

PL 10 -Servomotors (PM synchronous servomotors)

Objectives: Selection and sizing of permanent magnet servomotors (i.e. brushless synchronous servomotors) and respective drivers.

Documents available

PL classes:

1) SEW-Eurodrive-CMP-Servo-Motors.pdf;

Web sites:

www.sew-eurodrive.com ; www.lenze.com ; www.ia.omron.com ;
www.fagorautomation.com

1) Synchronous servomotor (i.e. permanent magnet-PM), or brushless AC servomotors

a) Main components and working principles

- *brushless* motor; wiring (coils) in the stator (armature) and rotor is a permanent magnet (inductor or field);

- coils are energized with sinusoidal electric signals (*brushless AC*) or DC commutated signals (initial solutions, BLDC or *brushless DC* motors);

- rotating or linear versions;

- requires the knowledge of the rotor position, using a position transducer, in order to set the appropriate sequence of the power supply connections to the stator coils. Based on the rotor's position information the objective is to control current in the stator's coils to ensure each magnetic field (rotor and stator) are aligned along directions (90°) that provide maximum torque. - requires a controller (*driver*) in order to be operated; the driver implements the control algorithms (current, speed, position, ...); in addition to control the electronics power circuit, motion control is also another main block of functionalities that characterizes the drivers.

b) Main characteristics and advantages

- can be considered the first, i.e. best, solution in applications requiring high accuracy in positioning and velocity capabilities as well as torque/force control;

- other alternatives that can be considered include, generally with lower accuracy capabilities, asynchronous servomotors and AC induction motors with a vector control (closed/open loop) variable frequency (VF) driver, AC induction motors with scalar (i.e. V/f) control VF driver, step motors, classical brushed DC motors (PM, ...) with respective feedback transducers and controllers.

- the rotor being a permanent magnet (PM), has lower inertia comparing with asynchronous servomotors, and therefore have shorter response times, ie. better dynamic behavior and acceleration capability;

- increased range of velocities;

- higher position and velocity accuracy;

- better efficiency weight ratios;

- better thermal capacity;

- capacity to maintain torque at standstill (i.e. zero speed);

- none or low maintenance, but difficult to repair.

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2) Characteristic curves

a) Torque/speed curves, limits in a dynamic operating zone

- constant maximum torque in a wide range of speeds
- peak torque, or maximum torque, is limited by the materials (permanent magnets) of the rotor. Above this limit, demagnetization or rotor materials failure are possible;
- the maximum available torque depends also on the driver's maximum current capability. If maximum driver's current is lower than the current corresponding to motor's peak torque, the maximum available torque will be lower than motor's peak torque;
- at higher speeds the increase in counter electromotive force at the stator coils, reduces the maximum torque available, i.e. it does not remain constant, due to driver's voltage limitations;
- **maximum load operating point** (maximum torque at the required speed) must be below dynamic curves:

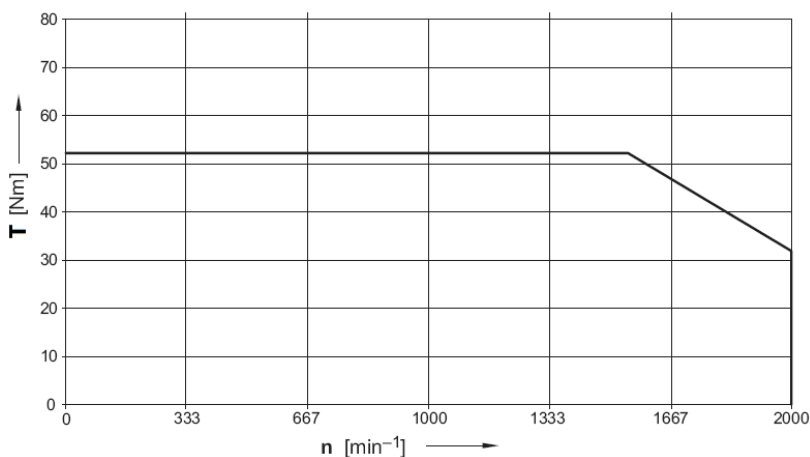


Fig. 1: Example of a maximum torque/speed characteristic curve

b) Torque/speed curves, limits defined by the thermal capabilities of the motor (thermal zone)

- represents the allowed torque as a function of velocity and isolation, or type of operating service class;
- normally torque decreases with increasing speed, due to losses in the core, hysteresis or Eddy currents;
- **effective, or rms, load torque, at average or effective speed, must be below the thermal limit torque curve:**

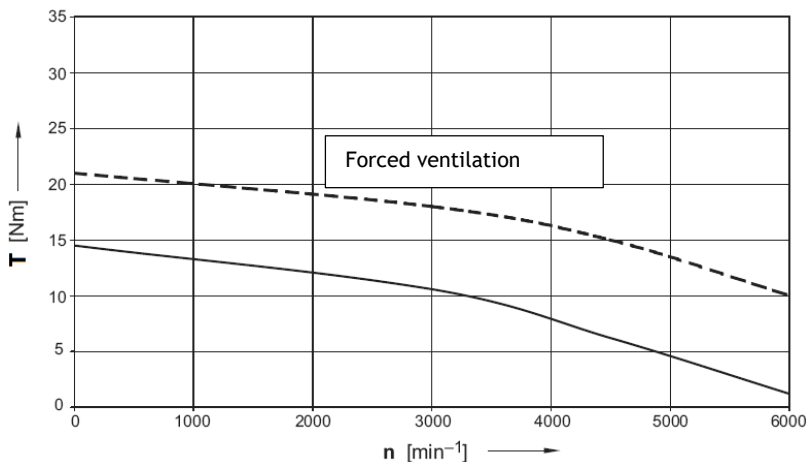


Fig. 2: Example of a continuous torque/speed characteristic curve

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c) Torque/current characteristic curves

- these curves allow the determination of the current corresponding to a given torque;
- close to a linear relation at lower values:

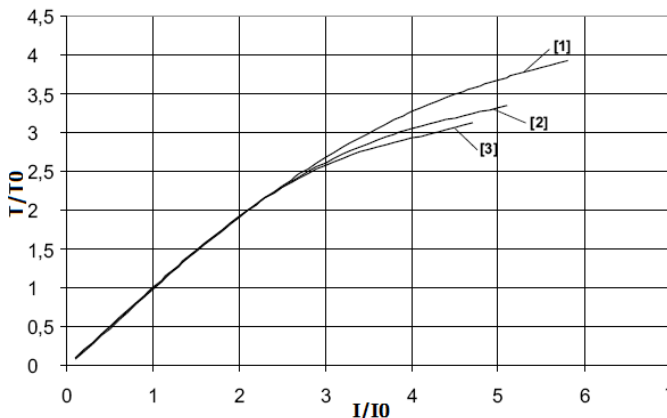


Fig. 3: Example of torque/current curves (3 motors)

3) **Selection and sizing a servomotor and respective controller (Driver)**

As in previous cases of selection and sizing of electric motors, is based on the analysis of the application requirements that will lead to the identification of a servomotor and driver capable of satisfying those requirements within the limits of thermal and dynamic behavior of the motor:

- load movements and positioning characteristics
 (velocity profile, positioning and velocity accuracies, ...)
- power, torque, speed range...
- operating modes or classes (S1, ...)
- load specific characteristic (constant, variable, vertical, horizontal, ...)
- environment conditions
- ...

A- Calculations based on the load movement requirements

- Calculation of total torque (T) or force (F)
- Calculation of angular (ω , n), or linear (v) velocity ...

B- Servomotor selection

B1- Tables with technical data of motors

- Nominal velocity
- Torque (stall, nominal, maximum or peak) ...

B2- Characteristic curves and verification of calculations with the selected motor

- Ratio of inertias (load, motor)*
- Thermal and dynamic zones of the motor (T, ω) curves*
- Effective operating point (effective torque, effective speed)*
- Maximum operating point (maximum torque, maximum speed)*

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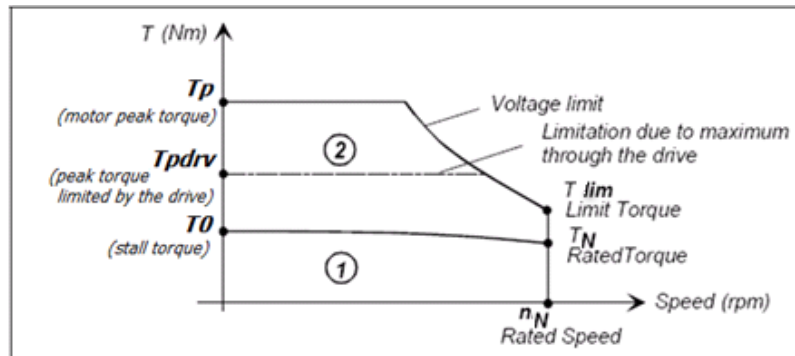


Fig. 4: Rotating servomotor, typical torque/speed characteristic curves and operating zones (adapted from <https://www.fagor.eus/en/fagor-automation/>). Zone (1), continuous operation. Zone (2), intermittent operation.

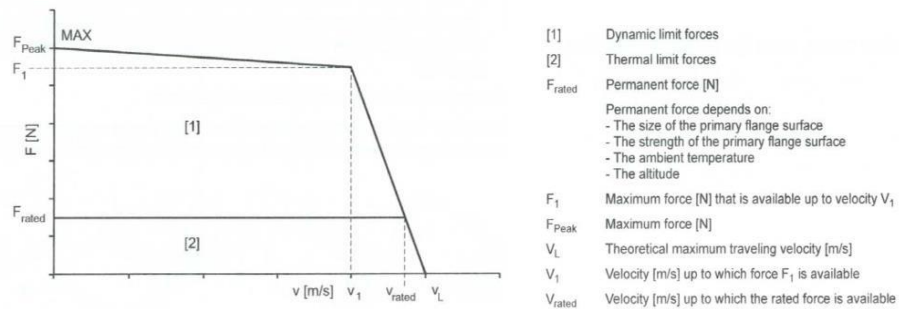


Fig. 5: Linear servomotors, typical force/speed characteristic curves and operating zones (SEWEurodrive Technology, www.sew-eurodrive.com). Zone (1), continuous operation. Zone (2), intermittent operation.

- Effective, or rms, torque:

$$T_{effective} = \sqrt{\frac{1}{t_{cycle}} \cdot (T_1^2 \cdot t_1 + T_2^2 \cdot t_2 + \dots + T_n^2 \cdot t_{n1})}$$

- Effective, or rms, speed:

$$n_{effective} = \sqrt[1.5]{\frac{1}{t_{cycle}} \cdot (n_1^{1.5} \cdot t_1 + n_2^{1.5} \cdot t_2 + \dots + n_n^{1.5} \cdot t_{n1})}$$

C- Driver selection

- The maximum output current of the driver, is determinant to establish the motor maximum delivered torque. If it is higher than the motor maximum torque, the driver must be configured to limit its output current according to the motor's maximum torque (i.e. current).

- If the curves torque/current are not available, a linear relation is normally used (Fig.3)

- Although motors and drivers may not belong to the same manufacturer, in general the configuration and selection is facilitated when they are from the same brand. Compatibility motor/driver tables are normally available and used to select the driver for a specific motor.

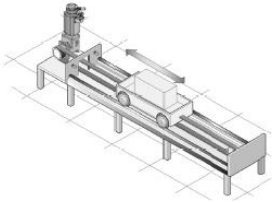
- Motors/drivers compatibility tables
- Peak torque = Peak current x Torque constant (K_t)
- Torque ratios: Peak torque/Stall torque (in general: 2 to 3)

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Exercise PL 10-1

Linear axis using a toothed belt and a servomotor.

(adapted from *SEW-Practical Drive Engineering*)

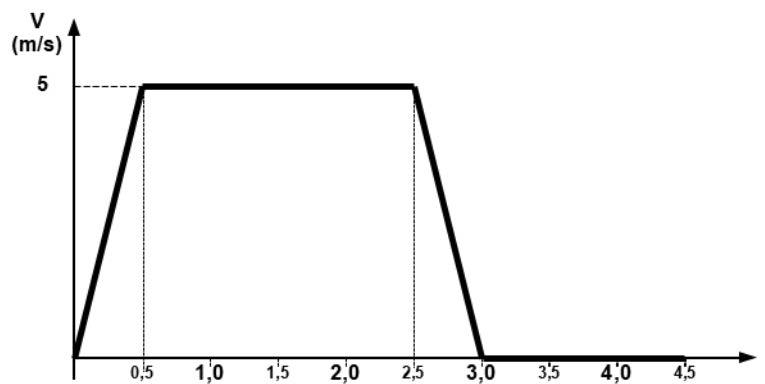


Consider moving a cart, guided along a horizontal axis, driven by a servomotor with a gearbox and a toothed belt. The moving profile in each direction and complementary data are described below:

- $L_{axis} = 13\text{ m}$
- $v_{max} = 5\text{ m/s}$
- $a = 10\text{ m/s}^2$
- $t_{cycle} = 4,5\text{ s}$

- $m_{load} = 150\text{ kg}$
- $m_{cart} = 80\text{ kg}$

- $\eta_{L-toothed\ belt} = 90\%$
- $D_{L-transmission\ wheel} = 250\text{ mm}$
- $\mu_{guides} = 0,1$



Consider also that a gearbox, with the following characteristics, was already selected (SEW: BSF502EBH02):

- $i_{transmission\ ratio} = 10$
- $n_N = 4500\text{ rpm}$
- $\eta_{gearbox} = 90,5\%$
- $J_{gearbox}^{motor} = 8,7 \times 10^{-4}\text{ kgm}^2$

Using the tables available with information of servomotors and drivers, verify if it is possible to select a specific motor and driver that satisfies the requirements of this application.

Solution: **Selecting a servomotor and respective driver from the given tables**

(SEW-Eurodrive-CMP-Servo-Motors.pdf)

A- Calculation of torques and speeds in reference to the motor shaft

The first selection of the motor is based on the speed and torque values from the application requirements (T and ω). Since a horizontal load movement is involved, the reference value for torque include both static and acceleration torques (i.e. total torque).

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- values calculated on output shaft of the gearbox

- speeds:

$$\left\{ \begin{array}{l} n_{output\ shaft}^{gearbox} = \frac{v_{max\ load}}{D_L/2} = \frac{5}{0,250/2} = 40\ rad/s = 382\ rpm \\ n_{input\ shaft}^{gearbox} = n_{output\ shaft}^{gearbox} \cdot i_{gearbox} = 382 \cdot 10 = 400\ rad/s = 3820\ rpm \end{array} \right.$$

- torques:

$$\left\{ \begin{array}{l} T_{accel\ load}^{gearbox} = \frac{1}{\eta_L} \cdot m_{total} \cdot a \cdot \frac{D_L}{2} = \frac{1}{0,9} \cdot 230 \cdot 10 \cdot \frac{0,250}{2} = 319\ Nm \\ T_{decel\ load}^{gearbox} = \eta_L \cdot m_{total} \cdot a \cdot \frac{D_L}{2} = 0,9 \cdot 230 \cdot 10 \cdot \frac{0,250}{2} = (-)259\ Nm \\ T_{static\ load}^{gearbox} = \frac{1}{\eta_L} \cdot m_{total} \cdot g \cdot \mu_L \cdot \frac{D_L}{2} = \frac{1}{0,9} \cdot 230 \cdot 9,81 \cdot 0,1 \cdot \frac{0,250}{2} = 31\ Nm \\ T_{total\ load\ start}^{gearbox} = 319 + 31 = 350\ Nm \\ T_{total\ load\ stop}^{gearbox} = -259 + 31 = -228\ Nm \end{array} \right.$$

- values relative to the motor shaft:

- speeds:

$$n_{motor\ shaft}^{motor} = n_{input\ shaft}^{gearbox} = 400\ rad/s = 3820\ rpm$$

- torques:

$$\left\{ \begin{array}{l} T_{accel\ load}^{motor} = \frac{T_{accel\ load}^{gearbox}}{i_{gearbox}} \cdot \frac{1}{\eta_{gearbox}} = \frac{319}{10} \cdot \frac{1}{0,905} = 35,3\ Nm \\ T_{decel\ load}^{motor} = \frac{T_{decel\ load}^{gearbox}}{i_{gearbox}} \cdot \eta_{gearbox} = \frac{259}{10} \cdot 0,905 = (-)23,4\ Nm \\ T_{static\ load}^{motor} = \frac{T_{static\ load}^{gearbox}}{i_{gearbox}} \cdot \frac{1}{\eta_{gearbox}} = \frac{31}{10} \cdot \frac{1}{0,905} = 3,4\ Nm \\ T_{total\ load\ start}^{motor} = 35,3 + 3,4 = 39\ Nm \\ T_{total\ load\ stop}^{motor} = -23,4 + 3,4 = -20,0\ Nm \end{array} \right.$$

B- Selecting a motor : T_{max} , n_N

$$\left\{ \begin{array}{l} T_{max\ motor} > T_{total\ load\ start}^{motor} = 39\ Nm; \\ T_{stall} > \frac{T_{max\ motor}}{2} \cong 19,5\ Nm \ ;(reference\ value\ for\ stall\ torque) \\ n_{nom\ motor} > 3820\ rpm \end{array} \right.$$

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- table (SEW-Eurodrive-CMP-Servo-Motors.pdf, page 26): motors nominal speed of 4500 rpm

Motor CMP80M

$n_N = 4500 \text{ rpm}$; $T_0 = 18,7 \text{ Nm}$; $T_{\max} = 62,6 \text{ Nm}$; $J_{\text{motor}} = 11,9 \times 10^{-4} \text{ Kg}\cdot\text{m}^2$; $I_0 = 20,1 \text{ A}$; $I_{\max} = 103 \text{ A}$;

Verification with data from selected motor

- Inertia ratio: $J_{\text{load}} / J_{\text{motor}} < 15$ (applications with toothed belts, ref. www.sew-eurodrive.com) (SEW-Eurodrive-CMP-Servo-Motors.pdf, page 32)

$$\left\{ \begin{array}{l} J_{\text{motor}} = 11,9 \times 10^{-4} \text{ kg}\cdot\text{m}^2 \\ J_{\text{load}}^{\text{motor}} = \frac{m}{\eta_{\text{global}}} \cdot \left(\frac{v}{\omega_{\text{motor}}} \right)^2 = \frac{230}{0,9 \cdot 0,905} \cdot \left(\frac{5}{3820 \cdot 2\pi/60} \right)^2 = 4,41 \times 10^{-2} \text{ kg}\cdot\text{m}^2 \\ \frac{J_{\text{load}}^{\text{motor}}}{J_{\text{motor}}} = \frac{4,41 \times 10^{-2}}{11,9 \times 10^{-4}} = 37 ; \text{higher than recommended! An alternative motor must be selected.} \end{array} \right.$$

Second motor selected: $J_{\text{motor}} > J_{\text{load}}/15 = 29,4 \times 10^{-4} \text{ kg}\cdot\text{m}^2$

- table (SEW-Eurodrive-CMP-Servo-Motors.pdf, page 28): motors with nominal speed of 4500 rpm, series CMPZ with additional inertia:

CMPZ80M

$n_N = 4500 \text{ rpm}$; $T_0 = 18,7 \text{ Nm}$; $T_{\max} = 62,6 \text{ Nm}$; $J_{\text{motor}} = 34 \times 10^{-4} \text{ Kg}\cdot\text{m}^2$; $I_0 = 20,1 \text{ A}$; $I_{\max} = 103 \text{ A}$;

- Inertia ratio: $J_{\text{load}} / J_{\text{motor}} = 13$

CMPZ80L

$n_N = 4500 \text{ rpm}$; $T_0 = 27,5 \text{ Nm}$; $T_{\max} = 107 \text{ Nm}$; $J_{\text{motor}} = 40,21 \times 10^{-4} \text{ Kg}\cdot\text{m}^2$; $I_0 = 27,8 \text{ A}$; $I_{\max} = 159 \text{ A}$;

- Inertia ratio: $J_{\text{load}} / J_{\text{motor}} = 11$ **motor selected (CMPZ80L).**

- Verification taking into account motor and gearbox inertia moments

Motor	CMPZ80M	CMPZ80L
$T_{\text{accel motor}}^{\text{motor}} = J_{\text{motor}} \cdot \alpha$ $T_{\text{accel inertia gearbox}}^{\text{motor}} = J_{\text{gearbox}}^{\text{motor}} \cdot \alpha$ $T_{\text{static load}}^{\text{motor}} = \frac{T_{\text{static load}}^{\text{gearbox}}}{i_{\text{gearbox}}} \cdot \frac{1}{\eta_L}$ $T_{\text{total load start}}^{\text{motor}}$ $T_{\text{total load stop}}^{\text{motor}}$	$\left(\begin{array}{l} = 34,0 \times 10^{-4} \cdot \frac{400}{0,5} = 2,72 \text{ Nm} \\ = 8,7 \times 10^{-4} \cdot \frac{400}{0,5} = 0,7 \text{ Nm} \\ = \frac{31}{10} \cdot \frac{1}{0,905} = 3,4 \text{ Nm} \\ = 35,3 + 3,4 + 2,72 + 0,7 = 42,12 \text{ Nm} \\ = -23,4 + 3,4 - 2,72 - 0,70 = -23,42 \text{ Nm} \end{array} \right.$	$\left(\begin{array}{l} = 3,21 \text{ Nm} \\ = 0,7 \text{ Nm} \\ = 3,4 \text{ Nm} \\ = 42,61 \text{ Nm} \\ = -23,91 \text{ Nm} \end{array} \right.$

- Calculations for effective (rms) torque and speed, considering the working cycle as the movement in one direction only: moving along the complete course of the axis, stop and repeat the same movement in the opposite direction.

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Effective torque ($T_{effective}$):

$T_{effective}$	$= \sqrt{\frac{1}{t_{cycle}} \cdot (T_1^2 \cdot t_1 + T_2^2 \cdot t_2 + \dots + T_n^2 \cdot t_{n1})}$
CMPZ80M	$\sqrt{\frac{1}{4,5} \cdot (42,12^2 \cdot 0,5 + 3,4^2 \cdot 2 + (-23,42)^2 \cdot 0,5)} = 16,22 \text{ Nm}$
CMPZ80L	$\sqrt{\frac{1}{4,5} \cdot (42,61^2 \cdot 0,5 + 3,4^2 \cdot 2 + (-23,91)^2 \cdot 0,5)} = 16,44 \text{ Nm}$

- Effective speed ($n_{effective}$):

$$n_{effective} = \sqrt[1,5]{\frac{1}{t_{cycle}} \cdot (n_1^{1,5} \cdot t_1 + n_2^{1,5} \cdot t_2 + \dots + n_n^{1,5} \cdot t_{n1})}$$

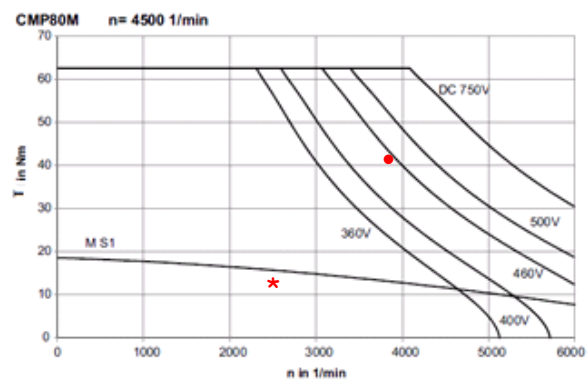
$$= \sqrt[1,5]{\frac{1}{4,5} \cdot \left(\left(\frac{3820}{2} \right)^{1,5} \cdot 0,5 + 3820^{1,5} \cdot 2 + \left(\frac{3820}{2} \right)^{1,5} \cdot 0,5 \right)} = 2479,7 \text{ rpm}$$

Synthesis of load requirements:

- effective operating point (*): $T_{eff} = 16,2 \text{ Nm}$; $n_{eff} = 2479,7 \text{ rpm}$
- max. operating point (•): $T_{max} = 42,12 \text{ Nm}$; $n_{max} = 3820 \text{ rpm}$

Motor curves, **CMPZ80M**, 460V:

- Stall torque: $T_0 = 18,7 \text{ Nm}$
- Max. torque: Típico = $62,6 \text{ Nm}$
- Nominal speed: $n_N = 4500 \text{ rpm}$
- $I_0 = 20,1 \text{ A}$



(SEW-Eurodrive-CMP-Servo-Motors.pdf, page 88)

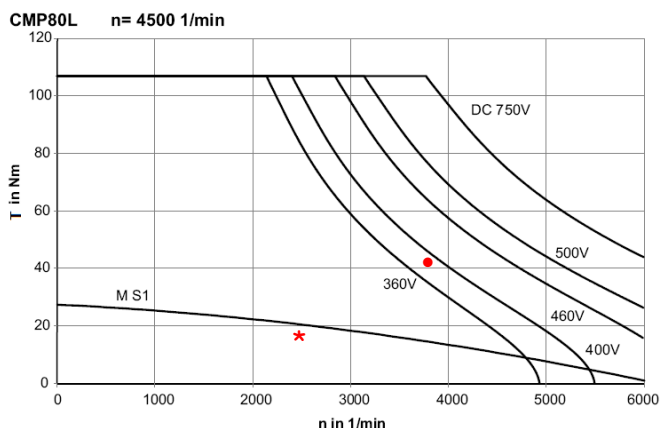
Synthesis of load requirements:

- effective operating point (*): $T_{eff} = 16,5 \text{ Nm}$; $n_{eff} = 2479,73 \text{ rpm}$
- max. operating point (•): $T_{max} = 42,61 \text{ Nm}$; $n_{max} = 3820 \text{ rpm}$

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Motor curves, **CMPZ80L**, 400V:

- Stall torque: $T_0 = 27,5 \text{ Nm}$
- Max. torque: Típico=107 Nm
- Nominal speed: $n_N = 4500 \text{ rpm}$
- $I_0 = 27,8 \text{ A}$



(SEW-Eurodrive-CMP-Servo-Motors.pdf, pág. 89)

C- Driver selection:

$I_{\text{driver}} \geq I_{\text{motor}}$, for the calculated torques

- table of correspondence *DRIVERS/Motors*: I_N , I_{max} , T_{max}

(SEW-Eurodrive-CMP-Servo-Motors.pdf, pág. 64)

Motor CPMZ80M

Moviaxis Driver: $I_N = 24 \text{ A}$; $I_{\text{max}} = 60 \text{ A}$; $T_{\text{max}} = 48,8 \text{ Nm}$

Driver: output voltage 460V

- torque/current curves of the selected motor (approx. linear relation): $I_{\text{eff}} = \frac{I_N \cdot T_{\text{eff}}}{T_N}$

$$I_{\text{eff}} = \frac{I_0 \cdot T_{\text{eff}}}{T_0} = \frac{20,1 \cdot 16,22}{18,7} = 17,4 \text{ A} \quad ; \quad I_{\text{max}} = \frac{I_0 \cdot T_{\text{máx}}}{T_0} = \frac{20,1 \cdot 42,12}{18,7} = 45,3 \text{ A}$$

Motor CPMZ80L

Moviaxis Driver: $I_N = 24 \text{ A}$; $I_{\text{max}} = 60 \text{ A}$; $T_{\text{max}} = 56 \text{ Nm}$

Driver: output voltage 400V

torque/current curves of the selected motor (approx. linear relation): $I_{\text{eff}} = \frac{I_N \cdot T_{\text{eff}}}{T_N}$

$$I_{\text{eff}} = \frac{I_0 \cdot T_{\text{eff}}}{T_0} = \frac{27,8 \cdot 16,5}{27,5} = 16,7 \text{ A} \quad ; \quad I_{\text{max}} = \frac{I_0 \cdot T_{\text{máx}}}{T_0} = \frac{27,8 \cdot 42,61}{27,5} = 43,1 \text{ A}$$

FURTHER COMMENTS AND RECOMMENDATIONS

In addition to the initially given references, it is included the following selection and sizing software applications that can be used for different types of motors and to complement the methods presented all along these lab classes.

ABB: DriveSize

new.abb.com/drives/software-tools/drivesize

(web version)

Lenz: Drive Solution designer

<https://systemdesigner.lenze.com/DriveSizing>

(web version)

SEW-Eurodrive: Drive selection

https://www.sew-eurodrive.de/os/ds/?country=DE&language=en_US

(web version)

Bosch Rexroth: Indrasize

<https://www.boschrexroth.com/media/24034f8e-4121-4b81-bb0c-3a4ab0d3b88a>

(requires download and installation)