maxon motor ag Brünigstrasse 220 CH – 6072 Sachseln www.maxonmotor.com	**PWM power stage: Current ripple & external motor chokes**	Version: 1.1 (Eng.) Author : WJ Date : 2022-07-05

Controller and Amplifiers with PWM power stages: Current ripple and external motor chokes?

Most modern motor controllers and amplifiers are based on a PWM power output adapting the required motor voltage by a PWM pulse width modulation. The PWM controlled motor voltage leads to a current ripple that reflects the increasing and decreasing current inside the winding each PWM cycle. The current ripple can be one factor of heating up of the motor windings (even at standstill or without a load attached). The maximum peak-to-peak level (I_{PP}) of the current ripple depends on different factors. The dependency of the factors can be also seen by the formulaes on the last two pages of this document.

Current Ripple: Influencing factors

- The PWM frequency f_{PWM} of the amplifier:
  - ➢ The higher the frequency the smaller the current ripple.
- The PWM scheme used by the amplifier:
  - ➢ 4-Q amplifiers with 2-Level PWM sheme show a higher current ripple than 1-Q amplifiers or 4-Q amplifiers with 3-Level PWM scheme.
- The supply voltage V_{CC}:
  - ➢ The smaller the supply voltage the smaller the current ripple.
- The effective total inductance L_{tot} of the motor windings and possibly existing motor chokes:
  - ➢ The higher the inductance L_{tot} the smaller the current ripple.
- The load with respect to the max. continuous (nominal) current I_{cont} of the motor (see catalog):
  - ➢ The smaller the load the higher the current ripple may be without overloading the motor.

Motor chokes?

Additional chokes (in addition to the inductance of the motor winding) can reduce the current ripple strongly. Such motor chokes can be integrated directly in the power stage of the controller (like typically done by maxon) or can be connected externally in series to the motor windings.
There are different benefits by the usage of motor chokes:

- Motor chokes protect the motor from overheating due to a too large current ripple:
  - ➢ The choke reduces the current ripple caused by the PWM and the additional heat production is lowered by this.
- In special cases motor chokes may be necessary to guarantee the stability of the current control loop:
  - ➢ There is sometimes a “Minimum terrminal inductance“ specified by the controller.
- Motor chokes prevent the amplifier’s peak current limitation to be tripped unmeant, e.g. in case of “DEC Module 24/2” and “DEC Module 50/5“ operated with low-inductance motors at high voltages.
- Motor chokes are strongly recommended when operating brush DC motors with CLL disks in case of amplifiers without built-in motor chokes.

maxon controllers and amplifiers:

Most maxon controllers have built in motor chokes and high PWM frequencies to elimininate the need of additional external motor chokes. The following tables provides an overview of most maxon controllers and amplifiers.

The technical data (PWM frequency, integrated chokes) of product types which are not listed below can be found in the data sheets in the maxon catalog (-> http://epaper.maxongroup.com), the maxon product websites or the "Hardware Reference" of the selected product variant. Further specification data can also be found all of these mentioned documents.

Of the integrated (usually three) chokes, only two are active at each time due to the winding commutation of brushless motors, i.e. the relevant inductance is calculated as the sum of the inductance of only two chokes in each case. This is also valid in case of brush motors. One motor choke is not powered up in this case.

Up-to-date maxon controllers and amplifiers

maxon Controller resp. Amplifier	**PWM frequency f_{PWM}**	**PWM Scheme**	**Built-in choke L_{int} (phase to phase)**	**Minimum required terminal inductance**
EPOS4 product line (Extract of the product range) • In principle, all EPOS4 product types have a "3-level PWM". • In principle, modules do not have chokes. These must be provided on the so-called motherboard. Observe the notes in the chapter "Motherboard Design Guide" of the respective "Hardware Reference".				
EPOS4 Micro 24/5	50 kHz	3-Level (4-Q)	-	-
EPOS4 Module 24/1.5	100 kHz	3-Level (4-Q)	-	-
EPOS4 Compact 24/1.5 CAN	100 kHz	3-Level (4-Q)	188 µH (=94µH + 94µH)	-
EPOS4 Compact 24/1.5 EtherCAT	100 kHz	3-Level (4-Q)	200 µH (=100µH + 100µH)	-
EPOS4 Module 50/5	50 kHz	3-Level (4-Q)	-	-
EPOS4 Compact 50/5 CAN	50 kHz	3-Level (4-Q)	18.8 µH (=9.4µH + 9.4µH)	-
EPOS4 Compact 50/5 EtherCAT	50 kHz	3-Level (4-Q)	20 µH (=10µH + 10µH)	-
EPOS4 Module 50/8	50 kHz	3-Level (4-Q)	-	-
EPOS4 Compact 50/8 CAN	50 kHz	3-Level (4-Q)	4.4 µH (=2.2µH + 2.2µH)	-
EPOS4 Compact 50/8 EtherCAT	50 kHz	3-Level (4-Q)	4.4 µH (=2.2µH + 2.2µH)	-
EPOS4 Module 50/15	50 kHz	3-Level (4-Q)	-	-
EPOS4 Compact 50/15 CAN	50 kHz	3-Level (4-Q)	4.4 µH (=2.2µH + 2.2µH)	-
EPOS4 Compact 50/15 EtherCAT	50 kHz	3-Level (4-Q)	4.4 µH (=2.2µH + 2.2µH)	-
EPOS4 50/5	50 kHz	3-Level (4-Q)	30 µH (=15µH + 15µH)	-

maxon Controller resp. Amplifier	**PWM frequency f_{PWM}**	**PWM Scheme**	**Built-in choke L_{int} (phase to phase)**	**Minimum required terminal inductance**
EPOS4 70/15	50 kHz	3-Level (4-Q)	30 µH (=15µH + 15µH)	-
EPOS4 Disk 60/8 CAN	50 kHz	3-Level (4-Q)	-	-
EPOS4 Disk 60/8 EtherCAT	50 kHz	3-Level (4-Q)	-	-
EPOS4 Disk 60/12 CAN	50 kHz	3-Level (4-Q)	-	-
EPOS4 Disk 60/12 EtherCAT	50 kHz	3-Level (4-Q)	-	-
ESCON product line • Except for the "ESCON EC-S" (= sensorless control) all ESCON product types have a "3-level PWM". Only the "ESCON EC-S" uses a 2-level PWM due to the Back-EMF detection for sensorless winding commutation. • In principle, modules do not have chokes. These must be provided on the so-called motherboard. Observe the notes in the chapter "Motherboard Design Guide" of the respective "Hardware Reference".				
ESCON Module 24/2	53.6 kHz	3-Level (4-Q)	-	-
ESCON 36/2 DC	53.6 kHz	3-Level (4-Q)	300 µH	-
ESCON 36/3 EC	53.6 kHz	3-Level (4-Q)	94 µH (=47µH + 47µH)	-
ESCON Module 50/4 EC-S	53.6 kHz	**2-Level (4-Q)**	-	-
ESCON 50/5	53.6 kHz	3-Level (4-Q)	60 µH (=30µH + 30µH)	-
ESCON Module 50/5	53.6 kHz	3-Level (4-Q)	-	-
ESCON Module 50/8 (HE)	53.6 kHz	3-Level (4-Q)	-	-
ESCON 70/10	53.6 kHz	3-Level (4-Q)	30 µH (=15µH + 15µH)	-
DEC modules				
DEC Module 24/2	46.8 kHz	1Q	-	-
DEC Module 50/5	46.8 kHz	1Q	-	-

NRND (= not recommended for new designs) and discontinued maxon controllers and amplifiers

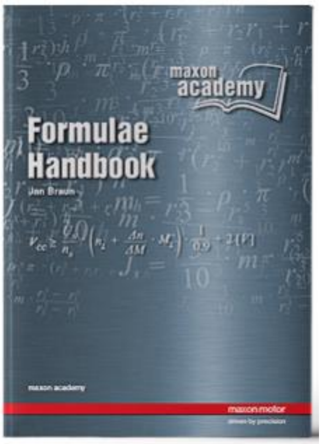
maxon Controller resp. Amplifier	**PWM frequency f_{PWM}**	**PWM Scheme**	**Built-in choke L_{int} (phase to phase)**	**Minimum required terminal inductance**
MAXPOS product line				
MAXPOS 50/5	100 kHz	3-Level (4-Q)	20 µH (=10µH + 10µH)	-
EPOS3 product line				
EPOS3 70/10	50 kHz	3-Level (4-Q)	44 µH (=22µH + 22µH)	
EPOS2 product line • In principle, all EPOS2 product types have a "3-level PWM".				
EPOS2 24/2	100 kHz	3-Level (4-Q)	94 µH (=47µH + 47µH)	-
EPOS2 Module 36/2	50 kHz	3-Level (4-Q)	20 µH (=10µH + 10µH)	-
EPOS2 24/5 EPOS2 P 24/5	50 kHz	3-Level (4-Q)	30 µH (=15µH + 15µH)	-
EPOS2 50/5	50 kHz	3-Level (4-Q)	44 µH (=22µH + 22µH)	-
EPOS2 70/10	50 kHz	3-Level (4-Q)	50 µH (=25µH + 25µH)	-
EPOS product line • In principle, all EPOS2 product types have a "3-level PWM".				
EPOS 24/1 #280937, #302267, #302287	50 kHz	3-Level (4-Q)	300 µH (=150µH + 150µH)	-
EPOS 24/1 #317270	50 kHz	3-Level (4-Q)	660 µH (=330µH + 330µH)	-
EPOS 24/5 EPOS P 24/5	50 kHz	3-Level (4-Q)	30 µH (=15µH + 15µH)	-
EPOS 70/10	50 kHz	3-Level (4-Q)	50 µH (=25µH + 25µH)	-
DEC product line				
DEC 24/1	39 kHz	1Q	300 µH (=150µH + 150µH)	-
DEC 24/3	39 kHz	1Q	-	-
DEC 50/5	39 kHz	1Q	-	-
DEC 70/10	50 kHz	2-Level (4-Q)	50 µH (=25µH + 25µH)	-
DECS 50/5	50 kHz	1Q	-	-
DES 50/5	50 kHz	3-Level (4-Q)	320 µH (=160µH + 160µH)	-
DES 70/10	50 kHz	3-Level (4-Q)	-	> 400µH

maxon Controller resp. Amplifier	**PWM frequency f_{PWM}**	**PWM Scheme**	**Built-in choke L_{int} (phase to phase)**	**Minimum required terminal inductance**
ADS product line				
ADS 50/5 ADS_E 50/5	50 kHz	2-Level (4-Q)	150 µH	-
ADS 50/10 ADS_E 50/10	50 kHz	2-Level (4-Q)	75 µH	-
MIP product line				
MIP 10	60 kHz	3-Level (4-Q)	1000 µH	-
MIP 50	60 kHz	2-Level (4-Q)	320 µH (=160µH + 160µH)	> 60µH @24VDC > 90µH @ 48VDC
MIP 100	60 kHz	3-Level (4-Q)	20 µH (=10µH + 10µH)	> 35µH @24VDC > 90µH @48VDC

Formulaes, …

If you want to calculate the expected motor current ripple and clarify if additional external motor chokes are required or not, there are some formulaes and rule of thumbs which help to clarify this quite easily.

The information on the following pages are taken out of maxon's "Formulae Handbook" (page 46).
(-> http://formulaehandbook.maxongroup.com)



The "Formulae Handbook" is the base of any drive selection and calculation focused on application requirements.

The "Formulae Handbook" provides a comprehensive overview and lots of formulas for drive engineering based on mechanical, electrical, and thermal aspects.

maxon's "Formulae Handbook" is for free!
Please contact your local maxon's sales representative
to get a printed version of maxon's formula handbook for free
or download the PDF version on maxon's website.

Your maxon sales representative will be pleased to assist you in the motor and controller selection based on the requirements of your application.

Calculation of the current ripple

Calculation of current ripple			
PWM scheme	**1-Q**	**2-level (4-Q)**	**3-level (4-Q)**
Maximum current ripple, peak-to-peak	$\Delta I_{PP,max} = \frac{V_{CC}}{4 \cdot L_{tot} \cdot f_{PWM}}$	$\Delta I_{PP,max} = \frac{V_{CC}}{2 \cdot L_{tot} \cdot f_{PWM}}$	$\Delta I_{PP,max} = \frac{V_{CC}}{4 \cdot L_{tot} \cdot f_{PWM}}$
Calculation L_{tot}	$L_{tot} = L_{int} + 0.3...0.8 \cdot L_{mot} + L_{ext}$		
The effective motor inductance in the case of square PWM excitation only amounts to approx. 30 – 80% of the catalog value L_{mot}. The catalog value L_{mot} is defined at a frequency of 1 kHz with sinusoidal excitation.			
– At a current ripple of $\Delta I_{PP} \leq 1.5 \cdot I_N$ the motor can still be loaded to approx. 90% of the nominal current I_N (catalog value). – At a current ripple of $\Delta I_{PP} > 1.5 \cdot I_N$, it is recommended to use an external motor choke, in accordance with the formula below.			

Rules of thumb

- maxon's 4-Q controllers use a 3-level PWM scheme, therefore the formulae
  $I_{PP} = V_{CC} / (4 * L_{tot} * f_{PWM})$
  can be used to determine the current ripple which is valid for 1-Q and 4-Q (3-level PWM) controllers.
- The effective inductance of the motor windings in case of a PWM frequency of 50 – 100 kHz will be just 30-80% of the value specified in the motor data sheet (which is based on a 1 kHz frequency). Therefore calculate the actual inductance of the motor by multiplying the specified value by 0.3.
- Do not miss the inductance of the internal motor chokes of the controller to calculate the total inductance L_{tot}. There are always just two of the internal chokes (phase-to-phase) active.
- If I_{PP} is lower than 1.5 times of the motor's nominal current (see motor data sheet) and the motor load is less than 90% of the specified motor's nominal torque, there is no additional external motor choke required.

Example

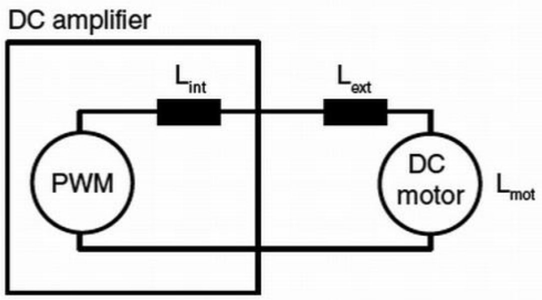
- Motor: ECi-40, #449464
  - Nominal current: 2.8 A
  - Terminal inductance: 0.39 mH
- ESCON 50/5, #409510
  - PWM frequency: 53.6 kHz
  - Built-in motor choke: 3 x 30 µH
- Supply voltage in use:
  - V_{CC}: 24 V
- Total inductance:
  - $L_{tot} = (0.3 * 0.39 \text{ mH}) + (2 * 0.03\text{mH})$
    $L_{tot} = 0.177 \text{ mH}$
- Current ripple:
  - $I_{PP} = V_{CC} / (4 * L_{tot} * f_{PWM})$
  - $I_{PP} = 24\text{V} / (4 * 0.177\text{mH} * 53.6\text{kHz})$
    $I_{PP} = 0.63 \text{ A}$
- Conclusion:
  - The current ripple (= 0.63A) is much less than the specified motor's nominal current (= 2.8A), i.e. there are no additional measures (e.g. external motor chokes) required for operation.

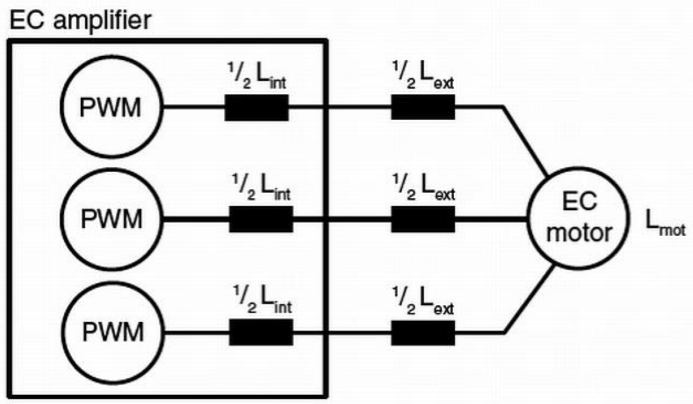
Estimation about the need of external motor chokes

Calculation, additional external motor choke		
PWM scheme	**1-Q and 3-level (4-Q)**	**2-level (4-Q)**
Rule of thumb	$L_{ext} = \frac{V_{CC}}{6 \cdot I_N \cdot f_{PWM}} - L_{int} - 0.3 \cdot L_{mot}$	$L_{ext} = \frac{V_{CC}}{3 \cdot I_N \cdot f_{PWM}} - L_{int} - 0.3 \cdot L_{mot}$

$L_{ext} \leq 0$ No additional motor choke required

$L_{ext} > 0$ Additional motor choke recommended





Symbol	Name	SI	Symbol	Name	SI
f_{PWM}	PWM frequency	Hz	L_{mot}	Terminal inductance, motor (catalog value)	H
I_N	Nominal current, motor (catalog value)	A	L_{tot}	Total inductance	H
L_{ext}	Inductance, additional external motor choke	H	V_{CC}	Supply voltage	V
			ΔI_{PP}	Current ripple, peak-to-peak	A
L_{int}	Inductance, built-in choke controller	H	$\Delta I_{PP,max}$	Maximum current ripple, peak-to-peak	A

Remark:

maxon controllers use high PWM frequencies (50 – 100 kHz) based on a 3-level PWM scheme, and there are often built-in motor chokes present optimized for the typically range of motors in use. Finally this reduces external wiring and reduces total costs of a system if there is no need for external motor chokes anymore.

Quite often there will be no need for external motor chokes if maxon controllers are in use. Anyway the formulaes above have to be taken into account to confirm this especially in case of a too hot motor or in case of using so-called “Module” product types without internal motor chokes.