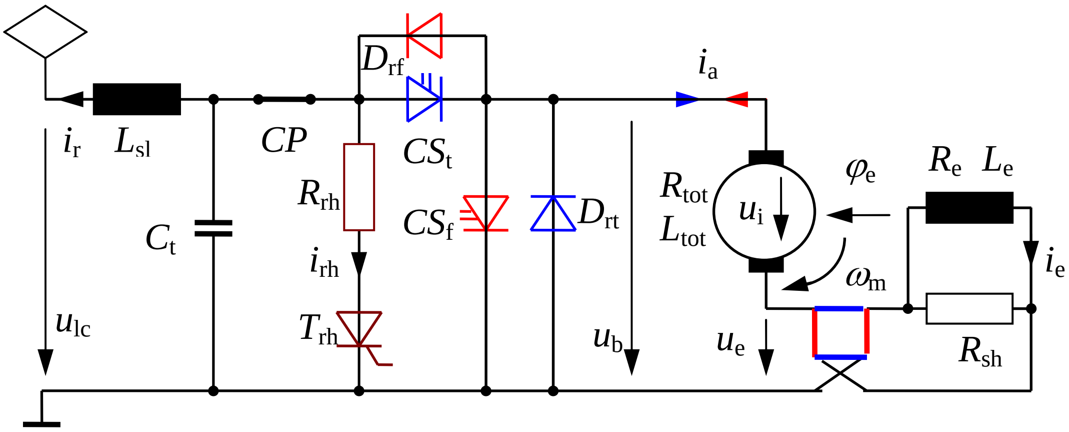

Fig. 4.76 DC-motor and chopper: traction.
Fig. 4.82 DC-motor and chopper: regenerative braking with series excitation.
Fig. 4.88A DC-motor and chopper: rheostatic braking with series excitation.

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}.

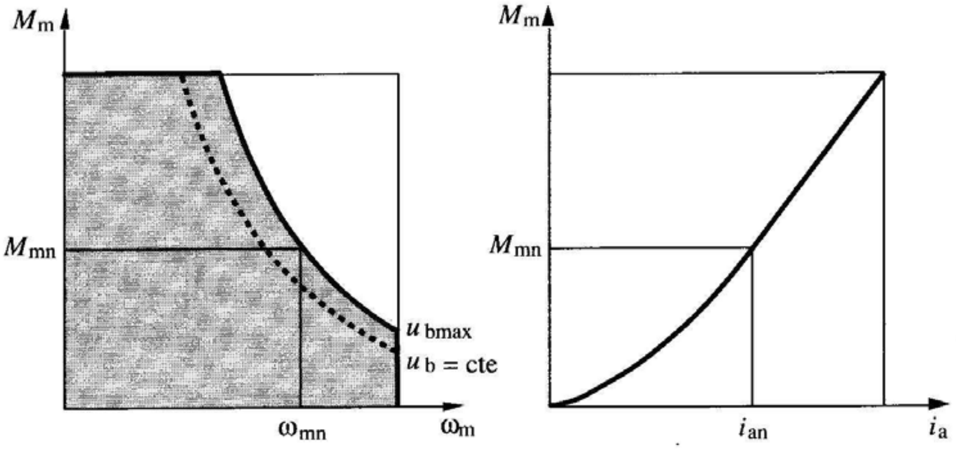

Fig. 4.79 DC-motor and chopper: traction characteristics.

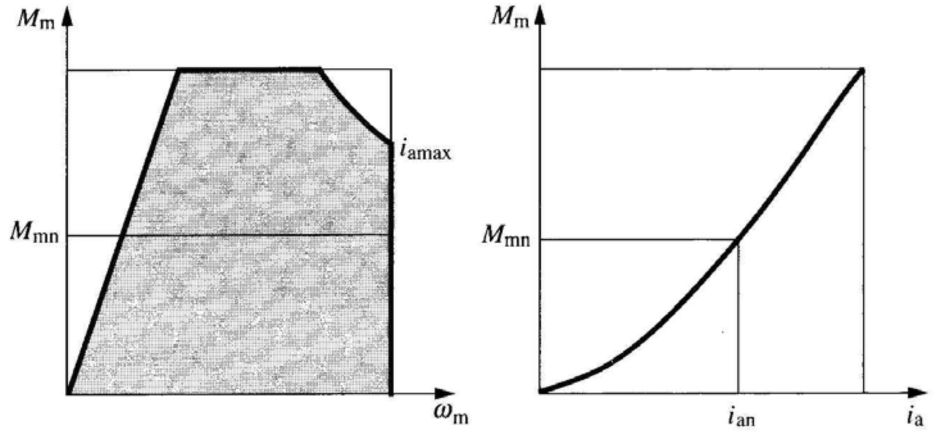

Fig. 4.85 DC-motor and chopper: regenerative braking characteristics with series excitation.

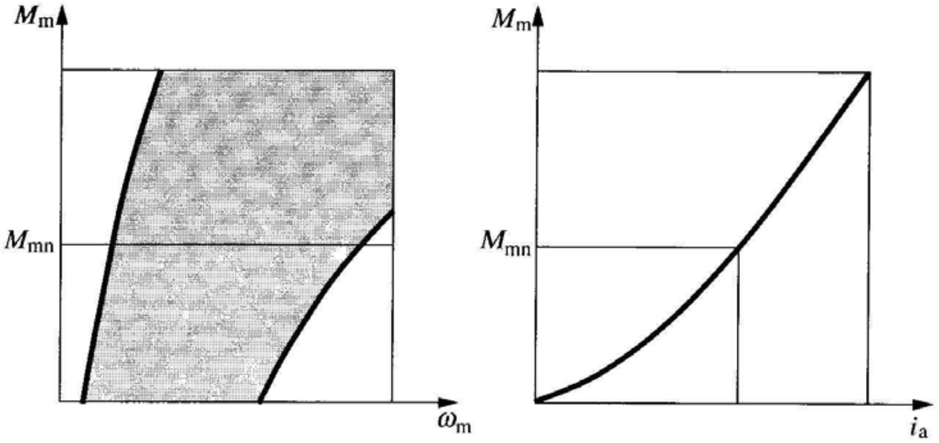

Fig. 4.90A DC-motor and chopper: rheostatic braking characteristics with series excitation.

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.

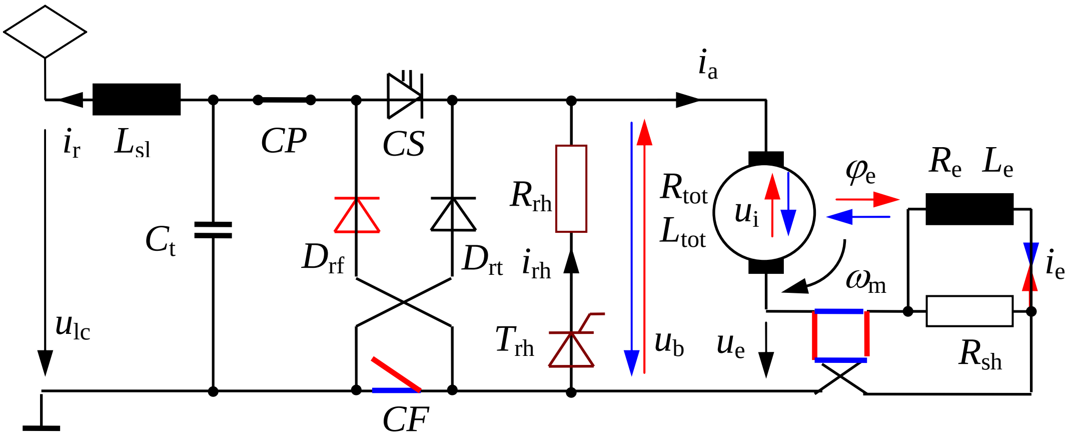

Fig. 4.87A DC-motor and chopper: traction.
Fig. 4.87B DC-motor and chopper: regenerative braking with series excitation.
Fig. 4.88A DC-motor and chopper: rheostatic braking with series excitation.

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 $\mathrm{CS_e}$. If this is controlled in order that the excitation current follows the armature current until full opening of main switch $\mathrm{CS_t}$, it is named *series-picture-moteur*. When $\mathrm{CS_t}$ 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 $\mathrm{CS_f}$ est inactive (or not installed), CP is open and an electromechanical switch often take place of T_{rh}. Braking point is controlled by $\mathrm{CS_e}$.

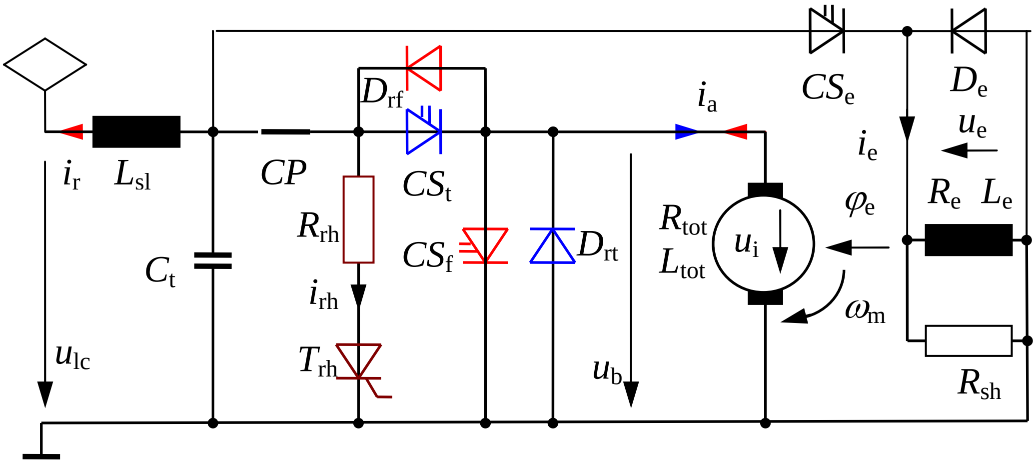

Fig. 4.95 DC-motor and chopper: traction at separate excitation.
Fig. 4.86A DC-motor and chopper: regenerative braking with separate excitation.
Fig. 4.88C DC-motor and chopper: rheostatic braking with separate excitation.

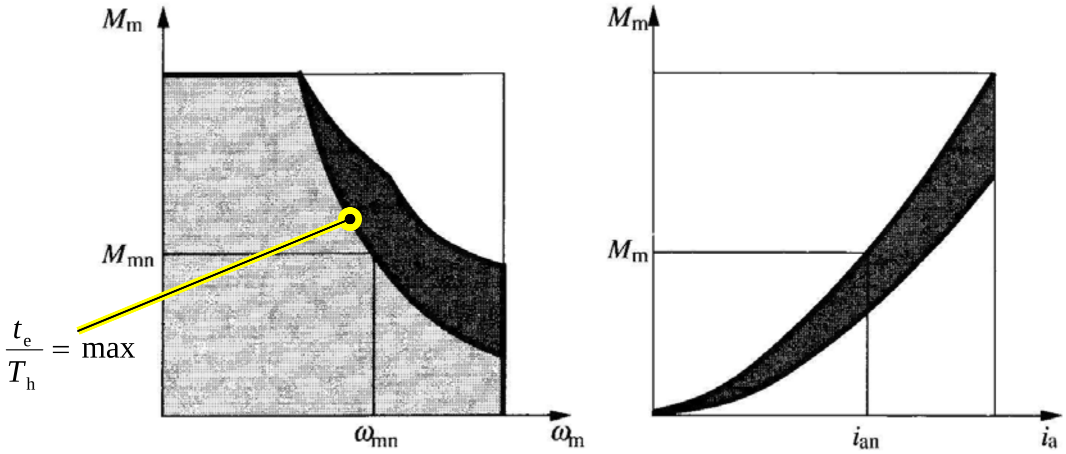

Fig. 4.97 DC-motor and chopper: traction characteristics at separate excitation: « series picture ».

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)

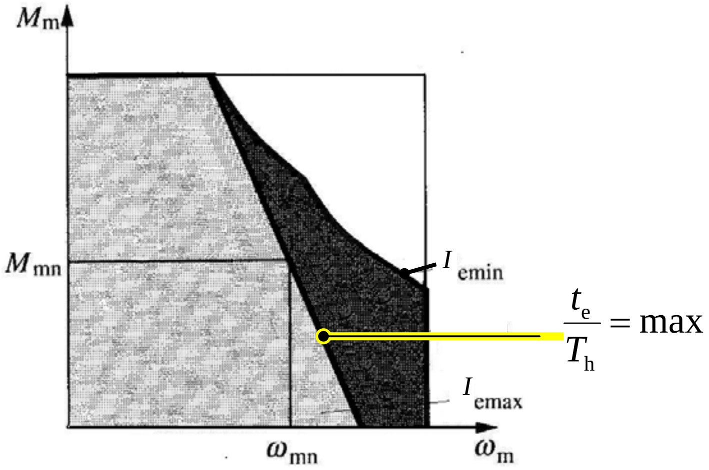

Fig. 4.97A DC-motor and chopper: traction characteristics at separate constant excitation.

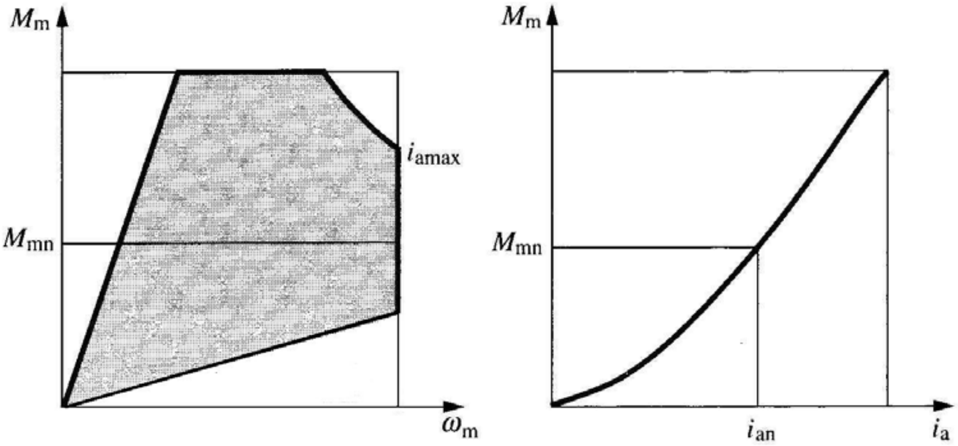

Fig. 4.90C DC-motor and chopper: rheostatic braking characteristics at separate excitation.

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.

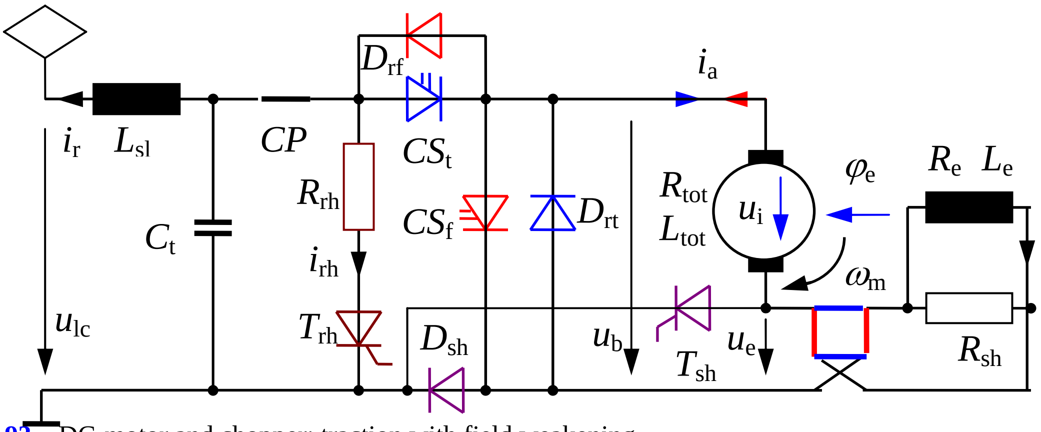

Fig. 4.93 DC-motor and chopper: traction with field weakening.

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).

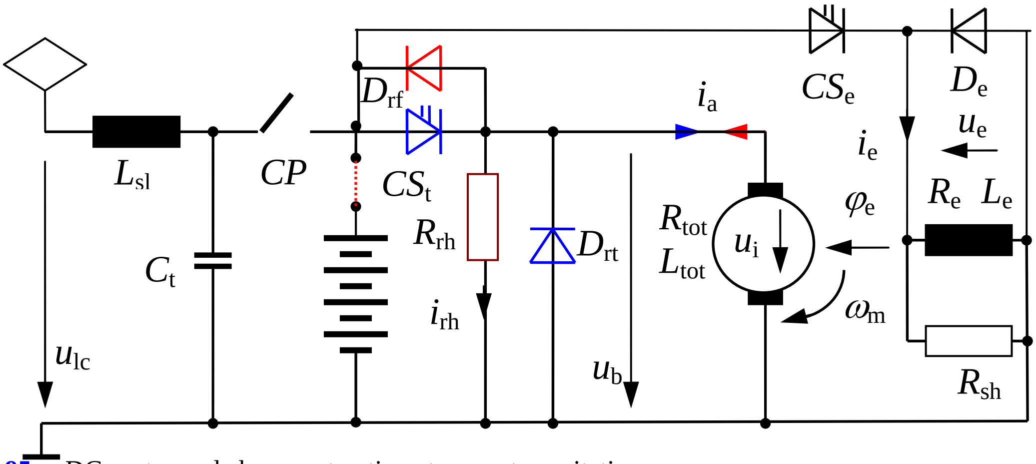

Fig. 4.95 DC-motor and chopper: traction at separate excitation.
Fig. 4.88B DC-motor and chopper: rheostatic braking with shunt excitation.

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.

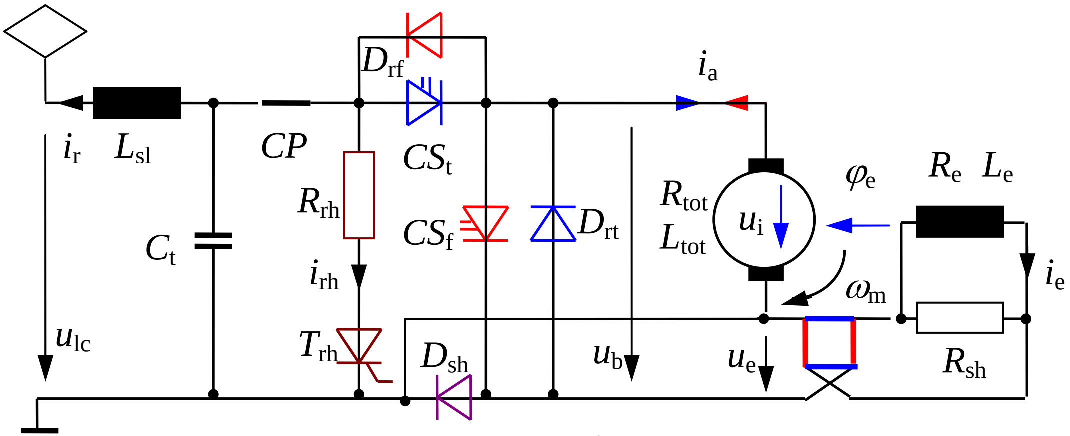

Fig. 4.98 DC-motor and chopper: traction with automatic field weakening.

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.

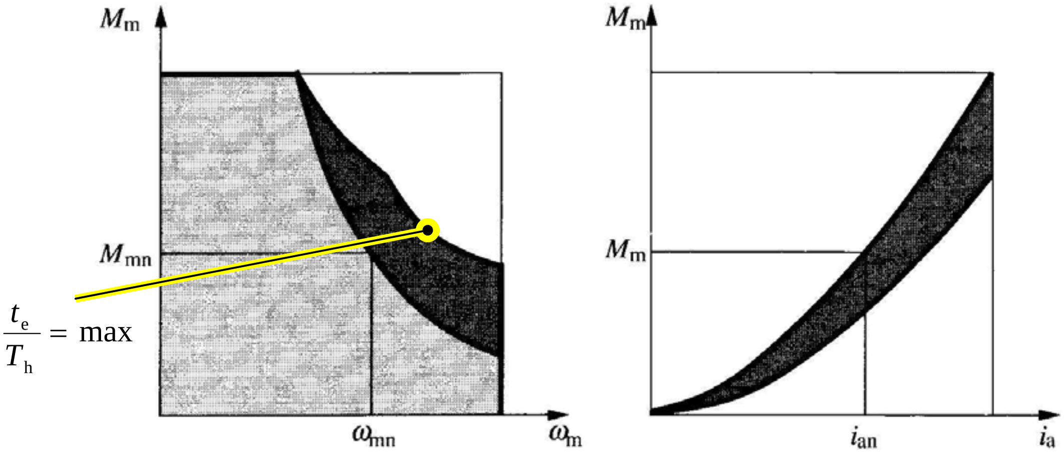

Fig. 4.97C DC-motor and chopper: characteristics in traction with automatic field weakening.