Motor data and operating ranges of maxon DC motors

- Motor behaviour: speed-torque line, current
- Motor data and operating ranges

DC motor as an energy converter

- electrical in mechanical energy
  - speed constant
  - torque constant
  - speed-torque line

\[ P_j = R \cdot I^2 \]

\[ P_{el} = U \cdot I \]

\[ P_{mech} = \frac{\pi}{30} n \cdot M \]

- applies to DC and EC motors
  - "EC" = "brushless DC" (BLDC)
maxon Motor Data and Operating Ranges

How to interpret the data of maxon motors?

### Characteristic motor data

- **Describe the motor design and general behaviour**
  - independent of actual voltage or current
  - strongly winding dependent values (electromechanical)
    - terminal resistance (phase to phase) \( R \)
    - terminal inductance (phase to phase) \( L \)
    - torque constant \( k_M \)
    - speed constant \( k_n \)
  - almost independent of winding (mechanical)
    - speed-torque gradient \( \Delta n/\Delta M \)
    - mechanical time constant \( \tau_m \)
    - rotor mass inertia \( J_{\text{rot}} \)

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### Table: Values at nominal voltage

<table>
<thead>
<tr>
<th>Nominal voltage (V)</th>
<th>No load current (mA)</th>
<th>Nominal speed (rpm)</th>
<th>Nominal torque (max. continuous torque) (mNm)</th>
<th>Stall torque (mNm)</th>
<th>Starting current (A)</th>
<th>Max. efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>201</td>
<td>867</td>
<td>0.68</td>
<td>4.93</td>
<td>3.76</td>
<td>58</td>
</tr>
<tr>
<td>3.0</td>
<td>117</td>
<td>467</td>
<td>0.70</td>
<td>5.82</td>
<td>1.97</td>
<td>76</td>
</tr>
<tr>
<td>6.0</td>
<td>32.1</td>
<td>29.3</td>
<td>0.70</td>
<td>6.08</td>
<td>1.72</td>
<td>58</td>
</tr>
<tr>
<td>9.0</td>
<td>22.2</td>
<td>22.2</td>
<td>0.70</td>
<td>6.08</td>
<td>1.72</td>
<td>58</td>
</tr>
<tr>
<td>12.0</td>
<td>22.2</td>
<td>22.2</td>
<td>0.68</td>
<td>5.98</td>
<td>2.00</td>
<td>57</td>
</tr>
<tr>
<td>15.0</td>
<td>18.5</td>
<td>18.5</td>
<td>0.68</td>
<td>5.98</td>
<td>2.00</td>
<td>57</td>
</tr>
<tr>
<td>18.0</td>
<td>16.5</td>
<td>16.5</td>
<td>0.70</td>
<td>7.06</td>
<td>2.00</td>
<td>57</td>
</tr>
<tr>
<td>21.0</td>
<td>10.7</td>
<td>10.7</td>
<td>0.68</td>
<td>7.06</td>
<td>2.00</td>
<td>57</td>
</tr>
<tr>
<td>24.0</td>
<td>3.9</td>
<td>3.9</td>
<td>0.70</td>
<td>8.14</td>
<td>2.00</td>
<td>57</td>
</tr>
<tr>
<td>27.0</td>
<td>2.9</td>
<td>2.9</td>
<td>0.70</td>
<td>8.14</td>
<td>2.00</td>
<td>57</td>
</tr>
<tr>
<td>30.0</td>
<td>2.9</td>
<td>2.9</td>
<td>0.68</td>
<td>8.14</td>
<td>2.00</td>
<td>57</td>
</tr>
</tbody>
</table>

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Winding resistance

resistance increases from left to right

<table>
<thead>
<tr>
<th>low resistance winding</th>
<th>high resistance winding</th>
</tr>
</thead>
<tbody>
<tr>
<td>thick wire, few turns</td>
<td>thin wire, many turns</td>
</tr>
<tr>
<td>low rated voltage</td>
<td>high rated voltage</td>
</tr>
<tr>
<td>high rated and starting currents</td>
<td>low rated and starting currents</td>
</tr>
<tr>
<td>high specific speed (min⁻¹/V)</td>
<td>low specific speed (min⁻¹/V)</td>
</tr>
<tr>
<td>low specific torque (mNm/A)</td>
<td>high specific torque (mNm/A)</td>
</tr>
</tbody>
</table>

Torque constant $k_M$

- produced torque is proportional to motor current
  \[ M = k_M \cdot I \]
  - defined by motor geometry and magnetic flux densities
  - measuring torques by measuring the current
  - for the motor: torque = current
  - unit: mNm/A

\[ I = \frac{M}{k_M} \]
Torque and current: torque constant

- **forces**: force on current leading conductor in a magnetic field
- **torque**: sum of all forces at the distance to the rotating axis
- **influencing parameters**: geometry, field density, winding number

\[ M = k_M \cdot I \]

- **current direction towards brush**
- **current direction towards flange**
- **magnetic field**

**Speed constant** \( k_n \)

- Induced voltage \( U_{\text{ind}} \) is proportional to motor speed \( n \)
  - law of induction: changing flux in a conductor loop
  - induced voltage proportional to speed
  - basically the inverse of \( k_M \), but in different units
  \[ n = k_n \cdot U_{\text{ind}} \]

- **Speed constant** \( k_n \)
  - mostly used for calculating no-load speeds \( n_0 \)
  - unit: \( \text{min}^{-1} / \text{V} \)

- **Generator constant** \( k_e \)
  - inverse of \( k_n \): motor as a generator (e.g. DC-Tacho). How much voltage is produced per rpm?
  - units: \( \text{mV} / \text{min}^{-1} \)
  \[ V / 1000 \text{ min}^{-1} \]
Motor as an electrical circuit

EMF: induced voltage $U_{\text{ind}}$
(winding) resistance $R$
winding inductance $L$

- voltage losses over $L$ can be neglected in DC motors

applied motor voltage $U$:

\[ U = L \cdot \frac{dI}{dt} + R \cdot I + \text{EMF} \approx R \cdot I + U_{\text{ind}} \]

\[ U_{\text{ind}} = U - R \cdot I \]

\[ \frac{n}{k_n} = U - R \cdot \frac{M}{k_M} \]

\[ n = k_n \cdot U - \frac{30'000}{\pi} \cdot \frac{R}{k_M^2} \cdot M \]

\[ n = k_n \cdot U - \frac{\Delta n}{\Delta M} \cdot M \]

Speed-torque line

\[ n = k_n \cdot U - \frac{\Delta n}{\Delta M} \cdot M \]

\[ n_0 = k_n \cdot U \]

$U > U_N$

$U = U_N$

$\Delta n$

$\Delta M$

$M_H$

$I_A$

$\frac{\Delta n}{\Delta M} \cdot M$
### Speed-torque gradient

by how much is the speed reduced $\Delta n$, if the output motor torque is enhanced by $\Delta M$?

$$\frac{\Delta n}{\Delta M} = \frac{30'000}{\pi \cdot k_M^2} \cdot R = \frac{n_1}{M_H}$$

**strong motor:**
- flat speed-torque line, small $\Delta n/\Delta M$
- not sensitive to load changes
- e.g. strong magnet, bigger motor

**weak motor:**
- steep speed-torque line, high $\Delta n/\Delta M$
- sensitive to load changes
- e.g. weak magnet, smaller motor

### Winding series

numerous winding variants adjust
- electrical input power (voltage, current of power supply)
- mechanical output power (speed, torque)

- basically constant for the winding series
- constant filling factor: a constant amount of copper fills the air gap
Values at nominal voltage

- at rated voltage \( U_N \)
- at rated current \( I_N \)

No-load operating point
- resulting no-load speed \( n_0 \)
- resulting no-load current \( I_0 \)

Rated working point
- resulting rated speed \( n_N \)
- resulting rated torque \( M_N \)

Motor at stall
- resulting stall torque \( M_H \)
- resulting starting current \( I_A \)
Friction and no-load

- Motor friction torque with 2 components
  - \( M_{VA} \): constant factor
  - \( c_5 \): speed dependent factor
  \( M_R(n) = M_{VA} + c_5 \cdot n \)

- No-load current corresponds to the friction torque
  - Good enough for most practical purposes (\( c_5 \) is small compared to \( M_{VA} \))

\[ M_R = k_M \cdot I_0 \]

Operating points

- Load operating points are characterized by a load speed \( n_L \) at a given load torque \( M_L \)
- Motor operating points lie on the speed-torque-line: select the motor voltage accordingly
maxon Motor Data and Operating Ranges
How to interpret the data of maxon motors?

**Acceleration**

acceleration at constant voltage:

![Graph of acceleration at constant voltage](image)

acceleration at constant current / torque:

![Graph of acceleration at constant current and torque](image)

**maxon standard tolerances**

- **Sources**
  - winding resistance  ± 7 %
  - magnetic properties  ± 8 %
  - friction and losses

- **Results**
  - General tolerance level  5 to 10 %
  - tolerance in no-load current  ± 50 %
  - tolerance in no-load speed  ± 10 %
    - weaker magnet => enhanced \(n_0\)
    - stronger magnet => reduced \(n_0\)
Influence of temperature

temperature coefficients

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlNiCo</td>
<td>- 0.02 % per K</td>
</tr>
<tr>
<td>Ferrite</td>
<td>- 0.2 % per K</td>
</tr>
<tr>
<td>NdFeB</td>
<td>- 0.1 % per K</td>
</tr>
<tr>
<td>Cu</td>
<td>+ 0.39 % per K</td>
</tr>
</tbody>
</table>

- example: RE motor

$\Delta T = + 50 K$

- $R$: + 19.5 %
- $k_n$: + 5 % (no-load speed)
- $k_M$: - 5 % (more current!)

stall torque $M_H$: - 22 %

Max. efficiency

$\eta = \frac{\pi}{30} \frac{n \cdot (M - M_R)}{U \cdot I}$

$\eta_{max} = \left(1 - \frac{I_0}{I_A}\right)^2 = \left(1 - \frac{M_R}{M_H}\right)^2$
Motor limits: operation ranges

**Continuous operation**
- higher ambient temperature
- heat accumulation

**Short term operation**
- lower ambient temperature
- good heat dissipation

### Motor Data

<table>
<thead>
<tr>
<th>Motor Data</th>
<th>Values at nominal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>V</td>
</tr>
<tr>
<td>No load speed</td>
<td>rpm</td>
</tr>
<tr>
<td>No load current</td>
<td>mA</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>rpm</td>
</tr>
<tr>
<td>Nominal torque (max. continuous torque)</td>
<td>mNm</td>
</tr>
<tr>
<td>Nominal current (max. continuous current)</td>
<td>A</td>
</tr>
<tr>
<td>Stall torque</td>
<td>mNm</td>
</tr>
<tr>
<td>Starting current</td>
<td>A</td>
</tr>
<tr>
<td>Max. efficiency</td>
<td>%</td>
</tr>
<tr>
<td>Characteristic motor data</td>
<td></td>
</tr>
<tr>
<td>Terminal resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>Terminal inductance</td>
<td>mH</td>
</tr>
<tr>
<td>Torque constant</td>
<td>mNm / A</td>
</tr>
<tr>
<td>Speed constant</td>
<td>rpm / V</td>
</tr>
<tr>
<td>Speed / torque gradient</td>
<td>rpm / mNm</td>
</tr>
<tr>
<td>Mechanical time constant</td>
<td>ms</td>
</tr>
<tr>
<td>Rotor inertia</td>
<td>gcm²</td>
</tr>
</tbody>
</table>

### Operating Range

- **Continuous operation**
- In observation (lines 17 and 19, temperature operation at 20°C)

- **Short term operation**
- The motor may be driven by precision

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Short-term operation at overload

- Motor may be overloaded for a short time and repeatedly
  - Limit: max. permissible winding temperature
  - Depends on thermal time constant of winding $\tau_W$ and amount of overload

Short-time operation

<table>
<thead>
<tr>
<th>Overload duration</th>
<th>Motor may be overloaded</th>
<th>Continuous operation</th>
<th>Permissible short-term operation</th>
<th>Thermally prohibited short-term operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_W$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2t_W$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3t_W$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4t_W$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5t_W$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values at nominal voltage

- Limit: max. permissible winding temperature
- Depends on thermal time constant of winding $\tau_W$ and amount of overload

Short-term operation at overload

<table>
<thead>
<tr>
<th>Motor Data</th>
<th>Values at nominal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nominal voltage V</td>
<td>1.5 3.0 6.0 9.0 12.0 14.0 15.0 18.0 21.0 30.0</td>
</tr>
<tr>
<td>2 No load speed rpm</td>
<td>10230 11700 9620 11800 11800 11200 11200 11200 11200 11200</td>
</tr>
<tr>
<td>3 No load current A</td>
<td>201 1.17 40.7 31.1 29.3 26.1 22.7 18.5 16.5 10.7</td>
</tr>
<tr>
<td>4 Nominal speed rpm</td>
<td>867</td>
</tr>
<tr>
<td>5 Nominal torque (max. continuous torque) mNm</td>
<td>0.68 0.75 0.84 0.94 1.04 1.15 1.25 1.36 1.48 2.35</td>
</tr>
<tr>
<td>6 Nominal current (max. continuous current) A</td>
<td>0.725 0.725 0.725 0.725 0.725 0.725 0.725 0.725 0.725 0.725</td>
</tr>
<tr>
<td>7 Stall torque mNm</td>
<td>4.93 4.51 4.02 3.64 3.28 2.94 2.62 2.32 2.05 1.96</td>
</tr>
<tr>
<td>8 Starting current A</td>
<td>3.76 1.97 0.721 0.709 0.519 0.450 0.377 0.310 0.275 0.164</td>
</tr>
<tr>
<td>9 Max. efficiency %</td>
<td>68 76 77 77 77 77 77 77 77 77</td>
</tr>
</tbody>
</table>

Characteristics

- Terminal resistance $\Omega$ | 0.399 1.52 8.32 12.8 23.1 31.1 39.8 58.9 76.2 183 |
- Terminal inductance mH | 0.017 0.0519 0.366 0.467 0.831 1.13 1.42 2.05 2.61 6.01 |
- Torque constant mNmm/A | 1.8 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 |
- Speed constant rpm/V | 729 |
- Speed (torque gradient) rpm/mNmm | 2220 |
- Mechanical time constant ms | 24.5 23.7 23.2 23.2 23.2 23.4 23.3 25.4 23.8 |
- Rotor inertia gmm² | 1.05 0.816 0.864 0.854 0.844 0.844 0.834 0.811 0.788 |

Values at nominal voltage

- Limit: max. permissible winding temperature
- Depends on thermal time constant of winding $\tau_W$ and amount of overload

Motor Data

- Characteristics
  - Terminal resistance $\Omega$
  - Terminal inductance mH
  - Torque constant mNmm/A
  - Speed constant rpm/V
  - Speed (torque gradient) rpm/mNmm
  - Mechanical time constant ms
  - Rotor inertia gmm²

Operating Range

- Continuous operation: (lines 17 and 19)
- In operation (lines 17 and 19): When temperature operation at 25°C
- Operation at 25°C: Thermal limit
- Short term operation: The motor may be overloaded for a short time and repeatedly.

Further Specifications

- Ambient temperature: –20°C to +125°C
- Max. permissible winding temperature: +125°C
- Max. permissible speed: 11900 rpm

Thermal motor data
describe the motor heating and thermal limits
- depend strongly on mounting conditions
- standard mounting:
  - heating and cooling
    - thermal resistance housing-ambient $R_{th2}$
    - thermal resistance winding-housing $R_{th1}$
    - thermal time constant of winding $\tau_{thW}$
    - thermal time constant of motor $\tau_{thS}$
  - temperature limits
    - ambient temperature range
    - max. winding temperature $T_{max}$

Nominal Torque and Temperature

Example for $T_{max} = 125 ^\circ C$
Mechanical motor data

describe maximum speed and the properties of bearings

- max. permissible speed
  - limited by bearing life considerations (EC)
  - limited by relative speed between collector and brushes (DC)

- axial and radial play
  - suppressed by a preload

- axial and radial bearing load
  - dynamic: in operation
  - static: at stall

Axial press fit force
(shaft supported)

Assigned power rating

- no general criteria
  - electrical power at the rated working point
  - output power at the rated working point:
    - or maximum output power at rated voltage
  - but also "marketing" factors

\[ P_{typ} = \frac{\pi}{30} \cdot n_N \cdot M_N \]

- anyway ...
  - assigned power rating is only a rough estimate
  - drive must fulfill both, torque and speed requirements