PL 6 – AC Motors – Selection (2)

Objectives: - Braking of AC induction motors (constant frequency)
- Practicing Exercises with three-phase induction motors

Documents available
PL classes:
1) SEW_DT71D4_ClassPL6.pdf
2) SEW_SDT100LS8_2_ClassPL6.pdf
3) SEW_Brake_Data_ClassPL6.pdf
4) SEW_Drive_Engineering_10522913_Project Planning for Drives .pdf (see *link*) https://download.sew-eurodrive.com/download/pdf/10522913.pdf

Braking Systems for Three-Phase Induction Motors

1. Introduction

In industrial applications, braking an induction motor is essential for safety, precision positioning, and reducing cycle times. Modern braking strategies are divided into two primary categories: **Electromechanical** (physical friction) and **Electrical** (electromagnetic interaction).

2. Electromechanical Braking

Electromechanical braking utilizes physical contact to arrest the motor shaft. It is often used as a "holding brake" to maintain position after the motor has stopped. These brakes are designed to be fail-safe: they engage automatically when power is removed and release only when the brake coil is energized.

- **Mechanism**:
    - **Friction Disc Braking Mechanism:** a friction disc, either flat or conical, is rigidly connected to the motor shaft. A spring forces this disc against a fixed surface to block movement (see video for flat friction disc)
- **Operation**:
    - **De-energized state (Safe State)**: when no electrical power is applied, the spring force engages the brake. This force defines the available braking torque (T_B)
    - **Energized state**: when the brake is energized, an electric actuator (typically a solenoid) overcomes the spring force and releases the friction disc, allowing the shaft to rotate. In conical-rotor brake motors (see Demag design), the brake release occurs automatically when the motor starts
- **Actuation Methods**:
    - Brake release can be achieved through an electric actuator (solenoid) that counteracts the spring force. The actuator may be powered by:
        - **Independent DC or AC Source** (Figure 1)
        - **Rectified AC voltage**: uses the motor's own phase currents via a rectifier bridge (Figure 2)
    - **In Conical-Rotor brake Motors** (see Demag), brake actuation relies directly on the motor's electromagnetic operation. When the motor is energized, the stator magnetic field produces not only a rotational torque but also an axial magnetic force. This axial force pulls the rotor axially, disengaging the brake. The friction disc has a conical geometry, and this axial movement assures the separation of the friction surfaces, releasing the brake (Figure 3). As a result, no external brake actuator or solenoid is required, since brake release is achieved purely by the motor's magnetic field. (https://www.demagcranes.com/en/products/drives/motors/conical-rotor-brake-motors, https://youtu.be/Es-xdcBcU38)

The operational performance of an electromechanical brake, specifically its response time during actuation (t_2) or deactivation (t_1), is not a fixed constant. These parameters are directly determined by the configuration of the control circuit and the specific type of power supply employed.

The choice of the various options and their conditions of use should be based on the information provided by the manufacturers of the motors.

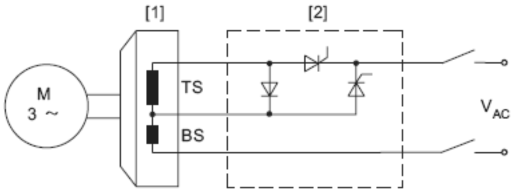


Figure 1 – Example from SEW – Drive Engineering- Practical Implementation – Disc Brakes

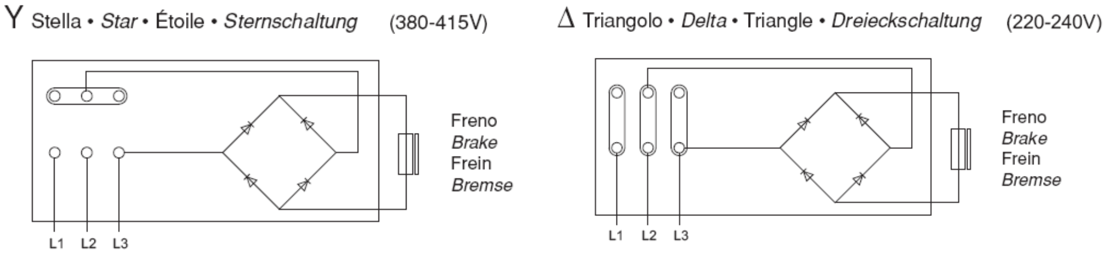


Figure 2 – Examples from Carpanelli Motori Elettrici- Technical catalogue

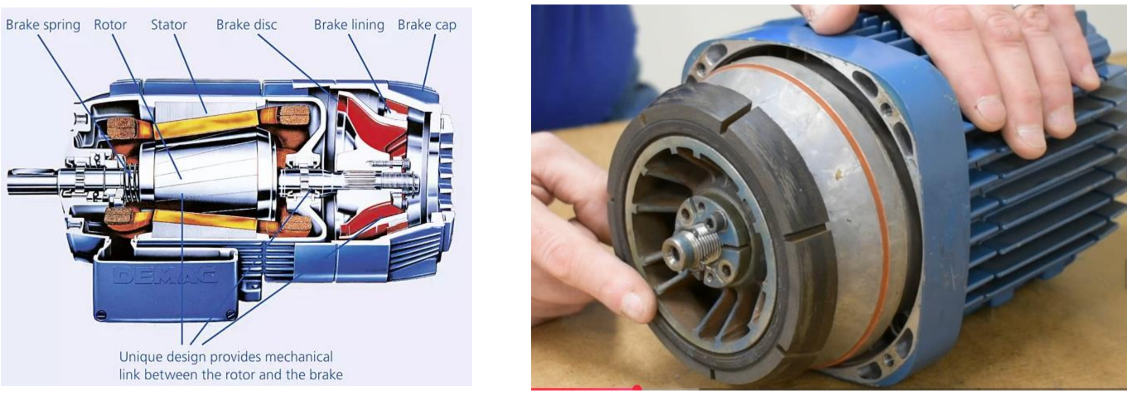


Figure 3 – Demag Conical-Rotor Brake Motor (KB series) using conical friction disk (ref)

2.1 Key technical data points to consider

2.1.1 Mechanical & Performance Ratings

- **Nominal Braking Torque (T_B):** the **static** torque exerted by the spring force when the brake is not actuated.
- **Permissible Braking Work (W_{max}):** the maximum energy the brake can dissipate in a single stop or per hour without overheating.
- **Maximum Operating Speed:** the highest RPM at which the mechanical brake can safely be engaged.

2.1.2 Dynamic Response Times

- **Application Time (t_2):** the interval between switching off the power and the brake actually engaging (reaching 10% or 90% torque).
- **Release Time (t_1):** the time required for the actuator (solenoid) to move the disc against the spring and free the shaft.
- **Switching Frequency:** the maximum number of braking operations permitted per hour to avoid thermal failure.

2.1.3 Electrical Specifications

- **Actuator Supply Voltage:** whether the solenoid requires an independent DC source or a specific AC rectified voltage.
- **Coil Current/Power:** the power consumption required to keep the brake released during motor operation.
- **Control Circuit Requirements:** specifications for the rectifiers or contactors needed to interface the brake with the motor power circuit.

2.1.4 Environmental & Maintenance Limits

- **Wear Allowance:** the minimum thickness of the friction disc before replacement is required.
- **Protection Rating (IP):** the level of protection against dust and moisture, especially for friction-based systems.
- **Manual Release Availability:** whether the unit includes a hand lever to release the brake during power failures or maintenance.

3. Electrical Braking Strategies

Electrical braking leverages the motor's ability to act as a generator, converting kinetic energy into electrical energy.

3.1 Regenerative Braking

Occurs when the motor is driven by the load above its synchronous speed (negative slip) (Figure 4).

- **Process**: the motor acts as a generator, returning active power to the grid.
- **Applications:** hoists, winches, or downhill conveyors where the load "overhauls" the motor.
- **Constraint**: the power supply must be capable of absorbing the returned energy.

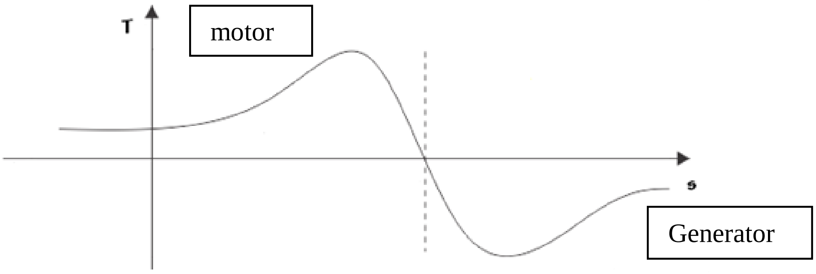


Figure 4 – Torque-speed curve for induction motor

3.2 Plugging (Reverse Current Braking)

Achieved by interchanging two stator phases while the motor is running, until the motor runs close to stopping (Figure 5).

- **Effect**: the rotating magnetic field reverses direction, creating a massive braking torque.
- **Warning**: this creates extremely high currents and mechanical stress. It should only be used after consulting manufacturer specifications.

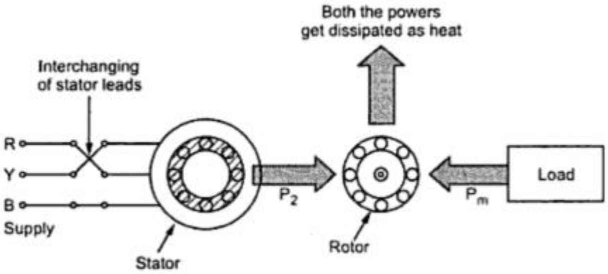


Figure 5 – Plugging (Reverse Current Braking)

3.3 DC Injection Braking

Consists of disconnecting the AC supply and injecting Direct Current into two phases of the stator windings. The DC current can be obtained from a power source or by rectification of the phases available for motor power (Figure 6).

- **Mechanism**: the DC current creates a stationary magnetic field. As the rotor moves through this field, a braking torque is generated.
- **Advantage**: smooth deceleration without the risk of the motor reversing direction.

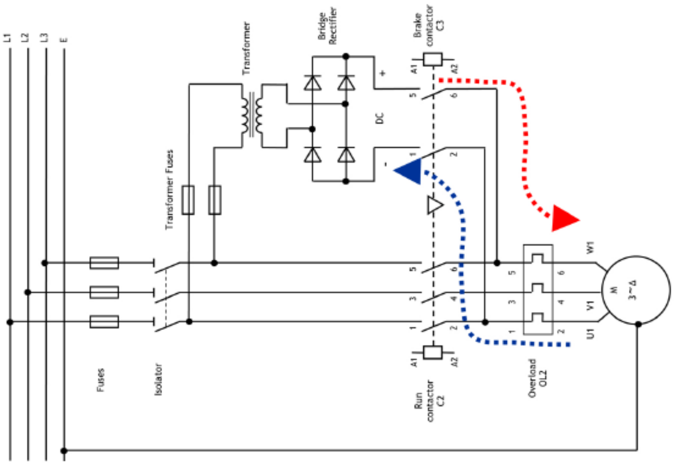


Figure 6 – DC Injection Braking

3.4 Dynamic & Self-Excited Braking

- **Self-Excited**: uses capacitors to maintain the magnetic field after the power is cut, dissipating energy through braking resistors or the windings themselves (Figure 7).
- **Phase Removal (Wound Rotor - legacy motors!)**: disconnecting or reconfiguring a phase to run the motor in an unbalanced "single-phase" mode, dissipating energy through rotor rheostats (Figure 8).

Ref. https://www.electrical4u.com/induction-motor-braking/

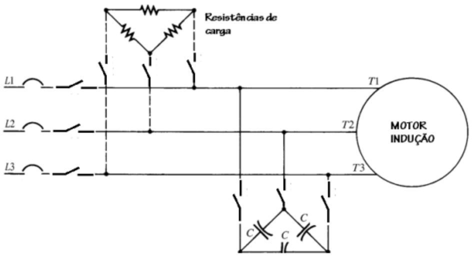


Figure 7 - Self-Excited

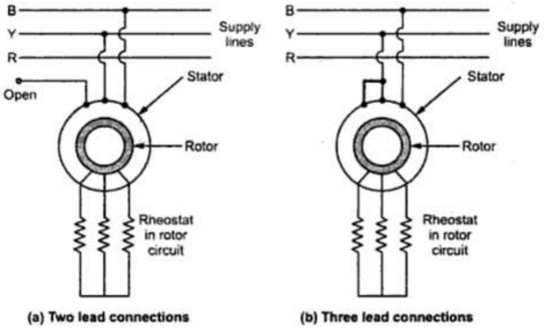
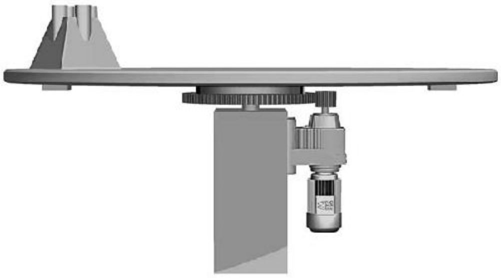


Figure 8 - Phase Removal (Wound Rotor)

2- Ex. TP6-1. Rotating table driven by a three-phase induction motor

Consider a rotating table and select a three-phase induction motor that meets the established drive requirements. Consider additionally the available data:



- $m_{moving\ parts} = 550\ kg$
- $m_{table\ moving\ mass} = 250\ kg$
- $\phi_{table} = 1.9\ \mathrm{m}$
- $\phi_{support\ bearings\ position} = 0.6\ \mathrm{m}$
- $\mu_{support\ bearings\ friction} = 0.015$
- $J^{table\ axis}_{total\ moving\ masses} = 650\ kgm^2$
- $n_{table} = 3.5\ rpm$
- $t_{acceleration} = 0.5\ s$
- $\eta_{global} = 71\ \%$, of the mechanical transmission system between the motor and the table (includes a gear box, pinion and sprocket, and a transmission ratio compatible with 4-pole motors per phase).

a) Choose a motor from the table in (SEW_DT71D4_ClassPL6.pdf) that best meets the specified requirements, in particular the indication for an acceleration time close to 0.5 seconds.
b) Represent the characteristic curve ($\boldsymbol{\omega}$,T), indicating the values corresponding to the chosen motor and the operating point for the maximum load.
c) What is the motor slip corresponding to the operating point?

3- Ex. TP6-2. Vertical load and motors with 2 velocities

(adapted from *SEW-Practical Drive Engineering*)

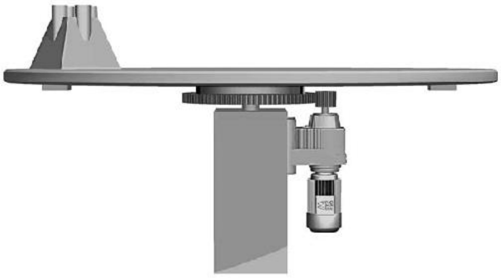
Consider a lifting platform for which you want to choose a two-speed three-phase induction motor that allows you to meet the drive requirements established according to the following data:

- $m_{load} = 300\ kg$
- $m_{moving\ platform} = 200\ kg$
- $v_{high} = 0.3\ m/s$
- $v_{low} = \frac{1}{4} v_{high}$
- $cdf = 50\%$
- $\eta_{global} = 85\ \%$
- transmission ratio compatible with 2/8 pole per phase motors

Normal travel will be done at high speed, both on the way up and down. The stop, on the ascent or descent movements, will be made through the brake incorporated into the motor, after switching to low speed.
Choose a motor from the table (SEW_SDT100LS8_2_ClassPL6.pdf) that is capable of meeting the specified requirements. Verify the motor's behaviour on the up and down movements, from start to stop conditions.

2- Ex. TP6-1. Rotating table driven by a three-phase induction motor

Consider a rotating table and select a three-phase induction motor that meets the established drive requirements. Consider additionally the available data:



- $m_{moving\ parts} = 550\ kg$
- $m_{table\ moving\ mass} = 250\ kg$
- $\phi_{table} = 1.9\ \mathrm{m}$
- $\phi_{support\ bearings\ position} = 0{,}6\ \mathrm{m}$
- $\mu_{support\ bearings\ friction} = 0.015$
- $J_{total\ moving\ masses}^{table\ axis} = 650\ kgm^2$
- $n_{table} = 3.5\ rpm$
- $t_{acceleration} = 0.5\ s$
- $\eta_{global} = 71\ \%$, of the mechanical transmission system between the motor and the table (includes a gear box, pinion and sprocket, and a transmission ratio compatible with 4-pole motors per phase).

a) Choose a motor from the table in (SEW_DT71D4_ClassPL6.pdf) that best meets the specified requirements, in particular the indication for an acceleration time close to 0.5 seconds.

b) Represent the characteristic curve ($\boldsymbol{\omega}$,T), indicating the values corresponding to the chosen motor and the operating point for the maximum load.

c) What is the motor slip corresponding to the operating point?

Solution problem 6.1: Rotating table with a three-phase induction motor

a) Selecting a motor from the motor´s table (**SEW_DT71D4_ClassPL6.pdf**) that closest satisfies the requirements established, in particular the acceleration time (0.5 sec).

Steps

1- Horizontal loads: use as reference for the motor´s nominal power (P_N) the total power (static + acceleration, i.e. P_{total}),

$$P_{total} = P_{acceleration\ J motor} + P_{acceleration\ J load} + P_{static}$$

Motor not selected yet:

$$P_{total} = P_{acel.Jload} + P_{static} = 246.6 + 18.2 = 264.8\ W$$

Load power, referred to motor´s shaft:

$$\begin{cases} P_{acel.Jload}^{motor} = T_{acel.Jload}^{motor} \cdot \omega_{motor} \\ or,\ P_{acel.Jload}^{motor} = \dfrac{T_{acel.Jload}^{load\ axis} \cdot \omega_{load}}{\eta_{global}} \\ T_{accel} = \boldsymbol{J} \cdot \alpha \\ \alpha = \dfrac{\Delta\omega}{\Delta t} \\ \Delta t = t_{accel} = 0.5\ sec \end{cases}$$

$$\begin{cases} P_{accel.Jload}^{motor} = \dfrac{477.1 \cdot 0.367}{0.71} = 246.6\ W \\ T_{accel} = 650 \cdot 0.734 = 477.1\ Nm \\ \alpha = \dfrac{0.367}{0.5} = 0.734\ rad/s^2 \\ \Delta t = t_{accel} = 0.5\ sec \end{cases}$$

$$\begin{cases} P^{motor}_{static} = \dfrac{T_{static} \cdot \omega_{load}}{\eta_{global}} \\ T_{static} = m_{total\_moving} \cdot g \cdot \mu \cdot \dfrac{\phi_{support\ bearings}}{2} \end{cases} \quad \begin{cases} P^{motor}_{static} = \dfrac{35.3 \cdot 0.367}{0.71} = 18.2\ W \\ T_{static} = (550 + 250) \cdot 9.81 \cdot 0.015 \cdot \dfrac{0.6}{2} = 35.3\ Nm \end{cases}$$

2- Selecting motor from table (SEW_DT71D4_ClassPL6.pdf):

$$\begin{cases} \mathrm{P_N} > \mathrm{P}_{total} \ \text{ or } (?^*):\ \mathrm{P_N} \approx \mathrm{P}_{total} \quad (^*) \\ motor\ 4\ poles \end{cases} \quad \begin{cases} \mathrm{P_N} \approx 264.8\ W \\ n_{sinc} = 1500\ rpm \end{cases}$$

(*) It should be taken into account that, using the total power (P_{total}) as a reference for the motor's nominal power (P_N), the motor will be oversized for operation at constant speed, since P_N will be much higher than P_{static}. Also the starting, and acceleration torque, of these type of motors are typically 2 to 3 times higher than nominal torque (T_N). So it can be justified that the selected motor´s power be less than the calculated total power, particularly if it is required for to limit the acceleration values.

To illustrate this situation various alternative motors were selected for evaluation.

3- Data from de selected motors SEW (1500 rpm) (SEW_DT71D4_ClassPL6.pdf)

Motor SEW: 1500rpm	157.08 rad/s	**DT71D4**	**DR63L4**	**DR63M4**	**DR63S4**
P_N	[kW]	0.37	0.25	0.18	0.12
n_N	[rpm]/[rad/s]	1380/144.51	1300/136.14	1320/138.23	1380/144.42
T_N	[Nm]	2.6	1.8	1.3	0.83
T_{start} (M_A)	[Nm]	4.68	3.24	2.34	1.99
J_M (with brake)	[$x10^{-4}kgm^2$]	5.5	5.6	4.8	4.8
Z_0 (BG)	[cycles/hour]	6000	10000	10000	10000

4- Verification of motors compatibility with load requirements.

- starting phase, calculating the acceleration time, assuming motor will work accelerate to nominal speed

$$\begin{cases} \Delta t = \dfrac{\left(J_{motor} + J^{motor}_{load}\right) \cdot \omega_N}{\sum T} = \dfrac{\left(J_{motor} + J^{motor}_{load}\right) \cdot \omega_N}{T_{accel} - T_{static}} = \dfrac{\left(J_{motor} + J^{motor}_{load}\right) \cdot \omega_N}{T_{accel} - \dfrac{P_{static}}{\omega_N}} \\ J^{motor}_{load} = \dfrac{J^{load\_axis}_{load} \cdot \left(\dfrac{\omega_{load}}{\omega_N}\right)^2}{\eta} \end{cases}$$

SEW Motor : 1500rpm	157.08 rad/s	**DT71D4**	**DR63L4**	**DR63M4**	**DR63S4**
P_N	[kW]	0.37	0.25	0.18	0.12
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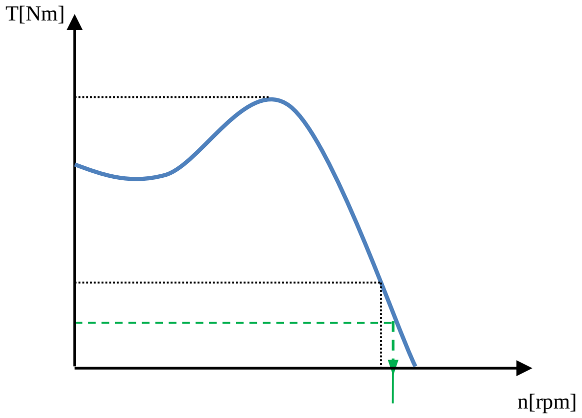
T_N	[Nm]	2.6	1.8	1.3	0.83
T_{start} (M_A)	[Nm]	4.68	3.24	2.34	1.99
J_M	[$\times10^{-4}$ kgm^2]	5.5	5.6	4.8	4.8
J_{load}^{motor}	[$\times10^{-4}$ kgm^2]	59.0	66.53	64.5	59.1
T_{static}	[Nm]	0.126	0.134	0.132	0.126
Δt	[sec]	0.205	0.316	0.434	0.495
$Z_0 \cdot K_p K_J K_T$	[cycles/hour]				

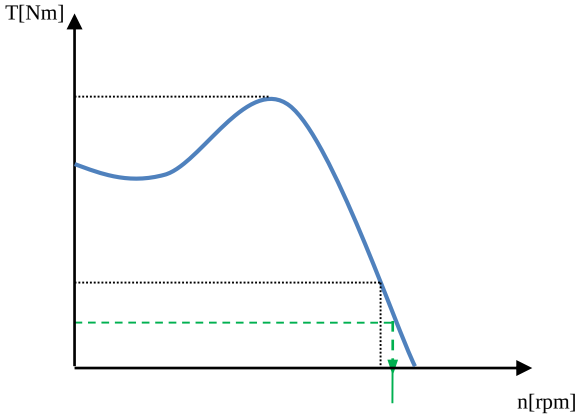
Comments:

- Given the difference between P_{accel} and P_{static} , the motor that best satisfies the acceleration time request (0.5 sec) is the motor with P_N (120 W), well below the calculated P_{accel} (246.6 W) and P_{static} (18.2 W) together, while keeping the acceleration and nominal torque well above the requirements.
- However, it should be noticed that other working operating conditions were not considered, i.e. duty cycle, starting/stopping frequency and inertias ratios (J_{load}/J_M).

As a suggestion, proceed with b) and c) considering the two identified motors.

b) Represent the characteristic curve (ω,T), indicating the values for the selected motor and the working point corresponding to maximum load.





c) Calculate the slip corresponding to the working point.

3- Ex. TP6-2. Vertical load and motor with 2 velocities

(adapted from *SEW-Practical Drive Engineering*)

Consider a lifting platform for which you want to choose a two-speed three-phase induction motor that allows you to meet the drive requirements established according to the following data:

- $m_{load} = 300\ kg$
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- $cdf = 50\%$
- $\eta_{global} = 85\ \%$
- transmission ratio compatible with 2/8 pole per phase motors

Normal travel will be done at high speed, both on the way up and down. The stop, on the ascent or descent movements, will be made through the brake incorporated into the motor, after switching to low speed.

Choose a motor from the table (SEW_SDT100LS8_2_ClassPL6.pdf) that is capable of meeting the specified requirements. Verify the motor's behaviour on the up and down movements, from start to stop conditions.

Solution problem 6.2: Selecting a motor from the motor´s table

(SEW_SDT100LS8_2_ClassPL6.pdf)

Selection steps

1- Vertical load movements: using as a reference for the nominal power of the motor (P_N) the static power (i.e. P_{static}),

$$P_{static} = m_{total} \cdot g \cdot v \cdot \frac{1}{\eta} = (300 + 200) \quad \cdot 9.81 \cdot 0.3 \cdot \frac{1}{0.85} = \frac{1471.52}{0.85} = 1731.2\ W$$

2- Motor selection from available motors table (SEW_SDT100LS8_2_ClassPL6.pdf):

$$\mathrm{P_N} > \mathrm{P}_{static} \quad \Rightarrow \quad \mathrm{P_N} > 1731.2\ W \ \Rightarrow \ \text{Motor (SDT100LS8/2):} \quad \mathrm{P_N} = 0.45\ /\mathbf{1.8}\ \text{kW}$$

3- Data of selected motor (**SDT100LS8/2**) (750/3000 rpm)

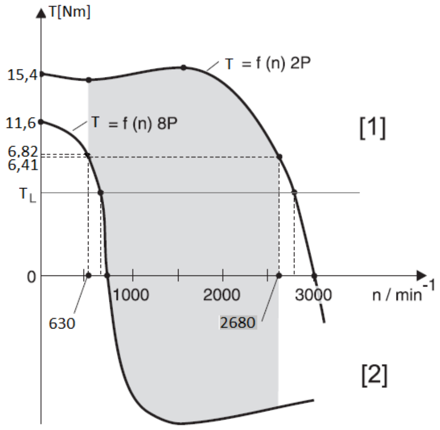
(8 poles)	(2 poles)
P_N = 0.45 kW;	P_N = 1.8 kW;
n_N = 630 rpm (ω_N = 65.97 rad/s);	n_N = 2680 rpm (ω_N = 280.65 rad/s);
n_{SINC} = 750 rpm (ω_{SINC} = 78.54 rad/s);	n_{SINC} = 3000 rpm (ω_{SINC} = 314.16 rad/s);
$T_N = P_N / \omega_N$ = 6.82 Nm;	$T_N = P_N / \omega_N$ = 6.41 Nm;
$T_{acel.}$ = 10.91 Nm; T_{start} = 11.59 Nm	$T_{acel.}$ = 14.10 Nm; T_{start} = 15.38 Nm
Z_0 = 9000 ; Option BGE	Z_0 = 2600 ; Option BGE

$T_{switching}$ = 2.5 x T_{acel} (8 pole) = 27.28 Nm

T_{brake} = 20 Nm

J_{motor} = 48.1 x 10^{-4} Kgm^2 ; (Option BGE) (brake control circuit)

The average regenerative braking torque ($T_{switching}$), available during the speed commutation phase (from 2 to 8 poles) due to generator operation, corresponds to the average difference between the torque curve of the 2-pole motor and the motor curve with 8 poles. It can be considered approximately as 2 to 2.5 times the starting torque of the 8-pole motor [adapted from SEW_Drive Engineering].



4- Verification of moving the load with the selected motor

i) **Ascending movement**: starting from zero to high speed, switching to low speed; stop with brake action. The load opposes movement.

- STARTING PHASE (2 poles)

- acceleration time: $t_{acel.} = 0.19\ sec$

$$\begin{cases} t_{acel} = \dfrac{J_{total} \cdot \Delta\omega}{\sum T} = \dfrac{5.482 \times 10^{-3} \cdot 280.65}{7.93} = 0.19\ sec \\ J_{total} = J_{motor} + J_{load} = 48.1 \times 10^{-4} + 6.72 \times 10^{-4} = 5.482 \times 10^{-3}\ Kgm^2 \\ \sum T = T_{acel} - T_{static} = 14.10\ -\ 6.17 = 7.93\ Nm \\ J_{load} = \dfrac{m}{\eta}\left(\dfrac{v}{\omega}\right)^2 = \dfrac{(300+200)}{\eta}\left(\dfrac{0.3}{280.65}\right)^2 = \dfrac{5.71 \times 10^{-4}}{0.85} = 6.72 \times 10^{-4}\ Kgm^2 \\ T_{static} = \dfrac{P_{static}}{\omega} = \dfrac{1471.52/h}{280.65} = \dfrac{5.243}{\eta} = \dfrac{5.243}{0.85} = 6.17\ Nm \end{cases}$$

- acceleration:

$$a = \frac{\Delta v}{t_{acel}} = \frac{0.3}{0.19} = 1.58\ m/s^2$$

- distance moved during acceleration:

$$s_{acel} = \frac{1}{2} \cdot v \cdot t_{acel} = \frac{1}{2} \cdot 0.3 \cdot 0.19 = 0.029\ m = 29\ mm$$

- Switching to low speed (8 poles)

- switching time $t_{switching} = 0.036\ sec$

$$t_{switching} = \frac{(J_{motor} + J_{load} \cdot\ h) \cdot \Delta\omega}{T_{switching} + T_{load} \cdot\ \eta} =$$

$$= \frac{(48.1 \times 10^{-4} + 5.71 \times 10^{-4} \cdot 0.85) \cdot (280.65 - 65.97)}{27.28 +\ 5.243 \cdot\ 0.85} = 0.036\ sec$$

- deceleration $a = -\ 6.37\ m/s^2$

$$a = \frac{\Delta v}{t_{acel}} = \frac{0.3 \cdot \dfrac{630}{2680} - 0.3}{0.036} = -6.37\ m/s^2$$

- distance moved during switching: $s_{switching} = 6.7\ mm$

$$s_{switching} = \frac{1}{2} \cdot (v_0 + v) \cdot t_{acel} = \frac{1}{2} \cdot (0.3 + 0.3 \cdot \frac{630}{2680}) \cdot 0.036 = 0.0067\ m = 6.7\ mm$$

- BRAKING at the final phase of the ascending movement

- response time of brake actuation: $t_{actuation} = 0.015\ sec$

(Data: SEW_Brake_Data_ClassPL6.pdf)

- velocity reduction before effective braking: $\Delta n = 121\ rpm$

$$\Delta\omega = \frac{T_{load}\ \cdot t_{actuation}}{J_{motor} + J_{load}\cdot\eta} = \frac{5.243\cdot\ 0.85\cdot 0.015}{48.1\times 10^{-4} + 5.71\times 10^{-4}\cdot 0.85} = 12.62\frac{rad}{s} = 120.55\ rpm$$

- distance moved during brake response time

$$s_{t2} = \frac{1}{2}\cdot(v_0 + v)\cdot t_{acel} = \frac{1}{2}\cdot(0.3\cdot\frac{630}{2680} + 0.3\frac{630-121}{2680})\cdot 0.015 = 0.00096\ m = 0.96\ mm$$

- braking time due to available torque brake: $t_{braking} = 0.012\ sec$

$$t_{braking} = \frac{(J_{motor}+J_{load}\cdot\ h)\cdot(\omega-\Delta\omega-0)}{T_{braking}+T_{load}\cdot\ \eta} = \frac{(48.1\times 10^{-4}+5.71\times 10^{-4}\cdot 0.85)\cdot(65.97-12.62)}{20+\ 5.243\cdot 0.85} = 0.0116\ sec$$

- deceleration during braking

$$a = \frac{\Delta v}{t_{braking}} = \frac{0.3\cdot\frac{630\text{-}121}{2680}}{0.012} = 4.75\ m/s^2$$

- distance moved during braking (t_B)

$$s_{t2} = \frac{1}{2}\cdot(v_0 + v)\cdot t_{acel} = \frac{1}{2}\cdot(0.3\cdot\frac{630-121}{2680} + 0)\cdot 0.0116 = 0.00033\ m = 0.33\ mm$$

- total distance moved during braking (t_2+t_B)

$$s_{total\ braking} = 0.96 + 0.33 = 0.00129\ mm$$

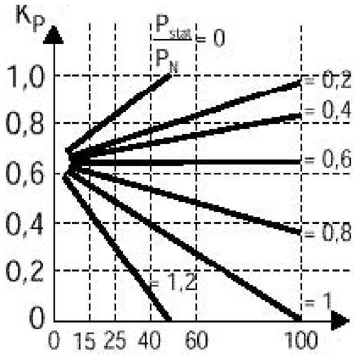
- Allowed starts and stops frequency in ascending movements (Z_p)

$$Z_p = Z_0 \cdot K_J \cdot K_M \cdot K_P = 2600 \cdot 0.88 \cdot 0.56 \cdot 0.32 = 410\ c/h$$

$$K_J = \frac{1}{1+\frac{\frac{J_{load}}{\eta}+J_{ventilator}}{J_{motor}}} = \frac{J_{motor}}{\frac{J_{load}}{\eta}+J_{ventilator}+J_{motor}} = \frac{48.1\times10^{-4}}{\frac{5.71\times10^{-4}}{0.85}+0+48.1\times10^{-4}} = 0.88$$

$$K_M = 1-\frac{\frac{T_{load}}{\eta}}{T_{acel}} = \frac{T_{acel}\cdot h - T_{load}}{T_{acel}\cdot\eta} = \frac{14.10\cdot0.85-5.243}{14.10\cdot0.85} = 0.56$$

$$K_P = 0.32 \qquad \begin{cases} \frac{P_{static}}{P_N} \\ cdf \end{cases} \Leftrightarrow \begin{cases} \frac{1731.2}{1800} = 0.96 \\ cdf = 50\% \end{cases}$$



ii) **Descend movement:** starting from zero to high speed, switching to low speed; stop with brake action. The load action is in the same direction of motor motion.

- START PHASE (2 poles)

- acceleration time: $t_{acel.} = 0.09\ sec$

$$\begin{cases} t_{acel} = \frac{\left(J_{motor} + \frac{J_{load}}{\eta}\right)\cdot\Delta\omega}{T_{acel}+T_{static}\cdot\eta} = \frac{\left(48.1\times10^{-4} + \frac{5.71\times10^{-4}}{0.85}\right)\cdot 314.16}{14.10+5.243\cdot0.85} = 0.09\ sec \\ \Delta\omega = \frac{3000\cdot2\pi}{60} = 314.16\ rad/s \end{cases}$$

- acceleration:

$$a = \frac{\Delta v}{t_{acel}} = \frac{0.3\cdot\frac{3000}{2680}}{0.09} = 3.73\ m/s^2$$

- distance moved during acceleration:

$$s_{acel} = \frac{1}{2}\cdot v\cdot t_{acel} = \frac{1}{2}\cdot0.3\cdot\frac{3000}{2680}\cdot0.09 = 0.0151\ m = 15\ mm$$

- Switching to low speed (8 poles)

- switching time $t_{switching} = 0.055\ sec$

$$\begin{cases} t_{switching} = \dfrac{(J_{motor} + J_{load} \cdot \eta) \cdot \Delta\omega}{T_{switching} - T_{static} \cdot \eta} = \dfrac{(48.1 \times 10^{-4} + 5.71 \times 10^{-4} \cdot 0.85) \cdot 235.62}{27.28 - 5.243 \cdot 0.85} = 0.055\ sec \\ \Delta\omega = \omega_{sinc}^{2poles} - \omega_{sinc}^{8poles} = \dfrac{3000 \cdot 2\pi}{60} - \dfrac{750 \cdot 2\pi}{60} = 314.16 - 78.54 = 235.62\ rad/s \end{cases}$$

- deceleration $a = -\,4.58\ m/s^2$

iii) $a = \dfrac{\Delta v}{t_{acel}} = \dfrac{0.3 \cdot \frac{3000}{2680} - 0.3 \cdot \frac{750}{2680}}{0.055} = 4.58\ m/s^2$

- distance moved during switching $s_{switching} = 11.5\ mm$

$$s_{switching} = \frac{1}{2} \cdot (v_0 + v) \cdot t_{acel} = \frac{1}{2} \cdot (0.3 \cdot \frac{3000}{2680} + 0.3 \cdot \frac{750}{2680}) \cdot 0.055 = 0.0115\ m = 11.5\ mm$$

- BRAKING at final phase of descent movement

- response time of brake actuation (t_2): $t_{action} = 0.015\ sec$

(Data: SEW_Brake_Data_classPL6.pdf)

- speed increase before effective brake action: $\Delta n = 121\ rpm$

$$\Delta\omega = \frac{T_{load} \cdot t_{action}}{J_{motor} + J_{load} \cdot \eta} = \frac{5.243 \cdot 0.85 \cdot 0.015}{48.1 \times 10^{-4} + 5.71 \times 10^{-4} \cdot 0.85} = 12.62\,\frac{rad}{s} = 120.55\ rpm$$

- distance moved during brake time response (t_2)

$$s_{t2} = \frac{1}{2} \cdot (v_0 + v) \cdot t_{acel} = \frac{1}{2} \cdot (0.3 \cdot \frac{750}{2680} + 0.3\,\frac{750 + 121}{2680}) \cdot 0.015 = 0.00136\ m = 1.36\ mm$$

- braking time due to available torque brake: $t_{braking} = 0.027\ sec$

$$\begin{cases} t_{braking} = \dfrac{(J_{motor} + J_{load} \cdot \eta) \cdot \Delta\omega}{T_{braking} - T_{static} \cdot \eta} = \dfrac{(48.1 \times 10^{-4} + 5.71 \times 10^{-4} \cdot 0.85) \cdot 78.62}{20 - 5.243 \cdot 0.85} = 0.027\ sec \\ \Delta\omega = (\omega_{sinc}^{8poles} + \Delta\omega) = 65.97 + 12.65 = 78.62\ rad/s \end{cases}$$

- deceleration during braking

$$a = \frac{\Delta v}{t_{braking}} = \frac{0.3 \cdot \frac{750+121}{2680}}{0.027} = 3.61\ m/s^2$$

- distance moved during braking (t_B)

$$s_{t2} = \frac{1}{2} \cdot (v_0 + v) \cdot t_{acel} = \frac{1}{2} \cdot \left(0.3 \cdot \frac{750 + 121}{2680} + 0\right) \cdot 0.027 = 0.0013\ m = 1.3\ mm$$

- total distance during braking (t_2+t_B)

$$s_{total\ braking} = 1.36 + 1.3 = 2.66\ mm$$

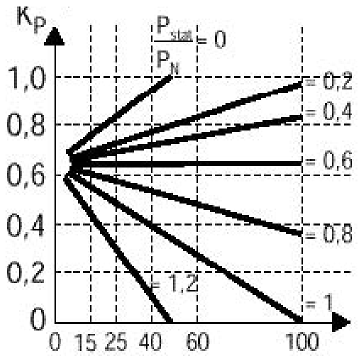
- Allowed starts and stops frequency in descending movements (Z_p)

$$Z_p = Z_0 \cdot K_J \cdot K_M \cdot K_P = 2600 \cdot 0.91 \cdot 0.68 \cdot 0.55 = 885\ c/h$$

$$K_J = \frac{1}{\frac{J_{load} \cdot \eta + J_{ventilator}}{J_{motor}} + 1} = \frac{J_{motor}}{J_{load} \cdot \eta + J_{ventilator} + J_{motor}} = \frac{48.1 \times 10^{-4}}{5.71 \times 10^{-4} \cdot 0.85 + 0 + 48.1 \times 10^{-4}} = 0.91$$

$$K_M = 1 - \frac{T_{load} \cdot \eta}{T_{acel}} = \frac{T_{acel} - T_{load} \cdot \eta}{T_{acel}} = \frac{14.10 - 5.243 \cdot 0.85}{14.10} = 0.68$$

$$K_P = 0.55 \qquad \begin{cases} \dfrac{P_{static \cdot h}}{P_N} \\ cdf \end{cases} \Leftrightarrow \begin{cases} \dfrac{1471.52 \cdot 0.85}{1800} = 0.69 \\ cdf = 50\% \end{cases}$$



K_C = number of permitted cycles, given by:

$$K_C = \frac{K_{1P} \cdot K_{2P}}{K_{1P} + K_{2P}} = \frac{410 \cdot 885}{410 + 885} = 280\ c/h$$

Sketch of the velocity profile, including starting/stopping phases in ascending (*Movimento subida*) and descending (*Movimento descida*) movements: