# Motor data and operating ranges of maxon DC motors

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

see E-learning tutorial on maxonmotor.com/academy

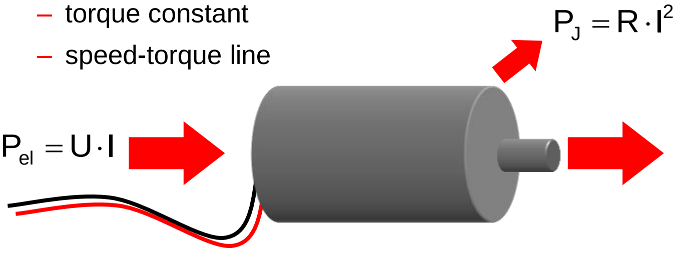


## DC motor as an energy converter

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

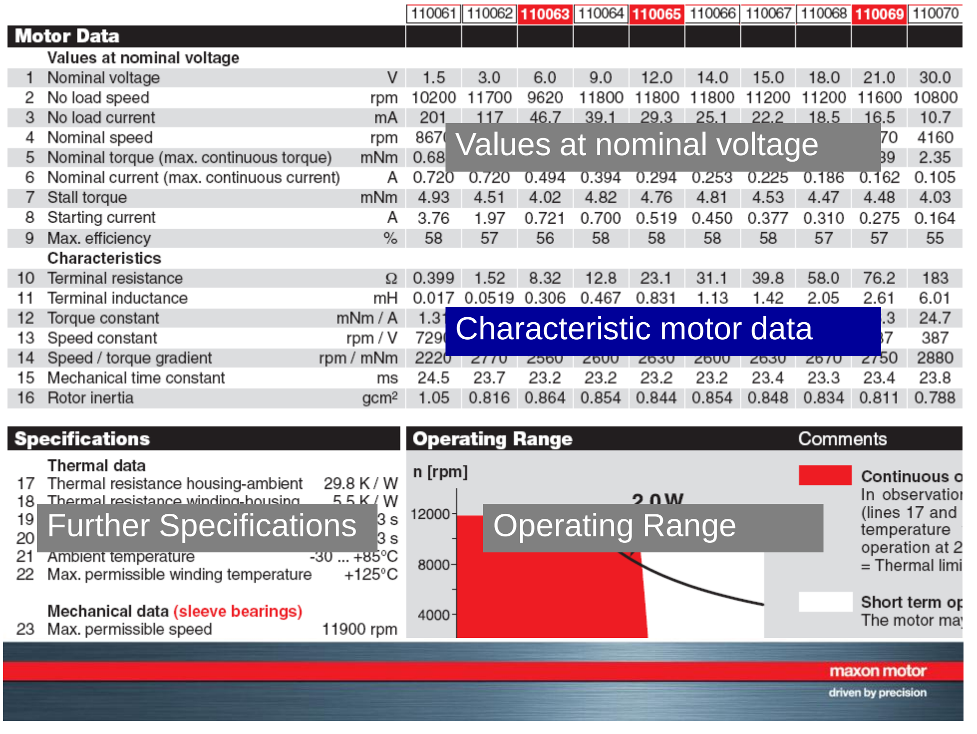
$$P_J = R \cdot I^2$$

$$P_{el} = U \cdot I$$



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

- applies to DC and EC motors
  - "EC" = "brushless DC" (BLDC)




## Characteristic motor data

describe the motor design and general behaviour

- independent of actual voltage or current

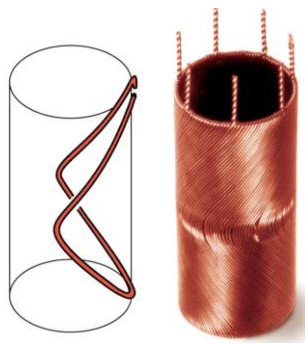
- strongly winding dependent values (electromechanical)
  - terminal resistance (phase to phase) R
  - terminal inductance (phase to phase) L
  - torque constant $k_M$
  - speed constant $k_n$
- almost independent of winding (mechanical)
  - speed-torque gradient $\Delta n/\Delta M$
  - mechanical time constant $\tau_m$
  - rotor mass inertia $J_{Mot}$

## Winding resistance

resistance increases from left to right

low resistance winding ↔ high resistance winding

- thick wire, few turns
- low rated voltage
- high rated and starting currents
- high specific speed ($min^{-1}$/V)
- low specific torque (mNm/A)



- thin wire, many turns
- high rated voltage
- low rated and starting currents
- low specific speed ($min^{-1}$/V)
- high specific torque (mNm/A)

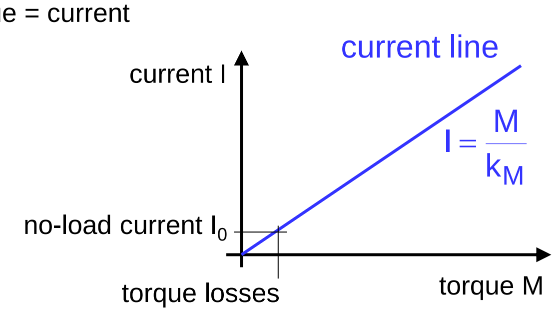


## Torque constant $k_M$

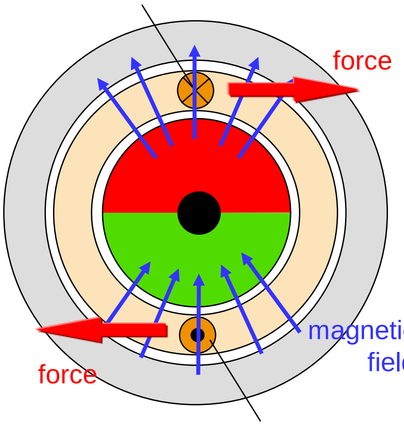
- produced torque is proportional to motor current

$$M = k_M \cdot I$$

  - defined by motor geometry and magnetic flux densities
  - measuring torques by measuring the current
  - for the motor: torque = current
  - unit: mNm/A



## 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 } **design**

$$M = k_M \cdot I$$

current I } **application**





## Speed constant $k_n$

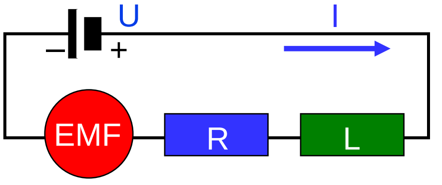
- Induced voltage $U_{ind}$ is proportional to motor speed n
  - law of induction: changing flux in a conductor loop
  - induced voltage proportional to speed
  - basically the inverse of $k_M$, but in different units
- Speed constant $k_n$
  - mostly used for calculating no-load speeds $n_0$
  - unit: $min^{-1}$ / V

$$n = k_n \cdot U_{ind}$$

$$n_0 = k_n \cdot U$$

- Generator constant $k_e$
  - inverse of $k_n$: motor as a generator (e.g. DC-Tacho). How much voltage is produced per rpm?
  - units: mV / $min^{-1}$
    V / 1000 $min^{-1}$

## Motor as an electrical circuit




applied motor voltage U:

$$U = L \cdot \frac{\partial I}{\partial t} + R \cdot I + EMF \cong R \cdot I + U_{ind}$$

$$U_{ind} = U - R \cdot I$$

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

$$n = k_n \cdot U - \left( \frac{30'000}{\pi} \cdot \frac{R}{k_M^2} \right) \cdot M$$

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

EMF: induced voltage $U_{ind}$

(winding) resistance R

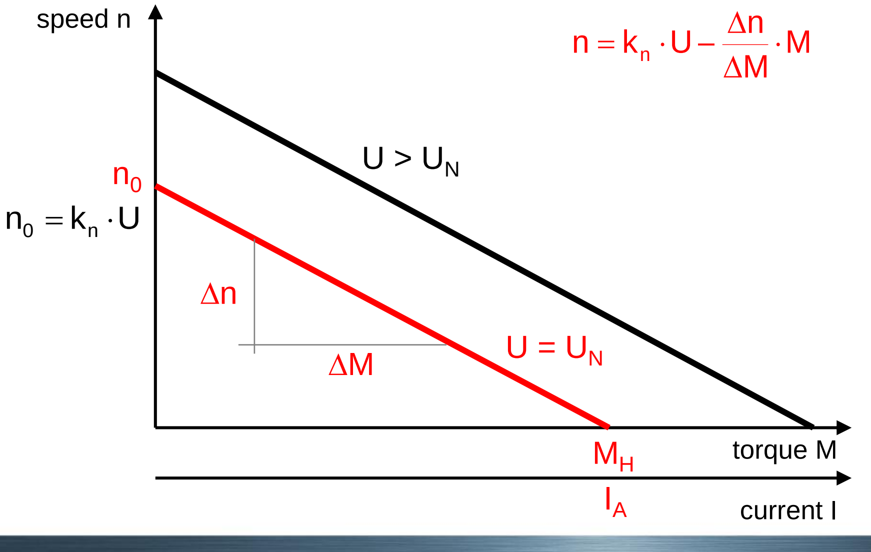
winding inductance L

- voltage losses over L can be neglected in DC motors



## Speed-torque line

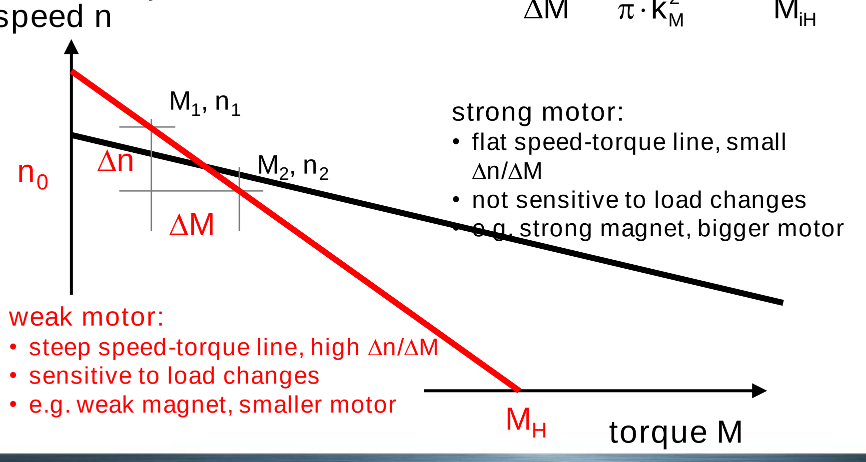
$$n = k_n \cdot U - \frac{\Delta n}{\Delta M} \cdot M$$



## Speed-torque gradient

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

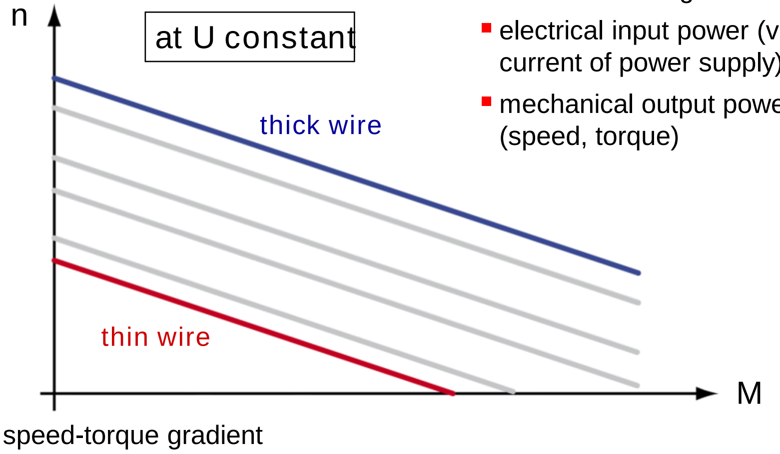
$$\frac{\Delta n}{\Delta M} = \frac{30'000}{\pi \cdot k_M^2} \cdot R = \frac{n_i}{M_{iH}}$$








## Winding series




numerous winding variants adjust

- electrical input power (voltage, current of power supply)
- mechanical output power (speed, torque)

speed-torque gradient

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

| | | | 110061 | 110062 | 110063 | 110064 | 110065 | 110066 | 110067 | 110068 | 110069 | 110070 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Motor Data** | | | | | | | | | | | | |
| | **Values at nominal voltage** | | | | | | | | | | | |
| 1 | Nominal voltage | V | 1.5 | 3.0 | 6.0 | 9.0 | 12.0 | 14.0 | 15.0 | 18.0 | 21.0 | 30.0 |
| 2 | No load speed | rpm | 10200 | 11700 | 9620 | 11800 | 11800 | 11800 | 11200 | 11200 | 11600 | 10800 |
| 3 | No load current | mA | 201 | 117 | 46.7 | 39.1 | 29.3 | 25.1 | 22.2 | 18.5 | 16.5 | 10.7 |
| 4 | Nominal speed | rpm | 867 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 70 | 4160 |
| 5 | Nominal torque (max. continuous torque) | mNm | 0.68 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 39 | 2.35 |
| 6 | Nominal current (max. continuous current) | A | 0.720 | 0.720 | 0.494 | 0.394 | 0.294 | 0.253 | 0.225 | 0.186 | 0.162 | 0.105 |
| 7 | Stall torque | mNm | 4.93 | 4.51 | 4.02 | 4.82 | 4.76 | 4.81 | 4.53 | 4.47 | 4.48 | 4.03 |
| 8 | Starting current | A | 3.76 | 1.97 | 0.721 | 0.700 | 0.519 | 0.450 | 0.377 | 0.310 | 0.275 | 0.164 |
| 9 | Max. efficiency | % | 58 | 57 | 56 | 58 | 58 | 58 | 58 | 57 | 57 | 55 |
| | **Characteristics** | | | | | | | | | | | |
| 10 | Terminal resistance | Ω | 0.399 | 1.52 | 8.32 | 12.8 | 23.1 | 31.1 | 39.8 | 58.0 | 76.2 | 183 |
| 11 | Terminal inductance | mH | 0.017 | 0.0519 | 0.306 | 0.467 | 0.831 | 1.13 | 1.42 | 2.05 | 2.61 | 6.01 |
| 12 | Torque constant | mNm / A | 1.31 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .3 | 24.7 |
| 13 | Speed constant | rpm / V | 729 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 37 | 387 |
| 14 | Speed / torque gradient | rpm / mNm | 2220 | 2770 | 2560 | 2600 | 2630 | 2600 | 2630 | 2670 | 2750 | 2880 |
| 15 | Mechanical time constant | ms | 24.5 | 23.7 | 23.2 | 23.2 | 23.2 | 23.2 | 23.4 | 23.3 | 23.4 | 23.8 |
| 16 | Rotor inertia | $gcm^2$ | 1.05 | 0.816 | 0.864 | 0.854 | 0.844 | 0.854 | 0.848 | 0.834 | 0.811 | 0.788 |

Values at nominal voltage

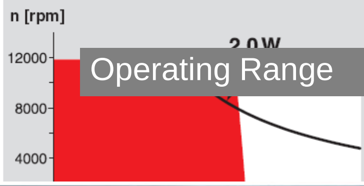
Characteristic motor data

**Specifications**

| | | |
|---|---|---|
| | **Thermal data** | |
| 17 | Thermal resistance housing-ambient | 29.8 K / W |
| 18 | Thermal resistance winding-housing | 5.5 K / W |
| 19 | [illegible] | 3 s |
| 20 | [illegible] | 3 s |
| 21 | Ambient temperature | -30 ... +85°C |
| 22 | Max. permissible winding temperature | +125°C |
| | **Mechanical data (sleeve bearings)** | |
| 23 | Max. permissible speed | 11900 rpm |

Further Specifications

**Operating Range**




**Comments**

**Continuous o**
In observatio
(lines 17 and
temperature
operation at 2
= Thermal limi

**Short term op**
The motor ma

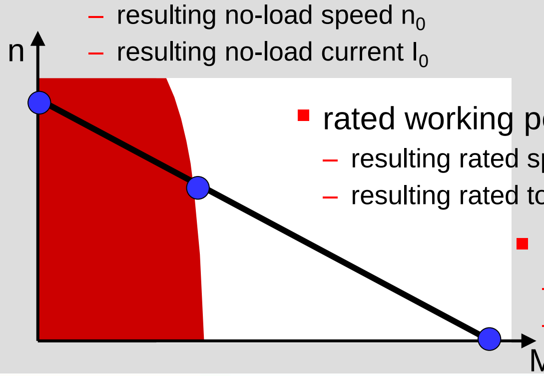
maxon motor
driven by precision

## Values at nominal voltage

describe the special working points:

- 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 $I_A$

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driven by precision

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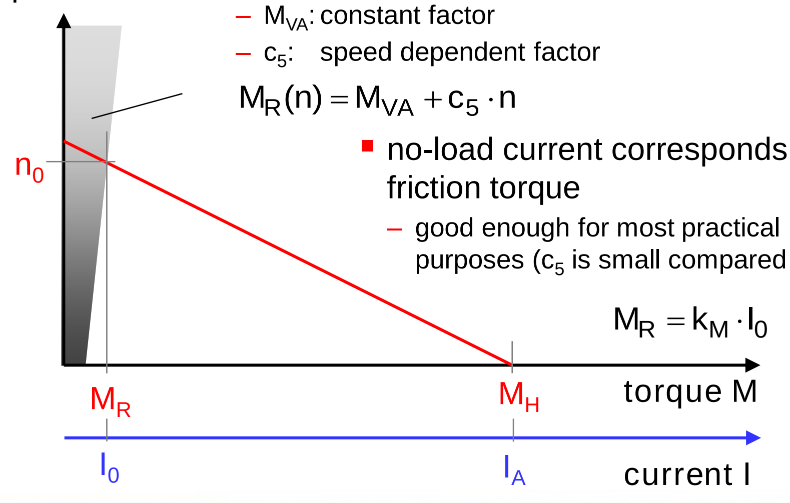
## Friction and no-load

- 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 $M_{VA}$)

$$M_R = k_M \cdot I_0$$

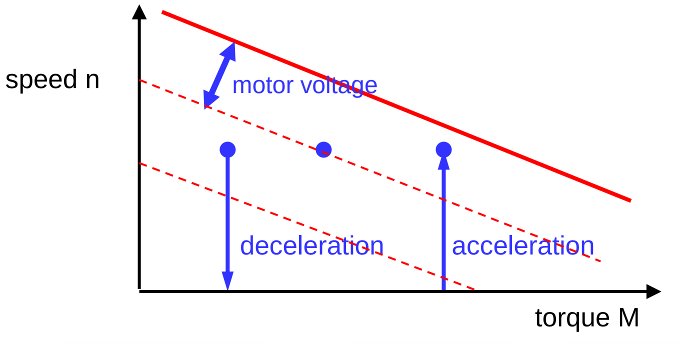







## Operating points

- 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



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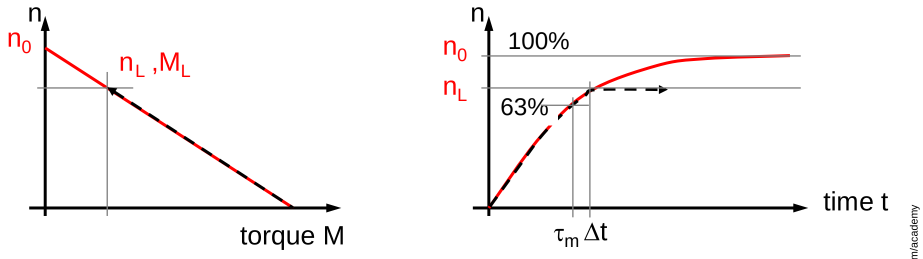
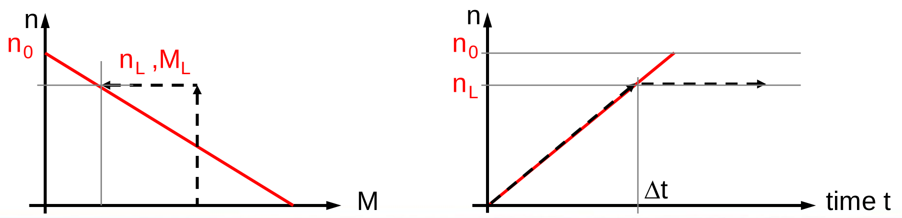
## Acceleration

acceleration at constant voltage:



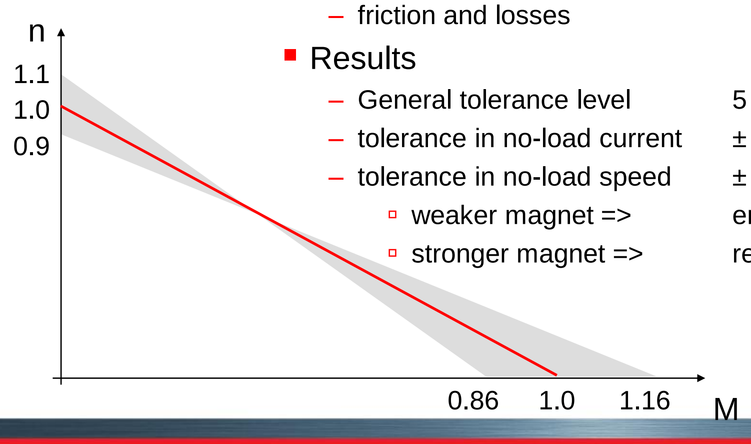

acceleration at constant current / torque:








## 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 $n_0$

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## Influence of temperature

temperature coefficients

Cu + 0.39 % per K

AlNiCo - 0.02 % per K
Ferrite - 0.2 % per K
NdFeB - 0.1 % per K

**temperature** **resistance** **magnetic properties**

- example: RE motor

$\Delta T$ = + 50K

R: + 19.5 %

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

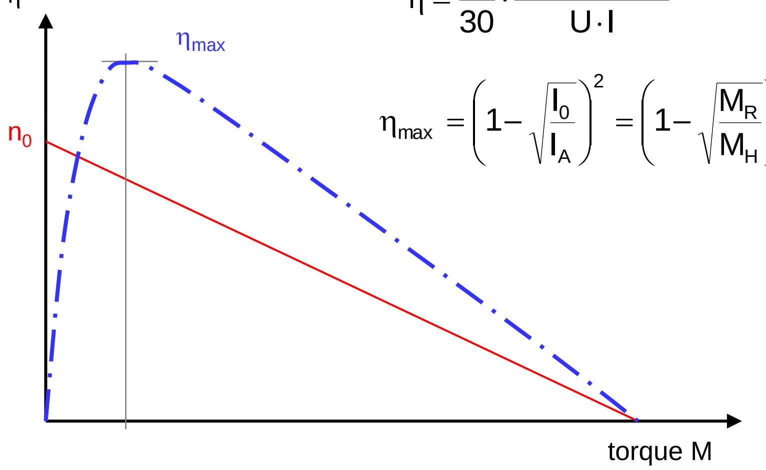
stall torque $M_H$ : - 22 %





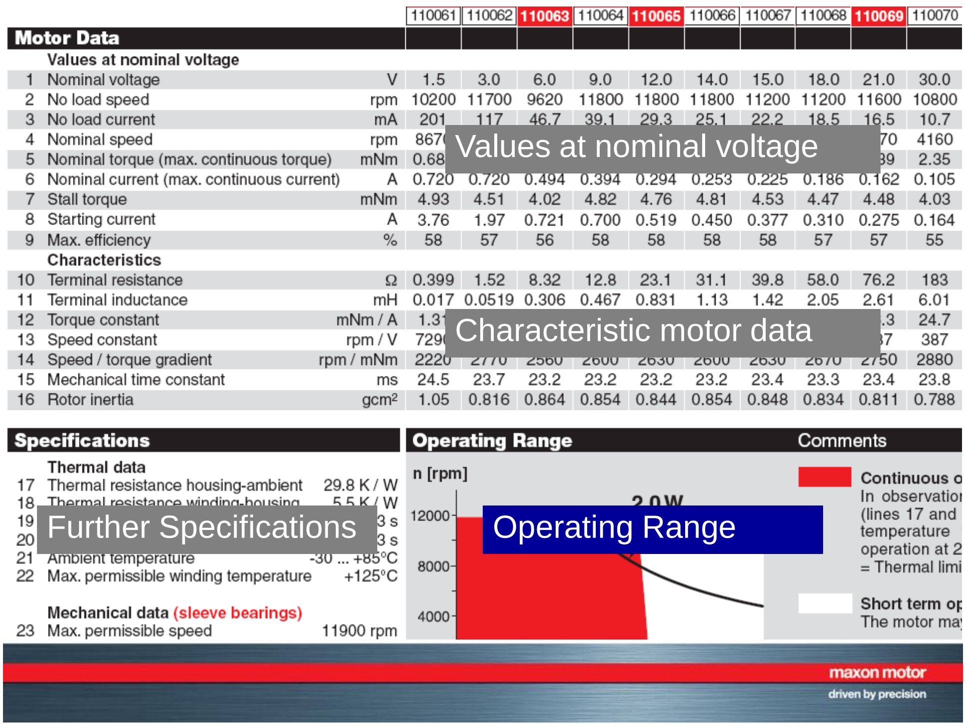
## Max. efficiency

efficiency η




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

$$\eta_{max} = \left(1 - \sqrt{\frac{I_0}{I_A}}\right)^2 = \left(1 - \sqrt{\frac{M_R}{M_H}}\right)^2$$




| | Motor Data | | 110061 | 110062 | 110063 | 110064 | 110065 | 110066 | 110067 | 110068 | 110069 | 110070 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Values at nominal voltage** | | | | | | | | | | | |
| 1 | Nominal voltage | V | 1.5 | 3.0 | 6.0 | 9.0 | 12.0 | 14.0 | 15.0 | 18.0 | 21.0 | 30.0 |
| 2 | No load speed | rpm | 10200 | 11700 | 9620 | 11800 | 11800 | 11800 | 11200 | 11200 | 11600 | 10800 |
| 3 | No load current | mA | 201 | 117 | 46.7 | 39.1 | 29.3 | 25.1 | 22.2 | 18.5 | 16.5 | 10.7 |
| 4 | Nominal speed | rpm | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4160 |
| 5 | Nominal torque (max. continuous torque) | mNm | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2.35 |
| 6 | Nominal current (max. continuous current) | A | 0.720 | 0.720 | 0.494 | 0.394 | 0.294 | 0.253 | 0.225 | 0.186 | 0.162 | 0.105 |
| 7 | Stall torque | mNm | 4.93 | 4.51 | 4.02 | 4.82 | 4.76 | 4.81 | 4.53 | 4.47 | 4.48 | 4.03 |
| 8 | Starting current | A | 3.76 | 1.97 | 0.721 | 0.700 | 0.519 | 0.450 | 0.377 | 0.310 | 0.275 | 0.164 |
| 9 | Max. efficiency | % | 58 | 57 | 56 | 58 | 58 | 58 | 58 | 57 | 57 | 55 |
| | **Characteristics** | | | | | | | | | | | |
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| 11 | Terminal inductance | mH | 0.017 | 0.0519 | 0.306 | 0.467 | 0.831 | 1.13 | 1.42 | 2.05 | 2.61 | 6.01 |
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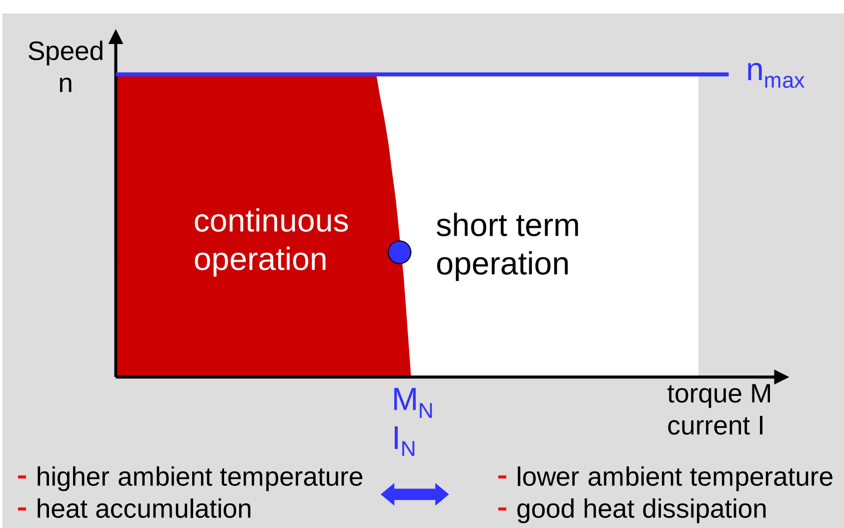
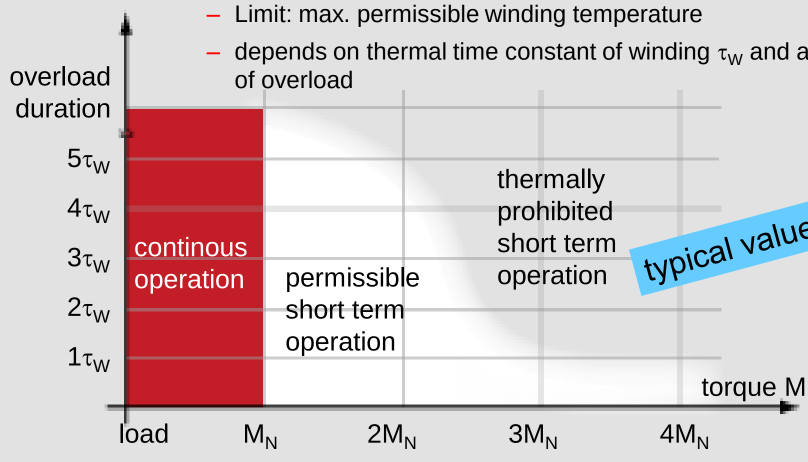
| 13 | Speed constant | rpm / V | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 387 |
| 14 | Speed / torque gradient | rpm / mNm | 2220 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2750 | 2880 |
| 15 | Mechanical time constant | ms | 24.5 | 23.7 | 23.2 | 23.2 | 23.2 | 23.2 | 23.4 | 23.3 | 23.4 | 23.8 |
| 16 | Rotor inertia | gcm² | 1.05 | 0.816 | 0.864 | 0.854 | 0.844 | 0.854 | 0.848 | 0.834 | 0.811 | 0.788 |

## Motor limits: operation ranges



## 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





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| 4 | Nominal speed | rpm | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4160 |
| 5 | Nominal torque (max. continuous torque) | mNm | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2.35 |
| 6 | Nominal current (max. continuous current) | A | 0.720 | 0.720 | 0.494 | 0.394 | 0.294 | 0.253 | 0.225 | 0.186 | 0.162 | 0.105 |
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| 13 | Speed constant | rpm / V | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 387 |
| 14 | Speed / torque gradient | rpm / mNm | 2220 | 2770 | 2560 | 2600 | 2630 | 2600 | 2630 | 2670 | 2750 | 2880 |
| 15 | Mechanical time constant | ms | 24.5 | 23.7 | 23.2 | 23.2 | 23.2 | 23.2 | 23.4 | 23.3 | 23.4 | 23.8 |
| 16 | Rotor inertia | gcm² | 1.05 | 0.816 | 0.864 | 0.854 | 0.844 | 0.854 | 0.848 | 0.834 | 0.811 | 0.788 |

Values at nominal voltage

Characteristic motor data

**Specifications**

**Thermal data**

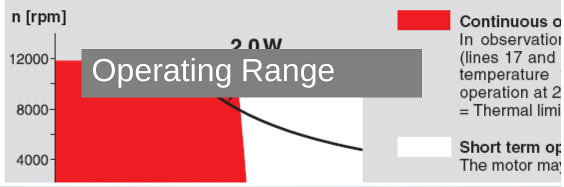
17 Thermal resistance housing-ambient 29.8 K / W
18 Thermal resistance winding-housing 5.5 K / W
19 [illegible] 3 s
20 [illegible] 3 s
21 Ambient temperature -30 ... +85°C
22 Max. permissible winding temperature +125°C

**Mechanical data** (sleeve bearings)

23 Max. permissible speed 11900 rpm

Further Specifications

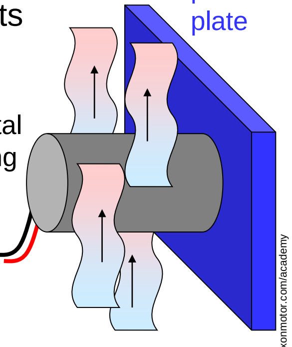
**Operating Range** Comments



## Thermal motor data

describe the motor heating and thermal limits

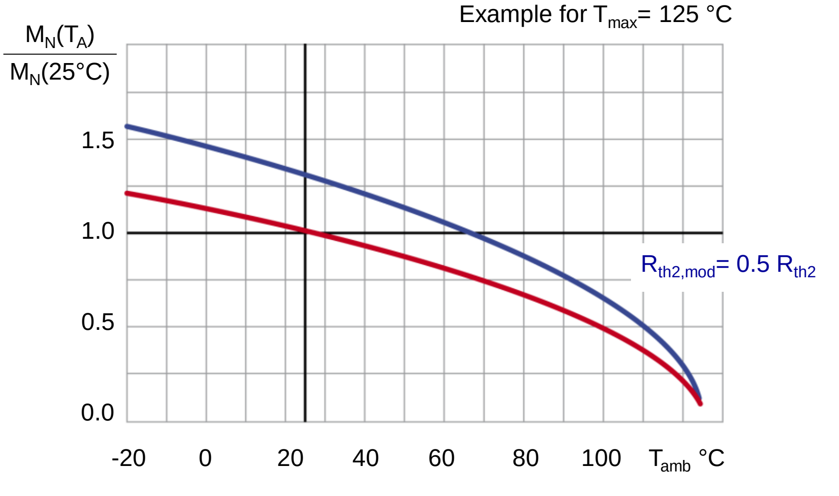
- depend strongly on mounting conditions
- standard mounting:




- 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 $T_{max}$

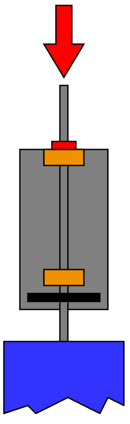


## Nominal Torque and Temperature



## Mechanical motor data

describe maximum speed and the properties of bearings



axial press fit force
(shaft supported)

- 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





## 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