This document seeks to help users to understand and simplify the process of selection, installation and the use of a VSD. Users should see it as a long-term relationship and investment when acquiring a VSD.

Introduction

Electric motors are the workhorses of industry and commerce. Each day large numbers of industrial electric motors are sold throughout the world. These motors are reliable and inexpensive. However they are fixed speed devices, and most applications require a variable speed output from the motor. Frequently this is obtained by coupling some mechanical device (clutch, gear, belt and pulley, etc.) to the motor. These methods are inefficient in terms of mechanical wear and energy consumption.

VSD advantages

VSDs have many advantages and manufacturers of VSDs claims different advantages for their units. This paper will cover a couple of basic functions which we use with most installations.

Speed Control

A fundamental function of a VSD is to adjust the speed of an electric motor. The basic command frequency for VSDs is normally from 0 Hz to 50 Hz, but mostly with the capability to be adjusted up to 400 Hz. If the base frequency of a motor is 50 Hz then the final speed will be 8 times the base frequency of the motor with the command frequency set at 400 Hz.

Due to their design, it is not practically normal for standard induction motors to operate at these high frequencies. In practice a command frequency set point of between 25 Hz and 75 Hz is acceptable without compromising performance or introducing any mechanical damage to the motor. At low frequency set points, care must be taken that there is enough cooling for the motor produced by the mechanical fan.

At high frequency set points mechanical failure may occur due to the mechanical design of the motor bearings normally rated at the design speeds of 2, 4, or 6 poles. At high frequency command speeds, care should be taken as torque loss may be experienced.

Torque control

Basic torque control is possible in an open loop system; however, the actual system response required must be considered. In an open loop system the VSD monitors the motor current and adjusts the voltage to perform torque control, depending on the installation. If the current of the motor does not vary sufficiently, very inaccurate results will be obtained.

Position control

With the aid of an optional interface card most VSDs have the ability to be used as a low cost position controller. Items to be taken into consideration are the dynamic response of the motor and control system. As a rule of thumb an open loop system with a standard squirrel cage induction motor is approximately 400 radians/second. In a closed loop system with a standard squirrel cage induction motor, feedback is approximately 600 radians/second. A full servo system is approximately 1000 radians/second.

Smooth controllable starting and stopping

A Simple adjustment of the time required to accelerate the motor from rest to full speed (Starting), normally 50 Hz, and from full speed to rest (Stopping), ensures a smooth controllable start and stop sequence. This reduces mechanical wear on the machine. Various types of starting and stopping curves are available by setting the correct parameters in the VSD as illustrated in figure 1a to c.

Energy saving

We know that a Direct On Line (DOL) starter will supply full voltage to the motor at the supply frequency with the current uncontrollable. The motor will use as much current as the load...
requires - normally between 600 to 700% of the full load current of the motor.

Before the days of Soft Starters and VSDs our alternative to control the starting current was with Star-Delta starters, which reduced the starting current to approximately 200%. Our next best device today to limit the starting current is to fit a Soft Starter. With Soft Starters we use the Phase Angle principle to control the voltage and therefore reduce the starting current while at the same time producing a smooth controllable start. The limitation is that these units are very basic and have limited adjustable time settings, normally from 0 to 60 seconds.

The current limiting features on VSDs ensure that when you accelerate a motor from rest, you will not exceed more than 100% of the full load current of the motor. Replacing DOL starters with VSDs will reduce the Current Demand when starting motors. VSDs will deliver maximum torque at the motor shaft while limiting the current to the full load current setting of the motor in the VSD.

It is the responsibility of every individual to use forms of energy effectively and efficiently. It is already well known in the Heating and Ventilation industry that volumes, flows and pressures of centrifugal fans, pumps and compressors can be controlled by mechanical means to match the demands of the system. Many of them do not consider the immense amount of energy (i.e. watts, i.e. money) that can be saved by using modern reliable electronic technology.

If the efficiency of the system can be improved the power demand drops proportionally with the increased efficiency. Almost all fans, pumps and compressors are over designed (just in case) and seldom do they work at their maximum designed efficiency point.

Fitting an inverter to a fan, pump or compressor motor varies the motor speed which then varies the characteristics of the fan, pump or compressor to operate at a different efficiency, producing energy savings.

The Affinity Laws say that flow is proportional to speed and kilowatts vary as the cube of the speed.

Flexibility

The flexibility to set up and configure a VSD for various applications, e.g. Constant torque, Variable torque, Hoisting and many others, allow users to customise units to suit their needs. See illustrations in Figs. 2 and 3.

User friendly

Most VSD are supplied with basic LCD or LED display keypads, with which the user can adjust parameters such as acceleration time, deceleration time, full load current, etc. This allows the user to customise the inverter for his application. Most VSDs have advanced units that could copy parameters from one unit to another. Apart from this basic function, most units available today are supplied with serial communication ports to interface with personal computers that allow users to analyse the behavior of their system.

Ability to interface with other intelligent control systems

Our demanding society forces managements to know what is happening in their plant and processes. Information from VSDs is not only for the engineer’s benefit, but also allows managements to see if they could increase their production safely without overloading the process or plant. This is normally done via the serial interface. It is also possible to integrate units into a complex network system.

Mechanical wear and tear

It is to the advantage of the users that where mechanical wear is part of the process, users could speed up or slow down their application to deliver the necessary production.

In a case study it was found that due to excessive wear, the life of a pump was approximately six months. A VSD was fitted to regulate the flow as the flow reduced due to impeller wear. This enabled the user to increase the speed of the pump to produce the required flow, increasing the life of the pump from six months to twelve months. The other benefit was that when the pump was still new the speed could be reduced according to the necessary flow required, saving energy and decreasing the wear on the impeller.

VSD disadvantages

VSDs Due do not have many disadvantages with respect to industrial standards and regulations. Most high quality VSDs comply with standards and regulations. Manufacturers improve their products with ongoing research and development programmes. To eliminate any disadvantages, manufactures will also advise users on how to install and operate their units.

Audible noise

Various stages of the switching frequency produce audible noise from the motor. Although this is not harmful to the motor, in most instances the noise is not acceptable. The noise is unpleasant and irritating in quiet offices, hospitals and other such environments. To overcome this problem most VSDs’ switching frequency could be increased to a higher value, which will eliminate the noise problem, but this will introduce harmonics. Therefore proper design of an installation should be done before using VSDs.

RFI

Radio Frequency Interference generated by VSDs can be very problematic, introducing faults on other equipment in close proximity to the installed unit. Most drives can be expected to meet the immunity requirements of the CENELEC generic standard EN50082-2.
Harmonics

VSDs, like most other electronic equipment, do not draw their current as a smooth sinusoidal supply. The supply current waveform is generally referred to in terms of the harmonics of the supply frequency, which it contains. The harmonic current causes harmonic voltage to be experienced by other equipment connected to the same supply. Because harmonic voltage can cause disturbance or stress to other electrical equipment connected to the same supply, because harmonic voltage can cause disturbance or stress to other electrical equipment connected to the same supply system, there are regulations in place to control it. If installations contain a large number of VSDs and/or other power electronic equipment such as UPSs, then they may have to be shown to satisfy the supply authorities’ harmonic guidelines before permission to connect is granted. As well as obeying regulations, users of drives need to ensure that the harmonic levels within their own plant are not excessive.

Some of the practical problems, which may arise from excessive harmonic levels, are:

- Poor power factor, i.e. high current for a given power
- Interference to equipment, which is sensitive to voltage waveform
- Excessive heating of neutral conductors (single-phase loads only)
- Excessive heating of induction motors
- High acoustic noise from transformers, bus bars, switchgear etc.
- Abnormal heating of transformers and associated equipment
- Damage to power factor correction capacitors

An important property of harmonics is that they tend to be cumulative on a power system, i.e. the contributions of the various harmonic sources add up, to some degree. This is different from other high-frequency electromagnetic compatibility (EMC) effects, which are generally localised and not significantly cumulative. It is important to differentiate harmonics from high-frequency EMC effects, which tend to cause interference to sensitive data and measuring circuits by stray coupling paths. With few exceptions, if harmonics cause disturbance it is through direct electrical connection and not through stray paths. Screening is rarely a remedial measure for harmonic problems.

Ignorance

The biggest disincentive to use VSDs and enjoy their ability to improve our lives is ignorance and unwillingness to change. “My motors worked for the last 20 years with Direct on Line starters - why should I complicate my life and let something that I do not understand and is very expensive, control my process?” Even worse, now I need to employ a highly qualified technical engineer to maintain my plant”. These remarks, and ignorance of the instruction manual, create a bad image of a product that improves life for all of us.

Selection criteria

Summarised is some of the basic criteria to successfully install a VSD

Supply Voltage

Always ensure that the correct voltage is available. In many cases user’s interpretation of a VSD is that you could supply the unit with single-phase 220 V AC and control a three-phase motor rated for 380 V AC. Most standard induction motors could operate with three phase 380 V AC with all six leads from the windings available and connected in a Star configuration. The same motor could operate with 3 Phase 220 V AC if the leads from the windings are connected in a Delta configuration. However, consult the motor manufacturer if it is not indicated on the motor nameplate.

Kilowatt size

It is not totally correct to select an inverter according to motor capacity in “kW”. It is better to select an inverter based on the rated current of a motor. If the inverter and the motor have the same capacity (kW), an increase in the number of motor poles reduces the efficiency and power factor of the motor increasing the rated current value.

Torque requirements

If we look at the following calculations we will understand why torque loss happens when running a motor above base speed. This will also explain some of the basic requirements why torque is an important factor when selecting a VSD.

Motor speed:

\[ n = \frac{60 \times f}{P} \]  

where:

- \( n \) = Motor speed (rpm)
- 60 = Seconds (s)
- \( f \) = Supply frequency (Hz)
- \( P \) = Pairs of motor poles (A four pole motor will have 2 pairs)

Motor torque:

\[ W = \frac{2 \times \pi \times M \times n}{60} \]  

where:

- \( W \) = Watts
- \( \pi \) = Pi (Mathematical constant = 3.142)
- \( M \) = Torque (Nm)

Example:

A mechanical engineer designs a machine that requires 405 Nm and a speed range from 100 to 175 rpm. By fitting a 10/1 ratio gearbox to the machine he reduces the input torque required to 40.5 Nm, while the minimum and maximum input speeds increase to 700 and 1750 rpm respectively. A four-pole 7.5 kW motor (1500 rpm @ 50 Hz) produces 47.8 Nm. We need to calculate if he will produce enough torque at the maximum speed.

To reduce the speed to 1000 rpm is not a problem, as long as he keeps the motor speed above 50% of the base speed to produce enough cooling.

A VSD will produce the full load torque of the motor up to the base frequency by changing the voltage to produce the necessary torque. Once the motor reaches its base speed and supply voltage the VSD can only change the frequency supplied to the motor to increase the speed - the VSD cannot supply a higher voltage than the supply voltage.

To calculate the torque produced by the 7.5 kW at 1750 rpm we have to manipulate the above formula.

\[ M = \frac{5700 \times 60}{2 \times 3.142 \times 1750} \]

\[ M = 40.9 \text{ Nm} \]

Therefore the 7.5 kW motor with a VSD fitted can produce the necessary torque at the correct speed. From this we can see that it is always necessary to check if the speed/torque range is within the capability of the Inverter and motor.

DC Injection braking

In most hoisting applications, the motor must be kept at zero speed and in position for a short period of time allowing the mechanical brake to open or close. To keep the motor in this position the inverter injects DC into the motor that causes it to produce torque at standstill (zero speed). This type of braking is sometimes misunderstood as DC Bus braking, which is explained in the next section. When selecting a VSD, and the applications requires this function, ensure that it is the function required.

DC Bus braking / resistive braking

DC Bus braking is able to control the
deceleration of induction motors without activating the over voltage protection function on VSDs. When applications require a fast deceleration function or the load is very unstable it could be controlled with this function. There are various methods to solve the problem depending on the application. It could be done with a regenerative system, feeding energy back to the mains or with a brake unit and brake resistors dissipating the energy through external resistors.

The main features of an AC regenerative system are:

- Energy saving
- Expensive to install
- The input current waveform is sinusoid
- The input current has a near unity power factor
- The output voltage for the motor can be higher than the available AC mains voltage
- The regenerative unit will synchronise to any frequency between 30 and 100 Hz, provided that the supply voltage is between 380 V – 10 % and 480 V + 10 %
- Under conditions of AC mains instability, a Mitsubishi drive regenerative system can continue to function down to approximately 270 V AC supply voltage without any effect on the DC Bus voltage and hence on the operation of the motor drives
- The regenerative and motor drives are identical

When using either the internal braking system of the VSD with resistors or an external brake unit with resistors we waste energy unnecessarily. This, however, is the cheapest solution and unfortunately selected by most customers.

Fig. 5: Inverter’s internal protection.

Installation tips and tricks

Environmental requirements

Most VSDs are supplied with a protection rating of IP20 (finger proof). This normally requires that the inverter needs to be mounted in a floor-standing enclosure or wall mounted panel, to increase the degree of protection. Refer to Table 1 for standard rating of protection.

Cooling

The reliable trouble-free operation of all industrial equipment is dependent upon operation in an environment for which that product was designed. The single most significant reason for the premature failure of a VSD controller is operation in excessive ambient temperature.

The design of the enclosure in which the drive is housed is therefore of critical importance. The following guidance covers the basic calculations necessary to ensure that heat generated by a drive can be satisfactorily transferred to the air surrounding the cubicle.
When making the calculation, remember to take account of all power dissipated inside the cubicle, and not simply that generated by the drive. Further, in the internal layout of the cubicle, where possible, avoid placing electronic components at the top (hot air rises!), and where possible provide fans to circulate internal air. Remember, as a rule of thumb, an electronic product's lifetime halves for every 7 °C temperature rise.

The enclosure itself transfers the internally generated heat into the surrounding air by natural convection, or external forced airflow. The greater the surface area of the enclosure walls, the better is the dissipation capability. Remember also, that only walls which are not obstructed (not in contact with walls, floor or another hot enclosure) can dissipate heat to the air.

Calculate the minimum required unobstructed surface area $A_e$ for the enclosure as follows:

$$ A_e = \frac{P}{k(T_e - T_{amb})} \quad (3) $$

where:

- $A_e$ = Unobstructed surface area (m²)
- $P$ = Power dissipated by all heat sources in the enclosure (W)
- $T_{amb}$ = Maximum expected ambient temperature outside the enclosure (°C)
- $T_e$ = Maximum permissible ambient temperature inside the enclosure (°C)
- $k$ = Heat transmission coefficient of the enclosure material (W/m²·°C).

Example

To calculate the size of an enclosure to accommodate the following:

- Two Mitsubishi 3,7 kW drives
- EMC filter for each drive
- Braking resistors mounted outside the enclosure
- Maximum ambient temperature inside the enclosure 40 °C
- Maximum ambient temperature outside the enclosure 30 °C
- Maximum dissipation of each drive = 190 W
- Maximum dissipation of each EMC filter = 25 W

Total dissipation = 2 x (190 + 25) = 430 W

The enclosure is to be made from painted 2 mm sheet steel having a heat transmission coefficient of 5,5 W/m²·°C. Only the top, the front and two sides of the enclosure are free to dissipate heat.

The minimum required unobstructed surface area $A_e$ for the enclosure is as follows:

$$ A_e = \frac{430}{5,5 (40-30)} \quad (4) $$

$$ A_e = 7,8 \text{ m}^2 $$

If we select an enclosure with a height (H) of 2 m, a depth (D) of 0,6 m, and a minimum width $W$:

- Dissipating surfaces $> 7,8 \text{ m}^2$
- Top + Front $> 7,8 \text{ m}^2$

$$ (W_{\text{max}} \times 0,6) + (W_{\text{min}} \times 2) + (2 \times 0,6 \times 2) > 7,8 \text{ m}^2 $$

$$ W_{\text{min}} > (7,8 - 2,4)/2,6 $$

$$ W_{\text{min}} > 2,1 \text{ m} $$

If the enclosure is too large for the available space it can be made smaller by:

- Reducing the power dissipation in the enclosure
- Reducing the ambient temperature outside the enclosure
- Increasing the permissible ambient temperature inside the enclosure if possible by derating equipment in line with manufacturer’s recommendations
- Increasing the number of unobstructed surfaces of the cubicle
- Circulating the air flow in a ventilated enclosure

In this case the dimensions of the enclosure are determined only by the requirements to accommodate the equipment making sure to provide any recommended clearances. The equipment is cooled by forced airflow. This being the case it is important is such arrangement to ensure that the air flows over the heat-generating components to avoid localised hot spots.

The minimum required volume of ventilating air is given by:

$$ V = \frac{3kP}{T_e - T_{amb}} \text{ m}^3/\text{hr} $$

Where:

- $V$ = Cooling air flow (m³/hr⁻¹).
- $P$ = Power dissipated by all heat sources in the enclosure (W).
- $T_{amb}$ = Maximum expected ambient temperature outside the enclosure (°C).
- $T_e$ = Maximum permissible ambient temperature inside the enclosure (°C)
- $k$ = ratio of $p_o$ / $p_i$

Typically, a factor of 1,2 to 1,3 can be used to allow for pressure drops in dirty air filters.

Example

To calculate the size of an enclosure to accommodate the following:

- Three Mitsubishi 15 kW drives
- EMC filter for each drive
- Braking resistors mounted outside the enclosure
- Maximum ambient temperature inside the enclosure 40 °C
- Maximum ambient temperature outside the enclosure 30 °C

Maximum dissipation of each drive = 570 W
Maximum dissipation of each EMC filter = 60 W
Total dissipation = 3 x (570 + 60) = 1890 W
Then the minimum required volume of ventilating air is given by:

**Electronic overload relays**

It is important to recognise that the non-sinusoidal waveforms, and variable frequency, associated with Inverters, invalidate the basis for protection afforded by most electronic overload relays. The use of such devices on the mains supply of an inverter is also invalid. Please consult the manufacturer before using any of these devices.

**Fusing**

Fuses should not be seen as an overload protection device; Inverters regulate the current flowing in the system and fusing needs to be designed to cater for catastrophic failure within the drive or a short circuit between cables. High rupturing capacity fuses (HRC) act as clearing devices for sustained high currents and are consequently well suited to this type of duty, and is commonly recommended by most drive manufacturers.

Typical fuse recommendations for three-phase AC Inverters are given in Table 2.

**Motor and inverter protection**

Apart from the VSD’s built-in motor overload protection, internal heat, short circuit and ground fault protection is provided. The electronic overload protection for the motor also takes into account the reduced cooling when the motor is operated at low speeds without forced ventilation.

**Long motor cables**

The use of chokes to facilitate the application of long motor cables is rare. It is usually simpler and more elegant to use a larger inverter rating.

Because of charging currents, long motor cable runs can cause a reduction in the torque available from the inverter. This could also cause the inverter to trip due to excessive current normally experienced with smaller capacity inverters.

The following guidelines give suggested limits for standard shielded cables. The capacitance of the cable is approximately 300 pF/m measured from the three phases together to the sheath. This is typical of steel wire armoured cable (SWA) and similar, where the individual phase conductors are surrounded by a further insulating medium before being covered by the screen. For other values of capacitance the length limits are approximately in inverse to the capacitance.

Note that individual separate phase conductors give lower capacitance, but may not be acceptable for EMC reasons. Cables where the screen is laid over the phase conductors and mineral insulated cables are known to have much higher capacitance and should be treated with caution.

**Maximum cable lengths at a specific supply voltage and switching frequency**

The above cable lengths are for Mitsubishi FR-A500 series VSDs. Please consult with the inverter manufacturer before installing.

For other switching frequencies:

\[
\text{Maximum cable length} = \frac{\text{maximum cable length at 3 kHz}}{3 \text{ kHz / switching frequency}}
\]

**Output chokes**

Calculation of the necessary inductance of the choke is complex. However the following guidelines might be helpful.
will be rather lower than the specified 50Hz inductance. A good rule of thumb is to specify an inductance of twice that determined by this calculation. The acceptable voltage drop at the working frequency determines the maximum value of inductance. Calculate this from the following expression:

\[ L_{\text{min}} = \frac{xV_{\text{DC}}}{2\pi f_{\text{max}} \sqrt{3}I_{\text{DC}}} \]  

(8)

where:

- \( x \) = Acceptable volt drop over the choke
- \( V_{\text{AC}} \) = Motor voltage rating (line to line RMS)
- \( f_{\text{max}} \) = Maximum inverter output frequency

If \( 2L_{\text{min}} \leq L_{\text{max}} \), then any value between these limits can be used.

If \( 2L_{\text{min}} > L_{\text{max}} \), then the inverter cannot operate with this length of cable and a higher rated inverter must be used.

Consideration must be given to the high frequency losses in the chokes. This can be estimated from the following expression:

\[ P = 0.866V_{\text{DC}}I_{\text{DC}} \]  

(9)

where:

- \( f_{\text{sw}} \) = Switching frequency

The factor 0.8 is a rough estimate of the fraction of the total losses dissipated in the choke. Note that the loss is proportional to the switching frequency so the lowest acceptable frequency should be selected.

It is now necessary to decide whether the choke is able to tolerate this loss. This is a difficult judgment. As a crude rule, the loss should not exceed 0.1 VA in the choke at maximum speed, i.e.:

\[ P \leq 0.2\pi f_{\text{sw}}L_{\text{choke}}I_{\text{max}}^2 \]  

(10)

The value is not critical and variations of \( \pm 50\% \) are acceptable. The power rating of the resistor should be at least 0.8P. Provision must be made for the resistor to dissipate this power without overheating itself or nearby equipment. Values of 100 W per phase are not uncommon.

**Supply impedance**

High quality commercial VSDs are designed to operate from typical industrial power distribution systems with a maximum fault level of ten to twenty times the inverter’s rated power. Problems can also occur if a drive system is installed close to the main power supply or power factor correction capacitors, both of which present low supply impedance to the drive. AC inverters fitted with DC link chokes are in general unaffected by low supply impedance.

A good rule of thumb is to ensure a total supply impedance of approximately 4% reactance. Where information about the supply is not known, it is good practice to fit line reactors of 2%.

There is no easy solution for high supply impedance as power lines carrying drive current need to be oversized, as do transformers used in order to minimize the impedance. This over sizing may need to be as high as five times that normally considered adequate.

**Brake resistor selection**

Firstly we need to understand what happens when a motor deCELERates to stop under a high inertia load. When the motor starts to decelerate and the load keeps on rotating the motor, the motor starts to act as a generator sending energy back to the VSD. With energy from the main supply and from the motor, now acting as a generator, the DC Bus voltage level starts to rise from approximately 560 V DC to levels that will activate a DC Bus over voltage trip. Most inverters can sustain levels up to 780 V DC before tripping. Some inverters equipped with internal braking circuits and resistors will control this rise in DC Bus voltage but only for a short duration. If a lengthy or heavy-duty brake cycle is required, it is best to fit external units that could cope with the extra energy safely.

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**Table 2: Fuse ratings.**

Estimate the cable capacitance (C), from one line to all others.

Typical values

- Screened/armoured cables where there is a plastic sheath between the phase and the screen: 130 pF/m
- Screened cables with no plastic sheath between cores and screen, mineral insulated cables: 300 pF/m
- Add an allowance for the motor capacitance: 1 nF is a reasonable estimate

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<th>Current (A)</th>
<th>Motor cable (mm²)</th>
<th>Fuse rating (A)</th>
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<tr>
<td>4 kW</td>
</tr>
<tr>
<td>5,5 kW – 11 kW</td>
</tr>
<tr>
<td>15 kW – 90 kW</td>
</tr>
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</table>

**Table 3: Long motor cables.**

- Decide on the available charging current \( L_{\text{choke}} = 1.41L(2 - k) \)
- Where:
  - \( I_{\text{n}} \) = Nominal rated r.m.s output current
  - \( k \) = Acceptable short term overload factor
- Factor 1.41 = Maximum DC link voltage
- Factor 2 = Inverter instant trip current to nominal output current
- Most inverters are rated at 150%, i.e. \( k = 1.5 \)
- Maximum DC link voltage can be calculated from the highest RMS AC supply voltage times 1.41
- Now calculate the minimum inductance per phase from the following expression

\[ L_{\text{max}} = \left( \frac{V_{\text{DC}}}{f_{\text{sw}}} \right)^2 \]  

(7)

If using standard iron-cored chokes, the inductance at the high frequencies involved
To reduce the cost and physical size of VSDs, and the fact that very few applications require DC Bus braking, manufacturers only provide units with limited DC Bus braking capabilities. Users should consult with manufacturers as to the capability of the units before installing them in these applications.

Two important factors to consider are the required braking torque and the duty cycle of the application. Kinetic energy of the motor and load

\[ KE = \frac{1}{2} J \omega^2 \]

where:
- \( J \) = Total inertia (kg m\(^2\)) of the motor, transmission and driven machine
- \( \omega \) = angular velocity

If there is gearing between the motor and the driven machine, \( J \) is the value reflected at the motor shaft.

As the energy regenerated is proportional to the square of the angular velocity, most of the energy in the system is concentrated at the higher operating speed, and is delivered to the resistor at the start of the deceleration.

Example:

A system inertia of 10 kg m\(^2\) is to be decelerated from full load speed to rest. We need to find the braking resistor value and maximum braking torque.

Drive rating = 30 kW

Motor rating = 30 kW

Motor full load speed = 1475 rpm

Motor nominal torque rating = 191 Nm

Repeat cycle time = 30 seconds

Resistor operating voltage = 660 V

Our first step is to determine the minimum deceleration time \( t_b \).

Maximum braking torque \( M_b \) is identical to maximum accelerating torque

\[ M_b = J_\omega \frac{\alpha}{\theta_b} = \frac{\pi}{30} \frac{\pi}{\theta_b} NM \]  \hspace{1cm} (13)

\[ \alpha \theta _b = \frac{30 M_\omega}{\theta_b} \]

But maximum deceleration occurs at 150% of motor nominal torque. The value to apply for \( M_\omega \) is therefore

\[ 1.5 \times 191 = 286.5 \text{ Nm} \]

So the actual deceleration time \( t_b \) is:

\[ t_b = \frac{1.5 \times 1475}{30 \times 286.5} \text{ seconds} \]

\[ = 5.39 \text{ seconds} \]

This is the minimum deceleration time. For

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<thead>
<tr>
<th>Name of Application</th>
<th>Load torque as percentage of full load driving torque</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Breakaway</td>
</tr>
<tr>
<td>Agitators</td>
<td>Liquid</td>
</tr>
<tr>
<td></td>
<td>Slurry</td>
</tr>
<tr>
<td>Blowers, centrifugal</td>
<td>Valve closed</td>
</tr>
<tr>
<td></td>
<td>Valve open</td>
</tr>
<tr>
<td>Blowers, positive-displacement, rotary, bypassed</td>
<td>40</td>
</tr>
<tr>
<td>Centrifuges (extractors)</td>
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</tr>
<tr>
<td>Compressors, axial-vane, loaded</td>
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</tr>
<tr>
<td>Conveyors, shaker-type (vibrating)</td>
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</tr>
<tr>
<td>Escalators, stairways (starting unloaded)</td>
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</tr>
<tr>
<td>Fans, centrifugal, ambient</td>
<td>Valve closed</td>
</tr>
<tr>
<td></td>
<td>Valve open</td>
</tr>
<tr>
<td>Fans, centrifugal, hot gases</td>
<td>Valve closed</td>
</tr>
<tr>
<td></td>
<td>Valve open</td>
</tr>
<tr>
<td>Fans, propellers axial-flow</td>
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<tr>
<td>Frames, spinning, textile</td>
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<tr>
<td>Grinders, metal</td>
<td>25</td>
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<tr>
<td>Machines, buffing, automatic</td>
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<tr>
<td>Machines, cinder-block, vibrating</td>
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<tr>
<td>Machines, key seating</td>
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<tr>
<td>Machines, polishing</td>
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<tr>
<td>Mills, flour, grinding</td>
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<tr>
<td>Mixers, chemical</td>
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<tr>
<td>Mixers, concrete</td>
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<tr>
<td>Mixers, dough</td>
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<tr>
<td>Mixers, liquid</td>
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<tr>
<td>Mixers, sand, centrifugal</td>
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<tr>
<td>Mixers, sand, screw</td>
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<tr>
<td>Mixers, slurry</td>
<td>150</td>
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<tr>
<td>Mixers, solid</td>
<td>175</td>
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<tr>
<td>Pumps, adjustable-blade, vertical</td>
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<tr>
<td>Pumps, centrifugal, discharge open</td>
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</tr>
<tr>
<td>Pumps, oil-field, flywheel</td>
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<tr>
<td>Pumps, oil, lubricating</td>
<td>40</td>
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<tr>
<td>Pumps, oil fuel</td>
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<tr>
<td>Pumps, propeller</td>
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<tr>
<td>Pumps, turbine, centrifugal, deep-well</td>
<td>60</td>
</tr>
<tr>
<td>Pumps, vacuum (paper-mill service)</td>
<td>40</td>
</tr>
<tr>
<td>Pumps, vacuum (other applications)</td>
<td>150</td>
</tr>
<tr>
<td>Pumps, vacuum, reciprocating</td>
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</tr>
<tr>
<td>Rolls, crushing (sugar cane)</td>
<td>50</td>
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<tr>
<td>Rolls, flaking</td>
<td>30</td>
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<tr>
<td>Screens, centrifugal (centrifuges)</td>
<td>40</td>
</tr>
<tr>
<td>Screens, vibrating</td>
<td>60</td>
</tr>
<tr>
<td>Separators, air (fan-type)</td>
<td>40</td>
</tr>
<tr>
<td>Washers, laundry</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 4: Application load torque percentages
example, let us decide on a more practical deceleration time of 7 seconds. We can now calculate the maximum braking torque to decelerate the load in 7 seconds:

\[ M_b = \frac{n^2}{30} \cdot J \cdot \frac{n}{N_b} \]
\[ M_b = \frac{10 \times 1475}{30 \times 7} \cdot N_w \]

\[ = 220,64 \text{ Nm} \]

Braking Power is:

\[ P_b = \frac{n \cdot M_b \cdot n}{30 \times 10^3} \cdot N_w = \frac{\pi \times 224,38 \times 1475}{30 \times 1000} \]
\[ = 34,65 \text{ kW} \]

Resistor resistance value (\( \Omega \)):

The motor is capable of delivering up to 150% of its full load rating for up to 60 seconds maximum, i.e.:

\[ 1,5 \times 30 = 45 \text{ kW} \]

It is therefore equally capable of regenerating the same short time power. As 45 kW is in excess of 35 kW required for the application, the value of the resistor is:

\[ R = \frac{V^2}{P_b} = \frac{660^2}{35 \times 1000} \]
\[ = 12,45 \Omega \quad (14) \]

Resistor power rating \( P_r \):

As the braking operates intermittently, the resistor can be selected from a range offering “intermittent” rather than “continuous” power absorption. Advantage can also be taken of the overload rating of the resistor by applying an overload factor, which will be derived from a set of cooling curves obtained from the manufacturer or supplier of the resistor. In this example, deceleration time is taken as 7 seconds, repeat cycle time 30 seconds. From typical data the overload factor is 2.

The power rating of the chosen resistor is:

\[ P_r = \frac{P_b}{\text{O/L Factor}} = \frac{35}{2} = 17,5 \text{ kW} \quad (15) \]

For practical purposes, it can be assumed that 15% to 20% of energy dissipated during the regenerative braking is due to electrical losses in the motor and inverter, and mechanical losses in the motor and load, all of which assist the braking. In practice, using the recommended resistor value will result in extra braking torque available. However, the rate of energy feedback from the load inertia is determined by the rate of deceleration.

A braking resistor must be installed in accordance with instructions provided by its supplier or manufacturer. The braking resistor should incorporate a thermal tripping device, which should be connected to a trip release mechanism to stop the VSD.

Resistors intended for braking duty should be capable of tolerating thermal shock. “Pulse rated” resistors are recommended.

Application selection

The following table is a guide to torque requirements in certain applications.

References


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