

# Thermal behavior of a stepper motor

## Introduction

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When a stepper motor is energized and rotates, its temperature rises due to both the Joule effect and Iron losses which are composed of **Hysteresis** and **Eddy current** losses.

**Hysteresis** loss is a heat loss caused by the magnetic properties of the stator material. The magnetic particles tend to line up with the magnetic field. As the magnetic field keeps changing directions, the continuous movement of the magnetic particles, as they try to align themselves with the magnetic field, produces molecular friction. This, in turn, produces heat.

The stator is made from soft iron, which is a conducting material with desirable magnetic characteristics. Any conductor will have currents induced in it when it is in a rotating magnetic field (created by the rotor). These currents that are induced are called **Eddy currents**. The power dissipated in the form of heat, as a result of the Eddy currents, is also considered a loss.

Iron losses are difficult to model and are insignificant at low speeds. Therefore, the following paragraphs will focus only on the Joule effect to help evaluate whether the motor will reach its thermal limits in given conditions of power supply, ambient temperature and duty cycle.

## Temperature dependency (Joule effect only)

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If a stepper motor is energized, its temperature will rise due to the heating of its windings. The equation that describes the change of the electrical resistance of the windings in function of its temperature is given by equation 1.

$$R(T) = R_0(1 + \alpha \cdot (T - T_0)) \quad (1)$$

With  $R_0$  the electrical resistance of the winding at a temperature  $T_0$  (usually 20°C), this value can be found in the datasheet on line 4 as shown in Figure 1 and  $\alpha$  the temperature coefficient of resistance = 0.0039 °C<sup>-1</sup>. Notions of power and time have been highlighted in the introduction and the next sections will show how to quantify their effect on the temperature.

### Influence of Power

The equation that link the energy to the temperature is given by equation 2.

$$T = R_{th} \cdot P + T_{amb} \quad (2)$$

Where  $R_{th}$  is the thermal resistance between the heat source (the windings) and the ambient air (this value can be found in the datasheet on line 16, see Figure 1),  $P$  is the power supplied to energize the motor and  $T_{amb}$  is the ambient temperature (it can be different than  $T_0$ ).

Therefore, the combination of equation 1 and 2 gives the link between power and temperature as seen in equation 3 (without current regulation) and 4 (with current regulation)<sup>1</sup>.

$$T = R_{th} \cdot \frac{U^2}{R_0(1+\alpha \cdot (T-T_0))} + T_{amb} \quad \text{If the motor is energized without current regulation} \quad (3)$$

$$T = R_{th} \cdot R_0(1 + \alpha \cdot (T - T_0)) \cdot I^2 + T_{amb} \quad \text{If the motor is energized with current regulation} \quad (4)$$

However, those equations provide the temperature after an infinite time, when the temperature of the motor is stable and has reached its maximal value. This is true if the motor is energized during a long time (typically 10 times its thermal time constant that you can find in line 17 of the datasheet) and  $T$  then corresponds to the maximum temperature that the motor can reach ( $T=T_{max}$ ).

Series AM1524						
Values at 20°C	AM1524	0450	0250	0150	0075	
Nominal current per phase (both phases ON)		0,45	0,25	0,15	0,075	A
Boosted current per phase (both phases ON)		0,9	0,5	0,3	0,15	A
Nominal voltage per phase (both phases ON)		2	3,5	6	12	V
Phase resistance		3,6	12,5	35	138	Ω
Phase inductance (1 kHz)		1,9	6,3	16,5	70,6	mH
Holding torque (at nominal current in both phases)		6	6	6	6	mNm
Holding torque at boosted current		10	10	10	10	mNm
Residual torque, typ.		0,51	0,51	0,51	0,51	mNm
Back-EMF amplitude		2,4	4,4	7,2	14,7	V/k step/s
Electrical time constant	0,5					ms
Rotor inertia	45·10 <sup>-9</sup>					kgm <sup>2</sup>
Step angle (full step)	15					°
Angular accuracy	±10					%
Angular acceleration, max.	222·10 <sup>3</sup>					rad/s <sup>2</sup>
Resonance frequency (at no load)	60					Hz
Thermal resistance	12,9 / 31,6					K/W
Thermal time constant	6 / 350					s

Figure 1 : Datasheet of the AM1524 stepper motor with values for electrical resistance, thermal resistance and thermal time constant.

### Influence of time (general equation)

If one provides a cyclic power supply to its motor the temperature may also depends on time, as shown in equation 5.

$$T == T_{amb} + (T_{max} - T_{amb}) \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \quad (5)$$

With  $T_{max}$  calculated from equation 3 or 4 and  $\tau$  the thermal time constant (it can be found in line 17 of the datasheet, see Figure 1). If the power supply is switched off, it takes also some time for the temperature to decrease as expressed in equation 6.

$$T = T_{amb} + (T_{max} - T_{amb}) \cdot e^{-\frac{t}{\tau}} \quad (6)$$

Figure 3 shows a typical temperature dependency for a stepper motor.

<sup>1</sup> For more information about the voltage and the current regulation please refer to our application note "Drivers and controllers: how to drive a stepper motor".

## Other influent parameters

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There are many other external parameters that influence the temperature of a motor. The most important ones are summarized in this section.

### Driving mode

The motor can be driven with a current regulation or not. If the motor is driven with a driver integrating a current regulation, the temperature will be higher since everything is optimized so that the current rises quickly in the phases.

### Speed

Speed influences the iron losses which are also participating to the heating of the motor. Indeed, the higher the speed, the higher the temperature. It is very difficult to quantify this effect and the only way to approximate the influence on the temperature is to collect experimental data. This means that another delta of temperature will be added to the previous equation and this delta can result in an increase of more than 30% of the temperature. A reasonable way to estimate the effect of the speed on the temperature is to multiply the speed in Hz by 0.003 in order to obtain the temperature increase in C° (experimental factor).

### Pressure

If the motor is working at low pressure, its temperature may rise much faster and higher because it cannot cool down thanks to convection losses. Therefore, the lower the pressure, the higher the temperature.

### Winding resistance

The resistance is the main actor of the Joule effect losses, thus the higher the resistance, the higher the temperature for a given current.

## A tool to facilitate the calculation

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The goal of this section is to quickly explain how to use the temperature calculator developed by FAULHABER PRECISTEP SA to simplify the calculation and provide a quick idea of the temperature the motor can reach. If one wants to learn more about the theory behind it, please refer to the previous sections.

When opening the FAULHABER Torque and Temperature calculator (available on the FAULHABER website), the window shown in Figure 2 appears. The Temperature button allows to open the window shown in Figure 3.

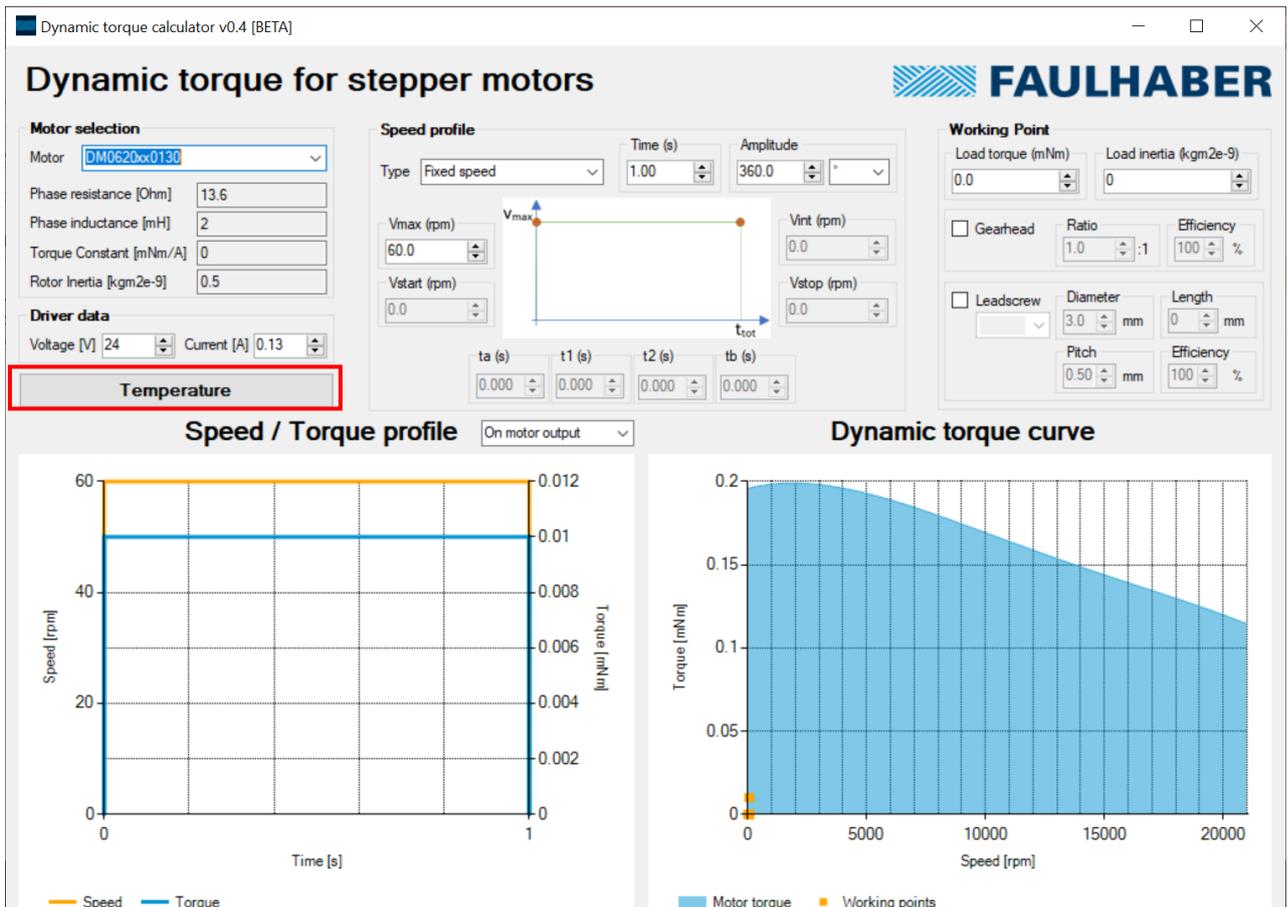


Figure 2 : Interface of the Torque and Temperature calculator.

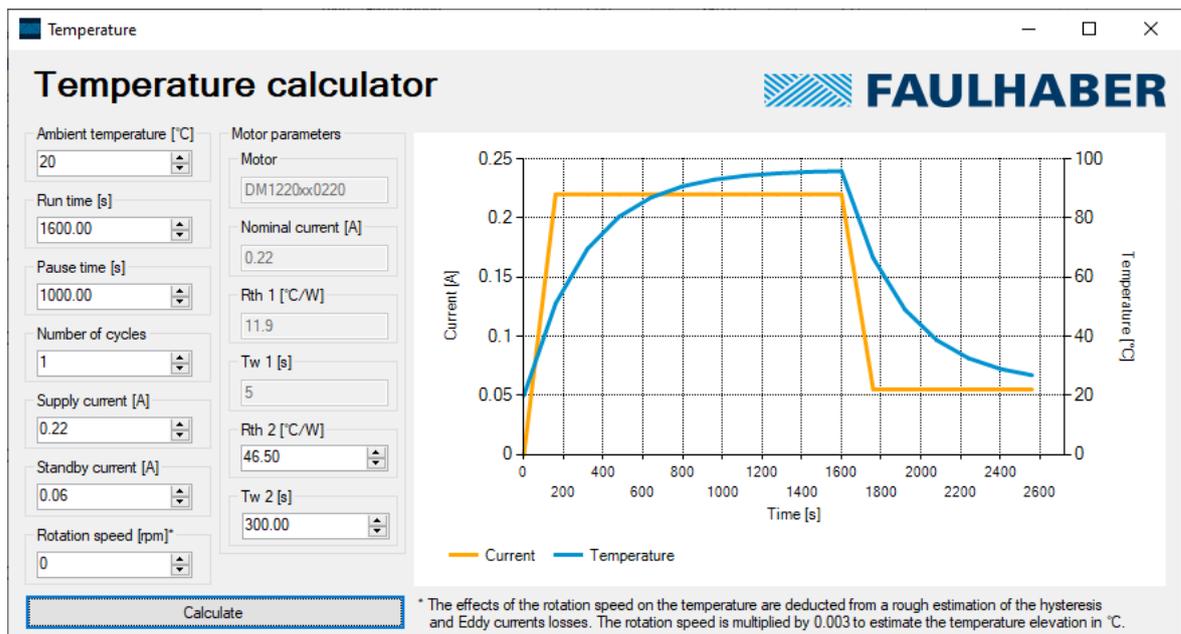


Figure 3 : Temperature in function of time for a DM1220SB0220 motor from FAULHABER PRECISTEP.

The user may then select different parameters, such as the run time and pause time, ambient temperature, number of cycles or currents. The “Calculate” button then displays the current and temperature curves for the selected parameters

For more details about the about the use of the Torque and Temperature calculator please refer to our user guide available on our website.

## What if the temperature is too high?

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If the temperature is too high, one may:

- Decrease the duty cycle
- Decrease the current whenever possible
- Add heat sink/fan or select a fixture material that will dissipate (ex: aluminum).

However, note that the calculation, although verified by practical tests at FAULHABER PRECISTEP, are estimations. It is always recommended to consider a safety margin or realize its own tests in the environment of the application.

## References

- [1] S. Motor, D. Considerations, and C. Problems, “APPLICATION NOTE STEPPER MOTOR DRIVER CONSIDERATIONS,” no. December 2003, pp. 1–11.
- [2] “Lead Screw Efficiency.” [Online]. Available: [http://www.askltd.co.jp/eng/technical\\_info/feed\\_screw](http://www.askltd.co.jp/eng/technical_info/feed_screw). [Accessed: 19-Jun-2013].
- [3] “Better Soldering.” [Online]. Available: [http://www.elexp.com/t\\_solder.htm](http://www.elexp.com/t_solder.htm). [Accessed: 20-Jun-2013].
- [4] “Eddy Currents.” [Online]. Available: [http://en.wikipedia.org/wiki/Eddy\\_current](http://en.wikipedia.org/wiki/Eddy_current). [Accessed: 20-Jun-2013].
- [5] “Stepper motor types.” [Online]. Available: [www.anaheimautomation.com](http://www.anaheimautomation.com). [Accessed: 18-Jun-2013].
- [6] Trinamic, “TMC223 Datasheet.” [Online]. Available: [http://www.trinamic.com/tmctechlibcd/integrated\\_circuits/TMC223/TMC223\\_datasheet.pdf](http://www.trinamic.com/tmctechlibcd/integrated_circuits/TMC223/TMC223_datasheet.pdf). [Accessed: 18-Jun-2013].
- [7] “The right and wrong of soldering.” [Online]. Available: [http://karma-laboratory.com/petridish/2005/01/the\\_right\\_and\\_w.html](http://karma-laboratory.com/petridish/2005/01/the_right_and_w.html). [Accessed: 20-Jun-2013].

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