Chapter 18

REQUIREMENTS AND STRINGENT SPECIFICATIONS FOR BRAKING SYSTEMS ON REGENERATIVE CONVEYORS

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Downhill, or regenerative conveyors have always been a challenge to the design engineer due to their natural instability under load. The last decade has seen the appearance of high tonnage, high negative lift conveyors with several hundred meters of drop. These conveyors have made necessary the development of new braking systems and intelligent drive controls to address their starting and stopping requirements under various load conditions. This paper describes the critical design criteria of large regenerative conveyors and some of the advances in mechanical braking systems and drive control technology developed by Conveyor Dynamics, Inc. (CDI) to address their specific requirements.

INTRODUCTION

The last decade has seen the development of larger and longer conveyors with increased lift and load capacity. These designs have been made possible by dramatic advances in conveyor design technology based on new techniques such as dynamic analysis modelling.

By accurately predicting belt tensions and peak stresses during transient operations, these new methods of analysis have enabled the use of lower safety factors and resulted in increased requirements for system integration and accurate torque control of the drive and brake systems. These new techniques can be applied to the design of any conveyor, but are most important for the design of several challenging categories of conveyors. Horizontal curve conveyors require careful control of the tension in their curves to minimize belt drift. Downhill, or regenerative conveyors are even more critical due to their natural instability under load. Steep uphill and high lift conveyors require precise acceleration and deceleration controls to minimize dynamic instabilities and insure material stability on the belt.

The design of such conveyors, and the interaction between their various components, require an integrated system approach and a careful evaluation of the available drive, brake, and control options. This paper describes the special requirements of downhill conveyors, their impact on equipment selection, and some of the techniques used to insure their safe operation.

DYNAMIC ANALYSIS MODELLING

One of the most powerful tools available today in the design of conveyor systems is dynamic analysis modelling. Dynamic analysis modelling is a method which analyses a belt as an elastic system with real time dynamic response. The belt is modelled as a series of connected elastic springs with individual masses and damping properties. This technique was developed to predict the creation and propagation of tension and velocity waves in conveyor belts during transient operations. It enables the accurate prediction of the dynamic behavior of the belt during starting and stopping phases, and allows the designer to simulate most types of drive and brake hardware and control algorithms.

The concept of dynamic analysis modelling of conveyor belts was first developed in the 1960's. Its use was pioneered by Conveyor Dynamics Inc. as early as 1980 [1], with the development of the BELTFLEX program and its release in 1982 [2]. Dynamic analysis is now widely used around the world, and is an important part of our integrated system approach to conveyor design.

Preliminary dynamic analysis of the design are first performed to tune the mechanical sensitivity of the system. This quickly narrows the choice of acceptable drive and brake options. Dynamic analysis then provides the frame work for an educated selection of components and control algorithms, and is used to establish the minimum accuracy required for torque delivery and the minimum speed of response of the selected hardware.

As an example, an important parameter to consider during the design of downhill conveyors is the launch rate of the drive pulley (Fig. 1). The launch rate is the sudden acceleration of the drive pulley when the drive power is suddenly removed on a fully loaded conveyor. This acceleration can be very fast since the complete tension differential across the pulley is suddenly applied to the relatively small inertia of the pulley and drive assembly. The launch rate, together with the maximum allowable belt overspeed, directly controls the speed of response required of the brake system. Dynamic analysis should be used to predict this rate, and to calculate the minimum drive inertia required to keep the brake response requirements at a realistic level.

After final selection of the drive and brake hardware, dynamic analysis modelling is used again to study and finalize the required control algorithms. It plays an important role in evaluating various approaches to the control system, from smart controllers requiring multiple feedback, to preemptive controllers based on preset steps and fixed timing of the control parameters.

At the final stage of the design, dynamic analysis is used to investigate the various failure modes of the selected equipment and their impact on the peak belt tensions. It can also be used to study the loop stability of the selected control algorithms, and the influence of such parameters as transducers response time, time delay in brake application, and maximum rate of change of drive torque.

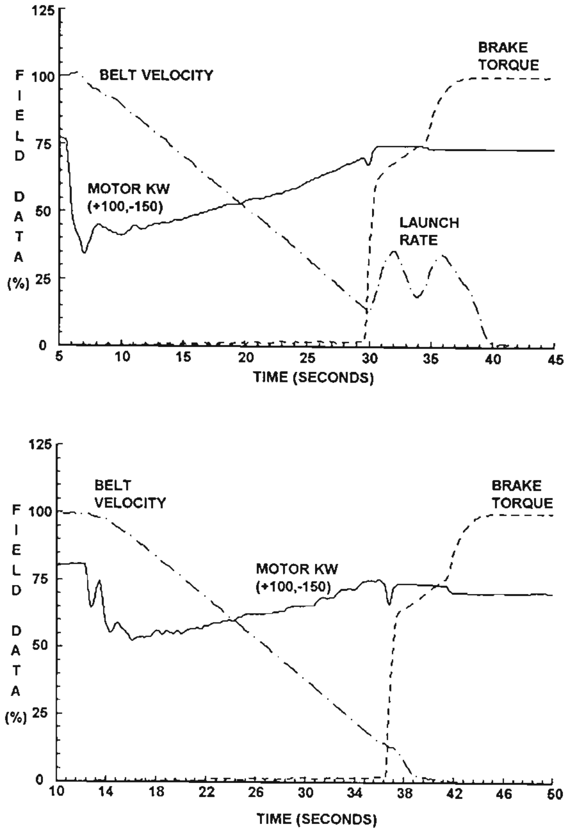

Figure 1 These field recordings show the stopping sequence of a fully loaded 4500 KW downhill conveyor with inverter drives and hydraulic disk brakes. The inverters were used to decelerate the conveyor to 15 percent speed, at which point the control was transferred to the brakes. The first plot shows a test taken before tuning of the transfer sequence. The second plot shows a similar test with the proper transfer timing. The transfer was tuned by adjusting the predictive coefficients and increasing the motor-brake overlap period to 200 msec. The first plot clearly shows the rapid acceleration of the drive pulley when the motor retarding torque is removed (launch rate).

DRIVE AND BRAKE SYSTEMS SELECTION

The proper design and selection of the drive and brake systems is extremely important. It directly influences the accuracy of the starting and stopping controls, and has a direct impact on the ability to control dynamic instabilities. Speed of response, torque accuracy and repeatability, control predictability, reliability, and failure modes are among the parameters which have to be evaluated. These parameters, combined with dynamic analysis modelling, directly influence the selection of the control algorithms.

The drive and brake selection has to take into account the technical requirements, the system cost, its reliability and its serviceability. The client preferences must be considered with the required system maintenance, the site maintenance procedures, and the expected competence of the maintenance personnel. Available support and spare parts availability are also important factors in remote locations.

An important consideration in the design of downhill conveyors is the drive's ability to deliver retarding torque below synchronous speed. All the major drive options, except for DC drives and eddy current drives, require initial brake control at very low speed to provide smooth acceleration and stopping of the belt. Inverter drives can provide retarding torque down to 8 percent speed, but usually still require brake control below this speed. Most commonly used drives cannot provide retarding torque until full speed and require brake control during the full starting sequence. This has a large impact on the design of the brake control and hardware since more energy is dissipated in the brake during starting than during stopping. This results from the increased torque required when the brake must resist both the gravity load and the motor driving torque during the start sequence.

It is very important to realize that the mechanical brake is the only mean of stopping a loaded downhill conveyor in case of motor failure. This is true even when the selected drive can normally provide retarding torque. As a result, the brake system is one of the most critical component in a downhill conveyor. The brake and its control system must always be designed to safely stop the fully loaded conveyor from full speed and under any failure condition. this critical requirement for a fail-safe design is covered in more detail later in this paper.

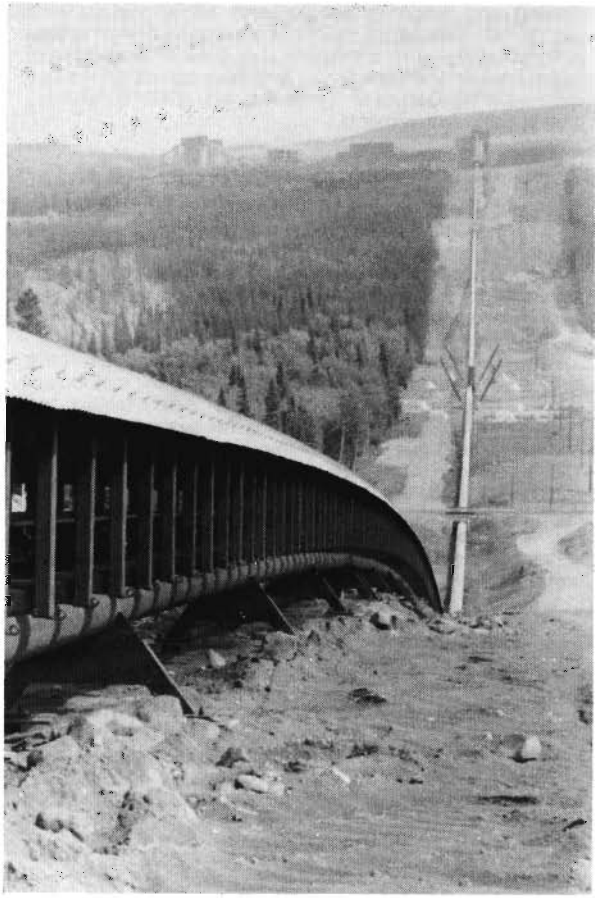

Figure 2 The C2 downhill conveyor at the Quintette Coal mine in British Columbia, Canada, is 7 km long and uses a single DC drive and hydraulic disk brakes.

As is often the case in engineering design, the final choice is usually a trade off between cost, simplicity and performances. The best choice is the simplest, most reliable system which will do the job satisfactorily.

There are many available options for the selection of conveyor drive and brake systems. The following is a short description of the most commonly used systems.

DC Drives

DC drives are available in any horsepower configurations. They can provide both driving and retarding torque at any speed, and are available with four quadrants control. Four quadrants control allows the drive to regenerate energy into the main electric grid.

DC drives are normally used when very precise torque and velocity controls are required, or when the conveyor needs to be run under load at low speed for extended period of time. Their ability to regenerate power can result in substantial electrical savings for large horsepower applications. Their ability to control speed down to a complete stop minimizes the duty on the brake system which can be sized for emergency use only. Their major disadvantages are high cost and high maintenance requirements.

Quintette Coal Ltd., in British Columbia, Canada, has two downhill overland conveyors, respectively 7 km and 6.5 km long (Fig. 2). Both conveyors are driven by single 2600 KW (3500 HP) DC motors. These conveyor have been in operation since 1983.

Inverter Drives

Once limited to medium power applications, Variable Speed Inverter Drives are now available in high horsepower, high voltage configurations. Most configurations can provide both driving and retarding torque at speed as low as 8 percent of full speed. Some inverter drives are available with four quadrants control.

An inverter drive can be bypassed when the conveyor reaches full speed. This increases the drive efficiency and decreases its duty. It also allows inverter drives to be shared between conveyors when simultaneous starting is not required.

Inverter drives are a good choice for conveyors which require accurate velocity control above 10 percent speed, or which need to be run under load over 50 percent speed for extended periods of time. They present similar advantages to DC drives, but require additional brake control in the very low speed range.

Figure 3 The P7 downhill conveyor at the Phelps Dodge Morenci copper mine in Morenci, Arizona, has 245 meters of drop and uses inverter drives and hydraulic disk brakes.

Their major disadvantages are high cost, high electrical noise, and sophisticated training requirements. Some types of inverter drives can generate an enormous amount of RF electrical noise, especially in the low to medium speed range, which can create problems with sensitive electronic control equipment.

The Mexicana de Cobre, La Caridad copper mine in Nacozari, Sonora, Mexico, was the first successful implementation of inverter drives on conveyors [3]. The concept was developed by CDI personnel in cooperation with the Ralph M. Parsons Company of Pasadena, California, and the Emerson Electric Corporation of Santa Ana, California. Four 450 KW (600 HP) variable voltage inverter drives are used to control the starting of 15 conveyors. The largest of two regenerative conveyors is driven by three 450 KW motors. The same inverters are used to control a large incline belt with four 450 KW motors. The system was commissioned in 1977 and is still in operation today.

The Phelps Dodge Morenci copper mine in Morenci, Arizona, recently commissioned a new in-pit crushing and conveying system. The installation has two downhill conveyors driven by current source inverter drives. The largest of the two conveyors has 245 meters of drop (Fig. 3). It is driven by two 2250 KW drives controlling four motors at two drive locations. All the drives have four quadrants capabilities and are bypassed at full speed. The system was commissioned in April of 1992.

Wound Rotor Motors

Wound rotor motors equipped with secondary step resistors can produce variable driving torque. Two different methods of resistor switching can used (Fig. 4). The traditional design uses two sets of contactors and provides one torque level per resistor element. The binary stack design uses one more set of contactors, but enables any combination of resistors to be selected. Three to eight resistor elements are commonly used depending on the application. Wound rotor motors are available in any horsepower configurations.

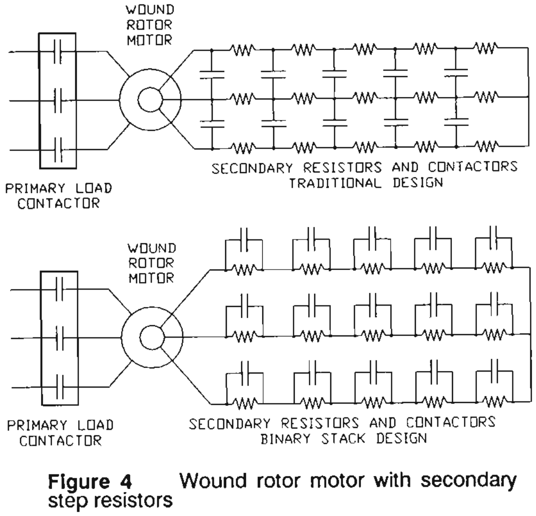

Figure 4 Wound rotor motor with secondary step resistors

Wound rotor motors are a good choice for most large conveyors because of their low cost, predictable torque and simple maintenance requirements. Dynamic analysis modelling can be used to optimize the timing sequence of the resistor steps, and a universal sequence covering all load conditions can usually be found (preemptive type control). Their major disadvantage is the inability to produce retarding torque until synchronous speed. This requires both the starting and the stopping sequences to be controlled by the brake.

Special attention has to be given to the thermal design of the resistor elements and to their thermal stability. This is especially true foı long starting sequences, where the extreme heat generated in the elements can change their resistance and alter the delivered torque.

The Kennecott Bingham Canyon copper mine in Bingham Canyon, Utah has five overland conveyors with wound rotor motors controls. Two long overland conveyors with regenerative sections are each by four 1125 KW motors with head and tail drives. The drive and proportional brake controls were designed by CDI. The drives use a binary stack with 7 elements and 22 steps. The step combinations, and the individual resistance of each element, were selected to provide a very gradual control of the torque. The preemptive controls were established by dynamic analysis and verified in the field. The system was commissioned in 1985 and is still in operation today.

Fluid Couplings

Induction motors equipped with fluid couplings are also commonly used. They can be divided into two basic types: fixed level couplings and variable level couplings. Variable level couplings are available in a variety of configuration, from simple delay chambers to complex system involving dynamic level adjustments and closed loop controls. Fluid coupling drives typically have very poor efficiency due to their permanent hydraulic slip.

Fluid couplings are a common way to provide soft acceleration control for low to medium horsepower applications. They can be a good choice for smaller conveyors with simple dynamic requirements because of their relatively low cost and simple maintenance requirements. Adjustable fill couplings are often used when load sharing between drives is important, or to provide some degree of variable speed control.

The nominal torque delivered by a fluid coupling is a non-linear function of its fluid level. The fluid temperature and its viscosity, and the time between starts (on delay chamber models) also deeply effect the torque level. In addition, there is an inherent phase lag, as much as three seconds, between the initial motor start and the establishment of a stable torque. All these considerations makes the coupling torque sometimes unpredictable, and makes fluid couplings difficult to use in fast closed loop controls.

The inability of a fluid coupling to produce retarding torque below synchronous speed requires the brake to control both the starting and the stopping sequences. In this case, the high level of torque delivered by fluid couplings substantially increases the duty on brake systems during starting sequences. When precise acceleration controls are required, the unpredictability of the coupling torque can make the brake control difficult and result in control instabilities.

The Cementos Mexicanos, Cementos Del Yaqui mine in Hermosillo, Sonora, Mexico has one downhill conveyor and one long overland conveyor with regenerative sections. The two conveyors and their control systems were designed by CDI. Both conveyors are driven by induction motors fitted with fluid couplings. The 3 km long overland conveyor has both head and tail drives. The tuning of the head and tail drives starting controls during commissioning proved very difficult due to the couplings torque variation with fluid level. Small differences in coupling fill resulted in large variations in torque between the head and tail drives. This created a speed differential between the pulleys, which was amplified by the elasticity of the fabric belt, and resulted in large dynamic instabilities. Fill differences as small as 0.25 liter were sufficient to induce dynamic instabilities. The problem was solved by incorporating adaptative brake controls to stabilize the belt acceleration at each station. The conveyors have been in operation since 1990.

The Placer Dome La Coipa mine in Copiapo, Chile has two downhill conveyors. Both conveyors are driven by single fluid coupling drives with delay chambers. The control system for both conveyors was designed by CDI. The conveyors have been in operation since 1991.

Hydraulic Disk brakes

Hydraulic disk brake systems are available in all sizes and in many different configurations. They can be of the high speed or low speed type. They can be hydraulically applied, or spring applied and hydraulically released. They are available with a variety of hydraulic units, from single valve control to redundant proportional controllers.

High speed disk brakes are located on the high speed side of the reducer and are usually small due to the lower torque required on the motor side of the reducer. Their main advantages are low cost and accurate torque control. An added advantage in some designs is the natural flywheel effect of their disks, which reduces the dynamic sensitivity of the conveyor. Their main disadvantages are small heat capacity and increased duty on the reducer. They also offer decreased safety compared to low speed brakes, as a reducer or low speed coupling failure results in the complete loss of braking capacity. High speed brakes are commonly used on uphill and flat conveyors, where their main functions are belt sequencing control to eliminate transfer chute pluggage, and tension control.

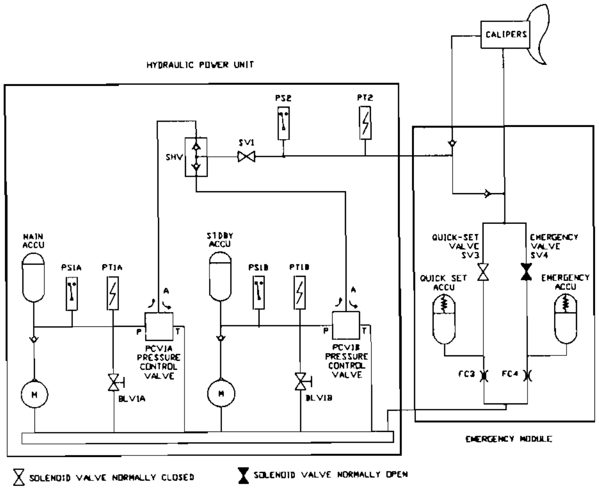

Figure 5 This simplified hydraulic schematic shows the major components required for proportional control of downhill conveyors disk brakes. It incorporates redundant components for pressure generation and control, emergency components, and quick-set components. The emergency and quick-set components are placed in a separate module located close to the disks.

Low speed disk brakes are located on the low speed of the reducer next to the drive pulley. They are much larger and more expensive for the same torque requirement. Their main advantages are increased safety, high thermal capacity due to larger disk sizes, and increased pad sweep area. Low speed brakes are a natural choice on downhill conveyor where their increased safety and large thermal capacity are essential.

Spring applied calipers are used whenever a fail-safe design is required. In those brakes, the pad pressure is supplied by sets of mechanical springs, and hydraulic pressure is used to release the pads. This insures that the maximum braking torque is always available, even during power failure. Spring applied calipers offer good torque control, but are slightly slower and are not as predictable as hydraulically applied calipers. This is due to the mechanical hysteresis in their spring sets, and to the variation in spring pressure with pad adjustment and pad wear. Their speed of response is usually in the 100 to 300 msec range, but they can be designed for faster applications if required.

Hydraulically applied calipers are mostly used on uphill and flat conveyors. They offer very precise torque control, fast response and low hysteresis.

The main disadvantages of hydraulic disk brakes are their high maintenance requirements and the sensitivity of their hydraulic systems. This is particularly apparent with proportional controllers, which are extremely sensitive to oil contamination. This problem can be reduced by the proper design of the hydraulic unit. Large sealed hydraulic tanks should always be used, preferably fitted with internal expansion bladders. This reduces the natural breathing due to temperature variations, and minimizes oil contamination. Multiple stage filters should be installed on all the tank intake and return lines. Additional very fine filters should be used on each port of sensitive pressure control valves. When system availability is critical, it can be significantly increased by the use of redundant components (Fig. 5) and the incorporation into the control system of manual control modes for maintenance purpose.

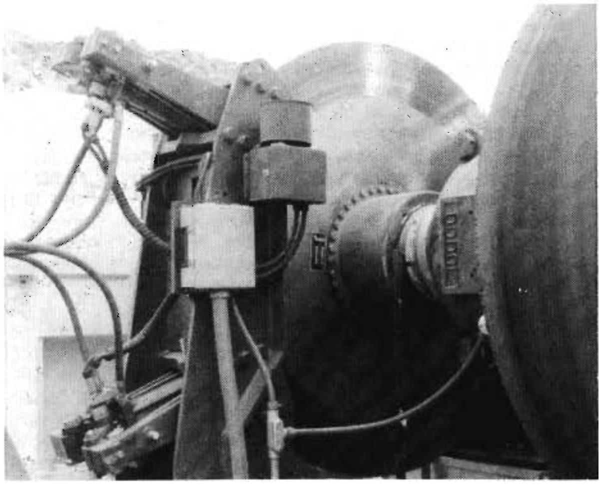

Figure 6 A typical low speed disk brake

Special consideration for a fail-safe design of disk brakes and their hydraulic units are covered in another chapter of this paper.

The two downhill conveyors at Quintette, the two downhill conveyors at Morenci, the two downhill conveyors at La Coipa, and the three overland conveyors at Kennecott use spring applied, hydraulically released low speed disk brakes (Fig. 6).

The hydraulic unit used for the Quintette conveyor is an eight step controller using pressure relief valves and solenoid valves on a common manifold. The manifold pressure is continuously adjusted by the control system according to the load conditions. The manifold is connected to the brake calipers by a very fast acting solenoid valve (Fig. 7). The original brake system installed on the conveyor used a proportional control valve coupled to an analog controller. This system experienced violent control instabilities which, on several occasions, resulted in belt overspeed in excess of 135 percent. Its reliability was also very poor because of coal dust contamination of the hydraulic fluid. CDI was contracted in 1984 to redesign the hydraulic unit and develop the first PLC based brake control system. The new unit was designed for high reliability and very fast response time (70 msec to full torque). Client preferences were a major consideration in the selection of a step controller. The hydraulic unit is completely sealed and incorporates internal bladders. The new system has been in operation since 1985 and has proven very reliable.

The hydraulic units used for the Morenci conveyors are fitted with proportional pressure control valves. All the pressure generation and control components are redundant to maximize availability (Fig. 5). The hydraulic design includes emergency and quick-set modules located next to each disk. These modules are used to speed up the initial brake application, and to provide emergency control in case of failure. The hydraulic design was a joint effort by CDI, Johnson Industries of Richmond, Canada, and Fluor Daniel Wright of Vancouver, Canada.

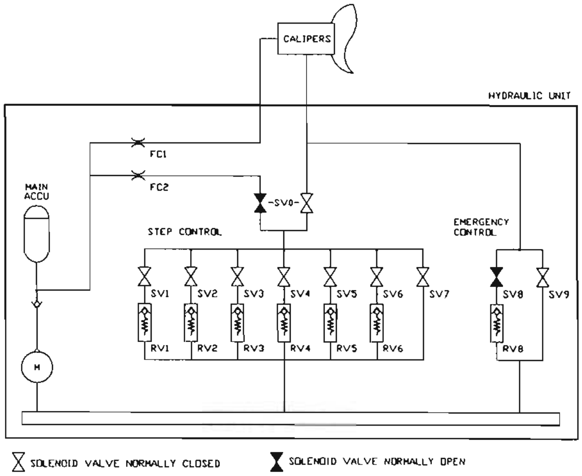

Figure 7 This simplified schematic shows the major components of the hydraulic unit designed by CDI for the Quintette downhill conveyor. This unit has a response time under 70 msec and very high reliability.

Pneumatic Brakes

Pneumatic brakes are always located on the low speed side of the reducer. They are made of several circular plates and are similar to a car clutch with one side bolted to the pulley frame. They can be pneumatically applied or spring applied, and are available with a variety of pneumatic controls. Pneumatic brakes are available in low to medium-high torque configurations.

Their main advantages are simplicity, medium cost, low maintenance requirements and robustness. Their main disadvantages are high hysteresis and low speed of response. Pneumatic brakes are difficult to use with proportional controls and are typically used with one way stepping controls. Their speed of response varies with the design of the pneumatic circuit and the size of the lines, but is usually in the 2 to 5 seconds range.

Pneumatic brakes are mostly used on conveyors when high reliability and low maintenance are important. They can be used on downhill conveyors when proportional control is not required and slow dynamic response is acceptable. They are not recommended for cold climates as the moisture in the air supply can freeze the brake action. Heat tracing can be used, but is difficult to make fail-safe.

The two conveyors at the Cementos Mexicanos mine in Hermosillo use spring applied, pneumatically released brakes. The pneumatic control is performed with a 15 stages binary control valve, and incorporates a fast dump valve placed next to the brake to improve its response time.

CONTROL HARDWARE AND INSTRUMENTATION

The most important considerations for the selection of the control hardware are accuracy, flexibility, speed of response, reliability and fail-safe considerations. The design should include provisions for emergency controls, self compensating controls, and transducers checking. These requirements usually preclude the use of relay systems, analog controllers, or hardwired system in general. The only available option with the necessary flexibility is a Programmable Logic Controller (PLC).

A PLC control system provides the ability to incorporate models generated during the dynamic simulation of the conveyors. Its inherent flexibility allows easy program customization in the field. It allows for an easy monitoring of the major component of the system (drives, brakes, belt, etc.) as well as complete interlocking and sequencing between conveyors, feeders and their components. This results in a superior level of protection for the system mechanical and electrical components. Finally, its solid state nature makes it far more reliable and easier to maintain than the electro-mechanical relays found in hardwired systems.

Uninterruptible Power Supplies (UPS) are required to keep the most important control functions active during power outages. The UPS must power the PLC, the velocity transducers, and the brake control components. 24 Volt DC, battery backed UPS's with regulated power supplies should be used in fail-safe designs because of their increased safety, improved reliability, and inherent noise filtering. In this type of UPS, the DC supply is used to charge a set of batteries, which directly power the equipment. This results in increased safety as the batteries can provide power, even in case of UPS failure. CDI manufactures a line of UPS specifically designed for such applications (Fig. 8). They incorporate battery protection and monitoring circuits, direct PLC interfaces, and watchdog circuits. Watchdog circuits are used to detect PLC failures by constantly monitoring the PLC scan time.

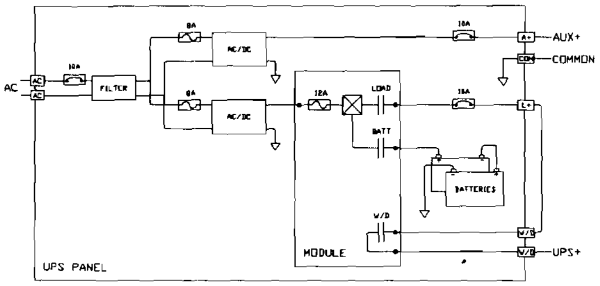

Figure 8 Simplified power flow of a CDI 24 Volt DC UPS panel. This panel has one battery backed output and one auxiliary output. The UPS module controls the power flow, monitors the battery voltage, and provides the PLC watchdog protection for the system.

An important consideration in the choice of control hardware is the need to incorporate both drive and brake controls into a single environment. Separating the drive and brake controls decreases the overall safety of the system and can lead to dangerous control instabilities when the drive and brake are operated simultaneously.

A careful selection of all the instrumentation is also required for a successful implementation of the control algorithms. The instruments selected should be fast, accurate, and noise free. This is especially important of the velocity transducers, or tachometers, which provide the primary control variable for the feedback loop in proportional systems. These tachometers must be able to operate without noise and accurately across the complete speed range, and must have a very fast response time of 20 msec or less to match the PLC scan time and fast belt response.

Because of the difficulty in locating instruments with the conflicting requirements of fast speed and low noise, CDI has developed a line of tachometers specifically designed for this application. The CDI tachometers use optical encoders with quadrature outputs, opto-isolated inputs, digital filtering techniques, and a proprietary adaptative filter stage to provide a very stable and noise free output. They offer very high noise immunity, very low noise level (under 10 mv), and fast response time (under 12 msec). These units have been designed for the industrial environment and have proved very reliable in the field.

CONTROL METHODS

The algorithms used to control the drive and brake systems are derived during the dynamic analysis modelling of the conveyor. This analysis defines the duration and shape of the velocity ramps required to minimize belt stresses, and the type of control required to achieve them.

The primary goal of the control system is to emulate these control algorithms while avoiding the creation of additional tension waves in the belt. It needs to provide maximum protection for the system and to incorporate back-up algorithms for emergency control. It may also need to incorporate self compensating controls to minimize the effects of transducer drift, transducer checking to insure the integrity of the signals used in the control loops, and manual modes of control for maintenance purposes.

Several types of control can be used. Smart, or adaptative controls are based on closed loop proportional type algorithms with single or multiple feedback. Preemptive controls are based on the emulation of preset sequences defined during the dynamic modeling of the conveyor. Mixed controls can also be used, where the control system uses feedback to select among several preemptive algorithms.

Adaptative controls are more difficult to implement but require less optimization and design work. They sometimes result in lower system cost because of their inherent accuracy enabling the use of lower safety factors. Adaptative controls automatically adjust for any loading conditions and can self compensate for instruments drift or variations in brake torque level due to pad wear and hydraulic system drift. However, they usually decrease reliability and increase the maintenance requirements of the system because of the more complex control components and more sensitive instruments used in their implementation.

Adaptative controls are typically used when precise velocity or tension controls are required, or when precise stopping times are specified. A typical application is for simultaneous stopping of multiple conveyors on the same route. They are also used when a fixed control sequence cannot be found to cover all the possible loading conditions of the conveyor.

Preemptive controls are easier to implement but require more design and optimization work, as universal sequences covering all load conditions have to be developed. Their design requires an accurate knowledge of actual drive and brake behavior in the field. For instance, the design of preemptive algorithms for conveyors using fluid couplings is difficult because coupling performance curves obtained from manufacturers are not always consistent with field observations. Preemptive controls usually result in more reliable and easier to maintain systems because of the simpler mechanical components and instruments used.

It is outside the scope of this paper to describe in detail the control algorithms used for various configurations of drive and brake systems. However, two factors are very important during the development and implementation of these algorithms: Firstly, the realization that the goal of the design is to minimize belt stresses, not velocity waves; Secondly, the simple fact that the best way to minimize dynamic waves is by not creating them.

Velocity waves are often created in a downhill conveyor during the transfer of power from motor to brake. This is due to the fast response of the drive pulley to torque variations during the transfer. The control algorithms should be designed to minimize this problem as much as possible. This can be done by using predictive-corrective algorithms, as described below, and by carefully timing the transfer sequence (Fig. 1). This transfer timing is critical and has to take into account the brake, drive and control system response times.

Predictive-corrective algorithms are based on the pre-calculation of the required brake torque from the running motors KW. This torque is applied very rapidly at the beginning of the braking cycle. The brake torque is then modulated slowly to control instabilities. The concept was first developed by CDI for the Quintette downhill conveyor in 1984. It has since been used successfully in many applications. This method relies on the accurate reading of motor KW and the ability to accurately and rapidly reach a pre-calculated brake torque.

It is not always possible to achieve a smooth transfer. For instance, a power failure on a loaded conveyor always results in overspeed of the drive pulley due to the time response of the brake. When velocity waves are generated, it can be more harmful to try to control them than to let them go through. The total elimination of velocity waves requires the application of very large brake torques. This increases the belt stresses and can result in control instabilities due to the natural propagation delay of the waves along the belt. The control system should use converging techniques to establish a precise stopping time, but should not overcompensate for velocity oscillations.

Finally, the control system software has to be developed with special considerations [4][5]. The PLC scan time has to be kept low, preferably under 25 msec, to insure a proper response time by the control system. All the analog input signals should be fully checked for out of range conditions and filtered through digital filters to insure noise free values. All the critical control signals should be checked against backup signals in order to detect inaccurate transducers. The filtering and checks performed on analog inputs is especially important for any signal used in a control loop since a noisy signal can result in violent oscillations of the control variables, and in possibly destructive reaction of the control system (Fig. 9).

The downhill conveyors at Morenci and at La Coipa use smart brake controls with predictive-corrective algorithms. The Morenci conveyors use their inverter drives as their primary starting and stopping controls above 10 percent speed. The brakes are used to provide the required speed regulation at low speed, and as back-up to the inverters. The La Coipa conveyors use their proportional brakes as their primary control during both starting and stopping sequences (Fig. 10). During the starting sequence, the brake is modulated to regulate the conveyor acceleration and resist the fluid coupling torque.

The downhill conveyor at Quintette was the first to use a predictive-corrective algorithm. It differs from the previous systems because of its semi-proportional control. In this design, the brake torque can only be increased after the initial brake application. This method was used because of the lower resolution available with a step controller, and to decrease the risk of oscillation induced by the apparent hysteresis of the control. The Quintette conveyor uses its DC drive as its primary starting and stopping control. The brake is used only as a back-up to the drive.

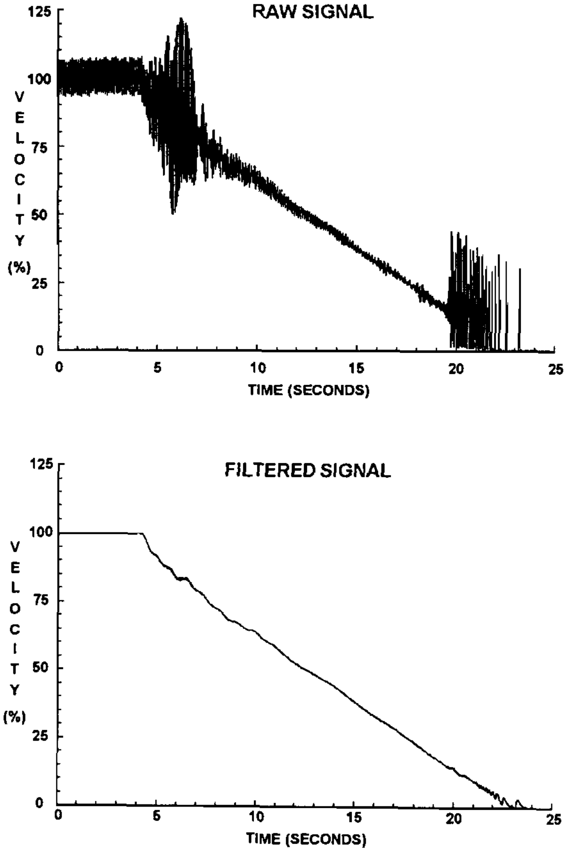

Figure 9 These plots shows the effect of signal filtering on the signal from an improperly mounted tachometer. The first plot shows the raw signal, the second plot shows the same signal after digital filtering. The noise has been removed without altering the original signal shape.

FAIL-SAFE DESIGN

During power outage or motor failure, some downhill conveyors can accelerate to destructive speed in two seconds or less. This natural instability under load imposes very stringent requirements on the design of their brake and control systems.

As mentioned earlier, the brake and its control system must be designed to safely stop the fully loaded conveyor from full speed and under any failure condition. To cover all the possible failure combinations, multiple levels of emergency control have to be designed.

The proper selection of the nominal brake torque is critical. The brake must be designed with a safety margin to account for pad or disk contamination, pad wear, and temperature influence. However, torque overcapacity can result in excessive torque application in case of sudden pressure loss in the hydraulic or pneumatic circuit. Excessive torque also increases the risk of control instabilities, as small pressure changes result in large torque variations.

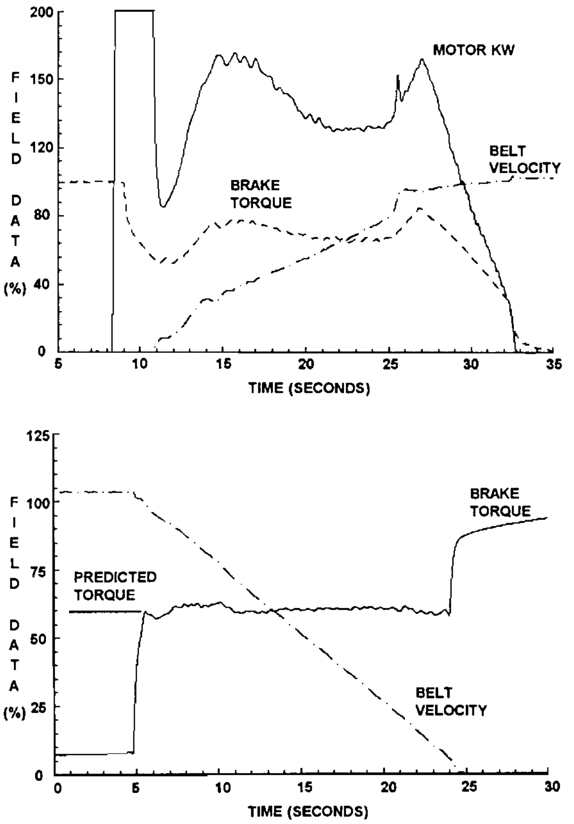

Figure 10 These field recordings show the starting and stopping sequences of a fully loaded downhill conveyor with delay chamber fluid coupling drives and hydraulic disk brakes. The starting sequence uses the brake to control the acceleration. The non-linearity of the fluid coupling torque can clearly be seen on the motor KW curve. The stopping sequence use a predictive-corrective algorithm where the brake torque is increased very fast to the pre-calculated level, then slowly modulated.

Fail-safe brakes using spring applied, hydraulically released calipers have to be used. The brake disks should be mounted on the low speed side of the reducer, before the low speed coupling. Each disk should be fitted with multiple calipers to insure adequate brake capacity in case of caliper failure. The calipers should be spaced evenly around the disk to maximize heat dissipation.

The brake hydraulic or pneumatic systems should incorporate large accumulators to provide the necessary system pressure for a complete controlled stop in case of pump or power failure. They should be equipped with emergency control components to allow for emergency torque control using fixed pressure curves in case of failure of the normal control elements. The emergency components should use normally open valves to maintain the fail-safe design. No manual adjustments of the critical components should be allowed to avoid possible human errors. In conveyors with limited brake redundancy, provision should be made for immediate venting of the brake pressure. Note that these emergency circuits should only be activated if absolutely required because of the high stresses generated in the belt.

The brake instrumentation should be of the highest possible quality. Back-up transducer should be used for critical control instruments, and redundant signals should be checked against each others to insure the integrity of the signals.

A thorough analysis of the failure modes for the mechanical, instrumentation and control equipment should be performed, and dynamic analysis of the worst failure cases should be done to study the impact on the equipment of emergency measures.

The PLC logic should incorporate alternate algorithms to use in case of instrument failure as well as emergency control measures. Several levels of alarms have to be recognized by the control system, and the corresponding actions identified. The PLC itself should be protected and monitored for failure. It should be powered from a UPS to keep the most important control functions active during power outages. This UPS should also power the brake control components and instrumentation. A watchdog circuit should be used to detect PLC malfunctions. The watchdog circuit should be able to trip the drive and trigger the emergency brake controls upon detection of a PLC failure.

Finally, the conveyor should be equipped with a centrifugal overspeed switch. This switch should not depend on electrical power and should be normally closed. It should be adjusted to open at high overspeed over the normal operating range of the conveyor, including any expected overspeed during motor to brake transfers. This switch provides the final level of protection for the system, and should be directly wired to the emergency control components in the hydraulic or pneumatic unit.

INTEGRATED APPROACH

The strong interaction between the dynamic behavior of a belt, its drive and brake components, and its control system requires an integrated system approach to the conveyor system design. Such an approach implies a complete understanding by the design engineers of the various elements involved, including dynamic behavior, drive and brake technology, and control theory.

It is no longer possible to consider drive, brake and control components as commodities and rely on the hardware suppliers to provide the proper equipment. The design engineers need to be involved in the detailed engineering of each component to insure compliance with the specifications and compatibility between the various components. Is should be clear, for instance, that the designers for a downhill conveyor need to be closely involved in the design of the brake hydraulic circuit, as the speed of response of the hydraulic system, its failure modes and its overall performance have a direct impact on the stability of the control loops, the dynamic behavior of the belt, and the safety of the system.

In contrast to the usual approach, where the control and instrumentation work is started late in the project, an integrated design returns significant benefits from an early and constant cooperation between the mechanical, instrumentation and control engineers. The control definition process should be started early in the design stage, and the control engineer should participate in the overall design effort. This link between the mechanical and control engineers is extremely important as it provides both engineers with a thorough understanding of the equipment to be controlled and of the sensitivity of the control parameters.

An integrated approach must include practical testing as well as theoretical design. It is very important to conduct as much testing as possible of the final drive and brake hardware prior to site delivery. This testing should be conducted by the design engineers, and preferably use the selected control hardware. It serves to verify the proper operation of the equipment and its compliance with the specifications. Special attention should be given during these tests to the time response of hydraulic and pneumatic circuits, and to the accuracy of preset emergency systems. As an added benefit, such testing can highlight I/O and instrumentation compatibility problems, which are always a lot easier and much less expensive to fix in the shop than in the field.

Finally, field testing of the completed conveyors should be performed. This final testing is very important, as it validates not only the design, but also its implementation, and provides the operation personnel with a high level of confidence in the new system. The tests should be done according to a pre-established sequence, starting with empty belt tests and slowly increasing the load to maximum design tonnage. All the control algorithms implemented in the PLC should be tested, including the various emergency braking modes. All the important parameters of the system should be recorded using portable data acquisition equipment. These signals should include at least belt speed, motor KW, and brake hydraulic pressure at each drive location. The result of each test should be carefully evaluated against the design criteria before proceeding to the next stage. This maximizes the test safety, as potential problems can be discovered before the full load tests.

A system approach, and the overall coordination and supervision of the design of each component, is essential to avoid expensive and often dangerous surprises at commissioning time. It is also the only means to achieve a true fail-safe design by evaluating the interaction of all the components involved in their various failure modes.

SPECIFICATIONS

Very precise specifications have to be issued for the brake and drive systems, especially in the case of lump-sum bids. Special emphasis has to be placed on critical parameters such as speed of response, fail-safe features, accuracy of torque delivery, noise immunity, and on components with unusually tight requirements. The specification should be as detailed as possible and leave no ambiguity for the hardware suppliers.

The choice of drive and brake systems should be based on the design requirements and the preliminary results of the dynamic analysis modelling. It should not be left to the equipment suppliers. Similarly, the design and specification of critical components cannot be left to equipment suppliers. Vital aspects of the specifications can be overlooked by vendors if they do not understand their justifications or importance. It is unrealistic to expect suppliers to be knowledgeable about advanced conveyor design and of its impact on equipment requirements.

Even with a proper set of specifications, unit responsibility for the final system should be maintained as much as possible. It is never in the interest of a vendor to provide unsuitable equipment, but this can happen very easily if the critical parameters of the system are not clearly identified, and if the proposed equipment is not fully checked.

CONCLUSION

Of all the considerations presented in this paper, the most important one is the simple realization that high negative lift, regenerative conveyors are complex, and potentially dangerous machines. Their design requires a constant preoccupation with safety, and an open frame of mind about new concepts and new techniques.

The rapid evolution of modern technology is changing conveyor engineering from an empirical approach, based on rules of thumb and established methods, to a more theoretical, and more challenging, field. As new concepts and new techniques are developed, the final role of the design engineer is to guide its client to the right choices, sometimes against established methods, and ultimately to a better and safer design.

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