ABB DRIVES

Technical guide No. 7

Dimensioning of a drive system

Dimensioning of a drive system

Dimensioning of a drive system is a task where all factors have to be considered carefully. Dimensioning requires knowledge of the whole system including electric supply, driven machine, environmental conditions, motors and drives, etc. Time spent at the dimensioning phase can mean considerable cost savings.

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Drive system

A single AC drive system consists typically of an input transformer or an electric supply, variable speed drive, an AC motor and load. Inside a single variable speed drive there is a rectifier, DC-link and inverter unit.

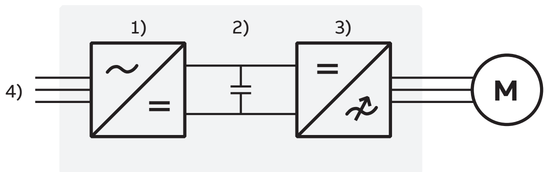

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Figure 1.1. A single variable speed drive consists of 1) rectifier, 2) DC-link, 3) inverter unit and 4) electric supply.

In multi-drive systems a separate rectifier unit is commonly used.
Inverter units are connected directly to a common DC-link.

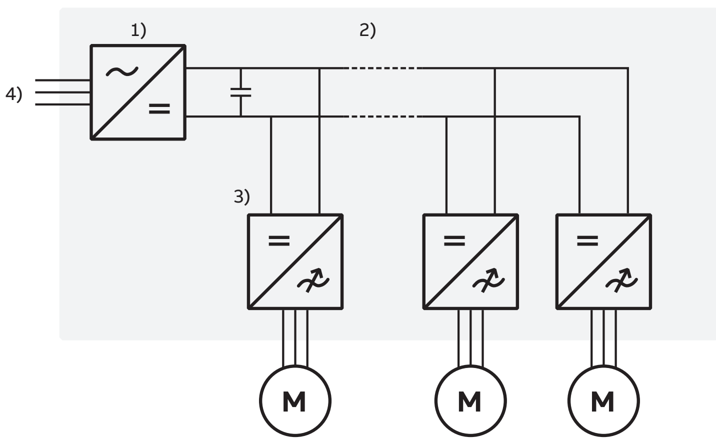

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Figure 1.2. A drive system which has 1) a separate supply section, 2) common DC-link, 3) inverter units and 4) electric supply.

General description of a dimensioning procedure

This chapter gives the general steps for dimensioning the motor and variable speed drive.

1) First check the initial conditions
In order to select the correct variable speed drive and motor, check the mains supply voltage level (380 to 690 V) and frequency (50 to 60 Hz). The mains supply network's frequency doesn't limit the speed range of the application.

2) Check the process requirements
Is there a need for starting torque? What is the speed range used? What type of load will there be? Some of the typical load types are described later.

3) Select the motor
An electrical motor should be seen as a source of torque. The motor must withstand process overloads and be able to produce a specified amount of torque. The motor's thermal overloadability should not be exceeded. It is also necessary to leave a margin of around 30% for the motor's maximum torque when considering the maximum available torque in the dimensioning phase.

4) Select the variable speed drive
The variable speed drive is selected according to the initial conditions and the selected motor. The drive's capability of producing the required current and power should be checked. Advantage should be taken of the drive's potential overloadability in case of a short term cyclical load.

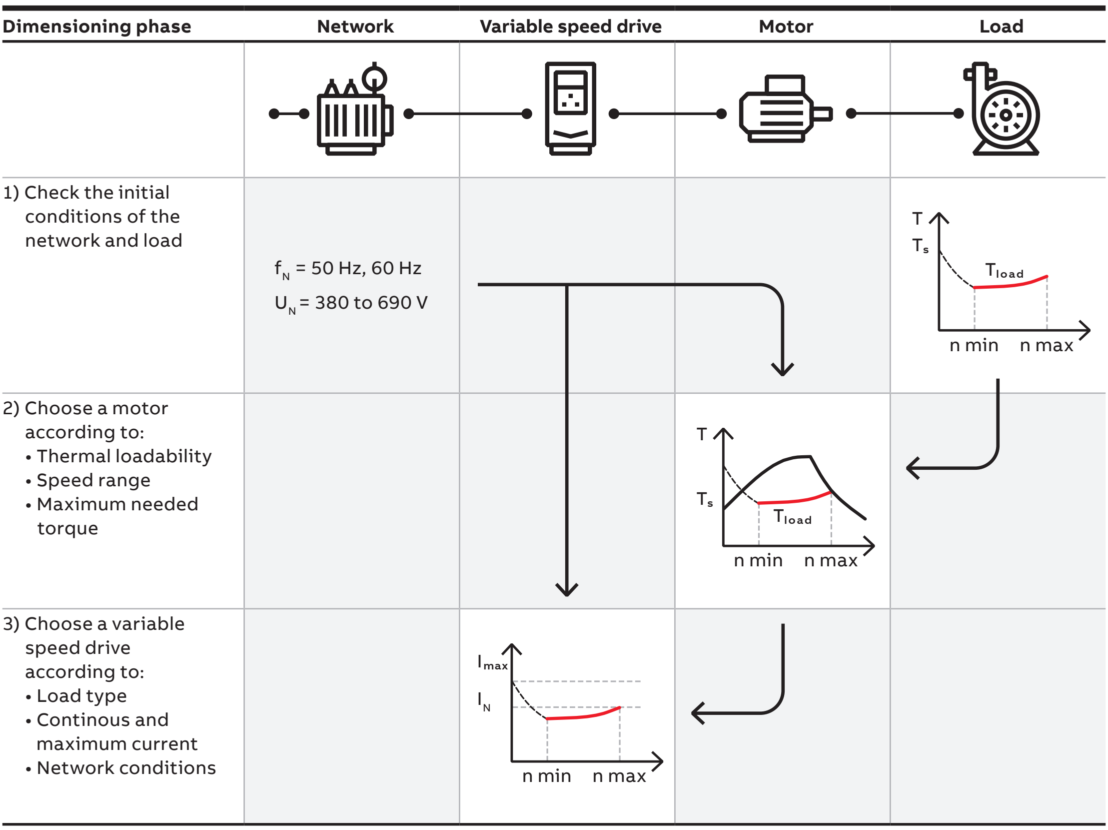

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Figure 2.1. General description of the dimensioning procedure.

Induction (AC) motor

Induction motors are widely used in industry. In this chapter some of the basic features are described.

Fundamentals

An induction motor converts electrical energy into mechanical energy. Converting the energy is based on electromagnetic induction. Because of the induction phenomenon the induction motor has a slip.

The slip is often defined at the motor's nominal point (frequency (f_n), speed (n_n), torque (T_n), voltage (U_n), current (I_n) and power (P_n)). At the nominal point the slip is nominal:

(3.1) $$s_n = \frac{n_s - n_n}{n_s} * 100\%$$

where n_s is the synchronous speed:

(3.2) $$n_s = \frac{2 * f_n * 60}{\text{pole number}}$$

When a motor is connected to a supply with constant voltage and frequency it has a torque curve as follows:

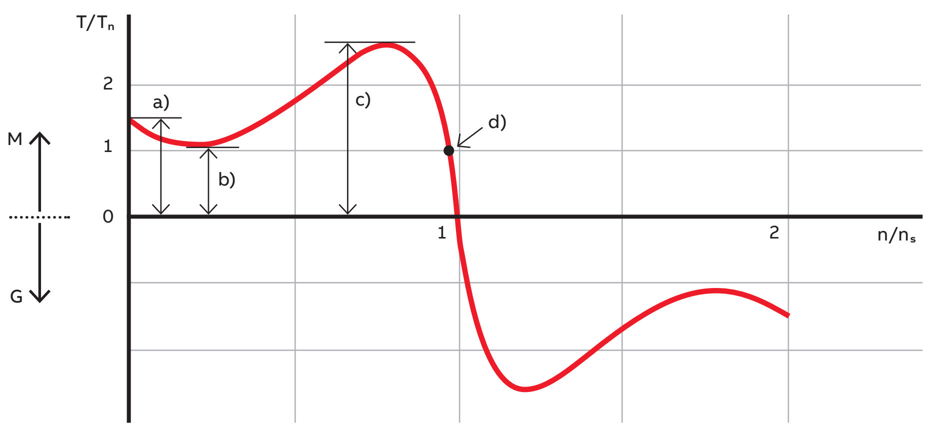

Figure 3.1. Typical torque/speed curve of an induction motor when connected to the network supply (D.O.L., Direct-On-Line). In the picture a) is the locked rotor torque, b) is the pull-up torque, c) is the maximum motor torque, T_{max} and d) is the nominal point of the motor.

A standard induction motor's maximum torque (T_{max}, also called pull-out torque and breakdown torque) is typically 2 to 3 times the nominal torque. The maximum torque is available with slip s_{max} which is greater than the nominal slip. In order to use an induction motor efficiently the motor slip should be in the range $-s_{max} \ldots s_{max}$. This can be achieved by controlling voltage and frequency. Controlling can be done with a variable speed drive.

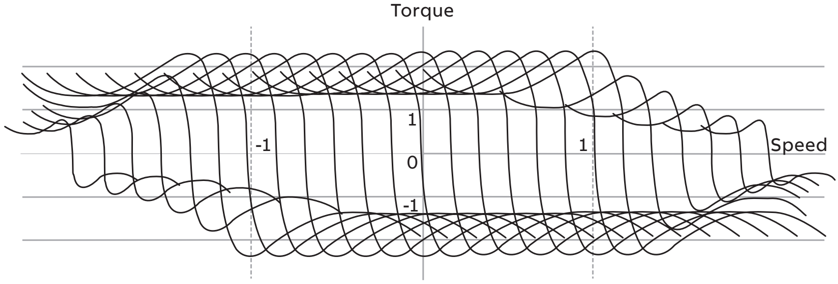

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Figure 3.2. Torque/speed curves of an induction motor fed by a variable speed drive. T_{max} is available for short term overloads below the field weakening point. Drives however, typically limit the maximum available torque to 70% of T_{max}.

The frequency range below the nominal frequency is called a constant flux range. Above the nominal frequency/speed the motor operates in the field weakening range. In the field weakening range the motor can operate on constant power which is why the field weakening range is sometimes also called the constant power range.

The maximum torque of an induction motor is proportional to the square of the magnetic flux ($T_{max} \sim \psi^2$). This means that the maximum torque is approximately a constant at the constant flux range. Above the field weakening point the maximum torque decrease is inversely proportional to the square of the frequency.

$$T_{max} \sim \left(\frac{f_n}{f_{act}} \right)^2$$

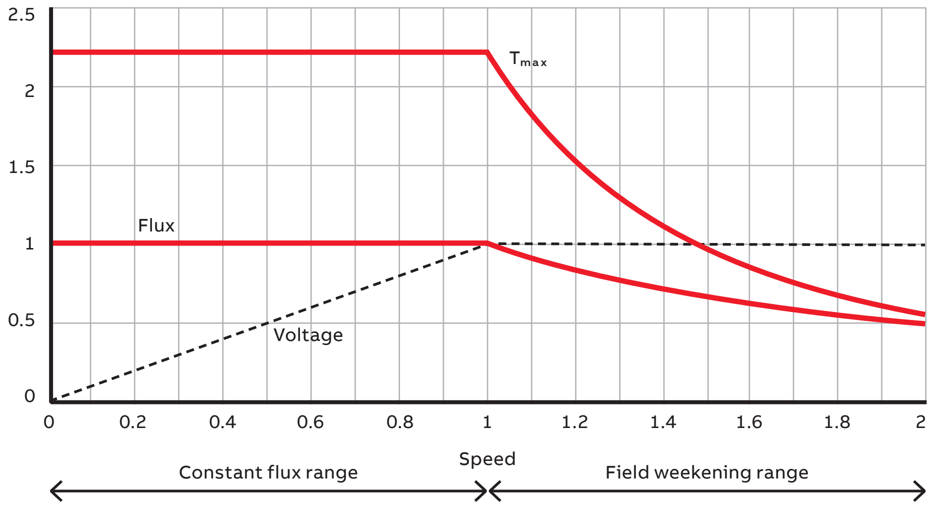

Figure 3.3. Maximum torque, voltage and flux as a function of the relative speed.

Motor current

An induction motor current has two components: reactive current (i_{sd}) and active current (i_{sq}). The reactive current component includes the magnetizing current (i_{magn}) whereas the active current is the torque producing current component. The reactive and active current components are perpendicular to each other.

The magnetizing current (i_{magn}) remains approximately constant in the constant flux range (below the field weakening point). In the field weakening range the magnetizing current decrease is proportional to speed.

A quite good estimate for the magnetizing current in the constant flux range is the reactive (i_{sd}) current at the motor nominal point.

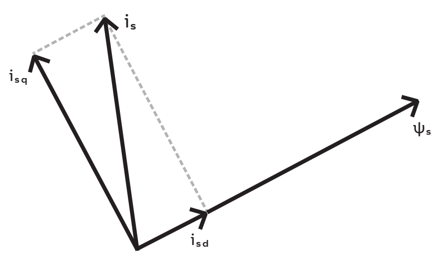

Figure 3.4. Stator current (i_s) consists of reactive current (i_{sd}) and active current (i_{sq}) components which are perpendicular to each other. Stator flux is denoted as ψ_s.

Constant flux range

Below the field weakening point the current components can be approximated as follows:

(3.3) $$I_{sd} = I_n \left(\sin(\varphi_n) + \cos(\varphi_n) \left[\sqrt{\left(\frac{T_{max}}{T_n}\right)^2 - 1} - \sqrt{\left(\frac{T_{max}}{T_n}\right)^2 - \left(\frac{T_{load}}{T_n}\right)^2} \right] \right)$$

(3.4) $$I_{sq} = I_n \left(\frac{T_{load}}{T_n} \right) \cos(\varphi_n)$$

The total motor current is:

(3.5) $$i_m = \sqrt{i_{sd}^2 + i_{sq}^2}$$

It can be seen that with zero motor torque the active current component is zero. With higher torque values motor current becomes quite proportional to the torque. A good approximation for total motor current is:

(3.6) $$i_m = \frac{T_{load}}{T_n} * I_n \text{, when } 0.8 * T_n \leq T_{load} \leq 0.7 * T_{max}$$

Example 3.1:
A 15 kW motor's nominal current is 32 A and power factor is 0.83. What is the motor's approximate magnetizing current at the nominal point? What is the total approximate current with 120% torque below the field weakening point.

Solution 3.1:
At the nominal point the estimate for the magnetizing current is:

$$I_{sd} = I_n \operatorname{Sin}(\varphi_n) = 32 * \sqrt{1 - 0.83^2} \text{ A} = 17.8 \text{ A}$$

The approximate formula for total motor current with 120% torque gives:

$$i_m = \frac{T_{load}}{T_n} * I_n = 1.2 * 32 \text{ A} = 38.4 \text{ A}$$

The approximate formula was used because torque fulfilled the condition
$0.8 * T_n \leq T_{load} \leq 0.7 * T_{max}$

Field weakening range

Above the field weakening point the current components also depend on speed.

(3.7)

$$I_{sd} = I_n \left(\frac{n_n}{n} \left(\sin(\varphi_n) + \cos(\varphi_n) \sqrt{\left(\frac{T_{max}}{T_n} \right)^2 - 1} \right) - \cos(\varphi_n) \sqrt{\left(\frac{T_{max}}{T_n} * \frac{n_n}{n} \right)^2 - \left(\frac{T_{load}}{T_n} * \frac{n}{n_n} \right)^2} \right)$$

(3.8) $$I_{sq} = I_n \left(\frac{T_{load}}{T_n} * \frac{n}{n_n} \right) \cos(\varphi_n) = I_n \left(\frac{P_{load}}{P_n} \right) \cos(\varphi_n)$$

Total motor current is:

(3.9) $$i_m = \sqrt{i_{sd}^2 + i_{sq}^2}$$

The motor current can be approximated quite accurately within a certain operating region. The motor current becomes proportional to relative power. An approximation formula for current is:

(3.10) $$i_m = \frac{T_{load}}{T_n} * \frac{n}{n_n} I_n = \frac{P_{load}}{P_n} I_n$$

Approximation can be used when:

(3.11) $$0.8 * \frac{n_n}{n} * T_n \leq T_{load} \leq 0.7 * \left(\frac{n_n}{n} \right)^2 * T_{max}$$

and

(3.12) $$0.8 * P_n \leq P_{load} \leq 0.7 * \frac{n_n}{n} * P_{max}$$

In the field weakening range the additional current needed in order to maintain a certain torque level is proportional to relative speed.

Example 3.2:
The motor's nominal current is 71 A. How much current is needed to maintain the 100% torque level at 1.2 times nominal speed ($T_{max} = 3 * T_n$).

Solution 3.2:
The current can be calculated by using the approximation formula:

$$i_m = \frac{T_{load}}{T_n} * \frac{n}{n_n} I_n = 1 * 1.2 * 71 = 85.2 \text{ A}$$

Motor power

The motor’s mechanical (output) power can be calculated from speed and torque using the formula:

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

Because motor power is most often given in kilowatts (1 kW = 1000 W) and speed in rpm revolutions per minute,

1 rpm = $\frac{2\pi}{60}$ rad/s, the following formula can be used:

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

The motor’s input power can be calculated from the voltage, current and power factor:

(3.15) $$P_{in} = \sqrt{3} * U * I * \cos(\varphi)$$

The motor’s efficiency is the output power divided by the input power:

(3.16) $$\eta = \frac{P_{out}}{P_{in}}$$

Example 3.3:
The motor nominal power is 15 kW and the nominal speed is 1480 rpm. What is the nominal torque of the motor?

Solution 3.3:
The motor’s nominal torque is calculated as follows:

$$T_n = \frac{9550 * 15}{1480}\,Nm = 96.8\,Nm$$

Example 3.4:
What is the nominal efficiency of a 37 kW (P_n = 37 kW, U_n = 380 V, I_n = 71 A and $\cos(\varphi_n)$ = 0.85) motor?

Solution 3.4:
The nominal efficiency is:

$$\eta_n = \frac{P_{out}}{P_{in}} = \frac{P_n}{\sqrt{3} * U_n * I_n * \cos(\varphi_n)} = \frac{37000}{\sqrt{3} * 380 * 71 * 0.85} \approx 0.931$$

Basic mechanical laws

Rotational motion

One of the basic equations of an induction motor describes the relation between moment of inertia (J [kgm²]), angular velocity (ω [rad/s]) and torque (T [Nm]). The equation is as follows:

(4.1) $$\frac{d}{dt}(J\,\omega) = J\frac{d\,\omega}{dt} + \omega\frac{dJ}{dt} = T - T_{load}$$

In the above equation it is assumed that both the frequency and the moment of inertia change. The formula is however often given so that the moment of inertia is assumed to be constant:

(4.2) $$J\frac{d\,\omega}{dt} = T - T_{load}$$

Torque T_{load} represents the load of the motor. The load consists of friction, inertia and the load itself. When the motor speed changes, motor torque is different from T_{load}. Motor torque can be considered as consisting of a dynamic and a load component:

(4.3) $$T = T_{dyn} + T_{load}$$

If the speed and moment of inertia are constants the dynamic component (T_{dyn}) is zero.

The dynamic torque component caused by acceleration/deceleration of a constant moment of inertia (motor's speed is changed by Δn [rpm] in time Δt [s], J is constant) is:

(5.4) $$T_{dyn,n} = J * \frac{2\,\pi}{60} * \frac{\Delta n}{\Delta t}$$

The dynamic torque component caused by a variable moment of inertia at constant speed n[rpm] is:

(4.5) $$T_{dyn,J} = n * \frac{2\,\pi}{60} * \frac{\Delta J}{\Delta t}$$

If the moment of inertia varies and at the same time the motor is accelerating the dynamic torque component can be calculated using a certain discrete sampling interval. From the thermal dimensioning point of view it is however often enough to take into account the average moment of inertia during acceleration.

Example 4.1:
The total moment of inertia, 3 kgm², is accelerated from a speed of 500 rpm to 1000 rpm in 10 seconds. What is the total torque needed when the constant load torque is 50 Nm?

How fast will the motor decelerate to 0 rpm speed if the motor's electric supply is switched off?

Solution 4.1:
The total moment of inertia is constant. The dynamic torque component needed for acceleration is:

$$T_{dyn} = 3 * \frac{2\ \pi}{60} * \frac{1000 - 500}{10}\ \text{Nm} = 15.7\ \text{Nm}$$

Total torque during acceleration is:

$$T = T_{dyn} + T_{load} = (15.7 + 50)\ \text{Nm} = 65.7\ \text{Nm}$$

If the motor's electric supply is switched off at 1000 rpm the motor decelerates because of the constant load torque (50 Nm). Following equation holds:

$$3 * \frac{2\ \pi}{60} * \frac{0 - 1000}{\Delta t} = - T_{load}$$

Time to decelerate from 1000 rpm to 0 rpm:

$$\Delta t = 3 * \frac{2\ \pi}{60} * \frac{1000}{50}\ \text{s} = 6.28\ \text{s}$$

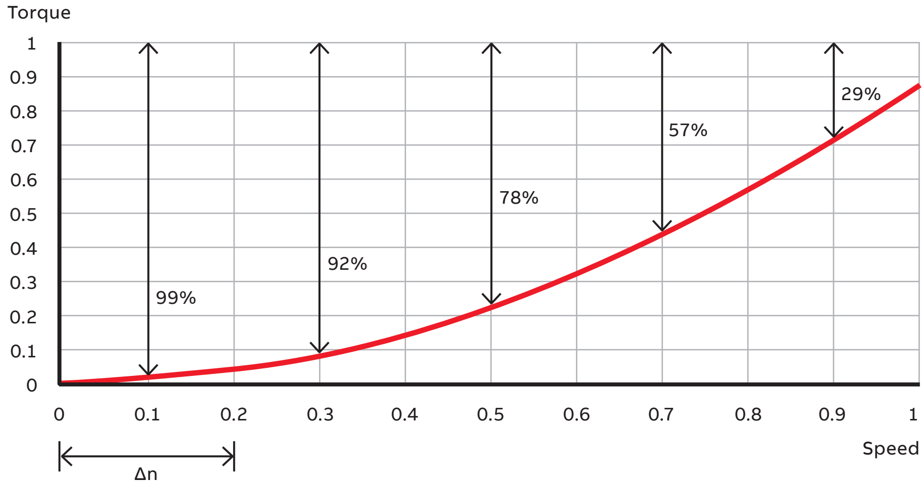

Figure 4.1. Torque characteristics of a fan. Speed and torque are shown using relative values.

Example 4.2:
Accelerating of a fan to nominal speed is done with nominal torque. At nominal speed torque is 87%. The fan's moment of inertia is 1200 kgm² and the motor's moment of inertia is 11 kgm². The load characteristics of the fan T_{load} is shown in figure 4.1.

Motor nominal power is 200 kW and nominal speed is 991 rpm.

Calculate approximate starting time from zero speed to nominal speed.

Solution 4.2:
Motor nominal torque is:

$$T_n = \frac{9550 * 200}{991} \text{ Nm} = 1927 \text{ Nm}$$

The starting time is calculated by dividing the speed range into five sectors. In each sector (198.2 rpm) torque is assumed to be constant. Torque for each sector is taken from the middle point of the sector. This is quite acceptable because the quadratic behaviour is approximated to be linear in the sector.

The time to accelerate the motor (fan) with nominal torque can be calculated with formula:

$$\Delta t = \frac{2\ \pi}{60} * \frac{J_{tot} * \Delta n}{T_n - T_{load}}$$

Acceleration times for different speed sections are:

0 to 198.2 rpm $$\Delta t = \frac{2\,\pi}{60} * \frac{1211 * 198.2}{0.99 * 1927}\,\mathrm{s} = 13.2\ \mathrm{s}$$

198.2 to 396.4 rpm $$\Delta t = \frac{2\,\pi}{60} * \frac{1211 * 198.2}{0.92 * 1927}\,\mathrm{s} = 14.3\ \mathrm{s}$$

396.4 to 594.6 rpm $$\Delta t = \frac{2\,\pi}{60} * \frac{1211 * 198.2}{0.78 * 1927}\,\mathrm{s} = 16.7\ \mathrm{s}$$

594.6 to 792.8 rpm $$\Delta t = \frac{2\,\pi}{60} * \frac{1211 * 198.2}{0.57 * 1927}\,\mathrm{s} = 22.9\ \mathrm{s}$$

792.8 to 991 rpm $$\Delta t = \frac{2\,\pi}{60} * \frac{1211 * 198.2}{0.29 * 1927}\,\mathrm{s} = 45.0\ \mathrm{s}$$

The total starting time from 0 to 991 rpm is approximately 112 seconds.

Gears and moment of inertia

Gears are typical in drive systems. When calculating the motor torque and speed range gears have to be taken into account. Gears are reduced from load side to motor side with following equations (see also figure 4.2):

(4.6) $$T_1 = \frac{T_2}{\eta} * \left(\frac{n_2}{n_1}\right)$$

(4.7) $$J_1 = J_2 * \left(\frac{n_2}{n_1}\right)^2$$

(4.8) $$P_1 = \frac{P_2}{\eta}$$

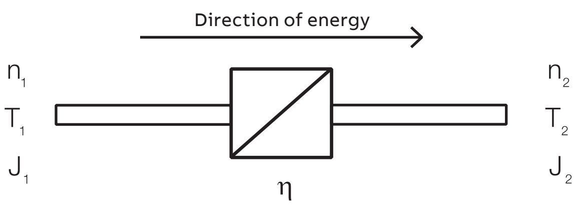

Figure 4.2. A gear with efficiency η. Gear ratio is $n_1 : n_2$.

Also all the moments of inertia (J [kgm^2]) within the system have to be known. If they are not known they can be calculated which is rather difficult to do accurately. Typically machine builders can give the necessary data.

Example 4.3:
A cylinder is quite a common shape for a load (rollers, drums, couplings, etc.). What is the inertia of a rotating cylinder (mass = 1600 kg, radius = 0.7 m)?

Solution 4.3:
The inertia of a rotating cylinder (with mass m [kg] and radius r [m]) is calculated as follows:

$$J = \frac{1}{2} mr^2 = \frac{1}{2} * 1600 * 0.7^2 \ kgm^2 = 392 \ kgm^2$$

In the case of a gear, the moment of inertia to the motor shaft has to be reduced. The following example shows how to reduce gears and hoists. In basic engineering books other formulas are also given.

Example 4.4:
Reduce the moment of inertia to the motor shaft of the following hoist drive system.

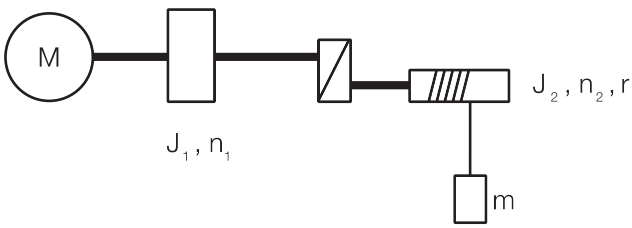

Figure 4.3. A Hoist drive system used in example 4.4.

The total moment of inertia consists of J_1 = 10 kgm^2,
J_2 = 30 kgm^2, r = 0.2 m and m = 100 kg.
The moment of inertia J_2 and mass m are behind a gearbox with gear ratio $n_1 : n_2$ = 2:1.

Solution 4.4:
The moment of inertia J_2 is reduced by multiplying with the square of the inverse of the gear ratio. The mass m of the hoist is reduced by multiplying it with square of the radius r and because it is behind the gearbox it has to be multiplied with the square of the inverse of the gear ratio, too.

Thus the total moment of inertia of the system is:

$$J_{red} = J_1 + \left(\frac{n_2}{n_1}\right)^2 [J_2 + mr^2] = 18.5 \ kgm^2$$

Load types

Certain load types are characteristic in the industrial world. Knowing the load profile (speed range, torque and power) is essential when selecting a suitable motor and variable speed drive for the application.

Some common load types are shown. There may also be combinations of these types.

1. Constant torque
   A constant torque load type is typical when fixed volumes are being handled. For example screw compressors, feeders and conveyors are typical constant torque applications. Torque is constant and the power is linearly proportional to the speed.

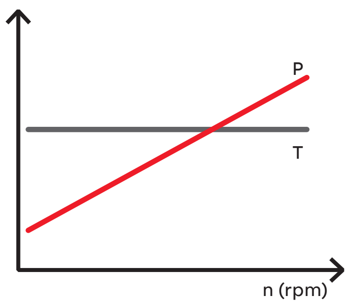

Figure 5.1. Typical torque and power curves in a constant torque application.

2. Quadratic torque
   Quadratic torque is the most common load type. Typical applications are centrifugal pumps and fans. The torque is quadratically, and the power is cubically proportional to the speed.

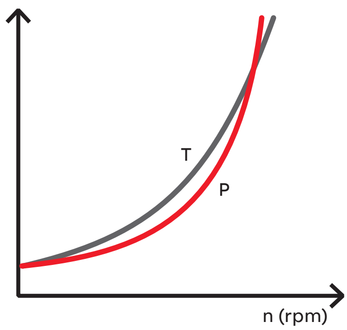

Figure 5.2. Typical torque and power curves in a quadratic torque application.

3. Constant power

A constant power load is normal when material is being rolled and the diameter changes during rolling. The power is constant and the torque is inversely proportional to the speed.

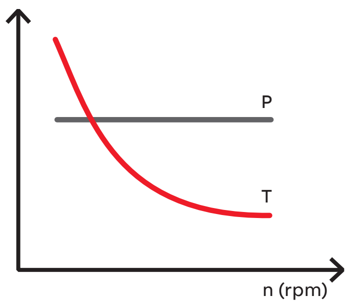

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Figure 5.3. Typical torque and power curves in a constant power application.

4. Constant power/ torque

This load type is common in the paper industry. It is a combination of constant power and constant torque load types. This load type is often a consequence of dimensioning the system according to the need for certain power at high speed.

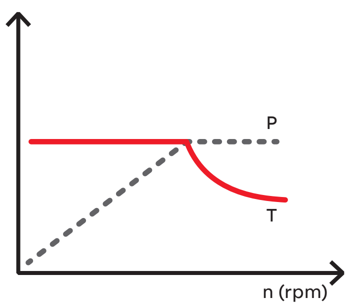

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Figure 5.4. Typical torque and power curves in a constant power/torque application.

5. Starting/breakaway torque demand
In some applications high torque at low frequencies is needed. This has to be considered in dimensioning. Typical applications for this load type are for example extruders and screw pumps.

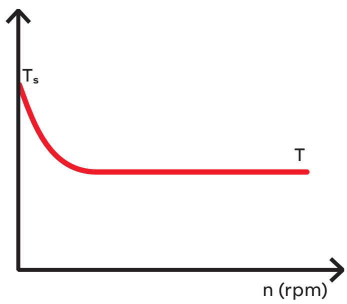

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Figure 5.5 Typical torque curve in an application where high starting torque is needed.

There are also several other load types. They are however hard to describe in a general presentation. Just to mention a few, there are different symmetrical (rollers, cranes, etc.) and unsymmetrical loads. Symmetry/non-symmetry in torque can be for example as a function of angle or time. These kinds of load types must be dimensioned carefully taking into account the overloadability margins of the motor and variable speed drive, as well as the average torque of the motor.

Motor loadability

Motor thermal loadability has to be considered when dimensioning a drive system. The thermal loadability defines the maximum long term loadability of the motor.

A standard induction motor is self ventilated. Because of the self ventilation the motor thermal loadability decreases as the motor speed decreases. This kind of behaviour limits the continuous available torque at low speeds.

A motor with a separate cooling can also be loaded at low speeds. Cooling is often dimensioned so that the cooling effect is the same as at the nominal point.

With both self and separate cooling methods torque is thermally limited in the field weakening range.

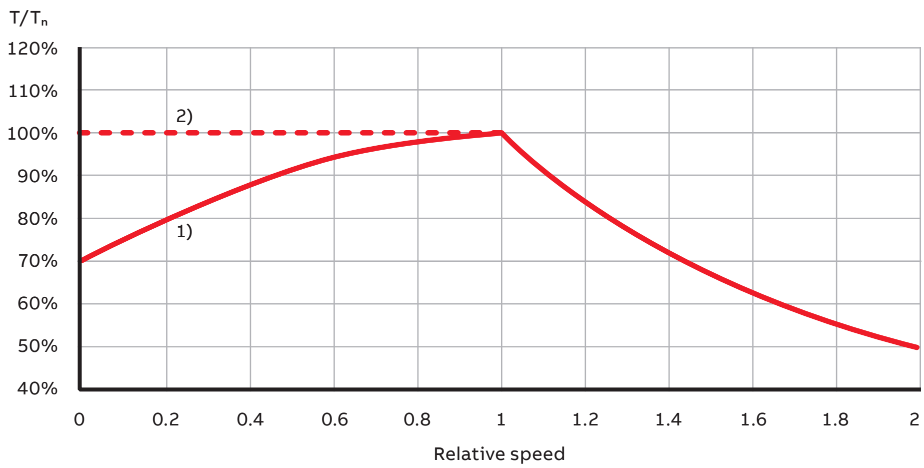

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Figure 6.1. A standard cage induction motor's typical loadability in a frequency controlled drive 1) without separate cooling and 2) with separate cooling.

An AC motor can be overloaded for short periods of time without overheating it. Short term overloads are mainly limited by T_{max} (check the safety margin).

Generally speaking, a variable speed drive's short term loadability is often more critical than the motor's. The motor thermal rise times are typically from 15 minutes (small motors) to several hours (big motors) depending on the motor size. The drive's thermal rise times (typically few minutes) are given in the product manuals.

Selecting the variable speed drive and motor

The motor is selected according to the basic information about the process. Speed range, torque curves, ventilation method and motor loadability give guidelines for motor selection. Often it is worth comparing different motors because the selected motor affects the size of the variable speed drive.

When selecting a suitable drive there are several things to be considered. Drive manufacturers normally have certain selection tables where typical motor powers for each drive size are given.

The dimensioning current can also be calculated when the torque characteristics are known. The corresponding current values can be calculated from the torque profile and compared to drive current limits. The motor's nominal current gives some kind of indication. It isn't however always the best possible dimensioning criteria because motors might for example be derated (ambient temperature, hazardous area, etc.).

The available supply voltage must be checked before selecting the drive. Supply voltage variations affect the available motor shaft power.
If the supply voltage is lower than nominal the field weakening point shifts to a lower frequency and the available maximum torque of the motor is reduced in the field weakening range.

The maximum available torque is often limited by the drive. This has to be considered already in the motor selection phase. The drive may limit the motor torque earlier than stated in the motor manufacturer's data sheet.

The maximum available torque is also affected by transformers, reactors, cables, etc. in the system because they cause a voltage drop and thus the maximum available torque may drop. The system's power losses need to be compensated also by the drive rating.

Pump and fan application (Example)

Some stages in pump and fan application dimensioning:

- Check the speed range and calculate power with highest speed.
- Check the starting torque need.
- Choose the pole number of the motor. The most economic operating frequency is often in the field weakening range.
- Choose motor power so that power is available at maximum speed. Remember the thermal loadability.
- Choose the variable speed drive. Use pump and fan rating. If the pump and fan rating is not available choose the drive according to the motor current profile.

Example 7.1:
A pump has a 150 kW load at a speed of 2000 rpm. There is no need for starting torque.

Solution 7.1:
The necessary torque at 2000 rpm is: $T = \frac{9550 * 150}{2000} \text{ Nm} = 716 \text{ Nm}$

It seems that 2-pole or 4-pole motors are alternative choices for this application.

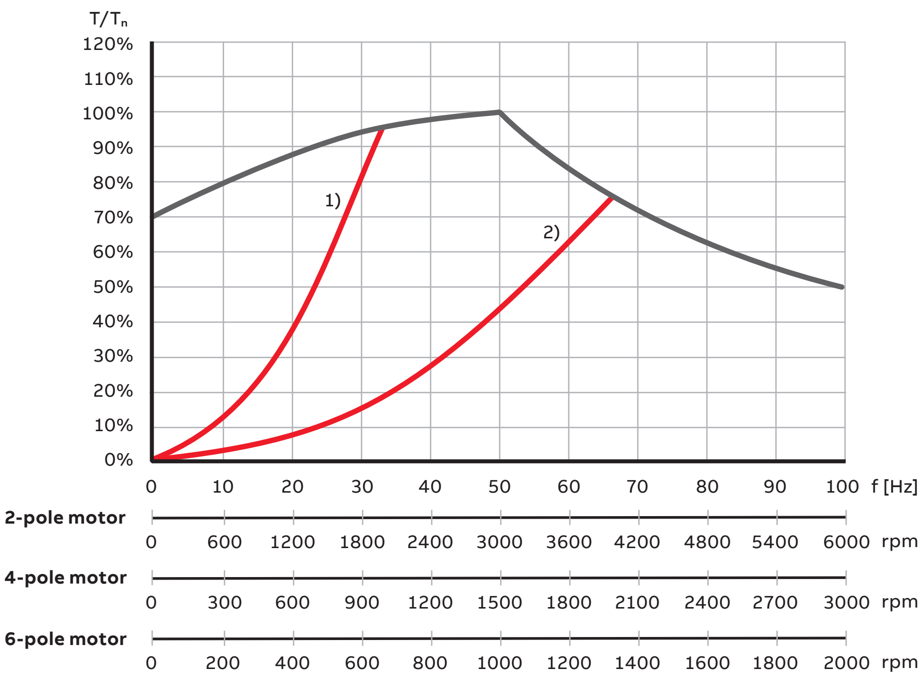

Figure 7.1 Motor loadability curves in a pump and fan application. Comparison of 1) 2-pole and 2) 4-pole motors.

1) Motor p = 2
For a 2-pole motor the loadability at 2000 rpm according to the loadability curve is about 95%. The motor nominal torque must be at least:

$$T_n \geq \frac{716}{0.95}\,\text{Nm} = 754\text{ Nm}$$

At 50 Hz the synchronous speed of a 2-pole motor is 3000 rpm. The corresponding nominal power must then be at least:

$$P_n \geq \frac{754 * 3000}{9550}\,\text{kW} = 237\text{ kW}$$

A 250 kW (400 V, 431 A, 50 Hz, 2975 rpm and 0.87) motor is selected.
The nominal torque of the motor is:

$$T_n = \frac{250 * 9550}{2975}\,\text{Nm} = 803\text{ Nm}$$

The motor current at 2000 rpm speed (constant flux range) is approximately:

$$i_m = \frac{T_{load}}{T_n} * I_n = \frac{716}{803} * 431\text{ A} = 384\text{ A}$$

2) Motor p = 4
For a 4-pole motor the loadability at 2000 rpm is 75%.
The minimum nominal torque of the motor is:

$$T_n \geq \frac{716\text{ Nm}}{0.75} = 955\text{ Nm}$$

At 50 Hz the synchronous speed of a 4-pole motor is 1500 rpm. The minimum power for a 4-pole motor is:

$$P_n \geq \frac{955 * 1500}{9550}\,\text{kW} = 150\text{ kW}$$

A 160 kW motor (400 V, 305 A, 50 Hz, 1480 rpm and 0.81) fulfills the conditions.
The approximated current at a speed of 2000 rpm (66.7 Hz) is:

$$i_m = \frac{T_{load}}{T_n} * \frac{n}{n_n}\, I_n = \frac{P_{load}}{P_n} * I_n = \frac{150}{160} * 305\text{ A} = 286\text{ A}$$

The exact current should be calculated if the selected drive's nominal current is close to the approximated motor current.

A 4-pole motor requires less current at the pump operation point. Thus it is probably a more economical choice than a 2-pole motor.

Constant torque application (Example)

Some stages in dimensioning of a constant torque application:
- Check the speed range.
- Check the constant torque needed.
- Check the possible accelerations. If accelerations are needed check the moments of inertia.
- Check the possible starting torque required.
- Choose the motor so that torque is below the thermal loadability curve (separate/self ventilation?). Typically the nominal speed of the motor is in the middle of the speed range used.
- Choose a suitable variable speed drive according to the dimensioning current.

Example 7.2:
An extruder has a speed range of 300 to 1200 rpm. The load at 1200 rpm is 48 KW. The starting torque requirement is 200 Nm. Acceleration time from zero speed to 1200 rpm is 10 seconds.The motor is self-ventilated and the nominal voltage is 400 V.

Solution 7.2:
The constant torque requirement is:

$$T = \frac{9550 * 48}{1200} \text{Nm} = 382 \text{ Nm}$$

A suitable motor is a 4-pole or a 6-pole motor.

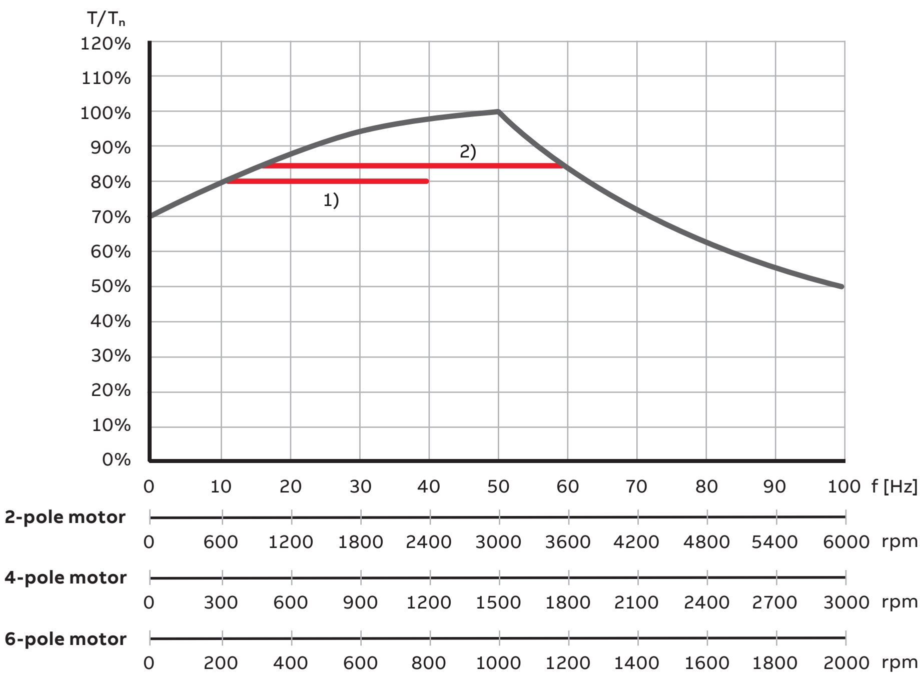

Figure 7.2. Motor loadability curves in a constant torque application. Comparison of 1) 4-pole and 2) 6-pole motors.

1) Motor p = 4
At 300 rpm speed the thermal loadability is 80%.
The estimated minimum nominal torque is:

$$T_n \geq \frac{382}{0.8} \text{ Nm} = 478 \text{ Nm}$$

The minimum motor nominal power is:

$$P_n \geq \frac{478 * 1500}{9550} \text{ kW} = 75 \text{ kW}$$

A suitable motor is for example a 75 kW (400 V, 146 A, 50 Hz, 1473 rpm and 0.82) motor. The motor nominal torque is:

$$T_n = \frac{75 * 9550}{1473} \text{ Nm} = 486 \text{ Nm}$$

Motor current is approximately ($T/T_n \approx 0.8$):

$$i_m = \frac{T_{load}}{T_n} * I_n = \frac{382}{486} * 146 \text{ A} = 115 \text{ A}$$

According to the calculated motor current a suitable drive can be selected for constant torque use. The starting torque requirement (200 Nm) is not a problem for this motor.

If the motor's moment of inertia is 0.72 kgm² the dynamic torque in acceleration is:

$$T_{dyn} = \frac{2\pi}{60} * \frac{1200}{10} * 0.72 \text{ Nm} = 9 \text{ Nm}$$

Thus the total torque during acceleration is 391 Nm (= 9 Nm + 382 Nm) which is less than the nominal torque of the motor.

2) Motor p = 6
At speeds of 300 rpm and 1200 rpm the motor loadability is 84%.
Thus the minimum nominal torque of the 6-pole motor is:

$$T_n \geq \frac{382 \text{ Nm}}{0.84} = 455 \text{ Nm}$$

The minimum value of the motor nominal power is:

$$P_n \geq \frac{455 * 1000}{9550} \text{ kW} = 48 \text{ kW}$$

A suitable motor could be for example a 55 kW (400 V, 110 A, 50 Hz, 984 rpm and 0.82) motor. The motor nominal torque is:

$$T_n = \frac{55 * 9550}{984} \text{ Nm} = 534 \text{ Nm}$$

The dimensioning current can be approximated at a speed of 1200 rpm:

$$i_m = \frac{T_{load}}{T_n} * \frac{n}{n_n} I_n = \frac{P_{load}}{P_n} * I_n = \frac{48}{55} * 110 \text{ A} = 96 \text{ A}$$

The nominal (continuous) current of the drive must be over 96 A.

The starting torque requirement is less than motor's nominal torque.

If the inertia of the motor is 1.2 kgm² the dynamic torque in acceleration is:

$$T_{dyn} = \frac{2\pi}{60} * \frac{1200}{10} * 1.2 \text{ Nm} = 15 \text{ Nm}$$

The total torque needed during acceleration is 397 Nm (= 15 Nm + 382 Nm) which is less than the nominal torque of the motor.

A 6-pole motor current is 19 A smaller than with a 4-pole motor.
The final drive/motor selection depends on the motor and drive frame sizes and prices.

Constant power application (Example)

Some stages in dimensioning of a constant power application:
- Check the speed range
- Calculate the power needed. Winders are typical constant power applications.
- Dimension the motor so that the field weakening range is utilized

Example 7.3:
A wire drawing machine is controlled by a variable speed drive. The surface speed of the reel is 12 m/s and the tension is 5700 N. The diameters of the reel are 630 mm (empty reel) and 1250 (full reel). There is a gear with gear ratio $n_2 : n_1 = 1 : 7.12$ and the efficiency of the gear is 0.98.

Select a suitable motor and drive for this application.

Solution 7.3:
The basic idea of a winder is to keep the surface speed and the tension constant as the diameter changes.

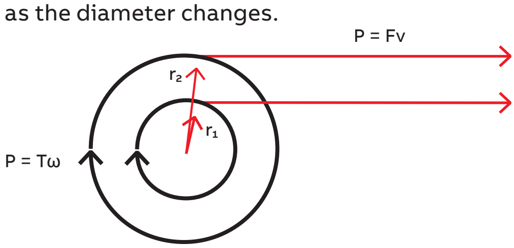

Figure 7.3. Basic diagram of a winder.

In rectilinear motion the power is: P = Fv
In rotational motion the power is: P = Tω

The relation between surface speed and angular velocity is:

$$v\,[m/s] = \omega * r = \frac{2\pi * n\,[rpm] * r}{60} \Leftrightarrow n\,[rpm] = \frac{60 * v}{2\pi * r}$$

Torque is a product of force and radius: T = Fr

By using the above formulas the motor can be selected:

$$P = 5700\ N * 12\ m/s = 68.4\ kW$$

$$T_1 = 5700\ N * \frac{0.63}{2}\ m = 1796\ Nm$$

$$n_1 = \frac{12 * 60}{\pi * 0.63}\ rpm = 363.8\ rpm$$

$$T_2 = 5700\ N * \frac{1.25}{2}\ m = 3563\ Nm$$

$$n_2 = \frac{12 * 60}{\pi * 1.25}\ rpm = 183.3\ rpm$$

The gear must be taken into account before choosing the motor.
Speeds, torques and power have to be reduced:

$$P = \frac{P}{\eta_{gear}} = \frac{68.4}{0.98}\ \text{kW} = 69.8\ \text{kW}$$

$$T_1 = \frac{1796}{0.98} * \frac{1}{7.12}\ \text{Nm} = 275\ \text{Nm}$$

$$n_1 = 363.8 * 7.12\ \text{rpm} = 2590\ \text{rpm}$$

$$T_2 = \frac{3563}{0.98} * \frac{1}{7.12}\ \text{Nm} = 511\ \text{Nm}$$

$$n_2 = 183.3 * 7.12\ \text{rpm} = 1305\ \text{rpm}$$

1) Motor p = 2

If a 2-pole motor is selected loadability at a speed of 1305 rpm is about 88% and 97% at 2590 rpm. The minimum nominal power of the motor is:

$$P_n \geq \frac{511 * 3000}{0.88 * 9550}\ \text{kW} = 182\ \text{kW}$$

A 200 kW (400 V, 353 A, 50 Hz, 2975 rpm and 0.86) motor is selected.
The motor nominal torque is:

$$T_n = \frac{200 * 9550}{2975}\ \text{Nm} = 642\ \text{Nm}$$

The dimensioning current is calculated according to a torque of 511 Nm:

$$i_m = \frac{T_{load}}{T_n} * I_n = \frac{511}{642} * 353\ \text{A} = 281\ \text{A}$$

2) Motor p = 4

If a 4-pole motor is selected it can be seen from the loadability curve that loadability at a speed of 1305 rpm is about 98% and about 60% at 2590 rpm. The minimum nominal power of the motor is:

$$P_n \geq \frac{511 * 1500}{0.98 * 9550} \text{ kW} = 82 \text{ kW}$$

A 90 kW (400 V, 172 A, 50 Hz, 1473 rpm and 0.83) is selected.
The motor nominal torque is:

$$T_n = \frac{90 * 9550}{1473} \text{ Nm} = 584 \text{ Nm}$$

Dimensioning in this case is done according to the motor current at 1305 rpm. The motor current is:

$$i_m = \frac{T}{T_n} I_n = \frac{511}{584} * 172 \text{ A} = 151 \text{ A}$$

With a 2-pole motor the field weakening (constant power) range was not utilized which led to unnecessary overdimensioning. A 4-pole motor is a better choice for this application.

Input transformer and rectifier

There are several types of input rectifiers. The rectifier type might limit the operation.

A conventional rectifier is a 6- or 12-pulse diode rectifier. Diode rectifiers only support motoring loads where the power flow is one way only.

In certain processes where the load can also be generating, the energy needs to be absorbed. For short generating loads the traditional solution has been a braking resistor where the power generated has been transformed into heat losses.
If however the load is generating all the time, a true 4-quadrant rectifier is needed.

Both the input transformer and the rectifier are dimensioned according to the motor shaft power and system losses. For example if high torque at low speed is delivered the mechanical power is nevertheless quite low. Thus high overloads do not necessarily mean high power from the rectifier point of view.

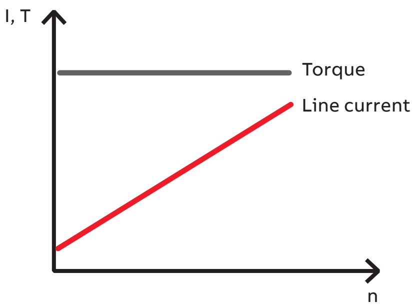

Figure 8.1. Line current in a constant torque application. Line current is small at low speed.

Rectifiers

Rectifiers are dimensioned according to motor shaft power. A single drive's input rectifier can be selected using the approximation formula:

(8.1) $$S_{rectifier} = \frac{P_{motor}}{0.9}$$

In drive systems where there is a common DC-link, there can be motoring and generating power at the same time. Rectifier power is then calculated approximately as follows:

(8.2) $$S_{rectifier} = \frac{\Sigma\, P_{motoring}}{0.9} - 0.9\,\Sigma\, P_{generating}$$

Transformer

An input transformer's power can be calculated as follows:

$$S_{transformer} = P_{total} * \frac{1.05}{k} * \frac{1}{\eta_r} * \frac{1}{\cos(\alpha)} * \frac{1}{\eta_c} * \frac{1}{\eta_i} * \frac{1}{\eta_m} \tag{8.3}$$

In the above formulas:

P_{total} is the total motor shaft power

k is the transformer loadability (k-factor)

1.05 stands for transformer voltage drop (impedance)

η_r is the rectifier efficiency

cos(α) is the rectifier control angle (= 1.0 for diode rectifier)

η_c is the AC choke (if there is one) efficiency

η_i is the inverter efficiency

η_m is the motor efficiency

Typically total shaft power is multiplied by a coefficient 1.2...1.35.

Example 8.1:
In a constant torque application the maximum shaft power needed is 48 kW at a speed of 1200 rpm. A 55 kW motor and 70 kVA inverter unit was selected.

Specify the rectifier and input transformer. A 6-pulse diode supply is used (efficiency 0.985), there is a DC-choke in the DC-link, inverter efficiency is 0.97 and motor efficiency is 0.95.

Solution 8.1:
For the rectifier the estimated power is:

$$S_{rectifier} = \frac{48}{0.9} \text{ kVA} = 53.3 \text{ kVA}$$

The choke efficiency is included in the inverter efficiency. Because of diode supply unit cos(α) = 1. The power of the input transformer (k = 0.95) is:

$$S_{transformer} = 48 * \frac{1.05}{0.95} * \frac{1}{0.985} * \frac{1}{0.97} * \frac{1}{0.95} \text{kVA} = 58.4 \text{ kVA}$$

Notes

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