Application for Drive Technology

applications & TOOLS

MICROMASTER 4

Application Description

Engineering Information with Examples
for MICROMASTER 4

SIEMENS

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2.4 Information regarding trademarks

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2.5 Revisions/author

Version	**Date/change**	**Author**
1.0	06/02, First Edition	Fusetti
2.0	11/02, revised German Edition	Uhlig

3 Mode of operation

3.1 General information

AC drive inverters allow three-phase induction motors to be used for variable-speed applications. AC drive inverters are replacing previous solutions using DC motors. It is very simple to control (closed-loop) the speed and the torque of a DC motor. The DC motor has several disadvantages, e.g. it is not a Standard motor, it has a lower degree of protection, and has commutators and brushes which require a considerable amount of service/maintenance. The induction motor can compensate for the inherit design disadvantages of DC motors, however it is more complicated to control (closed-loop) the speed and torque.

The speed of an induction motor is approximately proportional to the frequency of the rotating field of the supply. Assuming that K stands for the mechanical design data of the motor, the following equation applies:

$$n \approx K * f$$

This means that the supply frequency must be changed in order to change the speed. It must be taken into consideration that the magnetic flux in the motor is proportional to the ratio between the voltage and frequency:

$$\varphi \approx \frac{V}{f}$$

In order to avoid saturation or an excessively low magnetization of the magnetic circuit, the flux in the motor should be kept constant. This means that it is necessary to simultaneously change the motor voltage and frequency.

The torque of an induction motor is also proportional to the magnetic flux.

$$M \approx K * \varphi$$

The motor torque directly depends on the flux in the motor and is determined by the motor voltage and motor frequency.

Today, variable-speed AC drives predominantly use AC drive inverters with voltage DC link. The AC drive inverter converts the rigid line supply voltage with fixed voltage and frequency into a three-phase system with variable voltage and frequency. The first step is to rectify the line supply voltage and then create a three-phase system with the required frequency and voltage from the rectified DC voltage. Today, various techniques are available to precisely control (closed-loop) the speed and the torque – for example, Vector control.

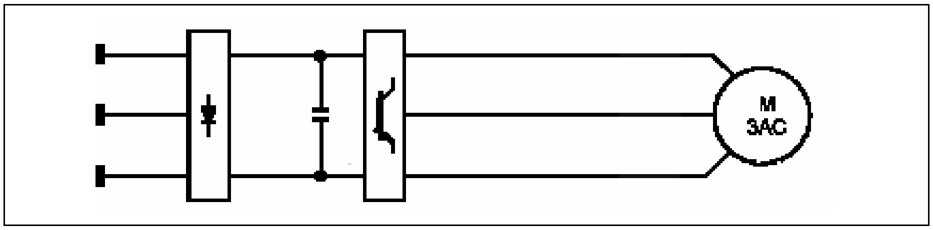

Fig. 3-1Basic circuit diagram of an AC drive inverter and motor

The following advantages are obtained when using variable-speed three-phase drives:

- Soft acceleration and braking
- Energy saving
- Operation with frequencies > 50Hz
- Additional functions in the AC drive inverter, for example: Motor protection, PID controller, logic functions
- Communications via a fieldbus
- And many more

3.2 Incoming and pre-charging circuit

The incoming circuit of an AC drive inverter comprises a rectifier, which converts the AC line supply voltage into the DC voltage of the DC link. Capacitors are connected in the DC link which have the following functions:

- To smooth the DC voltage which is rectified
- To provide the reactive power required by the motor
- To store energy which is released when commutating

The incoming rectifier, for small power ratings, is realized using either a one or three-phase uncontrolled diode bridge and a pre-charging circuit in front of the capacitors.

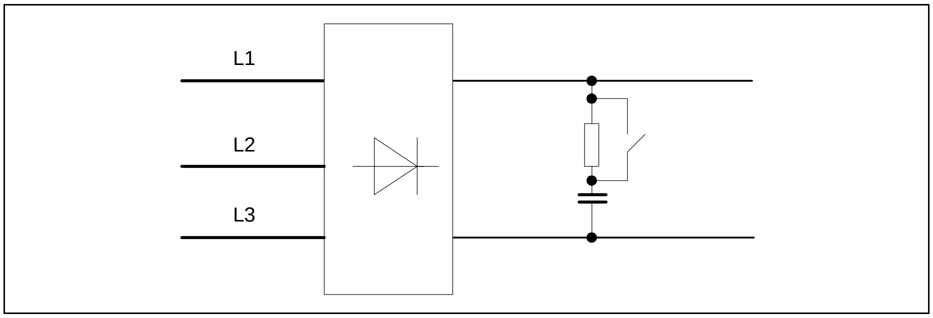

Fig. 3-2 **MICROMASTER 4 incoming circuit**

For MICROMASTER 4 drive units, the incoming circuit is configured corresponding to that shown Fig. 1-2. The pre-charging circuit comprises a limiting resistor, connected in series which limits the pre-charging current of the capacitor and which is bypassed after charging has been completed.

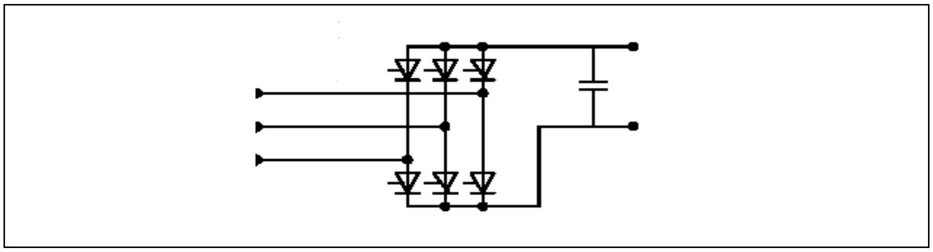

Fig. 3-3 **Thyristor incoming bridge**

For larger drive inverters $P_{inverter}$ > 600KW, generally thyristor bridges are used on the input side. The pre-charging for the capacitors is controlled by gradually increasing the firing angle of the thyristors. After pre-charging has been completed the thyristors remain turned-on.

3.3 Output circuit

The output circuit, comprising a three-phase transistor bridge, has the task of converting the DC link voltage of the DC link into a three-phase system with variable amplitude and frequency.

Earlier, various power electronic components were used, for example bipolar transistors, MOSFET, GTO etc. Today, the IGBT (Insulated Gate Bipolar Transistor) has clearly established itself. The IGBT has all of the advantages of a bipolar transistor, i.e. a high output current and a high pulse frequency. Further, it operates voltage-controlled and therefore only requires a low gating power which results in shorter clock times and a higher efficiency.

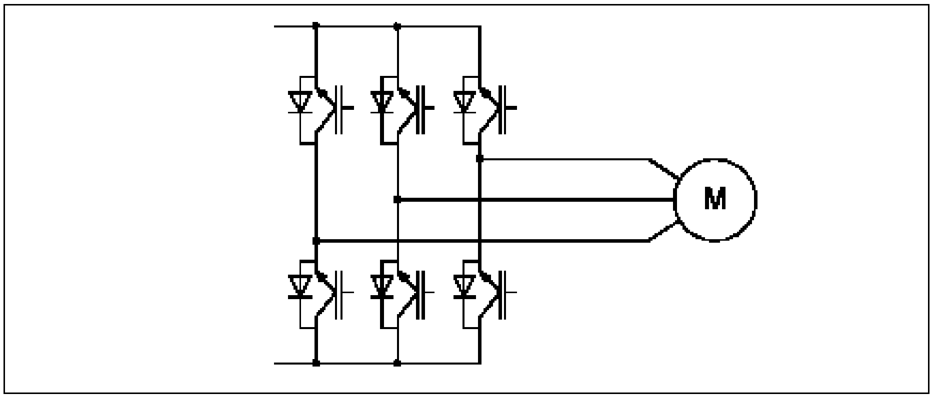

Fig. 3-4 **Output inverter**

The output transistors operate as switch, i.e. they change between conducting and blocking. In this way they connect the three phases of the motor alternating to the DC link thus generating a voltage vector with constant amplitude which rotates in space.

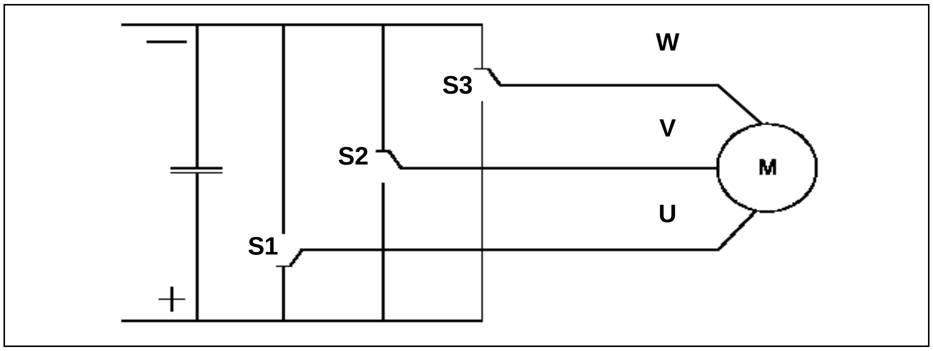

Fig. 3-5 **Generating a three-phase voltage using transistors S1..S3**

The winding connection U is connected to the positive arm of the DC link in Fig. 1-5. On the other hand, connections V and W are connected to the negative arm. This results in voltage vector U1, whose amplitude corresponds to the DC link voltage. If winding V is now switched to the positive arm of the DC link, then the resulting voltage vector rotates through 60º to U2. The amplitude does not change. Each of the possible switch settings can be assigned to a voltage vector U1 to U8.

Switch settings	**L1**	**L2**	**L3**	**U**
S1	+	-	-	U1
S2	+	+	-	U2
S3	-	+	-	U3
S4	-	+	+	U4
S5	-	-	+	U5
S6	+	-	+	U6
S7	+	+	+	U7
S8	-	-	-	U8

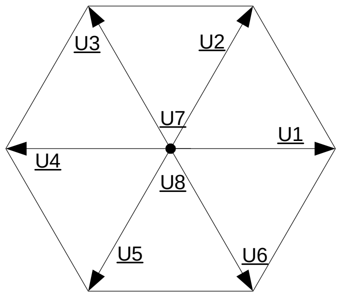

Fig. 3-6 **Space vector diagram with elementary space vector U1..U8**

In switch settings 7 and 8, all of the three winding connections are connected to the same potential which means that the resulting vector has a length of zero.

As already mentioned, the motor must be supplied with a variable frequency and voltage. This is the reason that it is not sufficient to individually clock S1 to S6 one after the other with the required frequency. The hexagonal waveform of the circulating voltage vector doesn't provide satisfactory results in practice. Suitable modulation techniques must be used in order to obtain a continually rotating voltage vector with a variable length. Suitable modulation techniques include, for example, pulse-width modulation (PWM) or space vector modulation.

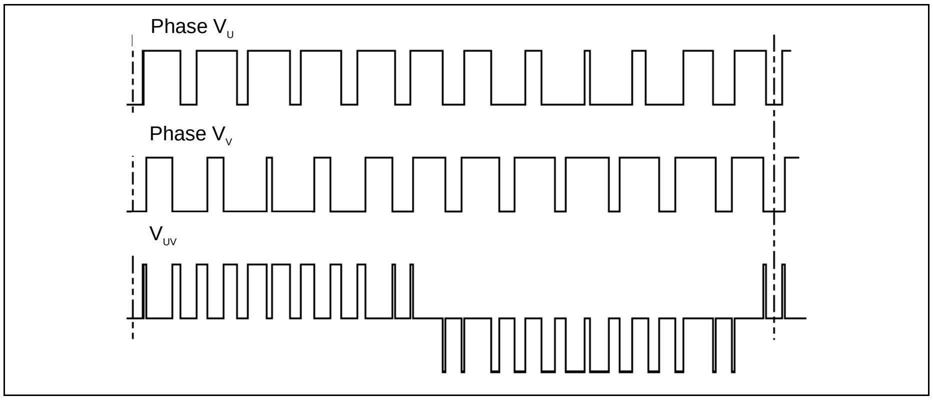

Fig. 3-7PWM output voltage

The individual conductor voltages remain pulsed when the PWM technique is used. Their carrier frequency corresponds to the control frequency of the transistor. The different voltage-time areas can be clearly seen which are formed corresponding to the pulse input. As a result of the rule according to which the pulses are modulated a current characteristic with an approximately sinusoidal waveform is obtained from the pulsed voltage characteristic under the influence of the motor inductance.

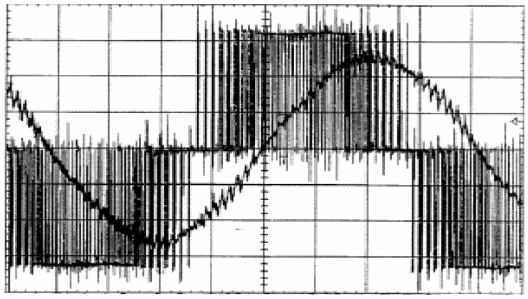

Fig. 3-8 Output voltage and current

It is important that the best possible sinusoidal current characteristic is obtained because all of the magnetic quantities and therefore the torque transferred through the air gap, depend on the current. If the current does not have a sinusoidal characteristic, then the losses in the motor increase and torque fluctuations can occur at the drive shaft.

3.4 Braking the motor

The motor with connected load must be able to be braked down to standstill in a controlled fashion. The transistor bridge in the output circuit of the AC drive inverter is bidirectional. This means that it allows current to flow in both directions. If the motor regenerates, e.g. when braking, the energy flows back into the DC link through the transistor bridge. However, the uncontrolled diode bridge in the incoming circuit of the AC drive inverter does not allow current to flow back into the line supply. The energy, coming from the motor remains in the DC link, charges the capacitors and therefore the DC link voltage increases . This means that the DC link voltage monitoring is quickly activated. When the upper voltage threshold is exceeded, all output transistors are blocked in order to protect the AC drive inverter. This means that the energy flow from the motor into the DC link is interrupted. The motor is no longer braked in a controlled fashion, but just coasts down.

In order to avoid the AC drive inverter from being tripped due to a fault as mentioned above, MICROMASTER 4 AC drive inverters have different functions:

- DC voltage controller
- DC current braking
- Dynamic braking
- Compound braking

One of the possibilities is to connect a braking resistor and a braking module to the AC drive inverter.

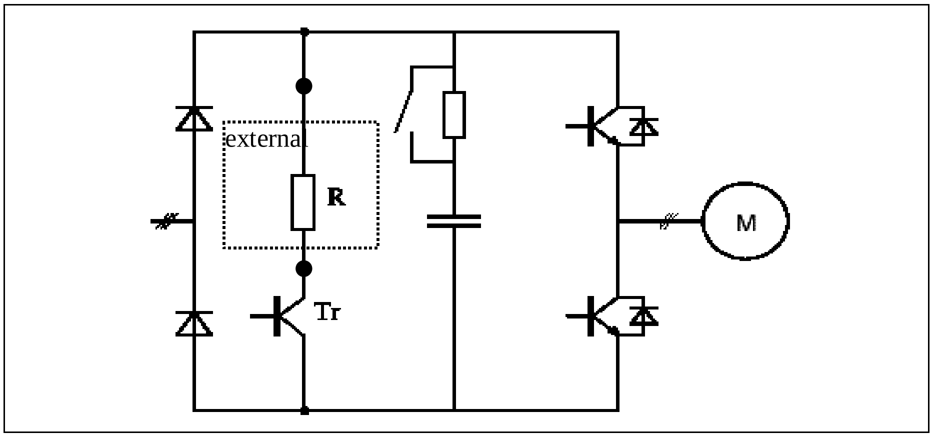

Fig. 3-9 Block diagram of the MICROMASTER 440 with braking resistor

In this case, an external resistor (R) is connected in parallel to the DC link which is supplied through a transistor (Tr). The DC link voltage is monitored. After a voltage threshold is exceeded, the load resistor is switched-in through the transistor. The energy which is regenerated is converted into heat in the resistor. The resistor must be dimensioned so that it can absorb the necessary power during the complete braking operation.

A second possibility to brake the motor down to standstill is DC braking. In this case, the motor is supplied with DC current through two phases of the output bridge which generates a constant magnetic field. The rotor is braked according to the principle of an eddy current brake. This method has the advantage that external components are not required. However, it also has various disadvantages:

- Braking is not precise, because the torque changes with the velocity and at velocities close to zero is extremely low.
- For a high braking torque, which approaches the rated motor torque, a higher current must be impressed.
- The braking torque depends on the speed-torque characteristics of the motor.
- All of the braking energy in the motor is converted into heat and the temperature rise can be significant.

4 Engineering the drive

4.1 Connection to the line supply

When AC drive inverters are operated, this has undesirable effects on the line supply. There are essentially two main causes of these effects:

- Non-linearity of the power electronic devices and components
- High control frequency of the output transistors

The magnitude of these effects depends very heavily on several factors, for example, the characteristics of the line supply, AC drive inverter type and power. In order to protect MICROMASTER 4 AC drive inverters and the line supply and to effectively dampen harmonics, there are various options and accessories.

The AC drive inverter should be connected to the line supply using the appropriate fuses or circuit-breakers in order to protect the incoming circuit. For MICROMASTER 4, semiconductor fuses are not required to protect the drive inverter. Standard fuses for cable protection, type gL or motor-protection circuit-breakers are adequate. The internal protective devices of the MICROMASTER are used to protect the output circuit.

Further, EMC filters and line reactors are available as options. The EMC filter dampens the high-frequency disturbances and noise generated by the pulse frequency of the output transistors. The subject of electromagnetic disturbances will be discussed in detail in Section 2.3.

The line reactor is used to reduce the harmonics fed back into the line supply from the AC drive inverter, such as low-frequency harmonics and periodic line dips.

4.1.1 Low-frequency harmonics

The following information refers exclusively to harmonic voltages and currents with low frequencies up to max. 1kHz which the AC drive inverter feeds back into the line supply.

The input circuit of the AC drive inverter comprises an uncontrolled diode bridge and the downstream capacitors in the DC link. The diodes only conduct if the line voltage exceeds the capacitor voltage. This means that the capacitors are briefly re-charged with high current pulses, e.g. after the DC link has been pre-charged, then the re-charging only occurs again at the next maximum of the line supply voltage. The current flow is only limited by the impedances of the line supply and the DC link. The current waveform is no longer sinusoidal as can be seen in the following diagram:

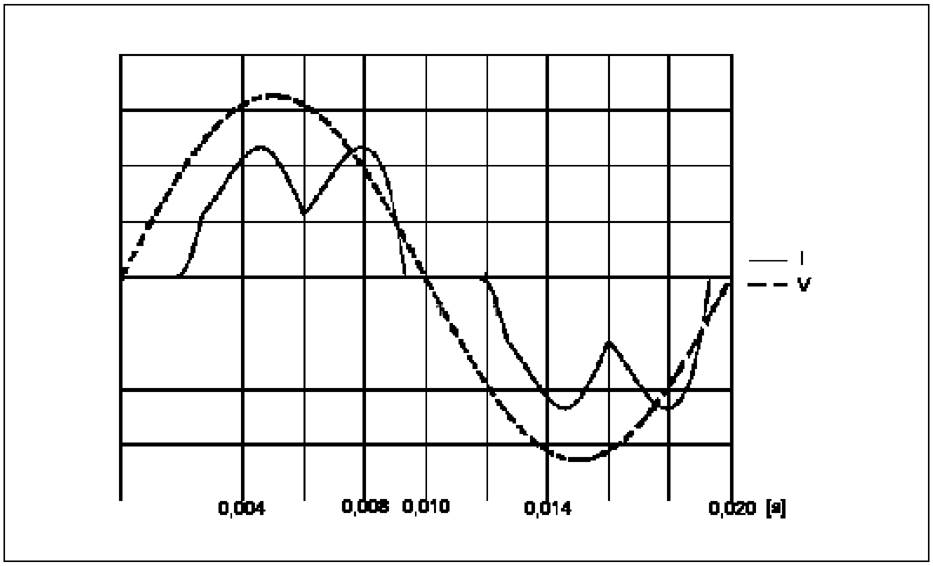

Fig. 4-1 **Voltage and current waveform of a line phase**

The Fourier analysis of the current indicates that in addition to the basic fundamental current there are also harmonic currents.

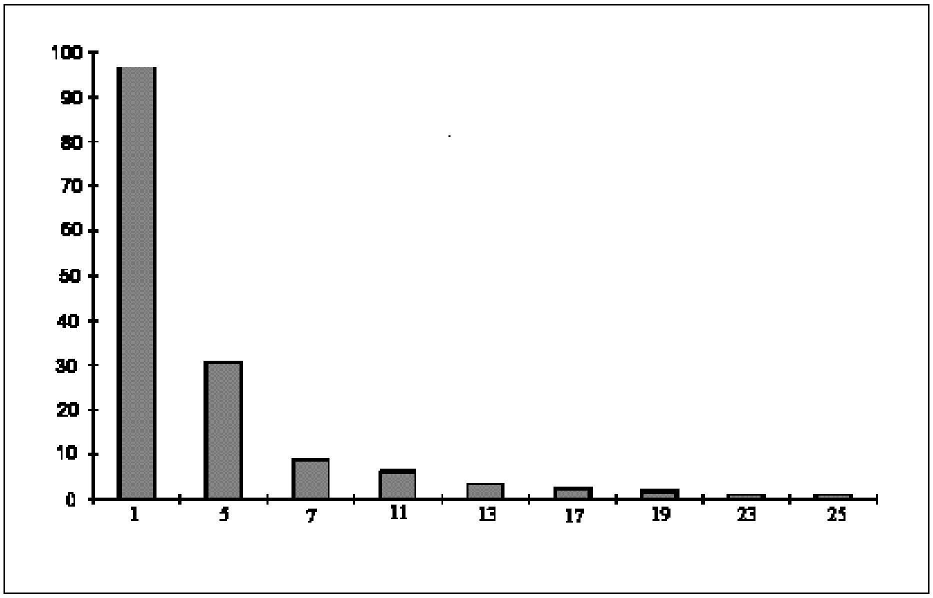

Fig. 4-2 **Harmonic spectrum**

For 6-pulse diode bridges, essentially only uneven harmonic voltages and currents, which cannot be divided by 3, occur on the line side.

The functional faults occurring in the line supply are just not due to the harmonic currents alone, but also to the voltage drops which are caused in this line supply by the various harmonic frequencies. The voltage waveform is distorted by these voltages due to the interaction with the line supply voltage.

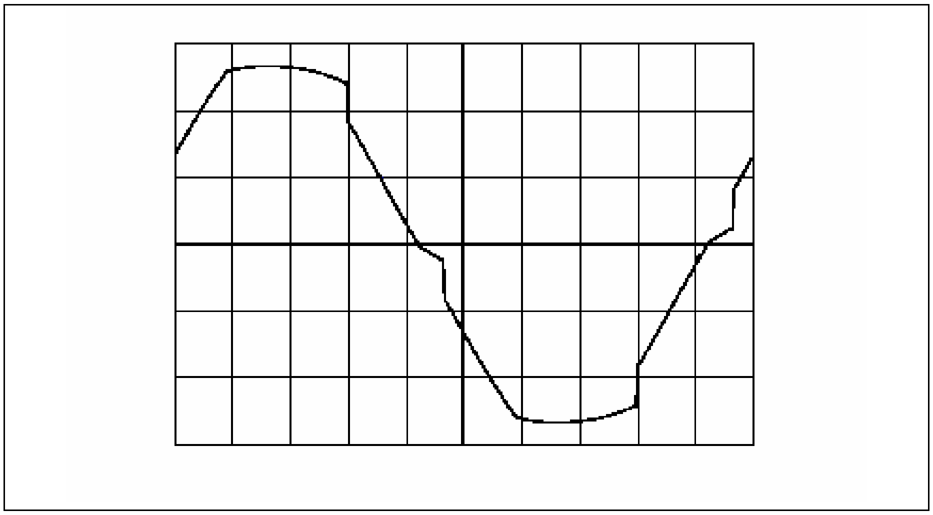

Fig. 4-3 Distorted voltage waveform

Parallel resonance can be excited in the line supply of the AC drive inverter due to the harmonic components. These effects occur, with a high degree of probability, if, for example, a reactive power compensation with unchoked capacitors is installed in the line supply.

The most effective way of limiting the harmonic feedback of an AC drive inverter to permissible values is to increase the line feeder inductance by using a line reactor. This line reactor limits the current rate-of-rise, extends the current flow time, reduces the current amplitude and in turn this **reduces the harmonic currents**. The current-time area of the pulsed currents remains constant in comparison to operation without any reactor. At the same time, by reducing the charging current peaks, the lifetime of the DC link capacitors is extended.

The question as to whether a line commutating reactor is required essentially depends on the ratio between the rated drive inverter power and the system fault level permissible for the particular drive inverter type. A line reactor must be used for MICROMASTER 4 if the following applies for the system fault level:

$$S_{K\_line} \geq 100 * S_{inv}$$

$$S_{inv} = \sqrt{3} * V_{line} * I_{inv\_input}$$

In most cases, the system fault level S_{K_line} is not known. This is the reason that we recommend that a line reactor is always used.

4.1.2 Line supply dips

The distortion of the line voltage is manifested in the form of periodic voltage dips, which are directly caused by commutation operations and are therefore also known as commutation dips. Commutation is the transition of current from an arm of the input bridge, which is conducting current to the next arm which is to conduct current. These inherit brief short-circuits result in dips in the line supply voltage whose magnitude is determined by the ratio between the line inductance and the inductance in series with the converter or AC drive inverter (i.e. commutating reactor).

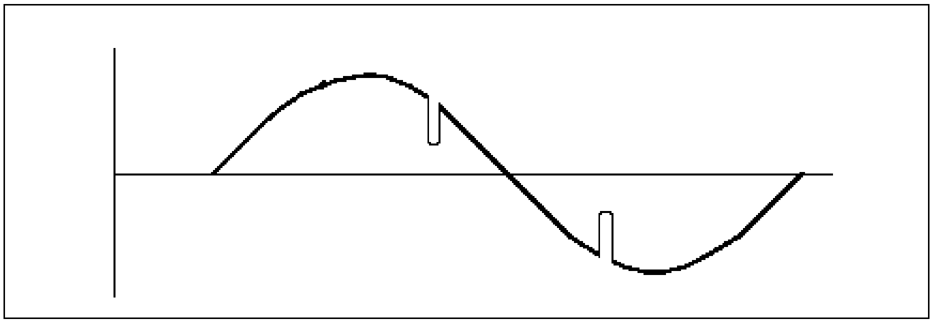

Fig. 4-4 Voltage waveform of a line phase

For uncontrolled diode bridges, which are used for MICROMASTER 4, this commutation always takes place close to the natural firing instant. This means that there is almost no "overlapping commutation". This means that the voltage gaps which can be seen are appropriately small. Larger commutation dips are typical for fully-controlled thyristor bridges such as are used in converters. Commutating reactors are used in the input circuit to dampen the voltage gaps and to limit the current for drive converters.

It is not necessary to use special commutating reactors for the MICROMASTER 4 series of AC drive inverters. If a line reactor is used, then this also handles the function of a commutating reactor.

4.2 Connecting-up the motor

A motor connected to an AC frequency inverter is subject to higher electrical and thermal stresses as a result of the pulse voltage waveform.

The voltage characteristic waveform comprises a sequence of pulses whose amplitude corresponds to the voltage of the DC link. The rise time of these pulses is determined by the switching time of the IGBTs of approximately 0.1µs. For a 400V supply, the voltage rates-of-rise (gradient) are given by:

$$\frac{dv}{dt} = \frac{400V * 1.35}{0.1s} \approx \underline{\underline{5kV / \mu s}}$$

The large voltage gradients are the main cause of overcurrent and voltage peaks which additionally load the AC drive inverter, the motor feeder cables and the motors.

4.2.1 Overcurrents at the output

Output currents at the AC drive inverter which are higher than actually required are due to the intrinsic capacitance of the motor feeder cable. These capacitances cannot be neglected for the frequencies which are relevant here.

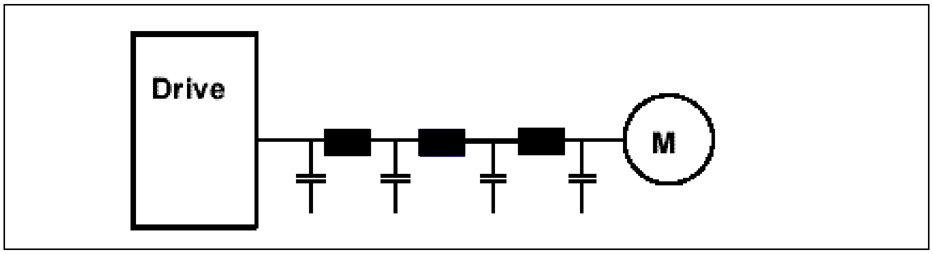

Fig. 4-5 **Capacitances of the motor feeder cable**

The sequence of pulses (pulse train) which are conducted along the cable cause the capacitors to be continually charged and uncharged. These charging currents are superimposed on the RMS current and additionally load the AC drive inverter.

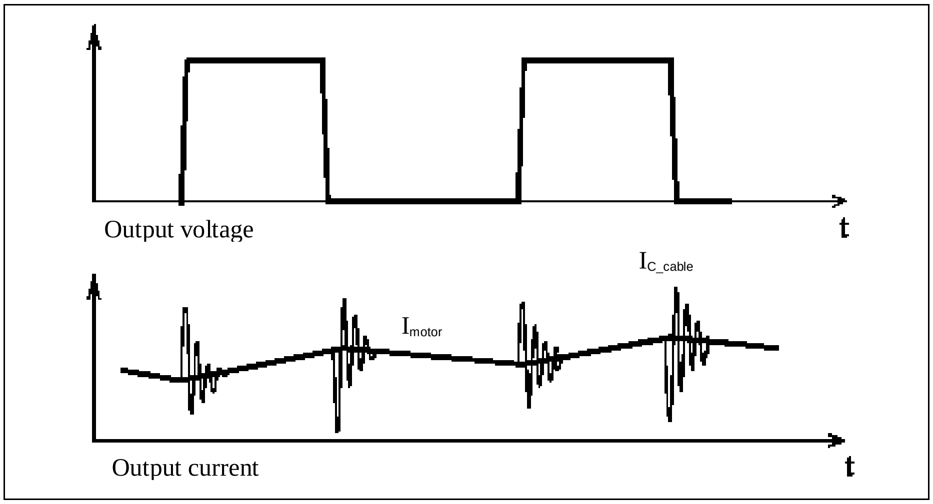

Fig. 4-6 **Output voltage and current**

The higher the capacitance involved, the longer the cable and the higher the pulse frequency of the AC drive inverter, then the higher are these currents.

The maximum cable lengths which can be connected are specified in the technical documentation for the AC drive inverter. The re-charging currents can be dampened and therefore the cable lengths extended by installing special output reactors.

4.2.2 Overvoltage conditions at the output

The voltage increase at the motor is caused by the steep voltage edges and the traveling wave which is generated. This traveling wave between the drive inverter output and the motor is propagated at a rate of 150 m/µs in the cable.

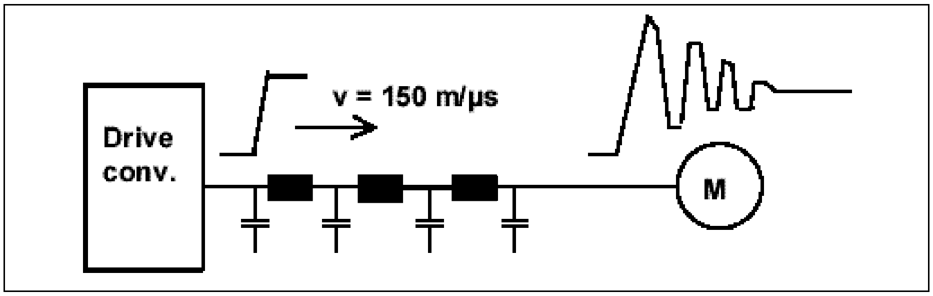

Fig. 4-7 **Voltage characteristic at the drive inverter output and at the motor**

When the traveling wave reaches the motor it suddenly sees a different characteristic impedance of $R_{mot} \approx 10..20 * R_{cable}$ and is reflected back to the AC drive inverter. It then gets reflected back to the motor etc. This settling operation is completed after approx. 1µs. For operation at rated voltage, voltage peaks can occur at the motor with a maximum value of:

$$V_{\max\_mot} = 1.9 * V_{DClink} = 2.6 * V_{line}$$

The voltage in the DC link continuous to increase in the transition phases, e.g. when the motor is braking and accelerating. This in turn results in an appropriate increase of the voltage peaks at the motor terminals.

In order that the voltage is reflected completely then the voltage rise time must be less than the propagation time of the traveling wave from the AC drive inverter to the motor.

$$\Delta t < t_{propagate} = \frac{l_{cable}}{v}$$

The critical cable length is obtained as follows:

$$l_{cable} > v * \Delta t = 150 \frac{m}{\cancel{\mu s}} * 0.1 \cancel{\mu s} = \underline{\underline{15m}}$$

The result is that the full voltage reflection is already obtained for short cable lengths of about 15 m and longer. This cable length must always be assumed in practice.

Output reactors and in the future also an LC filter will be available as option for the MICROMASTER 4 to reduce these voltage reflections. The output reactors dampen the voltage rise after the reactor and reduce the capacitive re-charging currents. The LC filters limit the voltage rise and reduce the voltage peaks. Further, they also influence the voltage waveform so that this approximates a sinusoidal waveform.

4.3 Electromagnetic compatibility

4.3.1 General information and relevant Standards

Electromagnetic faults and disturbances, e.g. strong magnetic fields and the effects of electrostatic discharge are summarized under the term electromagnetic compatibility. An AC drive inverter must itself be immune to external EMC effects and, in operation may only generate limited electromagnetic noise for other devices and equipment. The faults and disturbances emitted by AC drive inverters are mainly caused by the high clock cycle frequency of the output inverter.

In the past, these phenomena were investigated limited to critical cases associated with real functional faults. However, after the introduction of the 89/336/EEC Directive, this has been increasingly extended beyond the electromagnetic compatibility. This EMC Directive is restricted to the requirement that no electrical device may cause electromagnetic faults and disturbances in its environment nor be sensitive to faults/disturbances from the environment. However, the detailed issues regarding how these requirements are actually implemented is handled in the various application Standards. This is Standard EN-61800-3 for AC drive inverters and for use in residential areas, the specialist basic Standard for electromagnetic disturbances in residential areas EN50081-1. In the Standard a differentiation is made between applications in industrial and commercial working environments (Class A) and in residential environments (Class B).

- For applications according to Class A, the requirements placed on noise immunity are higher and the requirements placed on the emission of noise/disturbances on the other hand lower.
- For applications in accordance with Class B, the requirements are defined inversely.

It is important to emphasize that the AC drive inverter is considered, in the applicable Standards, as "Components" of a "System". Every EMC certificate and the resulting issuance of a CE mark must be for the complete system. The complete system is not automatically certified by just certifying the drive inverter just the same as every other component.

This means that all of the components, from the line supply up to the motor, must be installed and connected-up (cabled) according to the regulations specified in the EMC Standards. The designer of a plant/system can then either have his design certified by a special institute or can certify it himself by fulfilling the Standards. Generally, the plant/system is only subject to an in-depth analysis if problems associated with EMC noise and disturbances have already occurred.

4.3.2 Reducing electromagnetic noise and disturbances

Depending on how they are propagated, the faults are sub-divided as follows:

- Cable-borne noise/disturbances which propagate through the cables and shields
- Non cable-borne noise/disturbances as high-frequency noise which is propagated in the form of electromagnetic waves

Without any suitable measures, the noise/disturbances propagate themselves, e.g. in the form of noise currents, in an uncontrolled fashion throughout the complete plant or system through the connecting cables and the grounding/earthing system. The noise level can only be reduced by taking specific measures to suppress the two propagation types listed above. The objective is that noise and disturbances propagate along specific paths so that interaction with other plant/system parts and sections is reduced and the fault currents can be discharged in a specific way.

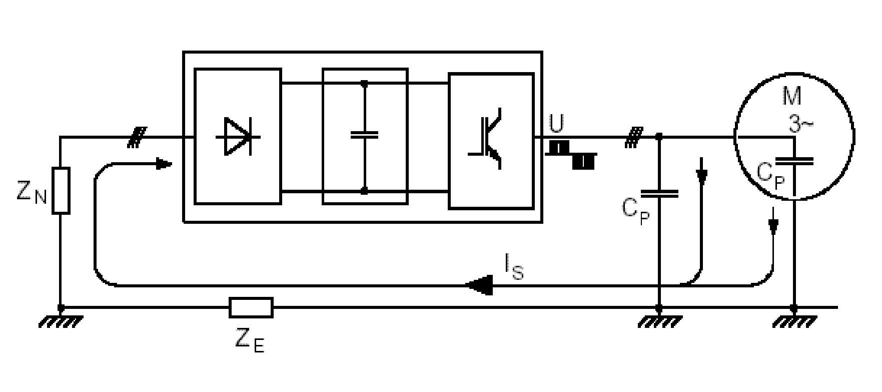

Fig. 4-8 Noise current flow for non-shielded motor feeder cables

The parasitic capacitances C_P are charged and discharged as a result of the pulsed output voltage of the AC drive inverter. The noise current must flow back to its source, i.e. the AC drive inverter. If non-shielded cables are used, the noise current flows back in an undefined fashion through impedances of the ground Z_E and the line feeder cable Z_N - e.g. through the foundation ground, cable trays and ducts etc. The noise current and the noise voltages which the noise current generates can negatively influence other devices and equipment and even damage these.

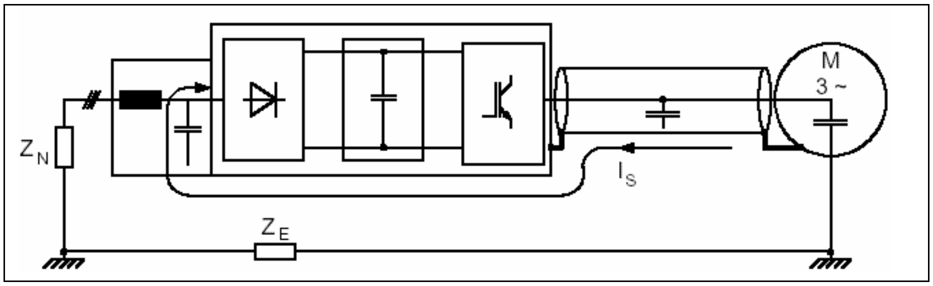

Fig. 4-9 Shielded motor feeder cables and installation of an EMC filter

Shielded cables are required in order to allow a fault current to flow back to the AC drive inverter in a defined way. The shielding must be connected through the largest possible surface area to the grounded drive inverter housing and the grounded motor frame. The cable shield may not be interrupted – for example, at cable connection locations (e.g. terminal points). In some cases it is practical to establish a potential bonding between the motor and drive inverter using a separate flat grounding cable with a large cross-section. This can then discharge some of the noise current.

A capacitive coupling through discharge capacitors is established so that the high-frequency noise current can flow back to the DC link of the drive inverter through the lowest possible impedance. MICROMASTER 4 drive units already have a basic noise suppression functionality.

Far better results are achieved if a special EMC filter is used at the line supply input of the AC drive inverter. Appropriate EMC filters for MICROMASTER 4 are offered as line supply input option or a filter which is already integrated in the drive unit.

The connection between the drive inverter and EMC filter must be kept as short as possible. A good connection between the drive inverter housing and the housing of the EMC filter is extremely important. In the most favorable case, the EMC filter can be mounted directly at the drive inverter, e.g. the MICROMASTER 4 sub-chassis filter. Otherwise, a shielded connecting cable should be used between the filter and drive inverter. Both the EMC filter and drive inverter must be connected to ground through the largest possible surface area. This is achieved by mounting them on a common conductive mounting plate/panel or the rear of the electrical cabinet which is well grounded.

In order to avoid noise being coupled-into signal cables we recommend that the motor feeder cables are separately routed and a minimum clearance is maintained to any signal cables. If at all possible, cables should not be routed in parallel. Other improvements are achieved if shielded signal cables are used.

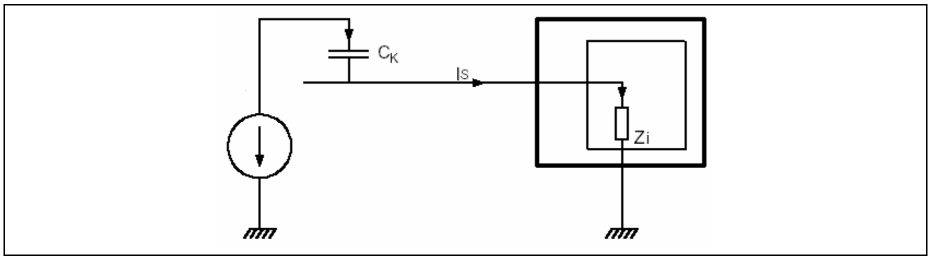

Fig. 4-10 Stray noise current I_S in a piece of electrical equipment

For capacitive coupling-in through C_K , noise current I_S results in a voltage drop across impedance Z_i . For sensitive components, e.g. microprocessors, input drivers of digital circuits etc., this voltage can result in functional faults or even the component being destroyed.

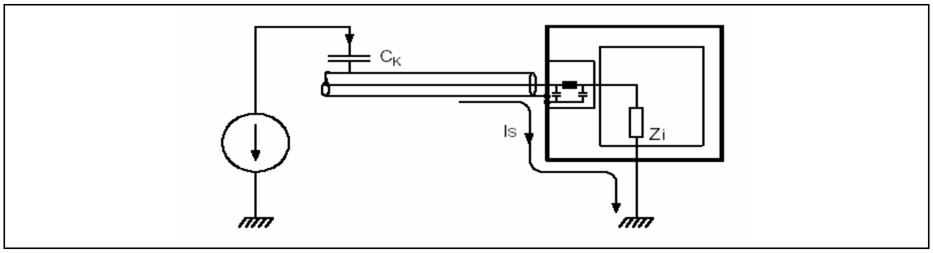

Fig. 4-11 Leakage noise current I_S

If shielded signal cables are used, noise current I_S is discharged to ground through the housing and has no effect on the internal circuits. The cable shield must be connected at both ends to ground through the largest possible surface area. For analog signals, this can cause signal noise. In this case, one end of the cable is connected to ground through a capacitor (0.01÷0.1 µF). This capacitor has a very low impedance at high frequencies.

5 Engineering the drive system

Engineering the drive system involves specifying all of the components which are required for the specific application. The principle design of a drive system is shown in Fig. 3-1.

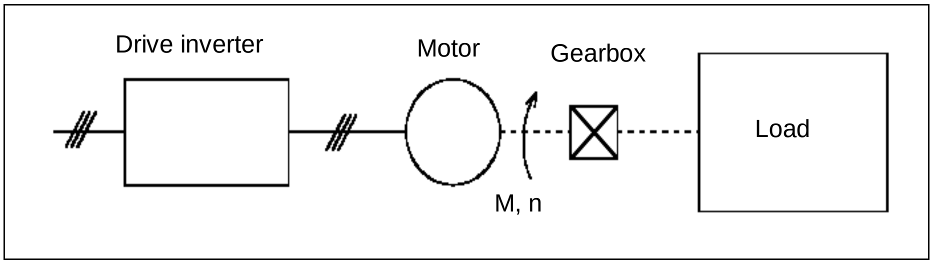

Fig. 5-1 Principle configuration of a drive system with load

Frequently, a drive system is engineered using user-friendly software tools.

The most important engineering steps include:

- Collecting the available mechanical data
- Defining a load characteristic or a load cycle for an application
- Calculating the relevant load and overload torques and speeds
- Selecting the gear ratio
- Selecting the optimum motor type
- Selecting the AC drive inverter based on the required load and overload currents

Additional selection criteria and influencing factors include:

- Permissible mechanical limiting speeds of the motors and gearboxes
- Thermal and dynamic motor torque limits
- Ambient temperature
- Installation altitude
- Temperature rise class of the motor

5.1 Load characteristics

Load characteristics are available for drives which are essentially used in steady-state operation. The load torque is represented as a function of the speed.

For constant-torque loads, the torque does not change if the speed changes.

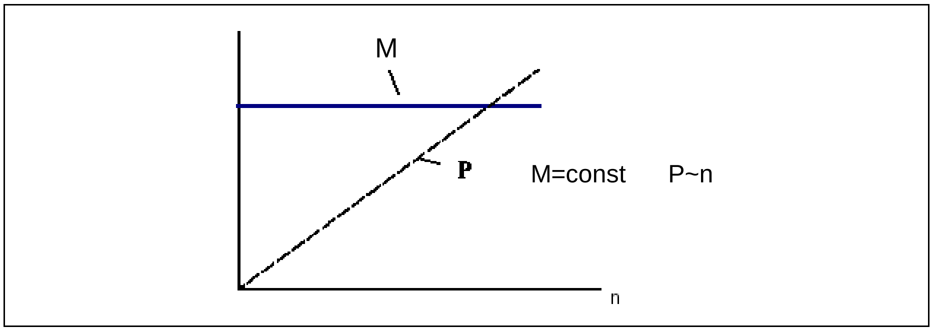

Fig. 5-2 **Constant load torque**

For loads with a square-law load characteristic, the load torque changes in proportion to the square of the speed. This is typical for machines to pump liquids and gases, e.g. for pumps, centrifuges and fans.

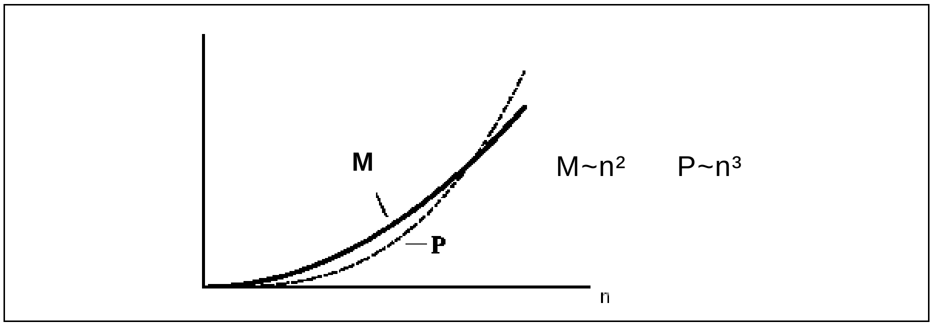

Fig. 5-3 **Square-law load characteristic**

When designing machines, it should be taken into account that displacement pumps (e.g. reciprocating, cell and toothed-wheel pumps) are machines with a constant torque.

Load characteristics where the torque typically increases proportionally and linearly with the speed include, for example, rolling mills.

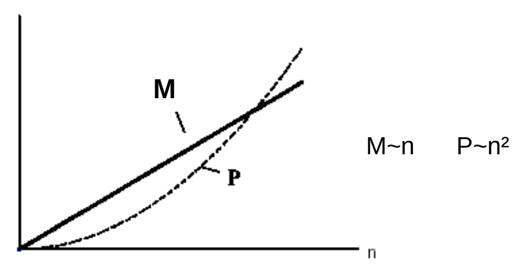

Fig. 5-4 **Linear load characteristic**

Drives where the torque reduces with increasing speed include, for example, winder and spindle drives.

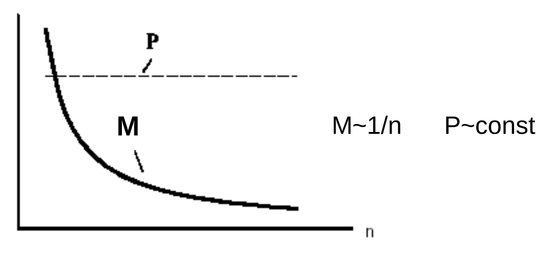

Fig. 5-5 **Decreasing load characteristic**

The types which were last mentioned are however special cases. The majority of applications are represented with the first two load types (with constant load and square-law load torque).

When dimensioning the motor it must be taken into account that standard induction induction motors are cooled using a shaft-mounted fan. The cooling power of this fan is proportional to n³. In principle, there is a direct relationship between motor torque, motor current and motor temperature.

For operation with square-law load torques, the load torque increases with the speed. The motor is always adequately cooled and is not thermally overloaded.

On the other hand, for operation with constant load, at low speeds the fan cannot dissipate all of the power loss (thermal energy). In this case a separately-driven fan must be mounted on the motor to avoid thermal overstressing or destruction of the motor.

5.2 Load cycles

Drives with periodic load curves depending on the particular application are engineered using a load cycle as basis. The load torque and speed, which cyclically change, must first be derived from the mechanical system and the conditions of the application, e.g. traversing gear. In this case, the torque comprises the accelerating torque, load torque, frictional torque etc.

When making the necessary calculations, it is practical to divide-up the complete cycle into several sub-sections – for example starting, constant velocity and braking. A motor can be selected after calculating the maximum torque and the effective (RMS) torque at the associated speeds. The matching AC drive inverter can be selected from the required motor currents derived from the motor torques.

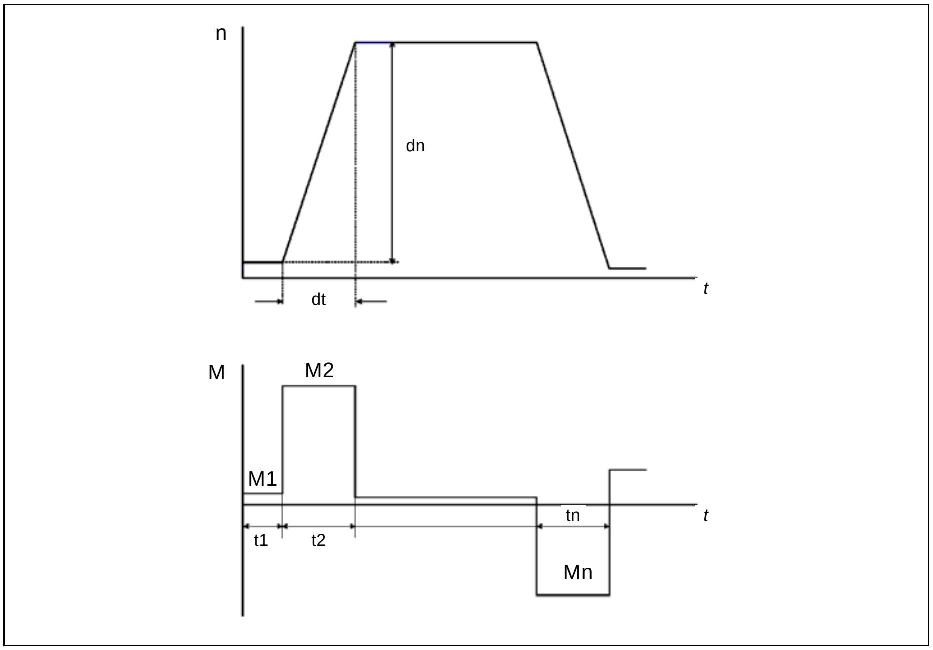

Fig. 5-6 Example of a speed and torque characteristic for a load cycle

The maximum torque is obtained from the highest load. The RMS torque is calculated as follows:

$$M_{rms} = \sqrt{\frac{M_1^2 * t_1 + M_2^2 * t_2 + ... + M_n^2 * t_n}{t_1 + t_2 + ...t_n}}$$

As can be seen in Fig. 3-6, torque M2 is required while accelerating the load. Torque M2 comprises the constant load torque M1 and the accelerating torque. When braking, the braking torque and the constant load torque are subtracted.

When providing the maximum load torques, the overload capability of induction motors as well as the AC drive inverters can be used. However, the following should be carefully observed:

- The dynamic and thermal torque limits of the motors in the constant flux range and in the field-weakening range
- The various overload cycles of the AC drive inverters which depend on the type and size of the drive unit.

For loads with square-law load torque (also known as variable torque), the drive inverter power is selected from a so-called VT table. The background for this is that for square-law load characteristics the maximum load point is only reached at rated speed. Frequently, no other overload factors have to be taken into consideration. For the AC drive inverter this means that a higher continuous load current is permissible but however a lower overload capability.

This means that for MICROMASTER 4 a higher permissible VT power is obtained for a particular drive unit – for example:

MM440 with Order No. 6SE6440-2UC24-0CA1

CT (Constant Torque)	**VT (Variable Torque)**
Power 4.0kW, I_{inv_out} =17.5A	Power 5.5kW, I_{inv_out} =22A
I_{inv_max}=1.5*17.5A for 60s cycle 300s	I_{inv_max}=1.1*17.6A for 60s cycle 300s

It should be observed that for fans with a high moment of inertia and where speed changes can occur relatively quickly, higher accelerating torques are demanded. For applications such as this, the drive inverter selection should be checked as far as the maximum motor currents require.

5.2.1 Torque limits of an induction motor

In order to change the speed of induction motors, the AC drive inverter adjusts the voltage and frequency. In order that the flux remains constant in the motor, the ratio between the voltage and frequency must remain constant. This also means that a constant torque is obtained.

$$M \approx \varphi \approx \frac{V}{f} = const$$

In the constant flux range, a constant torque is obtained as well as a constant motor current.

When the maximum drive inverter output frequency is reached, the V/f ratio can no longer be set to be constant. From this point onwards the induction motor goes into the field-weakening range. The motor speed can be further increased by increasing the frequency - e.g. up to the mechanical limiting speed.

In the field-weakening range the induction motor can be operated with approximately constant power. This means that also the losses and the motor current remain constant. In the field-weakening range the torque is proportional to 1/n.

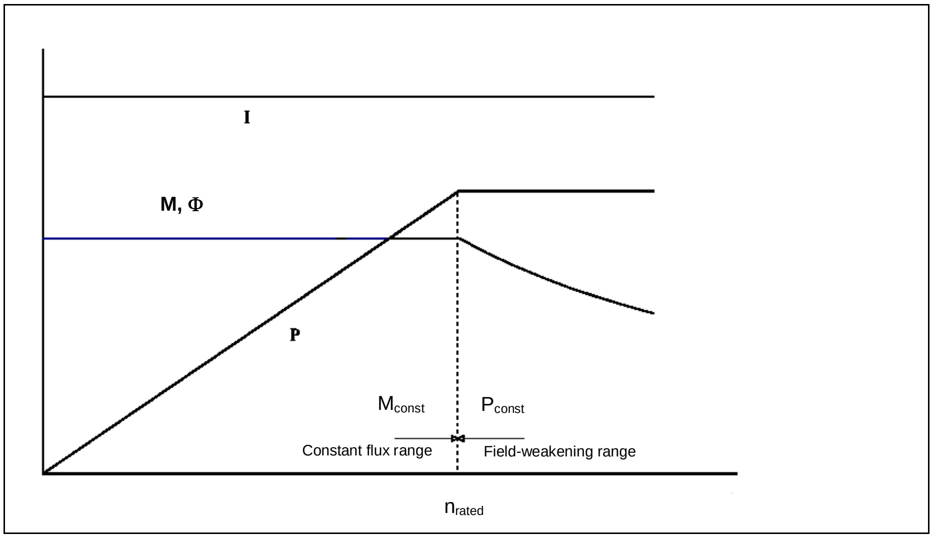

Fig. 5-7 Relationship between torque, flux, power and current

When dimensioning the motor, the specific torque limits of the drive must be maintained.

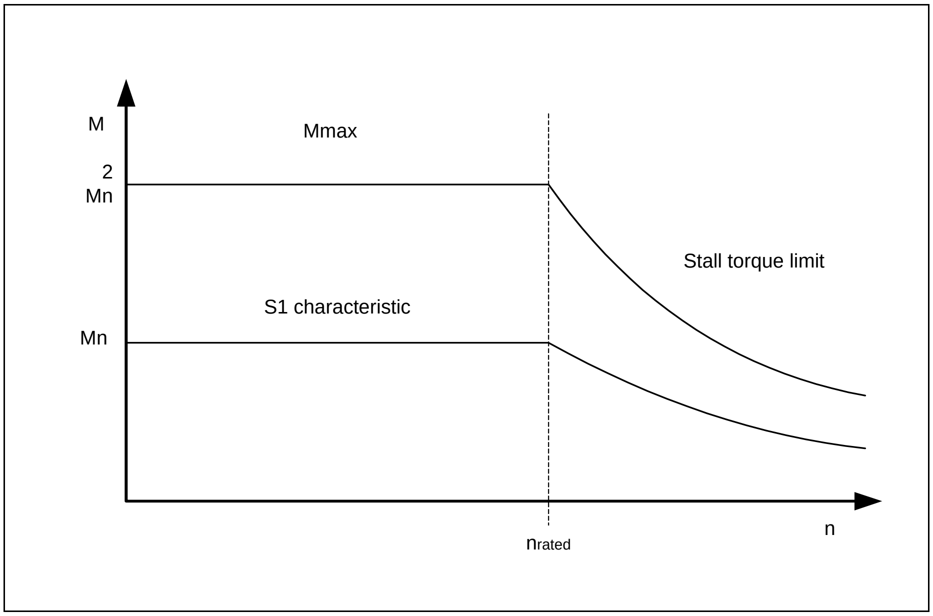

Fig. 5-8 **Limiting characteristic of the induction motor**

For continuous duty, the S1 limiting characteristic specifies the thermally permissible motor torque. For normal line supply operation the rated torque is the same as the S1 torque. For reasons of stability, the maximum torque should not be greater than 2 M_n. In the field-weakening range a sufficiently large clearance must be maintained to the stall limit. However it must also be noted that in the field-weakening range the motor stall torque decreases according to a square law.

In the field-weakening range the following applies for the torque

$M \approx \frac{1}{f}$, on the other hand, for the stall torque $M_{stall} \approx \frac{1}{f^2}$.

When engineering the drive, a safety margin of approximately 30% to the stall torque limit should be maintained in order to avoid the motor stalling.

6 Examples for engineering a drive

- Examples for engineering drives are provided in the following. The examples include the selection of the AC drive converter and the required additional optional components. The following conditions apply for all of these examples:
- Ambient temperature of 20°C for the AC drive inverter and 40 °C for the motor
- Installation altitude <1000m
- Motor utilized according to temperature Class F

6.1 Square-law load torque

6.1.1 Description

A drive motor has to be selected for a fan for a smoke extraction system. The speed will be controlled by the MM440 AC drive inverter as a function of the pressure. The fan must accelerate from standstill up to its rated speed in 30s. The drive is powered-up at the most once per hour. In operation, speed fluctuations of ± 5% within 5s are permissible as a result of the closed-loop control. The length of the cable between the motor and drive inverter is approx. 30 m.

6.1.2 Data

The following load data apply when dimensioning the motor:

Torque required by the fan, M_{fan} = 240 Nm

Fan speed n_{fan} = 1100 RPM

Moment of inertia of the fan J_{fan} = 10 kgm^2

Overall efficiency η=0.80

6.1.3 Calculation

The required drive power at the fan can be derived from the specified load characteristic.

$$P_{fan} = 0.105 * M_{fan} * n_{fan} = 0.105 * 240Nm * 1100RPM \approx \underline{\underline{28kW}}$$

The torque required by the fan in operation is known; the accelerating torque up to rated speed is now calculated:

$$M_{accel} = \frac{J_{fan} * \Delta n}{9.55 * t_{up}} = \frac{10kgm^2 * 1100RPM}{9.55 * 30s} \approx \underline{\underline{38Nm}}$$

The overall torque required for starting is given by:

$$M_{fan\_start} = M_{fan} + M_{accel} = 240Nm + 38Nm = \underline{\underline{278Nm}}$$

The load in this case has a square-law torque characteristic which means that the full torque is only required at the end of the acceleration phase.

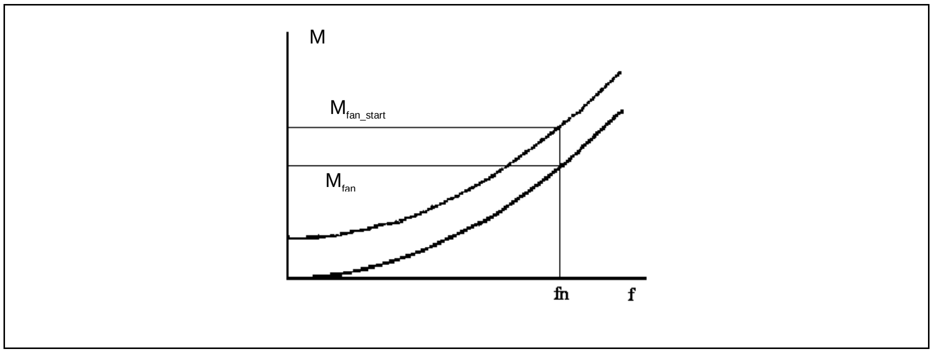

Fig. 6-1 **Torque characteristic**

The starting torque M_{fan_start} is required, at the most, once an hour and can be neglected when thermally dimensioning the motor. An AC drive inverter should be used which can supply the starting current.

We will now analyze the speed and torque fluctuations which occur during closed-loop controlled operation. Speed fluctuations of ±5% of the rated speed in 5s are permissible. The following applies for the required torque:

$$M_{fan\_reg} = \frac{J_{fan} * \Delta n}{9.55 * \Delta t} = \frac{10kgm^2 * 0.05 * 1100RPM}{9.55 * 5s} = \underline{\underline{12Nm}}$$

The most unfavorable case is closed-loop control at rated load and rated speed of the fan. The torque determined must be added in the sense of the maximum load torque; in the other it should be subtracted from it so that two values are obtained:

$$M_{fan1} = M_{fan} + M_{fan\_reg} = 240Nm + 12Nm = \underline{\underline{252Nm}}$$

$$M_{fan2} = M_{fan} - M_{fan\_reg} = 240Nm - 12Nm = \underline{\underline{228Nm}}$$

A symmetrical cycle is assumed for the worst load case (refer to Fig. 4.2) and the average torque in the cycle is calculated.

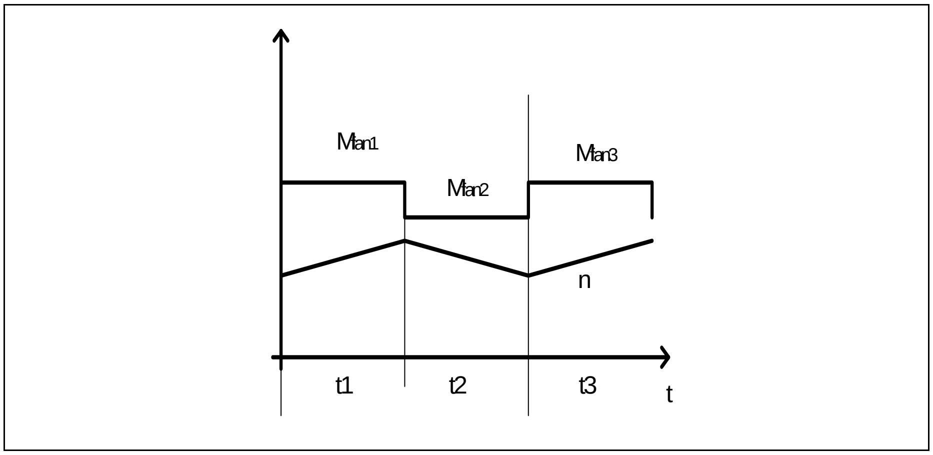

Fig. 6-2 **Symmetrical cycle**

$$M_{fan\_rms} = \sqrt{\frac{M_{fan1}^{2} * t_1 + M_{fan2}^{2} * t_2}{t_1 + t_2}}$$

$$M_{fan\_rms} = \sqrt{\frac{(252Nm)^2 * 5s + (228Nm)^2 * 5s}{5s + 5s}} \approx \underline{\underline{245Nm}}$$

It can be seen that the control, when it involves the RMS torque, doesn't result in a significant change from the required torque.

In the braking phase, this torque represents regenerative power with a magnitude given by

$$\Delta P_{fan\_reg} = 0.105 * M_{fan\_reg} * \Delta n = 0.105 * 12Nm * 55RPM = \underline{\underline{0.070kW}}$$

This power is less than 1% of the rated fan power. A braking resistor is not required as this power is dissipated by the internal losses in the AC drive inverter and the transmission losses.

Assuming that a four-pole motor with n=1500 RPM is being used in order to be able to use its full speed range, a gearbox must be used between the fan and motor with the following ratio:

$$i = \frac{n_{mot}}{n_{fan}} = \frac{1500}{1100} \approx 1.36$$

In this particular application, a four-pole motor is preferred over a six-pole motor with 1000 RPM as the latter would have to be operated with a significant level of field weakening in order to achieve the required speed.

The following motor torques (input into the gearbox) are obtained from the previous torque calculated for the load side (output from the reduction gearbox):

$$P_{mot} = \frac{1}{\eta_{total}} * P_{fan} = \frac{1}{0.8} * 28kW \approx \underline{\underline{35kW}}$$

$$M_{mot} = \frac{1}{\eta} * \frac{1}{i} * M_{fan} = \frac{1}{0.8} * \frac{1}{1.36} * 240Nm \approx \underline{\underline{220Nm}}$$

$$M_{mot\_rms} = \frac{1}{\eta} * \frac{1}{i} * M_{fan\_rms} = \frac{1}{0.8} * \frac{1}{1.36} * 245Nm \approx \underline{\underline{225Nm}}$$

$$M_{mot\_start} = \frac{1}{\eta} * \frac{1}{i} * M_{fan\_start} = \frac{1}{0.8} * \frac{1}{1.36} * 278Nm \approx \underline{\underline{255Nm}}$$

6.1.4 Selecting the components

When operating a fan, a load torque at the motor of 220Nm at 1500 RPM requires an RMS torque of 225Nm. A 1LA5220-4AA__ motor is the closest which can fulfill these requirements. However, the next largest motor and drive inverter should be used in order to take into account the various tolerances and data inaccuracies.

Motor 1LA5223-4AA__

P_n=45 kW; n_n=1470 RPM; M_n=293 Nm I_n=80 A; cos φ = 0.87

The maximum required torque is lower than the rated torque of the motor 1LA5223-4AA__, so that an overload current does not have to be calculated. The gearbox ratio can now be more precisely adapted together with the selected motor for another check. The appropriate load torque can then be subsequently calculated. Because the motor has such a large power reserve, we have decided not to check this.

The drive inverter can be designed for the rated motor current. Because the load being used has a square-law load torque, the drive inverter can be selected using the values listed in the VT table. For use in industrial environments, the drive inverter has an integrated Class A filter.

MM440 6SE6440-2AD33-7EA1

P_n = 45 kW (VT); I_n = 90 A

The matching input options include:

Line reactor 6SE6400-3CC08-3ED0

Fuses 3 x 3NA3032

Output reactors are not required due to the short length of the cable between the motor and AC drive inverter.

6.2 Constant-torque load

A material handling system with two axes – one horizontal and one vertical – is to be driven. An external module, which controls the AC drive inverter with analog signals, is used for the motion control. The connecting cable between the motors and the drive inverters is 100 m long.

6.2.1 Data

Table 6-1 Data for the calculation example

	Vertical axis	**Horizontal axis**
Traversing distance	s1 = 1m	s2 = 2m
Time	t1 = 2s	t2 = 2s
Weight	m1 = 500 kg	M2 =800kg

Each axis moves every 3 s. The motion is transferred using belt pulleys with a 20 cm diameter.

6.2.2 Calculation

When selecting the traversing profile of the axes, a triangular profile was selected which has the advantage of lower acceleration levels and therefore lower mechanical stress.

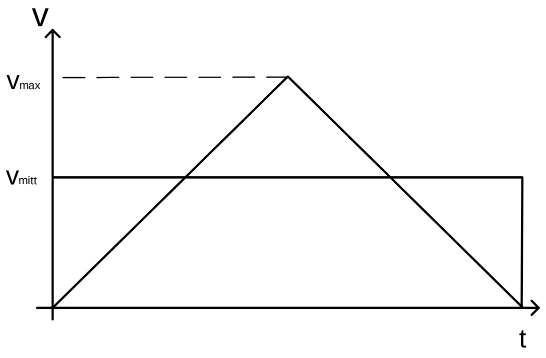

Fig. 6-3 Triangular traversing profile

Traversing distance $s = v_{av.} * t = \frac{1}{2} v_{\max} * t$

Maximum velocity $v_{\max} = 2 * v_{av.}$

Average velocity $v_{av.} = \frac{s}{t}$

Vertical axis

To start, the parameters for the cycle are calculated:

$$v_{av.\_1} = \frac{s_1}{t_1} = \frac{1m}{2s} = \underline{\underline{0.5m/s}}$$

$$v_{\max\_1} = 2 * v_{av.\_1} = \underline{\underline{1m/s}}$$

$$t_{accel\_1} = t_{bra\_1} = \frac{t_1}{2} = \frac{2s}{2} = \underline{\underline{1s}}$$

$$a_1 = \frac{v_{\max\_1}}{t_{accel\_1}} = \frac{1m/s}{1s} = \underline{\underline{1m/s^2}}$$

In order to raise the load, a force component is necessary to overcome the inertia and a second force component is required to equalize the force due to the weight. To accelerate the mass, a force of

$F_{accel\_1} = m_1 * a_1 = 500kg * 1m/s^2 = \underline{\underline{500N}}$ required.

Whereby the power required for acceleration is given by:

$$P_{accel\_1} = \frac{F_{accel\_1} * v_{\max\_1}}{1000} = \frac{500N * 1m/s}{1000} = \underline{\underline{0.5kW}}$$

The force and power required to raise the specified weight is then calculated:

$$F_{weight\_1} = m_1 * g = 500kg * 9.81m/s^2 = \underline{\underline{4905N}}$$

$$P_{weight\_1} = \frac{F_{weight\_1} * v_{\max\_1}}{1000} = \frac{4905N * 1m/s}{1000} \approx \underline{\underline{4.9kW}}$$

When raising the load, the maximum power is required while accelerating.

$$P_{H\_accel} = P_{accel\_1} + P_{weight\_1} = 0.5kW + 4.9kW = \underline{\underline{5.4kW}}$$

On the other hand, when braking while raising the load, the two powers must be subtracted from one another.

$$P_{H\_brake} = -P_{accel\_1} + P_{weight\_1} = -0.5kW + 4.9kW = \underline{\underline{4.4kW}}$$

The following powers are obtained when lowering the load.

$$P_{S\_accel} = P_{accel\_1} - P_{weight\_1} = 0.5kW - 4.9kW = \underline{\underline{-4.4kW}}$$

$$P_{S\_brake} = -P_{accel\_1} - P_{weight\_1} = -0.5kW - 4.9kW = \underline{\underline{-5.4kW}}$$

The translatory quantities are now converted into rotary quantities using the specified mechanical data.

Circumference of the belt pulley: $U = \pi * d = \pi * 0.2m = \underline{\underline{0.628m}}$

The maximum linear velocity corresponds to a maximum speed of:

$$n_{\max\_1} = \frac{v_{\max\_1}}{U} = \frac{1m/s}{0.628m} = 1.159s^{-1} = \underline{\underline{95.54RPM}}$$

When using a four-pole motor, $n_{mot} = 1500RPM$

The necessary reduction gearbox therefore has the step-down ratio

$$i = \frac{n_{mot}}{n_{\max\_1}} = \frac{1500RPM}{957.54RPM} = \underline{\underline{15.7}}$$

For a drive efficiency of 0.85 and a motor efficiency of 0.86, the following values are obtained for the required maximum and minimum motor torques:

$$M_{H\_accel} = \frac{9.55 * P_{H\_accel}}{\eta_{mot} * \eta_{mech} * n_{mot}} = \frac{9.55 * 5400W}{0.86 * 0.85 * 1500RPM} \approx \underline{\underline{47Nm}}$$

$$M_{H\_bra} = \frac{9.55 * P_{H\_brake}}{\eta_{mot} * \eta_{mech} * n_{mot}} = \frac{9.55 * 4400W}{0.86 * 0.85 * 1500\,\text{RPM}^{-1}} \approx \underline{\underline{38Nm}}$$

$$M_{S\_accel} = \eta_{mot} * \eta_{mech} \frac{9.55 * P_{S\_accel}}{n_{mot}} = 0.86 * 0.85 * \frac{9.55 * -4400W}{1500RPM} \approx \underline{\underline{-21Nm}}$$

$$M_{S\_bra} = \eta_{mot} * \eta_{mech} \frac{9.55 * P_{S\_brake}}{n_{mot}} = 0.86 * 0.85 * \frac{9.55 * -5400W}{1500RPM} \approx \underline{\underline{-25Nm}}$$

As has already been shown, motoring as well as regenerative torques occur. When calculating the average torque, a cycle comprising raising and lowering with a pause of 3s is assumed.

$$M_{rms\_1} = \sqrt{\frac{M_{H\_accel}^2 * t_{accel\_1} + M_{H\_bre}^2 * t_{bra\_1} + M_{S\_accel}^2 * t_{accel\_1} + M_{S\_bra}^2 * t_{bra\_1}}{(2s + 3s + 2s + 3s)}}$$

$$M_{rms\_1} = \sqrt{\frac{(47Nm)^2 * 1s + (38Nm)^2 * 1s + (-21Nm)^2 * 1s + (-25Nm)^2 * 1s}{10s}}$$

$$M_{rms\_1} \approx \underline{\underline{22Nm}}$$

Horizontal axis

The same procedure is essentially applied when engineering the drive for the horizontal axis. When calculating the various forces, the forces due to weight must be overcome as frictional forces, which tend to brake the movement.

The parameters of the cycle are calculated as follows:

$$v_{av\_2} = \frac{s_2}{t_2} = \frac{2m}{2s} = \underline{\underline{1m/s}}$$

$$v_{\max\_2} = 2 * v_{av\_2} = \underline{\underline{2m/s}}$$

$$t_{accel\_2} = t_{bra\_2} = \frac{t_2}{2} = \frac{2s}{2} = \underline{\underline{1s}}$$

$$a_2 = \frac{v_{\max}}{t_{accel\_2}} = \frac{2m/s}{1s} = \underline{\underline{2m/s^2}}$$

The required accelerating force is:

$$F_{accel\_2} = m_2 * a_2 = 800kg * 2m/s^2 = \underline{\underline{1600N}}$$

This means that the power required for acceleration is given by:

$$P_{accel\_2} = \frac{F_{accel\_2} * v_{\max\_2}}{1000} = \frac{1600N * 2m/s}{1000} = \underline{\underline{3.2kW}}$$

For a friction coefficient of 0.05, the following force is required for moving

$$F_{fric\_2} = F_{weight\_2} * \mu = (800kg * 9.81m/s^2) * 0.05 = \underline{\underline{392N}}$$

this means, that the power required is given by:

$$P_{fric\_2} = \frac{F_{fric\_2} * v_{\max\_2}}{1000} = \frac{392Nm * 2m/s}{1000} \approx \underline{\underline{0.8kW}}$$

For the traversing profile, for the acceleration phase, the max. power is obtained as follows

$$P_{\max\_2} = P_{accel\_2} + P_{fric\_2} = 3.2 + 0.8 = \underline{\underline{4kW}}$$

and when braking, a minimum power of

$$P_{\min\_2} = -P_{accel\_2} + P_{fric\_2} = -3.2 + 0.8 = \underline{\underline{-2.4kW}}\ .$$

Using the specified mechanical data, we can now convert the translatory quantities into rotary quantities.

Circumference of the belt pulley: $U = \pi * d = \pi * 0.2m = \underline{\underline{0.628m}}$

The maximum linear velocity corresponds to a maximum speed of:

$$n_{\max\_2} = \frac{v_{\max\_2}}{U} = \frac{2m/s}{0.628m} = 3.185s^{-1} = \underline{\underline{191.08RPM}}$$

When a four-pole motor is used, then $n_{mot} = 1500RPM$

This means that the reduction gearbox required has a step-down ratio of

$$i = \frac{n_{mot}}{n_{\max\_2}} = \frac{1500RPM}{191RPM} = \underline{\underline{7.85}}$$

For a mechanical drive efficiency of 0.85 and a motor efficiency of 0.86, the following values are obtained for the maximum and minimum motor torques required:

$$M_{mot\_\max 2} = \frac{9.55 * P_{\max\_2}}{\eta_{mot} * \eta_{mech} * n_{mot}} = \frac{9.55 * 4000W}{0.86 * 0.85 * 1500RPM} \approx \underline{\underline{35Nm}}$$

$$M_{mot\_\min 2} = \eta_{mot} * \eta_{mech} \frac{9.55 * P_{\min\_2}}{n_{mot}} = 0.86 * 0.85 * \frac{9.55 * -2400W}{1500RPM}$$

$$M_{mot\_\min 2} \approx \underline{\underline{-11Nm}}$$

When calculating the RMS torque, a cycle comprising traversing with a pause of 3s is assumed.

$$M_{rms\_\_2} = \sqrt{\frac{M^2_{mot\_\max 2} * t_{accel\_2} + M^2_{mot\_\min 2} * t_{bra\_2}}{(2+3)}}$$

$$M_{rms\_2} = \sqrt{\frac{(35Nm)^2 * 1s + (-11Nm)^2 * 1s}{5}} \approx \underline{\underline{16.5Nm}}$$

6.2.3 Selecting the components

This application requires a relatively high control accuracy at a relatively low velocity. This is the reason that a control loop with velocity feedback was selected (pulse encoder). The two axes, and especially the vertical axes, can remain stationary for a longer period of time with torque still being demanded. This is the reason that the motors have external fans.

Further, for safety reasons, both motors are equipped with holding brakes to lock the axes.

Vertical axis

A 1LA7113-4AA__ motor is the closest motor which can provide the precisely calculated torque (22 Nm). However, a somewhat larger motor should be used in order to take into consideration tolerance levels and inaccuracies in the data. Therefore, the following motor type was selected:

Motor	*1LA7130-4AA__-Z* *H64=mounted brake, separately-driven* *fan and pulse encoder* *P_n=5.5 kW, n_n=1440 RPM, M_n=36 Nm,*

In=11.4 A, cos φ = 0.83, J = 0.018 Kgm2

The influence of the motor moment of inertia should then be checked. The torque required to accelerate the rotor is calculated for this purpose:

$$M_{rotor\_accel1} = \frac{J_{mot1} * \Delta n}{9.55 * t_{accel\_1}} = \frac{0.018 kgm^2 * 1500 RPM}{9.55 * 1s} \approx \underline{\underline{2.8 Nm}}$$

If the RMS torque is re-calculated and this value inserted, then it will be seen that its influence can be neglected. The accelerating torque for the motor rotor only becomes relevant for high levels of acceleration if the rotor moment of inertia assumes a value which is comparable to the load to be accelerated or even exceeds this value.

For the selected motor, the rated torque lies below the maximum torque required from the load. This is the reason that the required drive inverter overcurrent must be calculated. For induction motors, the motor current for any particular load point is approximately given by:

Constant flux range $I_{motor} \approx \sqrt{I_\mu^2 + \left(\frac{M}{M_n}\right)^2 * I_w^2}$

Field-weakening range $I_{motor} \approx \sqrt{\left(\frac{n_n}{n}\right)^2 I_\mu^2 + \left(\frac{M}{M_n}\right)^2 * \left(\frac{n}{n_n}\right)^2 * I_w^2}$

The following is obtained with the rated motor current and its power factor:

Active current $I_w = I_n * \cos\varphi = 11.4 A * 0.83 = \underline{\underline{9.46 A}}$

No-load current $I_\mu = \sqrt{I_n^2 - I_w^2} = \sqrt{(11{,}4A)^2 - (9.46A)^2} = \underline{\underline{6.36 A}}$

Max. torque $M = M_{H\_accel} + M_{rotor\_accel1}$

$$M = 47 Nm + 2.8 Nm \approx \underline{\underline{50 Nm}}$$

For the total current, taking into account the point at which field weakening starts is earlier as a result of the limited MM440 output voltage, the motor current is given by:

$$I_{motor} \approx \sqrt{\left(\frac{0.91 * n_n}{n}\right)^2 I_\mu^2 + \left(\frac{M}{M_n}\right)^2 * \left(\frac{n}{0.91 * n_n}\right)^2 * I_w^2}$$

$$I_{motor} \approx \sqrt{\left(\frac{1310RPM}{1500RPM}\right)^2 (6.36A)^2 + \left(\frac{50Nm}{36Nm}\right)^2 * \left(\frac{1500RPM}{1310RPM}\right)^2 * (9.46A)^2}$$

$$I_{motor} \approx \underline{\underline{16A}}$$

Therefore the following the drive inverter was selected

MM440 with integrated Class A filter	*6SE6440-2AD25-5CA1*
	P_n = 5.5 kW,I_n = 13.2 A

In this case, a braking resistor is absolutely necessary because the motor regenerates when lowering the load. Starting from our traversing cycle (raise – pause – lower – pause) the braking resistor has a cycle comprising of 8s pause and 2s braking. The average braking power is calculated as follows without taking into account the efficiency:

$$\overline{P} = \frac{(\frac{P_{lowering\_accel}}{2} * t + \frac{P_{lowering\_brake}}{2} * t)}{t_{brake\_cycle}}$$

$$\overline{P} = \frac{(\frac{4.4kW}{2} * 1s + \frac{5.4kW}{2} * 1s)}{10s}$$

$$\overline{P} = \underline{\underline{490W}}$$

The average braking power must be lower than the permissible continuous braking power of the resistor. This is the reason that we select the following type:

Braking resistor	*6SE6400-4BD16-5CA0*
	P_n = 650 W ; P_{max} = 13 kW

The drive is then completed with the following options:

Cable protective fuses:	*3 x 3NA3007*
Line reactor:	*6SE6400-3CC02-2CD0*
Output reactor:	*6SE6400-3TC03-2CD0*
Pulse encoder module:	*6SE6400-0EN00-0AA0*

Output reactors must be used because shielded cables with a length > 50m (highest limit for shielded cables) are used for the motor feeder cable.

Horizontal axis

Motor type 1LA7107-4AA__ with a rated torque of 20 Nm is the closest motor to providing the torque required for the horizontal axis. Also in this case, a larger motor was selected for the same reasons.

Motor	*1LA7113-4AA__-Z*
	H64=mounting a brake, separately-driven
	fan and pulse encoder
	P_n=4 kW, n_n=1440 RPM, M_n=27 Nm,
	I_n=8.2 A, cos φ = 0.83, J = 0.011 Kgm^2

The influence of the motor moment of inertia must then be checked. The torque required to accelerate the rotor is calculated for this purpose:

$$M_{rotor\_accel2} = \frac{J_{mot2} * \Delta n}{9.55 * t_{accel\_1}} = \frac{0.011kgm^2 * 1500RPM}{9.55 * 1s} \approx \underline{\underline{1.73Nm}}$$

The torque required to accelerate the rotor is relatively small and can therefore be neglected when calculating the RMS torque.

With the rated motor current and its power factor, the following is obtained:

Active current $I_w = I_n * \cos\varphi = 8.2A * 0.83 = \underline{\underline{6.8A}}$

No-load current $I_\mu = \sqrt{I_n^2 - I_w^2} = \sqrt{(8.2A)^2 - (6.8A)^2} = \underline{\underline{4.6A}}$

Max. torque $M = M_{mot\_\max 2} + M_{rotor\_accel2}$

$$M = 35Nm + 1.73Nm \approx \underline{\underline{37Nm}}$$

For the total current, taking into account the point at which field weakening starts is earlier as a result of the limited MM440 output voltage, the motor current is given by:

$$I_{motor} \approx \sqrt{\left(\frac{0.91 * n_n}{n}\right)^2 I_\mu^2 + \left(\frac{M}{M_n}\right)^2 * \left(\frac{n}{0.91 * n_n}\right)^2 * I_w^2}$$

$$I_{motor} \approx \sqrt{\left(\frac{1310RPM}{1500RPM}\right)^2 (4.6A)^2 + \left(\frac{37Nm}{27Nm}\right)^2 * \left(\frac{1500RPM}{1310RPM}\right)^2 * (6.8A)^2}$$

$$I_{motor} \approx \underline{\underline{11.4A}}$$

Therefore the following the drive inverter was selected

MM440 with integrated Class A filter	*6SE6440-2AD24-0BA1*
	P_n = 4 kW, I_n = 10.2 A

A check should now be made as to whether a braking resistor is required for the traversing gear. The motor only regenerates when braking during a traversing cycle.

The average braking power is calculated as follows, without taking into account the efficiency:

$$\overline{P} = \frac{(\frac{P_{\min\_2}}{2} * t)}{t_{brake\_cycle}} \qquad \overline{P} = \frac{(\frac{2.4kW}{2} * 1s)}{5s}$$

$$\overline{P} = \underline{\underline{240W}}$$

The calculated braking power (thermal energy) must be dissipated using a braking resistor. When selecting the braking resistor the average braking power of the load cycle must be less than the continuous braking power of the resistor. This is the reason that we have selected the following components:

Braking resistor	*6SE6400-4BD16-5CA0*
	P_n = 650 W ; P_{max} = 13 kW
Cable protective fuses:	*3 x 3NA3007*
Line reactor:	*6SE6400-3CC01-4BD0*
Output reactor:	*6SE6400-3TC01-0BD0*
Pulse encoder module:	*6SE6400-0EN00-0AA0*

Output reactors must be used because shielded cables with a length > 50m (highest limit for shielded cables) are used for the motor feeder cable.

6.3 Winder

6.3.1 Description

In our particular example, the diameter and the closed-loop control of the tension force are calculated outside the AC drive inverter. The tension is indirectly controlled (closed-loop) by the torque limiting. The AC drive inverter receives, from the higher-level control, a torque and a velocity setpoint.

6.3.2 Data

Max. diameter	dmax = 1.5 m
Min. diameter	dmin = 0.18 m
Tension force	F = 100 Kg*9.81m/s²=981N
Web velocity	v = 200 m/min
Gearbox ratio	i = 4
Efficiency, gearbox	η=0.95
Weight of the full roll	m = 1000 Kg
Suppl. moment of inertia	Jsuppl=0.03kgm²
Ramp-up/ramp-down time	t=10s

6.3.3 Calculation

Velocity and torque are calculated for steady-state operation with both an empty and a full roll.

The following is obtained at the minimum diameter:

$$n_{\max} = \frac{v}{\pi * d_{\min}} = \frac{200m/\min}{\pi * 0.18m} = \underline{\underline{354RPM}} \qquad \text{(max. speed)}$$

$$M_{stat\_\min} = F * \frac{d_{\min}}{2} = 981N * \frac{0.18m}{2} = \underline{\underline{88Nm}} \qquad \text{(min. torque)}$$

On the other hand, at the maximum diameter:

$$n_{\min} = \frac{v}{\pi * d_{\max}} = \frac{200m/\min}{\pi * 1.5m} = \underline{\underline{42.4RPM}} \qquad \text{(min. speed)}$$

$$M_{stat\_\max} = F * \frac{d_{\max}}{2} = 981N * \frac{1.5m}{2} = \underline{\underline{736Nm}} \qquad \text{(max. torque)}$$

The winding power is calculated as follows:

$$P_{winder} = 0.105 * M * n = 736Nm * 42.4RPM \approx \underline{\underline{3.3kW}}$$

A winder has a negative speed – torque characteristic. This means that the power at all operating points is constant under steady-state operating conditions.

The required motor power is directly derived taking into account the efficiency. This is the RMS power provided by the motor. This is the reason that a motor with the same rated power can be used when optimally dimensioned. The rated motor speed would correspond to the min. speed and the max. speed would be reached when the drive is in the field-weakening range. The following values are obtained at the input to the reduction gearbox:

$$n_{motor-\max} = n_{\max} * i = 354RPM * 4 = \underline{\underline{1416RPM}}$$

$$n_{motor-\min} = n_{\min} * i = 42.4RPM * 4 = \underline{\underline{170RPM}}$$

$$M_{motor\_\max} = \frac{1}{\eta} * \frac{1}{i} * M_{stat\_\max} = \frac{1}{0.95} * \frac{1}{4} * 736Nm = \underline{\underline{193.68Nm}}$$

$$M_{motor\_\min} = \frac{1}{\eta} * \frac{1}{i} * M_{stat\_\min} = \frac{1}{0.95} * \frac{1}{4} * 88Nm = \underline{\underline{23.16Nm}}$$

As can be seen in our example, the min. speed does not correspond to the rated speed of a standard motor.

In a second step, the velocities and torques under dynamic load conditions are calculated with an empty and with a full roll.

Moment of inertia of the full roll:

$$J_{winder} = \frac{1}{2} * m * ((\frac{d_{\max}}{2})^2 + (\frac{d_{\min}}{2})^2)$$

$$J_{winder} = \frac{1}{2} * 1000kg * ((\frac{1.5m}{2})^2 + (\frac{0.18m}{2})^2) = \underline{\underline{285.30kgm^2}}$$

1) Accelerating under tension, empty winder

$$M_{accel\_1} = J_{\sup pl} * \frac{\Delta n}{9.55 * t_{up}} + M_{\min}$$

$$M_{accel\_1} = 0.03kgm^2 * \frac{354RPM}{9.55 * 10s} + 88Nm = \underline{\underline{88.11Nm}}$$

2) Accelerating with tension, full roll

$$M_{accel\_2} = (J_{\sup pl} + J_{winder}) * \frac{\Delta n}{9.55 * t_{up}} + M_{\max}$$

$$M_{accel\_2} = (0.03 + 285.30)kgm^2 * \frac{42.4RPM}{9.55 * 10s} + 736Nm = \underline{\underline{\underline{862.68Nm}}}$$

3) Deceleration without tension, empty winder

$$M_{decel\_1} = J_{\sup pl} * \frac{\Delta n}{9.55 * t_{up}} = 0.03kgm^2 * \frac{-354RPM}{9.55 * 10s} = \underline{\underline{\underline{-0.11Nm}}}$$

4) Deceleration without tension, full roll

$$M_{decel\_2} = (J_{\sup pl} + J_{winder}) * \frac{\Delta n}{9.55 * t_{down}}$$

$$M_{decel\_2} = (0.03 + 285.30)kgm^2 * \frac{-42.4RPM}{9.55 * 10s} = \underline{\underline{\underline{-126.68Nm}}}$$

For the torques in dynamic operation, then the maximum drive torque is necessary, logically, when accelerating under tension (Case 2); on the other hand, the maximum braking torque is required when braking without tension (Case 4).

The following torques are obtained, referred to the input of the gearbox:

$$M_{motor\_accel1} = \frac{1}{\eta} * \frac{1}{i} * M_{accel\_1} = \frac{1}{0.95} * \frac{1}{4} * 88.11Nm \approx \underline{\underline{\underline{23Nm}}}$$

$$M_{motor\_accel2} = \frac{1}{\eta} * \frac{1}{i} * M_{accel\_2} = \frac{1}{0.95} * \frac{1}{4} * 863Nm \approx \underline{\underline{\underline{227Nm}}}$$

$$M_{motor\_decel} = \frac{1}{\eta} * \frac{1}{i} * M_{decel\_2} = \frac{1}{0.95} * \frac{1}{4} * -127Nm \approx \underline{\underline{\underline{-34Nm}}}$$

6.3.4 Selecting the components

The information above leads to the conclusion that it makes sense to operate the motor with constant power. This is the reason that an eight-pole motor with a torque ≥ 194 Nm at 170 RPM is selected. The motor type 1LA5207-8AB is the closest that provides this value with a rated torque of 198 Nm. This motor is operated in the field-weakening range with constant power up to a speed of 1416 RPM. It should be checked as to whether sufficient motor torque is available at the maximum speed. In the field-weakening range, the winder is empty, which means that only the steady-state torque M_{motor_min} or the M_{motor_accel1} is required to accelerate the winder.

From the Catalog data it is known that $M_{stall} = 2.2 * M_n$

In the field-weakening range the max. motor torque is given by:

$$M_{mot\_\max} = M_{stall} * \left(\frac{n_n}{n_{\max}}\right)^2$$

In order to maintain a sufficiently large margin to the stall limit, a safety margin of approximately 30 % should be used.

$$M_{mot\_\max} = \frac{M_{stall}}{1.3} * \left(\frac{n_n}{n_{\max}}\right)^2 = \frac{2.2*198Nm}{1.3} * \left(\frac{725RPM}{1414RPM}\right)^2 = \underline{\underline{86.3Nm}}$$

This value lies far above the required values:

$$M_{motor\_\min} or M_{motor\_accel1} \leq 86.3Nm$$

When selecting the motor it is important to note that the motor is force-ventilated. We recommend that a pulse encoder is used in order that the torque is precisely controlled (closed-loop).

Motor	*1LA5207-8AB__-Z H61* *H61=sep.-driven fan+pulse encoder* *P_n=15 kW, n_n=725 RPM M_n=198 Nm* *I_n=32 A, cos φ = 0.78*

The matching MM440 with input filter Class A is the following type:

MM440	*6SE6440-2AD31-8DA1*
	Pn = 18.5 kW, In = 38 A, Imax = 57 A

When selecting the braking resistor a check must be made as to how high the maximum braking power is to brake the full roll (winder) without any tension. The maximum braking power is calculated as follows:

$$\hat{P} = 0.105 * M_{motor\_decel} * n_{motor\_\min}$$

$$\hat{P} = 0.105 * -34Nm * 170RPM \approx -\underline{\underline{0.6kW}}$$

In most cases, the average braking power in operation is extremely low. An operating cycle would have to be analyzed to make a precise calculation. If the conditions regarding maximum braking power are fulfilled, then we can select the sub-chassis braking resistor which matches the drive inverter type.

Braking resistor	*6SE6400-4BD21-2DA0*
	Pn = 1200 W, Pmax = 24 kW

The drive is complemented using the following options:

Cable protection fuses:	*3 x 3NA3022*
Line protection reactor:	*6SE6400-3CC04-4DD0*
Pulse encoder module:	*6SE6400-0EN00-0AA0*

7 Attachment

7.1 Formulas

Formula characters and units

Torque	M [Nm]
Force	F [N]
Power	P [W]
Diameter	d [m]
Speed	n [RPM]
Distance	s [m]
Time	t [s]
Velocity	v [m/s]
Angular velocity	ω [1/s]
Acceleration	a [m/s²]
Acceleration due to gravity	$g=9{,}81 m/s^2$
Friction coefficient	μ [–]
Mass	m [kg]
Moment of inertia	J [kgm²]

Mechanical system

Constant velocity	$v = \frac{s}{t}$	$a = \frac{\Delta v}{t}$
Angular velocity	$\omega = 2 * \pi * f = 2 * \pi * \frac{n}{60}$	
Constant acceleration	$s = \frac{1}{2} * \Delta v * t$	$s = \frac{1}{2} * a * t$
Force due to weight	$F_G = m_1 * g$	
Frictional force	$F_R = \mu * F_G$	
Torque	$M = F * \frac{d}{2}$	
Power	$P_{trans} = F * v$ $P_{red} = 0.105 * M * n$	
Moment of inertia of a hollow cylinder	$J = \frac{1}{2} * m * ((\frac{d_{\max}}{2})^2 + (\frac{d_{\min}}{2})^2)$	
Accelerating torque	$M_{accel} = \frac{1}{\eta} * \frac{J \; * \Delta n}{9.55 * t_{accel}}$	
Braking torque	$M_{brake} = \eta * \frac{J * \Delta n}{9.55 * t_{brake}}$	
RMS torque	$M_{rms} = \sqrt{\frac{M_1^2 * t_1 + M_2^2 * t_2 + M_3^2 * t_3 .....}{t_1 + t_2 + t_3 + ...}}$	
Ratio	$i = \frac{n_{mot}}{n_{load}}$	
Motor torque	$M_{mot} = \frac{1}{i} * M_{load}$	

7.2 Literature

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