Drivers and controllers: how to drive a stepper motor?

Introduction

The selection of a stepper motor starts with the analysis of the specifications requested by the customer. Anyone will aim at maximizing the torque at a given speed. The following will help to understand the factors influencing the torque and hence understand how to match appropriately the motor winding with the driver settings.

Reminder: basic physics

To understand the main parameters influencing the performance of a given stepper motor, it is important to understand the physics behind it.
Figure 1 illustrates the basic design of a stepper motor including a torque-speed factor ($k_T\omega$), an electrical resistance (windings) and an inductance (windings). *U* is the applied voltage and *I* the current in the windings.

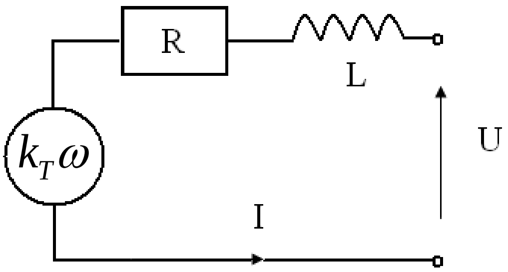

Figure 1 : Schematic design of a stepper motor.

The main formula expressing the behavior of a stepper motor is given by equation 1:

$$U = RI + k_T\omega(t) + L\frac{dI}{dt} \quad (1)$$

Where

- *RI* = Voltage to drive the current (resistance multiplied by current)
- $k_T\ \omega(t)$ = Voltage to compensate the back EMF[1] (k_T is the torque constant and ω the speed)
- *LdI/dt* = Voltage to establish/modify the current level

The torque is proportional to the current and can be expressed by equation 2:

$$M = k_T \cdot I \quad (2)$$

[1] Back EMF is the abbreviation of Back ElectroMotive Force. It corresponds to the voltage sensed backwards in the windings when the stepper motor is rotating.

As a consequence, the current can be deducted from the previous formula as shown in equation 3:

$$I = \frac{U - k_T \omega(t) - L \frac{dI}{dt}}{R} \quad \Rightarrow \quad I = \frac{U}{R}\left(1 - e^{-\frac{R}{L}t}\right) - \frac{k_T \omega(t)}{R} \qquad (3)$$

Figure 2 shows the current in the windings in function of time (ideal case where back EMF is zero). Due to the inductance of the stepper motor, it takes some time for the current to reach its max. value.

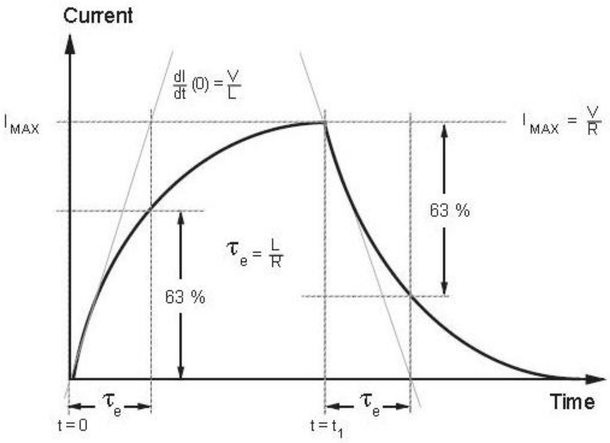

Figure 2 : Current in function of time. Current switched ON at *t=0* and switched OFF at $t=t_1$. Back EMF is set to 0; if this is not the case, the signal may have some oscillations due to the periodic back EMF shape.

Hence, the factors influencing the current, hence the torque, are the following:

- Inductance (*LdI/dt, L* = winding inductance)
  The inductance prevents the current to establish rapidly in the phases. Establishing the current rapidly becomes even more important when the motor speed (commutation speed) increases.
- Resistance (*R* = winding resistance)
  The resistance influences the maximal current set in the phase.
- The back EMF
  When the speed ω increases, the back-EMF proportional to $k_T\omega$ increases and the current decreases, hence the torque decreases. This explains why we observe on the torque/speed curves of the data sheet that the torque declines when speed increases.

L and *R* are given specifications of the motor's windings on one hand and the supply voltage U is often given by the system on the other hand. Eventually the resulting current I may bring the motor winding to its maximum tolerated temperature.

Definitions

The published motor torque performances are measurements achieved at the nominal current.
The nominal current is defined as the current that will bring safely the winding temperature near its limit at continuous operation (duty cycle 100%), at 20°C ambient temperature and without any heat sink (worst case).
The nominal voltage is the voltage that naturally brings the current to its nominal value (without need of current regulation device). The relationship is straightforward with the formula below.

$$I = \frac{U - k_T \omega(t) - L\frac{dI}{dt}}{R} \quad \Rightarrow \quad I = \frac{U}{R}\left(1 - e^{-\frac{R}{L}t}\right) - \frac{k_T \omega(t)}{R}$$

Depending on the application requirements and electronics involved, one will set supply voltage equivalent to the nominal voltage while others will supply a voltage much higher and limit the current to its nominal value by electronics (i.e: chopper of current). These two ways to drive stepper motors are described in the two next paragraphs.

Supply voltage = motor nominal voltage

The driver may be represented by a power supply with a constant voltage (which shall be set at the nominal motor voltage). The current is switched ON and OFF at the frequency of the clock for step commutation and energises the two motor windings in a defined sequence.

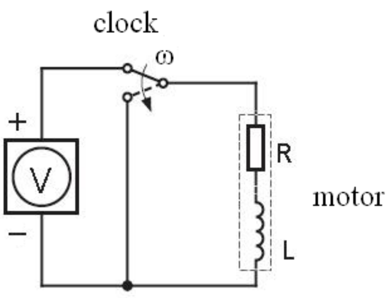

Figure 3 : Schematic of motor driven at its nominal voltage.

As long as the commutation speed (= motor speed ω) is low, there is no issue and the current has the time to reach its maximum value *U/R* corresponding to a maximal torque (according to Figure 2) before the next commutation for the next motor step occurs. This is represented by a blue and continuous line on Figure 4c. However, when the commutation speed increases (see Figure 4b), the current has not enough time to reach its expected value before the next motor step occurs and the peak current, consequently the motor torque, are reduced (see red dashed line of figure Figure 4c).

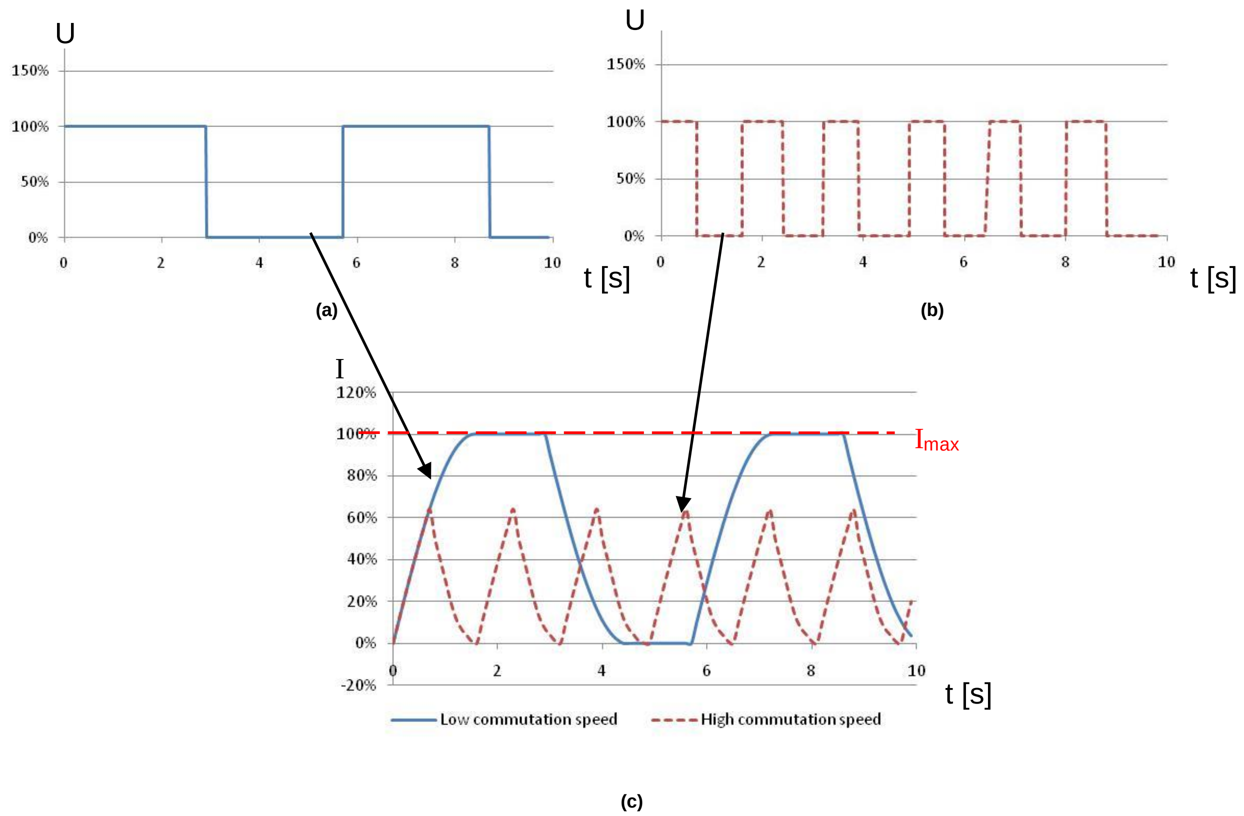

Figure 4 : Voltage shape for a low (a) and high (b) commutation speed. The resulting current is plotted in (c).

To obtain a higher torque at high commutation speed:

1. The easiest solution consist in increasing the current due to the relationship M=k.I. This can be achieved by simply increasing the supply voltage to a value above its nominal value but there is a risk in this case to reach the thermal limit of the motor winding. This is therefore possible in some cases only (time ON << time OFF and/or low temperature and/or in combination with heat sink (metal gearheads for instance)).
   N.B.: This will increase the current at all speeds.

2. The most common solution consists in applying a supply voltage higher than the motor nominal value and limiting at the same time the current to the nominal value by electronics (ex: chopper or PWM) to circumvent the risk of motor overheating. This is what is described in the following paragraph.

   With typical power supply between 12 and 24V, it will make sense in this case to select the motor winding in the datasheet with the lowest inductance.

Series AM1524

AM1524 ...	0450		0250		0150		0075		
	Current	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Drive mode
1 Nominal current per phase (both phases ON) [1]	0,45	–	0,25	–	0,15	–	0,075	–	A
2 Nominal voltage per phase (both phases ON) [1]	–	2	–	3,5	–	6	–	12	V DC
3 Phase resistance (at 20°C)	3,6		12,5		35		138		Ω
4 Phase inductance (1kHz)	1,9		6,3		16,5		70,6		mH
5 Back-EMF amplitude	2,4		4,4		7,2		14,7		V/k step/s

Figure 5 : Extract from the datasheet for an AM1524 stepper motor from FAULHABER PRECISTEP.

Supply voltage > motor nominal voltage

In a controlled current driver, the supply voltage is set higher than the motor nominal voltage and the current is controlled electronically and limited to a user defined value which shall be equal to the motor nominal current. There are different possibilities to control the current but we'll discuss here the most common which is the chopper driver (see Figure 6).
The chopper driver provides an optimal solution both to current control and fast current build-up and reversal. **The basic idea is to use a supply voltage which is several times higher than the nominal voltage of the motor** (typically 3x to 8x the motor nominal voltage).
The current rise rate, which initially is *U ⁄ L*, is thereby able to increase substantially.

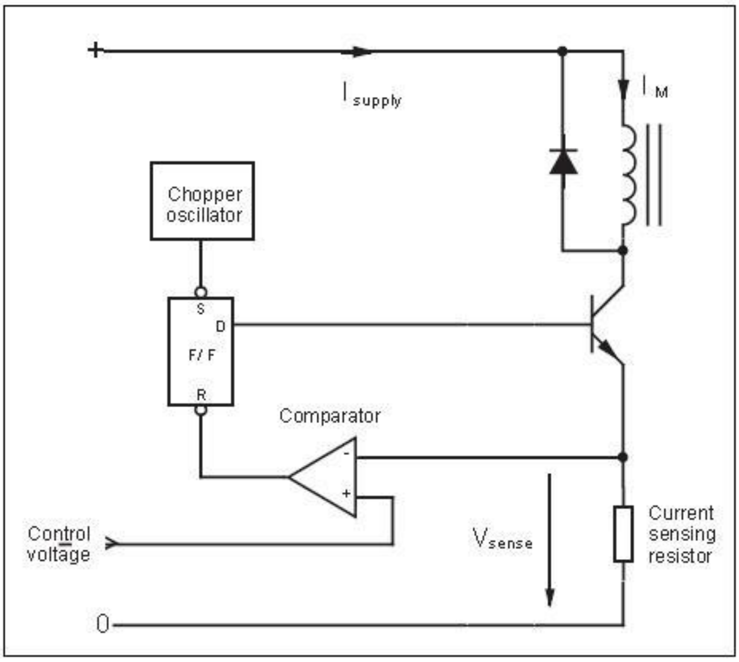

Figure 6 : Schematic of a driving system with a current regulation using a chopper.

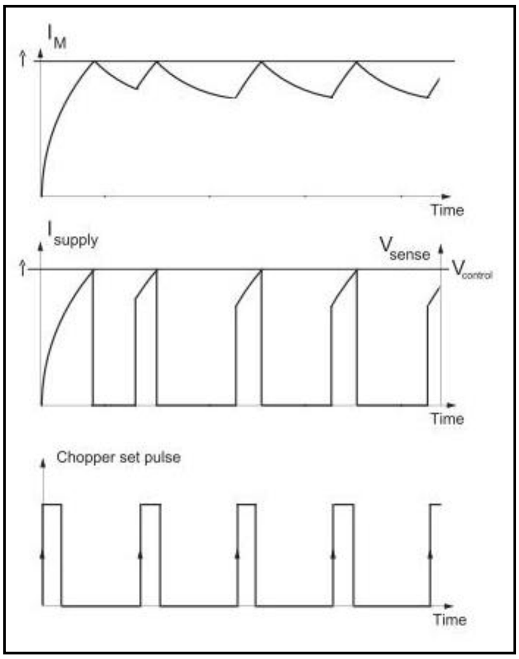

Figure 7 : Current shape in a current regulated electronics. I_M= motor phase current

By controlling the duty cycle of the chopper, an average voltage and an average current equal to the nominal motor voltage and current are created. The chopper is usually configured for constant current. Constant current regulation is achieved by switching the output current to the windings.
This is done by sensing the peak current through the winding via a current-sensing resistor, effectively connected in series with the motor winding. As the current increases, a voltage develops across the sensing resistor, which is fed back to the comparator. At the predetermined level, defined by the voltage at the reference input, the comparator resets the flip-flop, which turns off the output transistor.
The current decreases until the clock oscillator triggers the flip-flops, which turns on the output transistor again, and the cycle is repeated.
The advantage of the constant current control is a precise control of the developed torque, regardless of power supply voltage variations. It also gives the shortest possible current build-up and reversal time. The constant current mode is therefore less sensitive to the motor speed.

Figure 8 shows the consequence of increasing the voltage to twice the nominal voltage (200%). One can clearly see that the current rises faster to its maximal value which is desirable when using a motor at high speed (meaning high frequency) if one wants to avoid the effect shown on Figure 4c. This way, it is possible to reach the maximal current and thus the maximal torque at higher speed.

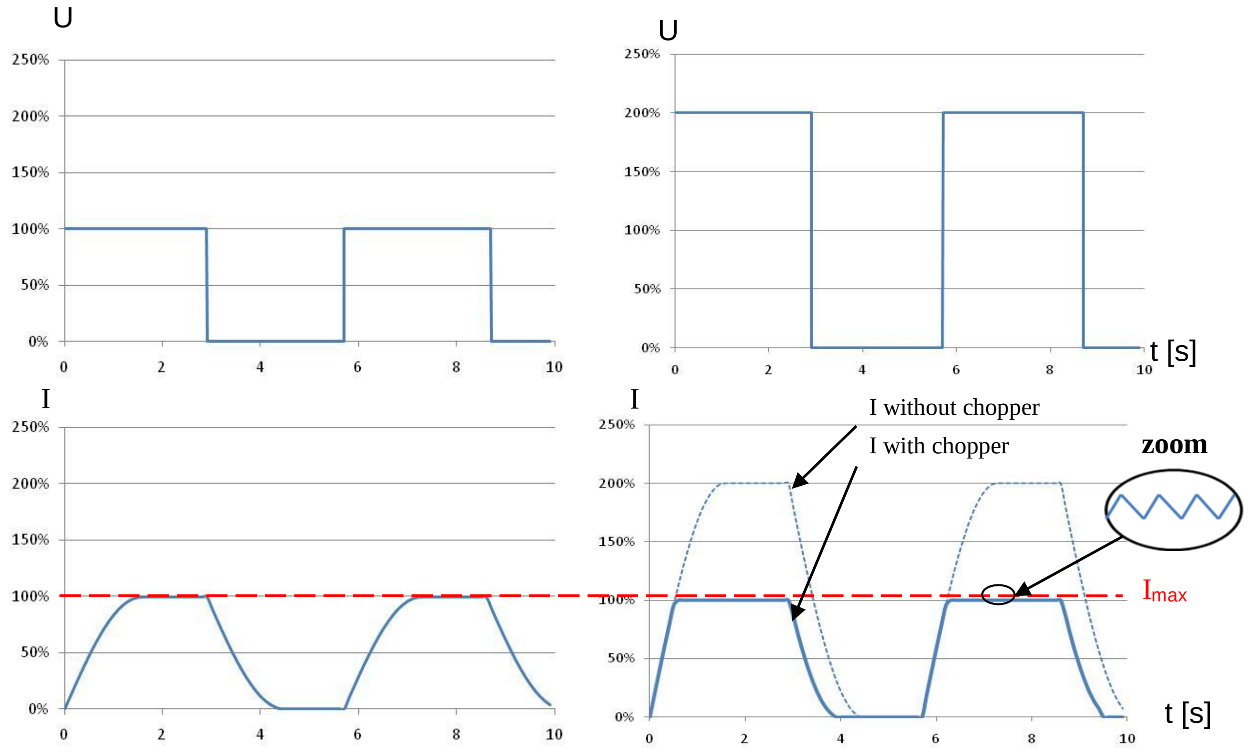

Figure 8 : Influence of increasing the voltage in a current regulated electronics.

The driver may be represented by a controlled current source trying to keep a constant maximum current through the winding by using a chopper. It uses a higher voltage than the nominal voltage of the motor to quickly establish the current. The result is a higher torque, especially at high speeds.

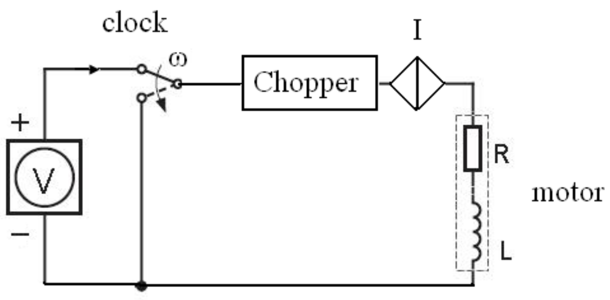

Figure 9 : Schematic of a current mode system.

The difference of current seen than the motor phases resulting of the difference between Figure 3 and Figure 9 is represented on the below graph.

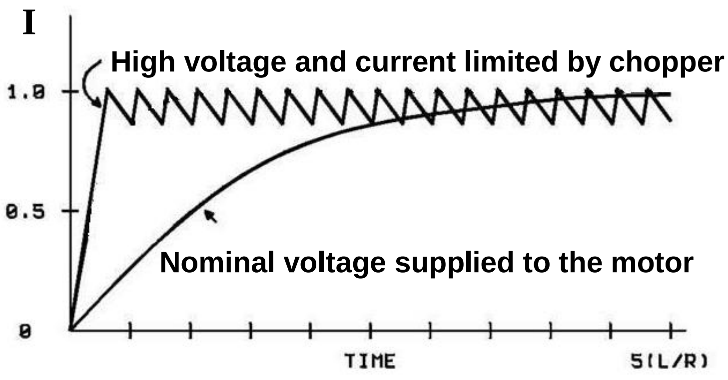

Figure 10 : Comparison of the current curve. [1]

The difference of motor behavior resulting of the difference between the circuitry Figure 3 and Figure 9 is represented on the below graph.

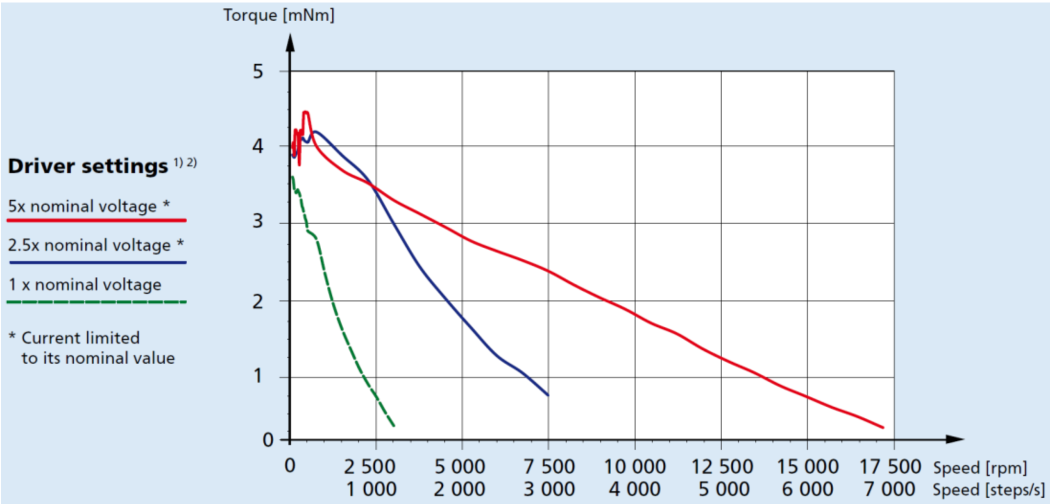

Figure 11 : Torque vs. speed curves for an AM1524 motor controlled by Trinamic TMCM-110 driver. The three curves correspond to three different driver supply voltage (i.e. 1x, 2.5x and 5x the motor nominal voltage).

In this particular case, it is easy to observe that the torque at 1x the nominal voltage drops quickly and that it starts to be delicate to use the motor above 2500rpm. On the other hand, at 5x the nominal voltage, the maximum speed of the motor without load is around 17’000 rpm

In other words, with a supply voltage given at 12V, it makes sense to use a current regulated driver with a motor with nominal voltage around 2 or 3Volts (and not paradoxically at 12V). The information regarding the nominal current on the motor datasheet is therefore only used to set the current on the driver itself.

Conclusion

From the previous explanations, we can now distinguish what to expect from the different type of drivers on the market

- Current regulated driver (for example: PRECIstep® MCST3601)
- Unregulated current drivers (for example: PRECIstep® AD VL M1S)

	Operating the motor with the supply voltage higher than the motor nominal voltage with current regulation	**Operating the motor with the supply voltage equalling the motor nominal voltage**
Advantages	- Higher torque at high speed. - Higher slew rate.	- Useful when no high voltage is available
Disadvantages	- Needs a relatively high voltage power supply.	- Low torque at high speed. - Microstepping impossible

References

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