

A Comparison of Drive Starting Mechanisms for Aggregate Belt Conveyors

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Abstract

The purpose of this paper is to describe the torque / speed characteristics, during starting conditions, of the most common drives used on belt conveyors today.

Requirements of a Belt Conveyor Drive

A belt conveyor is considered to be a constant torque device. In other words, the required driving torque is approximately constant at varying speeds (see figure 1). Other applications, such as a pump drive, have variable torque requirements (see figure 2).

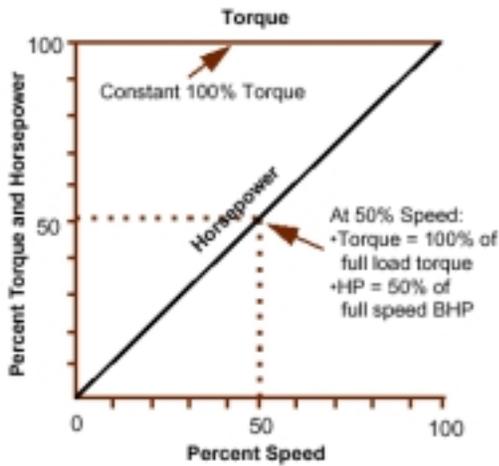


Figure 1 – Constant Torque Example

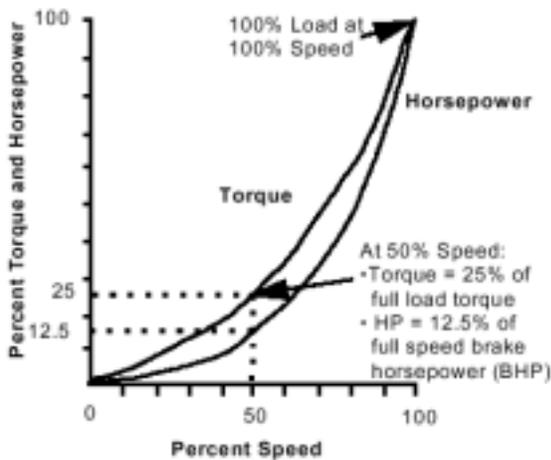


Figure 2 – Variable Torque Example

However, to increase the speed of a conveyor additional torque must be added until the desired speed is obtained. Newton's Second Law of Motion governs this relationship.

$$\Sigma F=ma$$

The most straightforward example would be a constant acceleration torque (see figure 3). In reality the acceleration torque is rarely constant. However, static calculation models as outlined in the Conveyor Equipment Manufacturers Association handbook (CEMA) make this assumption. When using static models the average acceleration torque is estimated over the entire acceleration time and assumed to be linear. Dynamic models, which are beyond the scope of this paper, allow acceleration torque values to vary in magnitude during the acceleration (or deceleration) period.

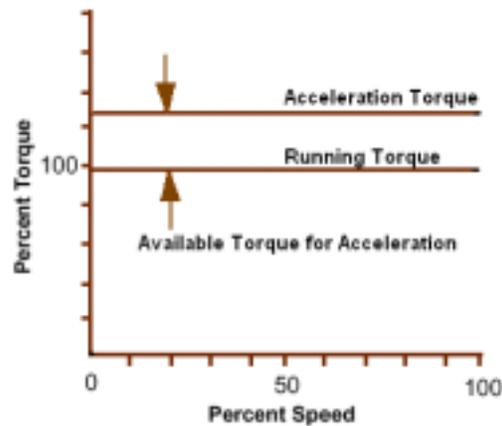


Figure 3 – Constant Acceleration Torque

It should be noted that, given a constant load, a larger acceleration torque results in a faster acceleration time and also higher peak belt tensions. Conversely, a smaller acceleration torque results in a longer start time and smaller peak belt tensions.

Across-The-Line AC Motor Start

Technically this is the most simple type of drive used on a belt conveyor. In this drive type an AC squirrel cage induction motor is started by simply throwing the contactor and energizing the motor. The resulting output torque, assuming that rated voltage is maintained, is strictly a function of the motor

design. NEMA has provided design standards that define the output torque characteristics of the most commonly used 3 phase motors up to approximately 250 hp (figure 4). In sizes larger than 250 hp manufacturers generally use the NEMA design codes in a relative manner (i.e., NEMA C has a greater locked rotor torque than a NEMA B motor).

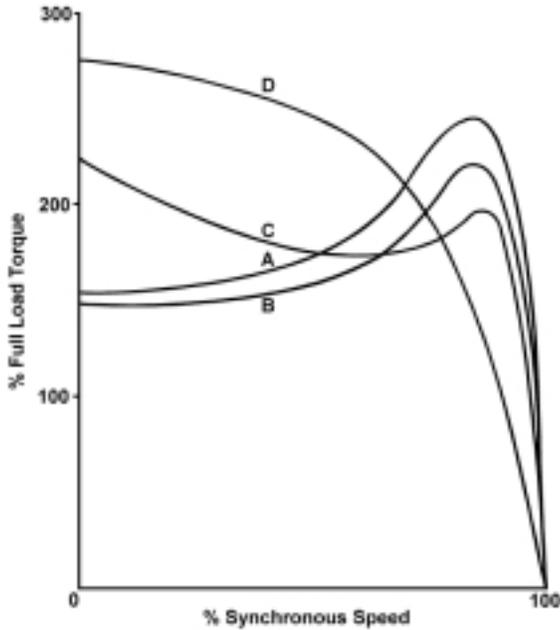


Figure 4 - NEMA Design Torque Standard

The most critical locations on the AC motor speed / torque curve have been named for definition purposes. These common names are provided in figure 5.

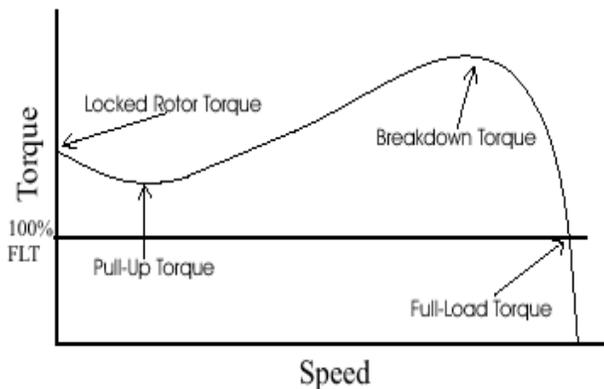


Figure 5 – Speed / Torque Nomenclature

The most rigorous method of determining average acceleration torque, for static calculations, is to

break the curve into several vertical sections, then sum the individual areas under the curve and finally divide by the number of sections.

The more common way is to apply the following simplified equation:

$$Avg.Accel.Torque = \frac{(FLT + BDT / 2 + BDT + LRT)}{3}$$

These static approximation methods work for most belt conveyors but can get the designer into trouble from time to time, especially on long and/or steep and/or fast conveyors. One item that needs to be examined is *breakaway torque*. Just because the drive provides enough average torque to accelerate the load doesn't mean that it provides enough torque to break it away from zero speed and get it moving. CEMA defines breakaway torque as twice the torque required to overcome the total friction plus the torque required to lift the load vertically. Locked rotor torque (LRT) needs to be greater than breakaway torque! A good static program makes this check.

In addition to examining the effect that average torque has on the conveyor components the belt designer needs to determine the effect of peak torque. It is not uncommon for the breakdown torque (BDT) of a NEMA C motor to be greater than 2.5 times full load torque (FLT). Generally the belting and pulley manufacturers allow a transient overload of 1.5 times full load operating load. An across-the-line start can easily cause tensions to exceed these maximums. These higher than normal loads can be designed into the conveyor if they are known up front.

Considering only average starting torque can cause the conveyor designer to undersize the take-up weight. It is not uncommon for conveyors with across-the-line starters to experience intermittent drive slip. This generally happens when peak torque (BDT) is input by the drive and the take-up has been sized for average torque but not peak torque. The result can be devastating. When the drive pulley slips during this condition, the tension on the T1 and T2 sides (high and low) of the drive pulley tries to equalize. This can subject a low tension bend or take-up pulley, just behind the drive pulley, to tensions that approach T1 tension. These pulleys are rarely, if ever, designed for this load condition and the result is low tension pulley failure. This condition is easily demonstrated with dynamic analysis.

Another common problem with across-the-line starts is caused by voltage dips during starting. If the power distribution system is not stiff enough to handle the huge inrush currents of an across-the-line start, the starting torque of the motors can be reduced to a point that the conveyor will not start. This is due to the fact that the output torque of an AC squirrel cage induction motor is reduced by the square of the applied voltage. In other words, a voltage drop of 10% would equate to a torque reduction of 19%. To calculate torque reduction, in this example, the remaining voltage (90%) is squared and then subtracted from 100%.

Reduced Voltage Starting

The reduced voltage starting of an AC squirrel cage induction motor is done for two basic reasons:

1. To reduce the inrush current that naturally occurs when a motor is started across-the-line. A typical current / speed graph is shown in figure 6. It is not uncommon for the inrush current to be 6 times or more than it is at full load torque. As stated above, high inrush currents cause the voltage in a power distribution system to sag. The cost of electrical power distribution equipment can become very high if it needs to be designed to handle the high inrush currents.

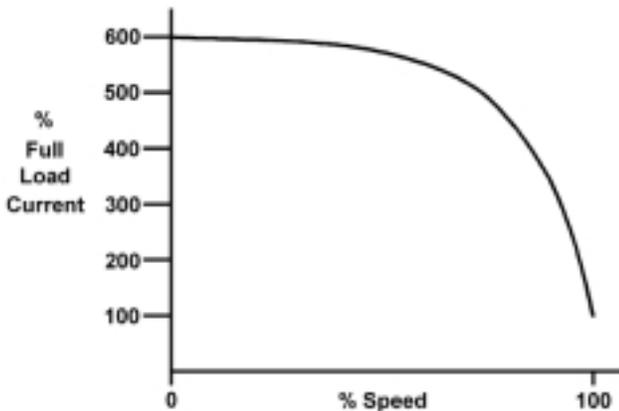


Figure 6 – Typical AC Motor Current vs. RPM

2. To reduce peak motor torque during starting conditions, which subsequently increases acceleration time. By reducing the peak torques the conveyor components can be designed for lower tension loads. This primarily includes belting, pulleys and

external support structure. This can result in significant cost savings.

Two common types of reduced voltage starters are the *Current Limiting* and the *Constant Torque* devices.

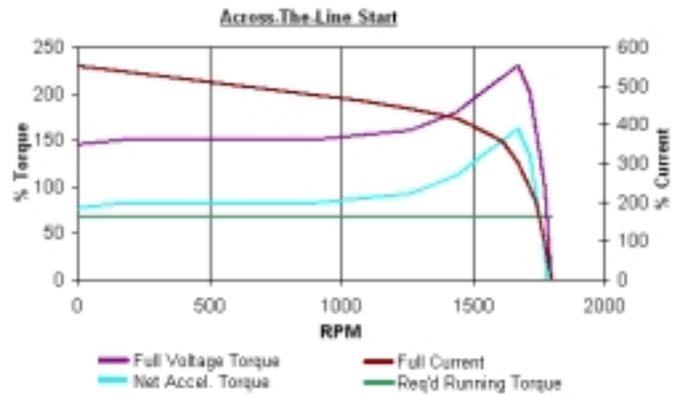


Figure 7 – Across-The-Line Start

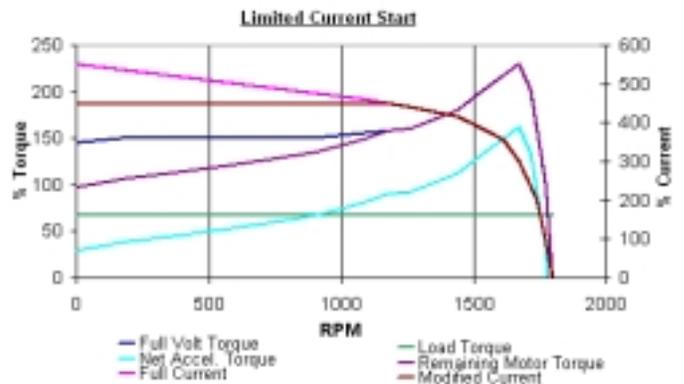


Figure 8 – Limited Current Start

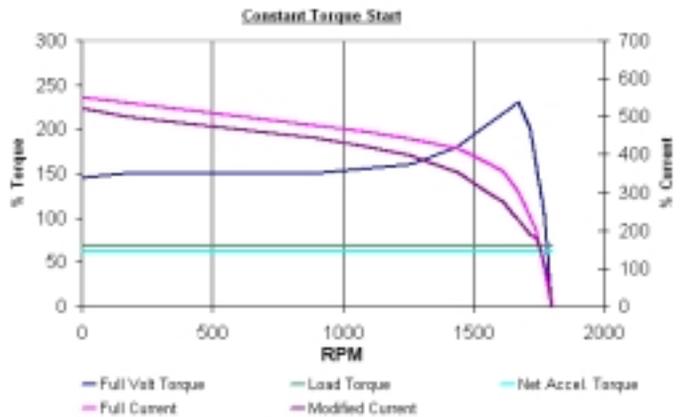


Figure 9 – Constant Torque Start

Graphs are included above (figures 7 through 8) that depict the same motor / conveyor application with an *Across-The-Line*, a *Limited Current*, and a *Constant Torque* start. After studying the graphs it becomes apparent that the best use of the limited torque start is to protect the power distribution system from high inrush currents. The constant torque start reduces the high torque peaks and protects the conveyor's mechanical components. In both cases the start time is increased because the overall magnitude of accelerating torque is reduced. However, neither method will make it easier to start a "hard-to-start conveyor." Correcting a hard starting conveyor is not a reason to use a reduced voltage starter!

It is often difficult to find a current / speed curve for a particular motor. However, it is not difficult to determine locked rotor amps as all AC motors have the *NEMA Locked Rotor Current Code Letter* stamped on its nameplate. A table with these codes is shown below.

Letter Designation	kVA/HP (Up to, but not including the upper limit)
A	0 - 3.15
B	3.15 - 3.55
C	3.55 - 4.0
D	4.0 - 4.5
E	4.5 - 5.0
F	5.0 - 5.6
G	5.6 - 6.3
H	6.3 - 7.1
J	7.1 - 8.0
K	8.0 - 9.0
L	9.0 - 10.0
M	10.0 - 11.2
N	11.2 - 12.5
P	12.5 - 14.0
R	14.0 - 16.0
S	16.0 - 18.0
T	18.0 - 20.0
U	20.0 - 22.4
V	22.4 and up

Figure 10 – NEMA Locked Rotor Codes

For three phase motors the locked rotor amps can then be determined from the following formula:

$$L.R.Current = \frac{KVA / HP * HP * 1000}{1.73 * Volts}$$

Where: KVA/HP is obtained from the chart in figure 10.

Another critical operating characteristic to check when utilizing a reduced voltage start, or an across-the-line start for that matter, is the *Equivalent Locked Rotor Time*. Most AC motor manufacturers can provide a *permissible locked rotor time*. This is a practical measure of the amount of heat that an AC motor can endure. Heat in a motor is a function of time and the square of the current. For instance, a manufacturer may provide the conveyor designer a permissible locked rotor time of 15 seconds. It is the conveyor designers' responsibility to determine what the actual equivalent locked rotor time is during the start that the motor is subjected to and compare it to that number. This can be accomplished quite easily on a spreadsheet by breaking the starting sequence into intervals and summing the time in each interval. Overland Conveyor Co., Inc. (OCC) breaks the start into single RPM intervals. The equation for determining the time (dt) in each interval step is as follows:

$$dt = \frac{WR^2 * N}{308 * T}$$

dt = Interval time, seconds
 WR = Total Inertia, lb_r-ft²
 N = RPM change
 T = Average interval torque, lb_r-ft

The equivalent locked rotor time in each interval (dt_{equiv}) can be determined from the following equation:

$$dt_{equiv} = \frac{I^2 * dt}{I_{LR}^2}$$

I = Average interval current
 I_{LR} = Actual locked rotor current

The final step is to sum the equivalent locked rotor time from each interval to get the total equivalent locked rotor time. It is essential that this number be less than the permissible locked rotor time for the motor.

Wound Rotor Start

A wound rotor motor is an AC squirrel cage induction motor with a special construction that enables the rotor windings to be extended outside the motor via collector rings and brushes (see figure 11).

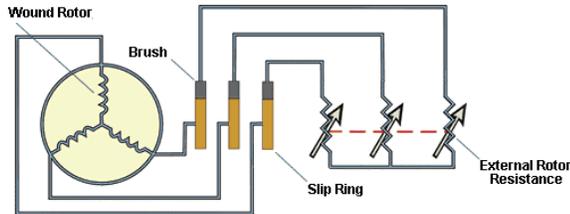


Figure 11 – Wound Rotor Schematic

Generally a finite number of individual resistors, referred to as steps, are used to modify the speed / torque characteristics of the motor. The result is a family of curves that the conveyor designer can use to modify the overall starting speed / torque of the conveyor (see figure 12).

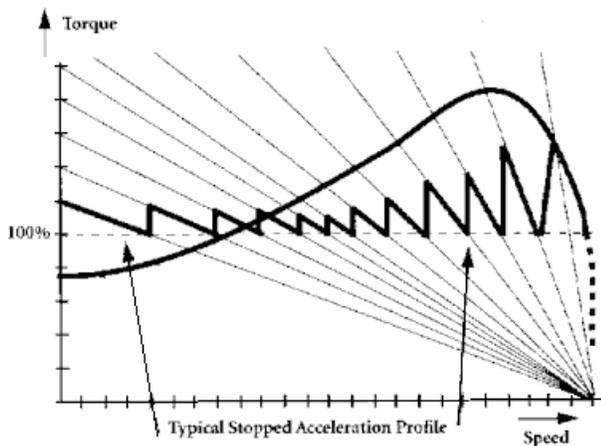


Figure 12 – Wound Rotor Speed / Torque

A closer approximation to a constant torque start is made with more steps. Generally the control theory is designed so that the conveyor is subjected to each speed / torque curve (step) for set period of time. Then it advances to the next resistor and hence the next step.

Traditionally the control theory for a given conveyor includes the number of steps, the slope of each speed / torque curve and the dwell time during each step. The design is based around one conveyor loading condition. However, this control design is somewhat self-correcting as lighter loads receive less torque

and heavier loads receive more torque. This means this type of drive is good for starting hard-to-start conveyors. But if the conveyor becomes too overloaded the components can still be subjected to the same peak stresses that it would see during an across-the-line start.

Since the motor is working on the linear, or 'right' side of the speed / torque curve (figure 4, 5) the currents are typically low during a start. They are generally in the 100% to 150% of full load current range. This helps keep the motor cool during an extended start time. However, the conveyor designer needs to be aware that the external resistors can become extremely hot during an extended start. It is not uncommon for the resistor banks to become red hot if they are misapplied!

Variable Frequency AC Drives

The variable frequency AC drive provides the conveyor designer with nearly ideal speed / torque characteristics. The example in figure 13 below will be used to illustrate these principles.

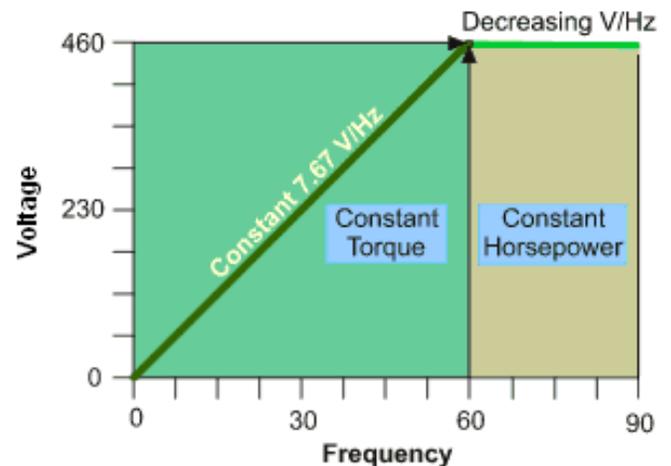


Figure 13 – VFD Freq. / Torque / Power

As the frequency is linearly increased from 0 to 60 hertz the speed of the motor is increased nearly linearly from 0 RPM to full load RPM. As long as the voltage is increased at the same rate (same volts per hertz ratio) the motor output torque is virtually constant until increased to motor rated voltage. Another way to look at this is in figure 14. The speed / torque curves shift from left to right as the voltage and frequency are increased. The only limitation on torque is set by the peak torque available from the speed / torque curve of the motor. Since we are operating on the linear or 'right' side of the speed / torque curve again, the current is kept to

a minimum. It is not unusual to see current values less than 150% throughout the starting sequence. This keeps the motor from building up too much heat.

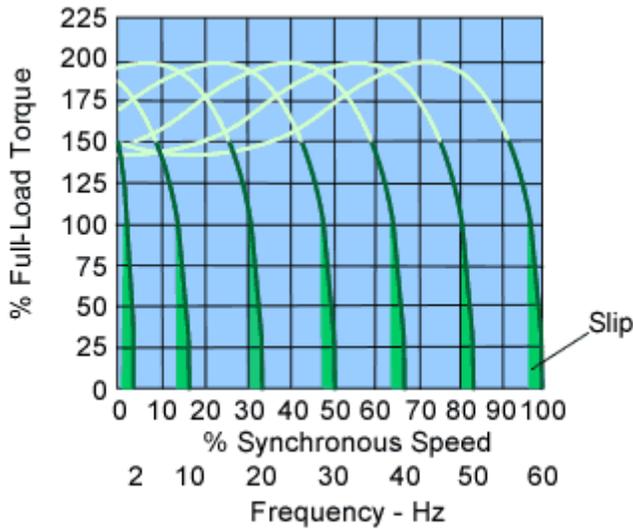


Figure 14 – VFD Speed / Torque Curves

In addition, the frequency can be increased further (past 60 hertz in this example); the result is that the motor speed continues to increase. However, beyond this base speed the horsepower is constant. Since power equals speed times torque it follows that torque is reduced after base speed.

DC Motor Start

The DC motor is also very friendly for controlling a conveyor. The designer can virtually dial in a desired ramp time or ramp shape for that matter. The DC motor output speed is linearly proportional to armature voltage from 0 speed to base speed (see figure 15). The base speed is an indication of how fast the motor will run with rated armature voltage and rated load amps at rated flux.

Between zero speed and the base speed the drive will also output a constant torque (see figure 16). The speed can then be increased beyond base speed by further increasing armature voltage. Beyond base speed the horsepower will be constant and the torque will decrease.

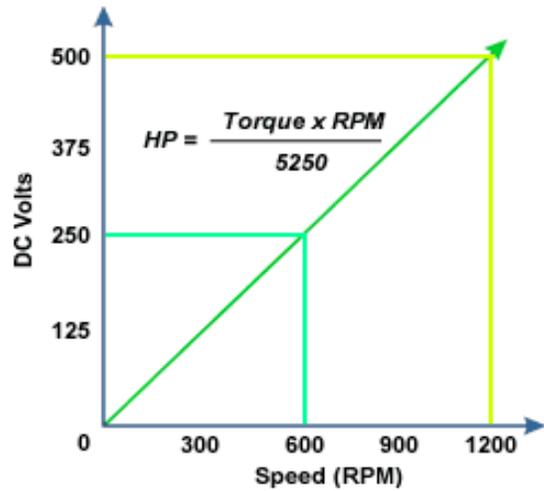


Figure 15 – DC Armature Voltage vs. Speed

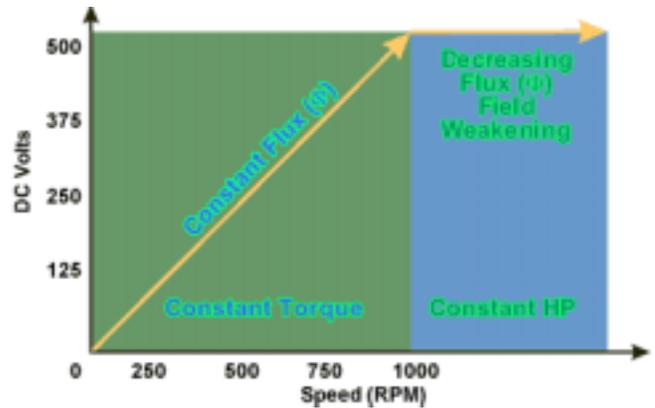


Figure 16 – DC Torque / Horsepower

Fixed Fill Fluid Coupling

A fluid coupling is a hydro-mechanical device that is generally located between an AC squirrel cage induction motor and a gearbox. The fluid coupling is made up of two main components – the impeller (pump) and the housing (turbine). A picture is shown in figure 17. The AC motor is started across-the-line. The fluid coupling allows the motor to come up to speed uncoupled from the load. The impeller imparts kinetic energy to the oil in the coupling. The oil then moves by centrifugal force across the blades of the turbine towards the outside of the coupling. Thus torque is transmitted from the motor to the load through the motion of the fluid.

The fact that the motor comes up to speed independent of the load allows this device to operate on the linear (right) side of the speed / torque curve. This means the conveyor

components are not needlessly subjected to the high peak motor stress and that the motor runs cooler as it is exposed to the high starting currents for a very brief time.

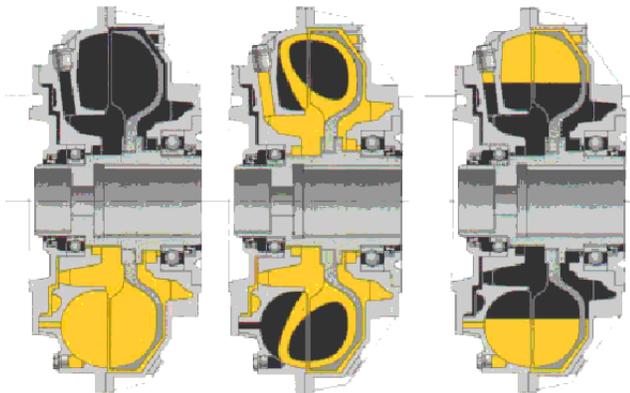


Figure 17 – Fixed Fill Fluid Coupling

It is important for the conveyor designer to match the requirements of the conveyor to the design of the fluid coupling. Each fluid coupling has its own speed / torque characteristics. The graph in figure 18 shows the differences in fixed fill fluid couplings produced by a single manufacturer.

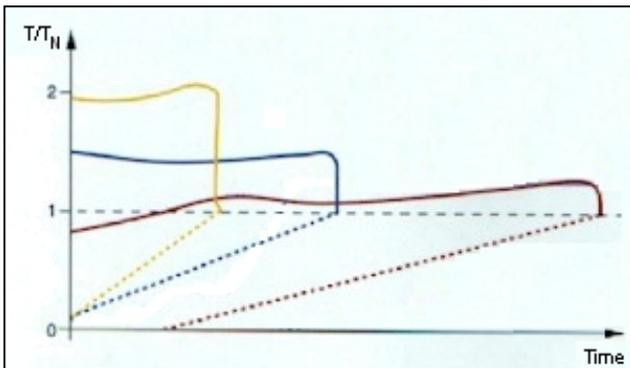


Figure 18 – Fixed Fill Speed / Torque Curves

In addition, it is the conveyor designer's responsibility to determine the proper fill level for the selected coupling (see figure 19). Increasing the fluid level in a coupling increases the starting torque and causes the conveyor to start faster. Conversely, a lower fluid level reduces torque and makes the conveyor start slower. The reduced fluid level also results in a higher slip rate between the input and output shafts. Slip is

always present in a fluid coupling. However, this is another factor that needs to be managed by the conveyor designer. Slip creates heat and a loss of efficiency. A slip rate that is too high can create excessive heat and damage the coupling.

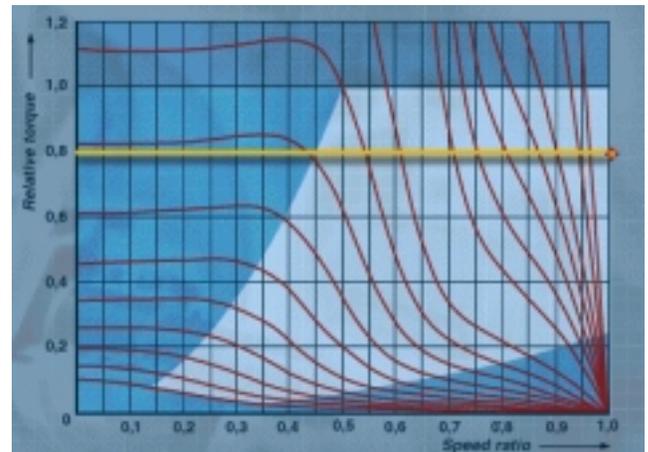


Figure 19 – Fixed Fill Coupling Fill Levels

Variable Fill Fluid Coupling

There are two basic types of variable fill fluid couplings – the scoop tube type (figure 20) and the drain type (figure 21).

The mechanisms of operation for these coupling types differ but the objective is the same. That objective is to be able to externally change the fluid fill level in the working chamber.

By externally changing the fill level the conveyor designer can design the drive for a low torque, long start and then, at the same time, a highly efficient fill level once the conveyor is up to speed.

This variable fill capability also provides the opportunity to adjust the conveyor torque once the conveyor is up to speed. This 'active control' feature is used to create load sharing of motors between drive pulleys and for 'target tension' control of tripper booster drives.

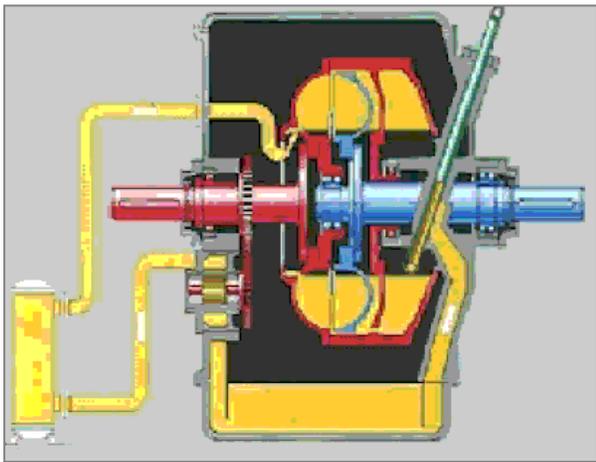


Figure 20 – Scoop Type Fluid Coupling

This drive also allows the AC motor to come up to speed independent of the load. The result, once again, is protection of the conveyor components from high peak motor torque and a cooler AC motor due to a very short duration at high starting current levels. After the motor comes up to speed an external hydraulic pressure is applied to a hydraulic cylinder that compresses the clutch stack. This pressure causes torque to be transmitted from the friction plates to the opposing plates. As the pressure is increased, the relative slip between these plates is decreased in a controllable manner from 100% to 0% (lockup).

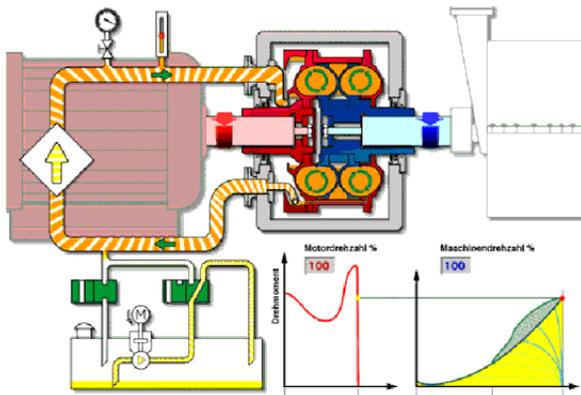


Figure 21 – Drain Type Fluid Coupling

A large amount of cooling oil is pumped through the clutch stack so that there is generally no actual clutch plate-to-plate contact. The torque is actually transmitted between plates via a thin film of oil.

Like the variable fill fluid coupling this drive can provide 'active' torque control.

Magnetic Coupling

On a belt conveyor the magnetic couplings is mounted between an AC motor and a gearbox (see figure 23).

Hydroviscous Drive

Another mechanical drive component that can be mounted between an AC motor and the conveyor drive pulley is a hydroviscous clutch (see figure 22). These devices are available in high speed (motor speed) or low speed (drive pulley speed) configurations.

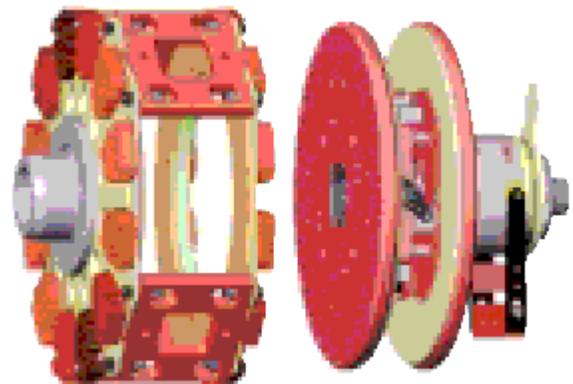


Figure 23 – Magnetic Coupling

This device operates on the principal of magnetic induction. It consists of two independent components that have no physical contact. A rotor assembly containing high-energy permanent magnets is mounted on the drive pulley side. A conductor assembly with copper rings is connected to the motor shaft. Relative motion between the magnets and copper rings creates a magnetic field that transmits torque through the air gap between the

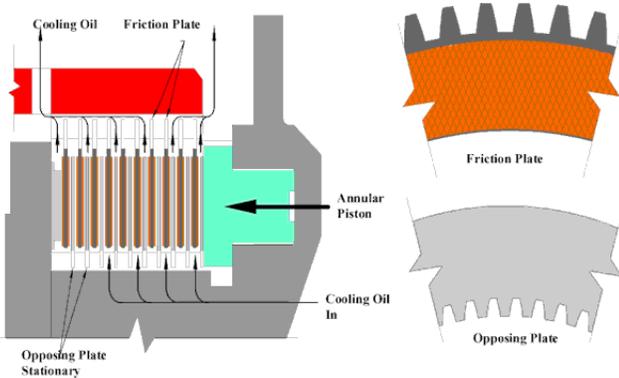


Figure 22 – Hydroviscous Clutch

coupling components. The width of the gap can be changed externally producing a controlled and variable output speed. This means that the AC motor with this drive component can be brought up to speed independent of the load. As stated earlier, this avoids subjecting the conveyor components to peak motor starting torque and the motor from long durations at peak starting currents.

This drive is also capable of 'active control' as the torque can be varied after the conveyor is up to speed by externally adjusting the air gap.

Conclusion

This paper was designed for the belt conveyor designer that has a good mechanical design

References:

Nave, Michael; 1998; "AC Variable Frequency Drive Application Considerations for Mining Belt Conveyors"; SME Bulk Material Handling by Conveyor Belt II

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expertise but little electrical engineering expertise. The purpose was to give a very brief description of each drive type and to explain the drive in terms of torque and speed output characteristics. The hope is that the average conveyor designer can digest the information in this paper and then apply the specific technical details from the drive manufacturer to produce accurate static conveyor models as described by CEMA.

All of the drive types described in this paper have their place and can be used successfully if they are applied properly!