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Current ripple due to PWM resulting in motor heating

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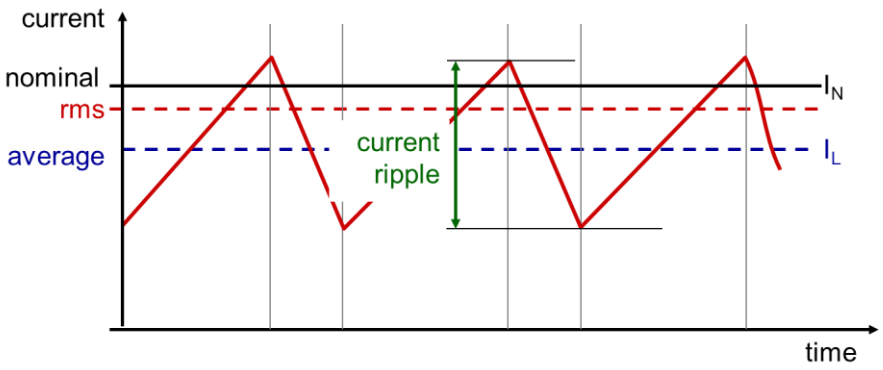
Introduction

Current ripple

PWM motor supply leads to a current ripple that reflects the exponentially decreasing current response upon applying the PWM voltage. The exponential current variation can be approximated by a triangular shape for high PWM frequencies (i.e. PWM cycle times shorter than the electrical time constant of the motor).



- The current ripple ΔI_{pp} increases with increasing PWM supply voltage V_{cc} and time duration of the PWM cycle.
- Enhancing the PWM frequency f_{PWM} allows less time for the current to increase and the ripple becomes smaller.
- A high inductance in the motor line L_{tot} dampens the current reaction and the ripple is reduced. For a 3-level PWM switching scheme (i.e. switching between the voltage levels $+V_{cc}$, 0, $-V_{cc}$) one gets the formula for the peak-to-peak current ripple

$$\Delta I_{pp} = \frac{V_{cc}}{4 \cdot L_{tot} \cdot f_{PWM}}$$

The total inductance sums the contributions from the motor, the built-in chokes of the controller, and external additional inductances.

Motor current

- The average current corresponds to the produced motor torque.
- The RMS (= root mean square) current value is responsible for the heating. Particularly dangerous are large current peaks; they contribute more than proportional to the power losses (power losses go with the square of the current). In order to avoid a too high winding temperature, the RMS current value must be smaller than the nominal motor current. The RMS current value is higher than the average value.

Remark:
Be aware that current ripple not only influences motor heating, but it may also affect the stability of the current control loop. However, this effect is not the topic here.

Calculation of heating

Let's try to put the motor heating into numbers and calculate the RMS current value I_{RMS} for a given average current I_L and current ripple ΔI_{pp}. It is sufficient to consider one linear increase.

$$I_{RMS} = \sqrt{\frac{1}{t_{on}} \int_0^{t_{on}} I(t)^2 \cdot dt} = \sqrt{\frac{1}{t_{on}} \int_0^{t_{on}} \left\{\left(I_L - \frac{\Delta I_{pp}}{2}\right) + \frac{\Delta I_{pp}}{t_{on}} \cdot t\right\}^2 \cdot dt}$$

$$I_{RMS} = \sqrt{\frac{1}{t_{on}} \int_0^{t_{on}} \left\{\left(I_L - \frac{\Delta I_{pp}}{2}\right)^2 + 2\left(I_L - \frac{\Delta I_{pp}}{2}\right)\frac{\Delta I_{pp}}{t_{on}} \cdot t + \left(\frac{\Delta I_{pp}}{t_{on}} \cdot t\right)^2\right\} \cdot dt}$$

$$I_{RMS} = \sqrt{\frac{1}{t_{on}} \left\{\left(I_L - \frac{\Delta I_{pp}}{2}\right)^2 t_{on} + \left(I_L - \frac{\Delta I_{pp}}{2}\right)\frac{\Delta I_{pp}}{t_{on}} \cdot {t_{on}}^2 + \left(\frac{{\Delta I_{pp}}^2}{3 \cdot {t_{on}}^2} \cdot {t_{on}}^3\right)\right\}}$$

$$I_{RMS} = \sqrt{\left(I_L - \frac{\Delta I_{pp}}{2}\right)^2 + \left(I_L - \frac{\Delta I_{pp}}{2}\right)\Delta I_{pp} + \frac{{\Delta I_{pp}}^2}{3}}$$

$$I_{RMS} = \sqrt{{I_L}^2 + \frac{{\Delta I_{pp}}^2}{12}}$$

This equation relates the thermal losses (RMS current) to the torque (load current) and the current ripple. Essentially, we see that with increasing ripple the difference between load current and RMS current becomes larger.

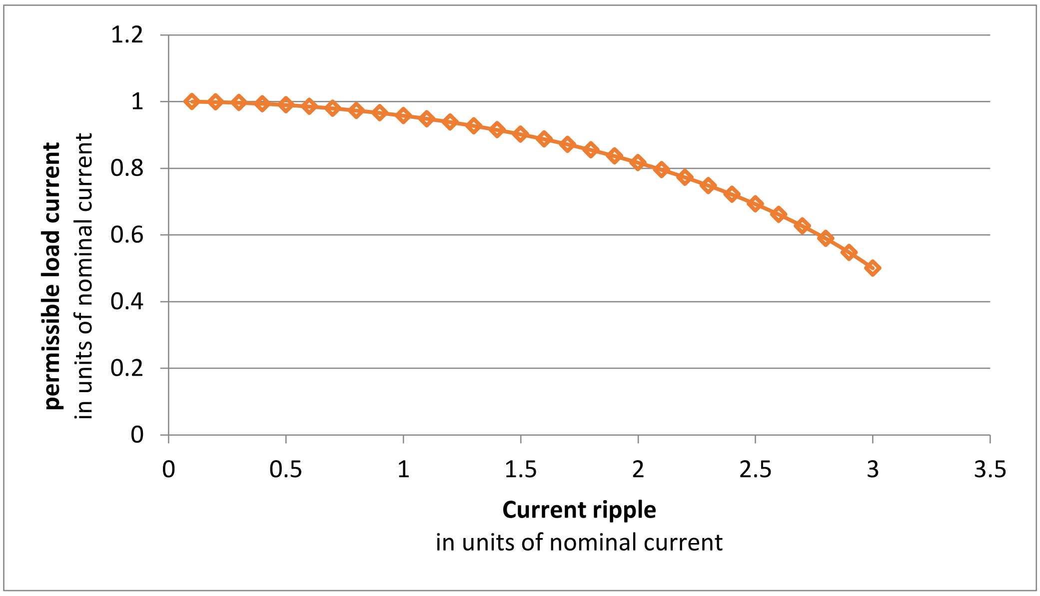
How much load remains?

As mentioned at the beginning, the current ripple is determined by the PWM frequency, the supply voltage, and the total inductance. For a given ripple one can calculate the permissible load current assuming that the RMS current should not exceed the nominal current of the motor I_N.

$$I_L < \sqrt{{I_N}^2 - \frac{{\Delta I_{pp}}^2}{12}}$$

Normalizing all currents with the nominal currents we get

$$\frac{I_L}{I_N} < \sqrt{1 - \frac{{\Delta I_{pp}}^2}{12 \cdot {I_N}^2}}$$



From the chart one can see that at a peak-to-peak current ripple of 1.5 times the nominal current the motor should only be loaded by about 90%. This implies that quite large current ripples can be tolerated from a thermal point of view, without losing too much motor performance. And never forget, that's the worst case scenario with 50% PWM duty cycle (in case of a 3-level PWM switching scheme), i.e. running the motor with half the supplied voltage.

How much ripple can be tolerated?
Are external motor chokes required?

The previous chart shows, the larger the ripple, the lower the permissible load. Assuming that we still want to exploit the motor torque by 90%, a maximum ripple of about 1.5 times the nominal current can be permitted.

For a given power supply voltage and PWM frequency we get a minimum total inductance

$$\Delta I_{pp} = \frac{V_{cc}}{4 \cdot L_{tot} \cdot f_{PWM}} < 1.5 \cdot I_N$$

$$L_{tot} > \frac{V_{cc}}{4 \cdot 1.5 \cdot I_N \cdot f_{PWM}} = \frac{V_{cc}}{6 \cdot I_N \cdot f_{PWM}}$$

The total inductance sums up the contributions from the motor L_{mot}, the built-in chokes of the controller L_{int}, and external additional inductances L_{ext}. Hence, we get a formula for extra additional motor chokes:

$$L_{ext} > \frac{V_{cc}}{6 \cdot I_N \cdot f_{PWM}} - 0.3 \cdot L_{mot} - L_{int}$$

In case the right side of the equation is negative, no external choke is needed; motor and controller inductances are large enough to still permit 90% of continuous motor torque (Remember: That was our assumption!).

Remark: Why 0.3 L_{mot}?
The motor inductance in the maxon catalog is measured with 1 kHz sinusoidal excitation. Typical PWM excitation is at several 10 kHz and the rectangular PWM signal contains much higher fourier frequencies. Measurements at higher frequencies show that – as a rule of thumb – the effective motor inductance is about one third of the catalog value.

Fully exploiting the motor?

Changing the condition to exploiting the motor torque by 99%, a maximum ripple of only 0.5 times the nominal current can be permitted. Accordingly, the formula for the external choke becomes

$$L_{ext} > \frac{V_{cc}}{2 \cdot I_N \cdot f_{PWM}} - 0.3 \cdot L_{mot} - L_{int}$$