<u>Exercise 4.1:</u> DC drive for foil stretching machine

A separately excited DC machine with converter feeding is used as a variable speed drive for a foil stretching machine. The motor is cooled by an externally driven fan. Drive data:

P = (20 ... 200 ... 200) kW for n = (140 ... 1400 ... 2100) 1/min

1) Sketch the electric circuit of the three-phase controlled rectifier bridge for armature and excitation winding of the dc machine, supplied by the 3x400V/50Hz grid. Draw DC machine as circuit symbol with armature winding, commutation winding, compensation winding and excitation winding.

2) Draw the power- and voltage-speed-curve, and the armature current and main flux, depending on speed, for the above given drive data.

3) Describe the operating method and the possibilities for the drive control to realise the desired operation for the given data.

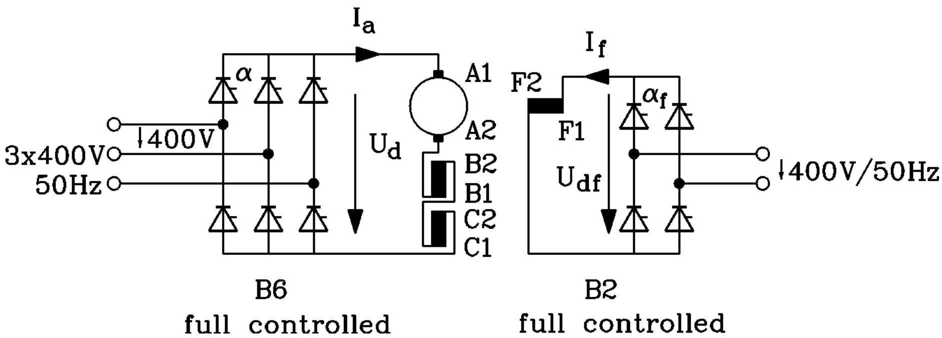
4) How has the electric circuit for the drive to be changed to realise the following data:
$-2100/\text{min} \le n \le 2100/\text{min}$, $-200\text{ kW} \le P \le 200\text{ kW}$?

5) Assume, that at 2100/min the reactance voltage of commutation reaches its limit. What has to be done with drive control, if an extension of speed range up to 2500/min is wanted ?

6) Is it possible to operate the DC machine at nominal torque and nominal current also at stand still ?

<u>Solution:</u>

1)



<u>Fig. 4.1-1:</u> One-quadrant DC drive with separate excitation

<u>Armature circuit:</u>
full controlled, three-phase
armature winding terminals: A1-A2
commutation winding terminals: B1-B2
compensation winding terminals: C1-C2

<u>Field circuit:</u>
full controlled, single phase
separate excitation winding terminals F1-F2

For variable speed operation an armature voltage variation is needed: n > 0, P >0: 1-quadrant operation. For that one inverter is sufficient ($I_a > 0$).

2) Voltage-speed-curve, armature current and main flux, depending on speed, for drive data: Fig. 4.1-2.

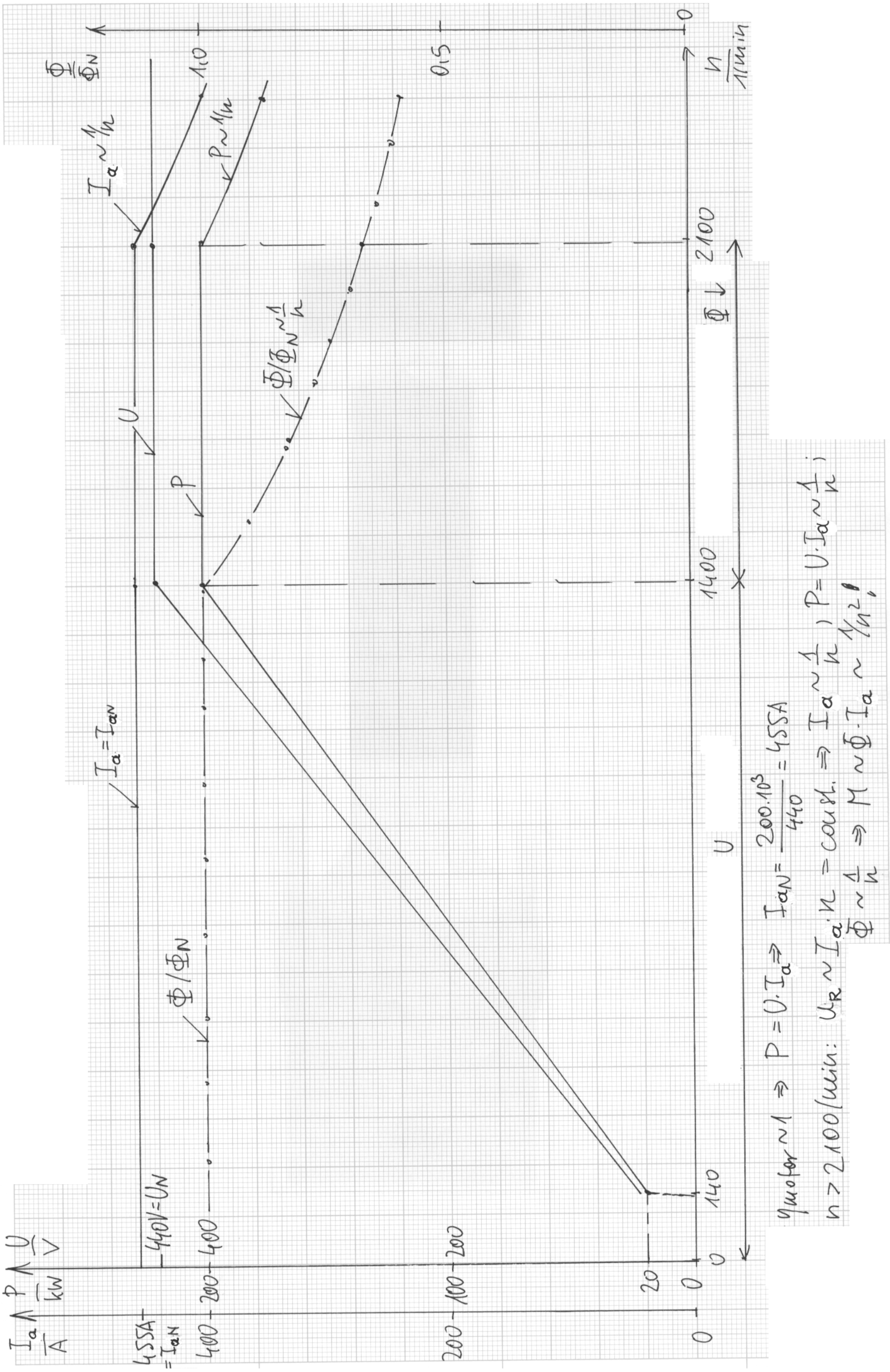


Fig. 4.1-2: Voltage-speed-curve, armature current and main flux, depending on speed

3) Adjustable parameters:

Power: $P = 2\pi \cdot n \cdot M$, Torque: $M = \frac{z \cdot p}{a} \cdot \frac{1}{2\pi} \cdot I_a \cdot \Phi$,

DC armature voltage: $U_d = U_i + I_a \cdot R_a$

Back EMF: $U_i = \frac{z \cdot p}{a} \cdot n \cdot \Phi$, main flux: $\Phi = \Phi(I_f)$, Field current $I_f = \frac{U_{df}}{R_f}$

Through the variable voltages U_d and U_{df} (which gives variable Φ) it is possible to adjust n and M. Variable armature voltage is realized by controlled rectification of grid voltage:

$U_d = U_{di} \cdot \cos\alpha$, α: control angel, U_{di}: ideal rectified voltage

$$U_{di} = \frac{3}{\pi}\sqrt{2} \cdot 400V = 540V \quad , \; U_{di} = \sqrt{2} \cdot U_{grid} \cdot \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \cos\varphi \cdot d\varphi \cdot \frac{3}{\pi} = \frac{3}{\pi}\sqrt{2} \cdot U_{grid}$$

Field voltage maximum at $\alpha_f = 0°$:

$$U_{dfi} = \frac{2}{\pi} \cdot \sqrt{2} \cdot U_{grid} = \frac{2}{\pi} \cdot \sqrt{2} \cdot 400 = 360V$$

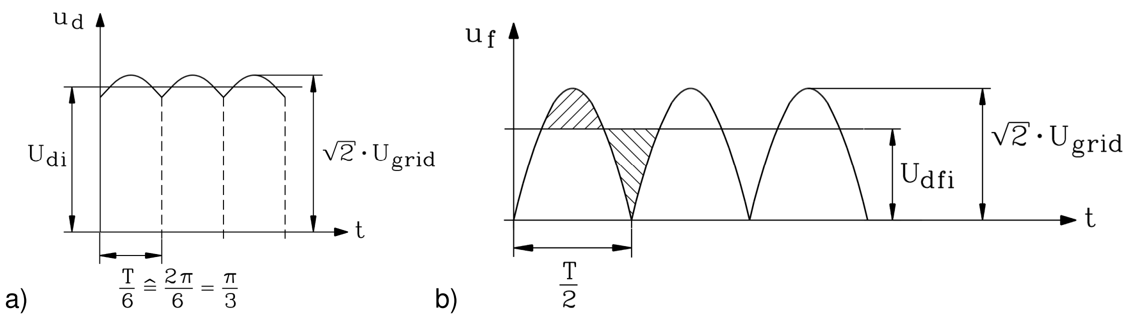


Fig. 4.1-3: a) Rectified 3-phase grid voltage for armature circuit, b) Rectified single-phase grid voltage for field circuit

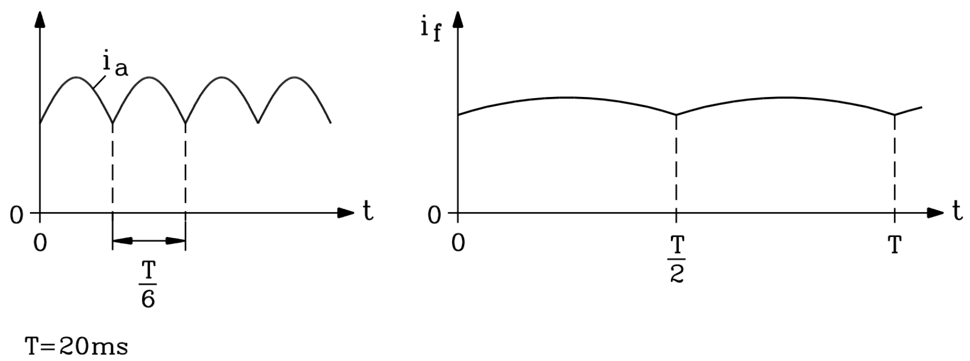


Fig. 4.1-4: Armature current i_a and field current i_f due to 3-phase and single phase rectification. Field current is smoothed by big excitation inductance L_f, whereas armature inductance L_a is much smaller, so armature current shows considerable ripple.

Due to three-phase rectification the armature current has harmonics with 6-times line frequency (6x50Hz=300Hz). Due to single-phase rectification the field current has a ripple with 2x50Hz = 100 Hz.

Armature voltage control limit: $440V = U_{di} \cdot \cos(35°) \geq U_d \geq U_{di} \cdot \cos(145°) = -440V$

The angle range 0 ... 35° and 145° … 180° is used as additional voltage margin for speed control. A certain limit angle < 180° is not surpassed, because at 180° it will not be possible to turn off the current of the thyristors (Fig. 4.1-5).

A torque reversal is not possible, because current cannot be reversed in the thyristors (1-quadrant operation) !

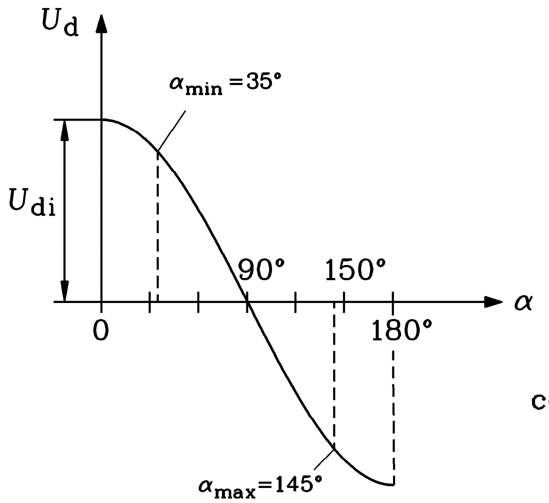


Fig. 4.1-5: Variation of armature voltage with thyristor ignition angle α

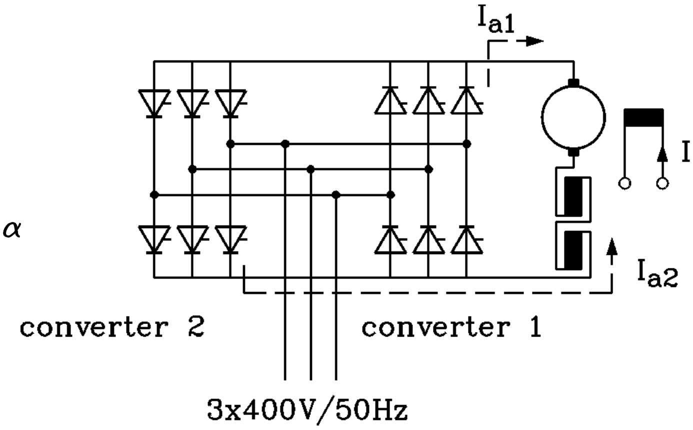


Fig. 4.1-6: Anti-parallel converter bridges for 4-quadrant operation

4) 4-quadrant operation:
Two anti-parallel converters are necessary to reverse torque for motor operation in negative speed direction. Converter 1 or converter 2 is active; the thyristors of the other one are blocked (no ignition signal at the thyristor´s gate). By switching for example from converter 1 to converter 2, a short pause without a current flow is required (Fig. 4.1-6).

1) Reactance voltage of commutation is limited to about 10 V, otherwise sparking is too much: $u_R \sim n \cdot I_a$, $u_{R,\max} = const.$ $=> I_a \sim 1/n => P \sim UI_a \sim 1/n$. Current has to be reduced above 2100/min to keep reactance voltage within the limit with rising speed (Fig. 4.1-2).
As above 1400/min is field weakening:
$\frac{\Phi}{\Phi_N} \sim \frac{1}{n} => \quad M \sim \Phi \cdot I_a \sim \frac{1}{n^2}$, torque decreases with square of speed. This can also be seen directly from power equation:
$P \sim \frac{1}{n} \sim n \cdot M => \quad M \sim \frac{1}{n^2}$

2) Full torque at speed zero is NOT possible, because due to $M_N = \frac{1}{2\pi} \cdot z \cdot \frac{p}{a} \cdot I_N \cdot \Phi_N$ at speed zero full current would be required. When the brushes conduct full armature current at stand still, the current-carrying commutator segments would not change. Danger of burning the segments must be avoided by reducing torque at stand still to about 50% rated torque. Above speed n ~ 2...5/min full torque may be applied.
At zero speed: Reduced brush current density $J_b < 5A/cm^2 \mathrel{\hat{=}} I_a \sim \frac{I_N}{2}$
At speed > 2 ... /min: Rated current I_N is possible: typical brush current density 10 A/cm^2.

Exercise 4.2: *Ward-Leonard* rotating converter

A *Ward-Leonard* converter set, installed 1955, is after refurbishment still in use as a variable speed elevator drive in a salt mine. The DC generator is driven by a 4-pole cage induction motor, which is supplied by the 3-phase 400 V/50Hz-grid. The data of the separately excited DC generator are:

DC Generator: $U_{G,N}$ = 440 V, P_N = 352 kW, I_N = 800 A, $n_{G,N}$ = 1470/min
$R_{G,a+K+W}$ = 0.025 Ω, (a: armature, K: compensation, W: commutation winding).

The speed of the generator is determined by the driving induction motor. Due to the small slip variation it is assumed to be constant independent of load. The DC generator supplies a separately excited DC motor as a variable speed drive with variable DC armature voltage. Data of the DC motor are:

DC motor: $U_{M,N}$ = 440 V, P_N = 324 kW, I_{aN} = 800 A, $R_{M,a+K+W}$ = 0.030 Ω, $n_{M,0}$ = 600/min: No-load speed (I_a = 0) at nominal excitation. The DC motor operates at constant nominal excitation.

The DC motor armature winding is connected to the DC generator armature circuit with two copper cables with a total DC resistance of R_{cable} = 0.01 Ω.

1.) Why should DC generator and DC motor be designed for the same rated current and voltage?
2.) Why is for the same armature voltage and current rating the rated power of the DC motor smaller than of the DC generator ?
3.) How big is lip of driving induction machine ?
4.) Draw the speed-current-curve n_M = f(I_a) of the DC motor as a four quadrant drive for a fixed excitation of the DC generator at no-load voltages U_{G0} = 440 V, 220 V, 0 V , -220 V, -440 V. Neglect the voltage drop at the motor and generator brushes. Scale: Abscissa: 100 A/cm, Ordinate: 50 min^{-1}/cm.
5.) Calculate the torque of the DC motor at the generator voltages of 4) at I_a = 600A.
6.) Now we assume, that the compensating winding of the DC generator is NOT used. Sketch the speed-current-curve $n_M = f(I_a)$ at U_{G0} = 440V in the first and second quadrant qualitatively. (Note: Motor is still compensated !). Explain the diagram !
7.) In reality the generator speed will vary between no-load and load due to the slip variation of the driving induction machine. Assume, that due to slip the speed of DC generator drops at rated load by 4%. Calculate and sketch the speed-current-curve $n_M = f(I_a)$ in the first and second quadrant at generator no-load armature voltage U_{G0} = 440V. Both DC-machines are compensated.

Solution:

1) DC generator and DC motor are designed for the same rated current and voltage, because both armature circuits are connected in series, so generator armature current is also motor armature current. Motor armature voltage is – compared to generator armature voltage - only smaller by the voltage drop at the connective cables, so both voltage ratings should be the same.
2) Motor rated power is its mechanical output power, whereas generator rated power is its electrical output power, which is the input power of the motor. So motor rated power is smaller by the motor losses than the electric input power.
3) Generator rated speed is induction motor rated speed: n = 1470/min. So induction motor slip is $s = \frac{f_{grid} / - n}{f_{grid} / p} = \frac{50/2 - (1470/60)}{50/2} = \underline{\underline{2\%}}$

4) n_G = const. = 1470/min:
Generator field current I_{fG} is chosen so, that U_{G0} = 440 V, 220 V, 0 V, -220 V, -440 V.

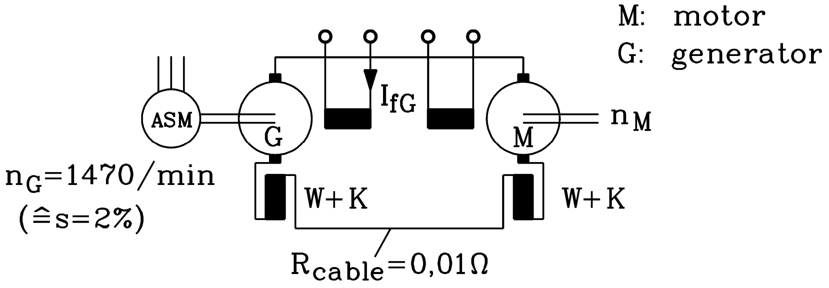


Fig. 4.2-1: *Ward-Leonard* converter set with induction motor, DC generator and DC motor

DC generator:	DC motor:
$U_{G0} = 440V$	$U_{MN} = 440V$
$P_e = P_N = 352$ kW	$P_N = 342$ kW$=P_m$
$I_N = 800$ A	$I_N = 800$ A $= I_{aN}$
$R_{aG} = 0.025\Omega$	$R_{aM} = 0.03\Omega$
	$n_{M0} = 600$/min (at $\Phi_{M,N}$; $I_a = 0$)

$$U_{Mi} = U_{G0} - I_a(R_{aG} + R_{aM} + R_{cable}) = k_{1M} \cdot n_M \cdot \Phi_M$$

$$R_{sum} = R_{aG} + R_{aM} + R_{cable} = 0.065\Omega$$

At $I_a = 0$: $U_{Mi} = U_{G0} = k_{1M} \cdot \Phi_M \cdot n_M$:

$$U_{G0} = 440V \Rightarrow n_M = 600/\min \Rightarrow k_{1M} \cdot \Phi_M = \frac{440}{600/60} = 44 \text{ Vs}$$

$$U_{G0} - I_{aMN} \cdot R_{sum} = k_{1M} \cdot \Phi_M \cdot n_M \quad \Rightarrow \quad n_M = \frac{U_{G0} - I_a \cdot R_{sum}}{k_{1M} \cdot \Phi_M} = n_{M0} - \frac{I_a \cdot R_{sum}}{k_{1M} \cdot \Phi_M}$$

U_{G0}	V	440	220	0	-220	-440	I_a
n_M	1/min	529	229	-71	-371	-671	800 A
n_{M0}	1/min	600	300	0	-300	-600	0 A
n_M	1/min	671	371	71	-229	-529	- 800 A

See diagram in Fig. 4.2-5 !

5) I_a = 600A : $M_{e_M} = \frac{z \cdot p}{a} \cdot \frac{1}{2\pi} \cdot \Phi_M \cdot I_a = k_{1M} \cdot \Phi_M \cdot \frac{I_a}{2\pi} = 44 \cdot \frac{600}{2\pi} = \underline{\underline{4201}}$Nm

6) Generator not compensated: Saturation due to armature field decreases flux at load current: $\Phi_G = \Phi_G(I_a)$, resulting in generator voltage drop, which leads to speed drop of motor.

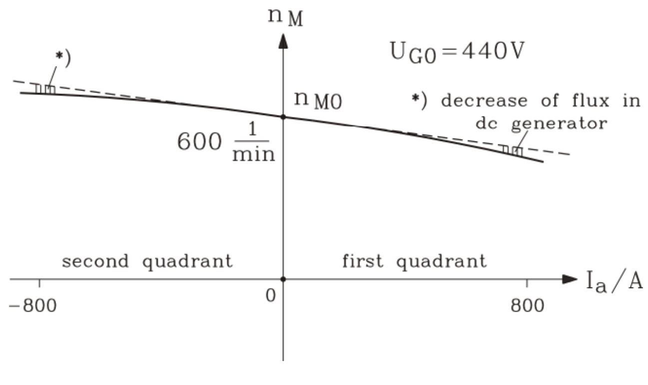
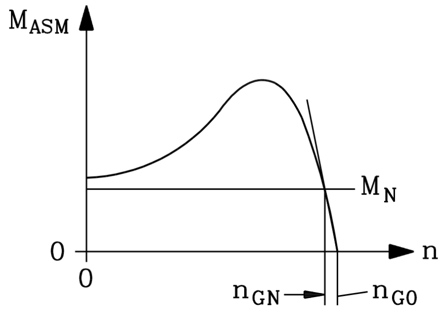


Fig. 4.2-2: Speed-current-curve with influence of flux decrease in DC generator

Decrease of flux is independent of current flow direction, so it depends on absolute value $|\pm I_a|$ => At small current no saturation occurs, and hence no flux decrease: $U_{G0} = k_{1G} \cdot \Phi_G \cdot n_G$. At I_a of about rated current flux decreases, therefore generator voltage drops; hence motor speed n_M will drop <u>in addition</u> to speed drop due to resistance voltage drop $R_{sum}I_a$.

7) Induction machine: Slip varies linear with load torque for torque range up to rated torque acc. to *KLOSS* function linearization at slip zero : $M_{ASM} \sim s = 1 - n_G/n_{G0}$. n_{G0} =1500/min = $n_{syn,ASM}$



<u>Fig. 4.2-3:</u> Speed-torque curve of induction motor and linearization at zero slip.

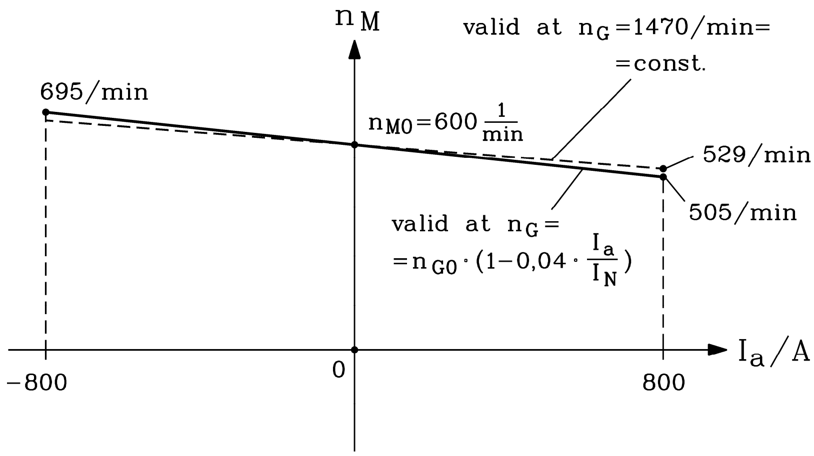
$n_{ASM} = n_{G0}$: at no load : $M_{ASM} = M_G = 0$: $I_a = 0$: 1500/min
$n_{ASM} = n_G$: drops at load: $M_{ASM} = M_G > 0$: $I_a > 0$.
At rated current: -4%: (1-0.04)·1500 = 1440/min
Generator speed drop leads to generator voltage drop at constant generator flux: Φ_G = const.
Generator no-load voltage: $U_{G0} = k_{1G} \cdot \Phi_G \cdot n_G$

Generator voltage at load current I_a : $U_G = U_{G0} \cdot (1 - 0.04 \cdot I_a / I_N)$
Note: In second quadrant power flow direction reverses. Induction machine is generator, slip is negative, generator speed increases, and so does generator voltage.
So DC motor speed will drop in 1st quadrant/ increase in 2nd quadrant, in addition to speed drop due to resistive voltage drop $R_{sum}I_a$.

$$n_M = \frac{U_{G0} \cdot (1 - \frac{I_a}{I_N} \cdot 0.04) - I_a \cdot R_{sum}}{k_{1M} \cdot \Phi_M}$$

$I_a = I_{aMN}$: $n_M = \frac{440 - 440 \cdot 0.04 - 52}{44} = 8.42 s^{-1} = \underline{\underline{505}}$ /min

$I_a = -I_{aMN}$: $n_M = \frac{440 + 440 \cdot 0.04 + 52}{44} = \underline{\underline{695}}$ /min



<u>Fig. 4.2-4:</u> Speed-current curve of DC motor at variable speed of induction motor

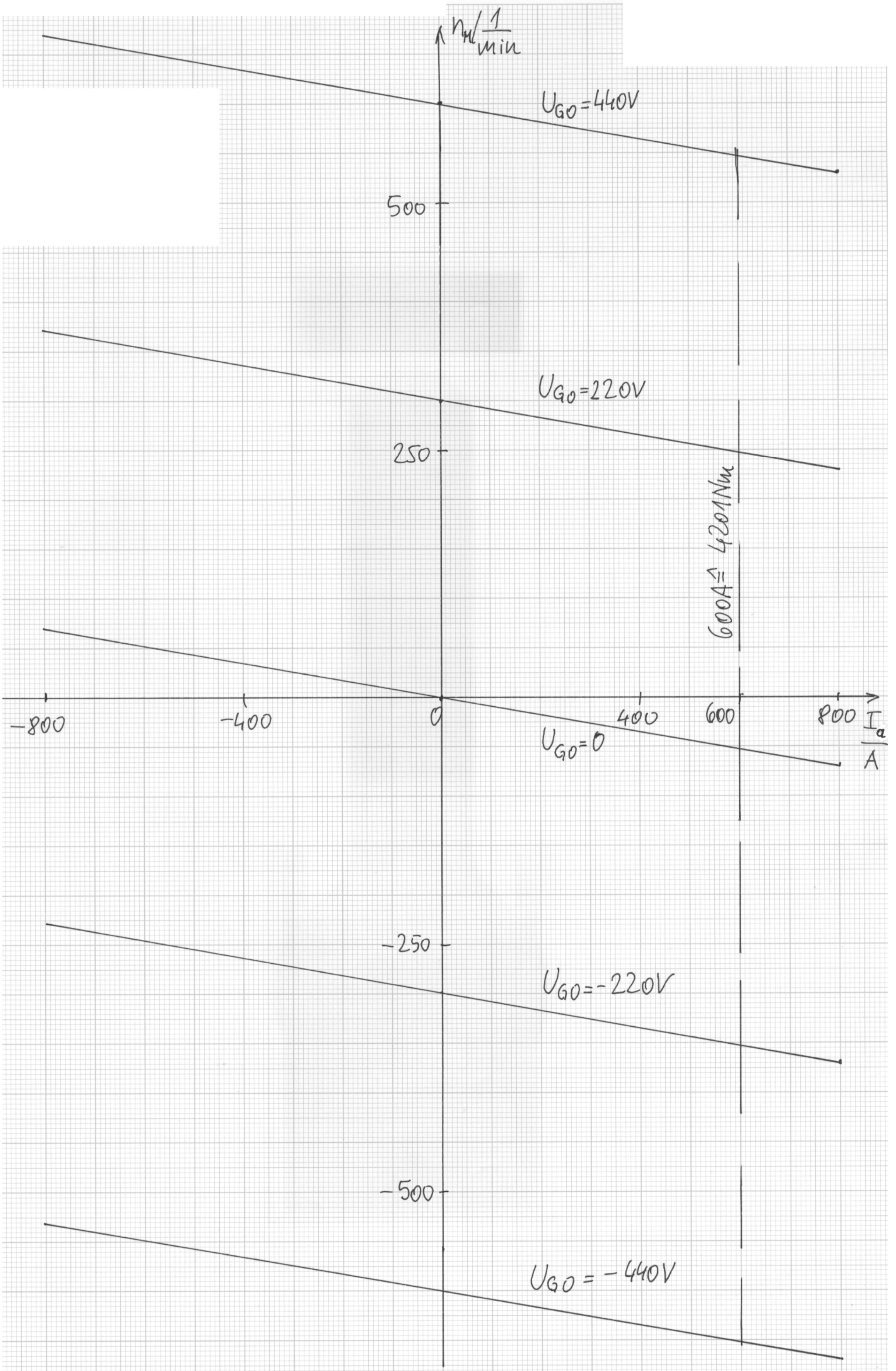


Fig. 4.2-5: Speed-current curves of DC motor at different armature variable voltage in all 4 quadrants

Exercise 4.3: D.C. drive for a coal-mine vehicle

In a coal-mine at *South Africa*, electric vehicles are used to transport the coal, in order to avoid exhaust gases of combustion vehicle, which is not allowed in underground environment. The electric vehicles are equipped with series-excited DC machines as vehicle drives. The DC machines are operated by vehicle battery and have following electrical data

$U_N = 440$ V, $I_N = 500$ A,

Winding data:

$R_a = 0.02\ \Omega$	armature resistance
$R_W + R_{RS} = 0.025\ \Omega$	commutation and series excitation winding
$N_{RS} = 10$	number of turns per pole of the series excitation winding
$k_1 = z \cdot (p/a) = 416$	armature constant

The characteristic of main flux versus exciting Ampere turns is given in Fig. 4.3-1. The brush voltage drop may be neglected !

1) How big is magnetic main flux Φ at nominal voltage and current?

2) What is the machine speed at nominal voltage and nominal current?

3) At nominal voltage, the machine is overloaded with $I_a = 2 \cdot I_N$. What is now the speed value?

4) Calculate rated torque and torque at $I_a = 2 \cdot I_N$! Compare current, speed and torque for 100% and 200% rated current!

5) Machine shall be started from standstill with a current of $1.5 \cdot I_N$. How big is the necessary series starting resistor R_v in armature circuit?

6) If wheel vehicle will lose friction contact ("sliding"), load torque decreases to zero = no-load condition $I_a \approx 0$. In that case, machine speed must be limited to 1.5-times rated speed. How big are the necessary Ampere turns (Θ_{NS} per pole), which must be designed by an additional parallel excitation winding in order to fulfil this requirement?

Solution:

1) $U_N = 440$ V, $I_N = 500$ A, $R_a = 0.02\ \Omega$, $R_{W+RS} = 0.025\ \Omega$

$N_{RS} = 10$ / pole, $k_1 = z \cdot \frac{p}{a} = 416$

Series excitation means $I_a = I_f = I_N$. So exciting Ampere turns are: $\Theta_f = N_{RS} \cdot I_a$

$\Theta_f = 10 \cdot 500\text{A} = 5\ \text{kA} \quad \rightarrow \quad \text{Fig. 4.3-1}: \Phi = \Phi_{RS} = \Phi_N = \underline{\underline{0.0425\ \text{Wb}}}$

2) $U_N = U_i + I_a \cdot R_{tot}$, $\quad U_b \approx 0$, $\quad U_i = z \cdot \frac{p}{a} \cdot n \cdot \Phi$, $\quad R_{tot} = R_{a+W+RS} = 0.045\ \Omega$

$U_i = 440 - 500 \cdot 0.045\ \text{V} = 417.5\ \text{V}$

$$n_N = \frac{U_i}{k_1 \cdot \Phi_N} = \frac{417.5}{416 \cdot 0.0425}\ \text{s}^{-1} = 23.6\ \text{s}^{-1} = \underline{\underline{1417\ \text{min}^{-1}}}$$

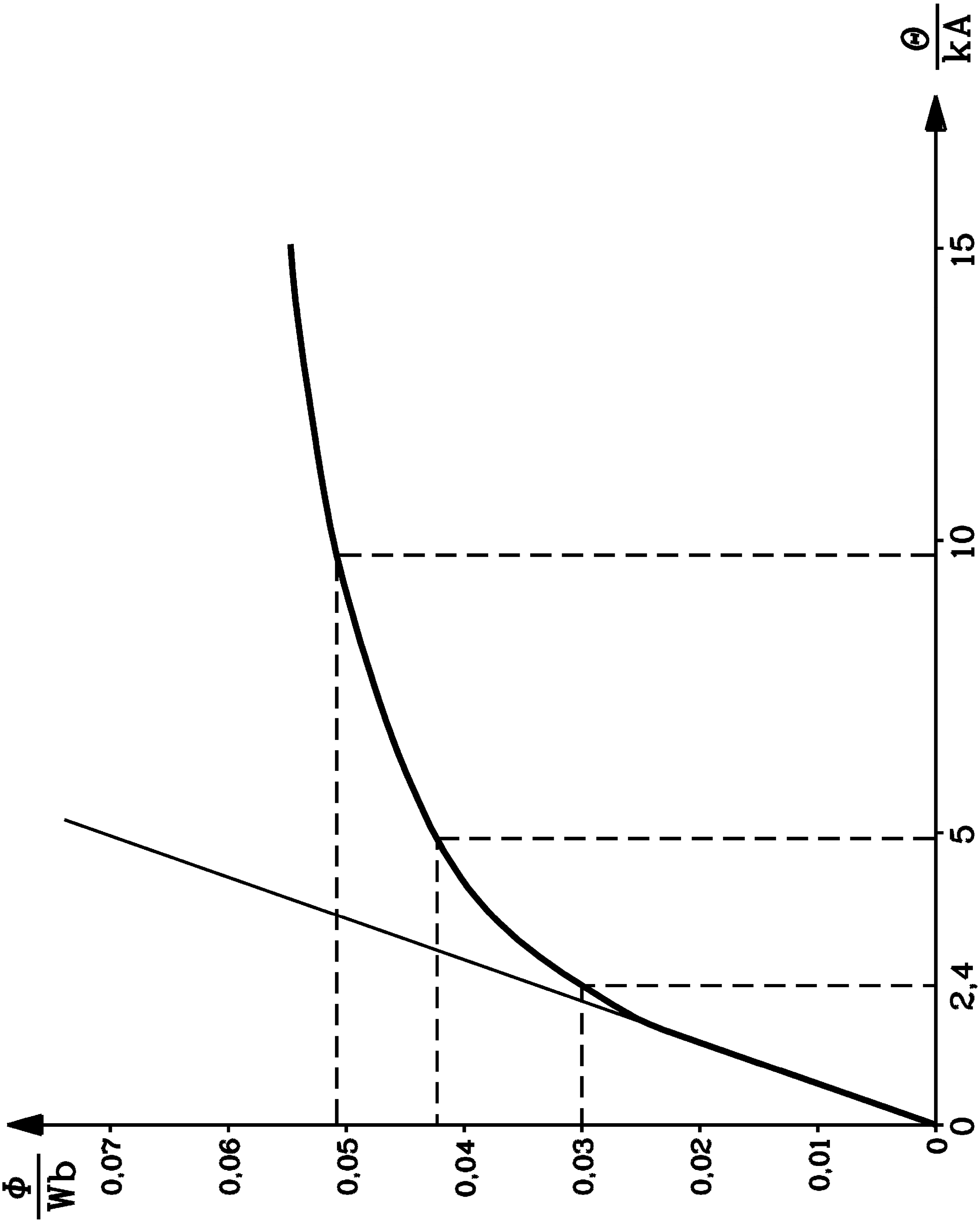


Fig. 4.3-1: Main flux versus excitation Ampere turns of DC series excited machine

3) $I_a = 2I_N$: $U_i^* = 440 - 2 \cdot 500 \cdot 0.045\ \mathrm{V} = 395\ \mathrm{V}$

$\Theta_f = 2 \cdot 500 \cdot 10\ \mathrm{A} = 10000\ \mathrm{A}$: $\Phi^* = 0.051\ \mathrm{Wb}$

$$n^* = \frac{U_i^*}{k_1 \cdot \Phi^*} = \frac{395}{416 \cdot 0.051} s^{-1} = 18.6\, s^{-1} = \underline{\underline{1117\, min^{-1}}}$$

4) $$M^* = \frac{1}{2\pi} \cdot z \cdot \frac{p}{a} \cdot I_a^* \cdot \Phi^* = \frac{1}{2\pi} \cdot 416 \cdot 1000 \cdot 0.051 = \underline{\underline{3376.6}}\, Nm$$

$$M_N = \frac{1}{2\pi} \cdot z \cdot \frac{p}{a} \cdot I_N \cdot \Phi_N = \frac{1}{2\pi} \cdot 416 \cdot 500 \cdot 0.0425 = \underline{\underline{1406.9}}\ Nm$$

$$\frac{M^*}{M_N} = \frac{I_a^* \cdot \Phi^*}{I_N \cdot \Phi_N} = 2 \cdot \frac{0.051}{0.0425} = \underline{\underline{2.4}}$$

	Speed	Armature current	Torque
	1/min	A	Nm
(1)	1417	500	1406.9
(2)	1117	1000	3376.6
(2) / (1)	0.79	2	2.4

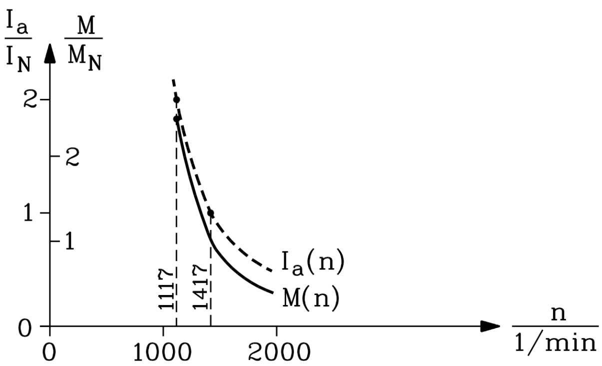


Fig. 4.3-2: Dependence of torque and current of speed in series excited DC motor is slightly different due to iron saturation (Fig. 4.3-1)

5) Stand still: $n = 0 \rightarrow U_i = 0$: $U_N = 0 + I_a \cdot (R_{tot} + R_v) \quad \Rightarrow \quad \frac{U_N}{1.5 \cdot I_N} - R_{tot} = R_v$

$1.5 \cdot I_N = 750$ A: Series starting resistor $R_v = \frac{440}{1.5 \cdot 500} - 0.045\, \Omega = \underline{\underline{0.542\, \Omega}}$

6) Auxiliary parallel excitation winding to prevent motor to speed up to infinite speed at zero load:
Necessary Ampere turns: $\Theta_{NS} = N_{NS} \cdot I_f$ for $n_0 = 1.5 n_N$
Zero load: $I_a = 0 : \Phi_{RS} = 0$:

$$I_a = 0: \quad U = k_1 \cdot n_0 . \Phi_{NS} = U_N \quad \Rightarrow \quad \Phi_{NS} = \frac{440}{416 \cdot 1.5 \cdot 23.6} Wb = 0.03\, Wb = \Phi\, .$$

From diagram 4.3-1 we get: $\Rightarrow \quad \Theta_{NS} = \underline{\underline{2400\, A}}$.

Exercise 4.4: DC Motor for Rotary Frequency Converter

A synchronous generator is driven by a DC motor with variable speed to serve as a variable frequency converter with sinusoidal voltage in a university´s lab. The DC motor is shunt-excited, with an auxiliary series excitation winding. The armature circuit comprises further the commutation and compensating winding.

DC motor data:
$U_N = 440$ V, $I_{aN} = 120$ A, $n_N = 1500$/min

Total armature winding resistance:
$R_{tot} = R_a + R_W + R_K + R_{RS} = 0.3\ \Omega$.

a = armature winding: terminals A1, A2 W = commutation pole winding: terminals B1, B2
K = compensation winding: terminals C1, C2 RS = series excitation winding: terminals D1, D2

NS = shunt excitation winding: terminals E1, E2

1) Draw the electric circuit of DC machine armature and excitation for motor operation in
   a) clockwise and
   b) anti-clockwise
   direction of rotation (see Fig. 4.4-1). For battery feeding (= fixed armature voltage) a series starting resistor in the armature circuit and a variable field circuit resistor for excitation control is needed. Check proper terminal connections! What do we have to consider in case of reversal of armature current, concerning the series excitation ?
2) Design the value of the necessary starting resistor, which enables the motor to start from standstill with $1.5 \cdot I_{aN}$? The brush voltage drop may be neglected!
3) The speed-current characteristic of the motor was measured as a pure series excited DC motor; the shunt excitation winding circuit was not connected (Fig. 4.4-1). The series excitation winding has $N_{RS} = 5$ turns per pole. Choose the *Ampere* turns $N_{NS} \cdot I_f$ per pole of the shunt excitation winding to enable the motor to operate at nominal load ($I_a = I_{aN}$) with nominal speed. Neglect for that case the armature winding voltage drop $I_a \cdot R_{tot}$! How big is the ratio of *Ampere* turns of series and shunt excitation !

Solution:
1)

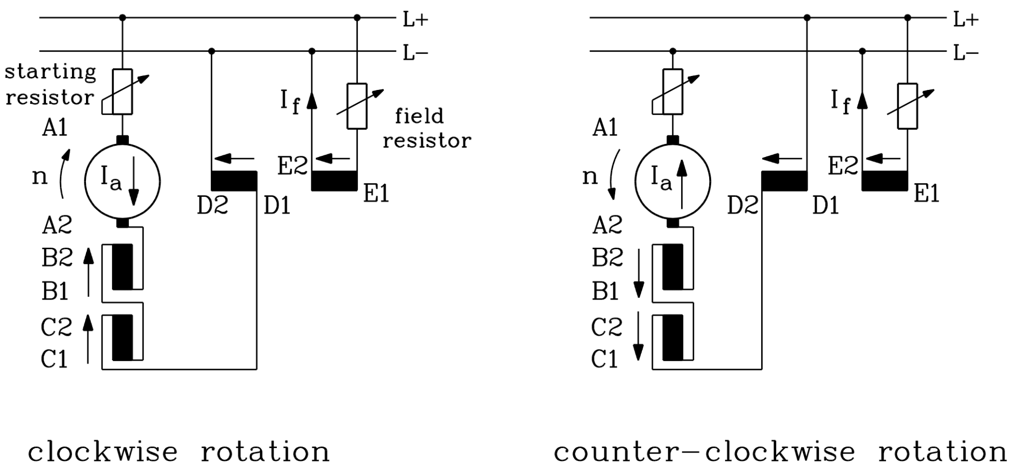


Fig. 4.4-1: Proper connection of winding terminals to the battery grid L+, L- for DC motor operation in a) 1st and b) 3rd quadrant

Clockwise rotation: This means, that the shaft is rotating in the clockwise direction, when seen from the front of the motor at the drive-end (Fig. 4.4-2). If this is motor operation, it is called 1st quadrant operation.

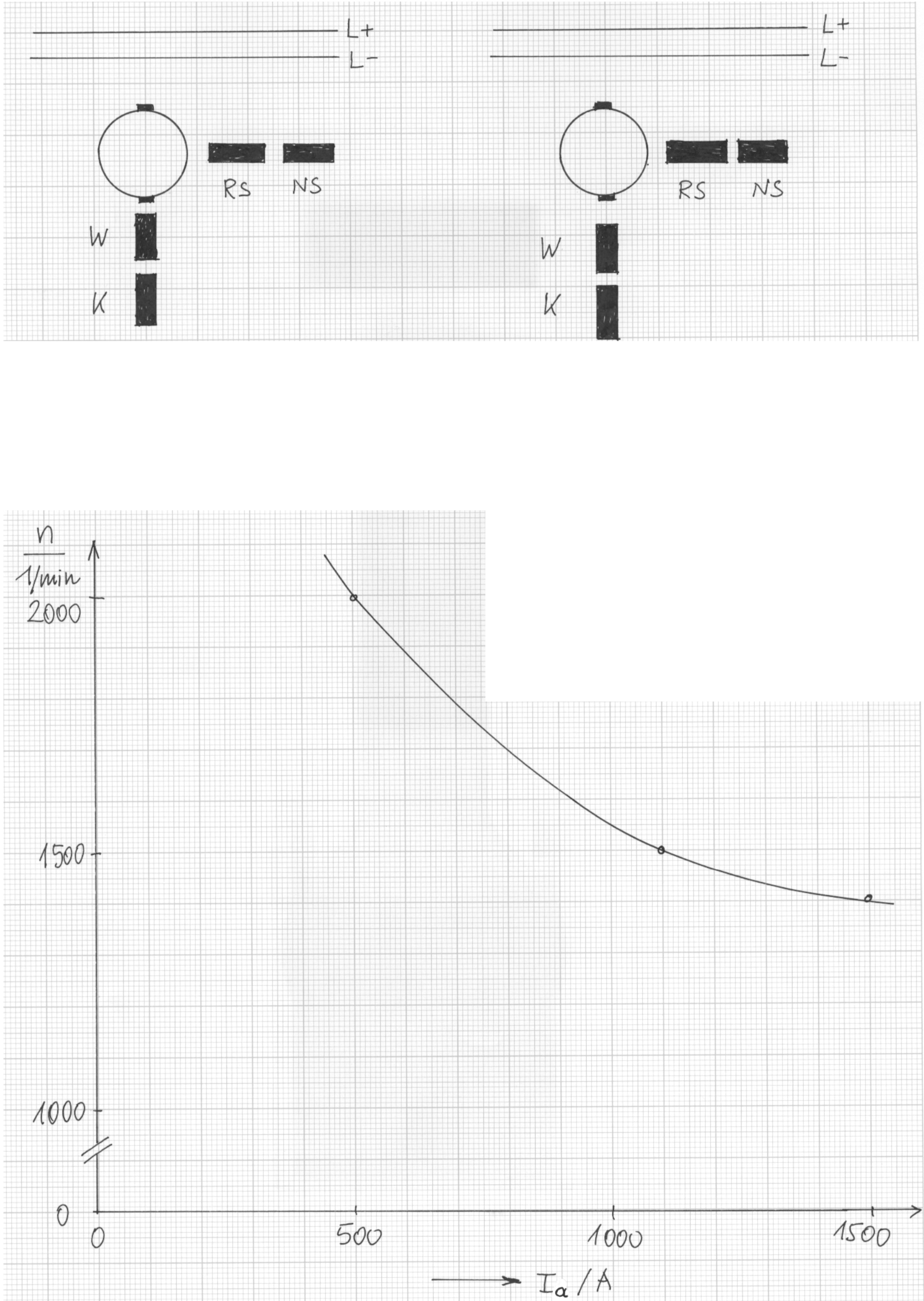


Fig. 4.4-2: Above: Winding terminals of motor, to be connected for clockwise and counter-clockwise motor operation, below: Speed-current curve of DC motor, operated only with series excitation winding

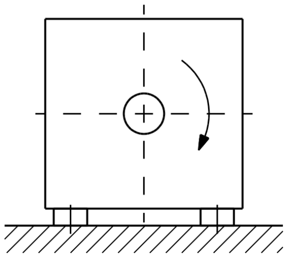


Fig. 4.4-3: Clockwise operation of motor

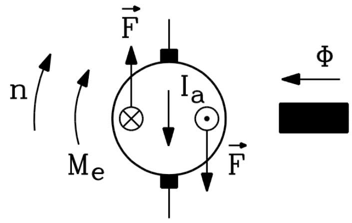


Fig. 4.4-4: Direction of motor torque

Rules of drawing the electric circuit: Rotor current in stator field give rotor conductor *LORENTZ* forces, which rotate the rotor into direction of positive main field = direction of electromagnetic motor torque (Fig. 4.4-3) !

a) As the direction of M_e is also the direction of n at motor operation ⇒ clockwise speed direction needs clockwise torque direction (Fig. 4.4-1, left).
b) For counter-clockwise rotation armature current must be reversed.

Series excitation winding at current reversal:
For current reversal, the connection of terminals D1, D2 of series excitation winding must be exchanged: connection D2-C2 instead of D1-C2. Otherwise, the series winding field would counter-act the shunt winding field, thus decreasing the main flux.

2) $U_{Batt} = U_i + I_a \cdot (R_v + R_{tot})$, $\quad U_i = k_1 \cdot n \cdot \Phi$

$n = 0 \quad : \quad I_a = 1.5 \cdot I_N \; ; \quad U_{Batt} = U_N \; ; \quad U_i = 0$

$$\Rightarrow \quad R_v = \frac{U_N}{I_a} - R_{tot} = \frac{440}{1.5 \cdot 120} - 0.3\,\Omega = \underline{\underline{2.14\,\Omega}}$$

3) a) At open shunt excitation winding connections (Fig. 4.4-2):

$N_{RS} = 5$ / pole, $I_f = 0$: $n_N = 1500\ \mathrm{min}^{-1}$: $U_{Batt} = U_i + I_a \cdot R_{tot}$:

Neglecting $I_a \cdot R_{tot}$, we get $U_N = U_i = k_1 \cdot n_N \cdot \Phi$. Acc. to Fig. 4.4-2 we get at that speed the current I_a = 1100 A. $\Theta = \Theta_{RS} = N_{RS} \cdot I_a = 5 \cdot 1100\ \mathrm{A} = 5.5\ \mathrm{kA}$ to get main flux $\Phi = \Phi(\Theta)$.

b) At series AND shunt excitation we need the same *Ampere* turns for the same main flux: $\Theta = \Theta_{RS} + \Theta_{NS} = N_{RS} \cdot I_a + N_{NS} \cdot I_f = 5500\ \mathrm{A}$ at U_N, n_N.

Thus we need at U_N, n_N due to I_{aN} = 120 A ⇒ $\Theta_{RS} = 120\ \mathrm{A} \cdot 5 = 600\ \mathrm{A}$ for the shunt excitation winding $\Theta_{NS} = N_{NS} \cdot I_f = 5500 - 600\ \mathrm{A} = \underline{\underline{4900\ \mathrm{A}}}$.

Excitation ratio: $\Theta_{RS} / \Theta_{NS} = 600/4900 = \underline{\underline{12.2\%}}$

Conclusion:
The main part of the necessary exciting Ampere turns are provided by the shunt excitation winding. Hence, the series excitation is only an auxiliary one.

Exercise 4.5: DC Motor for DC railway vehicle

In a copper mine in *Chile* DC powered railway vehicles for transporting copper ore are used. DC series excited motors with following data are used as traction drives:
U_N = 440 V, $\quad I_N$ = 500 A
The no-load voltage-exciter current characteristic of the machine is given in Fig. 4.5-1, measured at separated excitation and I_a = 0, $n = n_0$ = 1200/min. The motor is compensated and has a total

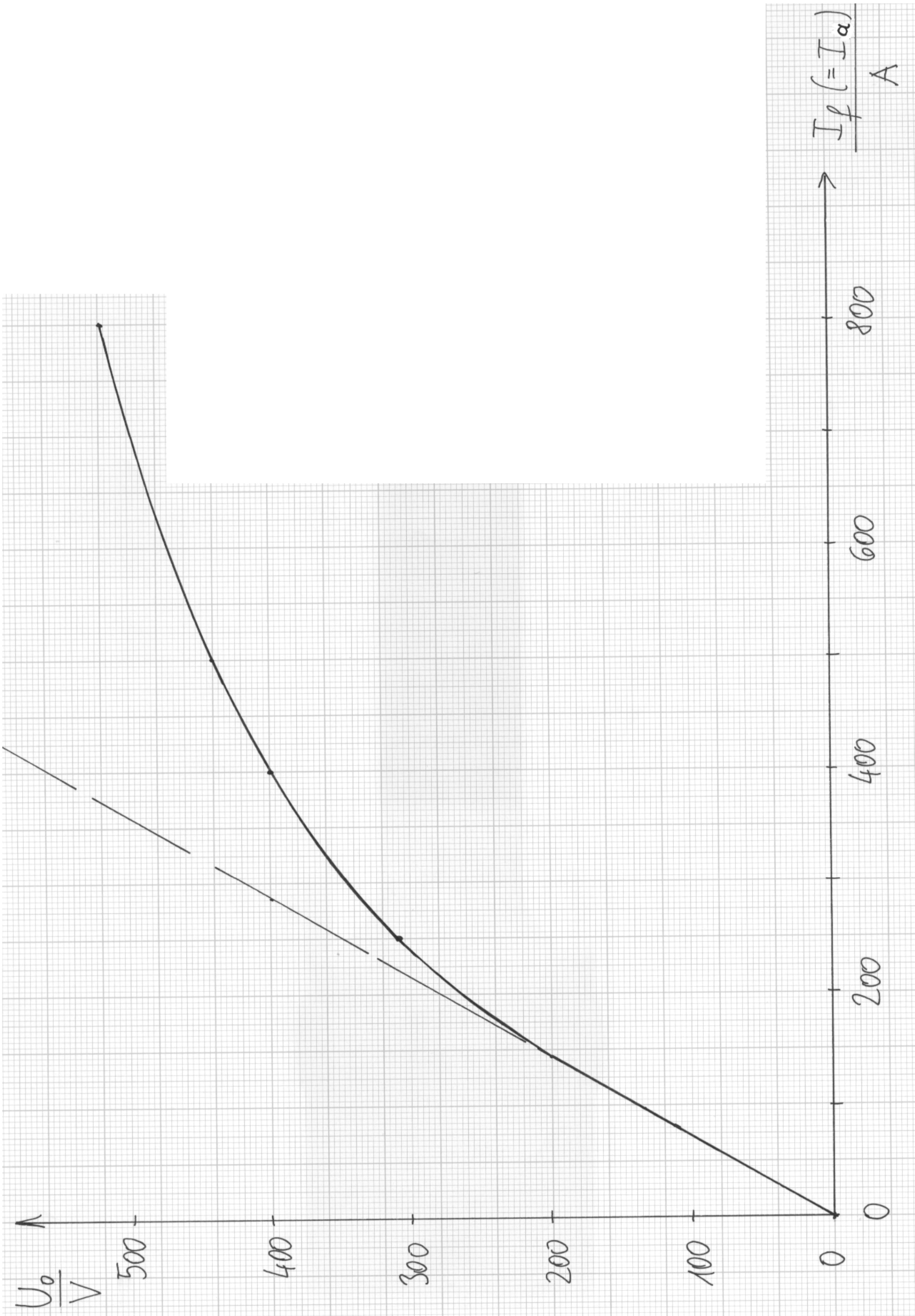


Fig. 4.5-1: No-load voltage curve in dependence of excitation current at 1200/min

resistance of armature circuit (including compensating, commutation and series excitation winding) $R_{tot} = R_a + R_W + R_K + R_{RS} = 0.045\ \Omega$.

1) At which speed is the motor rotating, if it is operated at <u>U = 220V</u> and a load current <u>I = 400</u> A ? Neglect the brush voltage drop.

2) Describe motor performance, starting from condition of 1), if the friction contact between wheel and rail is lost at wet weather condition. Note, that the armature voltage is kept constant.

3) Electric braking of the railway vehicle: How big is the necessary load resistor R_B which enables the machine as a generator at braking condition to generate a current <u>I = 500 A</u> at <u>n = 600/min</u> ? Determine terminal voltage and the electrical braking power in the load resistor !

4) With the condition of 3), what happens, when the speed decreases towards zero at a constant load resistor R_B?

<u>Solution:</u>

1) Series excited motor, operated at I_a = 400 A and 220 V:
$U = U_i + I_a \cdot R_{tot} + U_b \cong U_i + I_a \cdot R_{tot}$. At series excitation armature current is excitation current: $U_i = k_1 \cdot n \cdot \Phi(I_a)$. According to Fig. 4.5-1 we get at n_0 = 1200/min and 400 A excitation current a no-load voltage: $U_0 = U_i = k_1 \cdot n_0 \cdot \Phi(I_a)\big|_{I_a=400\text{A}} = 400\ \text{V}$.
From that we derive the ratio $\frac{U_0}{n_0} = k_1 \cdot \Phi(I_a) = \frac{400}{1200/60} = 20\ \text{Vs}$. At 220 V we get at load:

$$U = 220\ \text{V} = n \cdot k_1 \cdot \Phi(I_a = 400A) + I_a \cdot R_{tot} \Rightarrow n = \frac{220 - 400 \cdot 0.045}{20} = 10.1\ \text{s}^{-1} = \underline{\underline{606\ \text{min}^{-1}}}$$

2) If the load at the shaft is completely removed, torque is zero: M_e = 0. So, armature current is zero: I_a = 0 and hence flux is zero $\Phi \to 0$. Due to $n \cdot k_1 \cdot \Phi = U = 220\ \text{V}$ = const., speed n rises rapidly, the machine „over-speeds“ and will be destroyed.

3) Series excited generator with a load resistance R_B at n = 600 min^{-1}, I_a = 500 A:
$U_i = R_B \cdot I_a + R_{tot} \cdot I_a = k_1 \cdot n \cdot \Phi(I_a)$
According to Fig. 4.5-1: At 1200/min, $U_0 = k_1 \cdot n_0 \cdot \Phi(I_a = 500\ \text{A}) = 440\ \text{V}$, we get the ratio $k_1 \cdot \Phi(I_a = 500\ \text{A}) = \frac{440}{1200/60} = 22\ \text{Vs}$, and with that the proper value for load resistance at 600/min, 500 A:

$$R_B = \frac{k_1 \cdot n \cdot \Phi(I_a) - R_{tot} \cdot I_a}{I_a} = \frac{\frac{600}{60} \cdot 22 - 0.045 \cdot 500}{500} = \underline{\underline{0.395\ \Omega}}$$

The terminal voltage at the resistor is $U = R_B \cdot I_a = 0.395 \cdot 500 = \underline{\underline{197.5\ \text{V}}}$. The dissipated braking power in the load resistor is $P = U \cdot I_a = \underline{\underline{98.75\ \text{kW}}}$.

4) With decreasing speed n, the induced voltage U_i decreases: $U_i = k_1 \cdot n \cdot \Phi(I_a)$
The operating point P (Fig. 4.5-2) is moving towards smaller voltage U & current I_a. It will reach the origin at a certain speed n^* , which is NOT ZERO speed, but somewhat

lower than $n_1/2$. Then the generator braking operation with R_B is not possible any longer below this minimum speed n^*, because the armature current is already zero. Hence, below n^*, the machine is braking only by its (small) friction losses.

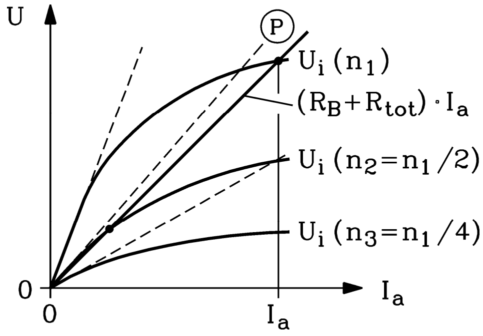


Fig. 4.5-2: Series excited generator operation at decreasing speed.

Note: The saturation effect, which is curbing the $U_i(n)$ curve, is necessary for operating the series excited generator on a resistor. Otherwise, no intersection between $U_i = (R_B + R_{tot}) \cdot I_a$ and $U = U_i = k_1 \cdot n \cdot \Phi(I_a)$ exists.

Exercise 4.6: DC Motor for a printing machine

For the movement of the paper inside a printing machine, a variable speed DC drive shall be designed. A separately excited dc machine with a compensation winding and the following rated data has been chosen:

$U_N = 440$ V, $I_N = 120$ A

The total armature resistance is $R_a = 0.3\ \Omega$. The open circuit voltage as a function of the exciting *Ampere* turns $U_0 = f(\Theta_f)$ has been measured (Fig. 4.6-1) at a rotor speed $n = 500$ min^{-1}. During final testing at the manufacturer´s test bench it was revealed, that due to over-commutation, the speed of the machine (at $U = U_N$ and constant excitation) INCREAESES from $n_N = 600$ min^{-1} under no-load conditions linearly to $n = 618$ min^{-1} at $I_a = I_N$.

1) Determine the exciting *Ampere* turns Θ_f, for which the motor no-load speed will be $n_0 = 600$ min^{-1}.

2) How do we have to choose the number of turns per pole of an auxiliary series excitation winding, so that for operation at rated voltage and excitation according to 1) the speed will be $n_0 = 600$ min^{-1} and at $I_a = I_N$ the speed will be $n = 550$ min^{-1} ? Neglect the resistance of the auxiliary series excitation winding.

3) At the customer, the machine shall be operated without auxiliary series excitation winding, being supplied by a 6-pulse controlled rectifier bridge. Sketch the electric circuit of the DC drive for one quadrant operation acc. to 3).

4) The voltage drop at the bridge due to current overlapping of two phases during the current commutation from one thyristor to the next, is considered by an equivalent armature resistance 0.15 Ω. Does the speed characteristic $n = f(I_a)$ for a constant voltage $U_{d0} = 440$ V and an excitation according to 1) still INCREASE with load in the range of $0 \le I_a \le I_N$? (U_{d0}: Rectified DC voltage without consideration of current overlapping in the bridge.)

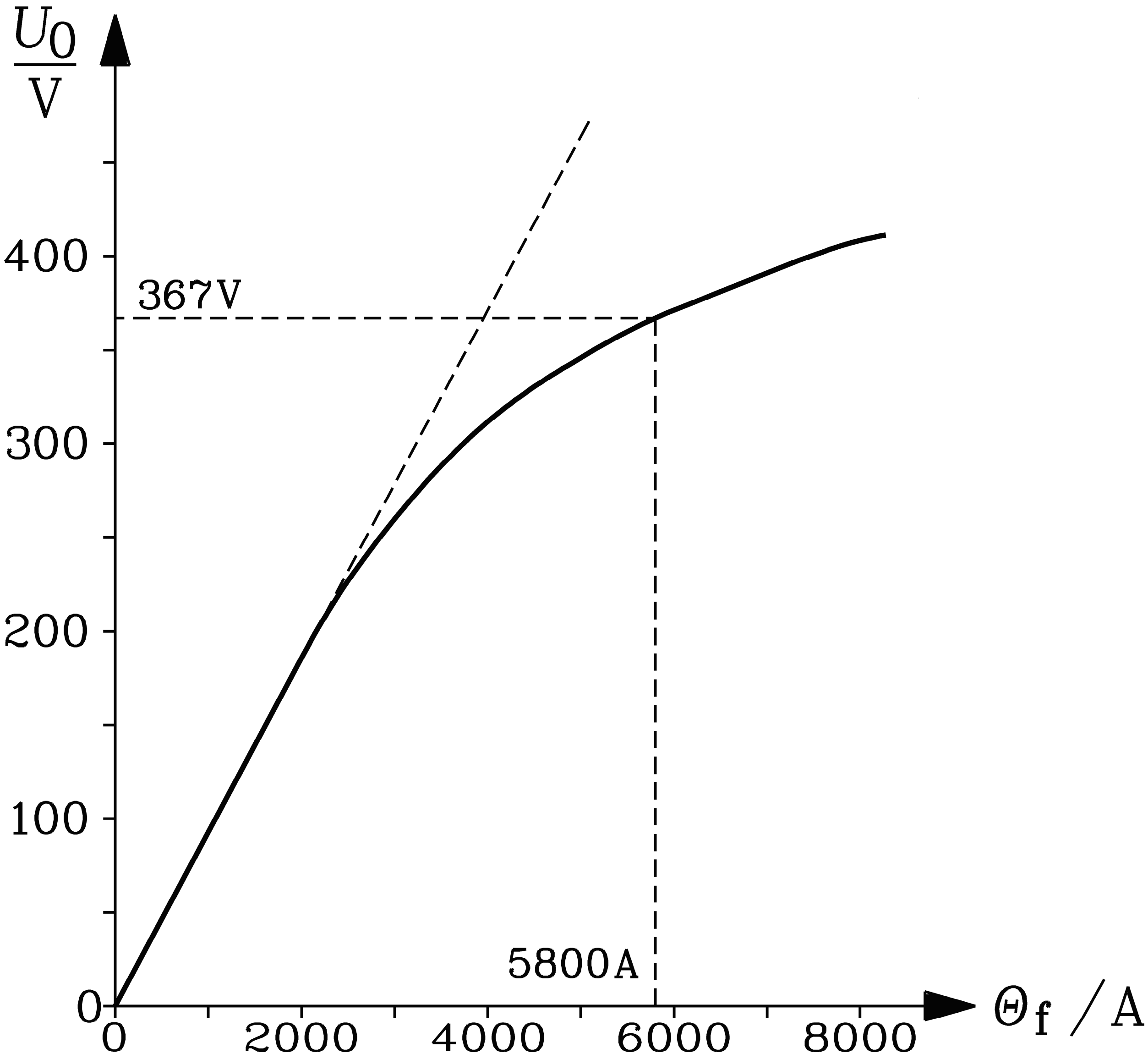


Fig. 4.6-1: Open-circuit voltage characteristic, depending on excitation Ampere turns, at 500/min

Solution:

1) $U_N = 440$ V, no-load operation: $I_a = 0$ A : $U_i = U_N = k_1 \cdot n \cdot \Phi(I_f) = 440$ V at 600/min.
At $n = 500$ min^{-1} the induced voltage U_i is by a factor 500/600 smaller: $5/6 \cdot 440\ \text{V} = 367\ \text{V}$
$\Rightarrow \Theta_f = \underline{\underline{5800\ \text{A}}}$ according to Fig. 4.6-1.

2) Due to over-commutation the main flux is reduced (Fig. 4.6-2) with increasing armature current. Hence, if this flux reduction is big enough, speed rises with rising load instead of decreasing (Fig. 4.6-3).

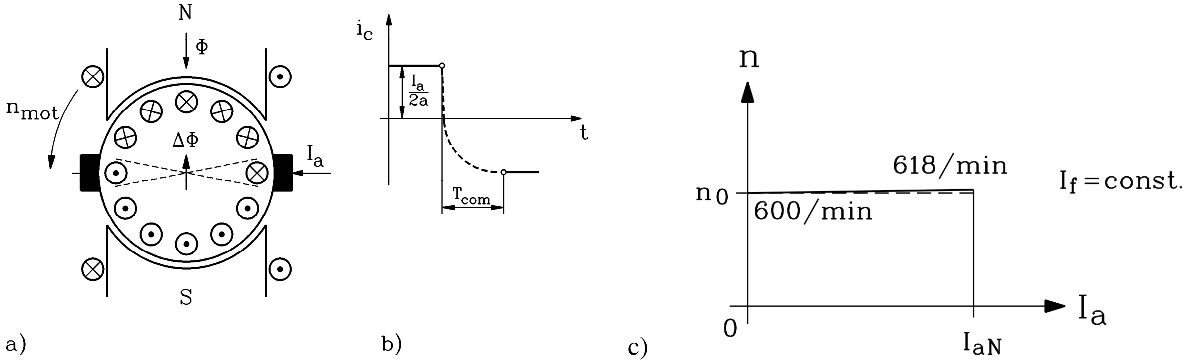


Fig. 4.6-2: a) The commutating coil has, due to over-commutation, already reversed coil flux linkage, hence, it excites a coil flux $\Delta\Phi$ that weakens the main flux Φ. b) The current commutates too quick due to too large commutation field of compoles (= over-commutation). c) Motor speed rises with rising load instead of decreasing.

$U = k_1 \cdot n \cdot \Phi + I_a \cdot R_a$ Fig. 4.6-2c): $n = n_0 \cdot \left(1 + \frac{I_a}{I_N}\frac{\Delta n}{n_0}\right)$ $\Delta n = 18/\min$

$$k_1 \cdot \Phi = \frac{U - I_a \cdot R_a}{n_0 \cdot \left(1 + \frac{I_a}{I_N}\frac{\Delta n}{n_0}\right)}$$ with $U = 440\ \mathrm{V}$ and $R_a = 0.3\ \Omega$

From that equation we calculate main flux

at no-load:	at rated load:
$I_\mathrm{a} = 0\mathrm{A}, n_0 = 600/\min$	$I_\mathrm{a} = 120\mathrm{A}, n = 618/\min$
$k_1 \cdot \Phi = 44\ \mathrm{Vs}$	$k_1 \cdot \Phi^* = 39.2\ \mathrm{Vs}$

Loss of flux: $k_1 \cdot \Delta\Phi = 39.2 - 44 = -4.77\ \mathrm{Vs}$

This loss of flux must be compensated by an additional series excitation winding. It shall be achieved: $n_\mathrm{N} = 550/\min, I_\mathrm{a} = 120\ \mathrm{A}, U = 440\ \mathrm{V}$. This means, that flux has to be kept constant:

$$\Rightarrow k_1 \cdot \Phi = \frac{440 - 120 \cdot 0.3}{550/60} = 44.0\ \mathrm{Vs}$$

The auxiliary series excitation winding has to fully compensate the loss of flux $k_1 \cdot \Delta\Phi$. According to Fig. 6.4-1 the reduced flux $k_1 \cdot \Phi^*$ induces a voltage U_0 at $n = 500\ \mathrm{min}^{-1}$ of $U_0^* = 39.2 \cdot 500/60 = 326.7$ V, which corresponds to *Ampere* turns $\Theta_\mathrm{f}^* = 4350$ A. Therefore, the auxiliary series excitation winding has to provide additional *Ampere* turns of $\Theta_\mathrm{RS} = 5800\ \mathrm{A} - 4350\ \mathrm{A} = 1450\ \mathrm{A}$, to keep flux of $k_1 \cdot \Phi = 44$ Vs constant.

$$N_\mathrm{RS} = \frac{\Theta_\mathrm{RS}}{I_\mathrm{aN}} = \frac{1450\ \mathrm{A}}{120\ \mathrm{A}} = 12.08 \qquad \Rightarrow \qquad N_\mathrm{RS} = \underline{\underline{12\ \text{turns/pole}}}$$

3) Power converter circuit for 1-quadrant motor operation:

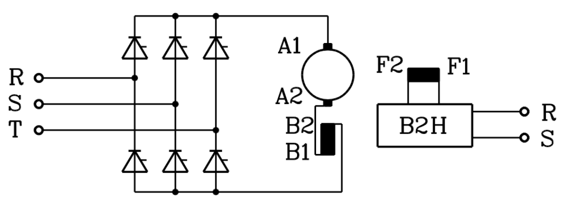


Fig. 4.6-3: Six-pulse, full controlled bridge for armature, two-pulse, half controlled bridge (cheaper!) for excitation

4) Current commutation from one thyristor to another gives finite overlapping time *ü*. This time increases with current: *ü* ~ I_a ! Rectified voltage is smaller due to that overlap by the value ΔU (so-called "*Dällenbach*"-voltage drop), which can be represented by an equivalent resistor R_{eq}.

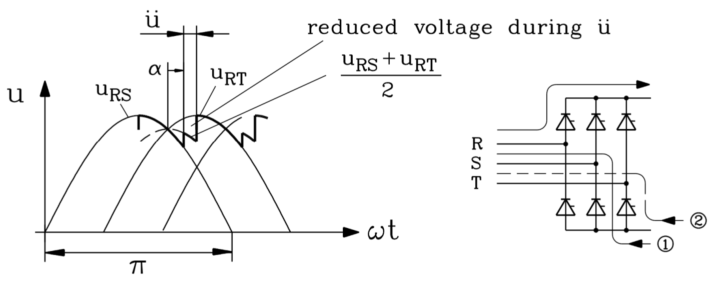


Fig. 4.6-4: Six-pulse, full controlled bridge: Current overlap during thyristor commutation from (1) to (2) yields additional voltage drop

The motor armature voltage is therefore $U_{di} \cdot \cos\alpha - \Delta U$ instead of $U_{di} \cdot \cos\alpha$.

From 2) we know: Flux reduction due to over-commutation at full load:

$$-k_1 \Delta\Phi \frac{I_a}{I_N} + k_1\Phi = k_1\Phi^*(I_a): \qquad I_a = I_N : k_1\Phi^*(I_N) = 39.2\,\text{Vs}$$

Additional voltage drop due to thyristor commutation:

$$R_{eq} \cdot I_a = \Delta U = 0.15 \cdot 120 = 18\,\text{V}$$

This additional voltage drop causes the speed to DECREASE down to 591/min with increasing load, even under over-commutation !

$$n = \frac{U - (R_a + R_{eq}) \cdot I_a}{k_1\Phi(I_a)} = \frac{440 - (0.3 + 0.15) \cdot 120}{39.2} = 9.85\,\text{s}^{-1} = 591/\text{min}$$

$$\underline{\underline{n(I_a = I_N) = 591/\text{min} < n_0 = 600/\text{min}}}$$

Result: The voltage drop ΔU stabilizes the motor.

Exercise 4.7: Different methods to brake electrically a DC motor at fixed voltage

A separately excited, compensated DC machine is operated with constant flux at a constant DC voltage in the test field of the manufacturer.

Motor data:

$U_N = 440$ V, $I_N = 120$ A, $n_N = 600$ min^{-1}

Total resistance of armature circuit: $R_a = 0.3\ \Omega$

1) Evaluate motor efficiency, assuming only armature resistive losses, without consideration of excitation losses ! Determine rated motor power, the rated torque and the no-load speed !

2) Starting from rated operation according to operating point 1), the torque is suddenly reversed, and the motor is loaded with negative rated torque as **“regenerative brake”,** operating point 2). Draw the *n*(*M*)-characteristic with both operating points 1) and 2) and give a power balance for both operating points.

3) The motor shall be used as drive for **an elevator**. For testing, adjustable speed is obtained by using a variable armature series resistance R_V. While lowering the load at speed

inversion after the lifting operation), the motor is operating as a braking generator. To which value does R_V need to be adjusted in order to provide lowering braking at $-n_N$ at rated torque (operating point 3)? Draw the $n(M)$-characteristic with operating point 1) and 3). Give a power balance for point 3).

4) The motor armature is – starting from operating point 1 – disconnected from the grid and switched to a **braking resistor R_B**. The motor acts as a braking generator, dissipating the power as heat in the braking resistor. How big must R_B be, so that the motor brakes with rated torque (operating point 4)? Draw the $n(M)$-characteristic with operating point 1) and 4). Give a power balance for point 4).

5) The motor armature supply voltage is – starting from operating point 1 – reversed to the negative rated voltage. This causes a current reversal, which yields **negative motor torque, thus braking the motor.**

a) How big is the armature current directly after reversing the voltage polarity?
b) Is this operating condition permissible?
c) How big does an armature series resistor R_V need to be, to ensure rated current after the voltage reversal (operating point 5)?
d) Draw the $n(M)$-characteristic with operating point 1) and 5). Give a power balance for point 5). Why does the motor need to be disconnected from the grid during braking operation?

Solution:

1)

$$P_{Cu} = R_a \cdot I_N^2 = 0.3 \cdot 120^2 = 4320\ \text{W} = \text{"total losses"}$$

$$P_{in} = P_{el} = U_N \cdot I_N = 440 \cdot 120 = 52800\ \text{W}$$

$$\eta_{mot} = \frac{P_{in} - P_{Cu}}{P_{in}} = \frac{52800 - 4320}{52800} = \underline{\underline{91.82\%}}$$

$$P_N = P_{mN} = P_{in,N} - P_{Cu} = 52800 - 4320 = \underline{\underline{48480\ \text{W}}}$$

$$M_N = \frac{P_N}{2 \cdot \pi \cdot n_N} = \frac{48480}{2\pi(600/60)} = \underline{\underline{771.6\ \text{Nm}}}$$

$$U_i = k_1 \cdot \Phi \cdot n,\ k_1\Phi = const.\ \text{(separate excitation)}:\ n_0 = \frac{U_N}{k_1\Phi}$$

$$n_N = \frac{U_i}{k_1\Phi} = \frac{U_N - I_N R_a}{k_1\Phi} \Rightarrow k_1\Phi = \frac{U_N - I_N R_a}{n_N}$$

$$n_0 = \frac{U_N}{U_N - R_a I_a} \cdot n_N = \frac{440}{440 - 120 \cdot 0.3} \cdot 600 = \underline{\underline{653.5/\text{min}}}$$

2)

$$U_N = U_i + I_a \cdot R_a,\ M_e = k_2\Phi \cdot I_a : M_N \to -M_N \Rightarrow$$

$$\text{Operating point 2}: U_N = U_i - I_N R_a : U_i = U_N + I_N R_a = 440 + 120 \cdot 0.3 = 476\ \text{V}$$

$$n = \frac{U_i}{k_1\Phi} = \frac{476}{40.4} = 1178/\text{s} = \underline{\underline{707/\text{min}}}$$

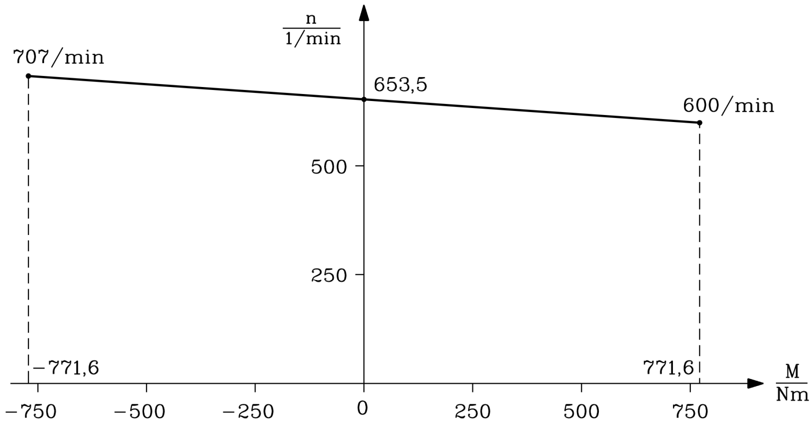


Fig. 4.7-1: Regenerative braking in the 2nd quadrant at 707/min

$P_e = P_m + P_{Cu}$ Power balance:

Operating point 1: $P_e = U_N I_N = \underline{\underline{52800\ W}},\ P_{Cu} = R_a I_a^2 = \underline{\underline{4320\ W}}$

$P_m = 2\pi n_N M_N = \underline{\underline{48480\ W}} = \underline{\underline{52800\ W - 4320\ W}}$

Operating point 2: $P_e = U_N(-I_N) = \underline{\underline{-52800\ W}},\ P_{Cu} = R_a(-I_N)^2 = \underline{\underline{4320\ W}}$

$$P_m = 2\pi n(-M_N) = 2\pi\frac{707}{60}(-771{,}64) = \underline{\underline{-57120\ W}}$$

$= \underline{\underline{-52800\ W - 4320\ W}}$

3) $U_N = U_i + I_a(R_a + R_V)$ $\quad I_a = I_N \Leftrightarrow M = M_N \quad U_N = k_1\Phi \cdot n,\quad n = -n_N$

$$R_V = \frac{U_N + k_1\Phi n_N}{I_N} - R_a = \frac{440 + 40.4\cdot(600/60)}{120} - 0.3 = \underline{\underline{6.73\,\Omega}}$$

Operating point 3: (Power balance)

$P_e = U_N I_N = \underline{\underline{52800\ W}}$

$P_m = 2\pi(-n_N)M_N = \underline{\underline{-48480\ W}}$

$P_{Cu} = (R_a + R_V)I_N^2 = 7{,}03\cdot 120^2 = \underline{\underline{101280\ W}}$

$= P_e - P_m = \underline{\underline{52800\ W - (-48480)\ W}}$

Both electrical and mechanical power are supplied to the motor and are dissipated inside R_a+R_V. Therefore, from an energy point of view, variable speed obtained by the utilisation of an armature series resistor is very disadvantageous (see Fig. 4.7-2).

4) Operating point 1: $U_N = U_i + I_a R_a \rightarrow 0 = U_i + I_a(R_a + R_B)$

$(U_i = 440 - 120\cdot 0{,}3 = 404\ V)$

Due to rotor inertia, speed n stays constant directly after reconnecting to R_B ($n = n_N$!)

$$M = -M_N \Rightarrow I_a = -I_N \Rightarrow I_a = \frac{-U_i}{R_a + R_B} = -I_N : R_B = \frac{-U_i}{I_a} - R_a \Rightarrow$$

$$R_B = \frac{-404}{-120} - 0.3 = \underline{\underline{3.067\,\Omega}}$$

$$I_a = -\frac{U_i}{R_a + R_B} \Rightarrow M \sim n : \text{Line through origin! See Fig. 4.7-3 !}$$

Operating point 4: (Power balance)

$P_e = U \cdot I_a = 0 \cdot I_a = \underline{\underline{0\ W}}$

$P_{Cu} = (R_B + R_a) I_a^2 = (3{,}067 + 0{,}3)120^2 = \underline{\underline{48480\ W}} = -P_m$

$P_m = 2\pi n_N(-M_N) = \underline{\underline{-48480\ W}}$

The mechanical power P_m is converted into heat inside the braking and armature resistors.

5) Operating point 1: $U_N = U_i + I_a R_a = k_1 \Phi \cdot n_N + I_N R_a$

Operating point 5: $U \to -U : -U_N = k_1 \Phi \cdot n_N + I_a R_a$ Because of the rotor inertia, the speed n stays constant directly after inverting the armature voltage!

a) $I_a = \dfrac{-U_N - k_1 \Phi \cdot n_N}{R_a} = -\dfrac{440 + 404}{0.3} = -2813.3\ \text{A (!) (23.4 times the rated current !)}$

$\Rightarrow 23.4^2 = 549.6$ times the rated losses !

b) The winding will be thermally overloaded and destroyed ! Not allowed operating point !

c) Design of series armature resistor to limit over-current:

$$I_a = \frac{-U_N - k_1 \Phi \cdot n_N}{R_a + R_V} = -\frac{440 + 404}{0.3 + R_V} = -120\ \text{A} = -I_N \Rightarrow R_V = \underline{\underline{6.73\ \Omega}}$$

d) See Fig. 4.7-4 for *n(M)*-curve !

The motor has to be disconnected from the grid at $n = 0\ \text{min}^{-1}$, otherwise it will accelerate up to $n_0' = -n_0$.

$-U_N = k_1 \Phi \cdot n + I_a (R_a + R_V)$: new no-load speed n_0'

$$n_0' = \frac{-U_N}{k_1 \Phi}(I_a = 0) = -\frac{440}{40{,}4} = -653.5/\text{min}$$

Operating point 5: (Power balance)

$P_e = -U_N \cdot (-I_N) = \underline{\underline{52800\ W}}$

$P_m = 2\pi n_N(-M_N) = \underline{\underline{-48480\ W}}$

$P_{Cu} = (R_V + R_a) I_N^2 = \underline{\underline{101280\ W = P_e - P_m}}$

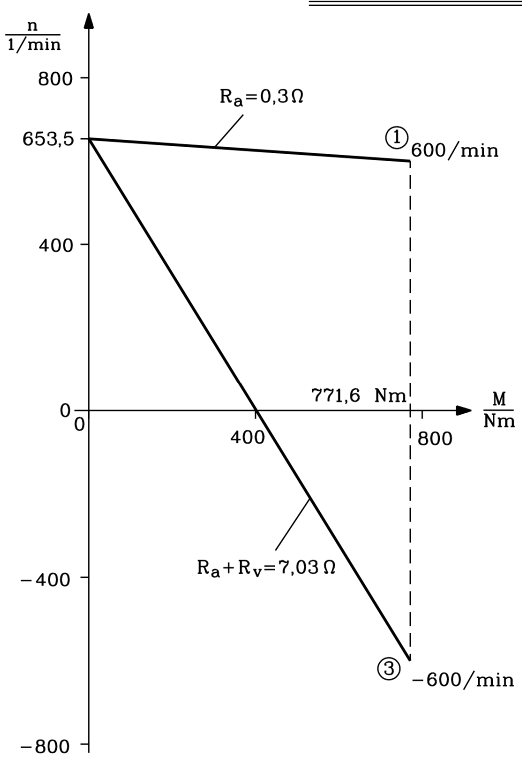


Fig. 4.7-2: Elevator operation: Lowering of load with series resistor: High resistive losses !

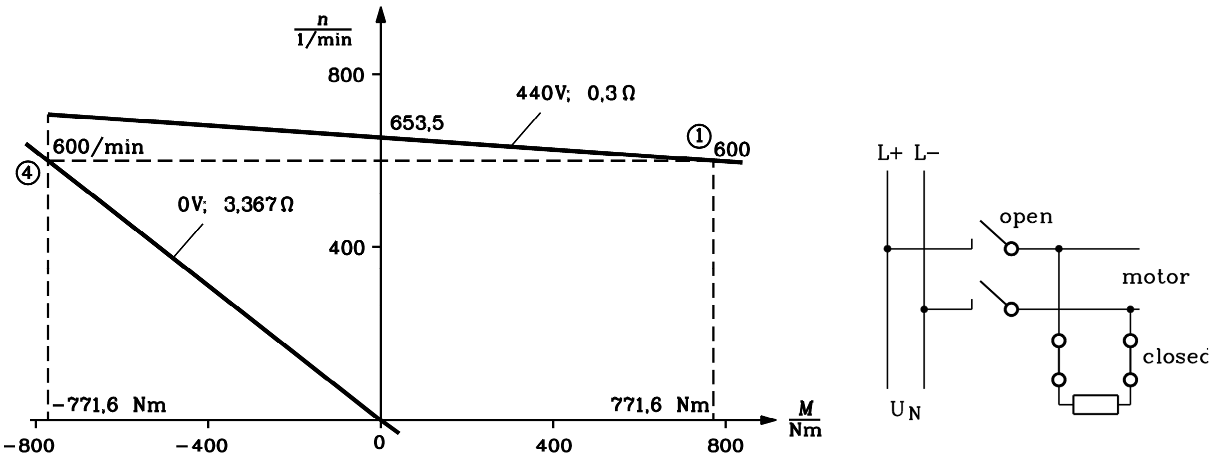


Fig. 4.7-3: Use of external resistor for braking of motor: Disconnection from voltage supply L+, L-, and switching to resistor.

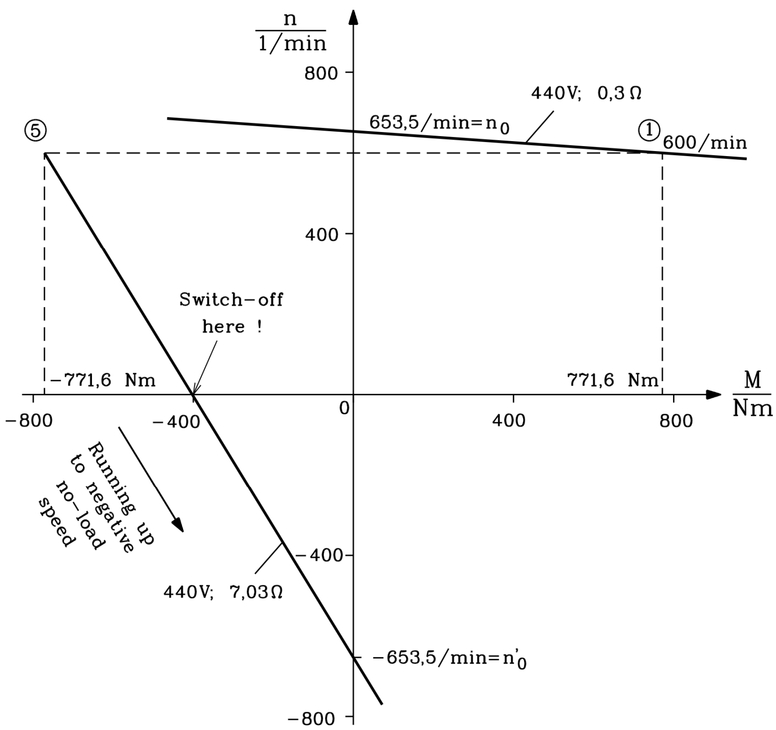


Fig. 4.7-4: Braking of DC motor by reversal of voltage. If full voltage is applied, an additional series resistor is necessary to limit current !

Exercise 4.8: DC hoisting motor for container crane

For a *Rotterdam* harbour container crane, two converter-fed, 6-pole, separately excited DC machines have been designed. To save costs, both machines are non-compensated.

Machine data:

P_N = 440 kW, n_N = 1000 min^{-1}, U_N = 780 V, η = 93 %

Design specifications of the motors:

Armature winding: Q = 75 armature slots, lap winding, u = 5, N_C = 1

Commutation (Inter-pole) winding: $N_{W,pole}$ = 13, Inter-pole air gap δ_W = 9 mm

Calculated reactance voltage of commutation at rated operation: u_R = 3.55 V

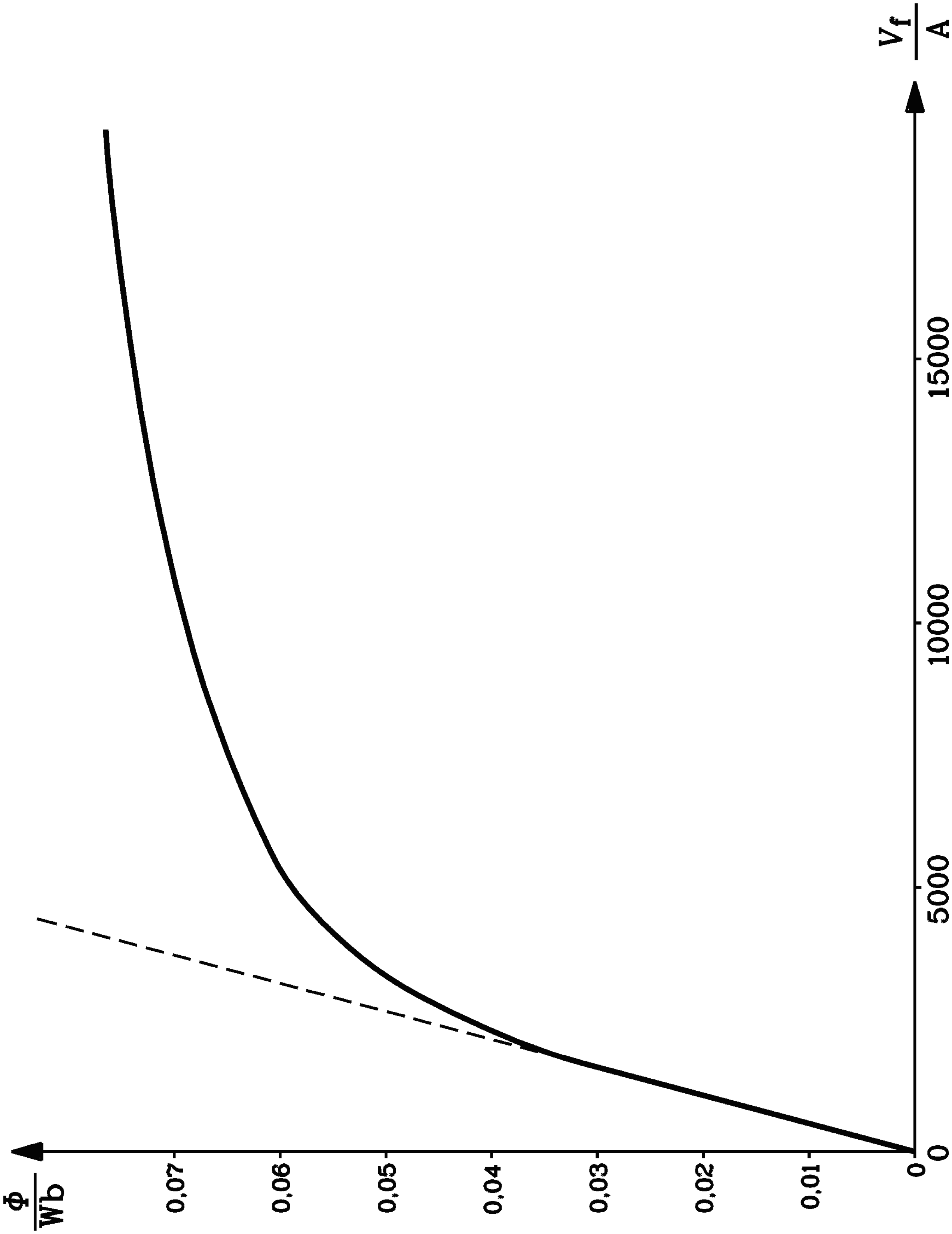


Fig. 4.8-1: Main flux versus exciting m.m.f. per pole

Total armature resistance: $R_a = 0.0426\ \Omega$, rotor diameter / length: 0.6 m / 0.24 m
Calculated magnetic characteristic $\Phi(V_f)$ according to Fig. 4.8-1.

1) Determine rated armature!
2) How big is the total number of armature conductors z and the number of commutator segments K ?
3) Calculate the magnetic inter-pole air gap flux density $B_{\delta W}$ at rated current!
4) How big is the induced voltage into the commutating winding (compole voltage) u_W at rated operation? Is the inter-pole magnetic circuit designed poperly or does the inter-pole air gap need to be adjusted? If so, how does it need to be changed?
5) Up to which maximum field weakening rotational speed n_R can the motor be operated without exceeding the permissible reactance voltage of commutation?
6) The excitation current shall be I_f = 24 A at rated operation. Chose the right number of turns N_f per pole ! Calculate the field current for P_N at n_R ! In both calculations, take a brush contact voltage of U_b = 2 V into consideration.

Solution:

1)
$$I_{a,N} = P_e / U_N = \frac{P_m}{\eta} \cdot \frac{1}{U_N} = \frac{P_m}{\eta \cdot U_N} = \frac{440000}{0.93 \cdot 780} = \underline{\underline{606.6\ \text{A}}}$$

2)
$$z = Q \cdot u \cdot N_C \cdot 2 = 75 \cdot 5 \cdot 1 \cdot 2 = \underline{\underline{750}} \qquad K = Q \cdot u = 75 \cdot 5 = \underline{\underline{375}}$$

3) Lap winding: $a = p = 3$, $2p = 6$, $N_{W,pole} = 13$

$$N_{a,pole} = \frac{z}{8 \cdot a \cdot p} = \frac{750}{8 \cdot 3 \cdot 3} = 10.417$$

$$B_{\delta,W} = \mu_0 \frac{N_{W,pole} - N_{a,pole}}{\delta_W} \cdot I_N = 4\pi \cdot 10^{-7} \frac{13 - 10.417}{9 \cdot 10^{-3}} \cdot 606{,}6 = \underline{\underline{0.219\ \text{T}}}$$

4)
$$v_a = d_r \cdot \pi \cdot n_N = 0{,}6 \cdot \pi \cdot \frac{1000}{60} = 31{,}4\ \text{m/s}\ (= 113\ \text{km/h}) \qquad l = 0.24\ \text{m}$$

$$u_W = 2 \cdot N_C \cdot v_a \cdot l \cdot B_{\delta,W} = 2 \cdot 1 \cdot 31{,}4 \cdot 0.219 \cdot 0{,}24 = \underline{\underline{3.30\ \text{V}}}$$

$u_R(I_N, n_N) = 3.55\ \text{V} > 3.3\ \text{V}$: The inter-pole winding is designed <u>too weak</u>.
Reducing the inter-pole air gap by adding additional iron sheets helps to correct that.
It shall be: $u_W = u_R$!

$$u_W \sim B_{\delta,W} \sim 1/\delta_W \Rightarrow \delta_{W,corr} = \frac{u_W}{u_R} \delta_W = \frac{3.30}{3.55} \cdot 9 = 8.37 \approx \underline{\underline{8.4\ \text{mm}}}$$

5) $u_{R,max} = 10\ \text{V}$ maximum permissible reactance voltage of commutation !

$$u_R \sim I_a \cdot n, \qquad u_{RN} = 3.55\ \text{V}$$

$$u_{R,max} = u_{RN} \frac{I_a}{I_N} \cdot \frac{n_{max}}{n_N} \bigg|_{I_a = I_N} \Rightarrow n_{max} = n_N \frac{u_{R,max}}{u_{R,N}} = 1000 \cdot \frac{10}{3.55} = 2817/\text{min}$$

$$n_R = n_{max} = \underline{\underline{2817/\text{min}}}$$

6) $I_{fN} = 24\ A,\ R_a = 0.0426\ \Omega$

$$U_N = U_i + R_a \cdot I_{aN} + U_b$$

$$U_{iN} = U_N - R_a \cdot I_{aN} - U_b = 780 - 0.0426 \cdot 606.6 - 2 = 752.2\,V$$

$$\Rightarrow U_{iN} = z \cdot \frac{p}{a} \cdot n \cdot \Phi_N \Rightarrow \Phi_N = \frac{752.2}{750 \cdot \frac{3}{3} \cdot \frac{1000}{60}} = 60.2\ mWb$$

$\Phi = 60.2\ mWb \Rightarrow \Phi(V_f) - characteristic\ Fig.\,4.8\text{-}1\ (see\ Fig.\,4.8\text{-}2) \Rightarrow V_{f,N} = 5400\ A$

$$I_{f,N} = V_{f,N} / N_f \Rightarrow N_f = \frac{5400}{24} = \underline{\underline{225}}$$

at P_N, n_R:

$P_N = \dfrac{U_N \cdot I_N}{\eta} \Rightarrow I_N = 606.6\ \text{A}$ also at n_R and with the same efficiency η:

$\Rightarrow U_i = \text{const.} = 752.2\ \text{V}$ at $n = n_R$, too.

$n_R = 2817/\text{min}:\ \Phi = \dfrac{752.2}{750 \cdot \frac{3}{3} \cdot \frac{2817}{60}} = 0.0214\ \text{mWb}$, From $\Phi(V_f) -$ characteristic

Fig. 4.8-1 we get: $V_f = 1100\ \text{A} \Rightarrow I_f = \dfrac{1100}{225} = \underline{\underline{4.89\ \text{A}}}$

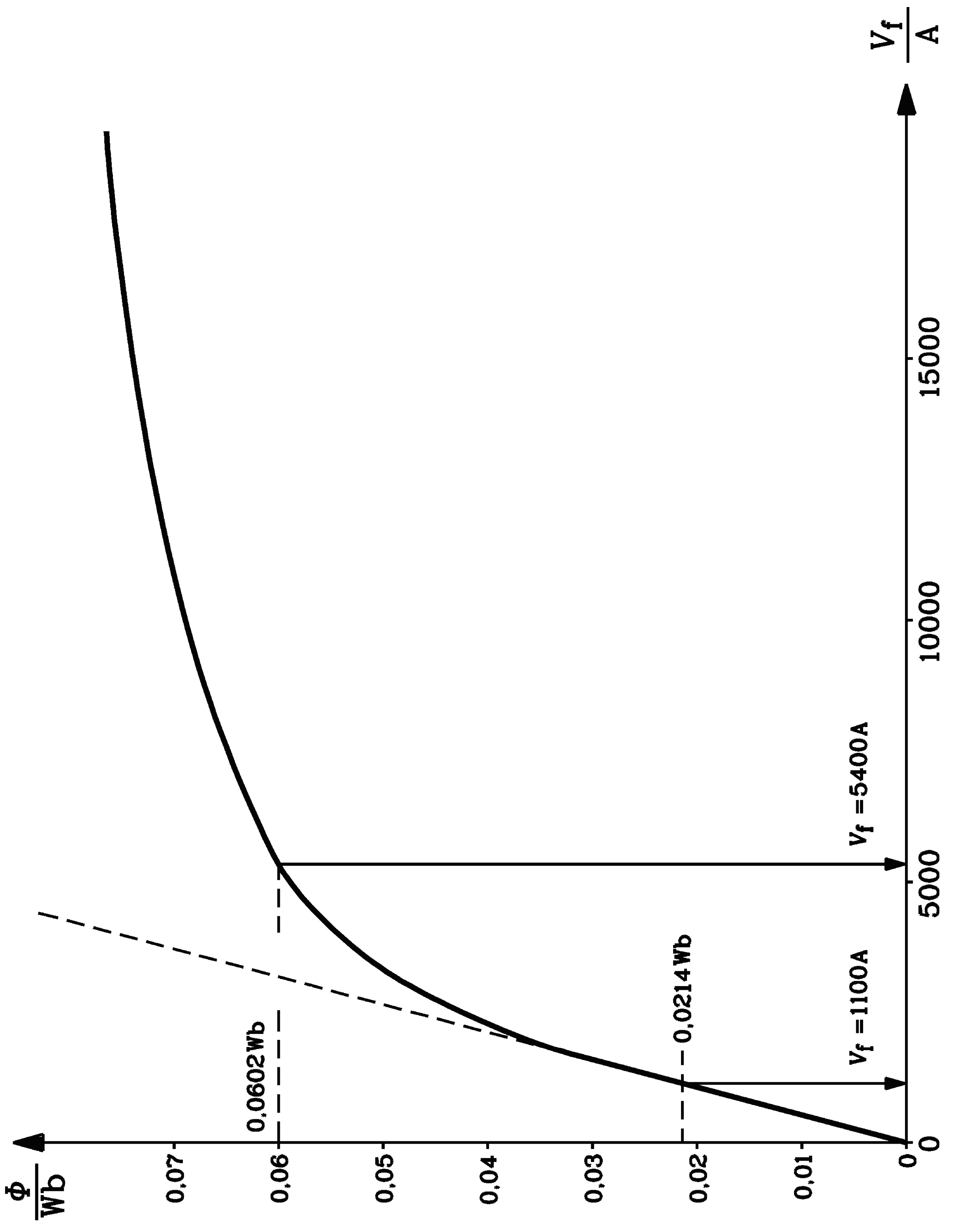


Fig. 4.8-2: Main flux versus exciting m.m.f. per pole: Flux at rated speed 1000/min and flux weakening 2817/min