Design fundamentals for drive systems on conveyors

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1. Keywords

Conveyor, conveyor drive, multiple drive, drive control system, variable voltage variable frequency control, variable speed drive, variable frequency drive, secondary resistance control (SRC), squirrel cage induction motor (SCIM), wound rotor induction motor (WRIM), fluid coupling, electronic soft starter, direct on line start, breakaway torque, acceleration torque, conveyor resistance forces, conveyor efficiency, conveyor drive de-rating.

2. Synopsis

The combination of a number of factors can result in conveyor drives being undersized or operating in an unsuitable manner. Some of these factors include:

- The trend to reduce drive sizes by reducing friction coefficients
- The trend towards using squirrel cage induction motors under variable voltage variable frequency controls combined without considering the drive characteristics
- Not analysing the operation and interaction of fluid couplings with the motor torque curve.
- Either not allowing for break-away resistances, or not allowing for some components of break-away resistances
- Not allowing for load sharing in multiple drive systems
- Not allowing for surge (transient but sustained variations in throughput)
- Procured drive and conveyor components being different to the design components resulting in different resistances and different drive characteristics

Correct conveyor drive design can be achieved by allowing for realistic load cases and ensuring that the drive system selected can provide adequate torque to overcome these resistances.

This paper discusses concepts for establishing conveyor resistances and the features of various drive technologies and de-rating factors which should be applied.

3. Introduction

Items which have contributed to undersize conveyor drives being designed, or drives being designed which have not operated correctly are discussed in this paper. Various trends which have led to these outcomes are discussed and methodologies which should be employed during design to ensure fit for purpose outcomes are also discussed.

The broad areas discussed by this paper include:

- Determination of conveyor resistances
- Assessment of de-rating factors
- Features of various conveyor drive technologies
- Design suggestions to minimise energy losses in conveyor systems

In addition to incorrect drive sizing, drives can fail due to control system issues and these are also discussed briefly as a precursor.

4. Drive control system philosophy

A conveyor that is operating and continues to operate safely with an alarm condition allowing an overload to be corrected will cause less problems than a conveyor that is stopped as soon as the alarm is raised. A back up trip should occur if the alarm condition is not resolved quickly. Two stage alarm/trip settings give excellent control and examples are:

- If the gearbox oil temperature reaches a preset safe limit, it will not fail immediately and therefore the conveyor should not be immediately stopped. A ten degree Celsius additional rise should trip the drive.
- An electric motor that reaches peak current for a few seconds will not burn out, however if this persists and the motor thermal rating is reached a trip is needed. Higher end motor protection relays (MPR) can accommodate a detailed motor thermal limit curve to allow for many over-current scenarios.
- The use of two stage belt wander detection/indication is strongly preferred.

Starting set up can cause spurious trip outs that mask the real reason for a conveyor not breaking away:

- When using delay fill fluid coupling drives, motion at full load conditions may take many seconds. Ensure that the zero speed trip timers allows for this.
- Ensure that the motor does not trip out on an arbitrary electrical limit that does not harm the motor (an 85% maximum current trip is often set on many mine drives). Proper setup of the MPR can eliminate this type of nuisance trip.
- Ensure that other instruments (oil pressure, flow, temperature, zero speed, vibration etc.) are bypassed for the starting duration unless deemed critical.
- Confirm the set up of the VSD is as required.
- Check the actual voltage drop under starting as this is drive dependant, with direct on line starting being the highest.

5. Conveyor resistances

The basic conveyor resistance forces are calculated by using the international standard, ISO 5048(1) in most parts of the world, with CEMA(2) (Conveyor Equipment Manufacturers Association) still finding preference in North America. Although both these methods provide a realistic assessment of resistance forces for most conveyor applications, other resistance forces must be considered, particularly during starting. These resistances include:

- Allowance for static friction (or break-away friction), sometimes referred to as 'stiction'.
- Allowance for full or blocked chutes.
- Allowance for inertial resistance of the belt and its components during acceleration.

5.1. Break-away friction

Often neglected, this resistance force can be significant, especially when analysing relatively long, flat (horizontal) conveyors where the resistance due to material lift is negligible and the frictional resistances summate to make the main resistance. It is common industry practice to multiply the artificial coefficient of friction (ISO

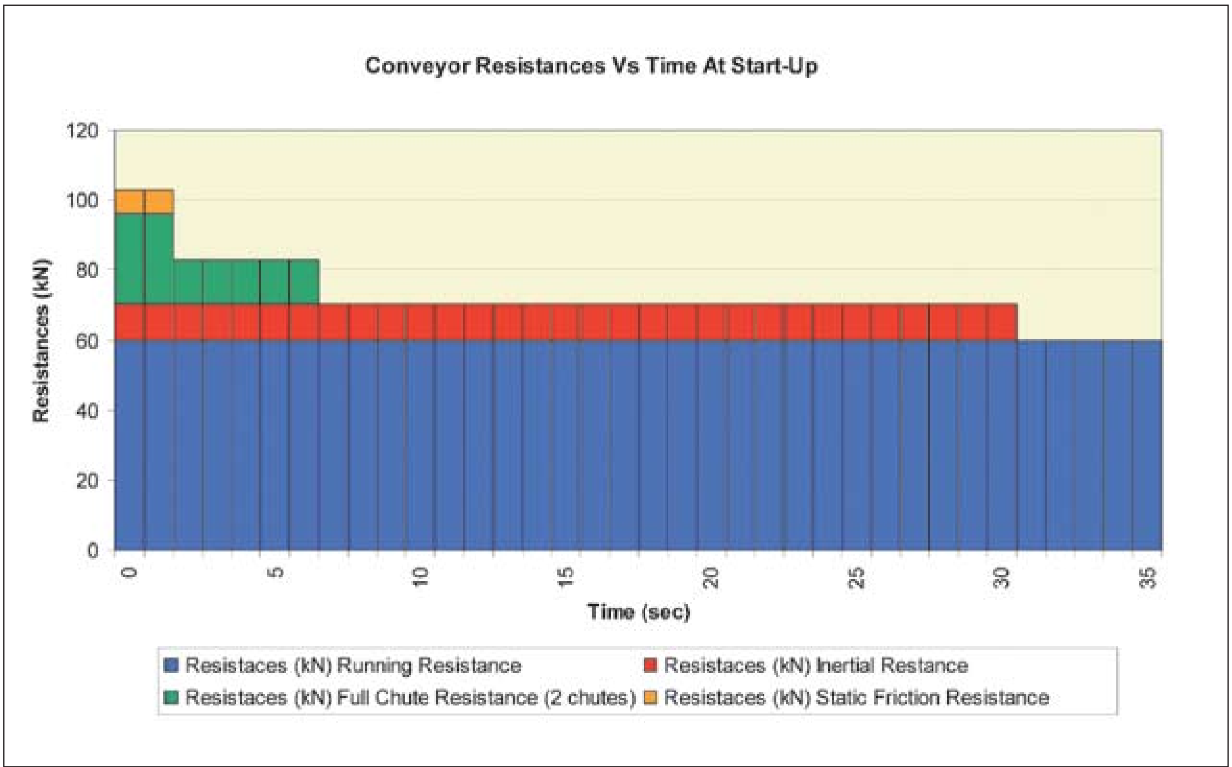

Figure 1. Example showing typical components of conveyor resistances at start-up.

5048) by a factor of 1.1 to 1.5 to calculate breakaway conditions.

5.2. Full chutes

Two types of philosophy apply to chute design:

- Traditional closed chute designs
- Open profile velocity chutes (sometimes referred to as 'hood and spoon' chutes or 'soft loading' chutes)

Many chutes are enclosed to control dust and also to act as storage containers in the event of an uncontrolled stop due to power failure, or an emergency stop. In the case where this type of chute becomes full, or becomes blocked, it acts in a similar fashion to a belt feeder hopper and exerts significant resistances on the conveyor. A conveyor which has multiple feed chutes discharging on to it may have a sizable proportion of its starting resistance comprised of resistance forces due to full chutes.

The profile velocity chutes which have become popular for handling relatively free flowing materials such as coal, generally are of an open design. As a general rule, to prevent spillage during an emergency stop, conveyor stopping times are controlled by using brakes or flywheels to ensure one conveyor does not feed onto the other in these circumstances. For this type of chute a case may exist for not allowing for full chutes resulting from an emergency stop.

Experience indicates that most chutes will block at some time for reasons beyond normal controlled conditions. When this happens it is preferable that the conveyor fed by the chute is able to self start.

In general, the full chute resistance forces can be conservatively calculated in a simple fashion by using the vertical pressure due to hydrostatic head of the material in the chute above the profile plate and multiplying it by the coefficient of internal shear of the material. This shear stress is then multiplied by the area of the shear plane behind the profile plate to obtain an estimate of the initial (break-away) 'pull out force' required. The time taken to empty the chute during acceleration should be calculated and taken into account when preparing the torque versus time graph for conveyor starting conditions. Once the material is flowing in the chutes some cushioning of the load onto the belt occurs in a similar way to that which is observed with belt feeders(3). An approximation of the resistances due to full chutes during acceleration (as opposed to break-away) can be determined by simply halving the resistances calculated for the break-away condition.

5.3. Inertial resistance during acceleration

In order to accelerate the belt and other live conveyor components (idlers, pulleys etc) to full running speed, there is an inertial resistance which must be overcome.

Although this resistance force can be low in modern designs which use electronic soft starters, secondary resistance and VVVF controls, it still should be calculated and included in the specifications used to size the conveyor drive and controller.

Most modern computer programmes determine the belt tensions for both running and acceleration scenarios. Therefore this resistance can be quite simply determined by subtracting the effective tension ($Te = T1 - T2$) for the acceleration case from the effective tension for the running case. Alternatively, it can be manually calculated with relative ease.

5.4. Torque versus time graph

A number of phases and component resistances are considered when analysing predicted motor torques during start-up.

During break-away conditions the resistances due to blocked chute conditions, the resistances due to static friction and the inertial resistances are added to the base running resistances. This analysis is conservative as it does not take the elasticity of the belt into account. With low acceleration rates the section of the conveyor adjacent to the drives may be moving whilst other areas of the belt will still be stationary. This behaviour reduces the effect of break-away resistances if the acceleration rate is sufficiently low and the belt length sufficiently long.

After initial break-away during acceleration the conveyor static friction resistances are zero. As the full chutes empty these resistance forces decrease until they become zero as well. For the majority of the acceleration phase of start-up, it is common only to have the inertial resistances to consider in addition to the base resistances for running conditions (Figure 1).

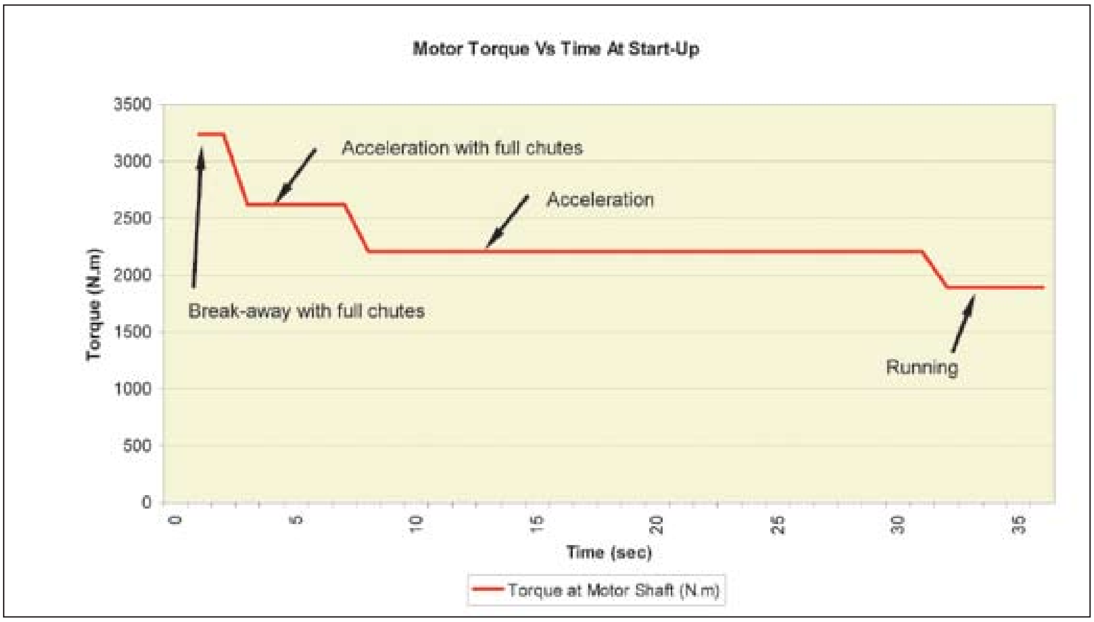

Figure 2. Example showing typical conveyor motor torque requirements during various phases at start-up.

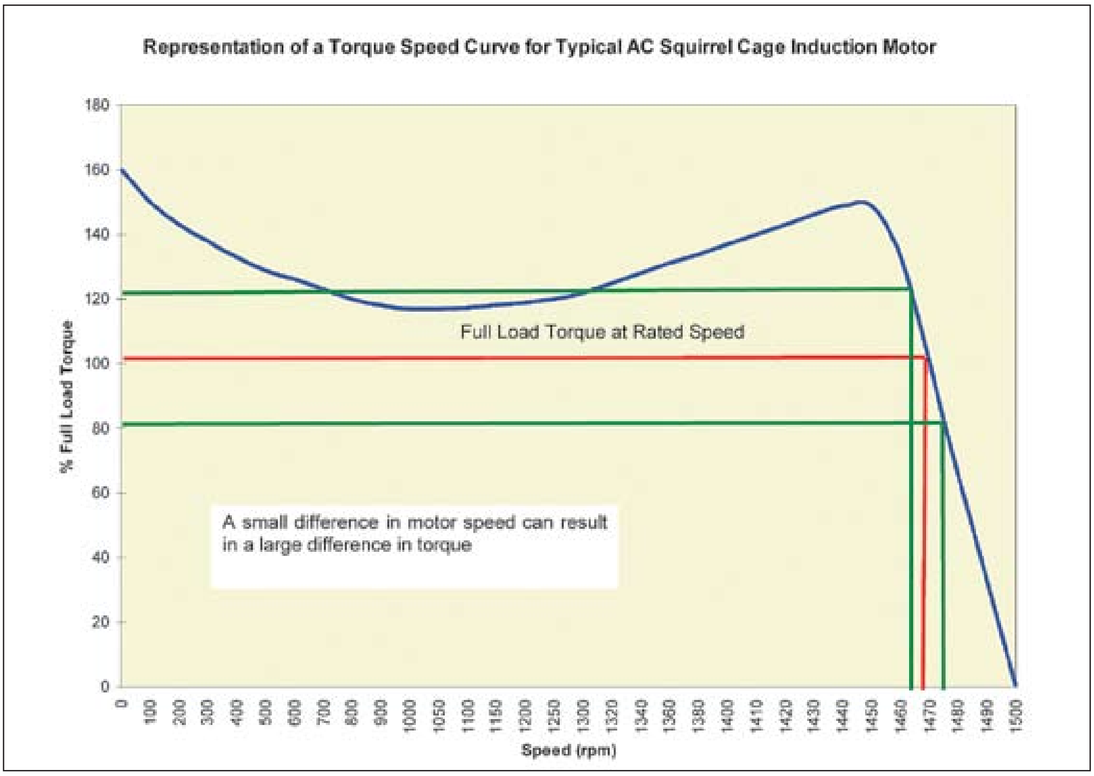

Figure 3. Representation of a typical torque speed curve for a squirrel cage induction motor.

The end result of the analysis of conveyor resistance forces during start-up should be a graph of torque at the motor shaft versus time. A typical example is shown in Figure 2.

5.5. Allowance for surge

It is normal industry practice to size a conveyor's drive power and volumetric capacity to allow for surge. This arises from inaccuracies and hysteresis effects in the control system which can result in throughputs in excess of the design values being fed over the conveyor for periods of time.

To determine if surge should be allowed for in addition to full chute conditions at start up, a study should be conducted to determine the probability of both the occurrences happening together. This probability can then be used to estimate the likely financial losses which may be incurred for a number of scenarios. A decision can therefore be made on a rational basis as to whether allowances for surge and full chutes should be added together as a condition for start-up.

It is often a surge condition over a period of time that causes a conveyor to trip out through electrical overload (time-current or temperature) or mechanical overload (oil temperature), leaving a situation where a conveyor restart with excess load and blocked feed chutes is needed.

6. De-rating factors

Various factors need to be considered when determining if a drive system will be capable of overcoming the resistances at start-up.

- Gearbox efficiency
- Fluid coupling efficiency (slip)
- Line losses from the controller to the motor
- Losses inherent in some types of motor - control system combinations e.g. VVVF and electronic soft starters

- Consideration for torque mismatch on multi-drive conveyors
- General motor safety factor

6.1. Gearbox efficiency

The losses incurred by transfer of power through a gearbox are well known and will not be explained in any detail in this paper, apart from saying that typical bevel helical gearbox efficiencies are in the order of 95% to 97%.

Other types of gearbox may not be as efficient and attention should be paid to ensuring the correct figures are used. Confirm that the procured gearbox has the same efficiency as the design.

6.2. Fluid coupling efficiency

Likewise, fluid couplings incur losses and as these are generally well known, they will not be discussed in detail in this paper. Typical efficiencies of fluid couplings are usually quoted in the range of 95% to 97%. Again, confirm that the procured coupling has the same efficiency as the design.

6.3. Line losses between the motor controller and motor

These electrical losses which occur between the motor controller and motor can typically be calculated. Typical values would be in the order of 2 to 5%. Other issues such as voltage drop should also be considered when establishing possible de-rating factors resulting from electrical issues.

6.4. Losses inherent in motor – controller combinations

It is essential to determine the torque available at the motor shaft by considering the drive system holistically. A motor which is controlled by a VVVF or electronic soft start may have its torque at start-up de-rated considerably to compensate for characteristics of the motor – controller combination.

The torque available from the motor shaft must be calculated on a case by case basis for any particular motor – controller combination. For example, motor efficiency ratings are reduced on squirrel cage induction motors that need to accommodate a VVVF drive.

Quoted torque characteristics for motors will vary significantly between suppliers and motor type. It is essential to ensure that the motor supplied has characteristics that match the design. Preferably the motor and controller should be procured as a package. If this is not possible, the drive supplier should be advised of the motor details (and vice versa) to ensure that torque – time requirements during starting can be met.

6.5. The effects of load sharing

Multiple drive systems have a number of factors which will affect the ability of the system to load share effectively.

- Differences in motor characteristics due to manufacturing tolerances
- Differences in drive pulley diameter due to manufacturing tolerances, wear, or material build up on the pulleys.
- Differences in oil fill in fluid couplings

Consideration of load sharing has become particularly important more recently with the modern trend of direct coupling motors into the drive train. Figure 3 depicts a typical torque-speed curve for a squirrel cage induction motor. It can be seen from this figure that a small change in motor speed at full running conditions will result in a relatively large difference in torque which can be delivered from the motor. If a small resultant change in rotational speed is forced onto the motors through mismatched pulley diameters or

Gearbox Efficiency	Fluid Coupling Efficiency	Electrical Line Losses	Load Sharing Tolerance	De-Rating for Motor Controller (Electronic Soft Start or VVVF)	General Motor Safety Factor	**Total De-Rating Factor**
0.97	N/A (1.0)	0.98	0.95	0.98	0.97	**0.86**

Table 1. Combined effect of drive de-rating factors (the example shown is a direct coupled dual drive with VVVF running at full speed).

mismatched motors, the effect on load sharing can be pronounced.

In extreme cases, lack of consideration for load sharing can result in trips at less than rated capacity. In one case known to the authors, a conveyor was designed using wound rotor induction motors with liquid resistance starters. At rated speed the motors were running direct on line (DOL) with no ability to cater for differences in pulley diameter. Even in its new condition the conveyor would not operate at more than 70% of its design throughput because one of the drives was working significantly greater than rated full load torque of the motor whilst the other motor was only operating at less than 50% of its capacity. Electronic soft starts with squirrel cage induction motors on multiple drives will also exhibit these problems at running conditions.

Fluid couplings which are incorrectly filled or poorly maintained can also lead to load sharing issues.

Motors which are direct coupled into the drive train can achieve compensation for load sharing by a number of methods:

- Providing a control system which measures torque differences between the drives and adjusts the motor speeds accordingly to target equal load sharing between the drives. Control systems in this category include
  - Squirrel cage induction motors using VVVF control. VVVF suppliers usually allow a tolerance of 5% to 10% between the drives for load sharing.
  - Wound rotor induction motors (WRIM) using PLC monitored secondary resistance controls (SRC). This type of system has found economic application on larger drives (> 750 kW) and in locations where rugged simple components become determining factors. With a motor protection relay (MPR) real power or stator current feedback input, the PLC ensures that load sharing is achieved, and the effects of all transients is for practical purposes, eliminated.
- Another method simply involves making the drives oversize to allow for one drive to operate above the normal load sharing point. Consequences of this approach are adverse power factors, lower drive efficiencies, layout impacts due to the larger drive dimensions and higher structural loads at motor stall conditions.

Multiple drives operating using VVVF control should be matched on torque, not speed. Attempting to match drives on speed may lead to instability and load sharing issues. When specifying controllers for multiple drive systems, the maximum expected speed difference between the primary and secondary pulleys should be included in documentation sent to the supplier.

6.6. Motor safety factor

Motor safety factors are often quoted in specifications as a cover-all for some or all of the above de-rating factors. By taking account of the various de-rating factors, it can be argued with a degree of certainty that a motor safety factor lower than what would usually be specified could be used. It is common place to specify motor safety factors between 10% and 15%, however, by taking account of the component de-rating factors a figure of 3% to 5% could be employed.

6.7. Combined effects of de-rating factors

By not taking full account of de-rating factors, drive systems can be undersized. Table 1 illustrates the combined effects of de-rating factors, which by themselves may be relatively inconsequential, but whose combined effect is significant.

7. Total effect of conveyor resistances and de-rating factors

Modern VVVF controllers are generally able to produce 150% full load current (FLC) for approximately 60 seconds with 10 seconds of these 60 seconds being as high as 200% FLC. With the breakdown torque of most motors being above 200%, at face value it would not be expected that starting would be an issue.

An analysis of the combined effects of the conveyor resistances and de-rating factors soon reveals that if the motor is sized to meet running requirements only, issues with starting can arise.

Taking the figures above (section 5), the ratio of break-away resistance to running resistance is 1.75. Applying the de-rating factors this ratio now becomes 2.0. What appeared to be a safe design now becomes marginal. Add to this the additional de-rating required to be applied to a VVVF drive while operating at low frequencies (start up conditions) and the design goes from being marginal to failing.

For larger drives in appropriate applications, wound rotor motors with secondary resistance controllers have and can be used as a means to mitigate the effects mentioned above. For such applications, typical results are: lower power requirements; higher torque availability; and higher starting availability.

It is also important to note that there may be design, cost and schedule impacts arising from the necessity to upgrade a "marginal or failed" conveyor design. These will affect system handover and may include the following issues:

- Mechanical design – Pulley, shaft, gearbox, coupling, belt, bearing design and selection
- Electrical design – Motor, VVVF, switchgear, cabling
- Structural – Supports, foundations

8. Energy considerations

There is an ever increasing requirement to minimise energy demands plant-wide for financial and environmental reasons. As a result of this, the conveyor designer is faced with the challenge of implementing appropriate measures to achieve less energy demanding conveyor systems.

This may be achieved through careful and complete design considerations coupled with good maintenance procedures in an attempt to minimise resistance forces within the conveyor system. In addition to this, energy losses in drive components (de-rating factors previously discussed) may also be targeted as potential energy saving areas. These topics will be discussed briefly with some suggestions of possible measures to take in the design process.

8.1. Conveyor resistances

The power required to run a conveyor is the product of the running resistances (effective tension) and the belt line velocity. The belt velocity is essentially pre-determined to achieve a target throughput with a given burden cross-section area for that particular material. Consequently any reductions in demand power of the conveyor need be achieved by attempting to reduce running resistances.

Basic resistances are typically calculated using ISO5048, CEMA or DIN 22 101 standards. These methods divide the overall resistance into component resistances or groups which summate to give the total resistance force of the conveyor. Some suggestions on reducing resistance forces in various areas are outlined below:

8.1.1. Minimise material lift (slope resistances):

The resistance due to the lifting of the material (and belt) is often a large component of the total resistance of the conveyor. It may be minimised by ensuring the conveyor lift is no larger than it needs be. The designer is reminded to beware of transfer height requirements to ensure adequate material transfer conditions exist at all loading/discharge points.

8.1.2. Avoid over design in belt selection:

The total mass of the belt of the conveyor system can be quite large, particularly in long conveyors. As the rated strength of the belt increases, so too does its mass. For example, an ST500 belt will have a carcass mass of approximately 5kg/m2 compared to a figure of approximately 14.5kg/m2 for an ST2000 belt. Over-conservatism in selecting belt safety factors is common and can lead to higher strength but heavier belts than required by the conveyor. Ultimately, the conveyor should not be designed with a heavier belt than needed.

8.1.3. Employ efficient material transfer points:

Efficient material transfers such as spoon type chutes, serve to limit the work needed to accelerate the material in the direction of the belt. Any reduction in the speed differential between the material loading velocity and the belt speed will reduce material accelerating resistances.

8.1.4. Avoid excessive skirt lengths in loading/discharge regions:

Skirt lengths in loading regions should be sized to be long enough to ensure the burden profile is stabilized on the conveyor. Loaded material should also be clear from feed areas before skirted sections cease and the material allowed to relax into its normal profile. Excessive skirt lengths should be avoided as they will increase material and belt frictional interactions with the skirtplates, thereby unnecessarily increasing overall conveyor resistances. This effect is compounded on conveyors with multiple feed or discharge points. Properly designed spoon chutes can also eliminate the requirement for skirting altogether.

8.1.5. Choose suitable idler type, spacing and understand belt sag effects:

Suitable idler selection (including bearings and seal types) and spacing will serve to reduce idler resistance forces. Factors which need be considered in selection include: type of service, operating conditions, load carried, belt speed, bearing loading, troughed heights and trough angle (e.g. resistances will increase with an increase in trough angle). Idler spacing also impacts on belt sag which is a function of idler spacing, belt tension and supported weight. Excessive belt sag (>1%) can have an adverse effect on power requirements and component reliability. High values of sag should be used with care and only where it is warranted (e.g. conveyor with a tripper to limit empty lift off curve).

In addition to the above items, reducing material carryback by employing and maintaining adequate belt cleaning systems and monitoring and correcting belt tracking problems will help reduce overall running resistances.

The above items are not an exhaustive list of areas where conveyor resistances can be reduced. It is instead intended to promote early thinking in the design stages and highlight the impacts design decisions will have on resistance forces and ultimately power requirements of the conveyor system.

8.2. Minimising drive de-rating effects

De-rating of conveyor drives may come from a number of sources depending on the drive configuration. They are sources of gratuitous energy losses and whilst they cannot be fully eliminated, attempts should be made to minimise their impacts if possible. Section 6 discusses various de-rating factors. These will each be considered in turn below with some suggestions on how to minimise their impact on the drive system:

8.2.1. Fluid coupling and gearbox efficiency:

Efficiency values for these components are typically 95-97%. There is essentially nothing which can be done to improve these values however proper maintenance schemes and maintaining correct fill levels will help ensure efficiencies do not drop below quoted values. Correct lubrication selection will also affect this value and lubrication used should be based on manufacturer's recommendation; higher viscosity oils will consume more energy.

8.2.2. Line losses between motor and controller:

These losses occur between the motor controller and motor and are dependent largely on the line length. As a result, conveyor drive units should be placed as close as practically possible to Motor Control Centres (MCCs) to limit line lengths and associated losses. Correct and suitable cable selection may also help reduce these losses.

8.2.3. Losses in motor-controller combinations:

These losses are inherent in the drive combination and little can be done to reduce such losses. A full understanding of the effects/losses for a drive combination may help decide its appropriateness for a particular application.

8.2.4. Load sharing effects:

These effects exist in multiple drive pulley systems where rotational speed variations exist or are forced onto the motors. Some methods to limit these effects are to:

- Monitor drive pulley diameters which may vary due to manufacturing tolerances, build up or wear
- Use identical motor manufacturer/models and preferably the same fabrication run (consecutive serial numbers) where possible to limit operating variations between motors
- Ensure fluid couplings are correctly filled and maintained
- Employ an adequate control system for direct coupled drives which measures torque sharing between drives and adjusts motor speeds accordingly to achieve equal load sharing

The above discussion has provided some information on areas of potential energy saving which the conveyor designer may target/consider to achieve a more efficient, less energy demanding conveyor system. However, maximum benefit from these design improvements will only be realised if a good maintenance regime is upheld and retained throughout the life of the conveyor system.

9. Conclusions

Undersizing of conveyor drives can be avoided by analysing and accounting for all conveyor resistances and drive de-rating factors. Incorrect analysis or application can result in either a failure to start or failure to run at the specified throughput, especially if the motor size selected is very close to the calculated theoretical conveyor demand power.

By taking the following resistances and de-rating factors into account, a designer can confidently predict correct drive motor sizing:

- Conveyor resistances
  - Running resistances calculated to a recognised standard and using the recommended friction coefficients
  - Inertial resistances during acceleration
  - Break-away resistances due to static friction
  - Resistances due to full chutes
  - Appropriate allowance for surge
- De-rating factors
  - Gearbox efficiency
  - Fluid coupling efficiency
  - Electrical line losses (motor control to motor)
  - Load sharing tolerance in the control system
  - De-rating factors associated with the drive control characteristics (these may be mitigated by using WRIM with a SRC on larger drives in some instances)
  - General motor safety factor

Although these additional resistances and de-rating factors are relatively small when considered individually, collectively the combined result is substantial and can not be ignored.

Careful considerations during the design phase of the conveyor combined with a good maintenance regime over the conveyor's life will help ensure the demand power of the conveyor is kept to a minimum, eliminating sources of unnecessary energy losses.

10. References

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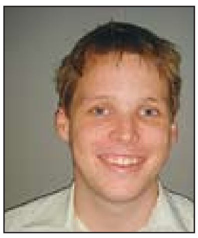
11. Acknowledgements

Thanks are given to Nicole Hampton (P.Eng) of Synergy Engineering Limited (Canada) for her assistance in providing information on PLC controlled secondary resistance controllers for wound rotor induction motors.



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