![FAULHABER]

Equivalent DC-current in FAULHABER SC and MC

Summary

The datasheets of FAULHABER motors specify different currents such as the no-load current and the rated current expressed as DC or equivalent DC-currents.

Measuring these currents of a motor connected to either a SpeedController (SC) or MotionController (MC) can be confusing. So here is which currents and voltages can be measurend and how to interpret them.

Applies To

All FAULHABER MCs and SCs.

Motor drivers using a PWM power stage.

Description

When configuring a FAULHABER SC or MC any current value – the rated, continuous and the peak-currents are expected to be the current at the motor, expressed either as a DC-current for a brushed DC-motor or an equivalent DC-current for a brushless DC-motor (BLDC).

Especially for the brushless ones it is however difficult to acutally measure these currents.

The general setup typically is like in Figure 1.
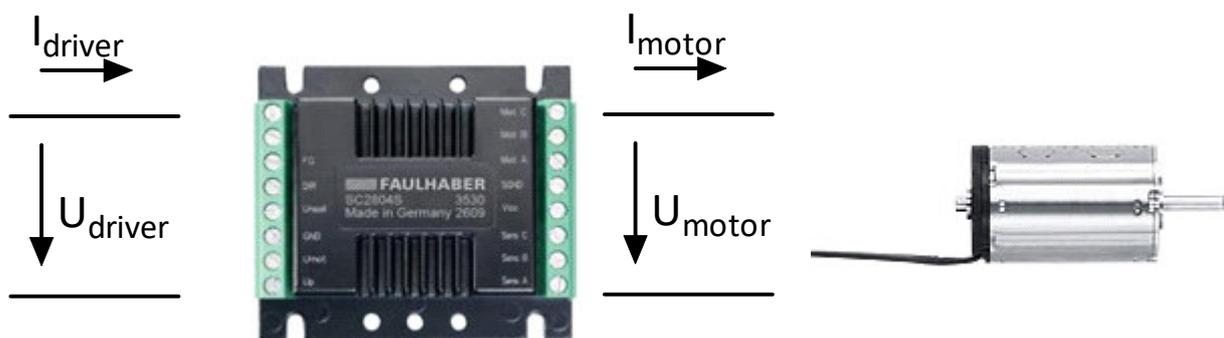
$$P = I_{driver} \times U_{driver} = I_{motor} \times U_{motor}$$

Figure 1 Currents and voltages at a motor driver

Either a brushed DC or a brushless DC motor is connected to a driver which is connected to a power supply.

Currents and voltages at a brushed DC-motor

The driver typically reduces the supply voltage U_{driver} by means of PWM to the required voltage at the motor U_{motor}.

The resulting voltage is required to compensate the EMF of the motor and to drive the necessary current across the winding resistance.

$$U_S = L\frac{di_A(t)}{dt} + Ri_A(t) + u_i(t)$$
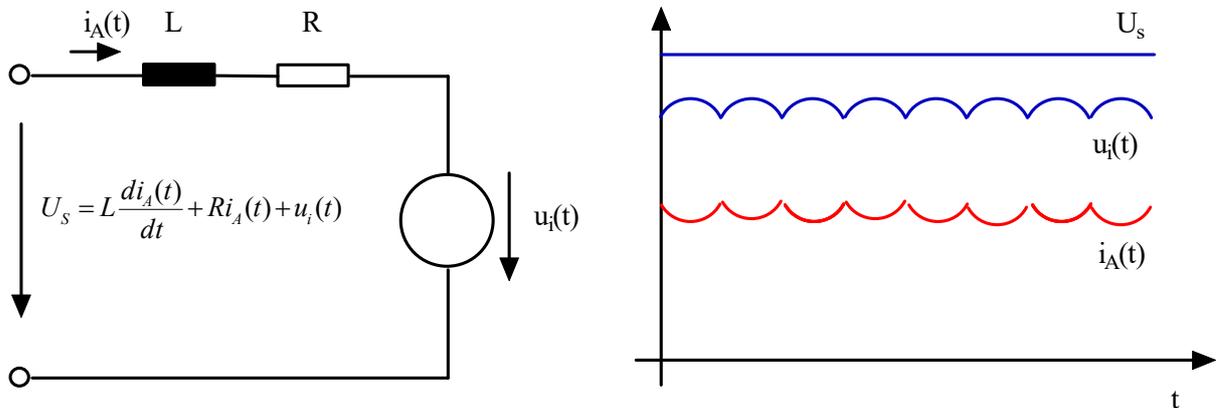
equivalent circuit of a brushed DC-motor   current and voltages at a brushed DC-motor

Figure 2 Description of a brushed DC-motor

In coreless motors the inductive part of the winding can be ignored for this calculation. So for a given working point the equation would be:

$$U_S \approx R_A i_A + u_i = R_A i_A + n k_E \tag{1}$$

Where R_A is the terminal resistance of the motor, i_A is the motor current, n the speed and k_E the back-EMF constant. At any given voltage the voltage is divided into a part which is lost at the terminal resistance and a part which compensates the back-EMF.
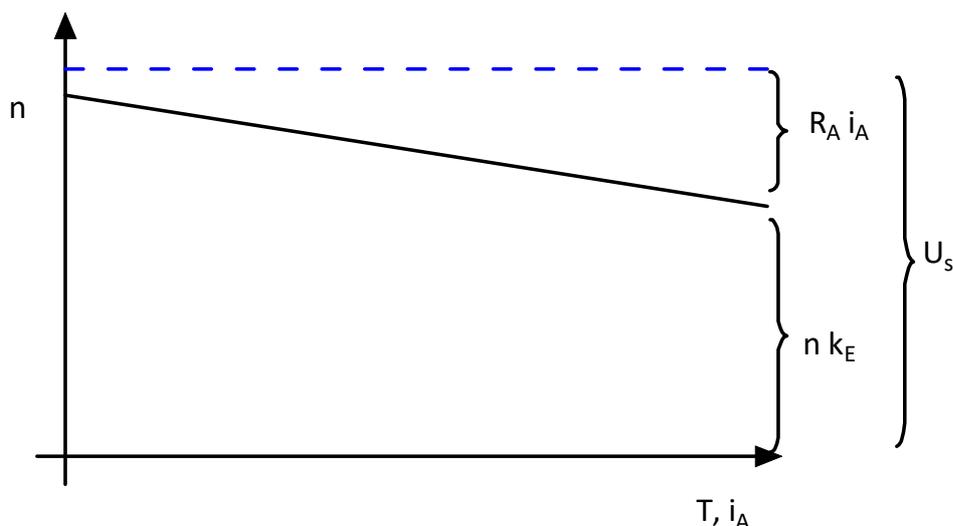
Figure 3 Working diagram of a coreless DC-motor

There are additional losses e.g. at the brushes of a copper-graphite commutated motor but these will be neglected here.

In reality u_i is not constant, not even at a constant speed because the voltage generated in the winding is commutated by the mechanic commutator having a finite number of segments – see Figure 2. So the equation (1) holds for the mean value of the voltages and currents only. But that's how the k_E is determined.

So for a brushed DC-motor the voltage and the current can easily be measured using a multimeter in between the driver and the motor using the DC-measuring range[1].

Using a multimeter in RMS mode might lead to wrong values.

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[1] The effective power of a motor connected to a DC supply can be calculated by $P_{motor} = U_S \, i_A$. U_S is a constant voltage whereas i_A is not constant but periodic. i_A can be expressed by a Fourrier series and using this P_{motor} can be expressed as $P_{motor} = U_S(\overline{i_A} + \sum_{n=1}^{\infty}(b_n \cos n\omega_0 t + a_n \sin n\omega_0 t))$.
As the mean values of any constant voltage with the harmonics of the currents equals 0 in any signal period the harmonic parts do contribute to the reactive power only but don't actually contribute to the effective power.

Example

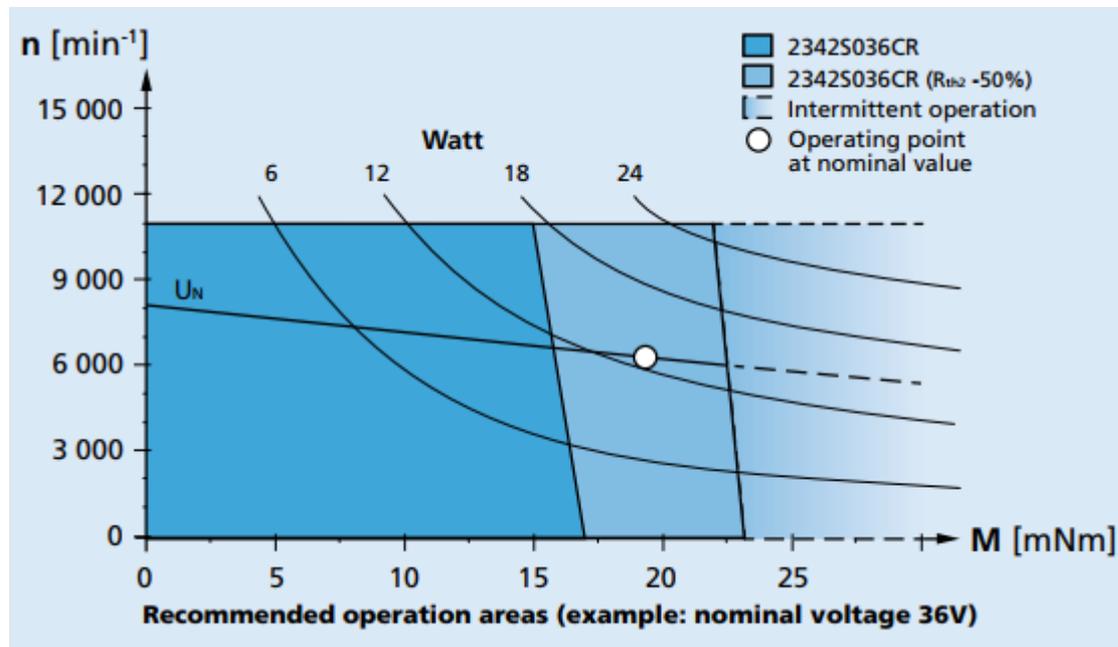Let's use a 2342S024 CR brushed DC motor having copper-graphite brushes.

Figure 4 Operating area of the 2342S CR motor

Relevant parameters of the 12V and the 24V version are:

	2342S012 CR	2342S024 CR	Unit
Terminal resistance R	1.9	7.1	Ω
Back-EMF constant k_E	1.4	2.73	mV / min^{-1}
Torque constant k_M	18.57	37.83	mNm/A
Rated torque	17	17	mNm
Rated current	1.5	0.78	A
Rated speed	6090	6470	min^{-1}

So if the motor would be conneted to a driver which is supplied with 24V and operated at a speed of 5000 min^{-1} @ 10mNm the operating point would be:

	2342S012 CR	2342S024 CR	Unit
motor current: $i_A = T / k_M$	0.74	0.38	A
Back-EMF: $u_i = k_E \times n$	7.0	13.65	V
motor voltage $Us = R_A\, i_A + n\, k_E$	8.4	16.4	V
duty cycle d	35.1	68.2	%
I_{driver}	0.26	0.26	A

To generate the U_S out of the U_{driver} the driver applies a PWM with the ratio

$$d = \frac{U_S}{U_{driver}} 100\%$$

Vice versa the supply current is reduced by the same factor compared to the motor current:

$$U_S = d\, U_{driver} \tag{2}$$

$$I_{driver} = I_{motor}\, d = i_A d \tag{3}$$

Using a different voltage version of the motor results in a diffent motor voltage and motor current. The actual power values however don't change which can easily be confirmed at the mechanic side, where the indentical working point (speed / torque) has been selected or at the supply side, where the consumed current at the same supply voltage is identical too.

This behavior is referred to as a so called **variable DC-transformer** as the DC values at the input side are transformed into DC-values (voltage / current) at the motor side by the ratio d.

But – obviously – the motor current can't be measurend at the supply side of the driver.

As the motor current is reduced by a variable factor depending on the actual duty-cycle, a motor used at different working points can't be protected by a fuse at the supply side of the driver which can be easily confirmed in the example. A rated motor current of 1.4A for the 12V version results in:

I_{driver} = 168mA @ d=12% - holding at n=0

I_{driver} = 700mA @ d=50%

I_{driver} = 1400mA @ d=100%

The motor driver can measure the real motor current and therefore can limit the actual current to the configured values. So even when only operating a DC-motor, using a motor driver can offer some additional protection for the motor which otherwise could easily be overloaded.

Currents and voltages at a brushless DC-motor (BLDC)

While at a brushed DC-motor at a steady state voltages and currents are constant and can be measured using a multimeter the situation is a little more complex at a BLDC-motor.

In a brushed DC-motor the mechanic commutator will commutate the current into the parts of the winding where the magnetic field generated by the current is offset to the magnetic field of the permanent magnet by 90°to generate the maximum torque/current.

In a BLDC-motor the magnet is the moving part of the motor and the the electronic commutation has to rotate the magnetic field generated by the three currents synchronously and relative to the magnet to generate the required torque.

So in addition to the reduction of the supply voltage by means of PWM the current is to be moved around the winding system by the electronics.

FAULHABER BLDC motors generate a sinusoidal back EMF. As with the brushed DC-motors the amplitude of the generated voltage is proportional to the speed of the motor.

The motor constants in the data sheet however are not given in per phase quantities but considering the motor being connected to an ideal B6-rectifier. The three sinusoidal voltages with a phase offset of 120° each are rectified into a 6-puls DC-voltage according to Figure 5.
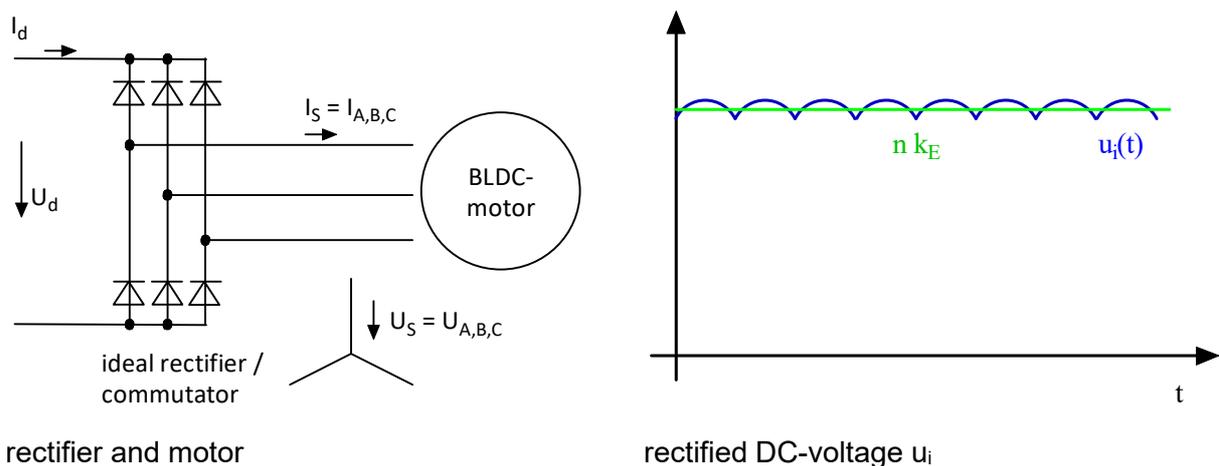

rectifier and motor   rectified DC-voltage u_i

Figure 5 BLDC motor connected to an ideal rectifier

Here U_d and I_d are the rectified DC-voltage and -current whereas U_S and I_S are the phase voltages and currents[2].

The resulting voltage of such a motor when driven externaly is very similar to the generated voltage of a brushed DC-motor. The pulse-count is 6 per magnetic pole pair and again a DC-voltage can be used to qualify the back-EMF of the motor.
In fact that is how the k_E of a FAULHABER BLDC motor is determined.

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[2] U_d and I_d are the theoretical rectified values oft he motor connected to the rectifier. Their relation to U_{driver} and I_{driver} are explained in Figure 8.

k_E is given as the DC-voltage U_d per speed of the motor. The resulting voltage can be expressed as a phase voltage too:

$$n \, k_E = U_d = 2 \, \frac{3}{\pi} \sqrt{2} U_{S,eff} \underbrace{\sin \frac{\pi}{3}}_{\frac{1}{2}\sqrt{3}} \approx 2.34 U_{S,eff} \tag{4}$$

Depending on the type of the driver BLDC-motors can either be operated using trapezoidal commutation – typically when connected to a SpeedController – or using sinusoidal commutation when connected to a MotionController.

Trapzoidal commutation

Using trapezoidal commutation is operating the BLDC motor very similar to the brushed DC. There is a single scalar voltage amplitude which is controlled to generate the required current and thus torque and there is the commutation which step by step applies the voltage to two of the phases. In such a pattern each of the phases is either connected to the positive voltage or to GND for 120° of one signal sequence and is switched off for the 60° in between. Therefore the current in trapezoidal commutation is passing exactly one of the upper legs into a phase and one of the lower legs of the power stage at any time (Figure 6). These currents could either be observed using a current probe and an oscilloscope or using the built-in recorder of a motor driver.
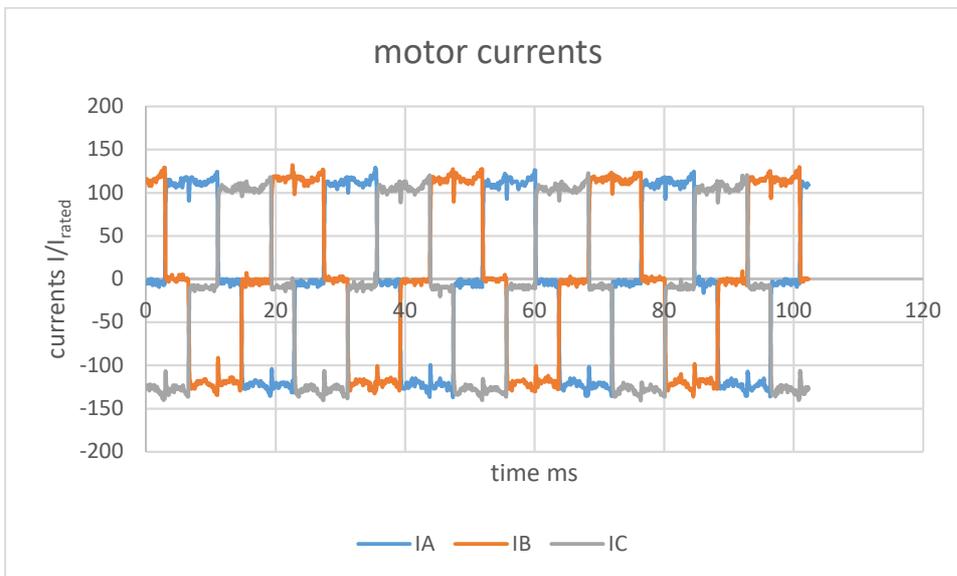
Figure 6 Phase currents of a BLDC-motor in trapezoidal commutation

If these currents would pass an ideal rectifier as in Figure 5 an enevelope of the current could be observed (Figure 7).
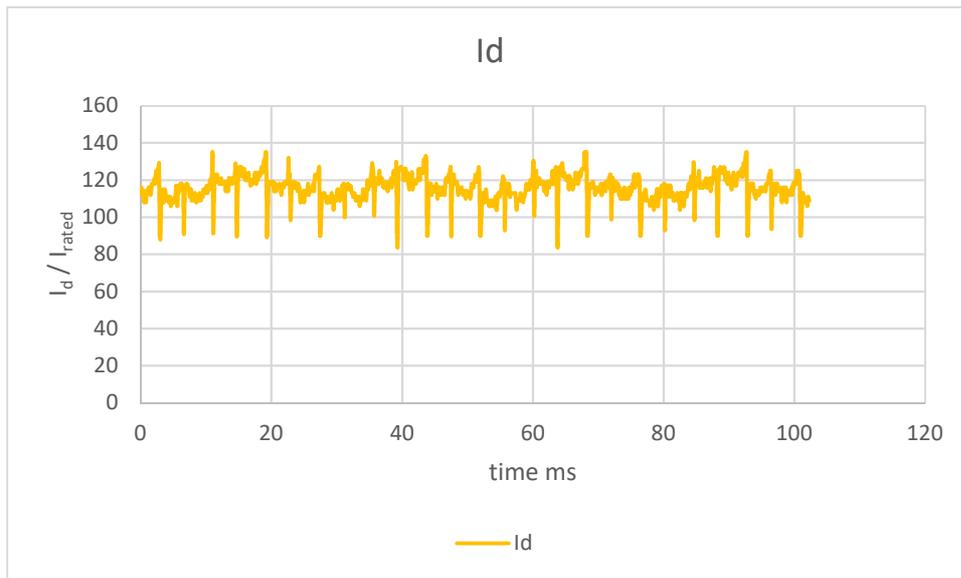
Figure 7 equvalent DC-motor current I_d of a BLDC motor

In the early times of power electronics these currents have been real because a BLDC was really operated from a two stage power electronics where the first stage was identical to what would have been used in DC-motor control – controlling the DC-voltage applied to a motor by means of a 1-Q step down converter and a second part where the variable DC-link voltage was commutated by Thyristors into the correct phases of the motor – similar to Figure 8. In such a circuit the recti-fied equivalent DC-voltage and -current of a BLDC-motor would be visible.

The equations for the 1-Q step down converter then would be the same as for the DC-motor in equations (2) and(3). So again while the supply voltage is reduced by the duty-cycle to the motor voltage the motor current is reduced by the same factor to the supply current.

Obviously this is the same situation as with the DC-motor
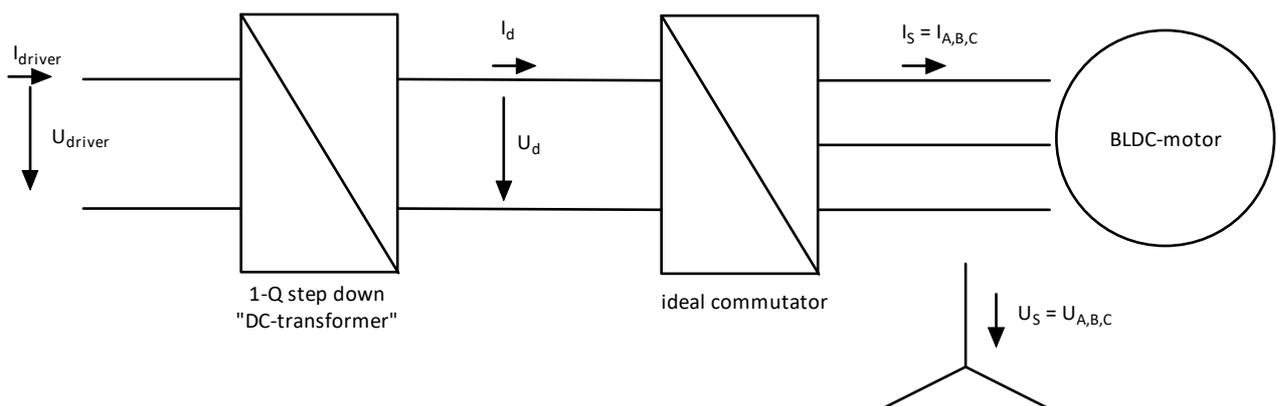
Figure 8 motor driver using a variable DC-link and ideal commutator

That's gone. State of the art are DC-link converters using a constant DC-link voltage where the step-down converter and the electronic commutator are functions of a single 3-phase MOSFET power-stage. The only quantities which can be measured directly are either the periodic voltages and currents at the motor or the values at the supply side – see Figure 1.

Example

Let's use a 2232 BX4 BLDC-motor.

As discussed above the currents and voltages of the motors are not given in per phase quantities but in equivalent DC quantities. Presented in such a way the behavior of a BLDC-motor connected to a motor driver can use the very same parameters as for the brushed DC-motor.

So the k_E is determined out of the rectified voltage, k_M is calculated based on k_E. R_A is measured between to phases as it's always two phases of the motor being active at the same time and even the characteristic currents are the rectified equivalent DC-values.
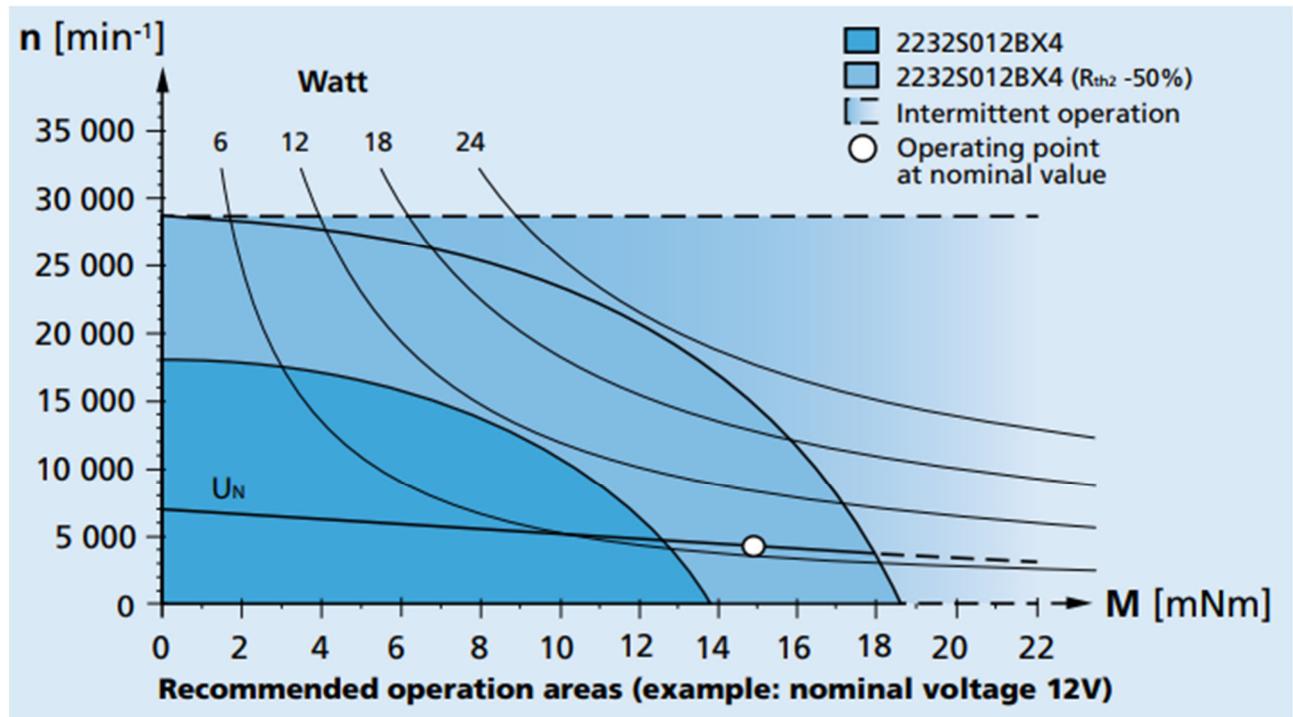
Figure 9 Operating area of the 2232 BX4 motor

Relevant parameters of the 12V and the 24V version are:

	2232S012 BX4	2232S024 BX4	Unit
Terminal resistance R	3.5	12.5	Ω
Back-EMF constant k_E	1.78	3.4	mV / min^{-1}
Torque constant k_M	17.0	32.4	mNm/A
Rated torque	14.7	14.6	mNm
Rated current	1.0	0.54	A
Rated speed	4450	4840	min^{-1}

So if the motor would be conneted to a driver which is supplied with 24V and controls the motor at a speed of 3000 min^{-1} @ 10mNm the operating point would be:

	2342S012 CR	2342S024 CR	Unit
motor current: $i_A = T / k_M$	0.59	0.31	A
Back-EMF: $u_i = k_E$ x n	5.34	10.18	V
motor voltage $Us = R_A\, i_A + n\, k_E$	7.4	14.1	V
duty cycle d	30.8	58.6	%
I_{driver}	0.18	0.18	A

Again the motor voltage is controlled by the driver to fit equation (1) for both variants. The motor current for the 12V version is roughly twice the motor current of the 24V version but the current into the driver is the same in both situations.

Obviously again at the supply side of the driver can't protect the motor, the driver however can.

As the motor current is reduced by a variable factor depending on the actual duty cycle, a motor used at different working points can't be protected by a fuse at the supply side of the driver which can be easily confirmed in the example. A rated motor current of 1.0A for the 12V version results in:

I_{driver} = 146mA @ d=15% - holding at n=0

I_{driver} = 500mA @ d=50%

I_{driver} = 1000mA @ d=100%

FAULHABER SpeedControllers and MotionControllers measure the phase currents and calculate the equivalent DC-current of the motor. Any limiting paramters are expected in these quantities.

Sinusoidal commutation

The back-EMF of FAULHABER BLDC-motors is sinusoidal, the motors can alternatively be operated using either scalar sinusoidal commutation or field oriented vector control.

In these cases the phase currents at any steady state are sinusoidal rather than the blocks of Figure 6.
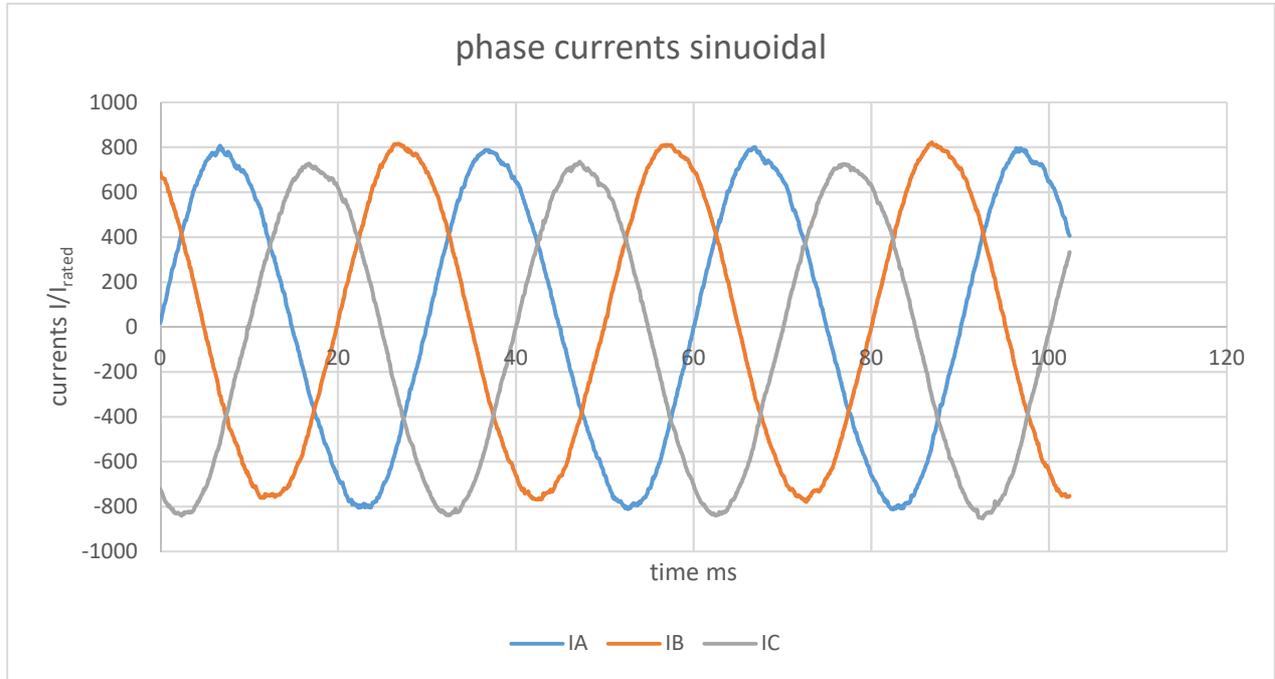
Figure 10 Phase currents of a BX4 BLDC servo captured by the recoder service of a MotionController

Sine-commutations allows for a more or less free angle between the back-EMF u_i and the motor current i_A. Here we will only consider the part of the current which is proportional to the torque. In a vector control scheme that's I_q. The equivalent DC-current of these sinusoidal currents can be calculated by a comparison of the currents in trapezoidal operation and the sinusoidal currents.

Table 1 phase currents

	0° … 30° : 0
	30° … 150° : +Id
$i_S(t) = \hat{I}_S \sin \omega_0 t$	150° … 210° : 0
	210° … 330° : -Id
	330° … 360° : 0
sinusoidal commutation	trapezoidal commutation
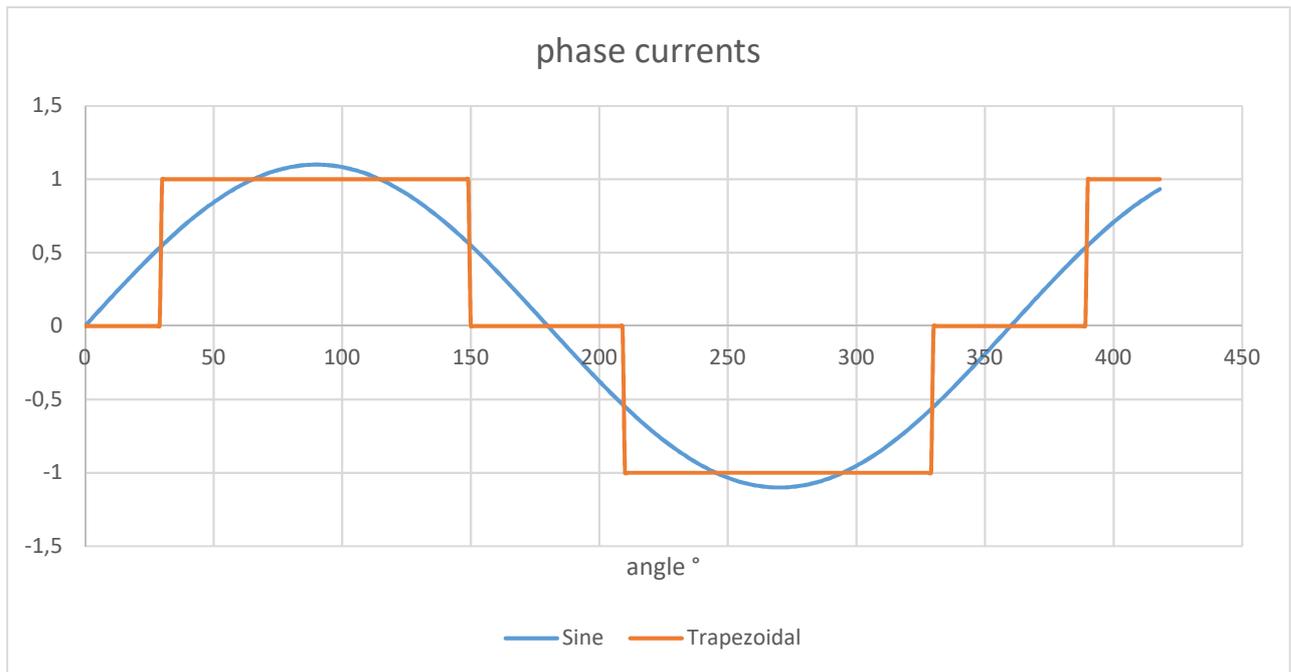
Figure 11 comparison of sine and trapezoidal currents

The currents can be considered to be equivalent, if the same torque is generated. As the back-EMF of the motors is sinusoidal too a Fourrier series can again be used to calculate the generated effective power.

In each of the phases the power at any time can be expressed as:

$$P_S = U_S I_S = \widehat{U}_S \sin \omega_0 t \times \sum_{n=1}^{\infty} (b_n \cos n\omega_0 t + a_n \sin n\omega_0 t)$$

Over a complete period of the signals only components having the same frequency as the back-EMF $u_i(t) = \widehat{U}_S \sin \omega_0 t$ contribute to the effective power. So the block-wise currents of the trapezoidal commutation and the sinusoidal currents are considered equal if their fundamental components are equal.

The two currents generate the same torque if:

$$I_d = \frac{\pi}{2\sqrt{3}} \hat{I}_S \approx 0.91 \, \hat{I}_S \approx 1.29 \, I_S \tag{5}$$

$$\hat{I}_S = \frac{2\sqrt{3}}{\pi} I_d \approx 1.1 \, I_d \tag{6}$$

Here $\hat{I}_S$ is the amplitude of the phase current, I_S is the effective (RMS) phase current and I_d is the equivalent DC-current which also equals the amplitude of the trapezoidal phase currents (see Figure 6).

So the equvivalent DC-current of the sinusoidal phase currents can be calculated from the amplitude of the phase currents multiplied by 0.91.

It is to be noted that the two different current shapes don't generate the same losses. Current losses are caused by the ohmic losses in the winding which are proportional to $i^2 R_A$. The RMS of the two currents wave forms is to be taken into account in the ohmic case.

Comparing two currents generating the same torque results in

$$\frac{I_{S,trap,eff}}{I_{S,Sine,eff}} = \frac{I_d \sqrt{2/3}}{I_d \sqrt{6}/\pi} = \frac{\pi}{3} \approx 1.05$$

Where here the subscript eff explicitly denotes the RMS values of the current waveforms.

Summary

- ⇨ The actual motor current can not be measured on the supply side of any driver, therefore a fuse cannot provide thermal motor protection. A properly configured driver however can.
- ⇨ In FAULHABER BLDC motor datasheets any current is not expressed in rms phase currents, but in a DC-equivalent current I_d. Same for the motor parameters k_E or k_M, expressed in DC-equivalent too.
- ⇨ The DC-equivalent current I_d equals the current amplitude of the phase currents when using trapezoidal commutation.
- ⇨ This I_d can be used to calculate the motor torque $T = k_M I_d$
- ⇨ To generate the same torque, sinusoidal currents will have about 10% plus in amplitude compared to the block currents of trapezoidal commutation (Figure 11).
- ⇨ Compared with sinusoidal currents, the block currents of trapezoidal commutation will generate additional 5% losses at the same torque

Differences in efficiency between trapezoidal commutation and sine commutations can hardly be observed in any application as there are in fact additional losses due to encoder errors or finite sampling times.

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