On the heating of motors in hand-held tools

Motors operated at the rated torque limit can get very hot. In continuous operation the winding can reach 155° resulting in a housing temperature of some 120°C. No surgeon would like to operate with such a hand-held tool not even at half of that temperature.
Neglecting friction, there are two main sources of power losses – and hence heating – in motors: The motor current in the winding and eddy current losses. Both of which can ba adversely affected by the motor controller and driver.

Joule power losses
The Joule power losses are linked to the current, i.e. the required torque load. As it is well known, these losses increase with the square of the current. High currents close to the nominal value will lead to temperatures unbearable for humans to touch; running the motor at currents of about half the nominal current results in moderate temperatures (typically below 50°C) that matches the sensitive human skin.

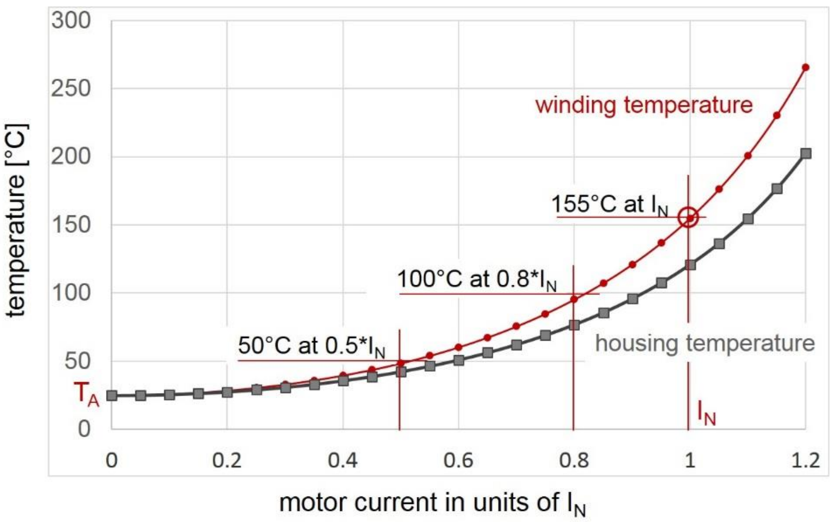

Fig. 1 Winding and housing temperature of a motor in continuous operation as a function of the motor current

For motor selection, this essentially means: go for an oversized motor!
The considerations so far are based on continuous operation where the maximum temperatures will only be reached after some 10 minutes. In hand-held tools one usually has intermittent operation at different current levels. Intermittent operation can expand to 30 minutes and more and hence should be treated as a continuous operation with the RMS average load. In such cases, the average heating of the motor housing is similar to continuous operation at the RMS current load.

Iron losses
The iron losses are related to speed. Eddy current losses increase with the square of speed, heating up the motors simply when rotating - even in no-load condition. In hand-held tools, this can be a problem for grinders and drills that operate at several ten-thousand rpm. Such high speed motors need special design precautions to limit eddy current heating. Typically, they are made with a low number of magnetic poles, a slotless winding, ultra-thin back iron

foils made of special low hysteresis materials. The maxon ECX SPEED series for instance combines these particular features. Their long shape with diameters between 16 and 22 mm perfectly fit into hand-held tools that operate at high speeds of several ten thousand rpm – as you may have guessed from their name.

PWM driver, inductance, and control parameters

However, it turns out that motor heating is not only a question of torque, speed and design but also of the PWM driver design and of control parameter setting. Recently, a customer complained about the high temperature of his motor (80°C and more) even when driven at no-load conditions. Upon investigating the case, we found that the driver and the supply voltage had a major effect.

Slotless windings have a very low inductance resulting in a very low electrical time constant. The current will react very fast upon voltage changes; that's good for dynamic behavior. However, when driven with pulse-width modulated (PWM) power stage (as most controllers do) the motor current is able follow these rapid voltage changes giving rise to a considerable current ripple. While the PWM voltage and the current ripple have no effect on the mechanical response of the motor – the motor reacts according to the average current and voltage values – the current ripple peaks, however, heat up the motor. In a similar way, very stiff control parameter settings can result in strong and fast current reaction with high current peaks and associated motor heating. Counter-measures for minimizing the current ripple are:

- Reducing the supply voltage of the PWM driver, in cases where this is possible by the speed requirements of the application.
- Increasing the PWM frequency to allow less time for the current ripple to build.
- Adding an extra inductance – a motor choke – in series to the motor lines in order to increase the electrical time constant and to dampen the current reaction. This last measure is not very attractive because it adds costs and requires extra space.
- Selecting softer control parameter.

The current ripple and the accompanying high-frequency magnetic field generate additional losses. The magnetic flux variation occur with the PWM frequency and can induce eddy currents in metallic parts of the motor (e.g. in the magnet), in addition to the skin effect in the winding wire. Both mechanisms can amount to a considerable part –30% and more – of the total losses and hence of the heating. The reduction of the current ripple is, therefore, of paramount importance.

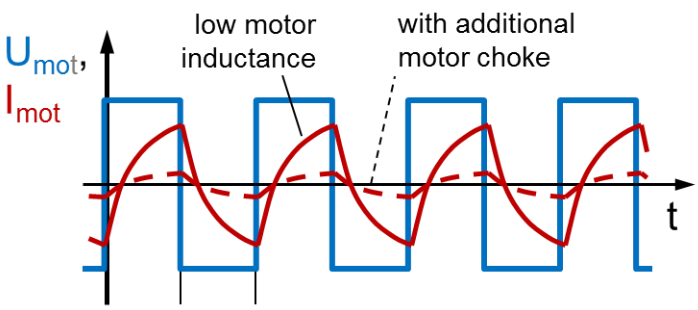

Fig 2. Current ripple at standstill with and without additional inductance (schematic). The average current (i.e. the average torque) is zero in both cases. The motor heating will be different.

maxon controllers take the low inductance of maxon motors into consideration. They work at high PWM frequencies of 50 to 100 kHz and are equipped with sufficient additional inductance for most motors.
The customer heating problem was easily resolved just by replacing the old over-dimensioned controller with a maxon ESCON controller. The ESCON solution exhibits a lower but sufficient power rating with a larger built-in inductance and operates at a higher PWM frequency than the old controller. Additionally, the temperature level was considerably lowered by reducing the supply voltage close to the minimum value needed.