Head and Tail Controls in Long Overland Conveyors

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Abstract

Advances in conveyor technology over the past decade have enabled the design and erection of very long overland belt conveyors. Such conveyors usually require head and tail drives to lower the belt tension and belt strength required. This paper provides an overview of the problems encountered in controlling the head and tail drives on such conveyors, and some of the solution developed by CDI for several such projects.

INTRODUCTION

Historically, belt conveyors have been limited to a few kilometers in length because of the high belt strength required for longer design. Advances in conveyor technology over the last decade, including the development of better design tools (dynamic modeling [1][2], curved conveyor modeling [3]), the availability of low rolling resistance rubber compounds [4][5][6], the improvements in belt splice efficiency and resulting lower belt safety factors [7][8], and the improvements in drive technology have enabled the design of single flight conveyors up to 20 km in length [3][4].

Such conveyors provide a significant reduction in capital and operating cost by eliminating transfer stations and the need for power distribution along the conveyor route. But they also require special design techniques to address the starting and stopping requirements under various load conditions, and present unique challenges to both the mechanical and control design teams.

This paper presents an overview of the drive options, control system architecture, control methods, and potential instability problems encountered during the design of long overland conveyors.

CONVEYOR DESIGN

The basic configuration of a long overland conveyor, including the number, type, and location of the drives and brakes and the location of the take-up, is always dictated by the topology of the terrain (uphill or downhill sections, curved sections, etc.) and by the belt dynamic behavior.

Each conveyor is unique and usually requires special tension control techniques to ensure proper tension distribution along the complete length of the conveyor [3]. Head and tail drives are almost always required to lower the belt tension and belt strength required. Constant torque or proportional brakes and flywheels are often used at either the head or the tail location to help with tension control during shutdown. Load cells may be used in the drive control loops to better control the belt tension and avoid drive slip.

The proper selection of drive components is always important in the design of conveyor systems as it directly influences the operation, reliability, and serviceability of the system [9][10]. The accuracy of the drive torque delivery, its repeatability, and its control predictability are the most important factors to consider in the case of long overland conveyors. Consequently, only a few of the many drive options available can be used for long overland conveyors. The following is a short description of the most commonly used drive systems.

Variable Speed Drives (Inverters)

Inverter drives are available in high horsepower, high voltage configurations and can provide accurate speed control at or near zero speed. They can provide both driving and retarding torque at any speed, and have very accurate drive torque delivery, excellent repeatability, and excellent control predictability. Their major disadvantages are high electrical noise and sophisticated training requirements.

Inverter drives are an excellent choice for long distance conveyors, and are probably used more today than all other types of drives combined.

The 15.6 km curved overland conveyor at the Zimbabwe Iron & Steel Co. (Zisco) mine in Ripple Creek, Zimbabwe (Fig. 1), uses four 250 kW Siemens inverter drives. Three drives are located at the head, and a single drive is located at the tail.

The 8.9 km curved K2 conveyor at the Ingwe mine in Middleburg, South Africa also uses head and tail inverter drives. The overland system includes three conveyors in a 13.4 km route. Conveyor K2 has regenerative sections and is driven by two head drives (630 kW and 315 kW) and a single tail drive (315 kW). Siemens manufactured all the inverters.

DC Drives

DC drives are available in any horsepower configurations. They present similar advantages to inverter drives and are also available with regenerative capabilities. Their major disadvantages are high cost and high maintenance requirements, especially when compared to the newest generation of inverter drives, and DC drives are seldom used now in conveyor applications.

Wound Rotor Motors

Wound rotor motors equipped with secondary step resistors can also be used. Wound rotor motors are available in any horsepower configurations. Their major advantages are low cost, predictable torque and simple maintenance requirements. Dynamic modeling has to be used to optimize the timing sequence of the resistor steps, and a universal sequence covering all load conditions has to be found (preemptive type control). Their major disadvantages are limited load-sharing capabilities, inability to run at variable speed, inability to produce retarding torque until synchronous speed, and thermal limitations.

Wound rotor motors are a good choice when they can be made to work, but are not used very often on long overland conveyors due to their limitations. They are usually limited to conveyors with relatively short starting times (under 100 seconds).

The Kennecott mine in Bingham Canyon, Utah, has five overland conveyors in its conveyor route. All the conveyors are driven by wound rotor motors with step resistors. Two conveyors have regenerative sections and are each powered by four 1125 kW motors with head and tail drives. The drives use a binary stack with seven elements and 22 steps.

Fluid Couplings (scoop-tube)

Induction motors equipped with scoop-tube type fluid couplings can also be used. This type of fluid coupling is available in any horsepower configuration. Their primary advantages are low maintenance requirements and simple maintenance procedures. Their major disadvantages are non-linear torque characteristics at low speed, poor efficiency (due to their permanent hydraulic slip), inability to produce retarding torque until synchronous speed, and thermal limitations.

Scoop-tube fluid couplings have been used in many projects, and are a good choice in harsh environment and remote locations, or when the competence of the maintenance personnel is low. However, inverter drives provide more flexibility at a similar cost and are often a better choice.

FIGURE 2. Indo Kodeco overland system

The Indo Kodeco mine in Kalimantan, Indonesia (Fig. 2), has five overland conveyors in its 25 km conveyor route (Fig. 3). All the conveyors are driven by induction motors coupled to Voith Turbo 650 SVNK scoop-tube fluid couplings. Each fluid coupling drive is equipped with a CDI drive controller. Three of the conveyors have head and tail drives. Conveyors C3 and C4 are driven by two 630 kW drives at the head and a single 400 kW drive at the tail.

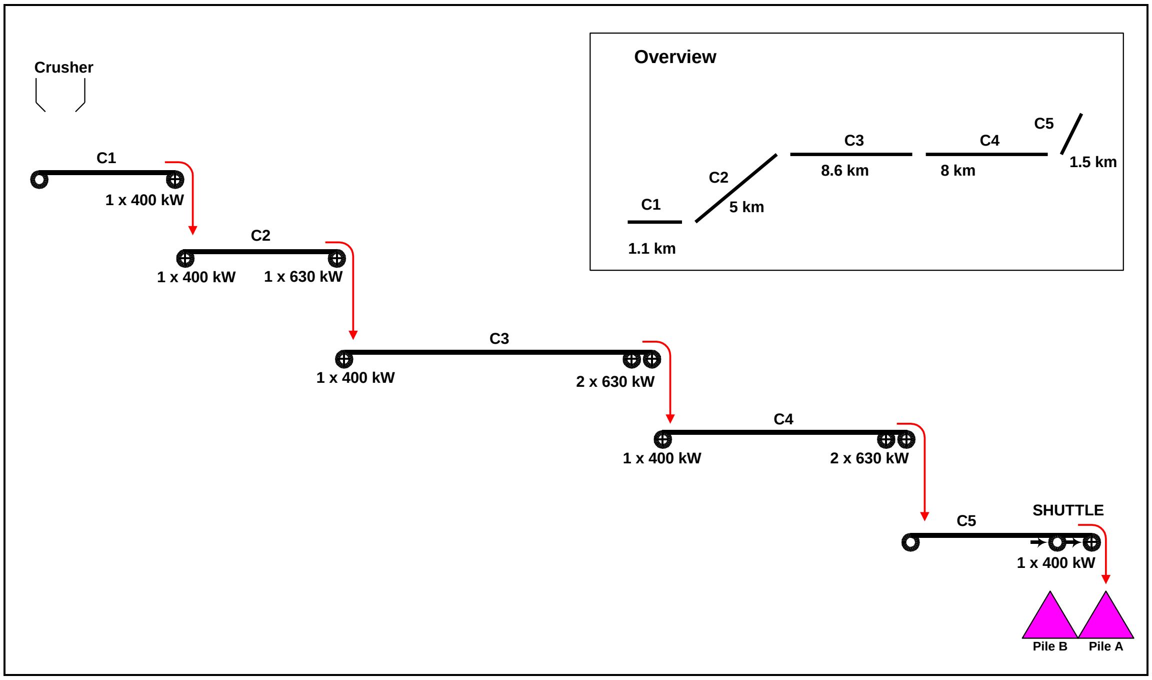

Fig. 3 Indo Kodeco System Layout

CONTROL SYSTEM ARCHITECTURE

The requirements to precisely control the belt tension over the length of a long distance conveyor and to synchronize and interlock the drives over several kilometers require the implementation of custom intelligent drive control algorithms and the use of reliable and predictable communications between the head and tail drive stations.

The best available option with the necessary power, speed and flexibility is a Programmable Logic Controller (PLC), which provides fast and predictable scan times and the ability to fully customize the control logic according to the design criteria derived from the dynamic modeling of the conveyor [11][12]. Consequently, PLC are almost always used for the control of long overland conveyors.

Several basic architectures can be used to set up the required communication link between the head and tail stations. The various architectures available are presented below.

Point to Point Serial Links

This approach is usually selected when there is only one conveyor in the route and a full network is not practical or necessary. Two PLC are used, one at each end of the conveyor, communicating over a serial communication link. Each PLC and its corresponding drive station is programmed as an independent component, with the interlocking, synchronizing and load-sharing information transmitted over the communication link.

The communication link usually consists of a single point to point serial link (Modbus, Siemens L1, etc.) transmitted over a radio connection (when line of sight can be achieved), a regular telephone line, or a similar low speed transmission media. Fiber optic communications are usually not used in this approach since the remote I/O or network options are always preferable if a fast physical link is available.

Because of the non-deterministic nature of serial communication links, their turn-around time is not predictable and it is difficult to rely on the PLC firmware to detect communication failure. In addition, their turn-around time can be very slow (5 to 15 seconds are common,). Consequently, it is the responsibility of the designer to optimize the turn-around time (to a maximum of 1 to 2 seconds) and check the integrity of the communications.

This approach is the least expensive and can be made to work extremely well. Its biggest drawbacks are the small amount of information that can be efficiently transmitted, the requirement to manually program, precisely control, and constantly check the communications to maintain the system integrity and the transmission speed, and the availability of a proper transmission media.

The installation at the Zisco mine uses a serial link and a radio connection to communicate between the head and the tail stations of its 15.6 km overland conveyor (Fig. 4). This installation includes three Modicon PLC. Two PLC are located at the mine end and communicate via a Modbus Plus connection. The third PLC is located at the head of the conveyor and communicates to the tail PLC via a Modbus link established with two radio modems. The complete system is controlled by a single operator in the crusher control room. The radio link is used for both interlocking, synchronizing, and load sharing of the conveyor drives, and for operator control and diagnostic information of the plant conveyors at the head end of the conveyor. This solution was made possible by the relatively flat topology of the terrain. The two radio modems are connected to high gain directional antennas located at the highest point available (top of the take-up tower and top of the stockpile building), which provided a direct line of sight connection.

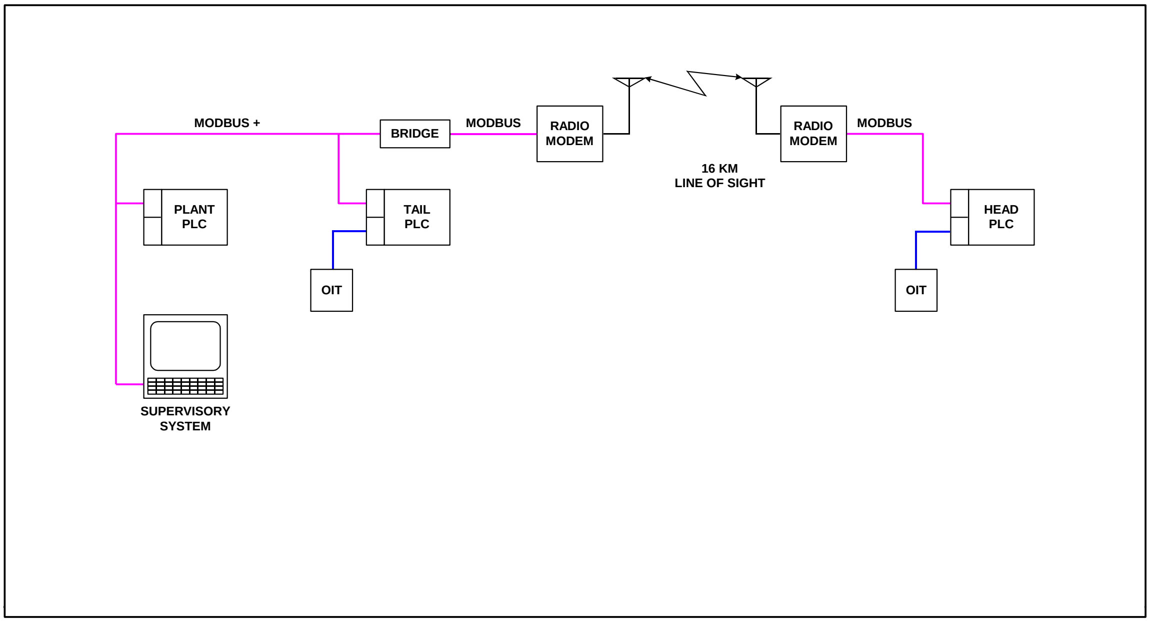

Fig. 4 Typical Serial Link Network Architecture - Zisco Project

Peer to Peer Networks

This approach is usually selected when the conveying system consist of several long overland conveyors (multiple flights), or when additional equipment requiring centralized control is located upstream or downstream of the conveying system loading and discharge points (stackers, reclaimers, crushers, plants etc.).

The normal approach is to put one PLC at the system loading station, one at the discharge station, and one at each transfer station. Each PLC is programmed with the head logic of the upstream conveyor and the tail logic of the downstream conveyor, and all the PLC are linked by a system wide network (Ethernet, Modbus Plus, Siemens H1, etc.). Each drive station is programmed as an independent component within its own PLC, and the network is used for interlocking, synchronizing, and load sharing of the various conveyor drives, and for operator control and diagnostic information.

Due to the high transmission speed and long distances involved, fiber optic communications are always required, and booster modules may be required at fixed intervals when maximum distances are exceeded.

PLC networks currently available, while faster than serial links, are also non-deterministic in nature and have similar limitations. Consequently, it is again the responsibility of the designer to check the integrity of the network. This can be achieved by setting individual token passing loops between each head/tail stations, and checking the data transfer for each internal loop independently.

This is the preferred approach today, its only drawback being the high cost of running a fiber optics cable along the entire conveyor length.

The installation at the Indo Kodeco mine uses a peer-to-peer network over a fault tolerant fiber optic connection to communicate between the various transfer stations of its 25 km conveyor route (Fig. 5). The system includes five Allen-Bradley PLC and one remote I/O station, and is connected via a Data Highway Plus network. The fiber optic network is used for interlocking and load sharing information of the overland conveyors, for operator control and diagnostics, and to carry video and telemetry information. In addition, local RS-485 networks are used at each substation to link the CDI drive controllers together and to the PLC. In order to eliminate potential timing problems in the main PLC network due to the distances involved, the network was separated into two sections. The two sections are connected by a bridge-multiplexer.

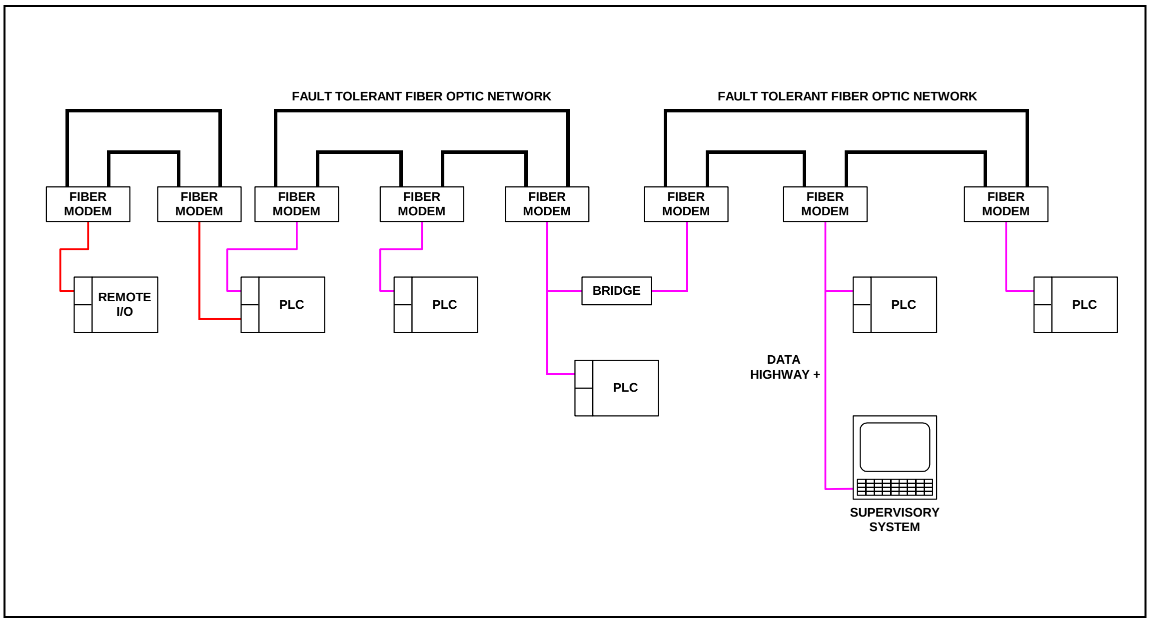

Fig. 5 Typical Peer-to-Peer Network Architecture - Indo Kodeco Project

Remote I/O Networks

This approach is sometimes selected when there is only one conveyor in the route and no equipment requiring control is located downstream of the conveyor discharge point. It uses a single PLC located at one end of the conveyor, and a remote I/O rack at the other end. This simplifies the communication task since this task is completely performed by the PLC firmware, and insures fast, reliable, and predictable turn around time.

As is the case with Peer-to-Peer networks, fiber optic communications are always required, and booster modules may also be required when maximum distances are exceeded.

This approach was used frequently in the past, before efficient PLC networks became available, but is now seldom used. It is usually preferable to install a full network, which provides a much more flexible system at a similar cost.

The installation at the MBR mine in Pico, Brazil, includes five Allen-Bradley PLC and two remote I/O stations. Both remote I/O stations communicate over fiber optic connections. One of the remote I/O station is used to control the mechanical brake located at the head of its TC18 overland conveyor (Fig. 6). This installation also includes a peer-to-peer network running over a fault tolerant fiber optic connection along the same conveyor route. The decision to use a separate remote I/O connection in this case was based on the expectation of very slow around time due to heavy loading of the main network (shared with other equipment), and the requirement to be able to run the system in case of network failure. This case exemplifies the need to conduct network-loading analysis, to establish a specification for the maximum turn around time acceptable for the control task, and to design the communication system accordingly.

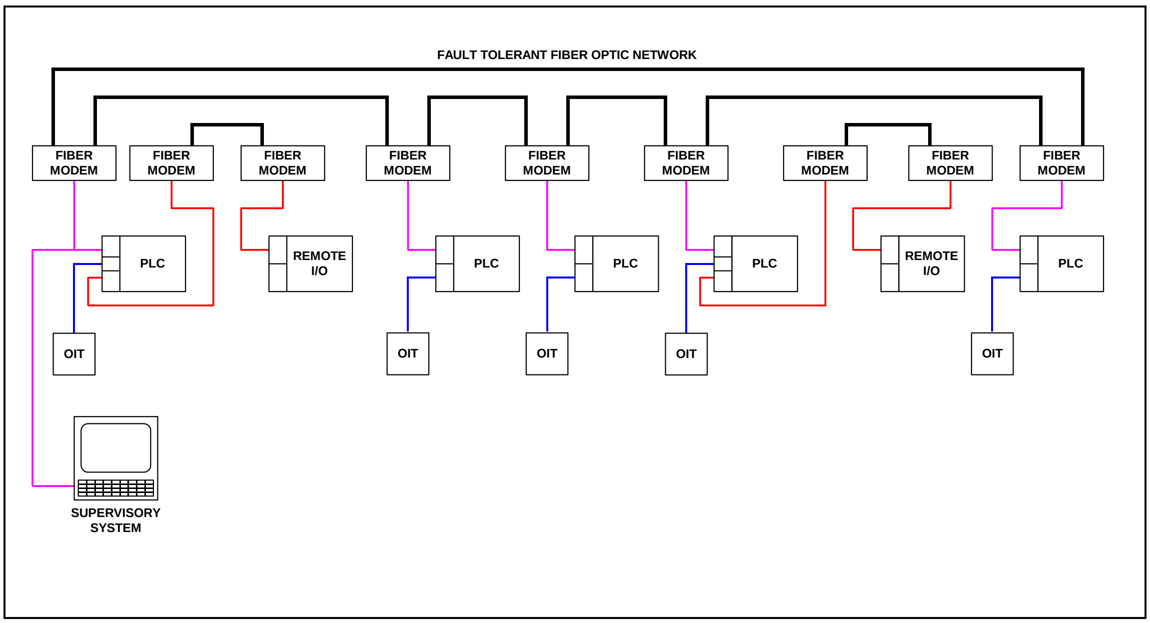

Fig. 6 Typical Mixed Network Architecture - Pico Project

CONTROL METHODS

The drive control algorithms required to maintain the belt tension within the design limits during the start and stop sequences of a long overland conveyor are always derived from the dynamic modeling of the conveyor. Among other parameters, this analysis defines the type of control loops, the duration and shape of the velocity ramps, the timing of each loop, and the required delays between the head and tail controls.

The primary goal of the control system is to emulate these control algorithms while avoiding the creation of tension waves or oscillations in the belt. In addition, it needs to provide maximum protection for the system and to dampen any instability generated by outside influences. The control logic may also includes back-up algorithms for emergency control, 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 [9]. Smart adaptive controls are based on closed loop proportional algorithms with single or multiple feedbacks. Preemptive controls are based on the implementation of preset sequences defined during the dynamic modeling of the conveyor. The type of control selected is always a result of the drive selection.

Adaptive controls are more difficult to implement but require less optimization and design work. They automatically adjust for any loading conditions and can self compensate for instrument drift. Preemptive controls are easier to implement but require more design and optimization work, as universal sequences covering all load conditions have to be developed. In addition, their design requires a deep and accurate understanding of actual drive behavior in the field. This type of control works well with simple conveyor topology.

In all cases, the control system software has to be developed with special consideration [11][12]. The PLC scan time should be kept low (under 25 msec), analog input signals should be checked for out of range conditions and filtered with digital filters to insure noise free values, and critical control signals should be checked against backup signals in order to detect inaccurate transducers.

The following sections provide basic descriptions of the various types of control algorithms used for head and tail controls in the design of long overland conveyors.

Adaptive Controls – Variable Speed Drives

Adaptive controls are always used with variable speed drives (DC and inverter drives). In this type of control, one drive is selected as the master at both drive stations. The master drives are controlled with speed loop with torque limits enabled, while the other drives are controlled with slave torque loops to their corresponding master. The tail and the head master drives are controlled independently. The speed ramps and torque limit signals are generated by the PLC at each station. The torque limit signal is used to perform the head to tail load sharing and to limit the drive torque when required or when load cells loops are active.

The various ramps, delays, and the basic sequence timing are derived from the dynamic modeling of the belt and vary greatly from case to case. However, the basic sequence is usually similar.

In the typical example of a conveyor with multiple head and tail drives and head take-up, the head drives are started first and slowly accelerated to a low preset dwell speed (typically 5% speed). The dwell speed is maintained for a fixed period of time, at which point the tail drives are started and ramped to the same speed. The dwell speed is used to pull the belt at the head and equalize the belt tension along the length of the conveyor. Starting the head drives first slowly raises the belt tension at the tail and insures that the tail tension is sufficient to avoid drive slip. Both head and tail drives are then accelerated to full speed on slow S-shaped ramps. The head and tail acceleration ramps are usually the same, but may be slightly different in some cases to help with load sharing. At some point along the starting ramp, the load-sharing algorithm is enabled, and the tail drive then switches from speed to torque control as required by the conveyor loading. In very long conveyors, when drive slip at the station furthest away from the take-up is likely under abnormal conditions, a load cell is normally used to detect low tension, and the control of the corresponding station master drive is switched from a speed or torque loop to a tension loop when such a condition is detected.

Adaptive controls are used to control the drives of the overland conveyor at the Zisco installation. Figure 7 shows a recording of the starting cycle of this conveyor.

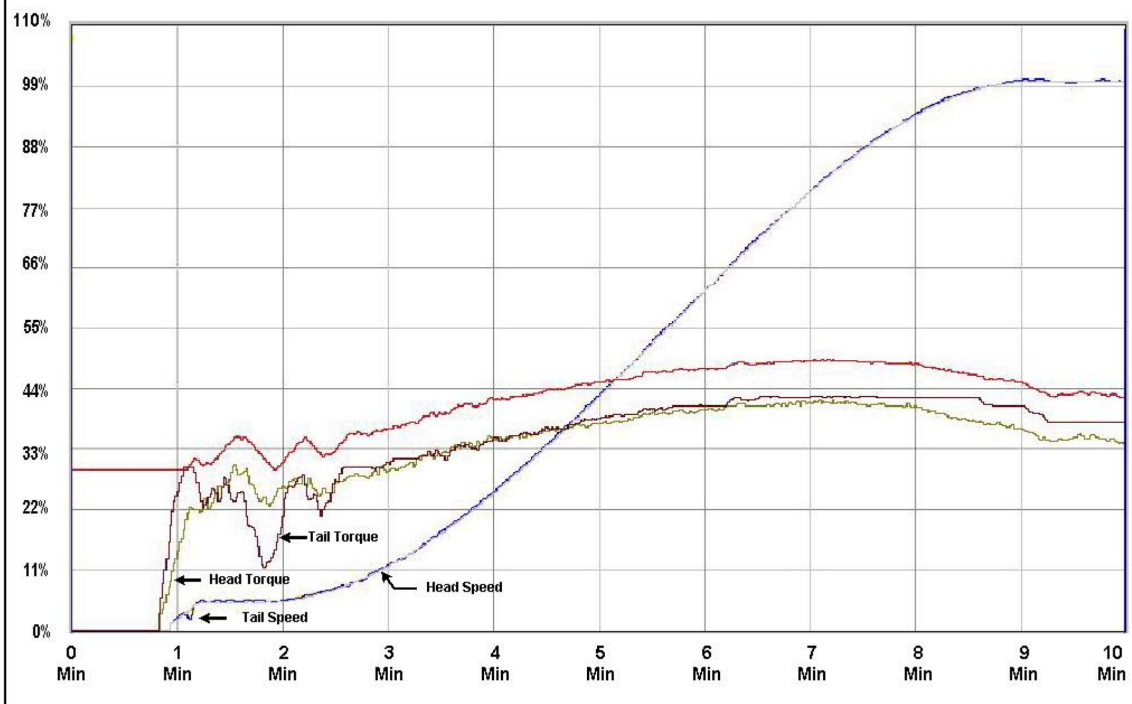

Fig. 7 Adaptive Inverter Controls - Loaded Conveyor Start - Zisco Project

250 kW Siemens inverter drives at the head and a single 250 kW Siemens inverter drive at the The conveyor is 15.6 km long, with complex vertical and horizontal curves, and is driven by three tail. The take up is located near the tail, and load cells are used to detect the belt tension at the head. When the start sequence is initiated, both head and tail drives are started simultaneously. The drives are accelerated to 5% speed over 20 seconds and maintained at that speed for a further 40 seconds. At this point, the head and the tail drives are accelerated to full speed over a 440 seconds S-shaped ramp. The total starting cycle lasts 500 seconds. The rate of change of the drive torque is limited to 2% per

seconds during the complete starting cycle, and the tail drive torque is limited to 150% at all times. The maximum torque of the head drives is controlled by the load cells. This is done to avoid potential drive slip at the head when the tension distribution is abnormal, as may be the case after an emergency shutdown of the conveyor. The load-sharing algorithm is disabled during the dwell period and is only enabled when the conveyor reaches 25% speed. When the load sharing is enabled, the tail drive becomes the conveyor master, and the head drives become slave to the tail. The Zisco overland conveyor was commissioned in 1996 and has been operating satisfactorily for over five years.

Adaptive Controls – Fluid Coupling Drives

The basic concepts and sequences described above apply to fluid couplings as well as inverter drives. However, a fluid coupling is just a mechanical component and does not posses the “intelligence” of an inverter drive. This fact, added to the highly non-linear torque response of a fluid coupling, makes the control of fluid coupling drives much more challenging.

At low belt speed, a fluid coupling torque is extremely dependent on the scoop position and corresponding fluid level in its working chamber. In some recorded cases, a change of scoop position from 10% to 15% can result in an increase of coupling torque from 50% to 200%. Consequently, adaptive controls can only be used with scoop-tube fluid couplings when the scoop control actuator is good enough to provide accurate and predictable control of the coupling torque (better than +/-0.25% accuracy, including hysteresis).

Two approaches are possible when using fluid coupling drives in adaptive controls on long overland conveyors.

The first approach is to program all the required controls in the PLC. This requires complex PLC programming, as the PLC has to handle all the control loops in addition to its normal functions. This includes the loops normally done by the drive (master speed loop, slave torque loop, and local load sharing) in addition to the loops normally done by the PLC (head to tail load sharing, torque limit controls, and tension loop). In addition, the scoop control has to be extremely accurate, which requires a high-end actuator control module.

The other approach is to use a “black-box” controller like the CDI drive controller. This controller was designed to perform all the closed loop controls normally performed by an inverter type drive, to control all the coupling auxiliary equipment (motor, pumps, coolers, etc.), and to protect the drive and the conveyor from overload conditions. The use of this controller greatly simplify the PLC logic by making the fluid coupling look like an inverter type drive, while providing better controls and equipment protection than could be done in a PLC

Adaptive controls are used to control the overland conveyor drives at the Indo Kodeco installation. Figure 8 shows the starting cycle of conveyor C3. Conveyor C3 is 8.6 km long and is driven by two 630 kW drives at the head and a single 400 kW drive at the tail. The take up is located near the head. All the drives are coupled with Voith Turbo 650 SVNK scoop-tube fluid coupling. All the fluid coupling drives are equipped with CDI drive controllers. When the start sequence is initiated, the head drives are started first and accelerated to 5% speed over 5 seconds. 35 seconds later, the tail drive is started and accelerated to the same speed over 5 seconds (note that the tail may already be moving by then, in which case the tail drive torque is simply ramped up slowly). After a further 15 seconds, both the head and the tail drives are accelerated to full speed over a 250 seconds S-shaped ramp. The total starting cycle lasts 310 seconds. The torque of the head drives is limited to 105% during the starting cycle, while the torque of the tail drive is limited to 115%. The load-sharing algorithm is disabled during the dwell period, and is only enabled when the conveyor reaches 25% speed. When the load sharing is enabled, the primary head drive becomes the conveyor master, and the tail drive becomes slave to the head. The local drive load sharing at the head is performed by the CDI controller, and the head to tail load sharing is handled by the PLC. The indo Kodeco system was commissioned in 1997 and has been operating satisfactorily for over four years.

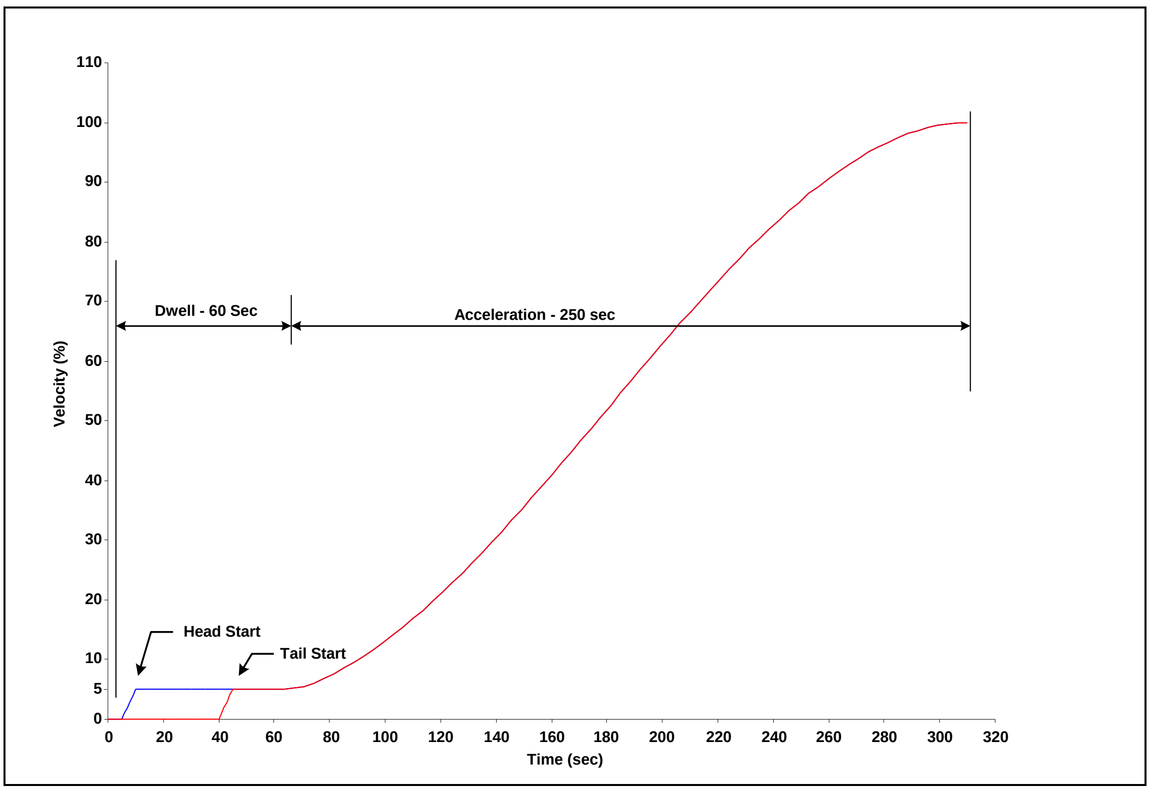

Fig. 8 Adaptive Fluid Controls - Conveyor Start Sequence - Indo Kodeco Project

Preemptive Controls – Wound Rotor Motors

This type of control is much simpler to implement than adaptive controls because most of the work is done during the dynamic modeling of the belt, and the control logic simply has to implement a fixed sequence of events.

In the typical example of a conveyor with multiple head and tail drives and head take-up, the head drives stepping sequence is started first followed by the tail drives after a fixed time delay. Both head and tail drives then go through their own (and different) stepping sequence, usually reaching the last step at the same time. The stepping sequence is different for each drive, even for drives at the same location.

In this type of control, the acceleration time of the conveyor varies with the load and an empty conveyor reaches full speed much earlier that a full conveyor. Furthermore, the actual torque developed by the motors varies with the load and load sharing cannot be maintained during the start sequence. Consequently, the belt tension cannot be controlled as accurately as with adaptive controls. Load sharing of wound rotor motors can be done at full speed, but presents its own set of challenges as described later in this paper.

Preemptive controls are used to control the overland conveyor drives at the Kennecott installation in Bingham Canyon, Utah. This overland system consists of five overland conveyors with wound rotor motors and secondary step resistors. Two of the conveyors have regenerative sections and are each powered by four 1125 kW motors with head and tail drives. The drives use a binary stack with seven 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.

Preemptive Controls – Fluid Couplings

Preemptive controls are sometimes used with scoop-tube fluid couplings when the conveyor topology is simple, or when the scoop actuator hardware is not accurate enough to precisely control the coupling torque at low speed. This usually happens when the actuator has too much hysteresis. This type of actuator cannot be used in closed loop controls, as it can cause large speed and torque oscillations at low speed as the control loop tries to compensate for the actuator hysteresis.

When preemptive controls are selected, preset scoop motions are generated during the belt dynamic modeling and the drives are accelerated by changing their scoop-tube position according to these preset curves. The effect of the actuator hysteresis is minimized by always moving the scoop in the same direction, and the open control loop eliminates control instabilities. The basic sequences are similar to the wound rotor motor case. Different scoop-tube curves and timing are used at the head and tail drive stations. As is the case with wound rotor motors controls, the acceleration time of the conveyor varies with the load. The actual torque developed by the couplings also varies with the load, and load sharing is difficult to maintain during start sequences.

Preemptive controls are used to control the fluid coupling drives of the overland conveyors at the Mineraçaõ Rio do Norte (MRN), installation in Porto Trombetas, Brazil. The system is composed of two overland conveyor routes conveying ore from the Papagaio and Saraca mines to a stacking and reclaiming plant. The two routes include four overland conveyors. All the overland conveyors are equipped with multiple 400 kW motors coupled to Voith 750 SVTL fluid couplings. The original design of the system called for adaptive drive controls. However, the very large hysteresis and poor accuracy of the scoop-tube actuators used forced the use of preemptive controls for all the fluid coupling drives. Figure 9 and 10 show the starting cycle of conveyor C9 using preset scoop-tube ramps under empty and loaded conditions. As can be observed, the starting time of the conveyor changes with the load. However, the drive torque application is steady and results in smooth acceleration of the conveyor in all load cases. The MRN system was commissioned in 1997 and has been operating satisfactorily for over 4 years.

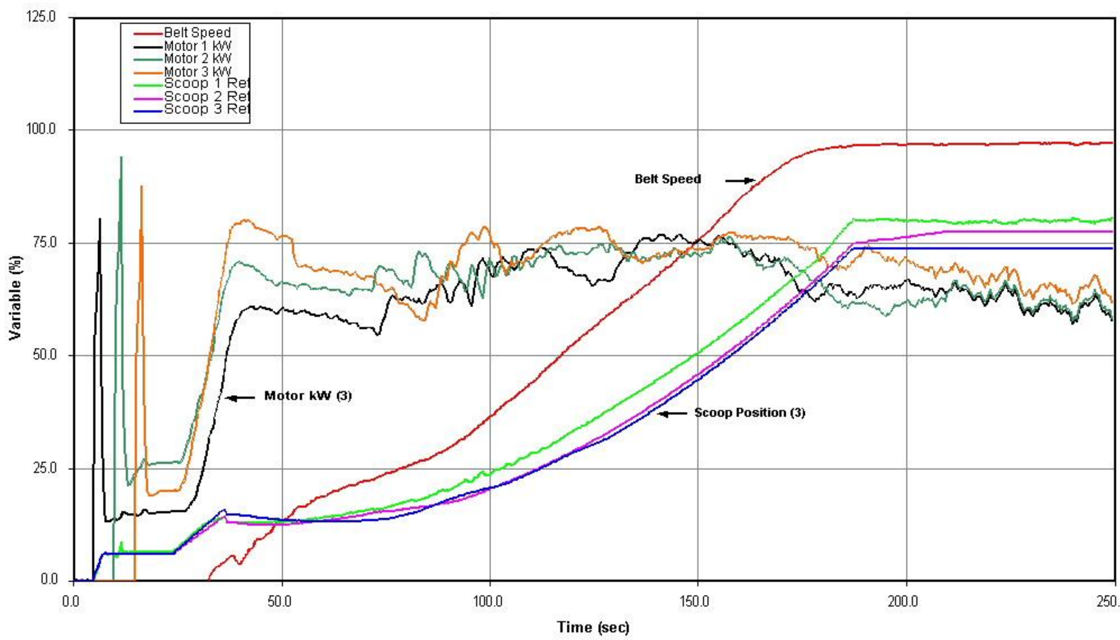

Fig. 9 Preemptive Fluid Coupling Controls - Loaded Conveyor Start - MRN Project

Drive Load-sharing under Adaptive Controls

Load sharing of the drives is usually required to make full use of the power installed on the conveyor, to avoid individual drive overloads, and to equalize the duty and wear on the drives, motors and reducers.

The local torque control of the slave drives is usually performed by the master drives in the case of DC or inverter drives, and by the PLC or the drive controller in the case of fluid couplings.

Load sharing between the head and tail drives has to be done by the PLC for several reasons. First, the drives usually cannot communicate between the head and tail stations. Even when a drive network is available, this would require a separate communication link, which would then be redundant to the PLC link. Secondly, drive firmware is designed for local load sharing of rigidly coupled drives, and cannot be configured for the special conditions and timing involved in load sharing drives coupled through several kilometers of elastic belt.

Load sharing the head and tail drives is always required after the conveyor has reached full speed, but is not required or even advised during the first phase of the starting cycle (dwell period) as it defeats the purpose of the dwell phase and may result in drive slip at the station furthest from the take-up. In most cases, the load sharing is kept completely disabled until the conveyor reaches 20 or 30% speed. At this point the load sharing control is enabled with a wide dead band in order not to influence the speed loop unless required, and is only fully enabled when the belt reaches full speed.

It is important to note that all the control loops are actually active together (speed, tension and torque loops), but that only one is dominant at any point. The transition between control loops is based on the feedback signals (speed, tension and torque) and on dynamics control bands. The transition between the various loops involved is a critical component of the control logic, and improper switching can result in potentially damaging oscillation of the drive torque.

Head to tail load sharing is always required after the conveyor has reached full speed because the head and tail drives have a natural tendency to shed the load between each other. This is due to the integral term of the master drives speed loop responding to the apparent speed difference between the head and the tail stations. During the start cycle, as the speed reference continuously varies, the main driving element of the drive control is the proportional term of the speed loop. raised slightly higher than the master station speed setpoint. The torque of the slave station drives then slowly rises until they reach their torque limit, which effectively changes the slave station drive control from a master speed loop to a slave torque loop. The torque limit signal is then varied by the PLC to control the head to tail load sharing.

The timing and tuning of the load sharing control loop is critical as the belt response time between the head and the Once the belt has reached full speed and the speed reference is kept constant, the integral term of the speed loop slowly grows to eliminate the remaining speed error. Since the actual speed of the belt at the head and tail station are always different (due to the belt tension variation between the head and the tail and because instruments cannot be perfect), one station always sees a lower belt speed and consequently increases its torque. Without head to tail load sharing, this effect always results in one station taking the entire load, while the other just idle.

Typically, the head to tail load sharing is done by switching one of the masters drives from a speed loop to a torque loop trough the use of a torque limit signal. When the conveyor reaches full speed, or whenever the load sharing is enabled, the slave station speed setpoint is slowly tail is very slow and well within the bandwidth of the control loops. Improper tuning of this loop can lead to head to tail torque oscillations.

Load sharing of fluid couplings under adaptive controls is similar to load sharing of inverters. The scoop position of the master drive is normally controlled by a speed loop to maintain a fixed coupling slip (typically 3 to 4%), while the scoop positions of the slave drives are controlled by torque loop to load share the drives.

The load sharing of the drives on the Zisco overland conveyor can be observed in figure 7. The three drives at the head load share at all time during the starting cycle. The tail drive torque is initially very different from the head drives torque, but converges to it as the conveyor accelerates and the load sharing is enabled. All the drives torque track each other to within 2-3 % during the remaining of the starting cycle, and close to less than 1% after the conveyor has reached full speed.

Load-sharing of Wound Rotor Motors

Load sharing of wound rotor motors can only be achieved at full speed, and can only be done at one load (usually full load). It is done by changing the transformer taps of each motor, therefore changing the permanent slip of the motors. This is always true of wound rotor motor design, but in the case of long overland conveyors, the head and tail drive stations are usually feed from independent grids. This can impact the load sharing between the head and tail, as each station will react to its own grid instabilities and voltage variations.

Fluid Coupling Drive Load-sharing under Preemptive Controls

Load sharing of fluid couplings under pre-emptive controls can be done in several ways. In the first and simplest method, the scoop final position at the end of the starting sequence is independently adjusted on each fluid coupling to load share the drives under full load. This method is simple but has limited benefits. The drives only load share when the conveyor is fully loaded, and the load sharing is affected by grid voltage variation, even so this effect is minimized by the high hydraulic slip of fluid couplings. In the second method, the scoop position of the master drive is kept constant, but the scoop position of the slave drives is slowly adjusted by a simple integral control loop to load share the drives. This is the preferred method as it greatly improves the load sharing while remaining simple.

The same concept can be used to provide some level of load sharing during the acceleration cycle. In this case, the integral control loop is kept active during the starting cycle, and the corrective term is added to the preset scoop ramp.

This method was used successfully to load share the fluid coupling drives on the overland conveyors in the MRN project, as can be observed on figure 9 and figure 10.

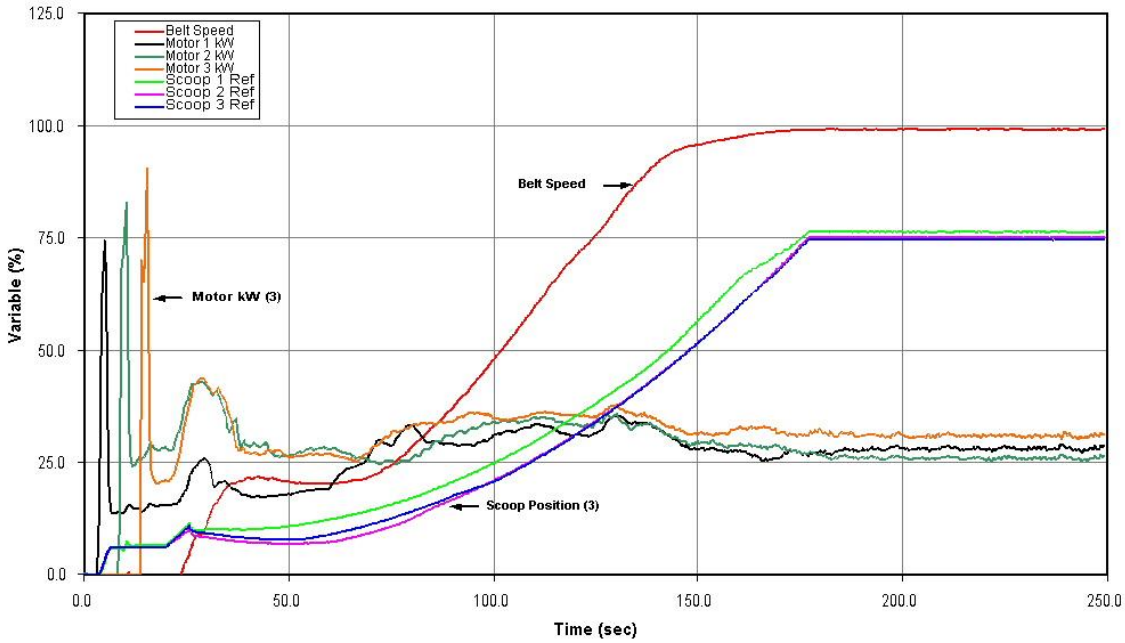

Fig. 10 Preemptive Fluid Coupling Controls - Empty Conveyor Start - MRN Project

Control Instabilities

As mentioned several times throughout this paper, all the control algorithms used in long overland conveyor controls are derived from dynamic modeling of the belt. Dynamic analysis modeling is a very powerful tool, which can predict the mechanical behavior of the conveyor and helps in establishing its sensitivity to perturbations. However, the dynamic model works in a perfect world where all the instruments are perfects, all the signals are noise free, and all the drives are perfectly tuned. Unfortunately, the real world does not work this way, and many factors can create or contribute to control instabilities. It is possible to use the dynamic model to simulate these factors. However, the combinations are infinite, and this approach can only realistically be used to study the effect of known problems, usually after a belt develops dynamics problems in the field (forensic engineering).

The best solution to avoid instabilities is to identify the most likely causes of such instabilities, and to develop the control logic to eliminate them before they can develop. In practice, all the control loops have to be programmed with special features, including, non-linear terms, digital filters, and dead bands to account for the normal elastic behavior of the belt and its natural tendency to oscillate at given frequencies, and for the inaccuracy of the instruments and their noise level.

Several types of instabilities are common in long overland conveyors.

Local Loop Instabilities. Torque oscillations between local drives within one drive station are a common problem. These oscillations are usually very fast, with large torque variations over short time periods. Drive slip is not uncommon as the belt tension between the drive pulleys change rapidly. This type of instability can be very damaging to the drive components (reducers, pulley), and to the belt and splices. Damages to the rest of the conveyor itself are unusual since the problem tends to stay localized at the drive station and does not propagate through the conveyor.

The problem is usually induced by improper tuning of the slave torque loop. Drive firmware is designed with the assumption of rigidly coupled drives, and even the small elasticity of the belt between the drives can make these loops difficult to tune. The probability of this problem occurring increases with the distance between drives, and it is a very common problem when drives are separated by a few hundred feet. Since the slave torque loops are normally done by the drives, the solution usually resides in proper tuning of the drive parameters.

Figure 11 shows a typical example of slave torque loop instabilities, with out-of-phase oscillations of the primary and secondary drive torque. In this case, the instabilities were not too severe and subsided after the conveyor reached full speed. The problem was fixed by tuning the torque loops in both the master and slave drive.

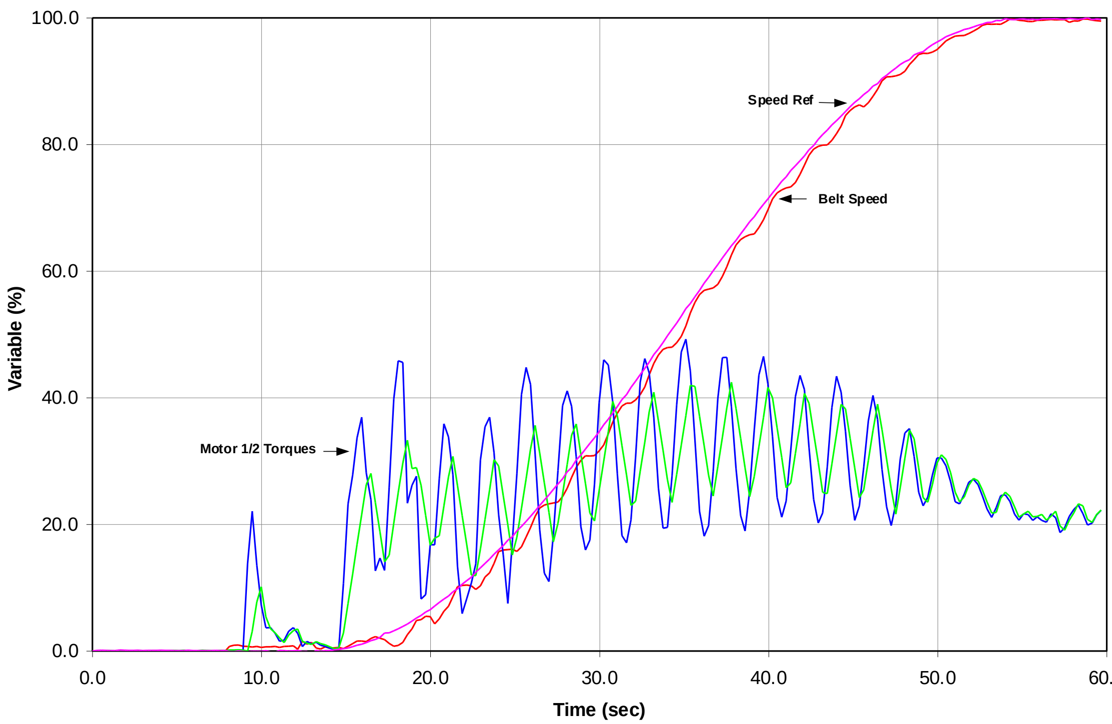

Fig. 11 Typical Slave Torque Loop Instabilities

Speed loop instabilities at one drive station are usually slower than torque instabilities as they result from a resonance effect between the drive torque control and the local belt mechanical response. This type of instability usually starts slowly, with the magnitude of the speed oscillation increasing rapidly, and can be very damaging as the resulting velocity and tension waves propagate through the complete conveyor. The problem is usually induced by improper tuning of the master speed loop, and the solution normally resides in proper tuning of both the PLC and the drive loops. The PLC to drive interface logic should also be carefully checked, and the PLC logic sometimes changed to address possible limitations in the drive's internal loops.

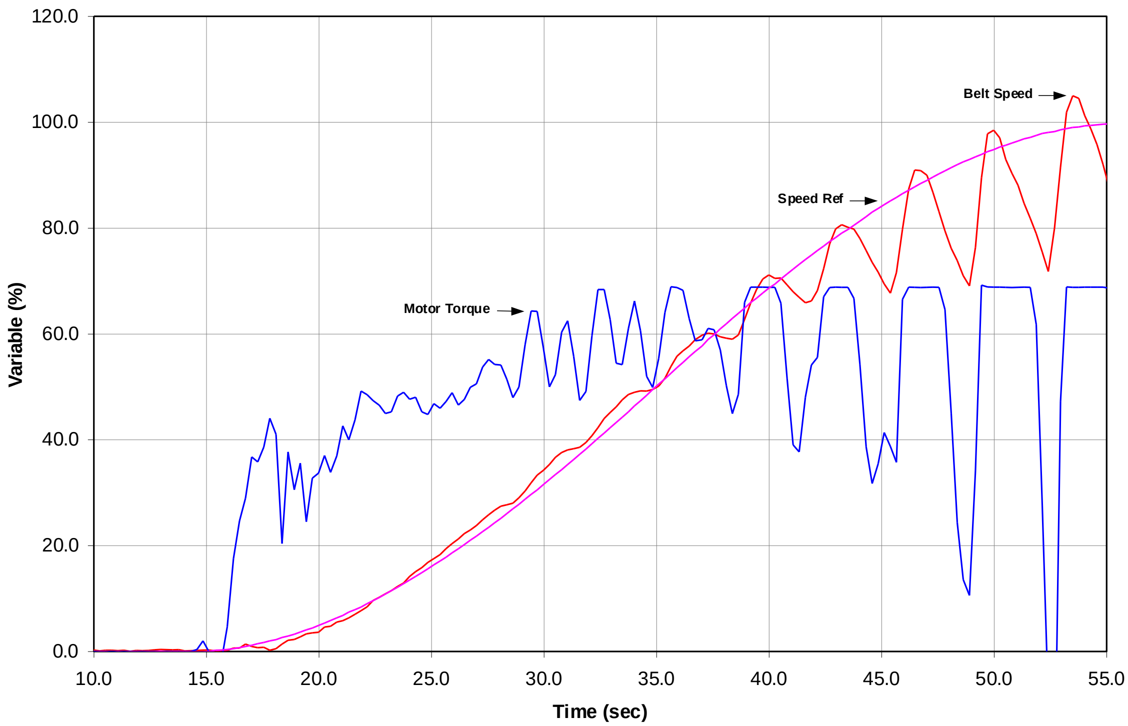

Fig. 12 Typical Master Speed Loop Instabilities

Figure 12 shows a typical example of master speed loop instabilities, with increasing magnitude of both the speed and torque oscillations. In this case, both the primary and secondary drive torque tracked each other perfectly, and only one is shown on the graph. In this example, the instabilities were quite severe and resulted in a conveyor shutdown by the PLC. The problem was fixed by tuning the speed loop in the master drive. The PLC logic did not have to be modified. Figure 13 shows a recording of the starting cycle of the same conveyor after proper tuning of the control loops.

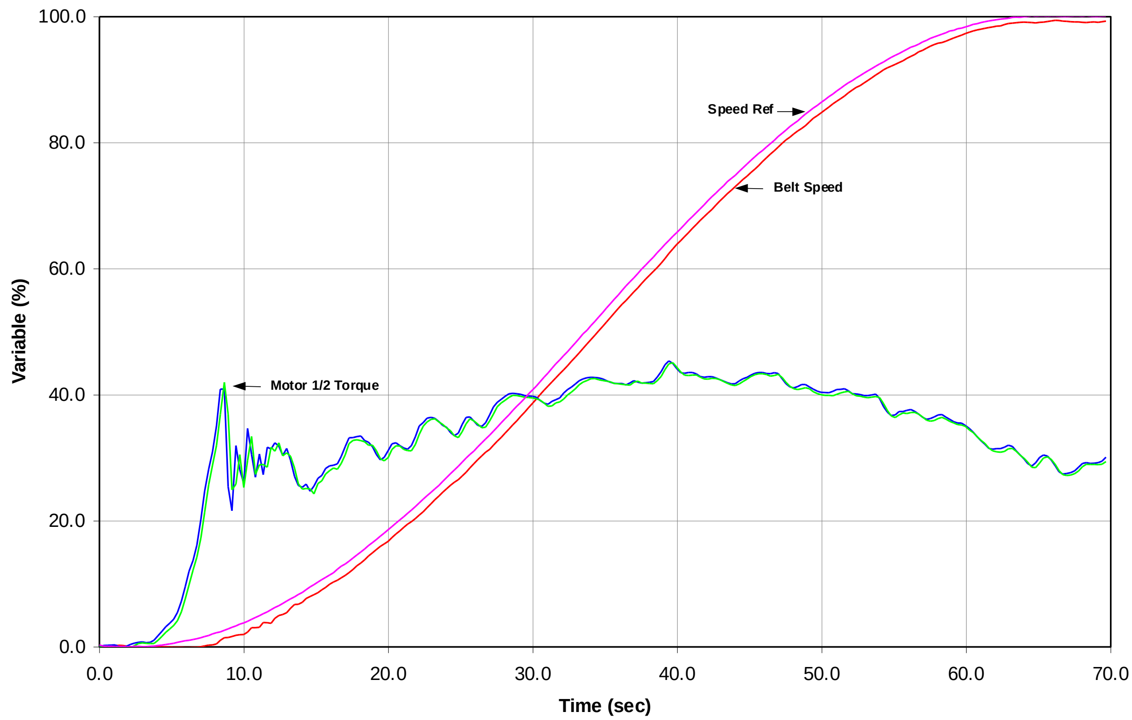

Fig. 13 Conveyor Start After Proper Drive Loop Tuning

Head to Tail Instabilities. Head to tail instabilities are always very slow, as they result from the wave propagation delay between the head and the tail stations. This type of oscillation is not usually damaging but interferes with proper load sharing of the drives. In most cases, the oscillations are due to improper tuning of the load sharing algorithms, resulting in the slave station master drive continuously switching from speed control to torque control. However, the oscillations can also be due to improper tuning of the master drive speed loop, or from interactions between the two loops.

Figure 14 shows a typical example of head to tail instabilities. This problem was solved by tuning both the master drive speed loop and the slave station load-sharing loop.

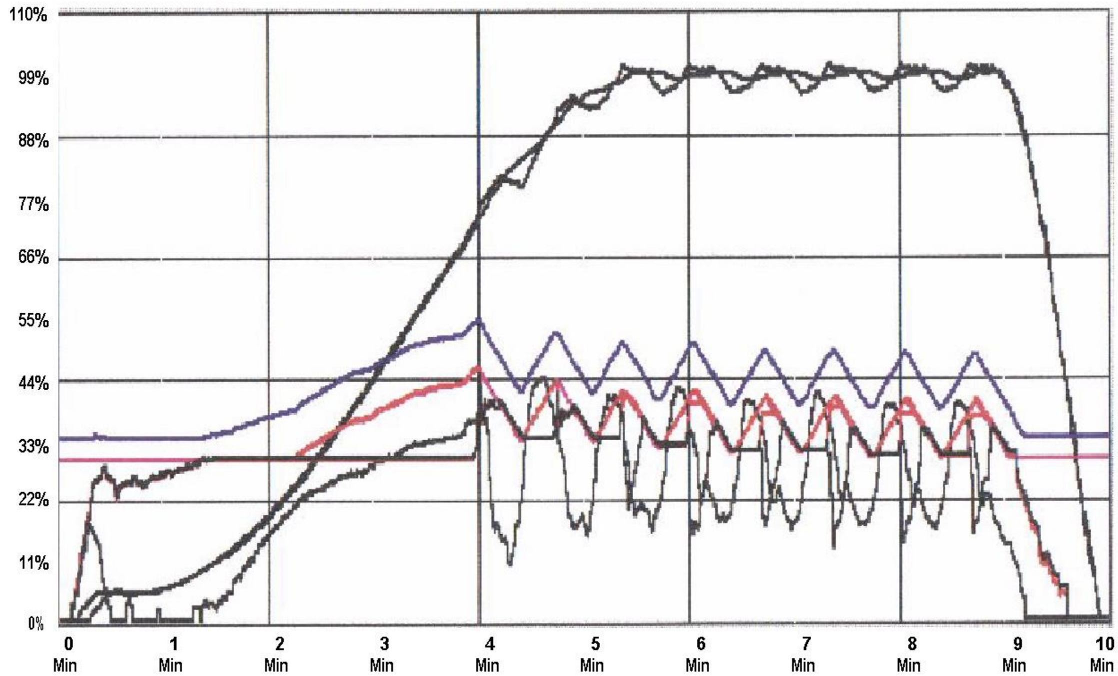

FIGURE 14. Typical head/tail torque instabilities

Other Considerations. Control loop instabilities can also result from excessive noise on the control and feedback signals, from ground loops, or from ground voltage variations. This can be avoided by proper grounding of all equipment within the substation, proper shielding of the cables, and proper filtering of the signals. In addition, drive digital or optical networks should always be used for drive-to-drive communication when available. Similarly, fast deterministic network connections should always be used when available for communication between the PLC and the drives (Profibus, ControlNet, etc.).

Poor instruments and inaccurate actuators are also a common cause of loop instabilities. The instruments and transducers used in a closed loop control should be fast, accurate, and noise free. Similarly, the actuators used should be accurate, repeatable, and have low hysteresis. A typical example of instabilities caused by a poor actuator is shown in Fig. 15. In this case, a scoop actuator with large hysteresis (+/- 2%) was used to control fluid coupling drives in an adaptive control loop. The large torque surge induced by small changes in scoop position can easily be seen, as well as the scoop actuator hysteresis.

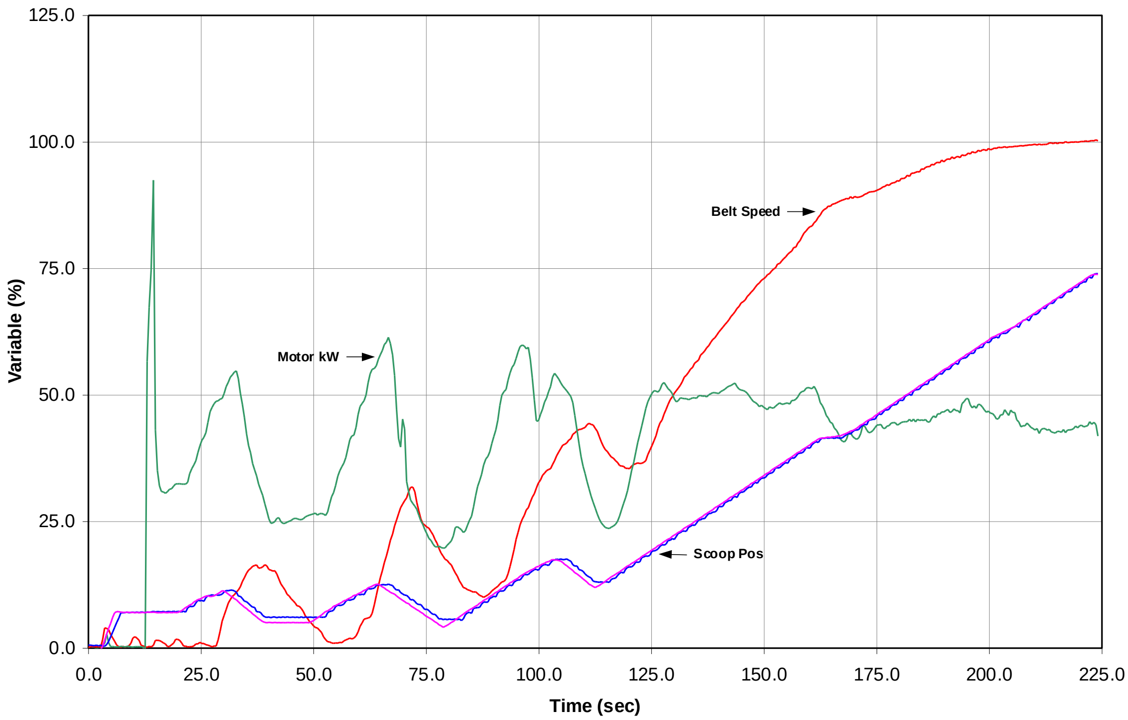

Fig. 15 Typical Fluid Coupling Instabilities

CONCLUSION

The methods and solutions outlined in this paper have been developed to address the specific requirements of long overland conveyors, and have been successfully implemented in many installations throughout the world. However, each conveyor is unique and creates its own set of challenges, and the solutions outlined in this paper can only provide a starting point to help with the new challenges that await us.

Figures

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