THE PRACTICAL EFFECTS OF VARIABLE SPEED DRIVE USE ON THE CONVEYOR SPEED REDUCER

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INTRODUCTION

The use of Variable Speed Drive technology, hereafter referred to as VSD, is becoming more commonplace on conveyor drives. This is due to the operating freedom given by VSD. The most used feature of VSD is its soft-start capability. VSD also allows for the operation of the induction motor at various speeds, which provides a cost effective option to control belt throughput, making the belt system more efficient.

The use of VSDs on conveyor drives has not been studied from the perspective of their effects on the speed reducer. With the conveyor gear unit being the most costly item on the conveyor drive, it is important that the use of a VSD does not have a detrimental effect on the reducer. The aim of this paper is to educate users on the effects, adverse and beneficial, that the VSD can have on speed reducers, and to ensure that gear manufacturers take into consideration the adverse effects when designing speed reducers.

BACKGROUND

CONVEYOR DRIVE

The conveyor drive generally used in industry consists of an induction motor (i) coupled to a speed reducer (iii) through a flexible coupling (commonly a grid-type coupling, ii), with the entire drive being coupled to the conveyor pulley shaft through a rigid flanged coupling (iv), as shown in Figure 1.
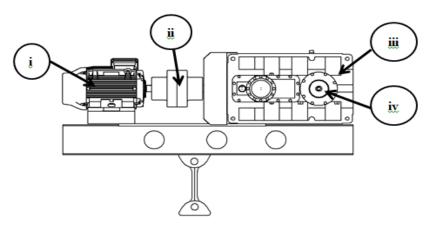

Figure 1. Conveyor drive

The size of conveyor drives applicable to this discussion range from 90 kW up to 1 500 kW installed motor capacity.

Variable Speed Drives

The VSD commonly used in conveyor applications is a Variable-Voltage-Variable-Frequency (VVVF) converter with an AC motor. The converter controls the motor speed by varying the frequency of the supply to the motor, while the motor torque is controlled by the variable supply voltage. (Figure 2).
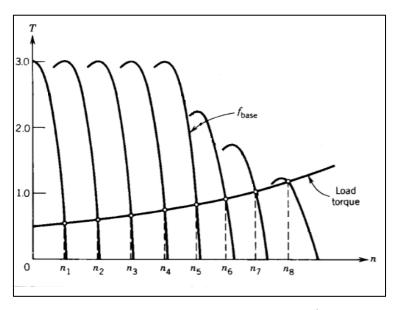

Figure 2. VVVF torque vs speed curves [1]

Depending on the motor and VSD used, the motor is de-rated for constant flux or maximum torque operation below 0.8 per unit frequency, which at 50 Hz equates to 40 Hz operation or 1 200 rpm. However, there is a torque limitation that limits the frequency to 0.1 per unit frequency or 5 Hz at a nominal frequency of 50 Hz. For a 4-pole motor the minimum 5 Hz operation is equal to a speed of 150 rpm.

VSD operation can be categorised into four quadrants of operation, with quadrant i being forward driving; quadrant ii; forward braking, quadrant iii; reverse driving, and quadrant iv being reverse braking. The four quadrants are shown in Figure 3. High performance applications such as conveyors utilise all four quadrant loads, where torque is applied in any direction. Dynamic braking, often used on conveyors to decrease the stopping time of the inertial load, is a quadrant iv operation. Dynamic braking converts the kinetic energy of the inertial load into regenerative power by applying a reverse torque, which is dissipated in the form of heat in braking resistor within the VSD.

Figure 3. Four quadrants of VSD operation

In practical terms, this means that both the motor speed and torque can be simultaneously varied, allowing for the motor to be ramped during start-up. The VSD reduces the supply voltage to the motor, reducing the motor torque at start-up, preventing the high start-up torques of a direct-online start. It also means that the VSD can produce 150% of nominal motor torque at less than 50% of the rated motor current from standstill. During start-up, the VSD gradually increases the supply voltage and frequency, increasing the speed and torque supplied by the motor, thus ramping up the motor and drive. A ramp-down is achieved using the reverse; by gradually decreasing the supply voltage and frequency, the motor speed gradually decreases. As the motor frequency approaches the minimum limit, the motor is shut off and allowed to coast. However, if a shorter stopping time is required, dynamic braking can be used to apply an additional braking torque, while still maintaining a smooth deceleration.

THE PRACTICAL IMPLICATIONS

ADVANTAGES OF VSD USE ON CONVEYOR SPEED REDUCERS

Reduced Mechanical Wear
With the VSD having the capability to limit the torque through the conveyor drive during start-up, the peak loads seen through the gear unit are reduced. This reduction in torque results in a reduction in contact stresses, σ_P, and bending stresses, σ_b, within the gear teeth. The AGMA contact and bending stress of the gears follow the following relationship:

$$\sigma_b \propto T$$

$$\sigma_p \propto \sqrt{T}$$

In other words, if the start-up torque for a VSD is half that of a motor starting direct online, the bending stress experienced by the teeth is 0.5 times lower, while the contact stress is 0.707 times lower, as seen in Figure 3.
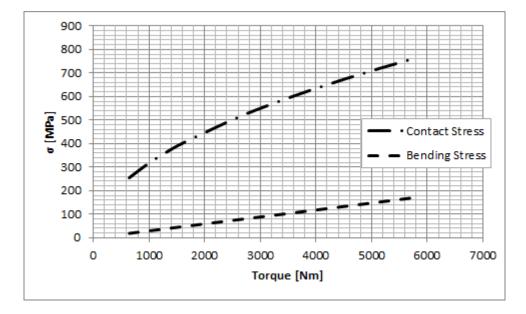
Figure 4. Gear teeth stress with torque

The stresses induced in the gear affects the achievable fatigue life of the gears. The AGMA standard which covers the fatigue life is AGMA 2001-D04, Appendix E. For a higher induced stress, the number of cycles to fatigue failure is lower, as seen in Figure 4.
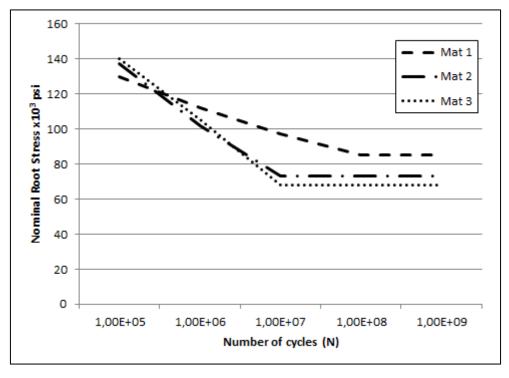

Figure 3. Fatigue life of low alloy carburised gears with nominal stress [2]

In simple terms, the lower the stresses induced in the gear, the longer the gear can operate prior to failure. This is applicable to all conveyors, irrespective of motor capacity, where the VSD is used as a soft-start device.

4

The VSD also has the ability to extend the stopping time or smoothing the deceleration of the conveyor, reducing the stresses induced in the gear unit.

Fault Ride-through Capabilities

The fault ride-through capability of a VSD is its ability to allow the motor to freewheel in the event of an electrical disturbance, such as a power dip. The conveyor drive then slows down due to inertial effects of the loaded belt. Once the disturbance has passed, the motor and drive are slowly ramped up back to full operating torque conditions. This capability can limit the number of stop-starts experienced on the belt, thus reducing the overall start-up peak load cycles, reducing the stresses induced on a speed reducer.

DISADVANTAGES OF VSD USE ON CONVEYOR SPEED REDUCERS

Induced Shaft Failures

While VSDs have many advantages with regards to use on conveyors, they also have disadvantages that must be taken into consideration. One of these disadvantages is induced shaft failures.

Rotating equipment, such as conveyor drives with a VSD, are subjected to various disturbances, both mechanical and electrical. These disturbances can result in torque oscillations being applied to the speed reducer, and may stimulate twisting oscillations of the rotating input shaft. It has been shown that shaft failure is mostly due to the frequency of a drive's oscillating torque and not by its magnitude. Hence, even the smallest magnitude oscillating torque can be detrimental. To mitigate this disadvantage, the frequency of the oscillating torque must not lie close to the natural frequency of the shaft. [3]

For VSD applications, the motor voltage is generated by a variable-voltage-variable frequency converter. Several aspects of VSD operation influence the motor voltage. This influence can vary the magneto motive forces i.e. the forces relating to the radial magnetic attraction between the motor's rotor and stator. These forces can lead to torsional oscillation.

Certain operating points or transients can create an externally applied load onto the input shaft that may be of its natural frequency. This applied torque can then induce strong vibrations and stresses in the shaft, leading to induced shaft failures.[3] These shaft failures generally occur in the form of fatigue failures, as shown in Figure 4.
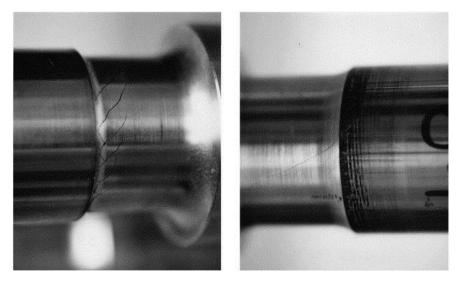
Figure 4. Oscillating torque induced fatigue shaft failures [4]

Bearing Failures

Bearing failures due to VSD use occur due to induced voltages. The VSD induces these voltages onto the motor shaft. If a metallic high speed coupling capable of transmitting this voltage is used, the voltage is transmitted to the input shaft of the speed reducer. These induced voltages cause pitting, fluting and ultimately bearing failure. [5]

From the very first moment of operation, the VSD induces a destructive voltage, present on the motor shaft, until an alternative path to ground is accessed. This path can be via the input shaft and bearings of the speed reducer.

Inside the bearing, once the voltage exceeds the breakdown potential of the bearing's oil film layer, the bearing currents cause an electrical discharge machining (EDM) effect, which pits both the bearing raceways and the roller elements. (Figure 6). This destructive effect can continue until the bearing becomes so severely pitted that fluting occurs. (Figure 7). This results in excessive vibration and noise, and ultimately failure.
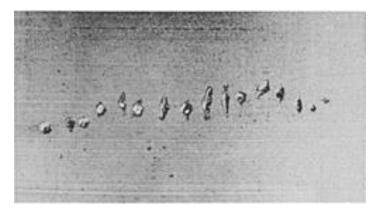

Figure 5. Electrically induced bearing pitting [6]

Figure 8. Bearing fluting[6]

To prevent the alternative path to ground going through the speed reducer, it is recommended that an insulating input coupling be used. This can be a pin and bush type coupling, with rubber bushes, or a spider type coupling. The use of rubber in these couplings electrically isolates the speed reducer input shaft from the motor shaft, thus preventing destructive induced shaft voltages.

Lubrication Failure

The most common means of lubricating a speed reducer is splash lubrication. Splash lubrication is simply dipping the gears in the lubricating oil as they rotate. The rotating gears, in turn, splash the oil onto the bearings, which circulate the oil within itself as it rotates. Splash lubrication is generally recommended for tangential gear speeds varying from 4 m/s to 15 m/s. Splash lubrication needs at least 3 m/s tangential speed gear speed to be effective.[7]

For tangential gear speeds higher than 15 m/s and below 4 m/s, forced-feed or spray lubrication is recommended. For low speed operation, less oil flow is required than for high speed operation. For low speed operation, a shaft-driven pump should be installed on the first intermediate or second reduction pinion shaft. This pump should feed oil both directly into the bearings, especially the high-speed input shaft bearings, and onto the gear mesh of all gears with a tangential speed below 4 m/s. The bearings can be fed through oil ports directly into the bearings or through oil troughs located within the gear case. It is important that all VSD controlled conveyor drives be checked for slow speed operation by the gear manufacturers.

A simple flange-mounted shaft-driven pump can be retro-fitted onto most standard speed reducers without a problem. A 0.37 kW pump can supply 9–14 ℓ/min, while a 0.55 kW pump can supply 18–22 ℓ/min at normal operating speed.[8] These oil flow rates easily lubricate most speed reducers during slow speed operation of 50% and 25% of nominal motor speed.

Thermal Failure

Most conveyor gear units are cooled through convection and radiation. The gear unit radiates heat generated to the ambient environment. The degree of heat radiated is based on the gear case properties. The use of fins along the gear case can increase the surface area of radiation. However, in the harsh climate of southern Africa, the component of the heat dissipated through radiation is very low. The bulk of the heat

generated in the speed reducer is dissipated through convection. Convection is induced over the gear unit through the use of a shaft-mounted fan. The fans normally used on speed reducers are radial flow fans.

Although the VSD does not supply constant power to the gear unit at the slower operating speeds, the heat generated in the gear unit is usually higher than the heat the gear unit dissipates through radiation. At these slower operating speeds, the gear unit fan cannot supply sufficient airflow over the gear unit to dissipate the generated heat. According to the AGMA standard for the thermal capacity of geared reducers, AGMA ISO 14179-1, the heat transfer coefficient for a fan-cooled gear unit is determined relative to the air speed achieved over the gear unit (Table 1).

Air Speed over unit [m/s]	Heat transfer coefficient [kW/(m2°C)]
2,5	0,015
5,0	0,024
10,0	0,042
15,0	0,058

Table 1. AGMA heat transfer coefficient for fan-cooled gear units [9]

This shows that the air speed over the unit is proportional to the rotational speed of the fan. This means that a VSD driving a speed reducer at 1 450 rpm, that generates 15 m/s air speed over the unit, will generate approximately only 10 m/s at 980 rpm. The resultant effect is that the unit running at 980 rpm should have 27.6% less thermal rating than the unit operating at 1 450 rpm.

It is important for the life of the conveyor gear unit that it is operated at a moderate operational temperature. The life of the lubricating oil is dependent on the operating temperature of the oil. It is generally stated that the life of the lubricating oil is halved for every 10°C above 90°C operating temperature. For optimal operational bearing an operating temperature of 60°C–80°C is advised.

It is recommended that the unit be adequately thermally sized for all operating conditions. Alternatively, a secondary cooling unit can be used during periods of slow speed operation where the risk of high temperature operation occurs.

CASE STUDY

The following is a typical speed reducer used on a conveyor drive:

A nominal motor installed capacity of 110 kW at a nominal motor speed of 1 480 rpm
An absorbed motor power of 85% of nominal motor power
A unit mechanical rating of 168 kW at 1 450 rpm with an overall unit ratio of 11.598:1
A unit thermal rating of 84 kW at a 40°C ambient temperature

A bevel gear ratio of 2.05:1
A second reduction helical gear set of a 19 tooth pinion, 42 tooth wheel at a 8 mm normal module with an 11° helix angle

Consider a load cycle for a variable speed application with the following operating parameters:

    i.   Full speed, full load – 20% of time
    ii.   75% speed, full load – 20% of time
    iii. 50% speed, full load – 20% of time
    iv. 25% speed, full load – 20% of time
    v.   25% speed, empty   – 15% of time

At nominal motor speeds, the speed reducer exceeds the requirements of a 1.5 mechanical service factor and 1.0 thermal service factor.

However, if the effects of variable speed operation on the thermal rating of the unit are considered, Table 1 indicates that the airflow over the unit decreases proportionally, the results of which are shown in Table 2.

Percentage of Motor Nominal Speed	Thermal Rating of unit [kW]	Absorbed Power of Motor [kW]
100	84.0	76.5
75	60.8	56.2
50	35.2	37.5
25	17.9	18.8

Table 2. Thermal rating of a speed reducer for variable speed application

It can be seen from Table 2, below 75% of nominal speed the thermal rating drops below that of the absorbed power of the motor, indicating that the unit cannot be used for extended periods without external cooling. In this case study it is recommended that a secondary cooling unit be used for slow speed operation.

When considering the effects of variable speed operation on the lubrication of the speed reducer, a simple calculation is used to ensure adequate lubrication from splash. This is shown below for this case study.

Second reduction wheel speed = 1480/2.05/(42/19) = 326.60 rpm
Second reduction wheel pitch circle diameter (PCD) = 42x8/cos(11°) = 342.29 mm
Second reduction nominal tangential speed = 326.60x2π/60x (0.3423/2) = 5.85 m/s

This equates to the tangential speeds as shown in Table 3. This table clearly demonstrates that below 75% of the nominal motor speed, the tangential speed of the gear is below the recommended 4 m/s required for adequate splash lubrication.

Percentage of Motor Nominal Speed	Wheel Tangential Speed [m/s]
100	5.85
75	4.39
50	2.93
25	1.46

Table 3. Tangential gear speeds for a sample speed reducer

In this case study, a shaft-mounted pump, placed on the second reduction pinion shaft, is used to supply lubricating oil to the bearings during slow speed operation.

Therefore, from this case study, it is seen that the effects of variable speed operation on thermal capacity and lubrication must be investigated during the selection of the speed reducer.

CONCLUSIONS

It is widely recognised that using a VSD on a conveyor drive is beneficial. However, there are both pros and cons to the use of a VSD. The aim of this paper is to present both the advantages and disadvantages. While there are many advantages to VSD use, only two were highlighted in this paper, namely, reduced mechanical wear and fault ride-through capabilities.

The first and most important advantage of VSD use is reduced mechanical wear. This increases the effective life of the conveyor drive components, most especially the speed reducer. The VSD achieves this through a lower peak torque during start when compared to traditional direct online starts. This lower peak torque results in a lower fatigue load through the speed reducer, increasing the number of cycles that the unit can complete before fatigue failure.

The second advantage – fault ride-through capabilities – is the ability of the VSD to allow the motor to freewheel in the event of an electrical disturbance. Once the disturbance has passed, the VSD slowly ramps the motor up to full operating conditions. This lessens the effects of stop-starts on the speed reducer, increasing its effective life.

While many are familiar with the benefits of VSD use, the disadvantages are less commonly known, and were focused upon in this paper. Induced shaft failures, due to oscillations in the torque resulting from disturbances of both a mechanical and electrical nature, are one such disadvantage.

Another weakness is bearing failure due to voltages induced in the motor shaft transmitted to the speed reducer input shaft. This problem can however, be mitigated through the use of an insulating coupling, like a pin and bush type coupling, with rubber bushes.

Lubrication failures are also discussed in this paper. This type of failure occurs when operating speeds are below those required for splash lubrication of the speed reducers. This is simply solved by the use of a shaft driven pump, installed on the intermediate or second reduction pinion shaft. The pump is used to deliver lubricant to the bearings and those gears which cannot self-lubricate, through dipping into the oil contained within the unit.

The final disadvantage discussed in this paper is thermal failures of the unit. Due to slow speed operations made possible by VSD use, the shaft mounted fan used as a standard to cool speed reducers becomes less efficient. It is important that the unit is correctly sized thermally for all operating conditions.

When selecting a VSD and speed reducer, all operational information should be given to the relevant parties. It is important that the end users and speed reducer manufacturers be aware of the potential pitfalls of VSD use and mitigate against these effects during the design of the conveyor drive.

It is recommended that conveyor manufacturers specify the selection of speed reducers for all operational conditions of speed and load when VSDs are used. It is suggested that conveyor manufacturers moderate all gear units selected by gear unit manufacturers, in accordance with the basic operational requirements of thermal capacity and lubrication.

For larger, more costly drives, it is advised that a study be completed to investigate the electromechanical interactions of the VSD and conveyor drive, through the overlap of the natural frequencies of the mechanical components and the electrical frequencies of operation of the VSD, and ensure that these frequencies are always offset.

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