# CASE STUDY: CORRECTING MECHANICAL AND CONTROL PROBLEMS ON ESSROC'S MULTI-DRIVE STATION HORIZONTALLY CURVED CONVEYOR

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## Abstract

Essroc Cement's overland conveyor features three drive stations, transports material on both sides of the belt, and can discharge material at three locations. When originally commissioned, the conveyor was plagued by numerous mechanical and control related failures. This paper describes the mechanical and control modifications that were required to make this conveyor reliable.

## Introduction

In November 2005, Essroc Cement, part of the Italcementi Group, commissioned a long overland conveyor at their Nazareth plant in Pennsylvania. This conveyor, tagged CV-105, was designed to transport 1000 tph of limestone from the quarry to the kiln, and 400 tph of hot clinker (at 300°F) at back from the kiln to a handling facility about halfway back.

Conveyor CV-105 is 8969 ft (2733 m) long. It gains 152 ft (46 m) of elevation in the first 1570 ft (480 m), then is mostly flat for the remaining 7400 ft (2250 m) (Figure 1). After the limestone is discharged at the head pulley, hot clinker is loaded onto the return side of the belt. This clinker can be discharged at one of two locations.

The conveyor is powered by six motors at three different drive locations. Two motors are located at a booster station 1500 ft from the tail, three motors are located at the head station, and one motor is located on the return side at the second clinker discharge pulley, 7400 ft away from the head (Figure 1). The design of the conveyor is further complicated by nine horizontal curves (Figure 2), seven of which have a horizontal radius of 1312 ft (400m).

By early 2006, it was clear that conveyor CV-105 and its drive controls were not functioning properly. Large speed and motor torque oscillations were common, which regularly tripped the conveyor. The conveyor was usually very difficult to start, and large belt tension variations on both the carry and the return sides resulted in significant side travel of the belt in the horizontally curved sections, which resulted in extensive belt edge damage.

The original designers of the system hired the manufacturer of the drives and PLC to correct the problems. After 9 months of site work, the manufacturer's experts got the conveyor to a fairly stable condition. However, failures were not uncommon. The belt in the tail turnover would occasionally buckle and flip over, causing days of downtime, and there were many splice failures and at least one take-up cable failure. This suggested that, under some conditions, the belt tension fell too low, allowing the belt to buckle in the turnover, while at other times the belt tension climbed too high, damaging the belt splices and breaking the cable. Furthermore, the conveyor was often difficult to start when the temperature changed, which required additional tuning of the drives.

In addition to the tension related problems, the belt itself seemed to be degrading. Mine personal reported finding numerous rusty cables, as well as cables that appeared to have failed in tension.

Following a splice failure in October 2008, Essroc commissioned Conveyor Dynamics Inc (CDI) to review the conveyor design and conduct a site survey to see if anything could be done to improve the reliability of the conveyor.

Since being contacted in 2008, Conveyor Dynamics, Inc. has performed a number of site surveys, several mechanical design changes, and has completely rewritten the control software for the drives and the conveyor. The focus of this article is on the result of this work and the significant improvements that were achieved.

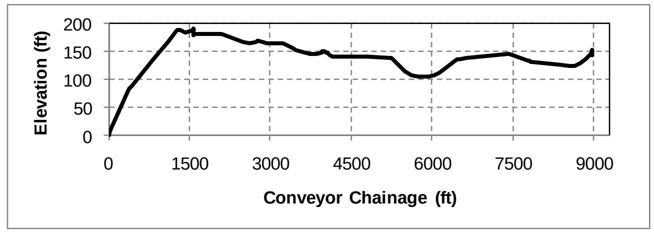


Figure 1: Conveyor Elevation

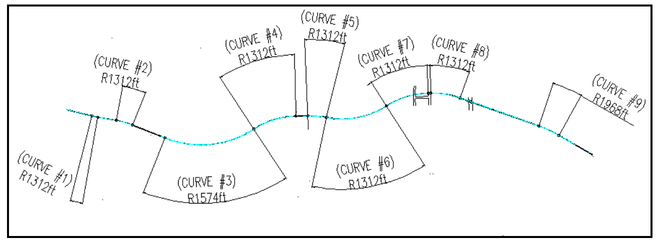


Figure 2: Conveyor Plan

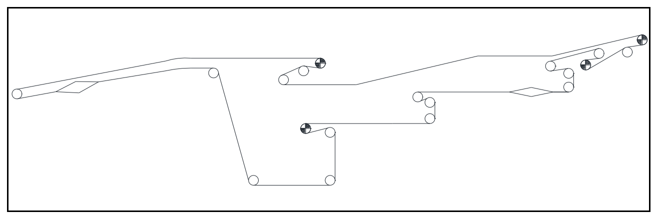

Figure 3: Pulley Location Sketch

Figure 4: 400m Horizontal Curve

## Summary of CDI Activities at Essroc

In October 2008, CDI visited Essroc to conduct its first site survey and noted the following:

- 6-inch diameter sheaves were used to guide the 6x37, ¾" diameter wire rope from the counterweight to the take-up trolley. The minimum sheave diameter required for this type of cable is 18 times the diameter of the wire rope (Shigley), or about 333% larger than the sheaves that were installed (Figure 5).

- The belt side-travel in the horizontally curved sections of the conveyor was grossly excessive. There was a large amount of spilled material in these curved sections, and the edge of the belt was extensively damaged (no side-guide rollers are used in the system, Figure 6).

CDI recommended increasing the diameter of the sheaves to 20”. Essroc accepted and, in the spring of 2009, CDI returned to the site to record the behavior of the belt before and after installing the new sheaves. Testing showed that the old sheaves were indeed preventing the take-up from moving, therefore allowing large variations of belt tension. Installing new sheaves with a larger diameter freed the counterweight to move and reduced these variations. However, the motor torque recordings taken during this trip showed that the drive control algorithms implemented by the PLC manufacturer were also inadequate and created large tension fluctuations in the belt.

In November 2009, the frequency of belt failures increased substantially and Essroc asked CDI for a complete mechanical audit of the system and for a proposal to replace the complete control software to eliminate the large drive torque variations and resulting excessive belt tensions.

At the same time, Essroc commissioned Belterra to conduct a full scan of the belt. This scan revealed extreme damage throughout the belt carcass and Essroc decided to replace the complete belt as soon as possible. By spring 2010 the frequency of belt failures increased and Essroc was forced to limit the maximum tonnage to 300 tph to avoid immediate belt failure. Even at this light tonnage, the conveyor experienced several belt failures each week until the new control logic was installed.

A review of the belt specification also revealed that the installed belt was only rated for short peaks of 300°F rather than continuous operation at this temperature. This might have contributed to premature belt failure along with the high tension generated by the non-functioning take-up, the poor control system, and various buckling events.

CDI’s mechanical audit pointed out a number of shortcomings in the conveyor design and made a number of recommendations including,

- CDI recommended installing a capstan brake on the take-up to increase the tension in the tail turnover area during emergency stop (motor trips, power loss, etc.). This type of brake is inserted between take-up sheaves and, when applied, increases the take-up resistance to motion, therefore increasing the effective take-up tension. The brake is released during normal operation and only applies during emergency stops. Following this recommendation, Essroc commissioned CDI to design and supply a capstan brake that fits in CV-105’s current take-up trolley gallery. CDI sourced the frame and capstan from RAS Pulley, and the brake caliper from Johnson Industries, then shipped the final assembly to Essroc.

- To further increase the belt tension in the tail area, CDI also recommended installing a low-speed, normally-applied, mechanical brake on the return-side booster drive pulley. This brake is kept released during normal motor stops and only applied in case of emergency stop. Following this recommendation Essroc purchased a new low speed coupling that included a brake disk from Sumitomo Drive Technology. Sumitomo also supplied a Johnson Industries brake with this assembly.

- CDI recommended replacing the control system with a control system developed by CDI for long overland conveyors with multiple, widely spaced drive stations (Nordell, Steven, Cornet). This control system required the installation of additional instrumentation on the conveyor:

    - Load cells had to be installed on pulleys located after the two booster drives (carry-side booster and return-side booster) to measure the belt tension after these drives. A load cell was already installed at the carry-side booster location but was not used by the existing control system. Essroc purchased an additional load cell from Sentran LLC, and installed this load cell on a pulley near the return booster.

    - Tachometers had to be installed on all drive pulleys and on one snub pulley at each drive station to improve the low-speed control of the belt and enable the detection of drive slip. CDI recommended the use of its own DEFT tachometers. These instruments were designed by CDI specifically for conveyor applications. They offer fast response, low output ripple, high linearity, and excellent noise immunity, which makes them ideally suited for industrial machine applications requiring precision speed control and monitoring.

Essroc finished installing this new equipment before the new belt arrived on site, and asked CDI to install and commission the new control system and equipment to demonstrate its performance on the old belt first. CDI developed the new control logic and tested the control algorithms in its Bellingham, WA, office. Once on site, the new PLC code was downloaded, the drive parameters extensively modified, and the new control system tested in less than three days. The new control logic immediately showed a dramatic increase in performance, and testing showed that the new control removed the high and low tension swings. Over the following month, Essroc gradually increased the maximum tonnage to 500tph without failing the old belt.

In December of 2010, a new Goodyear belt was installed and the maximum tonnage was increased back to its nominal value. The conveyor has now been operating without major problems for over 11 months.

Figure 5: Old 6” sheave lying next to the new 20” sheave that replaced it.

Figure 6: Large side travel in unloaded 400m horizontal curve

## Impact of Sheave Replacement

Following the delivery of the new, larger sheaves (Figure 5), CDI visited Essroc to record the behavior of the belt before and after installation of the new sheaves. A number of instruments, including: strain gauges, load cells, and tachometers were installed, and several starting and stopping tests, under various loading conditions, were conducted to determine how the belt performance changed after the sheave replacement.

Before conducting the tests, a load cell was installed on a crane and the counterweight was lifted to measure its weight. The counterweight weighed 12,000 lbs, which, if free to move, would produce 6,000 lbs of belt tension at the take-up pulley.

After weighing the counterweight, the load cell was removed from the crane and installed between the take-up cable and the take-up trolley. This allowed direct measurement of the belt tension at the take-up pulley, and of the hysteresis in the sheave assembly.

In addition to the load cell, strain gauges were installed on the drive pulleys shafts to measure the actual motor torques applied to the conveyor, and speed wheels fitted with CDI DEFT tachometers were installed at the three drive locations to measure the belt speed.

The first series of tests were conducted with the old, small, sheaves. Figure 7 shows that, with the old sheaves installed, the belt tension at the take-up pulley increased to nearly 12000 lbs (twice its nominal value) after the motors were tripped at the end of a loaded motor-stop test. This clearly shows that the small sheaves prevented the take-up from moving up. 20 minutes later, the tension still had not returned to its normal levels of 6000 lbs. When the conveyor was started again, the tension first dropped to 6000 lbs (Figure 8a), but soon increased again to 8000 lbs as the loading of the conveyor changed. The belt tension at the take-up pulley was then recorded during 25 minutes of continuous operation. This test showed the belt tension continuously changing according to the average load on the conveyor, and sometimes dropping substantially below 6000 lbs (Figure 9a).

The same tests were conducted after the new sheaves were installed. The new sheaves greatly reduced the variation in belt tension at the take-up trolley (Figure 7b, Figure 8b, and Figure 9b). This significantly reduced the likelihood of tension related failures.

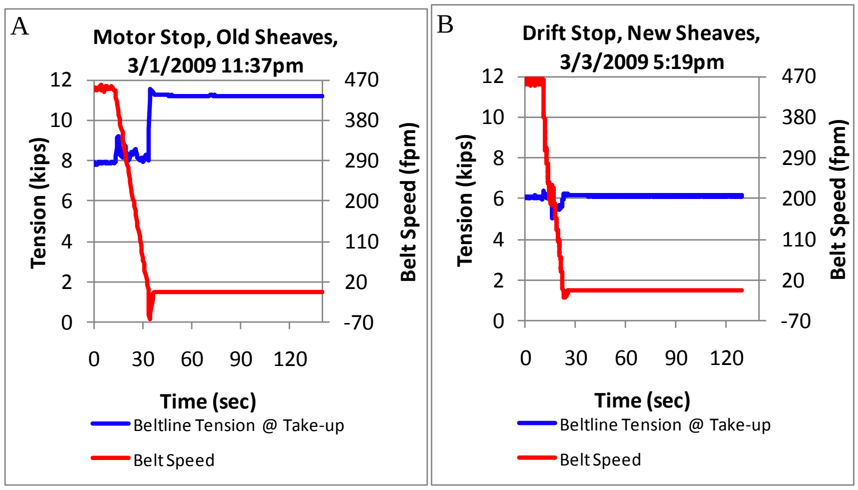


Figure 7: Belt tension on the take-up pulley during a conveyor stop before and after the new sheaves were installed.

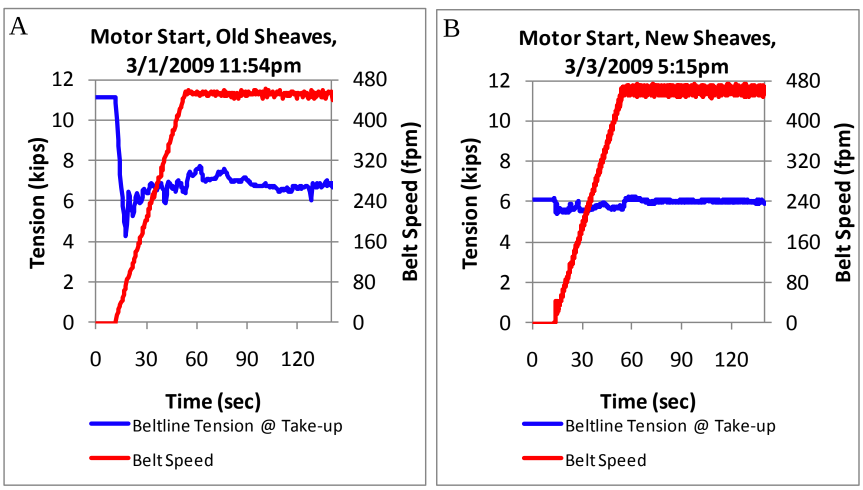


Figure 8: Belt tension on the take-up pulley during a conveyor start before and after the new sheaves were installed.

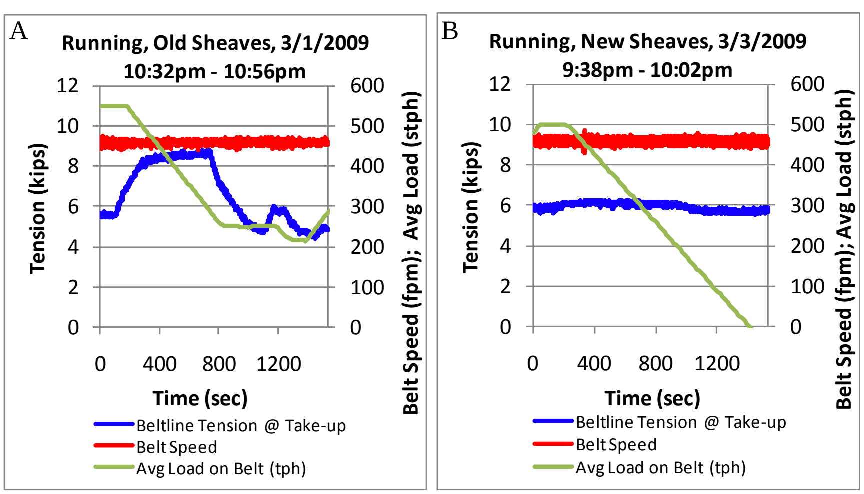


Figure 9: Belt tension on the take-up pulley during normal operation before and after the new sheaves were installed.

## Drive Torque Control

During the tests conducted on site in the spring of 2009, all six motor torques were recorded. Figure 10 shows the head drives torque plotted against the carry-side booster drives torque and the return-side booster drive torque under running conditions (excluding starting and stopping) for all the loading conditions that were observed during the three days of testing. The drive torque at each drive station was clearly controlled to maintain a constant load-sharing ratio between the head and the two booster stations, *independently of the conveyor loading or of the location of the material on the belt.*

Consequently, while the motors' torques were shared reasonably well when the conveyor was loaded over its complete length, this control scheme created unnecessarily large tensions in empty sections of belt as the material moved through the belt (during conveyor loading and unloading). This resulted in large, and damaging, levels of side travel in horizontally curved sections (Figure 11.). The damages to the edges of the belt were made worse by the absence of any side-guide rollers in the horizontally curved sections of the conveyor.

The control of such a conveyor is always a complicated issue, requiring specialized drive control algorithms similar to the control systems designed by CDI for the Zisco (Ref 1), and Curragh (Ref 2) conveyors. The absence of side-guide rollers in this case made proper torque control and belt tension management even more critical for the prevention of excessive side travel.

CDI's approach to controlling such a conveyor, and to booster-stations control in general, is to independently control the drive torque at each station. Each drive station should only provide the torque required to pull the portion of the belt and material directly upstream of its location, and all drive stations should act independently of one another except during starting and stopping sequences (Ref 3).

The best way to achieve this decoupling between drive stations is to control the head drives with a normal speed-control loop, but to control the booster drives with tension-control loops using load cells to measure the belt tension on the downstream side of the booster stations. This method effectively creates "virtual" take-up after each booster station, decoupling them from each other's and from the head drive station.

The design, parameterization, and implementation of such controls is not trivial, as the wrong algorithms or the wrong parameters can easily creates torque oscillations between drive stations and result in unstable conditions. It requires the control engineer to have good understanding of the tension wave mechanics of the belt itself as well as a good understanding of the various control loops available in modern drives. However, when properly designed and tuned, this type of controls is extremely effective at belt tension management, very stable, and very safe for the belt.

It should be noted that a load cell was already installed at the carry-side booster drive station. It seems that the original system designers had envisioned a similar drive control methodology for the carry-side booster drive, but were unable to tune their controls well enough to prevent unstable speed oscillations. After 9 months of testing, they settled on a simple, fixed ratio, load-sharing scheme that unfortunately was not suited for this conveyor.

CDI modeled the Essroc conveyor with its proprietary BeltStat software. The conveyor model was calibrated to the actual motor torques and tensions recorded in the field, providing an accurate picture of the tension distribution in the conveyor under various load situations.

Figure 12 shows the tension distribution when limestone is loaded on the belt between the tail and the carry-side booster station, and clinker is loaded on the return side of the belt. Note that under this loading condition, the belt is empty between the carry-side booster station and the head. Under the old control scheme, the head drives still delivered the bulk of the required torque, even though the belt was empty between the carry-side booster and the head. This effectively raised the belt tension in all the horizontal curves near the carry-side booster station, causing excessive side travel of the empty belt in these sections. Without side-guide rollers, the high belt tensions lifted the belt all the way into the structure, which resulted in extensive damage to the edges of the belt (Figure 11).

Figure 12b shows the tension distribution after implementation of the new control scheme by CDI. The tension-control algorithm increases the torque of the carry-side booster drives and reduces the torque of the head drives, resulting in significantly lower tension in the empty belt sections and in a much better, and more logical, tension distribution in the conveyor.

Similarly, Figure 13 shows the tension distribution when limestone is loaded on the belt between the carry-side booster station and the head, but not before, and clinker is loaded on the return side of the belt. Under the old control scheme, the carry-side booster drives were load-shared to the head station drives and provided a significant amount of torque even though there was no material to lift out of the pit. This resulted in very low belt tensions after the booster station, which resulted in high belt sag and potential pulley slip.

Figure 13b shows the tension distribution for this loading condition after implementation of the new control scheme by CDI. The tension-control algorithm eliminates the low tension problem after the booster drive station and holds the tension stable.

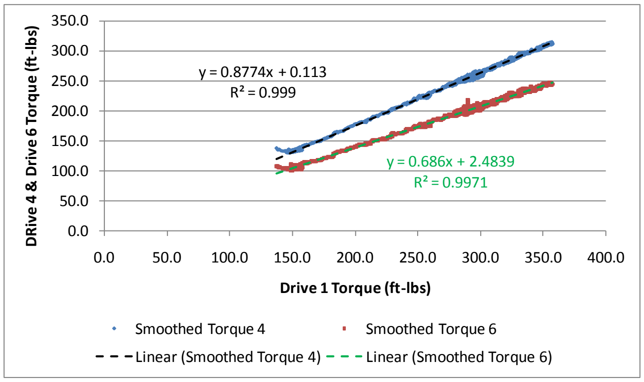


Figure 10: Distribution of motor torque created by the *original Essroc control system* during normal operation. Drives 1, 2, and 3 have equal torque (head drives), Drives 4 and 5 also have equal torque (carry-side booster drives), and Drive 6 is the return-side booster.


Figure 11: Edge damage caused by excessive side travel in horizontal curves.

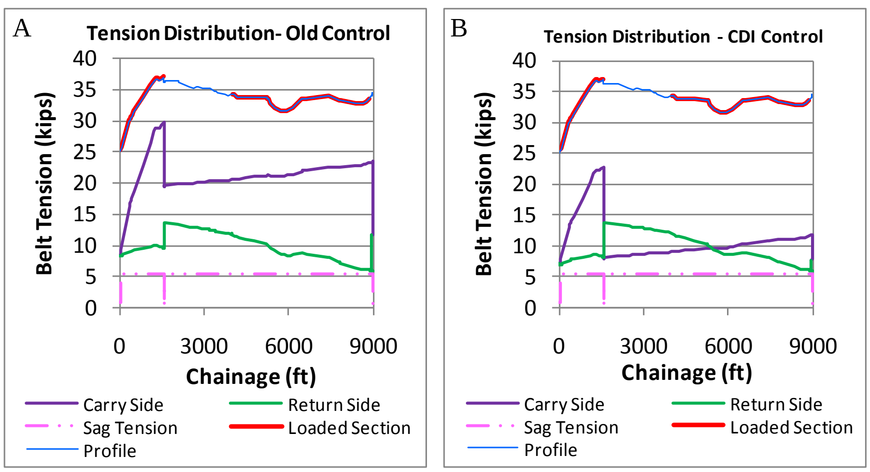


Figure 12: BeltStat predicted tension distribution for the original and the new (CDI) drive control schemes, with limestone loaded between the quarry and the carry-side booster station, and clinker loaded on the return side.

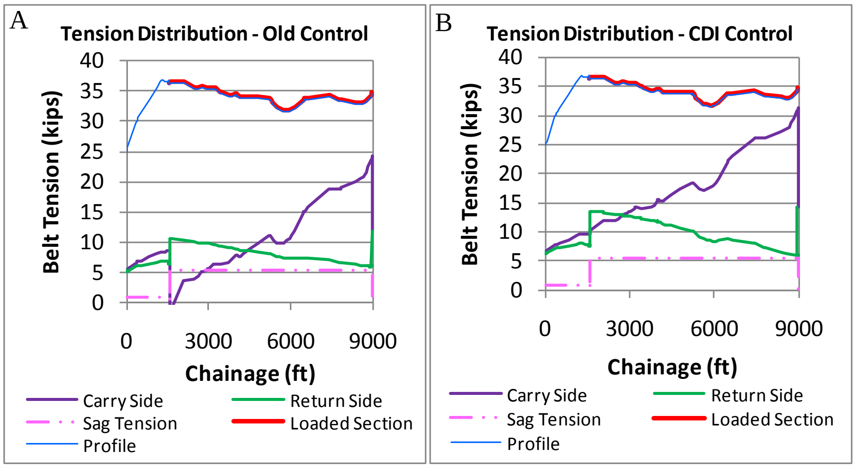


Figure 13: BeltStat predicted tension distribution for the original and the new (CDI) drive control schemes, with limestone loaded between the carry-side booster station and the head, and clinker loaded on the return side.

## Dynamic Behavior of Conveyor during Emergency Stops

In addition to the static modeling of the conveyor using BeltStat, dynamic analysis of the belt was conducted using CDI's proprietary BeltFlex software (4). The analysis was performed for various transient conditions (starting, motor-stop, and emergency-stop) under various loading conditions.

The emergency-stop modeling showed some serious tension problems under some loading conditions. The worst case occurred when limestone was loaded between the tail and the carry-side booster station, and clinker was loaded on the return side of the belt. In case of motor trip (power failure) under this loading condition, the limestone on the incline part of the conveyor (out of the pit) slowed down quickly, while the inertia of the clinker on the return side of the conveyor caused the belt in this section to slow down relatively slowly. This resulted in low belt tension in the tail section and potential belt buckling in the tail turnover.

Since this condition happened when the motors were tripped, it was indicative of a mechanical design problem that could not be fixed through controls and required a mechanical solution.

Part of the solution applied by CDI was to install a capstan brake on the take-up (Figure 14). A capstan brake is installed on the take-up sheaves assembly and, when applied, increases the take-up resistance to motion, therefore increasing the effective take-up tension. In this case, a spring-applied, electrically-released brake was selected to insure application in case of power failure. The capstan brake is kept released at all time during operation, and only applies in case of motor trip or power failure.

The capstan brake significantly improved the tension distribution during emergency stops, but not enough to completely eliminate the low tension problem in the tail turnover under some conditions. Consequently, a mechanical brake was also installed on the return-side booster drive to increase the tension of the belt entering the tail turnover. A spring-applied, hydraulically-released brake was selected to insure application in case of power failure. Just like the capstan brake, this brake is kept released at all time during operation, and is only applied in case of motor trip or power failure.

Dynamic modeling showed that these two brakes completely eliminated the low tension problem in the tail turnover (Figure 15). This was later confirmed by field-testing.

Figure 14: Capstan Take-up Brake

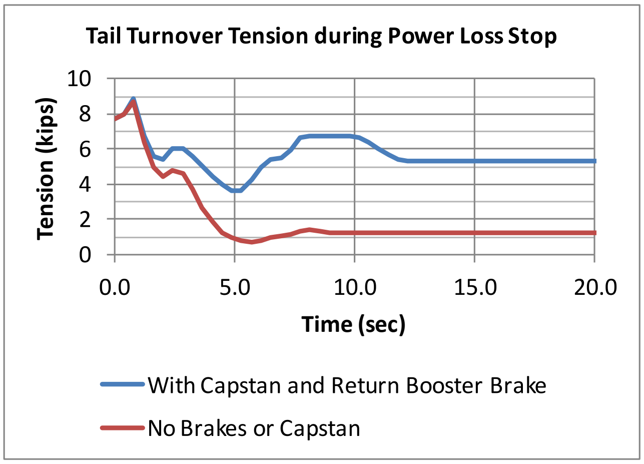


Figure 15: Simulated emergency stop with and without the capstan brake and the return-side booster brake. In this example, limestone is loaded from the tail to the carry-side booster drive and clinker is loaded on the return side of the conveyor. Without the brakes, the tension at the tail drops below 1000 lbs. With the brakes installed, the tension stays above 3000 lbs.

## Starting and Stopping Controls

The dynamic modeling of the conveyor also included simulation of the starting and motor-stop sequences under various loading conditions.

The simulations were first performed using the old torque control scheme, which showed the same problems that were apparent in the static modeling, but amplified by the transient conditions.

The modeling performed using the new CDI torque control scheme again showed that it completely eliminated these problems.

Tests performed on site before and after installation of the new CDI control system confirmed this result. The following recordings show the motor torque at each drive station and the belt tension after each booster drive during fully loaded conveyor starts and motor-stops. The belt tension was recorded by two load cells mounted under two pulleys located on the low-tension side of the drives.

Figure 16 shows the response of the conveyor during a start using the original control and the CDI control. The original control scheme generated large fluctuations in motor torque and huge swings in belt tension (both high and low). The belt tensions are nearly constant and the motor torques are far more stable with the new CDI control scheme.

Figure 17 shows the response of the conveyor during a motor-stop using the original control and the CDI control. Again, the original control scheme generated large fluctuations in belt tension (both high and low). No large tension swings were observed with the new CDI control scheme.

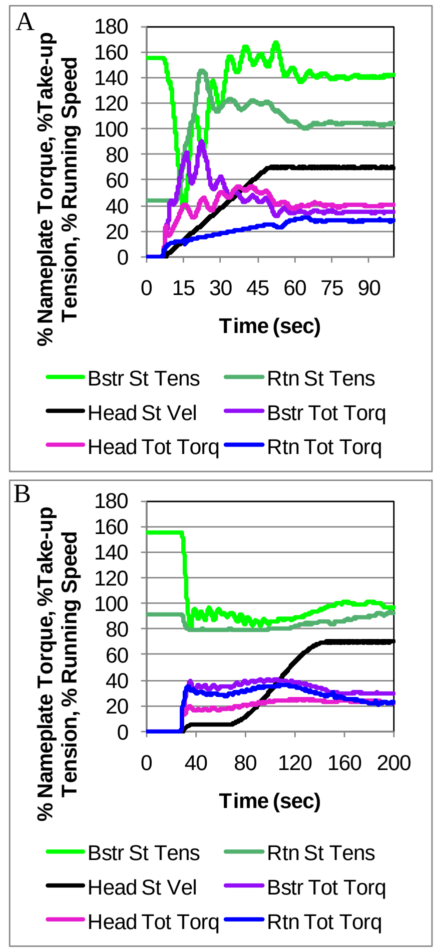


Figure 16: Recorded motor torques and belt tensions after the booster drives (at the load cells locations) during a conveyor start fully loaded before (A) and after (B) installation of the new CDI drive controls.

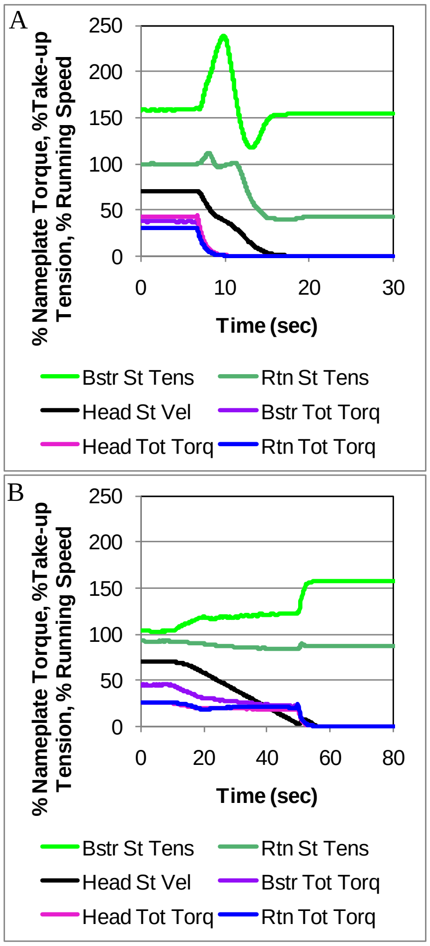


Figure 17: Recorded motor torques and belt tensions after the booster drives (at the load cells locations) during a motor stop fully loaded before (A) and after (B) installation of the new CDI drive controls.

## Conclusions

Preeminent PLC, VFD drive, or brake manufacturers are often asked to provide the control for their own components. While their design engineers usually have a good understanding of their own equipment, they typically do not understand the control requirements of long overland conveyors. This often results in low reliability, unstable operation, or even dangerous operating conditions for both the equipment and its operators.

The Essroc conveyor is an excellent example of a conveyor with complex physics. Although relatively light in tonnage, the conveyor is an ambitious system with multiple drive stations spaced far apart, extremely tight horizontal curves, and material on both the carry and return sides of the conveyor.

As originally designed, the system was unreliable and expensive to operate. CDI and Essroc worked together to fix the various design and control problems. The final solution involved both mechanical and control changes, and required the use of some of the most advanced technology available in conveyor design.

By the end of the project, CDI and Essroc were able to fully correct all the original designers' mistakes. The Essroc conveyor is now operating reliably at full design tonnage, and we are fully confident it will continue to do so for many years.

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