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Vector Controlled Variable Speed Drives - A Viable Alternate for Driving Conveyors

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VECTOR CONTROLLED VARIABLE SPEED DRIVES – A VIABLE ALTERNATE FOR DRIVING CONVEYORS

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1. INTRODUCTION

Many advances in the performance of electric drives have been made over the last decade. Similarly large conveyors have advanced with longer and faster conveyors becoming more commonplace. This has led to stricter requirements for the conveyor drives as the dynamic behaviour of the conveyor must be taken into consideration.

Traditionally conveyor belt systems were designed using standards such as DIN22101 or ISO5048, which are largely based on static analysis, where the belt is treated as a rigid body. This type of analysis does not describe the complete behaviour of conveyor belts so new design techniques, including the analysis of the dynamic performance, were developed by Nordell [1], Funke [2] and Harrison [3].

2. REQUIREMENTS FOR MODERN CONVEYOR DRIVES

Funke [2] was the first to show that the drive drum motion induced circulating elastic waves in the conveyor belt. These waves were shown to induce dynamic tensions in the belt which were superimposed on the tensions calculated using the static methods previously described. In certain cases the dynamic tensions induced can be sufficiently severe to damage the conveyor structure. Funke [2] demonstrated that by controlling the rate of rise of the drive torque the amplitudes of the dynamic tensions can be reduced to acceptable levels. *The ability to control the output torque of a drive* is the first criterion that can be used to evaluate and compare different conveyor drive systems.

Braking conveyors results in similar behaviour to starting. Drives may be used to reduce the speed of a conveyor gradually as opposed to suddenly removing the drive torque, which could cause dynamic problems.

Conveyors are generally designed to have a certain lifetime and must therefore be able to cater for increases in load carrying capacity. The modern trend is to operate the conveyor fully loaded at all times and to reduce the speed when the full capacity is not required. This improves the operating efficiency and reduces the number of cycles on the mechanical components per ton conveyed. This load related speed philosophy gives the second criterion for evaluating and comparing conveyor drives, ie. *The ability of the drive system to operate continuously at the lower speeds depending on the loading.*

The third criterion relates to cost considerations. *Both initial and running costs must be considered.*

Most conveyor installations are located remotely. Hence the fourth criterion is that *maintenance should be uncomplicated and easy to perform.*

3. CONVENTIONAL CONVEYOR BELT DRIVES

3.1 Induction motor.

The squirrel cage induction motor is probably the most common drive used for conveyors. These motors are robust, easy to maintain and inexpensive. They will operate at high efficiency provided that they are suitably loaded. However the speed of the motor is dependent on the supply frequency and cannot be easily adjusted. A typical torque-speed characteristic for a deepbar induction motor is shown in Figure 1.

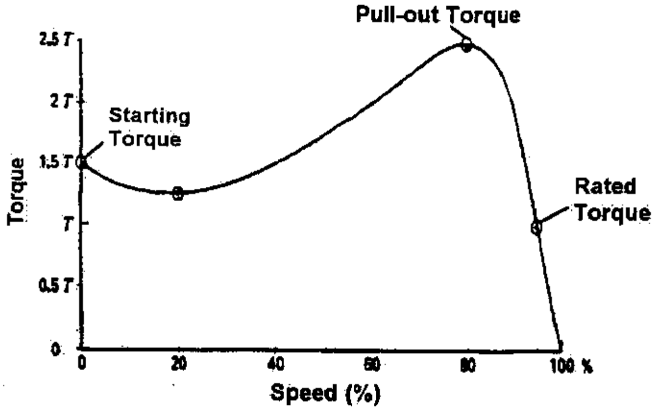

Figure 1. Torque-speed characteristic of an induction motor.

It can be seen in Figure 1 that the pull-out torque is typically 250% of the rated torque of the motor. As the conveyor is accelerated past the 'speed of maximum torque', the sudden rise in torque is reflected in the belt tensions. Such a start-up would require the belt mechanical components and the belt to be over-designed to withstand the stresses caused during starting. Therefore the squirrel cage induction motor is not suitable for directly driving conveyors unless some method is used to prevent the maximum pull-out torque from being applied to the conveyor.

The torque-speed characteristic of the induction motor may be modified by changing the rotor circuit resistance. The family of torque-speed curves that results is shown in Figure 2.

Torque control can be achieved by continually decreasing the external resistance as the conveyor speed is increased. A much flatter torque-speed characteristic is achieved and, if the notching is carefully selected, far less belt stress occurs when compared with direct on line starting of a squirrel cage motor.

A continuous torque-speed curve may be achieved by using moveable electrodes in an electrolyte solution to provide an infinitely variable resistance. However, this type of control is not suitable for extended use at low speeds as the power dissipated in the rotor circuit makes the drive inefficient. This type of drive is popular in industry although it is usually used together with a fluid coupling.

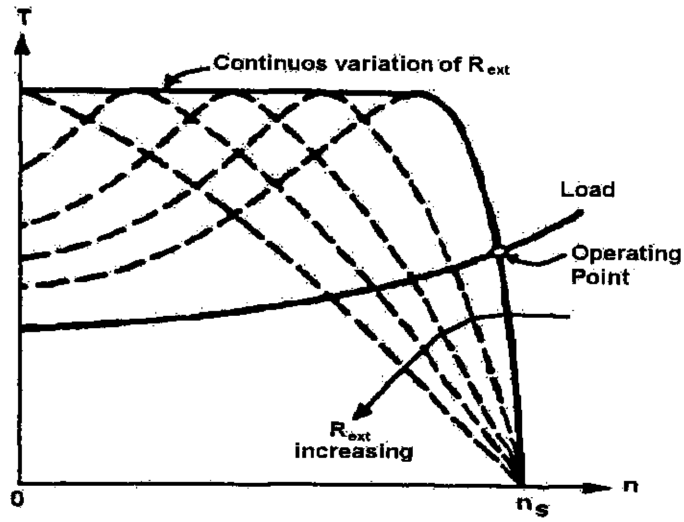

Figure 2. Torque-speed curves of wound rotor induction motor with varying rotor circuit resistance.

3.2 Fluid couplings.

Fluid couplings are usually employed between the induction motor and the reducer to control the torque applied to the conveyor drive pulley. The principle of operation of this coupling is that a fluid, usually oil, is set in motion by the impeller around the periphery of the enclosing shell. The runner is in turn 'dragged' along by the moving oil. The characteristic of the coupling is dependent on the amount of fluid in the working circuit, the viscosity of the fluid and the coupling diameter.

During the start up of the conveyor the induction motor is allowed to run up under reduced load or no load, depending on the type of coupling. The pull-out torque is applied to the impeller, accelerating it quickly to rated speed before the coupling fluid is properly set in motion. Once the fluid is circulating steadily the retarding torque caused by the conveyor is reflected via the fluid at the input shaft. The induction motor slows down slightly and the torque transmitted increases to match the load requirements. As the motor is running near rated speed it is operating in the linear region of the torque-speed curve to the right hand side of the pull-out torque peak (see Figure 1).

Drives incorporating fluid couplings are one of the most widely used for conveyors. This is due to their reliability and simple maintenance. There are a number of different types of fluid couplings giving longer time delays to reach full speed, which in turn gives better starting control, eg the delay fill coupling. Only the variable fill couplings are suitable for extended use at low speeds.

3.3 Clutches

Clutches are used in a similar way to fluid couplings in controlling the torque applied to the drive pulley of a conveyor. The drive motor is allowed to accelerate to full speed while the load is stationary, the two being de-coupled by the clutch. As the clutch is engaged, the load torque is applied at the motor shaft slowing it down slightly and thereby increasing the drive torque. While the conveyor is accelerating, the slip due to the differing speeds of the load and motor is taken up by the clutch.

Frictional clutches (including centrifugal clutches) offer acceptable torque control for conveyors, but are seldom used in large conveyor applications due to the heating caused by an extended start up. Similarly they are not suitable for variable speed drive applications.

Eddy current clutches have also been used as torque control devices. In this type of clutch the transmission of torque is via magnetic coupling. These clutches provide good torque control and are suitable for extended run-up times and for variable speed applications, provided they are properly sized. The efficiency of the coupling is not so good as they usually run with a slip of between 3 – 5%. They are also bulky and may not be suitable where space is limited.

3.4 Soft Starters

The output torque of an induction motor is proportional to the square of the applied voltage. The soft starter is incorporated between the supply and the motor and it controls the motor terminal voltage. The disadvantage of this method is that the motor torque still varies with the speed, and although the starting torque can be reduced, the pull-out torque has still to be encountered. Therefore the benefits of soft starting do not extend above approximately 10% of rated speed, where the starting torque may be controlled.

A variation of the soft starter is that the starter output voltage is adjusted to keep the current drawn constant. A two stage current limit is used where initially the limit is set at a value to accelerate the conveyor and is later reduced to a steady state value. The method ensures that excessive currents do not flow but it has the disadvantage that the current and torque are not related to each other in a linear manner for all values of slip, ie. Controlling the current does not imply that the torque is similarly controlled.

4. POWER ELECTRONIC VARIABLE SPEED DRIVES

Power Electronic controllers for variable speed AC drives have made great advances over the past ten years. New methods of control have been developed which give more accurate control on the motor torque making them more suitable for conveyor drives.

The speed of the induction motor is dependant on the frequency of the supply and the number of poles of the stator winding (ie. $n_1 = f / p$). The frequency of the electrical supply is fixed by the supply authorities, so the power electronic converters convert the fixed frequency supply to a variable frequency supply for the motor, giving the required speed variations. The relationship between the motor voltage V, the motor magnetic flux Φ and the supply frequency is

$$V = \frac{2\pi}{\sqrt{2}} \Phi f N K_w$$

where N = the number of turns of the stator winding per phase and
K_w = the stator winding factor.

This relationship shows that if the voltage supplied to the motor is kept constant then the motor flux must increase if the frequency is reduced. It is not possible to increase the motor flux significantly because the magnetic steel saturates. Therefore, controllers operate with a constant Volts / Hz characteristic thereby ensuring that the motor flux is kept constant as the frequency, and the hence speed, varies.

It may also be shown that the torque developed by an induction motor can be expressed as

$$T = K' \Phi I \cos\theta_2$$

where I = the stator current and
θ_2 = the angle between the rotor current and rotor emf. (In the normal operating region of the torque speed curve θ_2 is almost 0° and $\cos\theta = 1.0$).

Hence , if the motor flux Φ is kept constant, then the torque is directly proportional to the motor current.

A number of these drives are discussed below.

4.1 Scalar Controlled Drives

In the case of the scalar controlled drives, the motor flux is constant so the torque speed characteristics of the motor at different frequencies are similar, except for the speeds of operation. Typical characteristics are as shown in Figure 3.

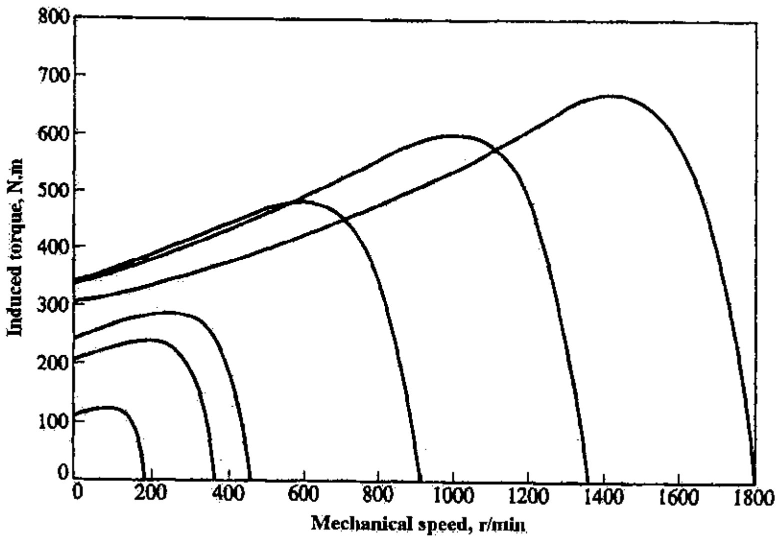

Figure 3. Torque speed characteristics for variable frequency and constant flux operation.

The motor operates in the "linear region" of the torque speed characteristic at all speeds and therefore high values of power factor and efficiency are obtained. Also effective speed control is achieved especially at speeds below rated. Under such conditions auxiliary cooling is usually provided for the motor. Such drives are more costly than the simple soft starter, but they are still very cost effective.

4.2 Vector Controlled Drives

In this form of control the angle between the motor flux Φ and the motor current I, ie δ, is kept constant at 90 ^{O}. This is achieved by resolving the stator current vector into two components, one in phase with the magnetising flux vector and one in quadrature with it. The in phase component is responsible for the flux in the motor, similar to the field current in the dc machine. The quadrature component is responsible for the torque and is similar to the armature current in the dc machine. The motor current vectors are derived by the controller, from the torque speed requirements, and these vectors are then transformed back to the three phase form and used as references for the inverter. The control achieved is more accurate, although the inverter is much more complex.

4.3 Cycloconverter Drives

A cycloconverter is a power electronic system that generates a variable voltage, variable frequency supply from a fixed frequency supply without using a dc link. This system can only produce frequencies well below the supply frequency and is therefore only suitable for control at low speeds (typically the output frequency is 16 Hz from a 50Hz supply). Accurate torque control is possible using a cycloconverter by incorporating vector control.

Due to the low speed nature of this drive system, a "reducer" on the conveyor is usually not necessary. This cost reduction is then offset by the high cost of the converter. These drive systems may operate over a wide speed range and they have high efficiency.

4.4 Slip Energy Recovery

In the case of the wound rotor induction motor the overall efficiency of the drive may be improved by replacing the rotor resistance controller with a rectifier / inverter. The energy that was previously dissipated in the rotor resistances is now returned to the supply. Good steady state control of the torque is possible although the dynamic control is markedly inferior to the vector control methods.

This system is suitable for operation at speeds below rated although the power factor is poor below approximately 70% of rated speed.

5 COMPARISON OF DRIVES

Conventional conveyor drive systems and variable speed drive systems are evaluated according to the same criteria. The results are presented in Table 4.1. The results indicate that the performance of variable speed drives exceeds that of conventional drives and are therefore very suitable for driving modern conveyor systems.

Table 5.1 Summary of the merits of conveyor drive systems studied.

Drive system	Torque Control	Speed Control	Cost		Maintenance
			Initial	Running	
Squirrel cage induction motor	poor	poor	good	good	good
Wound rotor induction motor	> ave.	< ave.	ave.	ave.	ave.
Fixed fill fluid coupling	< ave.	poor	> ave.	> ave.	good
Delay fill fluid coupling	ave.	poor	> ave.	> ave.	good
Scoop control fluid coupling	> ave.	ave.	ave.	> ave.	good
Drain type fluid coupling	> ave.	ave.	> ave.	> ave.	good
Frictional clutch	ave.	poor	good	> ave.	ave.
Hydraulic clutch	ave.	< ave.	-	> ave.	good
Eddy current clutch	> ave.	ave.	-	ave.	good
Soft starter	ave.	< ave.	good	good	< ave.
Scalar controlled AC drive	> ave.	good	< ave.	good	< ave.
DC drive	good	good	< ave.	ave.	< ave.
Vector controlled AC drive	good	good	poor	good	poor
Cycloconverter drive	good	good	poor	good	poor
Slip energy recovery	> ave.	> ave.	< ave.	ave.	< ave.

Where good — Implies that the criterion is totally satisfied

> ave. — Implies that the drive displays above average qualities

ave. — Implies that the drive displays average qualities

< ave. — Implies that the drive displays below average qualities

poor — Implies unsatisfactory performance with respect to the criterion

\- — Implies that no information could be obtained

6. SIMULATION OF A CONVEYOR DRIVEN BY A VARIABLE SPEED DRIVE

In order to assess the merits of using a variable speed drive to drive a conveyor system, the whole system should be simulated. This requires modelling the conveyor belt, the conveyor drive system and the variable speed drive. Jackson did this by using the CASED simulation package.

6.1 Modelling a conveyor

Conveyor models can be divided into two broad categories. The first category includes models that use a continuous medium to represent the belt while in the second category the belt is divided into discrete mass elements separated by some form of connecting element that represents the elastic behaviour of the belt. The equations used to describe the conveyor behaviour as a continuum system involve numerous simplifications, such as the assumption of steady resistance to motion. The discrete method presents a more detailed representation of the belt including certain non-linear effects.

In the discrete method the belt is partitioned into separate elements or nodes. These nodes are interconnected by spring elements that model the tension in the conveyor. A schematic diagram depicting the inter-connection of these nodes is shown below.

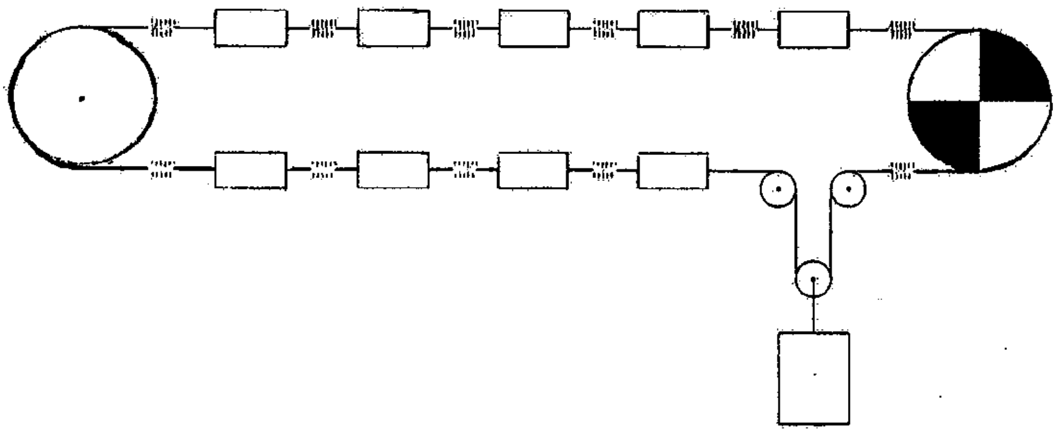

Figure 4. Schematic diagram of a discrete mass spring model of a conveyor.

Each node represents a section of the conveyor structure, either a section of the belt and a pulley or a combination of belt and pulleys. The carry and return strands are divided into an equal number of parts and the drive and tail pulleys are treated as separate elements. The sectional elements used to model the conveyor may be generalised as shown in Figure 5.

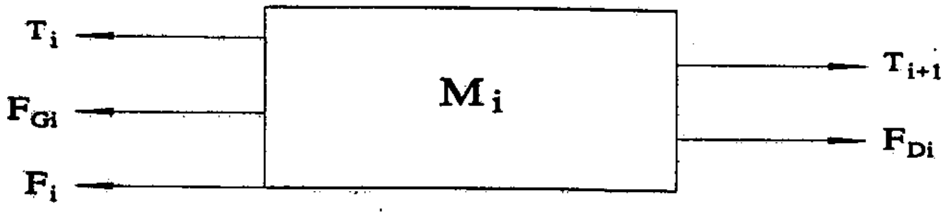

Figure 5. A single conveyor element used for the discrete model.

In this element, M_i = nodal mass
T_i / T_{i+1} = belt tension on either side of the element
F_i = frictional losses
F_{Gi} = effect of gravity
F_{Di} = drive force

The general equation of motion for the above element is then

$$X_i = \frac{1}{M_i}(F_{Di} + T_{i+1} - T_i - F_{Gi} - F_i)$$

This belt model described above is suitable for simulating conveyor belts that are empty or that are being continuously loaded and have an even load distribution along their entire length. To simulate a partially loaded belt, the belt nodal masses have to be modified at every time step of the solution integration process.

6.2 The Drive Model

The simulation of the drive and conveyor system was carried out using the CASED (Computer Aided Simulation of Electrical Drives) package developed by the Machines Research Group of the Department of Electrical Engineering at the University of the Witwatersrand, Johannesburg. A wide variety of converter models are available within CASED, as described by McCulloch [4].

A typical electric drive system consists of a converter, a motor and a controller. The drive chosen for the simulation of the conveyor system is a Pulse Width Modulated (PWM) inverter feeding a squirrel cage induction motor. Space vector control was selected as the control strategy for the drive thereby providing the accurate torque control necessary for this application.

A PWM inverter is implemented by using a conventional inverter bridge as shown in Figure 6.

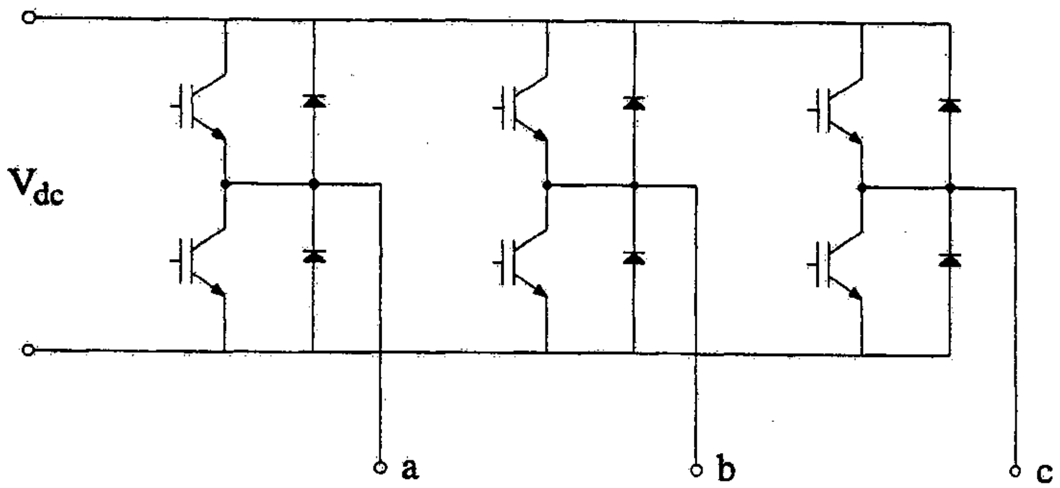

Figure 6. Conventional three-phase inverter bridge.

In this case the bridge is supplied from a dc source and the ***motor current*** is controlled. Pulse Width Modulation actually refers to the strategy used to switch the switching elements (thyristors, IGBT's etc) such that the desired motor current waveform is achieved. One method of generating the switching signals for PWM is by comparing the output currents of the inverter with a desired reference current. The error signal is obtained by subtracting the actual current from the reference current and then by comparing the error to a fixed frequency triangular carrier wave. When the current error signal is greater than the carrier wave the inverter is switched positively and when it is less the inverter is switched negatively. Switching positively implies triggering the upper device in the inverter leg and switching negatively the lower device. Typical current error, carrier and resulting voltage waveforms are shown in Figure 7.

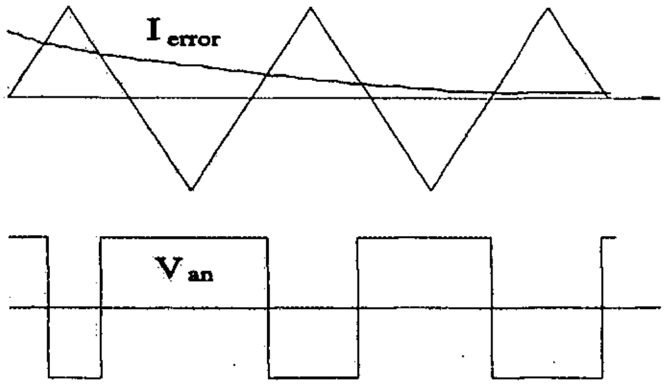

Figure 7. Typical PWM waveforms showing the current error, carrier and phase voltage waveforms.

The switched nature of the voltage waveform is apparent. However the motor current waveform is far more sinusoidal (fundamental with a high frequency ripple superimposed on it) owing to the low pass filtering action of the induction motor inductance.

The induction motor is modelled by reducing it to its Kron Primitive form, as described by O'Kelly and Simmons [5]. The three-phase windings on the rotor and stator of the motor are transformed to two-phase orthogonal equivalents giving the structure shown in Figure 8.

The frequency of the transformed stator and rotor currents remains unchanged at supply and slip frequency respectively. The rotor is then transformed from a rotating reference frame to a stationary reference frame, resulting in all currents being at supply frequency. The resultant two phase quantities are represented by the concentrated coils arranged in quadrature with one another on the stator and rotor, as shown in Figure 8.

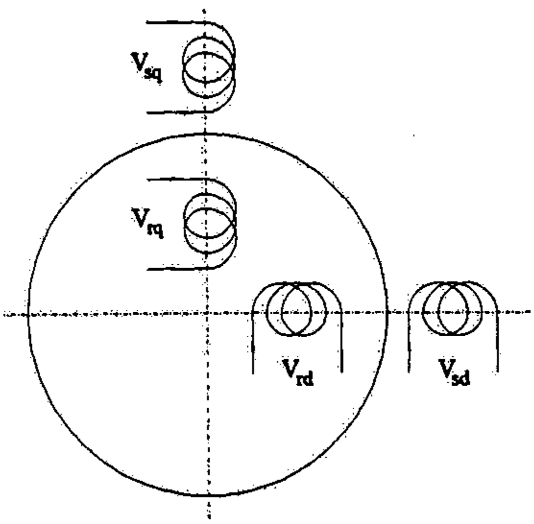

Figure 8. Schematic diagram showing the Kron Primitive form of a motor.

As with the converter CASED has the facility of modelling the induction motor with different degrees of complexity. The effect of the high frequency rotor current present during starting can be included in the more accurate model as described by Levy et al.

From a control point of view, the dc motor is far superior to the induction motor supplied by a fixed frequency ac supply. The induction motor has a highly interactive multi-variable control structure than that of the dc machine. Space Vector Control is a method of de-coupling the control variables and thereby allowing the induction motor to behave as a separately excited dc machine. This overcomes the control disadvantages of the induction motor.

It can be shown that the component of the stator current vector in phase with the rotor magnetising current vector (or the rotor flux) is responsible for the flux in the motor. This is similar to the field current in a separately excited dc motor. The component of the stator current in quadrature with the rotor magnetising current vector is the torque producing component, which is analogous to the armature current in the separately excited dc motor. Therefore it is possible to get extremely fast and accurate torque and speed control by using these two stator current components.

The controller makes use of the reference speed and torque and the actual motor speed as inputs to generate reference values for the direct and quadrature components of the stator current. These references are then transformed into three phase quantities to be used as reference currents for the PWM inverter. The actual currents are compared with these values and error currents calculated, from which the PWM switching signals for the inverter are generated.

7. PREDICTED AND EXPERIMENTAL RESULTS – CONVEYOR WITH FLUID COUPLING

A conveyor being driven via a fluid coupling was modelled by Jackson [6] and the predicted performance was compared with actual measurements taken on the conveyor. This conveyor formed part of the development of a new colliery in Mpumalanga, South Africa. The conveyor transports coal from the colliery to a rapid loading terminal. The coal feed rate is 1000 tons/hour over a distance of approximately 3.2 km, following a tightly curved route.

The steel cord belt is driven by a dual tandem drive configuration. Belt tension is maintained by means of a gravity take-up system. During starting the drive torque to the conveyor is regulated by means of fluid couplings on each of the three drive motors.

The behaviour of the conveyor under starting and stopping conditions was measured for two operating conditions, namely fully laden (1000 t/h) and empty. The quantities measured, for each case, were the motor input power for each of the three drives, the belt speed at the drive and at the take-up and the take-up displacement. A schematic diagram of the layout of the drive pulleys is shown in Figure 9.

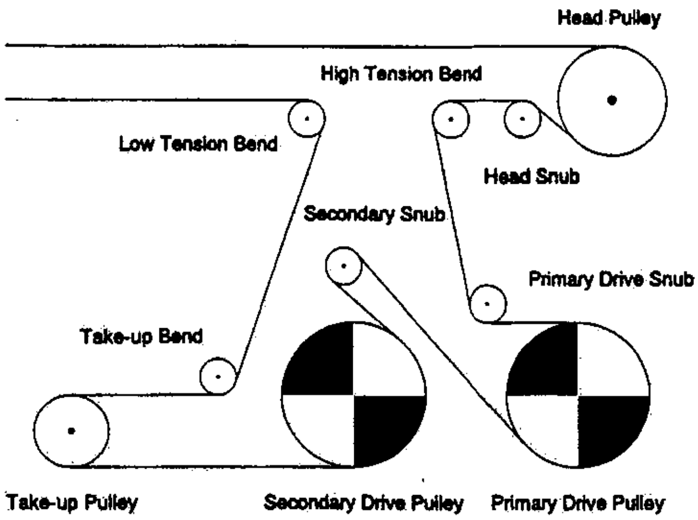

Figure 9. Schematic diagram of the conveyor drive pulley arrangement.

The measured and predicted results for starting the fully laden conveyor are shown in Figures 10 to 13. In each case the correlation between predicted and measured characteristics is very acceptable and therefore ***it may be concluded that the modelling procedure is accurate enough for design purposes.***

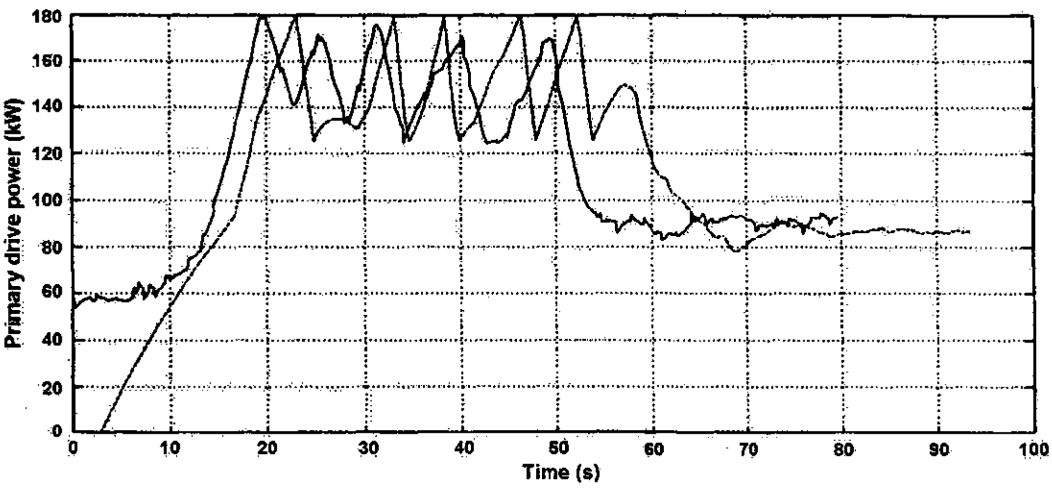

Figure 10. Predicted (--) and measured (-) primary drive power for starting the fully laden conveyor.

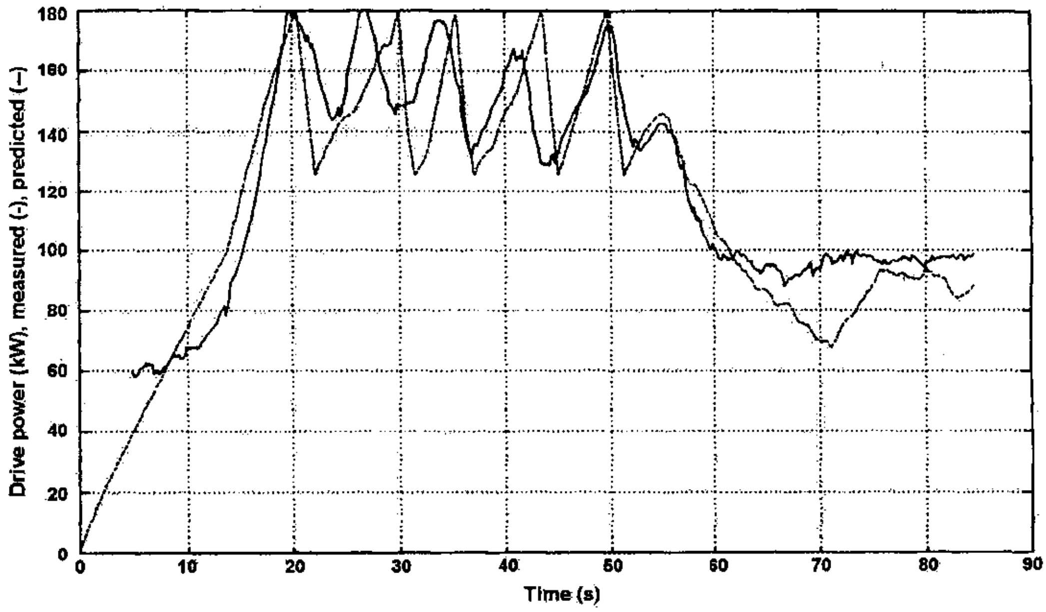

Figure 11. Predicted (--) and measured (-) secondary drive power for starting the fully laden conveyor.

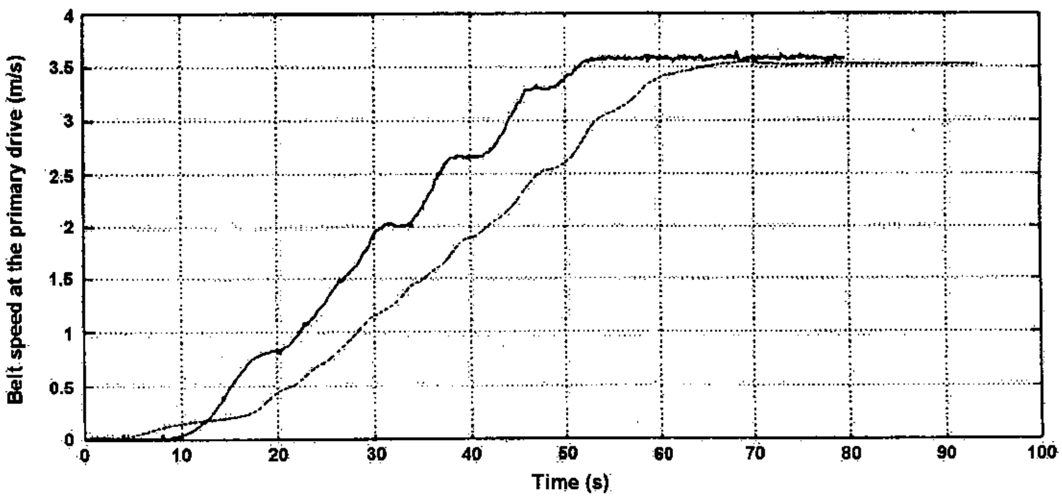

Figure 12. Predicted (--) and measured (-) belt speed at the primary drive for starting the fully laden conveyor.

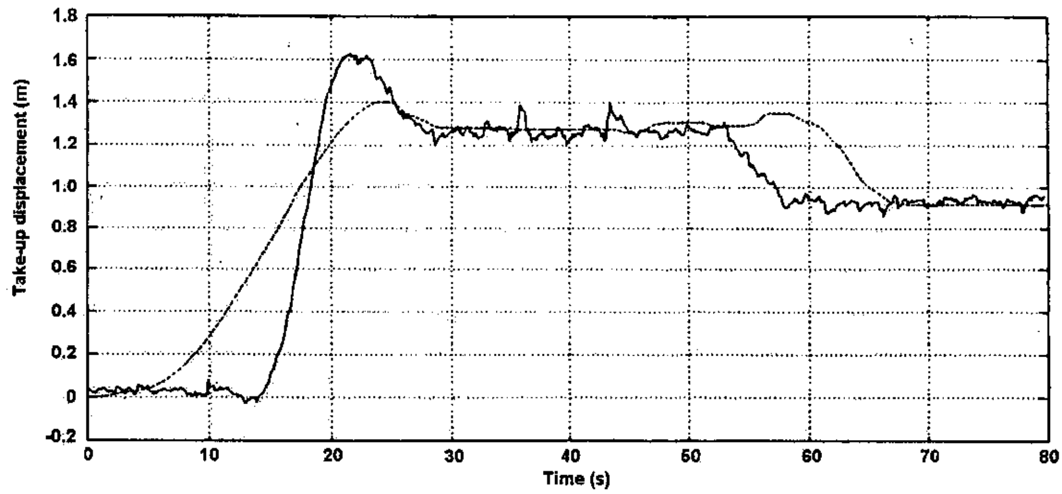

Figure 13. Predicted (--) and measured (-) take-up carriage displacement for starting the fully laden conveyor.

8. PREDICTED RESULTS – CONVEYOR DRIVEN VIA A VARIABLE SPEED DRIVE [6]

The simulation tools developed and proven were used to assess the operation of the same conveyor when run via a variable speed drive. The final system simulated was as shown in the block diagram of Figure 14. The initial parameters used in the model came from the design of the conveyor using static design procedures.

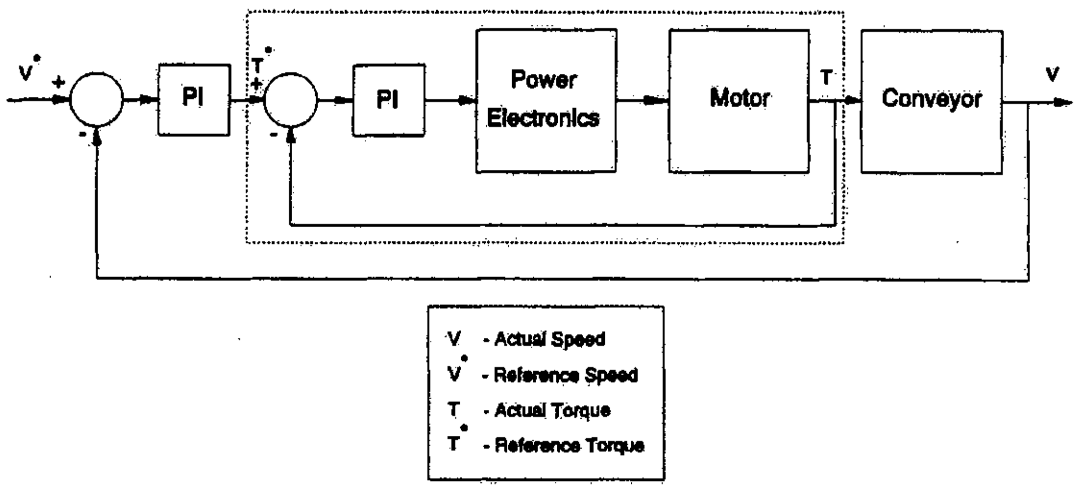

Figure 14. Block diagram of the components of the conveyor system.

In terms of the static design the required run up time, to rated speed of 3.57m/s, was 38s. To meet this starting criterion, a linear ramp from zero to rated speed in 38s was used as the speed reference for the controller. The necessary primary drive torque and resulting belt speed are plotted in Figure 15, where it is seen that the primary drive torque must rise steeply to a maximum value of 1300 Nm. The conveyor follows the speed reference closely and settles to rated speed in approximately 45s. The highest tension peak in the conveyor belting occurred in the section between the head pulley and the primary drive pulley. This is shown in Figure 16.

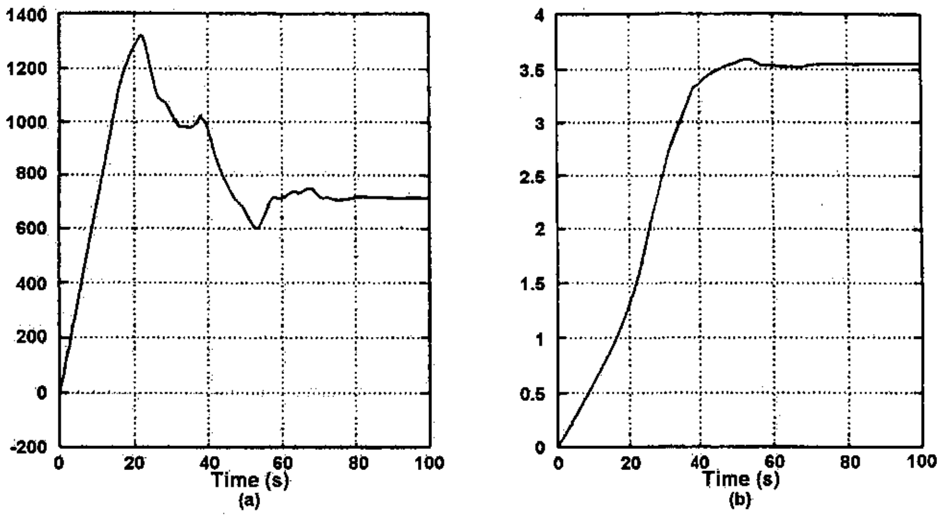

Figure 15. Primary drive torque (a) and Belt speed (b) for initial design.

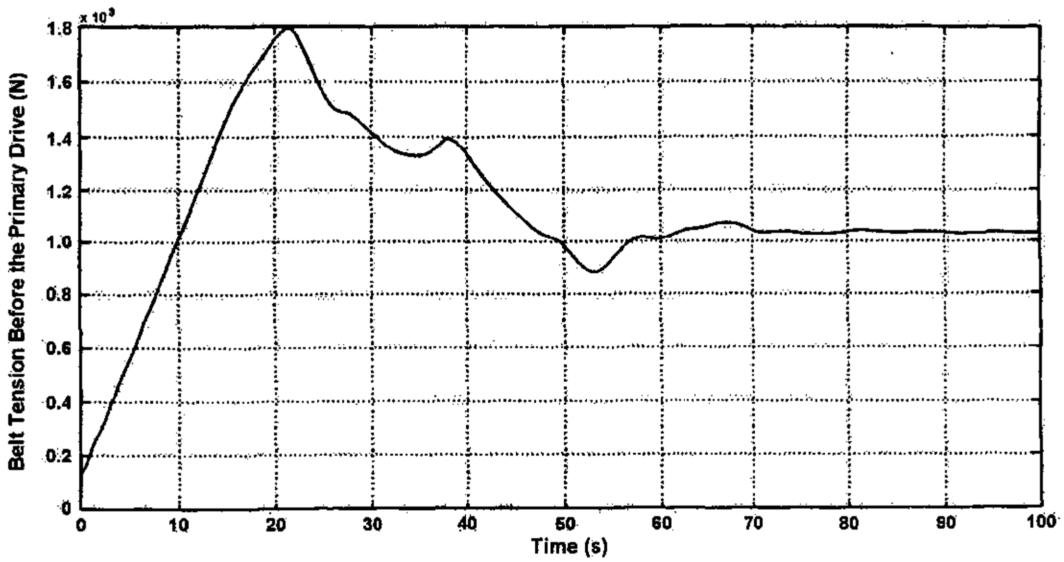

Figure 16. Belt tension before the primary drive (original design).

The tension ratio across the secondary drive exceeded the limit specified for belt slip and the take-up carriage moved smoothly through a total displacement of 4.17m. This design was thus inadequate and the following solutions were proposed.

In order to limit the peak belt tension it was proposed to limit the drive torque, as these follow similar trends. Hence a torque limit of 125% of the steady state torque, at rated speed, was applied. The resultant motor torque and belt speed are plotted in Figure 17 and the associated belt tension in Figure 18.

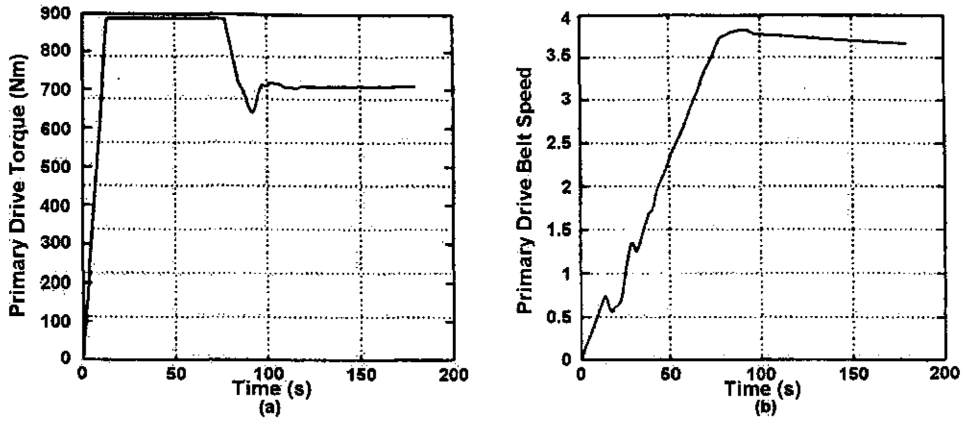

Figure 17. Primary drive torque (a) and belt speed (b) with torque limit imposed.

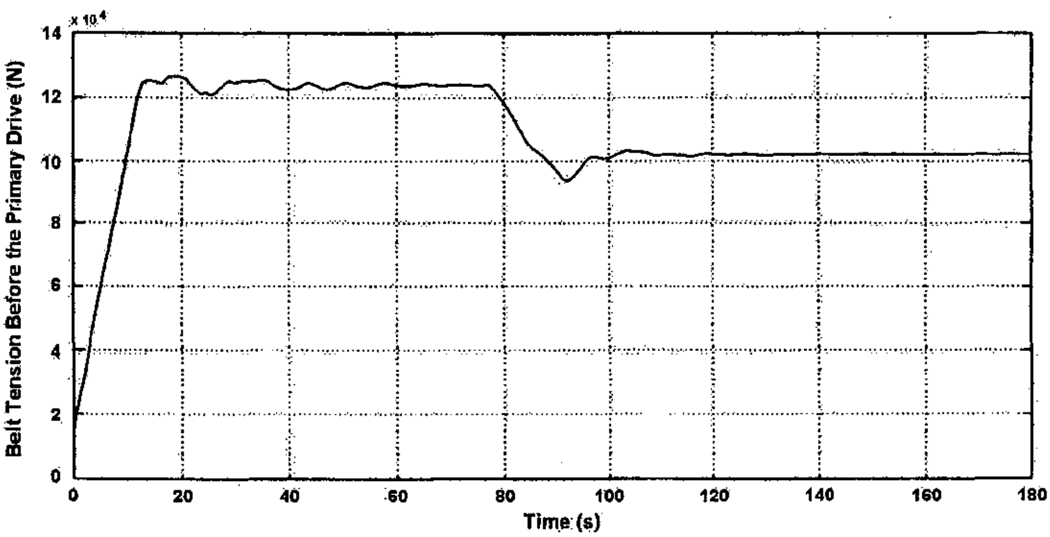

Figure 18. Associated belt tension before the primary drive during torque-limiting.

The torque-limiting region is entered shortly after the conveyor is started and is only left once the conveyor reaches rated speed. The belt speed is also more oscillatory owing to the fact that when the system is in the torque-limiting region, the controller is unable to control the conveyor speed.

The problem of torque-limiting is overcome by applying a reference speed signal with a slope less than that for the conveyor given in Figure 17. Under these conditions the it is possible for the drive to control the conveyor without exceeding the torque limit.

The results shown in Figures 19 and 20 are for the conveyor started with a reference speed signal rising linearly to rated speed in 120s. A slightly higher torque limit of 133% of steady state torque was used in this case as a safeguard against over stressing the belt in the case of a malfunction.

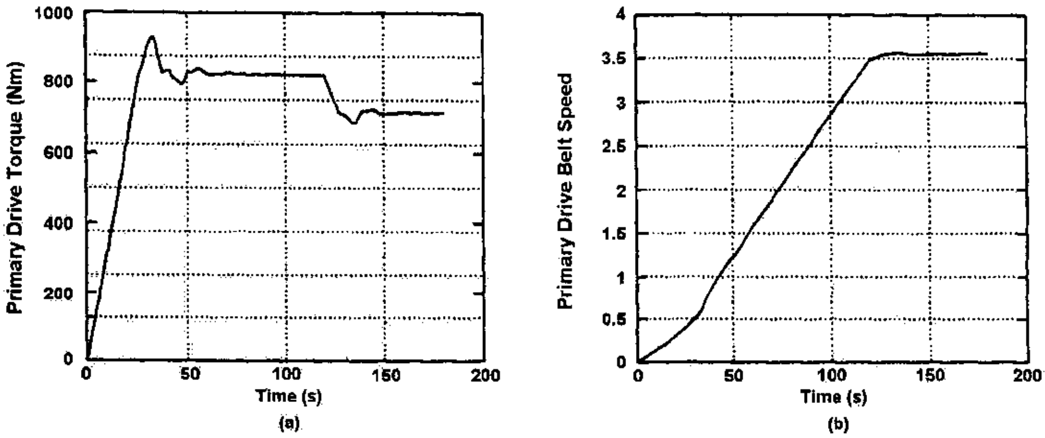

Figure 19. Primary drive torque (a) and Belt speed (b) – run up time 120s.

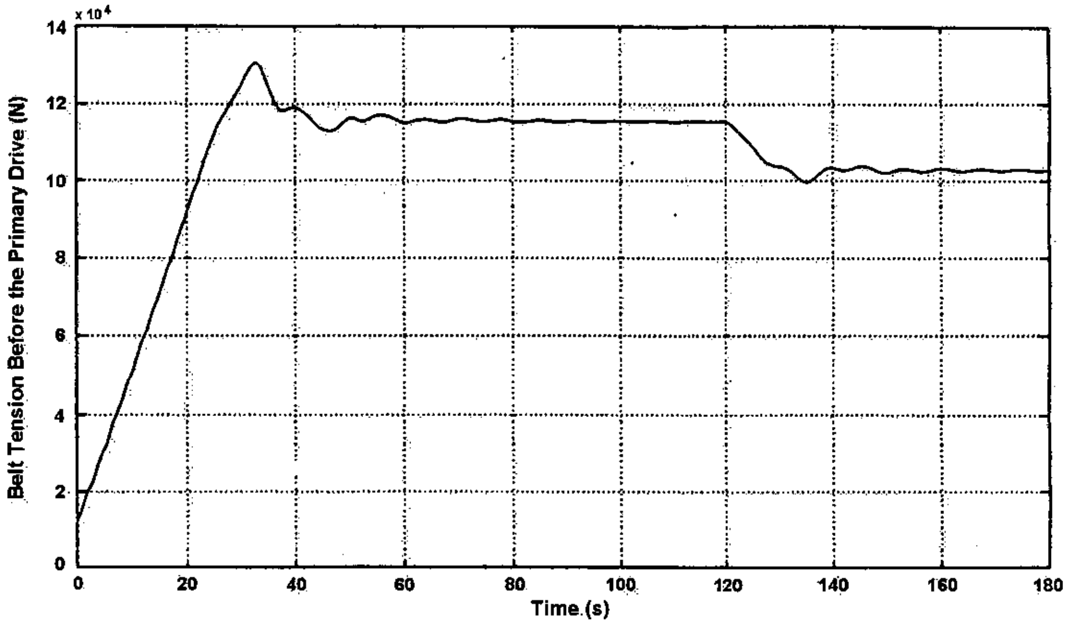

Figure 20. Belt tension before the primary drive – run up time 120s.

This result shows how the belt tension can be limited by controlling the starting time of the conveyor. The lower tension is due to the smaller acceleration force required to track the speed reference. This improvement in the peak belt tension is achieved while still retaining full control over the drive during starting.

9. CONCLUSIONS

This paper has demonstrated how the two main criteria of controlling a modern AC variable speed drive, namely speed and torque control, can be used to improve the performance of a conveyor. It has also demonstrated how a conveyor system can be designed using the simulation tools developed. Also the effective use of the CASED simulation package has been demonstrated in this application.

10. REFERENCES

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