Technical guide No. 7 - Basic formulas
基本公式

Road show 3

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ABB Automation

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Technical guide No. 7 - Basic formulas

Purpose and targets of the presentation
内容和目的

- **Purpose of the presentation 内容**
  - **Show the typical formulas used in basic dimensioning**

    说明基本选型公式
- **The targets of the presentation are that you: 目的**
  - **Can do also manual calculations of basic dynamical systems (e.g. acceleration time)**

    动态系统的手工计算

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AC motor - Power 交流电机的功率

- **Motor's mechanical output power can be calculated from speed and torque:**
  通过速度和力矩计算电机的输出功率

$$P_{out}[kW] = \frac{T[Nm]*n[rpm]}{9550}$$

$$P_{out}[W] = T[Nm]*\omega[rad/s]$$

$$\omega[rad/s] = \frac{2\pi}{60}*n[rpm]$$

$$1\,kW = 1000\,W$$

- **Motor's input power can be calculated from voltage, current and power factor:**
  通过电压，电流和功率因数计算电机输入功率

$$P_{in}[W] = \sqrt{3}*U[V]*I[A]*\cos(\varphi)$$

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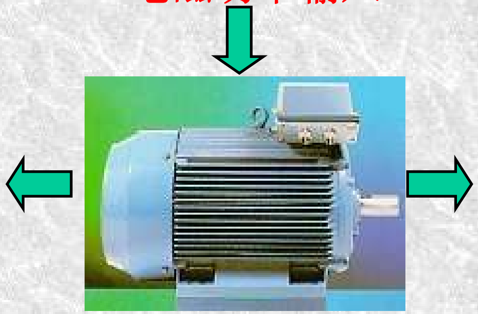
AC motor - Power 交流电机的功率

- **Motor's efficiency is output power divided by input power:**
  电机效率是输出功率/输入功率

$$\eta = \frac{P_{out}}{P_{in}}$$



- **At nominal point AC motor's output power is:**
  电机额定点的输出功率

轴头电功率 $P_{out}[W] = P_n[W] = \sqrt{3} * U_n[V] * I_n[A] * \cos(\varphi_n) * \eta_n$ **or**

轴头机械功率 $P_{out}[kW] = P_n[kW] = \frac{T_n[Nm] * n_n[rpm]}{9550}$

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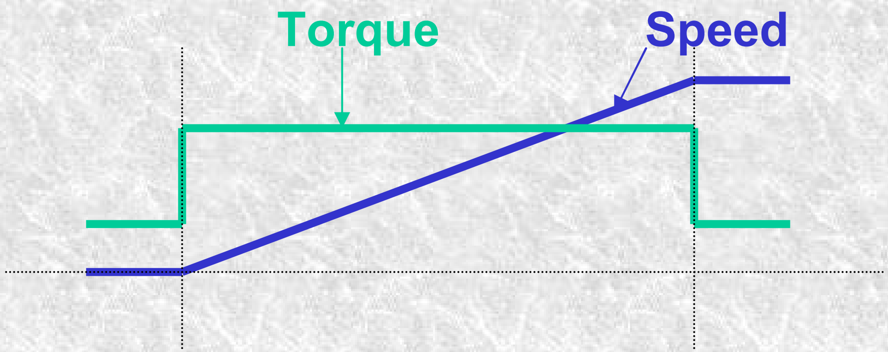
AC motor - Mechanical laws of rotational motion
AC电机的转动原理

- One of the fundamental equations for an electric motor is:

电机转子的加速规律

$$J\frac{d\omega}{dt} = T - T_{load}$$



- Motor torque consists of dynamic and load component. Dynamic component changes the speed:

电机力矩包含动态力矩分量和负载力矩分量

$$T = T_{dyn} + T_{load}$$

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AC motor - Mechanical laws of rotational motion
AC电机的转动原理

- **Dynamic torque component changes the motor speed:**

  动态力矩分量影响电机转速

$$T_{dyn}[Nm] = J[kgm^2] * \frac{d\omega[rad/s]}{dt}$$

- **In practice the dynamic component is calculated as follows:**

  动态分量的工程计算

$$T_{dyn}[Nm] = J[kgm^2] * \frac{2\pi}{60} * \frac{\Delta n[rpm]}{\Delta t[s]}$$

- **The total torque needed in acceleration is thus:**

  加速过程中总的力矩是

$$T[Nm] = T_{dyn} + T_{load} = J[kgm^2] * \frac{2\pi}{60} * \frac{\Delta n[rpm]}{\Delta t[s]} + T_{load}$$

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AC motor - Mechanical laws of rotational motion
AC电机的转动原理

Example: AC motor's and load's total moment of inertia is 3 kgm^2. Constant load torque is 50 Nm.

举例：电机和负载的总转动惯量是**3 kgm^2**，恒定负载力矩**50 Nm**

A) What is the torque needed to accelerate the motor from 0 rpm to 1000 rpm speed in 10 seconds?

问题**A)**：电机转速在**10**秒内从**0**加速到**1000rpm**，需要多大力矩？

B) If the electric supply is switched off at 1000 rpm speed how fast will the motor decelerate to 0 rpm speed?

问题**B)**：如果电机运行在**1000rpm**时，停止供电，
那么电机减速至**0rpm**要多少时间？

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AC motor - Mechanical laws of rotational motion
AC电机的转动原理

Solution: 答案

A) The total torque needed for acceleration is the sum of dynamic and load components. 加速过程中总力矩是动态和负载力矩之和

$$T = T_{dyn} + T_{load} = 3 * \frac{2\pi}{60} * \frac{1000}{10} \; Nm + 50 \; Nm = 81.4 \; Nm$$

B) The motor decelerates because of the load torque (50 Nm), Actual motor torque is zero. Then:

减速过程中，仅靠负载力矩起作用**(50 Nm)**，电机本身没有任何力矩起作用

$$J[kgm^2] * \frac{2\pi}{60} * \frac{\Delta n[rpm]}{\Delta t[s]} = -T_{load} \Leftrightarrow \quad \Delta t[s] = 3 * \frac{2\pi}{60} * \frac{1000}{50} \; s = 6.28 \; s$$

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Moment of inertia & gears 惯性矩和齿轮箱的因素

- 'Inertia' (moment of inertia) is important to know in many dimensioning cases.
  选型时必须知道惯性(转动惯量)。
- Generally $J[kgm^2]$ can be given by motor and machine manufacturers.
  制造厂通常给出转动惯量：$J[kgm^2]$
- Sometimes it can be calculated quite easily. For a cylinder shape the moment of inertia is proportional to mass and quadratically proportional to radius of the cylinder: $J = m*r^2$.
  转动惯量很容易计算。
  圆筒型的转动惯量与其质量和半径的平方成正比：$J = m*r^2$
- Energy stored to a rotating mass is: $E = 0.5*J*\omega^2$
  旋转体储存的能量是：$E = 0.5*J*\omega^2$

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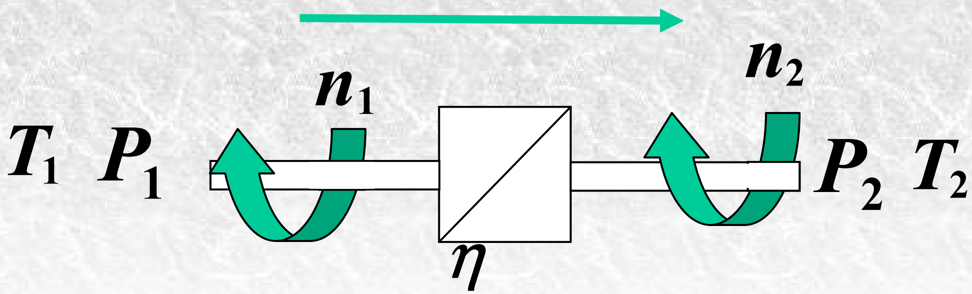
Moment of inertia & gears惯性矩和齿轮箱的因素

- When gear is used power, torque, moment of inertia, spring constant of a shaft, etc. must be reduced.
  使用齿轮箱时，功率，转矩，转动惯量，轴的弹性系数等必定会减小

$$T_1 = \frac{T_2}{\eta} * \left(\frac{n_2}{n_1}\right) \qquad J_1 = J_2 * \left(\frac{n_2}{n_1}\right)^2 \qquad P_1 = \frac{P_2}{\eta}$$

Direction of energy 能量传递方向



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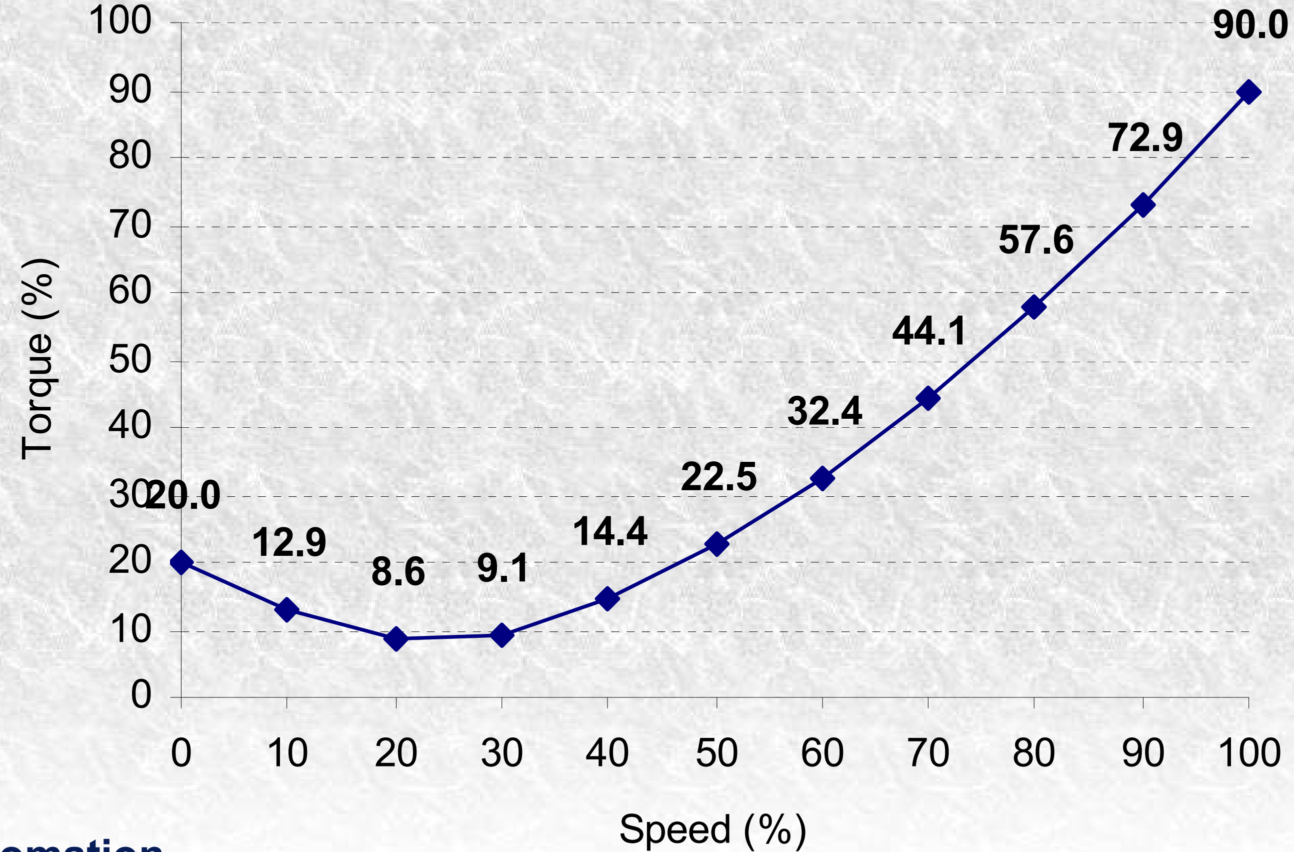
Calculation example 计算举例

- A fan has following load characteristics

一个风机有如下的负载特性



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Calculation example 计算举例

- A following motor has been selected:
  电机选型如下

P_n	=	110 kW
U_n	=	400 V
I_n	=	202 A
$\cos(\phi_n)$	=	0.83
n_n	=	991 rpm
J_{motor}	=	5 kgm^2

- Fans moment of inertia is $J_{fan} = 995\ kgm^2$
  风机转动惯量：$J_{fan} = 995\ kgm^2$

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Calculation example计算举例

- **Task 1: What is the nominal torque of the motor? What is the nominal efficiency of the motor?**

  电机的额定力矩是多少?

  电机的额定效率是多少?

- **Task 2: Estimate the starting time from 0 to 100% speed if accelerating is done with nominal torque.**

  如果以额定力矩加速，估算电机转速从**0**上升到**100%**的额定速度的起动时间。

Solution

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Calculation example

Task 3: Estimate the deceleration time from 100% to 0% speed if it is assumed that the average braking torque over the whole speed range (in generating mode, flux braking is utilised) is 4.5%.

Hint: **Divide the speed range into sectors and calculate the times over the sectors.**

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Calculation example - Solution

Task 1:

- Nominal torque of the motor is: 电机的额定力矩

$$T_n[Nm] = \frac{9550 * P_n[kW]}{n_n[rpm]} = \frac{9550 * 110}{991} Nm \approx 1060\ Nm$$

- Nominal efficiency of the motor is:电机的额定效率

$$\eta_n = \frac{P_{out}}{P_{in}} = \frac{P_n[W]}{\sqrt{3} * U_n[V] * I_n[A] * \cos(\varphi_n)} = \frac{110000}{\sqrt{3} * 400 * 202 * 0.83} \approx 0.947$$

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Calculation example - Solution

Task 2:

- **Speed range is divided into 10 sectors.** 速度范围分成**10**段
- **Acceleration time for each sector is calculated using formula:**
  每一段的加速时间用下列公式计算

$$\Delta t[s] = J[kgm^2]*\frac{2\pi}{60}*\frac{\Delta n[rpm]}{T_{dyn}} = J[kgm^2]*\frac{2\pi}{60}*\frac{\Delta n[rpm]}{T_n - T_{load}}$$

- **In each sector average value of load torque is used. For example in sector 1 the average load torque is (20+12.9)/2 % = 16.45 % and the dynamic accelerating torque (T_n-T_{load}) is 100 % - 16.45 % = 83.55 %.**
  每段都使用负载力矩的平均值。例如第一部分的平均力矩是：
  (20+12.9)/2 % = 16.45 %， 动态加速力矩(**T_n-T_{load}**)是：
  100 % - 16.45 % = 83.55 %.

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Calculation example - Solution

Task 2:

$$0-99.1\ rpm \qquad \Delta t[s]=J[kgm^2]*\frac{2\pi}{60}*\frac{\Delta n[rpm]}{T_n-T_{load}}=1000*\frac{2\pi}{60}*\frac{99.1}{0.8355*1060}\ s=11.7\ s$$

$$99.1-198.2\ rpm \qquad \Delta t[s]=1000*\frac{2\pi}{60}*\frac{99.1}{0.8925*1060}\ s=11.0\ s$$

$$198.2-297.3\ rpm \qquad \Delta t[s]=1000*\frac{2\pi}{60}*\frac{99.1}{0.9115*1060}\ s=10.7\ s$$

$$297.3-396.4\ rpm \qquad \Delta t[s]=1000*\frac{2\pi}{60}*\frac{99.1}{0.8825*1060}\ s=11.1\ s$$

$$396.4-495.5\ rpm \qquad \Delta t[s]=1000*\frac{2\pi}{60}*\frac{99.1}{0.8155*1060}\ s=12.0\ s$$

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Calculation example - Solution

Task 2:

$495.5 - 594.6\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.7255 * 1060} s = 13.5\ s$

$594.6 - 693.7\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.6175 * 1060} s = 15.9\ s$

$693.7 - 792.8\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.4915 * 1060} s = 19.9\ s$

$792.8 - 891.9\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.3475 * 1060} s = 28.2\ s$

$891.9 - 991\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.1855 * 1060} s = 52.8\ s$

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Calculation example - Solution

Task 2:

- The total acceleration time is the sum of all sector times: 186.8 seconds! 总时间为每段时间之和

- Sector width affects the accuracy of this kind of approximation.每一部分的宽度影响近似类型的精度

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Calculation example - Solution

Task 3:

- Speed range is divided into 10 sectors.
- Deceleration time for each sector is calculated using formula (T = - 4.5%):

$$\Delta t[s] = J[kgm^2] * \frac{2\pi}{60} * \frac{\Delta n[rpm]}{T_{dyn}} = J[kgm^2] * \frac{2\pi}{60} * \frac{\Delta n[rpm]}{T_{load} + T}$$

- In each sector average value of load torque is used. For example in sector 10 the average load torque is (90+72.9)/2 % = 81.45 % and the dynamic decelerating torque is 81.45% + 4.5 % = 85.95 %.

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Calculation example - Solution

Task 3:

$991 - 891.9\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.8595 * 1060}\ s = 11.4\ s$

$891.9 - 792.8\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.6975 * 1060}\ s = 14.0\ s$

$792.8 - 693.7\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.5535 * 1060}\ s = 17.7\ s$

$693.7 - 594.6\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.4275 * 1060}\ s = 22.9\ s$

$594.6 - 495.5\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.3195 * 1060}\ s = 30.6\ s$

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Calculation example - Solution

Task 3:

$$495.5 - 396.4\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.2295 * 1060}\ s = 42.7\ s$$

$$396.4 - 297.3\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.1625 * 1060}\ s = 60.2\ s$$

$$297.3 - 198.2\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.1335 * 1060}\ s = 73.3\ s$$

$$198.2 - 99.1\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.1525 * 1060}\ s = 64.2\ s$$

$$99.1 - 0\ rpm \qquad \Delta t[s] = 1000 * \frac{2\pi}{60} * \frac{99.1}{0.2095 * 1060}\ s = 46.7\ s$$

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Calculation example - Solution

Task 3:

- **The total deceleration time is the sum of all sector times: 383.7 seconds!**
- **Sector width affects the accuracy of this kind of approximation.**