EPOS4

Positioning Controllers

Application Notes

epos.maxonmotor.com

Document ID: rel6835

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READ THIS FIRST

These instructions are intended for qualified technical personnel. Prior commencing with any activities…

- *you must carefully read and understand this manual and*
- *you must follow the instructions given therein.*

EPOS4 *positioning controllers are considered as partly completed machinery according to EU Directive 2006/42/EC, Article 2, Clause (g) and* **are intended to be incorporated into or assembled with other machinery or other partly completed machinery or equipment**.
Therefore, you must not put the device into service,…

- *unless you have made completely sure that the other machinery fully complies with the EU directive's requirements!*
- *unless the other machinery fulfills all relevant health and safety aspects!*
- *unless all respective interfaces have been established and fulfill the herein stated requirements!*

1 About

1.1 About this Document

1.1.1 Intended Purpose

The purpose of the present document is to provide you specific information to cover particular cases or scenarios that might come in handy during commissioning of your drive system.
Use for other and/or additional purposes is not permitted. maxon motor, the manufacturer of the equipment described, does not assume any liability for loss or damage that may arise from any other and/or additional use than the intended purpose.

The present document is part of a documentation set. The below overview shows the documentation hierarchy and the interrelationship of its individual parts:
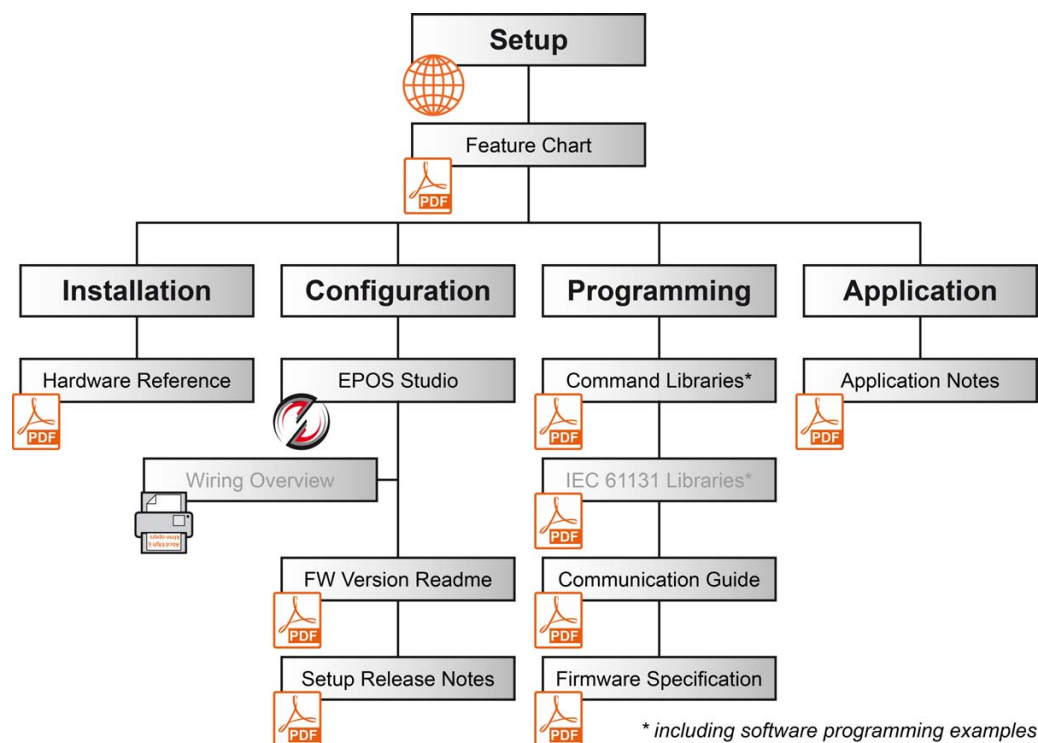

Figure 1-1   Documentation structure

Find the latest edition of the present document as well as additional documentation and software for EPOS4 positioning controllers also on the Internet: →http://epos.maxonmotor.com

1.1.2 Target Audience

This document is meant for trained and skilled personnel working with the equipment described. It conveys information on how to understand and fulfill the respective work and duties.

This document is a reference book. It does require particular knowledge and expertise specific to the equipment described.

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1.1.3   How to use

Take note of the following notations and codes which will be used throughout the document.

Notation	Explanation
EPOS4	stands for "EPOS4 Positioning Controller"
Compact	referring to any of the EPOS4 Compact versions
Compact CAN	referring to a fully integrated, compact, ready-to-use EPOS4 assembly of plug-in module and CANopen connector board (such as "EPOS4 Compact 50/8 CAN" or "EPOS4 Compact 50/15 CAN")
Module	referring to an EPOS4 plug-in module version (such as "EPOS4 Module 50/8" or "EPOS4 Module 50/15") for use with EPOS4 connector boards or customer-specific motherboards
«Abcd»	indicating a title or a name (such as of document, product, mode, etc.)
(n)	referring to an item (such as order number, list item, etc.)
*	referring to an internal value
***	referring to a not yet implemented item
➔	denotes "see", "see also", "take note of", or "go to"

Table 1-1   Notations used

In the later course of the present document, the following abbreviations and acronyms will be used:

Short	Description
STO	Safe Torque Off

Table 1-2   Abbreviations and acronyms used

1.1.4   Symbols and Signs

Requirement / Note / Remark
Indicates an action you must perform prior continuing or refers to information on a particular item.

Best Practice
Gives advice on the easiest and best way to proceed.

Material Damage
Points out information particular to potential damage of equipment.

1.1.5   Trademarks and Brand Names

For easier legibility, registered brand names are listed below and will not be further tagged with their respective trademark. It must be understood that the brands (the below list is not necessarily concluding) are protected by copyright and/or other intellectual property rights even if their legal trademarks are omitted in the later course of this document.

Brand Name	Trademark Owner
Adobe® Reader®	© Adobe Systems Incorporated, USA-San Jose, CA

Table 1-3   Brand names and trademark owners

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1.1.6 Sources for additional Information

For further details and additional information, please refer to below listed sources:

#	Reference
[1]	IEC/EN 60204-1: Safety of machinery – Electrical equipment of machines
[2]	IEC/EN 61800-5-2: Adjustable speed electrical power drive systems

Table 1-4   Sources for additional information

1.1.7 Copyright

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CH-6072 Sachseln   Web   www.maxonmotor.com

1.2   About the Devices

maxon motor control's EPOS4 positioning controllers are small-sized, full digital, smart positioning con-trol units. Their high power density allow flexible use for brushed DC and brushless EC (BLDC) motors with various feedback options, such as Hall sensors, incremental encoders as well as absolute sensors in a multitude of drive applications.

1.3   About the Safety Precautions

IMPORTANT NOTICE: PREREQUISITES FOR PERMISSION TO COMMENCE INSTALLATION

EPOS4 positioning controllers are considered as partly completed machinery according to EU Direc-tive 2006/42/EC, Article 2, Clause (g) and **are intended to be incorporated into or assembled with other machinery or other partly completed machinery or equipment**.

> **WARNING**
>
> *Risk of Injury*
> *Operating the device without the full compliance of the surrounding system with the EU direc-tive 2006/42/EC may cause serious injuries!*
> * *Do not operate the device, unless you have made sure that the other machinery fulfills the require-ments stated in EU directive!*
> * *Do not operate the device, unless the surrounding system fulfills all relevant health and safety aspects!*
> * *Do not operate the device, unless all respective interfaces have been established and fulfill the stated requirements!*

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2 Controller Architecture

CONTENT

2.1 In Brief

A wide variety of operating modes permit flexible configuration of drive and automation systems by using positioning, speed and current regulation. The built-in CANopen interface allows online commanding by CAN bus master units as well as networking to multiple axes drives.

Good quality velocity PI control is made possible by the use of algorithms for estimating the motor rotation velocity from the measured rotor position that are based either on a low pass filter or on a velocity observer.

OBJECTIVE

The present application note explains the EPOS4 controller architecture.

In addition to PID position regulation, the functionalities of the built-in acceleration and velocity feedforward are described.

The functionality of the velocity PI controller, the low pass filter, and the observer used for estimating the velocity are described. The benefits of each velocity estimation method are highlighted and illustrated by using practical examples.

SCOPE

Hardware	Order #	Firmware Version	Reference
EPOS4		0100h	Firmware Specification

Table 2-5   Controller architecture | Covered hardware and required documents

TOOLS

Tools	Description
Software	«EPOS Studio» Version 3.00 or higher

Table 2-6   Controller architecture | Recommended tools

2.2 Overview

The EPOS4 controller architecture contains three built-in control loops.

- Current regulation is used in all modes.
- Position or velocity regulation is only used in position-based or velocity-based modes, respectively.
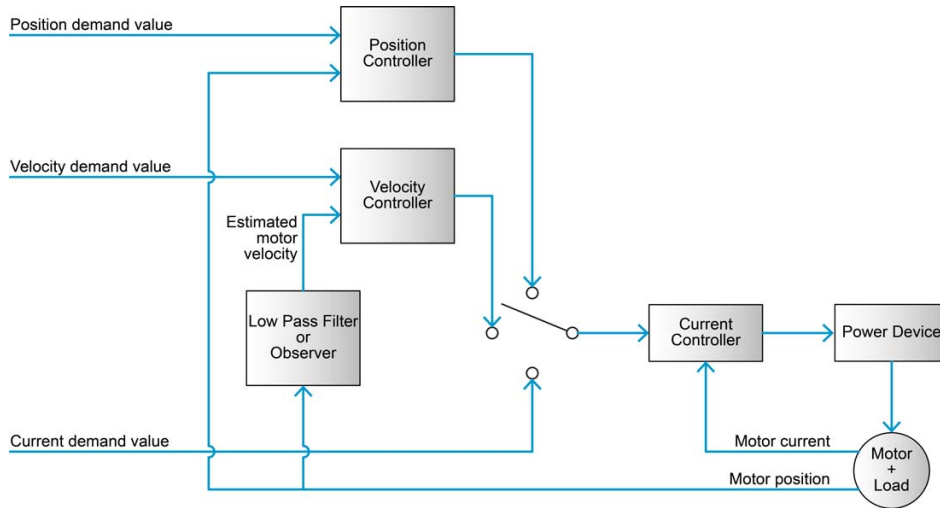

Figure 2-2   Controller architecture | Overview

2.3 Regulation Methods

2.3.1 Current Regulation

During a movement within a drive system, forces and/or torques must be controlled. Therefore, as a principal regulation structure, EPOS4 offers current-based control.
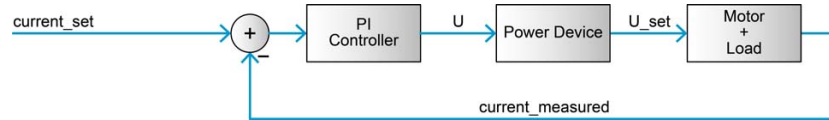

Figure 2-3   Controller architecture | Current regulator

CONSTANTS

Sampling period: $T_s = 0.04 \, \text{msec}$

OBJECT DICTIONARY ENTRIES

Symbol	Unit	Name	Index	Subindex
K_{P_EPOS4}	$\dfrac{mV}{A}$	Current controller P gain	0x30A0	0x01
K_{I_EPOS4}	$\dfrac{mV}{A \cdot \text{msec}}$	Current controller I gain	0x30A0	0x02

Table 2-7   Controller architecture | Current regulation – Object dictionary

CONVERSION OF PI CONTROLLER PARAMETERS (EPOS4 TO SI UNITS)

$$K_{P\_SI} = 0.001 \cdot K_{P\_EPOS4}$$

$$K_{I\_SI} = K_{I\_EPOS4}$$

Current controller parameters in SI units can be used in analytical or numerical simulations via the following transfer function:

$$C_{current}(s) = K_{P\_SI} + \frac{K_{I\_SI}}{s}$$

ANTI-WINDUP

In order to prevent degradation of the control performance when the control input stays at the limit value for long time, an anti-windup algorithm is implemented preventing the integral part of the PI controller to take values larger than the ones bound on the control input.

TRANSPORT DELAY OF THE CONTROL LOOP

Total transport delay of the current regulation loop is always smaller than 0.06 msec.

2.3.2 Velocity Regulation (with Feedforward)

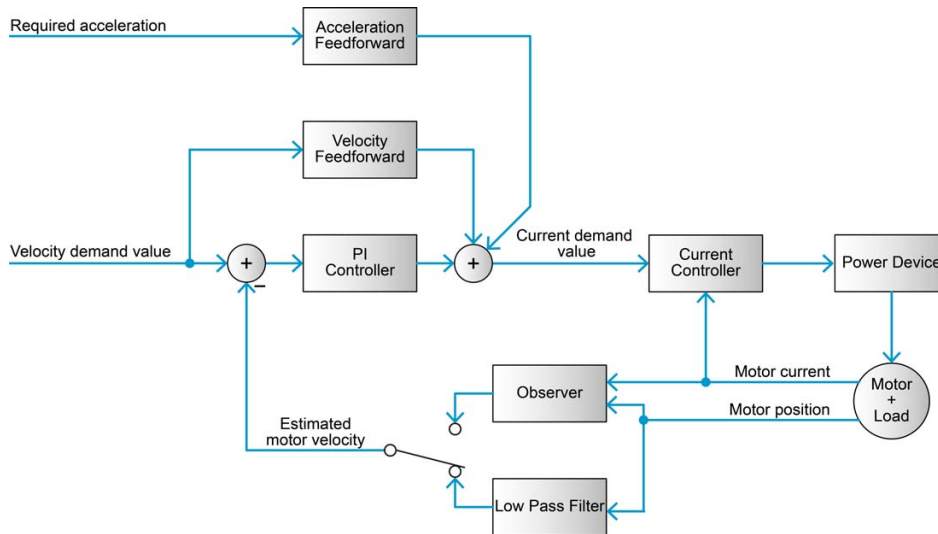EPOS4 offers velocity regulation based on the subordinated current control.

Figure 2-4   Controller architecture | Velocity regulator with feedforward

CONSTANTS

Sampling period: $T_s = 0.4 \, \text{msec}$

OBJECT DICTIONARY ENTRIES FOR CONTROLLER

Symbol	Unit	Name	Index	Subindex
$K_{P\omega\_EPOS4}$	$\dfrac{mA \cdot \sec}{rad}$	Velocity controller P gain	0x30A2	0x01
$K_{I\omega\_EPOS4}$	$\dfrac{mA}{rad}$	Velocity controller I gain	0x30A2	0x02
FF_{ω_EPOS4}	$\dfrac{mA \cdot \sec}{rad}$	Velocity controller FF velocity gain	0x30A2	0x03
FF_{α_EPOS4}	$\dfrac{mA \cdot \text{msec}^2}{rad}$	Velocity controller FF acceleration gain	0x30A2	0x04

Table 2-8   Controller architecture | Velocity regulation – Object dictionary

CONVERSION OF PI CONTROLLER PARAMETERS (EPOS4 TO SI UNITS)

$$K_{P\omega\_SI} = 0.001 \cdot K_{P\omega\_EPOS4}$$

$$K_{I\omega\_SI} = 0.001 \cdot K_{I\omega\_EPOS4}$$

$$FF_{\omega\_SI} = 0.001 \cdot FF_{\omega\_EPOS4}$$

$$FF_{\alpha\_SI} = 0.001 \cdot FF_{\alpha\_EPOS4}$$

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Velocity controller parameters in SI units can be used in analytical or numerical simulations via transfer function for the PI controller:

$$C_{velocity}(s) \ = \ K_{P\omega\_SI} + \frac{K_{I\omega\_SI}}{s}$$

ANTI-WINDUP

An anti-windup algorithm is implemented to prevent integration wind-up in PI controller, when the actuators are saturated.

LOW PASS FILTER

The estimation of the motor velocity can be done by using the differentiated measured motor position, which is low pass filtered in order to eliminate the effects of measurement noise. The transfer function of the low pass filtered estimation functionality that can be used in simulations has the following form:

$$C_{FilterEstimator}(s) \ = \ \frac{1}{1 + \dfrac{K_{P\omega\_SI}}{48 \cdot K_{I\omega\_SI}} \cdot s}$$

OBSERVER

An alternative to the low pass filter is the use of an observer. Thereby, the observed velocity is calculated in two steps. First; prediction of the velocity, position, and external torque, based on the parameters that define the mechanical transfer function of the system. Second; correction of the predicted values based on the newly measured rotor position.

OBJECT DICTIONARY ENTRIES FOR OBSERVER

Symbol	Unit	Name	Index	Subindex
k_{m_EPOS4}	$\dfrac{mNm}{A}$	Torque constant	0x3001	0x05
l_{θ_EPOS4}	1	Velocity observer position correction gain	0x30A3	0x01
l_{ω_EPOS4}	Hz	Velocity observer velocity correction gain	0x30A3	0x02
l_{T_EPOS4}	$\dfrac{mNm}{rad}$	Velocity observer load correction gain	0x30A3	0x03
r_{EPOS4}	$\dfrac{\mu Nm}{rpm}$	Velocity observer friction	0x30A3	0x04
J_{EPOS4}	gcm^2	Velocity observer inertia	0x30A3	0x05

Table 2-9   Controller architecture | Velocity observer – Object dictionary

All parameters relevant for the observer operation can be entered either manually or can be obtained from the EPOS4 auto tuning procedure. The auto tuning automatically executes the identification experiments, identifies the relevant parameters that characterize the drive train, and calculates the values of the observer correction gains.

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CONVERSION OF OBSERVER PARAMETERS (EPOS4 TO SI UNITS)

$$k_{m\_SI} = 0.001 \cdot k_{m\_EPOS4}$$

$$J_{SI} = 0.0000001 \cdot J_{EPOS4}$$

$$r_{SI} = \frac{0.00003}{\pi} \cdot r_{EPOS4}$$

$$l_{\theta\_SI} = l_{\theta\_EPOS4}$$

$$l_{\omega\_SI} = l_{\omega\_EPOS4}$$

$$l_{T\_SI} = 0.001 \cdot l_{T\_EPOS4}$$

The transfer functions characterizing the two steps in the observer calculations and that can be used in numerical simulation of the velocity controller with observer are the following:

PREDICTION STEP

$$\theta_{Observed} = \frac{\omega_{Observed}}{s}$$

$$\omega_{Observed} = \frac{k_{M\_SI} \cdot i_{Measured} - T_{Observed}}{J_{SI} \cdot s + r_{SI}}$$

CORRECTION STEP

$$\theta_{Observed} = \theta_{Observed} + l_{\theta\_SI} \cdot (\theta_{Measured} - \theta_{Observed})$$

$$\omega_{Observed} = \omega_{Observed} + l_{\omega\_SI} \cdot (\theta_{Measured} - \theta_{Observed})$$

$$T_{Observed} = T_{Observed} + l_{T\_SI} \cdot (\theta_{Measured} - \theta_{Observed})$$

WHEN SHOULD THE LOW PASS FILTER BE USED TO ESTIMATE THE VELOCITY?

The estimation of the motor velocity based on differentiating the motor position measurement and low pass filtering does not rely on any additional information on the mechanical system to which the motor is attached. Therefore, it is suitable in cases when there is no information on the mechanical properties of the system available or when the characteristics of the system change significantly over time.

Typical examples are cases in which the moment of inertia or viscous friction that the motor encounters change significantly during operation.

The solution with the filter gives good results in cases when a high-resolution position sensor is used and when the motor is operated at relatively high velocities (more than 20% of nominal motor speed). However, in cases when the resolution of the position sensor is low and/or the motor operates at low speed, the estimation with the observer results in a better control performance.

WHEN SHOULD THE OBSERVER BE USED TO ESTIMATE THE VELOCITY?

In order to use the observer for estimating the rotational velocity of the motor, parameters, such as inertia and viscous friction coefficient of the drive system, need to be known and must be stable over time and should not change a lot during operation. In EPOS4, there is an option to identify all the required parameters by using the «Auto Tuning Wizard».

The use of the observer brings most advantages when the position feedback sensor has a low resolution. Typical example is the use of Hall sensors for feedback instead of an incremental encoder, or the use of incremental encoders with up to 500 counts per turn. In general, the use of the observer provides a less noisy estimation of the rotor velocity resulting in better regulation and less audible noise especially at low operational velocities.

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In addition, the velocity observer can be set stiffer (compared to the case when the filter is used) due to better quality of the estimated feedback signal resulting in a very good dynamical response.

However, when encoders with high resolution (above 500 counts pro revolution) are used, the performance of the system with observer is similar to its performance in the case when the low pass filter is used.

TRANSPORT DELAY OF THE CONTROL LOOP

Total transport delay of the velocity regulation loop is always smaller than 0.4 msec.

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2.3.3 Position Regulation (with Feedforward)

EPOS4 is able to close a positioning control loop based on the subordinated current control.

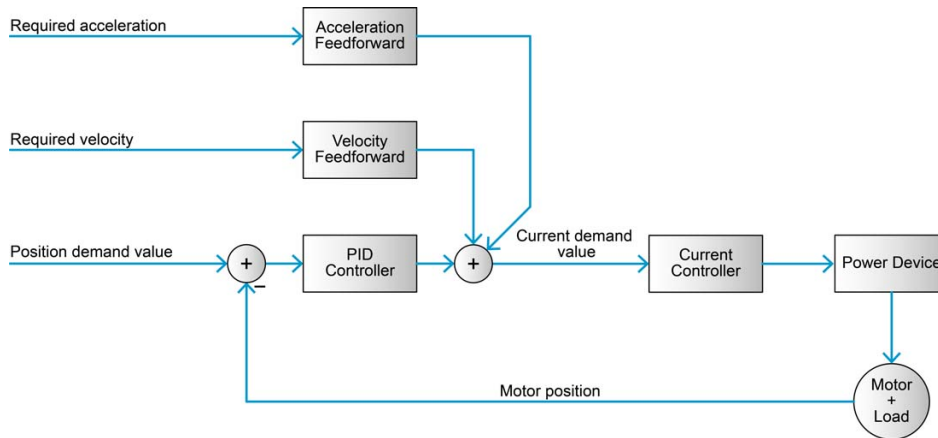Figure 2-5   Controller architecture | Position regulator with feedforward

CONSTANTS

Sampling period: $T_s = 0.4\,\text{msec}$

OBJECT DICTIONARY ENTRIES

Symbol	Unit	Name	Index	Subindex
K_{PP_EPOS4}	$\dfrac{mA}{rad}$	Position controller P gain	0x30A1	0x01
K_{IP_EPOS4}	$\dfrac{mA}{rad \cdot \sec}$	Position controller I gain	0x30A1	0x02
K_{DP_EPOS4}	$\dfrac{mA \cdot \sec}{rad}$	Position controller D gain	0x30A1	0x03
FF_{ω_EPOS4}	$\dfrac{mA \cdot \sec}{rad}$	Position controller FF velocity gain	0x30A1	0x04
FF_{α_EPOS4}	$\dfrac{mA \cdot \sec^2}{rad}$	Position controller FF acceleration gain	0x30A1	0x05

Table 2-10   Controller architecture | Position regulation – Object dictionary

The position controller is implemented as PID controller. To improve the motion system's setpoint following, positioning regulation is supplemented by feedforward control. Thereby, velocity feedforward serves for compensation of speed-proportional friction, whereas acceleration feedforward considers known inertia. In addition, the differential part of the PID Controller signal is low pass filtered before it is added to the proportional and integral part. Low pass filtering is done to prevent negative influence on the control performance by the differentiation of noisy measured motor position.

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CONVERSION OF PI CONTROLLER PARAMETERS (EPOS4 TO SI UNITS)

$$K_{PP\_SI} = 0.001 \cdot K_{P\_EPOS4}$$

$$K_{IP\_SI} = 0.001 \cdot K_{I\_EPOS4}$$

$$K_{DP\_SI} = 0.001 \cdot K_{D\_EPOS4}$$

$$FF_{\omega\_SI} = 0.001 \cdot FF_{\omega\_EPOS4}$$

$$FF_{\alpha\_SI} = 0.001 \cdot FF_{\alpha\_EPOS4}$$

Position controller parameters in SI units can be used in analytical or numerical simulations via transfer function:

$$C_{position}(s) = K_{PP\_SI} + \frac{K_{IP\_SI}}{s} + \frac{K_{DP\_SI} \cdot s}{1 + \frac{K_{DP\_SI}}{10 \cdot K_{PP\_SI}} \cdot s}$$

ANTI-WINDUP

The anti-windup method is used to prevent integration wind-up in PID controller when the actuators are saturated.

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2.3.4 Operation Modes with Feedforward

Acceleration and velocity feedforward are effective in «Profile Position Mode» (PPM), «Profile Velocity Mode» (PVM), and «Homing Mode» (HMM). All other operating modes are not affected.

PURPOSE OF VELOCITY FEEDFORWARD

Velocity feedforward provides additional current in cases, where the load increases with speed, such as speed-dependent friction. The load is assumed to proportionally increase with speed. The optimal velocity feedforward parameter in SI units is:

$$FF_{\omega\_SI} = \frac{r_{SI}}{k_{m\_SI}}$$

Meaning: With given total friction proportional factor in SI units r_{SI} relative to the motor shaft, and the motor's torque constant also in SI units k_{m_SI}, you ought to adjust the velocity feedforward parameter to:

$$FF_{\omega\_EPOS4} = 1000 \cdot FF_{\omega\_SI} = 1000 \cdot \frac{r_{SI}}{k_{m\_SI}}$$

PURPOSE OF ACCELERATION FEEDFORWARD

Acceleration feedforward provides additional current in cases of high acceleration and/or high load inertias. The optimal acceleration feedforward parameter in SI units is:

$$FF_{a\_SI} = \frac{J_{SI}}{k_{m\_SI}}$$

Meaning: With given total inertia in SI units J_{SI} relative to the motor shaft, and the motor's torque constant in SI units k_{m_SI}, you ought to adjust the acceleration feedforward parameter to:

$$FF_{\alpha\_EPOS4} = 1000 \cdot FF_{\alpha\_SI} = 1000 \cdot \frac{J_{SI}}{k_{m\_SI}}$$

TRANSPORT DELAY OF THE CONTROL LOOP

Total transport delay of the position regulation loop is always smaller than 0.4 msec.

2.4 Regulation Tuning

maxon motor's «EPOS Studio» features regulation tuning as a powerful wizard allowing to automatically tune all controller, estimator, and feedforward parameters described above for most drive systems within a few minutes.

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2.5   Application Examples

Find below "in-practice examples" suitable for daily use.

2.5.1   Example 1: System with High Inertia and Low Friction

SYSTEM COMPONENTS

Item	Description	Setting
Controller EPOS4 Compact 50/8 CAN (520885)		
Motor maxon DCX 32 L 110 W 36 V	No load speed (line 2)	n_0 = 7940 rpm
	No load current (line 3)	I_0 = 103 mA
	Nominal current (line 6)	I_n = 2.93 A
	Terminal resistance (line 10)	R = 0.764 Ω
	Terminal inductance (line 11)	L = 0.254 mH
	Torque constant (line 12)	k_m = 42.9 mNm/A
	Rotor inertia (line 16)	J_{motor} = 76.8 gcm^2
Encoder HEDL 5540	Encoder counts per turn	500 pulses/revolution
Mechanical load Disc	Inertia	J_{load} = 1800 gcm^2

Table 2-11   Controller architecture | Example 1: Components

2.5.1.1   Current Regulation – Simulation Part

SIMPLE MODEL OF THE DRIVE PLANT

The following parameters can be deduced:
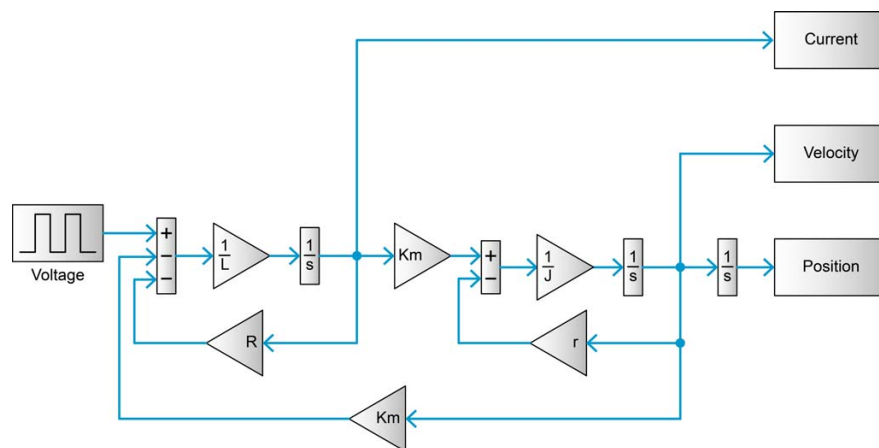
Figure 2-6   Controller architecture | Example 1: Model of the plant

INPUT/OUTPUT PARAMETERS

Input is the voltage at the motor winding.

Outputs are current, velocity, or position.

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MODEL PARAMETERS

Resistance $\quad\quad\quad\quad\quad R = 0.764[\Omega]$

Inductance $\quad\quad\quad\quad L = 0.254[mH]$

Torque constant $\quad\quad k_m = 42.9\left[\dfrac{mNm}{A}\right]$

Mass inertia $\quad\quad\quad J = J_{motor} + J_{load} = 1876.8[gcm^2]$

Viscous friction (approximated from the friction at no-load divided by the no-load speed of the motor)

$$r = \frac{k_m I_o}{n_o \dfrac{2\pi rad}{1}\dfrac{1 min}{60 \sec}} = \frac{4.41 mNm}{831.45 rad/\sec} = 5.3\left[\frac{\mu Nm}{rad/\sec}\right]$$

Note

- *All model parameters, expect the load inertia (J_{load}), can be taken from the motor data sheet in the maxon catalog.*
- *All parameters (R, L, k_m, I_0, n_0) taken from the motor data sheet are nominal variables, they have tolerances (for more details ➔ additional document «Standard Specification No.100»).*

CURRENT CONTROL

The figure below depicts the model of the PI current controller.
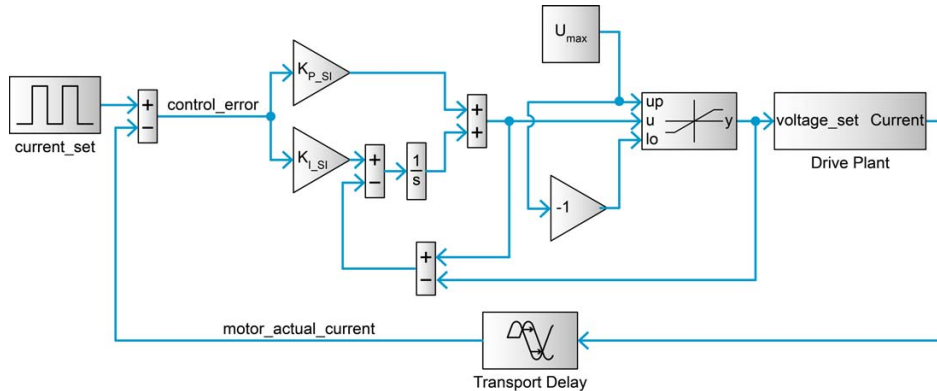
Figure 2-7   Controller architecture | Example 1: Current regulation

MODEL PARAMETERS OF CURRENT CONTROL

- EPOS4 PI current controller gains converted in SI Units.
- Transport delay = 0.060 msec.
- U_{max} corresponds to the nominal voltage of the motor (for details ➔ maxon catalog, motor data, line 1).

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2.5.1.2 Velocity Regulation with Feedforward - Simulation Part

The figure below displays the model of the PI velocity controller. The PI velocity controller is connected to the current regulation.
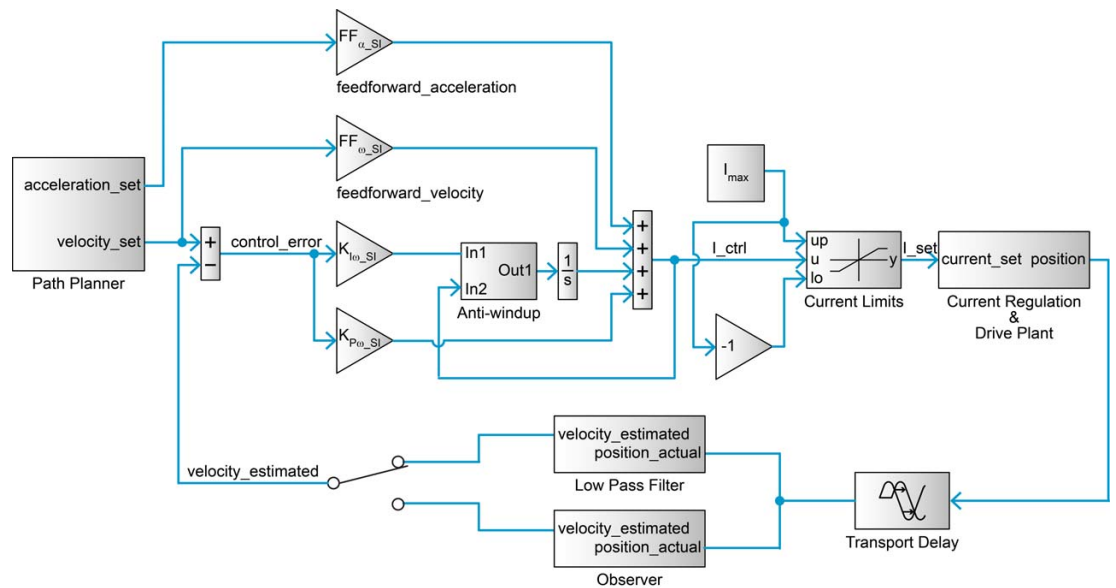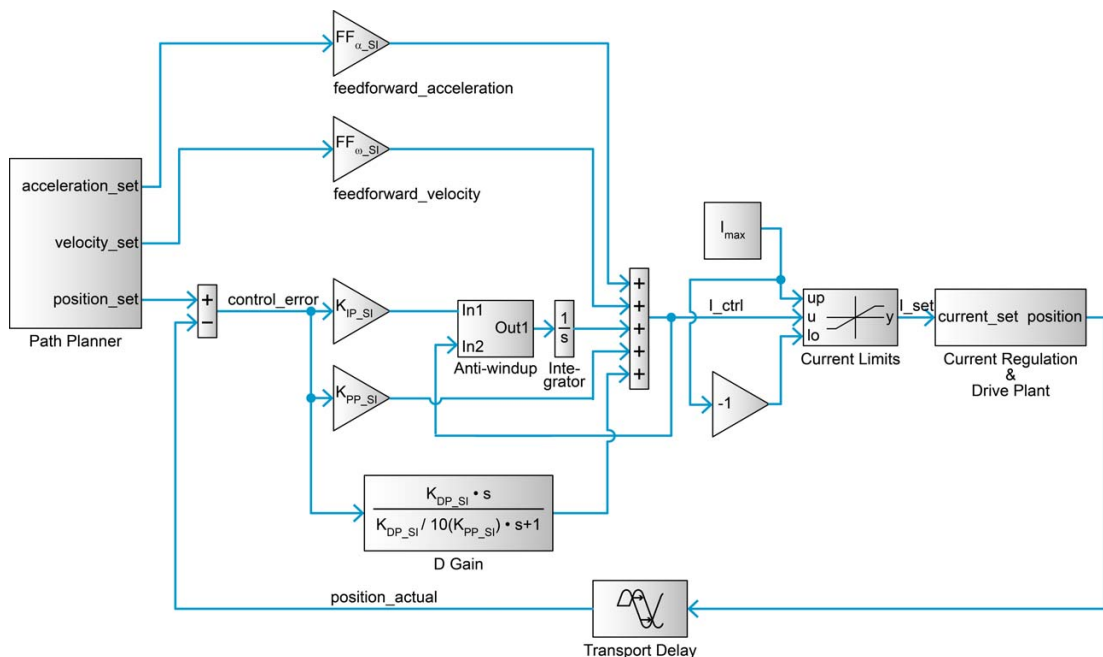

Figure 2-8   Controller architecture | Example 1: Velocity regulation

INPUT/OUTPUT PARAMETERS

- Inputs are the path planner set acceleration and set velocity.
- Outputs are the motor actual position and the motor estimated angular velocity.

MODEL PARAMETERS OF VELOCITY CONTROL

- EPOS4 PI velocity controller gains converted in SI Units.
- EPOS4 feedforward gains converted in SI Units.
- Transport delay = 0.4 msec.
- I_{max} corresponds to the motor's nominal current (for details ➜maxon catalog/motor data/line 6).

INPUT/OUTPUT PARAMETERS OF LOW PASS FILTER / OBSERVER

- Input is the motor actual position.
- Output is the motor estimated angular velocity.

MODEL PARAMETERS OF LOW PASS FILTER

- EPOS4 PI velocity controller gains converted in SI Units.
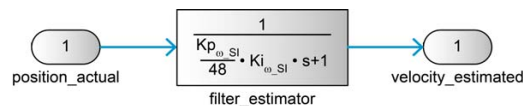
Figure 2-9   Controller architecture | Example 1: Velocity regulation – Low pass filter

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MODEL PARAMETERS OF OBSERVER

- The observer is implemented as Matlab function in Simulink.
- The relevant observer parameter, converted in SI Units, are:

Mass inertia $\quad\quad\quad\quad\quad J_{SI}$

Motor torque constant $\quad\quad k_{m\_SI}$

Viscous friction $\quad\quad\quad\quad r_{SI}$

Position correction gain $\quad l_{\theta\_SI}$

Velocity correction gain $\quad l_{\omega\_SI}$

Disturbance torque
correction gain $\quad\quad\quad\quad l_{T\_SI}$

POSITION REGULATION WITH FEEDFORWARD – SIMULATION PART

The figure below displays the model of the PID position controller with feedforward. The PID position controller is connected to the current regulation.

Figure 2-10   Controller architecture | Example 1: Position control with feedforward

INPUT/OUTPUT PARAMETERS

- Inputs are the path planner set acceleration, set velocity and set position.
- Output is the motor actual position.

MODEL PARAMETERS OF POSITION CONTROL

- EPOS4 PID position controller gains converted in SI Units
- EPOS4 Feedforward gains converted in SI Units
- Transport delay = 0.4 msec
- I_{max} corresponds to the motor's nominal current (for details ➔maxon catalog/motor data/line 6)

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2.5.2 Example 2: System with Low Inertia and High Friction
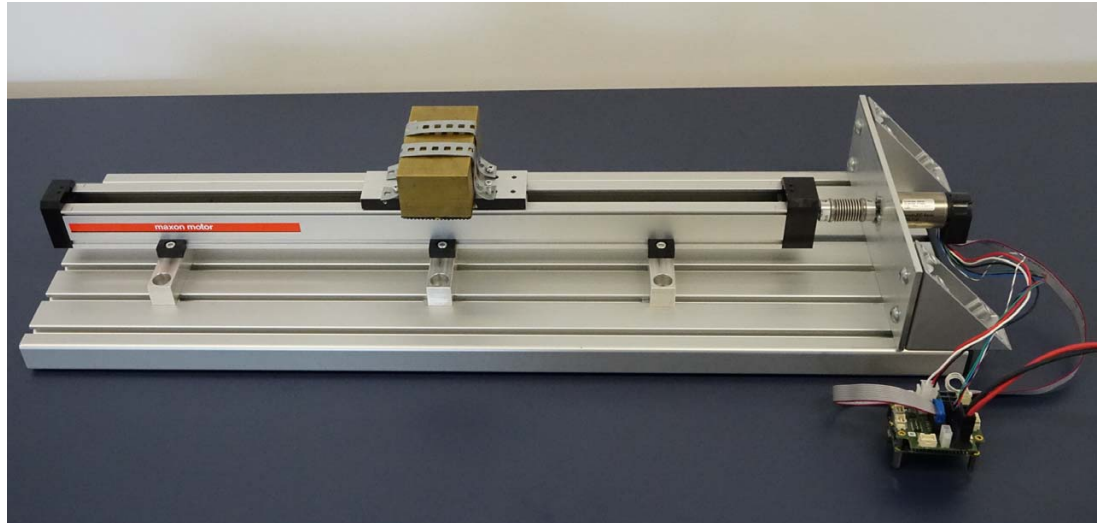
Figure 2-11   Controller architecture | Example 2: System with low inertia/high friction

SYSTEM COMPONENTS

Item	Description	Setting
Controller EPOS4 Compact 50/8 CAN (520885)		
Motor maxon EC-4pole 30 (309758)	No load speed (line 2)	n_0 = 17800 rpm
	No load current (line 3)	I_0 = 270 mA
	Nominal current (line 6)	I_n = 2.82 A
	Resistance phase to phase (line 10)	R = 0.836 Ω
	Inductance phase to phase (line 11)	L = 0.118 mH
	Torque constant (line 12)	k_m = 25.5 mNm/A
	Rotor inertia (line 16)	J_{motor} = 18.3 gcm^2
Encoder AEDL-5810 (516208)	Encoder counts per turn	5000 pulses/revolution
Mechanical load Linear drive	Inertia	J_{load} = 170 gcm^2
	Friction $M_r = 6.88mNm \cdot \text{sgn}(\omega) + 445.7 \dfrac{\mu Nm}{rad/\sec} \cdot \omega$	

Table 2-12   Controller architecture | Example 2: Components

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SIMPLE MODEL OF THE DRIVE PLANT

The following parameters can be deduced:
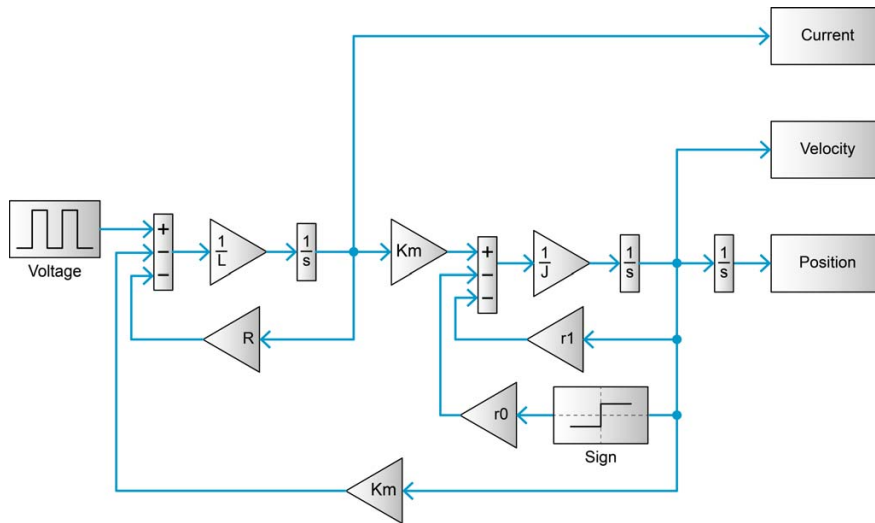
Figure 2-12   Controller architecture | Example 2: Model of the plant

INPUT/OUTPUT PARAMETERS

Input is the voltage at the motor winding.

Outputs are current, velocity, or position.

MODEL PARAMETERS

Resistance	$R = 0.836[\Omega]$
Inductance	$L = 0.118[mH]$
Torque constant	$k_m = 25.5\left[\dfrac{mNm}{A}\right]$
Mass inertia	$J = J_{motor} + J_{load} = 188.3[gcm^2]$
Viscous friction (approximated from the friction at no-load divided by the no-load speed of the motor)	$r_1 = \dfrac{k_m I_o}{n_o\dfrac{2\pi rad}{1}\dfrac{1min}{60sec}} = 445.7\left[\dfrac{\mu Nm}{rad/\sec}\right]$
Static friction	$r_o = k_m I_o = 6.88[mNm]$

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2.6 Best Practice Example
«Differences in the use of Observer and Filter to estimate Motor Velocity»

Velocity regulation in EPOS4 can be configured by choosing either the low pass filter or the observer for estimating the motor velocity from the position measurement signals. The configuration choice is made in the «Startup Wizard» dialog box under the tab «Regulation» as illustrated in the following figure.
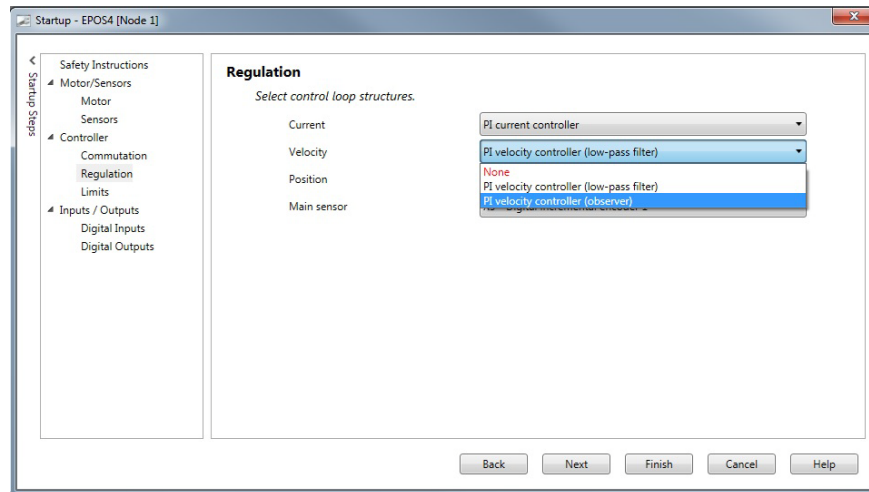
Figure 2-13   Controller architecture | Case 1: Configuration of velocity regulation mechanism

In the following examples we show two typical cases, the use of the observer for estimating the rotational velocity of the motor to increase the control performance compared with the case of using the low pass filter. In addition, we show an example in which the use of the observer does not bring much advantage and can, in fact, result in reduced control performance if the mechanical characteristics of the system are not well-identified or if they change over time.

2.6.1   Case 1: System with Low-Resolution Incremental Encoder

SYSTEM COMPONENTS

Item	Description	Setting
Controller EPOS4 Compact 50/8 CAN (520885)		
Motor maxon DCX 35 L, 80 W, 12 V	No load speed (line 2)	n_0 = 8140 rpm
	No load current (line 3)	I_0 = 321 mA
	Nominal current (line 6)	I_n = 6.0 A
	Terminal resistance (line 10)	R = 0.0792 Ω
	Terminal inductance (line 11)	L = 0.0263 mH
	Torque constant (line 12)	k_m = 13.7 mNm/A
	Rotor inertia (line 16)	J_{motor} = 99.5 gcm^2
Encoder ENX16 EASY	Encoder counts per turn	256 pulses/revolution
Mechanical load Disc	Inertia	J_{load} = 250 gcm^2

Table 2-13   Controller architecture | Case 1: Components

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After running the regulation tuning algorithm, we obtain the following set of parameters which describe the velocity controller used by EPOS4.

Index	Subindex	Name	Value	Unit
0x3001	0x05	Torque constant	14.452	$\frac{mNm}{A}$
0x30A2	0x01	Velocity controller P gain	324.927	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x02	Velocity controller I gain	2675.916	$\frac{mA}{rad}$
0x30A2	0x03	Velocity controller FF velocity gain	0.000	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x04	Velocity controller FF acceleration gain	2.466	$\frac{mA \cdot \sec^2}{rad}$
0x30A3	0x01	Velocity observer position correction gain	0.600	1
0x30A3	0x02	Velocity observer velocity correction gain	151.120	Hz
0x30A3	0x03	Velocity observer load correction gain	78.971	$\frac{mNm}{rad}$
0x30A3	0x04	Velocity observer friction	0.000	$\frac{\mu Nm}{rpm}$
0x30A3	0x05	Velocity observer inertia	357.503	gcm^2

Table 2-14   Controller architecture | Case 1: Velocity regulation with low pass filter parameters, real

Note that the same control parameters are used for both experiments, low pass filter and observer. These parameters were obtained during the auto tuning procedure where the filter in closed loop was selected. The auto tuning algorithm normally gives different parameters when the observer is selected. These parameters correspond to a more aggressive PI controller as it can better utilize the advantages present when the observer is used in closed loop (more about this point is said later on after the presentation of the results).

The comparison of the two different velocity estimation algorithms is done by looking at the step response of the controller for a reference of 1000 rpm and to the ripple in the case of 50 rpm velocity reference.

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The measured step response data are given in the following figure.
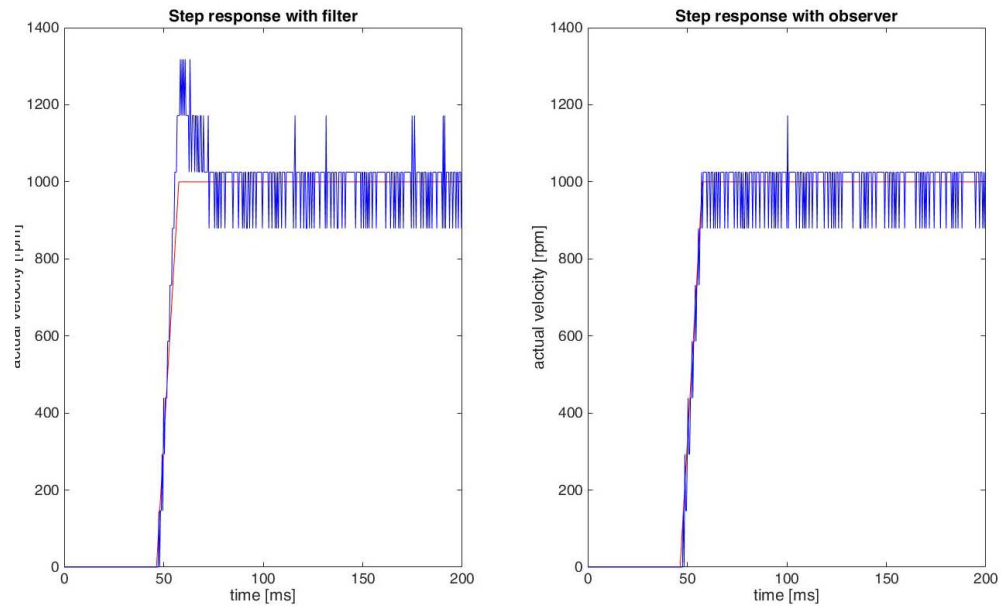
Figure 2-14   Controller architecture | Case 1: Comparison of velocity step responses

These results show the advantage of using the observer instead of the low pass filter. The controller with observer in closed loop results in much smaller overshoot and, hence, tighter reference following. The main reason for this is that the observer introduces much less phase shift in the loop than the filter would.

As a result, the velocity PI controller can be made more aggressive in the case when the observer is used compared to the use of the filter. Thus, using the observer allows much tighter reference tracking. This fact is illustrated by a step response performance comparison for the following set of control parameters which correspond to a more aggressive PI controller than in the first experiment:

Index	Subindex	Name	Value	Unit
0x3001	0x05	Torque constant	14.452	$\frac{mNm}{A}$
0x30A2	0x01	Velocity controller P gain	1127.098	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x02	Velocity controller I gain	12838.180	$\frac{mA}{rad}$
0x30A2	0x03	Velocity controller FF velocity gain	0.000	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x04	Velocity controller FF acceleration gain	1.368	$\frac{mA \cdot \sec^2}{rad}$
0x30A3	0x01	Velocity observer position correction gain	0.600	1
0x30A3	0x02	Velocity observer velocity correction gain	351.120	Hz
0x30A3	0x03	Velocity observer load correction gain	280.971	$\frac{mNm}{rad}$
0x30A3	0x04	Velocity observer friction	0.000	$\frac{\mu Nm}{rpm}$
0x30A3	0x05	Velocity observer inertia	357.503	gcm^2

Table 2-15   Controller architecture | Case 1: Velocity regulation with observer parameters, real

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Comparison of the step responses for the more aggressive controller is given in the following figure. As can be seen, the controller with observer shows a very good performance while the performance of the controller with low pass filter deteriorates and the overshoot becomes extremely high. Additionally, the use of the filter with these high control gains results in significant amplification of audible noise.

In order to exploit this advantage of the observer, the PI controller obtained in auto tuning has higher gains when the observer is used, than when the low pass filter is used.
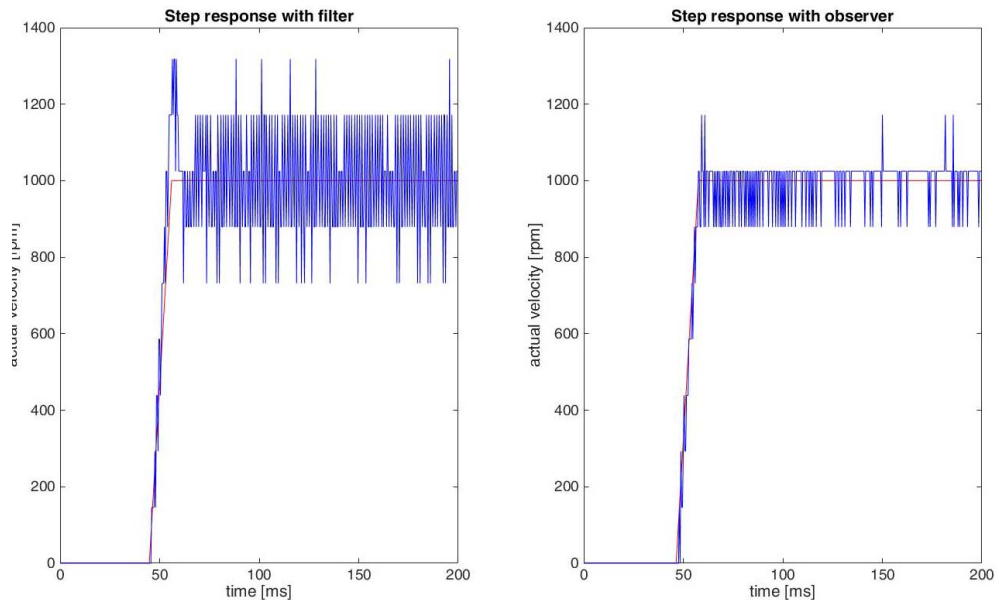
Figure 2-15   Controller architecture | Case 1: Comparison of velocity step responses

In addition to the step response, we also compare the steady state control performance at a low rotational velocity reference value of 50 rpm. The following comparison is given for the tuning parameters in ➜Table 2-15. The averaged values of the measured velocity are shown and compared for the two velocity estimation strategies.
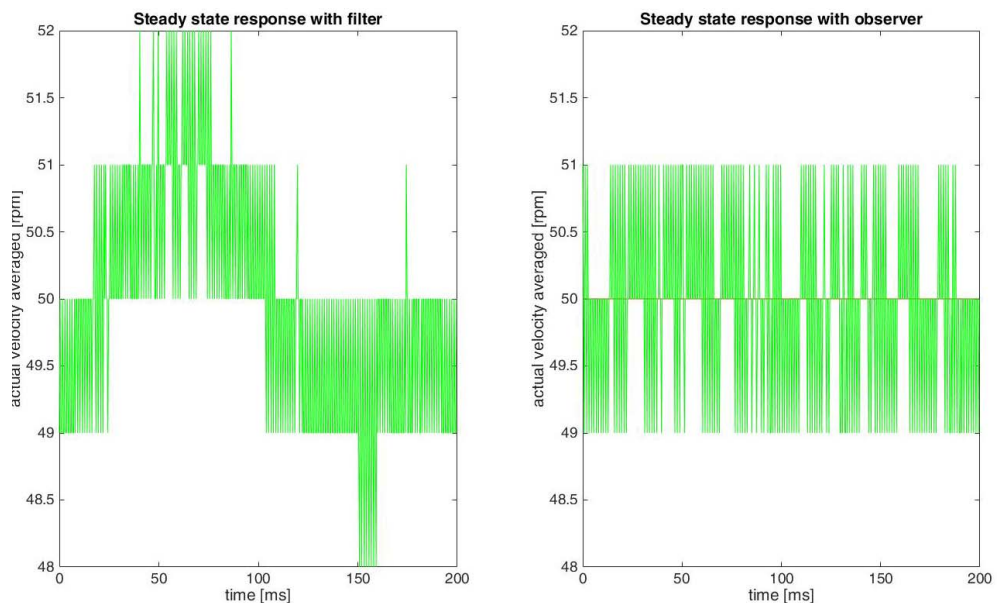
Figure 2-16   Controller architecture | Case 1: Comparison of velocity steady states

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At very low velocity, the estimate obtained when the observer is used has higher quality and therefore the overall closed loop results in less ripple at steady state (i.e. more tight velocity reference following), as can be seen in ➜Figure 2-16.

2.6.2 Case 2: System with Hall Sensor

SYSTEM COMPONENTS

Item	Description	Setting
Controller EPOS4 Compact 50/8 CAN (520885)		
Motor maxon EC-i 40 (496660) 7 pole pairs	No load speed (line 2)	n_0 = 8000 rpm
	No load current (line 3)	I_0 = 352 mA
	Nominal current (line 6)	I_n = 5.7 A
	Resistance phase to phase (line 10)	R = 0.207 Ω
	Inductance phase to phase (line 11)	L = 0.169 mH
	Torque constant (line 12)	k_m = 37.5 mNm/A
	Rotor inertia (line 16)	J_{motor} = 44 gcm^2
Encoder Built-in Hall sensors	Encoder counts per turn	42 pulses/revolution (7 pole pairs x 6 Hall sensor states)
Mechanical load Two discs coupled to the motor through a belt	Inertia	J_{load} = 324 gcm^2

Table 2-16   Controller architecture | Case 2: Components
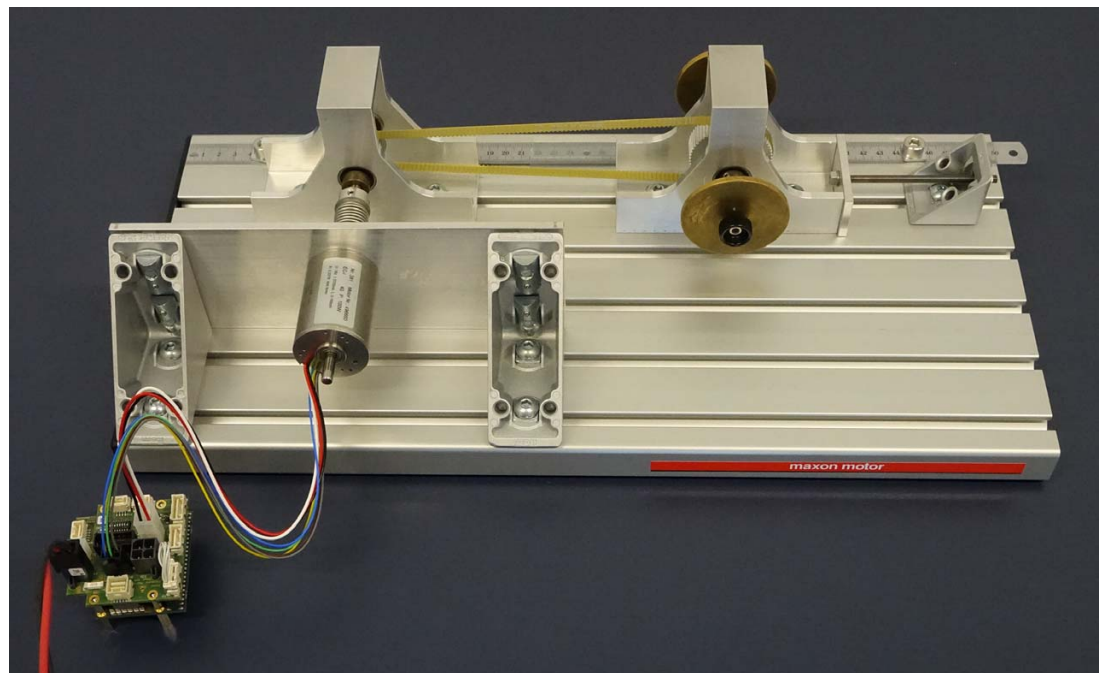
Figure 2-17   Controller architecture | Case 2: Belt drive system

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The advantages of using the observer instead of the filter for estimating the motor velocity are best visible in the case when the motor has no incremental encoder, but when a Hall sensor is used for both commutating the motor and estimating its velocity.

The control and observer parameters used in the experiments are the following:

Index	Subindex	Name	Value	Unit
0x3001	0x05	Torque constant	38.120	$\frac{mNm}{A}$
0x30A2	0x01	Velocity controller P gain	138.551	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x02	Velocity controller I gain	10494.003	$\frac{mA}{rad}$
0x30A2	0x03	Velocity controller FF velocity gain	89.548	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x04	Velocity controller FF acceleration gain	0.601	$\frac{mA \cdot \sec^2}{rad}$
0x30A3	0x01	Velocity observer position correction gain	0.399	1
0x30A3	0x02	Velocity observer velocity correction gain	68.056	Hz
0x30A3	0x03	Velocity observer load correction gain	67.834	$\frac{mNm}{rad}$
0x30A3	0x04	Velocity observer friction	0.366	$\frac{\mu Nm}{rpm}$
0x30A3	0x05	Velocity observer inertia	402.538	gcm^2

Table 2-17   Controller architecture | Case 2: Velocity regulation parameters, real

We compare the averaged measured motor velocity for a square velocity profile in the cases when the low pass filter and observer are used for estimating the rotor velocity respectively.
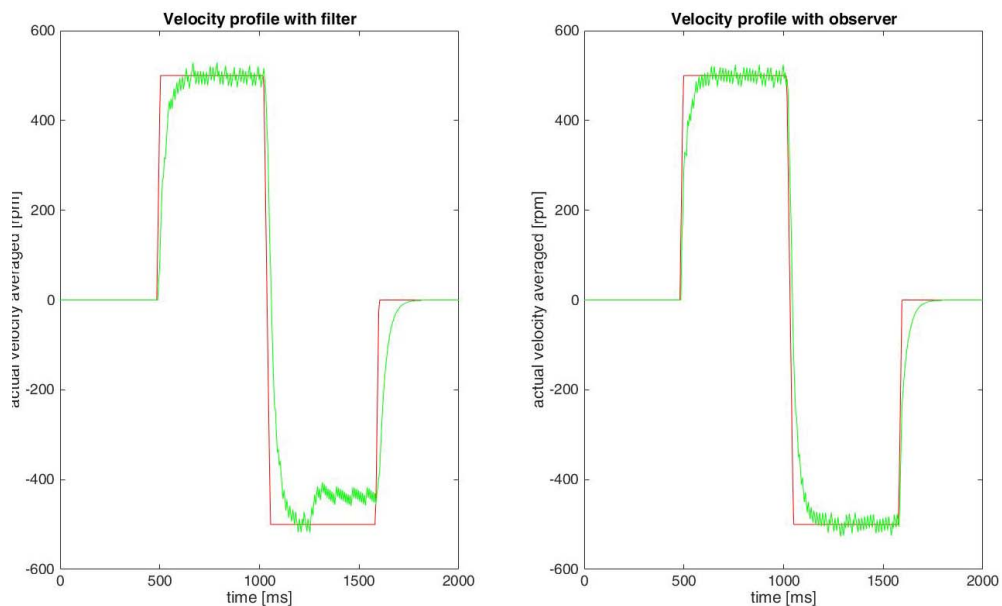
Figure 2-18   Controller architecture | Case 2: Comparison of velocity step responses

As can be seen, the use of the observer leads to tighter velocity reference tracking. In addition, the controller with the observer in closed loop produces much less audible noise during operation.

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2.6.3 Case 3: System with High-Resolution Encoder

SYSTEM COMPONENTS

Item	Description	Setting
Controller EPOS4 Compact 50/8 CAN (520885)		
Motor maxon EC 4pole 30 (309758)	No load speed (line 2)	n_0 = 17800 rpm
	No load current (line 3)	I_0 = 270 mA
	Nominal current (line 6)	I_n = 2.82 A
	Resistance phase to phase (line 10)	R = 0.836 Ω
	Inductance phase to phase (line 11)	L = 0.118 mH
	Torque constant (line 12)	k_m = 25.5 mNm/A
	Rotor inertia (line 16)	J_{motor} = 18.3 gcm^2
Encoder AEDL-5810 (516208)	Encoder counts per turn	5000 pulses/revolution
Mechanical load Two discs coupled to the motor through a belt	Inertia	J_{load} = 324 gcm^2

Table 2-18   Controller architecture | Case 3: Components

In this application example, the encoder resolution is very high and therefore the controller with the filter in closed loop has very similar behavior as the closed loop with the observer.

The control parameters, obtained from auto tuning for which the comparison is made, are the following:

Index	Subindex	Name	Value	Unit
0x3001	0x05	Torque constant	26.518	$\frac{mNm}{A}$
0x30A2	0x01	Velocity controller P gain	968.601	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x02	Velocity controller I gain	16748.581	$\frac{mA}{rad}$
0x30A2	0x03	Velocity controller FF velocity gain	0.000	$\frac{mA \cdot \sec}{rad}$
0x30A2	0x04	Velocity controller FF acceleration gain	1.313	$\frac{mA \cdot \sec^2}{rad}$
0x30A3	0x01	Velocity observer position correction gain	0.650	1
0x30A3	0x02	Velocity observer velocity correction gain	369.465	Hz
0x30A3	0x03	Velocity observer load correction gain	53.370	$\frac{mNm}{rad}$
0x30A3	0x04	Velocity observer friction	0.000	$\frac{\mu Nm}{rpm}$
0x30A3	0x05	Velocity observer inertia	348.148	gcm^2

Table 2-19   Controller architecture | Case 3: Velocity regulation parameters, real

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The comparison of the controller transient behavior is done by experiments in which a 1000 rpm step should be followed.
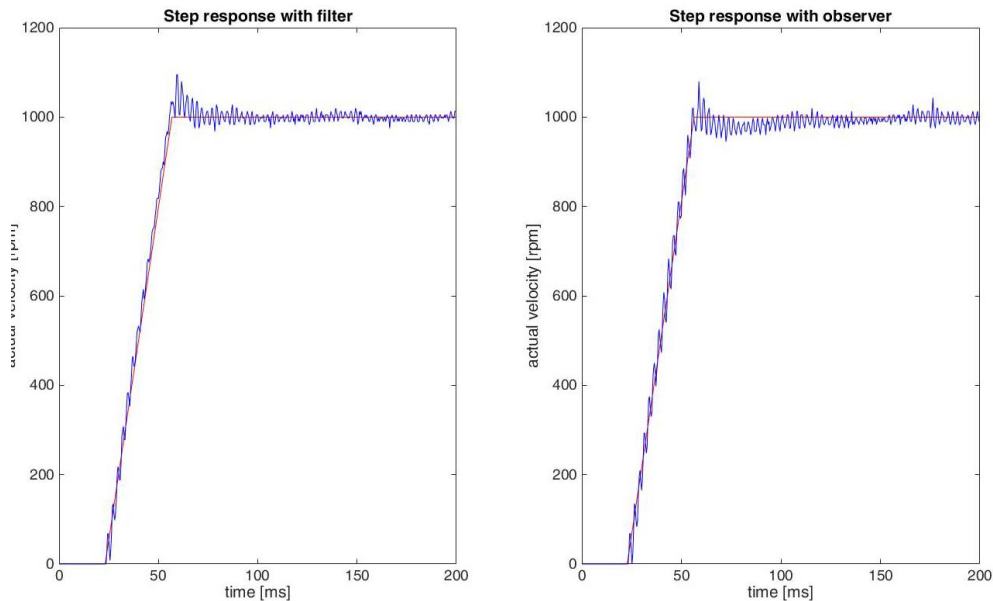
Figure 2-19   Controller architecture | Case 3: Comparison of velocity step responses

In addition, we compare the steady state controller behavior for a constant reference of 20 rpm.
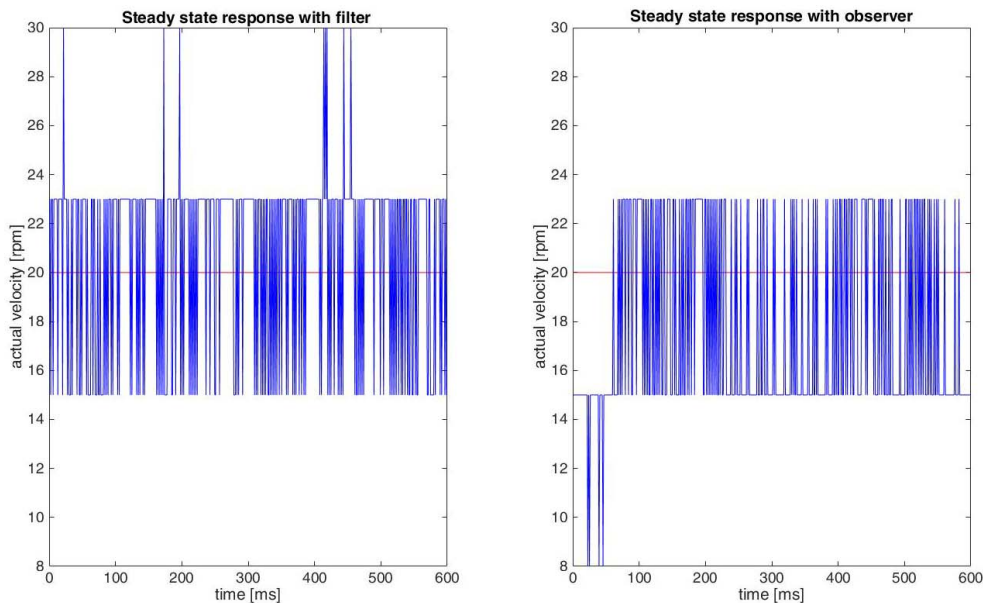
Figure 2-20   Controller architecture | Case 3: Comparison of velocity steady states

As can be seen, there is very little to no difference in the control performance. The reason is that the quality of the position and hence the velocity measurement is very good. Therefore, using the model of the mechanical system to which the motor is attached, as is done when the observer is used does not bring a lot of benefit. On the contrary, in such cases it may happen that the performance of the closed loop with observer becomes worse than the performance with the filter if the mechanical model parameters are not accurate or if they change over time.

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2.7   Conclusion

The described application examples show that it makes sense to use the observer for estimating the rotational velocity of the motor in cases when the position sensor has low resolution and when the parameters of the mechanical system are constant and can be well identified. In these cases, the use of the observer results in less ripple at low velocities and allows for more tight dynamic following of the reference signal than in the case when the low pass filter is used. On the other hand, when position sensors with high resolution are used, the use of the observer cannot bring much benefit, but instead could lead to deterioration in control performance if the mechanical model of the system is not accurate. In these cases it is better to use a filter for estimating the rotational velocity.

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3   Safe Torque Off (STO) Functionality

CONTENT

3.1   In Brief

The EPOS4 offers the Safe Torque Off (STO) safety feature based on IEC/EN 61800-5-2.

The present application note explains how to setup and configure the EPOS4 controller for the STO functionality. EPOS4's certification of the STO functionality is under way but not yet finalized.

Pin numbering in the diagrams shown is related to EPOS4 controllers that feature connectors.

3.2   Precautionary Measures

> ⚠️ **WARNING**
>
> ***Risk of Injury***
> ***Operating the device without the full compliance of all relevant safety regulations and/or neglecting the basic working principle of Safe Torque Off (STO) may cause serious injuries!***
> - *Carry out a comprehensive and thorough risk assessment covering the entire safety system and all safety-relevant aspects to ensure that the STO function will fulfill all relevant safety requirements of the application.*
> - *The STO function **does not** cut the power supply to the drive and **does not** provide electrical isolation.*
> - *The STO function **can prevent** unexpected motor rotation of an electronically commutated motor (EC motor, BLDC motor, brushless DC motor) in a save manner. Even in error condition with one or more short-circuited power stage transistors, an electronically commutated motor will not be able to generate torque over a relevant rotation angle.*
> - *Vice versa, the STO function **cannot prevent** unexpected motor rotation of a mechanically commutated motor (DC motor, brushed motor) in a safe manner. Despite of the STO functionality, an error condition of short-circuited power stage transistors may lead to unexpected motor rotation.*

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3.3 Description
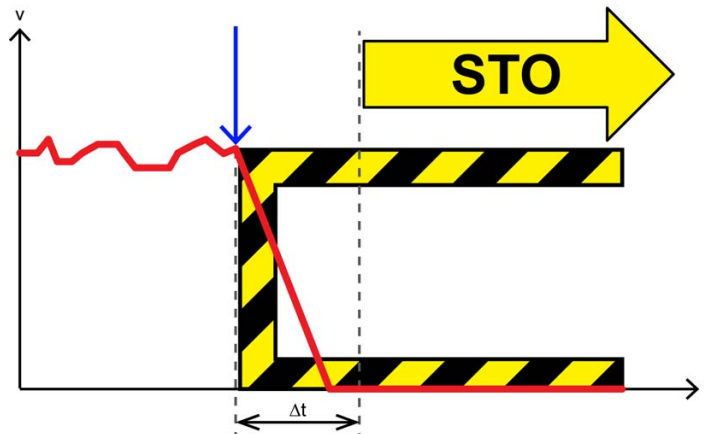
Figure 3-21   Safe Torque Off (STO) | Working principle

The STO function is the most common and basic drive-integrated safety function. It ensures that no torque-generating energy can continue to act on a motor and prevents unintentional starting.

STO has the immediate effect that the drive can no longer supply any torque-generating energy. STO can be used whenever the drive will be brought to a standstill in a sufficiently short time by load torque or friction, or if coasting down of the drive is not relevant to safety. STO enables safe working when, for example, the protective door is open (restart interlock) and has a wide range of uses in machinery with moving axes (such as handling or conveyor systems).

Mechanical brakes must be used if output shafts of motors or gearboxes are affected by forces that could trigger a movement once the motor has been shut down. Possible applications are vertical axes or motors with high inertia.

The STO function can be utilized to perform a safe stop according to IEC/EN 60204-1, stop category 0 (uncontrolled stop by immediate shut-down of the power supply to the actuators).

3.4 Functional Diagram
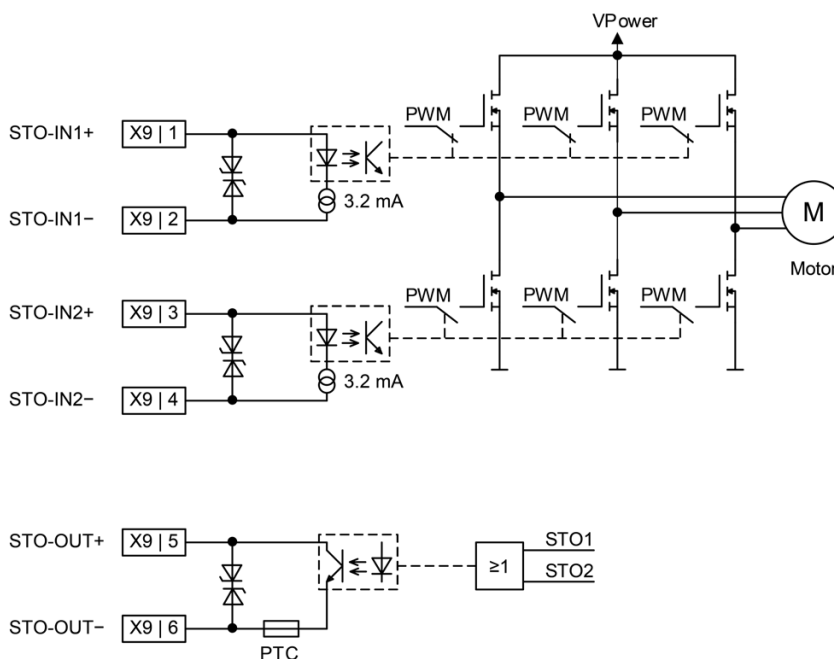
Figure 3-22   Safe Torque Off (STO) | Functional diagram

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Interrupting the current to either STO1 or STO2 input will disable the drive output. Thus, the power supply to the motor is cut by stopping the switching process of the output transistors in a safe way.

The STO output is activated when either STO1 or STO2 input is powered. For details on the STO logic states ➜Table 3-20.

3.5 STO Idle Connector

In order to activate the power stage, **either** both STO inputs must be powered **or** the «STO Idle Connector» (520860) must be plugged.

Do not use the activation voltage V_{STO} (+5 VDC) for any other purpose.

The «STO Idle Connector» is included with every EPOS4 controller that features connectors.
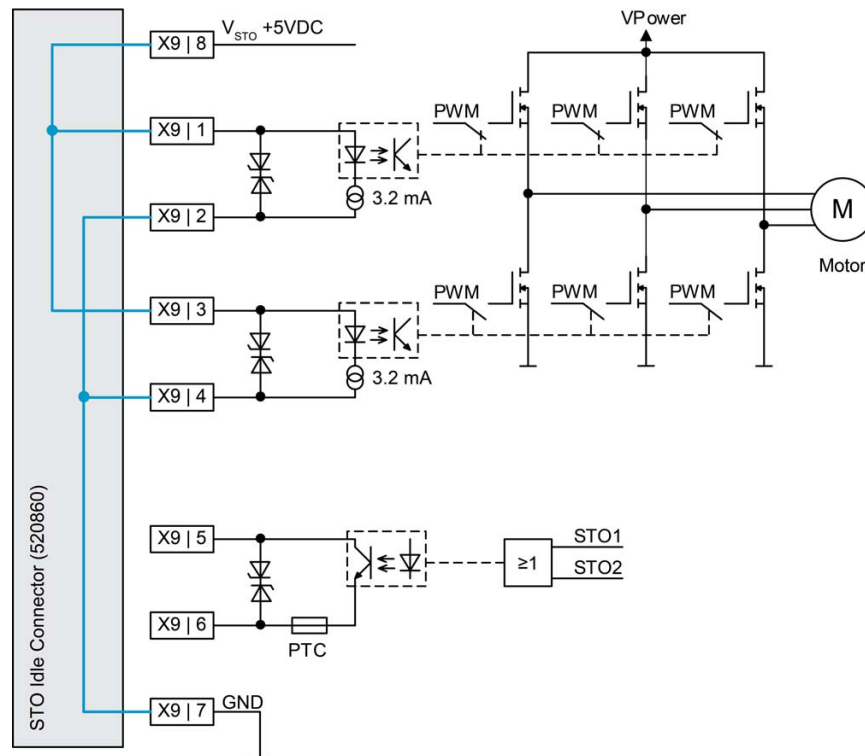
Figure 3-23   Safe Torque Off (STO) | STO Idle Connector

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3.6   STO Inputs 1 & 2

3.6.1   Specifications

Safe Torque Off inputs 1…2	
Circuit type	Optically isolated input
Input voltage	0…+30 VDC
Max. input voltage	±30 VDC
Logic 0	<1.0 VDC
Logic 1	>4.5 VDC
Input current at logic 1	>2 mA @ 5 VDC typically 3.2 mA @ 24 VDC
Reaction time	<25 ms
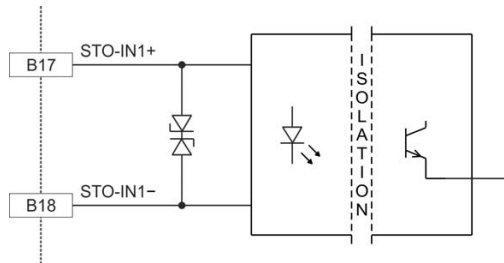
Figure 3-24   Safe Torque Off (STO) | STO-IN1 circuit (analogously valid for STO-IN2)

3.6.2   Test Pulses

The STO1 and STO2 inputs are designed for use with fail-safe output terminals with test pulses.
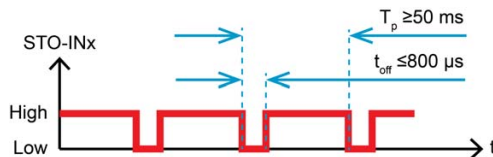
Figure 3-25   Safe Torque Off (STO) | Test pulses

Test pulses that do not fulfill the stated specifications for T_p and t_{off} can have a negative impact on the power stage gate control and can lead to unpredictable behavior.

3.6.3   Input Current

To achieve a fail-safe current measurement supervision on the output terminal, the current threshold must be lower than the typical STO input current (3.2 mA @ 24 VDC).

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3.7 STO Output

3.7.1 Specifications

Safe Torque Off output	
Circuit type	Optically isolated output with self-resetting short-circuit protection
Max. input voltage	±30 VDC
Max. load current	15 mA
Leakage current	<10 µA @ +30 VDC
Max. voltage drop	1.3 V @ 2 mA 2.5 V @ 15 mA
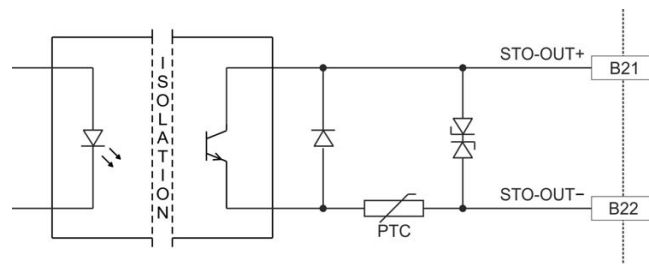
Figure 3-26   Safe Torque Off (STO) | STO-OUT circuit

3.7.2 Diagnostics

The STO output is used for proof test of the EPOS4's internal STO functionality. Thereby, the proof test must be triggered by an external logic.

Proof test is essential to reveal any dangerous, undetected failure after a given period of time.

STO Logic State			
STO-IN1	**STO-IN2**	**STO-OUT**	**Power Stage**
0	0	open	inactive
1	0	closed	inactive
0	1	closed	inactive
1	1	closed	active

Table 3-20   Safe Torque Off (STO) | Logic state

For diagnostics, maintain the reaction time of <25 ms between STO input state change and the STO output state change.

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Comparison of maxon Serial V1 vs. V2 Protocol for RS232
In Brief

4 Comparison of maxon Serial V1 vs. V2 Protocol for RS232

4.1 In Brief

With the introduction of the EPOS4 series, the positioning controllers' RS232 transmission protocol has been optimized and is now identical to the USB transmission protocol. This results in higher stability and improved performance of the RS232 serial communication data flow.

4.2 Description

> **Note**
> *The protocol change has an effect on RS232 communication, only. Hence, USB communication remains unchanged.*

The differences between the protocols «maxon V1» and «maxon V2» are as to the following details.

Type of controller	Interface	
	RS232	**USB**
EPOS2	maxon V1	maxon V2
EPOS4	maxon V2	maxon V2

Table 4-21   Protocol change – Overview

The two protocols feature different RS232 data flow while transmitting and receiving frame for EPOS2 and EPOS4 positioning controllers.
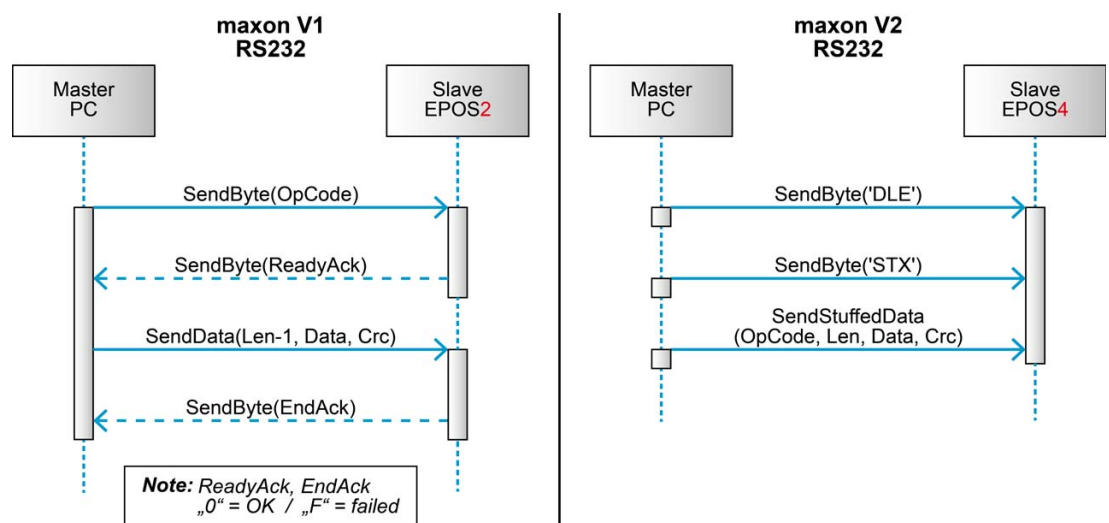
Figure 4-27   RS232 communication – Sending a data frame to EPOS2 (left) vs. EPOS4 (right)

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Comparison of maxon Serial V1 vs. V2 Protocol for RS232
Description

4.2.1 maxon Serial V1

The data bytes are sequentially transmitted in frames. After sending the first frame byte (OpCode), the Master needs to wait for the "Ready Acknowledge". A frame composes of…

- header,
- variably long data field, and
- 16-bit long cyclic redundancy check (CRC) for verification of data integrity.

OpCode (8-bit)	Len-1 (8-bit)	Data[0] (16-bit)	…	Data[Len-1] (16-bit)	CRC (16-bit)
HEADER		DATA			CRC

Figure 4-28   maxon serial V1 protocol – Frame structure

4.2.2 maxon Serial V2

The data bytes are sequentially transmitted in frames. The first two bytes (DLE/STX) are used for frame synchronization. Therefore, there is no need to wait for an acknowledge and thus, communication is simplified compared to maxon serial V1 protocol. A frame composes of…

- synchronization characters,
- header with data stuffing,
- variably long data field with data stuffing, and
- 16-bit long cyclic redundancy check (CRC) for verification of data integrity with data stuffing.

DLE (8-bit)	STX (8-bit)	OpCode (8-bit)	Len (8-bit)	Data[0] (16-bit)	…	Data[Len-1] (16-bit)	CRC (16-bit)
SYNC		HEADER		DATA			CRC
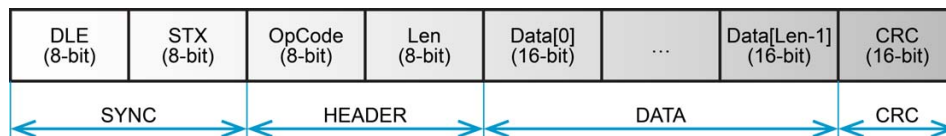
Figure 4-29   maxon serial V2 protocol – Frame structure

Note
For further details on commissioning, control possibilities, and command instruction examples for an EPOS2 ➜separate document «EPOS2 Communication Guide».

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