ENGINEERING TOMORROW

Danfoss

Handbook | VLT® Frequency Converters

Chapter 9
Sizing and Selection of Frequency Converters

Facts Worth Knowing about Frequency Converters

VLT® THE REAL DRIVE

9 Sizing and Selection of Frequency Converters

9.1 Get the Drive Rating Right

Selecting the right Frequency Converter is a key aspect of designing a variable speed drive system. If the selected unit is too small, it will not be able to control the connected motor optimally at all necessary operating points. If, on the other hand it is too large, there is a risk that the motor will not always be controlled properly, and the design may not be cost-effective.

For the design of most FC's, knowledge of the following basic parameters is sufficient:

- Rating of FC from motor specifications
- Current distribution in the FC (cos φ of the motor)
- Overload capacity
- Control range and field weakening
- Derating of FC
- Regenerative energy
- Motor cable length
- Environment
- Central versus de-centralised installation

After clarification of the basic design parameters for an application, design and analysis of the mechanical components is carried out. The motor to be used must be determined before a suitable FC can be selected. In facility service systems, for example, final selection often takes place only shortly before the building is completed.

Only at this time are most of the components to be used defined, so that an optimised analysis of flow conditions can be carried out reliably.

The more dynamic and challenging the application, the greater the number of factors that must be taken into account in the design. Since FC manufacturers can save costs by restricting the technical features, for each particular case it is necessary to confirm that the features needed for the drive are actually available.

9.2 Rating of the Frequency Converter from Motor Specifications

A widely used method for selecting FC's is simply based on the rated power of the motor to be used. Although manufacturers specify the power ratings of their FC's, this data normally relates to standard four-pole motors. Since the rated currents of motors differ significantly at the same power depending on the construction of the motor (e.g. standard motor and geared motor) and its number of pole pairs, this method is only suitable for providing a rough estimate of the proper FC size. Fig. 9.1 – Nominal current for 1.50kW motors of different poles and manufacturer – shows examples of the rated currents of various 1.5 kW motors.

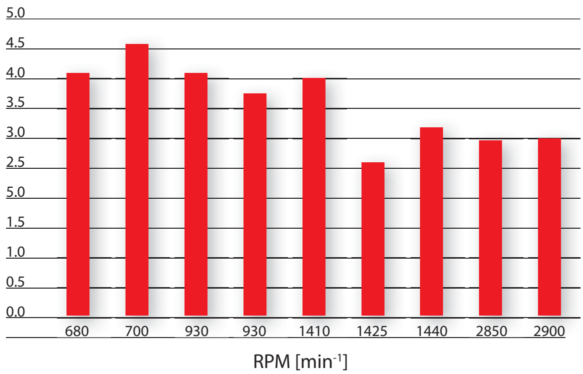

Fig. 9.1 Nominal current for 1.50kW motors of different poles and manufacturer

Furthermore, it should be noted that the current drawn by a motor depends on whether it is connected in star or delta configuration. For this reason FC's should be selected based on the rated current for the type of configuration selected (star or delta).

In addition to the motor current, the required motor voltage must be taken into account. Many FC's can operate over a wide mains supply voltage range (e.g. 3 x 380 – 500V) and thus provide a wide output voltage range. However, the apparent power that the unit can supply is constant over the whole voltage range. Thus the maximum output current is higher at a lower mains voltage and, correspondingly, lower at a higher voltage.

Fig 9.2 Identification data of a Danfoss frequency converter

The nameplate in Fig. 9.2 Identification data of a Danfoss frequency converter comes from a 0.75 kW FC. The specified current values apply to two different voltage ranges. The FC can deliver 2.4 A with a mains voltage of 380 – 440 V. If the unit is supplied with a mains voltage of 441 – 500 V, it can deliver 2.1 A. However, the apparent power available with both voltage ranges is always 1.70 kVA.

9.3 Overload Capacity

When selecting a FC, the load conditions of the application should always be taken into account first. A fundamental distinction is made between quadratic and constant load characteristics, which are the most common in practice.

When a FC controls a motor, torque limits can be set for that motor. Selecting a FC with an apparent power rating that matches the rated current or power of the motor ensures that the required load can be driven reliably. However, an additional reserve is necessary in order to enable smooth acceleration of the load and also cater for occasional peak loads.

Below are examples of a constant load torque characteristic. If a load is placed on a conveyor belt, the torque that must be applied to transport the load is constant over the entire speed range.

Application	Excess load
Lifting equipment	160%
Conveyor belt	160%
Stirrer / Mixer / centrifuge	160%
Rotary piston compressor / piston compressor	150%
Spiral pump (thick sludge)	150%
Sludge dehydration press	150%
Piston pump	150%
Rotary gate valve	150%
Rotary piston blower	110%
Surface aerator	110%
Metering pump	110%
Booster pumps (2-stage)	110%
Recirculation pump	110%
Side channel blower for pool aeration	110%

Table 9.1 Typical overloads in constant torque applications

With a constant load, an over-load reserve of approximately 50 to 60% for 60 seconds is typically used. If the maximum over-load limit is reached, the response depends on the FC used. Some types switch off their output and lose control of the load. Others are able to control the motor at the maximum over-load limit until they trip for thermal reasons.

A quadratic load characteristic usually occurs in applications where increasing speed leads to an increasing quadratic load torque. Fans and centrifugal pumps are amongst the types of equipment that display behaviour of this kind. Furthermore, most applications with a quadratic torque characteristic, such as centrifugal pumps or fans, do not require rapid acceleration phases. For this reason excess load reserves of 10 % are usually chosen for quadratic torques.

See next page with examples of a quadratic load torque characteristic.

Application	Excess load
Fan	110%
Well pump	110%
Booster pump / centrifugal pump	110%
Filter infeed pump	110%
Groundwater pump	110%
Hot water pump	110%
Non-clogging pump (solid materials)	110%
Centrifugal pump / fan	110%
Primary and secondary heating pump	110%
Primary and secondary cooling water pump	110%
Rainwater basin evacuation pump	110%
Recycling sludge pump	110%
Spiral pump (thin sludge)	110%
Submerged motor pump	110%
Excess sludge pump	110%

Table 9.2 Typical overloads in variable torque applications

Even with quadratic load and an over-load capacity of 10% modern FC's can be set up to have a higher break-away torque at start to ensure the proper start of the application.
Remember to consider whether the application will always require a quadratic torque. For example, a mixer has a quadratic torque requirement when it is used to mix a very fluid medium, but if the medium becomes highly viscous during processing, the torque requirement changes to constant.

9.3.1 Energy Efficiency Concerns

In chapter 4 Saving Energy with Frequency Converters we have seen different considerations to be taken to save energy. It is important to remember, that the most energy efficient solution is where the machine, the motor and the FC are selected for the best system efficiency. For example fans speed will typically differ from nominal speed, and so the motor, but many motors have their highest efficiency at a speed between 75 and 100% of nominal speed.

Some brands of FC have a built-in software function, which secure the best motor shaft power related to the FC input power.

9.4 Control Range

The advantage of a FC lies in its ability to regulate smoothly the speed of the motor. However, a wide variety of limits are set for the available controlling range.

On the one hand the possible controlling range (speed range) depends on the control algorithms available of the unit. With the simple U/f control, control ranges that can vary within 1:15 can usually be achieved. If a control algorithm with a voltage vector control is used, a range of 1:100 is possible. If the actual motor speed is fed back to the FC by an encoder, adjustment ranges from 1:1,000 to 1:10,000 can be realised.

In addition to the limits of the control algorithms used, the field-weakening range around the rated frequency of the motor and also low speed running must be taken into account. At low speeds, the motor's self-cooling capacity is reduced. Therefore, in the event of continuous operation in this speed range, either a separately powered external fan must be used to cool the motor or the shaft load must be reduced. The speed below which the torque must be reduced can be found in the manufacturer's data sheets.

If the motor is operated in the field-weakening range, the reduction in the available torque with 1/f and the breakdown torque with $1/f^2$ must also to be taken into account The field-weakening range begins when the FC can no longer hold the U/f ratio constant. In Europe this point typically lies at 400 V/50 Hz and in North America at 460 V / 60 Hz.

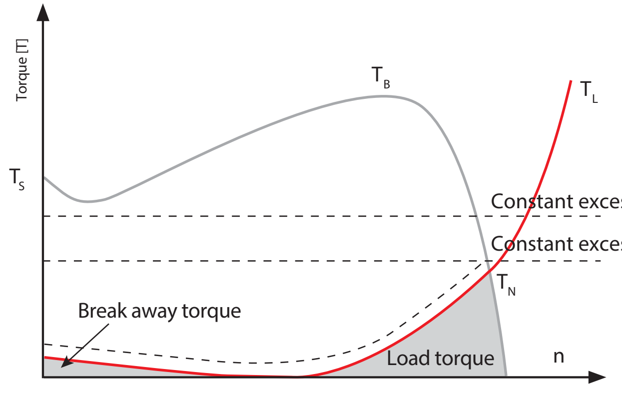

Fig. 9.3 Frequency converter with an optimised characteristic for quadratic loads and an over-load of 110%. In order to achieve higher breakaway torque, the drive is sometimes started with a constant torque before the quadratic characteristic is used

Sometimes motor manufacturers specify higher available torque at a lower duty cycle. A design optimised for intermittent operation can be economical, but it requires a more complex design as shown in Fig. 9.4 Obtaining a good match in speed selection.

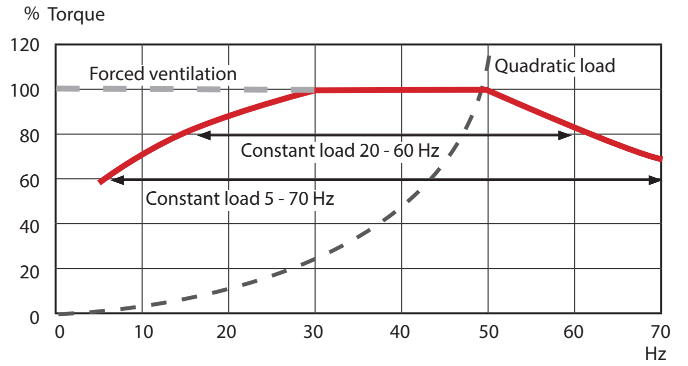

Fig. 9.4 Obtaining a good match in speed selection

9.5 Derating of FC

Maximum ambient temperatures are defined for FC's, as for all electronic units. If the maximum ambient temperature is exceeded, it could lead to failure of the FC, but it also reduces the life-time of the electronics. According to Arrhenius' law, the life-time of an electronic component is reduced by 50% for each 10°C that it is operated above its specified temperature. If FC's have to be operated continuously near the maximum rated operating temperature and the specified life-time of the FC still must be maintained, one option is to derate the power.

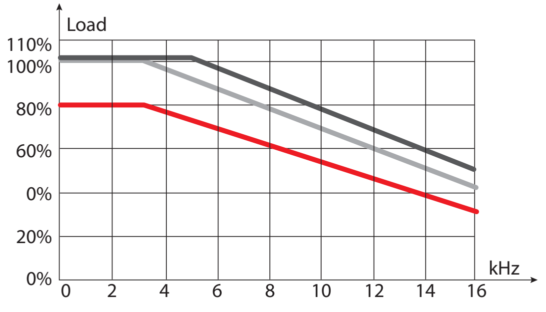

Fig. 9.5 Power reduction diagram for switching frequency and temperature

In the diagram 9.5 Power reduction diagram for switching frequency and temperature, the switching frequency of the inverter is plotted on the X axis. The output current (in %) of the unit is plotted on the Y axis.
Higher switching frequencies result in less irritating motor noise levels. However, the power dissipation in the inverter increases with the switching frequency, leading to additional heating of the unit. Reducing the switching frequency allows the switching losses to be reduced. If the switching frequency is too low, the motor tends to run less smoothly. The switching frequency is thus always a compromise between noise generation, smooth running, and losses.

If, for example a unit is operated at an ambient temperature of 45°C, it can continuously deliver 100% of its rated output current at a switching frequency of 4 kHz. If the ambient temperature increases to 55°C, a current of only around 75% is possible in continuous operation without a reduction of life-time. If the reduction of life-time is not acceptable, a larger FC with sufficient power reserve must be used.

Power derating curves must be observed not only at elevated temperatures, but also at reduced air pressures, such as when FC's are used at elevations above 1000 metres.

9.6 Regenerative Energy

If a motor is driven by an FC that during deceleration the rotor will run faster than the rotating magnetic field causing the motor to act as a generator.
Depending on how much energy is fed back from the motor and how often, various measures must be taken. If the power exceeds the total power losses of the motor and the FC, the intermediate circuit voltage will increase until, at a defined voltage, the FC disables its output and consequently loses the control of the motor.

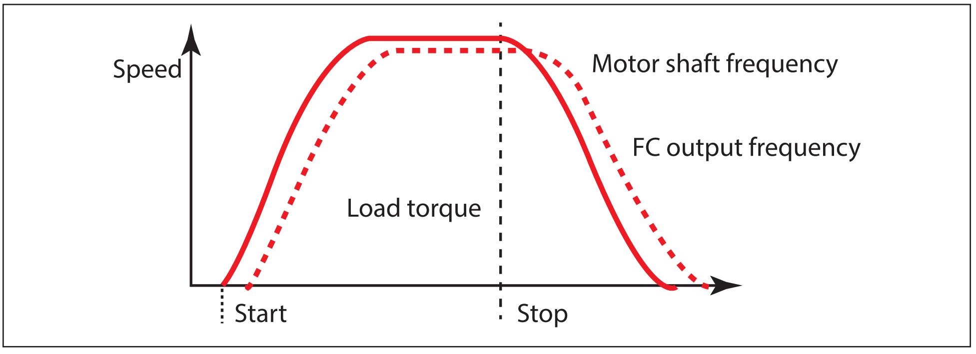

Fig. 9.6 Start/Stop illustrations for regenerative principle

A simple way to avoid such an overvoltage situation is to oversize the FC which would then be able absorb more regenerative energy and hence reduce the risk over-voltage. However, this is often a more expensive solution compared to dynamic braking methods, including the possibility of feeding back the energy to the supply grid. For details please refer to the corresponding subsections in chapter 3 Frequency Converters and Motors.

9.7 Motor Cables

The power components of FC's are designed for specific motor cable lengths. If the specified cable length is exceeded, malfunctions can occur and the FC could trip with an error/alarm message. The capacitance of the cable used is partly responsible for this behaviour. If the capacitance at the FC output exceeds a specified value, transients can occur on the cables that can lead to a malfunction of the FC.

Most manufacturers prescribe shielded cables for their FC's to prevent potential EMC problems. If the user decides on other suitable measures for compliance with EMC requirements then unshielded cables can be used. Since the unshielded cable places a lower capacitive load on the FC, a longer cable length is possible in this case. Typically cable lengths that can be used are 50 m / 75 m (shielded) or 150 m /300 m (unshielded).

Not using shielded motor cables can only be recommended if other measures are taken. Even if an installation operates properly during its acceptance test without shielded motor cables, EMC problems can occur sporadically, or as a result of modifications or extensions to the installation. The financial expenditure then required to eliminate such problems is usually greater than the money saved by using unshielded cables.
When installing cables, care must be taken to avoid additional inductance resulting from routing cables in the form of an air-core coil and additional capacitance resulting from parallel conductors.

If several motors are connected in parallel to the output of a FC, the lengths of the individual motor cables must be added together to determine the connected cable length. Here it should be noted that some manufacturers specify geometrical addition of the individual cable lengths. In such cases, daisy-chaining the motor cable is advisable (Fig. 9.7 Total motor cable length is the sum of all connected parts).
A star formation can cause problems due to the additional capacitance between the individual conductors.

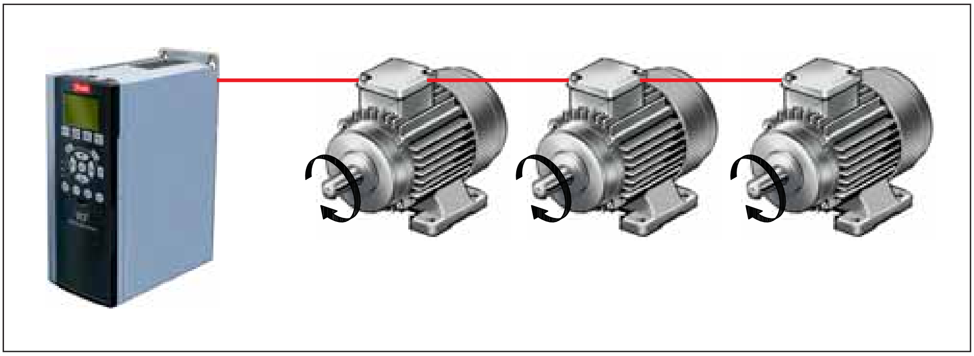

Fig. 9.7 Total motor cable length is the sum of all connected parts

9.8 Environment

Several considerations to the environment should be taken before installing a FC. The following factors should be checked:

- Ambient temperature
- Altitude
- Environment
- EMC
- Harmonic distortion

Minimum and maximum ambient temperature limits are specified for all FC's. Avoiding extreme ambient temperatures prolongs the life of the equipment and maximises overall system reliability. If the FC is installed in environment where the ambient temperature is higher than specified, derating of the power is needed, see Derating of FC.
The cooling capability of air is decreased at lower air pressure. Above 1000 m derating of FC's should be considered.

Electronic equipment is sensitive to the environment. For instance moisture, dust and temperature can all influence the reliability of electronics. Reduced reliability causes downtime in the application with reduced productivity as a result. Therefore it is important to choose the right solution for the actual application.
Basically, it is important to protect the electronics from a harsh environment. The best way to do that is to avoid the harsh environment by placing the electronics outside the harsh environment.

In most cases you cannot directly see how critical the environment is. It depends mainly on 4 factors, the concentration of pollutants present, dirt, the relative humidity and temperature. Most FC manufactures offer these solutions to minimize the effect of the environment:

- Mount the FC's in a central cabinet with long motor cables. In this way the FC's are remote from the critical environment
- Install air-conditioning in the control cabinet that ensures critical environment does not contact the FC's and other electronics. (Positive-pressure).
- Some FC's are fitted with a cold plate. With this solution you can place the FC inside a cabinet and via the cold plate the heat is transmitted to the outside. Then the FC's electronics are kept away from the critical environment
- Use a FC which is fitted with a sealed enclosure. FC manufacturers today offer an enclosure ingress protection up to IP66/Nema 4X which will protect the electronics from the outside environment and eliminates the cost of a separate enclosure
- Order the FC's with conformal coating which will significantly improve protection against chlorine, hydrogen sulphide, ammonia and other corrosive environments

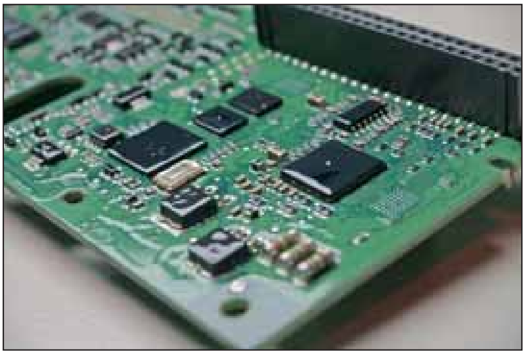

Fig. 9.8 Printed circuit board with conformal coated

The FC is mostly used by professionals of the trade as a complex component forming part of a larger appliance, system, or installation. Therefore note that the responsibility for the final EMC and harmonics properties of the appliance, system or installation rests with the installer who has to ensure compliance with the local regulations.

For details about EMC and harmonics please refer to chapter 5 Electromagnetic Compatibility and chapter 7 Mains Interference.

9.9 Centralised versus Decentralised Installation

The most common form of installation is beyond doubt centralised installation of FC's in control cabinets. The advantages of centralised control cabinet technology lie, above all, in the protected installation of the units and centralised access to them for power, control, maintenance, and fault analysis.

With installation in the control cabinet, the primary aspect that must be taken into account is heat management, not only of the units but also of the whole installation. As a result of the heat dissipation in the control cabinet, additional cooling of the control cabinet may be necessary.

Depending on the FC manufacturer's mounting regulations, minimum distances must be maintained above and below the unit and between the unit and adjacent components. For better heat removal, direct mounting on the rear wall of the control cabinet is recommended. Some manufacturers also specify minimum distances between the individual units. It is however, preferable to mount the units side-by-side if possible in order to utilise mounting surface area effectively.

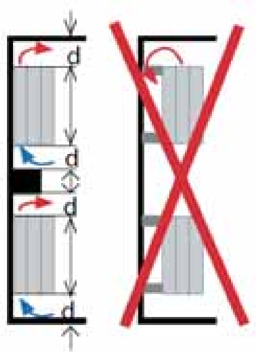

Fig. 9.9 Recommendations for mounting of converters (centralised solution)

A disadvantage of centralised installation in some cases is the long cable lengths to the motors. While the use of shielded cables definitely reduces the RFI effects of the motor cable, these effects are not completely eliminated.

As an alternative to centralised installation, a decentralised approach to the lay-out of a facility can also be chosen. Here the FC is located very close to or directly on the motor.

Motor cable lengths are thereby reduced to a minimum. In addition, decentralised installation offers advantages in fault detection, since the relationship between the controllers and their associated motors is easy to see. In decentralised configurations, a field-bus is usually used to control the drives.

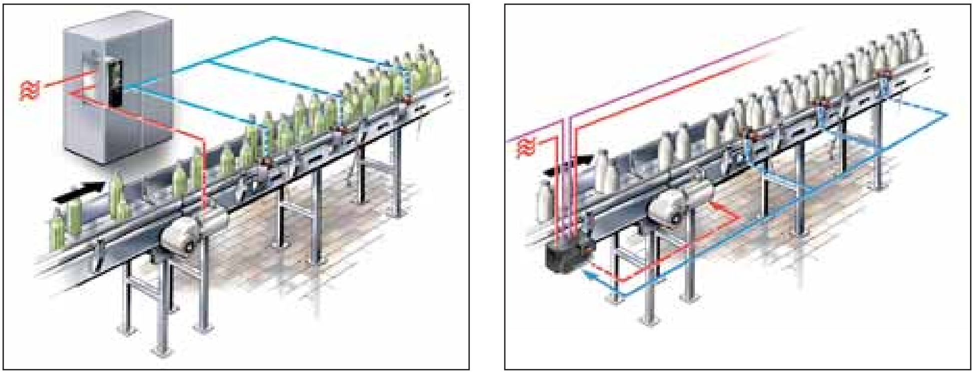

Fig. 9.10 Two concepts – different sets of benefits

When planning a decentralised installation, factors such as ambient temperatures, mains voltage drops, the limited motor cable lengths, etc. must be taken into account. Important factors such as these are often overlooked in the high-level design of engineering projects.

For example, not only the decentralised units but also the supply cables must be suitable for the installation environment. For instance the field-bus cable must be suitable for a harsher environment and sometimes also of the flexible type. In addition, installation of units in inaccessible locations should be avoided in order to ensure quick access for servicing.

Another major consideration is the segmentation of a decentralised network. For economic reasons it is beneficial to combine units into groups or segments. Careful consideration must be given to determining which segments require other segments for their operation, and which segments can, must, may, or should continue to operate autonomously. For example, if certain chemical processes cannot be interrupted, the failure of a lower-level segment must not be allowed to disrupt important segments.

Finally the expertise that is necessary for the installation of a decentralised network should not be underestimated. In addition to knowledge of the field-bus systems used, the technician must be aware of the structure (what happens to the total system if an individual unit fails) and the ambient conditions of a decentralised network and must be able to estimate these effects.
Although decentralised units are always more expensive than centralised units, well-conceived decentralisation concepts can achieve savings of around 25% compared

to centralised systems. The potential for savings in the installation arise from reduced cable lengths and from using equipment modules that have already been built and tested by the machine manufacturer or supplier.

9.10 Examples

The following examples illustrate the basic procedure for selecting a FC in the design process. Here the data sheet reproduced below is used for the selection process. The VLT® AutomationDrive FC 302 is selected as a FC that can operate with a 150m shielded cable.

		P11K		P15K		P18K		P22K	
		HO	NO	HO	NO	HO	NO	HO	NO
Output Current									
Continuous (380-440 V)	[A]	24	32	32	37.5	37.5	44	44	61
Intermittent (380-440V)	[A]	38.4	35.2	51.2	41.3	60	48.4	70.4	67.1
Continuous (441-500 V)	[A]	21	27	27	34	34	40	40	52
Intermittent (441-500 V)	[A]	33.6	29.7	43.2	37.4	54.4	44	64	57.2
Output Power									
Continuous (400 V)	[KVA]	16.6	22.2		26		30.5		42.3
Continuous (460 V)	[KVA]	21.5		27.1		31.9		41.4	
Typical shaft output	[kW]	11	15		18.5		22.0		30.0
Max. Input Current									
Continuous (380-440 V)	[A]	22	29		34		40		55
Intermittent (380-440V)	[A]	35.2	31.9	46.4	37.4	54.4	44	64	60.5
Continuous (441-500 V)	[A]	19	25		31		36		47
Intermittent (441-500 V)	[A]	30.4	27.5	40	34.1	49.6	39.6	57.6	51.7
Estimated power loss at rated max. load	[W]	291	392	379	465	444	525	547	739
Efficiency		0.98							
Max. cable size (mm^2)	([AWG^2])	16 (6)				35 (2)			
Max. pre-fuses	[A]	63				80			

Table 9.3 Data for the VLT® AutomationDrive

Example 1
A 15.0 kW, 3 x 400 V motor (4-pole) is installed together with a transport system (a screw conveyor with a break-away torque of approximately 160%). The current consumption of the motor is 30.0A in continuous operation.

Recommended solution 1
A VLT® AutomationDrive P15K (typical for a 15 kW motor with a high constant load torque) can supply 32 A in continuous operation and has sufficient excess load reserve (160 % / 60 s) to enable it to be used in this application.

Example 2
A 15.0 kW, 3 x 400 V motor (4-pole) is installed together with a centrifugal pump (break-away torque of approximately 60 %).
The current consumption of the motor is 30.0 A at its rated speed.

Recommended solution 2
A VLT® AutomationDrive P11K (typical for an 11 kW motor with a high constant load torque) can nevertheless supply 32 A with a nominal excess load torque of 110 % / 60 s (max.) and can therefore be used in this application. The unit also has tailored functions for additional energy savings.

ENGINEERING
TOMORROW

Contributors:
John Bargmeyer, Michael Burghardt, Norbert Hanigovszki, Marie Louise Hansen, Anna Hildebrand Jensen, Johnny Wahl Jensen, Hans Seekjar, Ana-Mari Tataru-Kjar, Firuz Zare, Thomas Jansen and Martin Černý.

DKDD.PM.403.A3.02