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Modeling of an Integrated Energy Efficient Conveyor System Model using Belt Loading Dynamics

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Abstract

Objectives: From an industry specific perspective, there is continuous pressure on manufacturing companies to reduce the operating expenditure by reducing the electricity cost by developing the energy efficient equipment and products especially conveyor systems. **Methods/Statistical Analysis:** Conveyor belts are the material handling equipment that is widely used in industry to move the material from the one place to another or from one process to next process. Conveyors are generally driven with electric motors. Conveyor systems are the one of the major consumers of electricity industries, which consumes up to 40% electricity of the total operating cost, while the remaining 60% is due to operational costs and maintenance. **Findings:** In this work, efficiency of a conveyor system is evaluated by integrating all the factors that have an influence on the electricity costs of the conveyor system. Using variable speed drive mechanism, an energy efficient conveyor system is developed by physically modeling the speed of the belt and conveyor loading dynamics mechanism under no load, marginally loaded and full loaded conditions. For the energy efficient conveyor system, different start-up of conveyor methods are evaluated as a baseline reason of generating the motor torque in comparison to rated voltage as an optimal energy management tool to develop a relationship across the power consumption, conveyor belt speed and belt loading dynamics. **Application/Improvements:** The design of energy efficient conveyor system model by controlling multiple drive units in industrial units.

Keywords: Conveyor Loading Dynamics, Conveyor System, Energy Efficiency, Variable Speed Drive

1. Introduction

Energy consumption plays an increasingly significant role in industries today. Industries are pressurized to improve their energy consumption trends from a financial and an environmental perspective. Energy consumption forms a significant part of operating expenditure in industry. Through the ongoing drive in industries to become more cost effective, the need still exists to explore and investigate more opportunities to lower the operating costs. Electricity is one of the operating cost mechanisms that can be lowered by the effective utilization of resources and operating characteristics. Conveyor belts are one of the major consumers of electricity in the materials handling facilities in industry. In an industrial processing unit, conveyor belt can consume up to 40% electricity of the total operating cost while the remaining 60% is due to operational costs and maintenance[1]. The focus on electricity cost savings on conveyor belts in past was more on the energy reduction of mechanical and electrical component deployed on the conveyor system in an individual form[2]. The concept of improving the energy consumption and system efficiencies by controlling multiple drive units is of great interest recently. This has leaded the concept of evaluating the electricity cost efficiency of a conveyor system by integrating all the factors that can influence the energy efficiency and electricity costs of the conveyor system. In this work, efficiency of a conveyor system is evaluated by integrating all the factors that have an influence on the electricity costs of the conveyor system. Using variable speed drive mechanism, an energy efficient conveyor system is

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developed by physically modeling the speed of the belt and conveyor loading dynamics mechanism under no load, marginally loaded and full loaded conditions. The modeling of operational power consumption baseline is also formulated to propose an energy efficient conveyor system. The rest of paper proceeds as follows: Section 1 briefly introduces the importance of conveyor system in industries focusing the energy efficiency requirement. The conveyor belt system structural design is discussed in Section 2. Section 3 discusses the different methods to control the start-up time of conveyor system. In Section 4 the modeling the conveyor belt energy requirements and loading dynamics is presented. Impact of conveyor speed on conveyor energy consumption is discussed in Section 5. Section 6 concludes the research work.

2. Conveyor Belt System Structural Design

Like any system design, conveyor system design is also based on some key design parameters which can have a great influence on the operating characteristics of the conveyor system. In the first place, a conveyor is designed to move a certain amount of material at a certain rate over a specific distance. This can be horizontal displacement of material or it can be vertical displacement. An example of this is an incline conveyor. The typical conveyor belt is illustrated in Figure 1. A typical conveyor belt system in total consists of the following components: 1. Rubber belt, 2. Head pulley with gearbox and electrical motor, 3. Tail pulley, 4. Carry idlers, 5. Return idlers and 6. Take-up Pulley[3]. The pulley is classified as tail pulley and a head pulley. The material to be conveyed is loaded onto the conveyor near the tail pulley and discharged again at the head pulley. In simple conveyor designs, the drive unit is normally situated at the head pulley. In more complex designs, the drive pulley is situated somewhere in the middle of the conveyor on the return side of the conveyor. A take up pulley gives the belt the required tension. This pulley is usually placed a certain distance away from the head pulley. The tensioning of a belt can vary from a fixed tension by using a mass over a pulley or a mechanical tensioner like a bolt and nut. Control systems with electric motors and hydraulic arms also exist that controls the tension in the belt. There are also carrying and return idlers. The idlers have cylindrical wheels under the conveyor belt that support the belt and in the case of the carrying idlers, the load. The return idlers generally support the conveyor belt returning back mechanism, but it is sometimes also used to carry material as well. A typical application of such mechanism is for the underground mining application where the run of mine material is carried on the top and the waste material is carried on conveyor belt return to do back filling. This ultimately reduces the conveyor energy consumption as energy is generated back to system on the returning part of conveyor system.

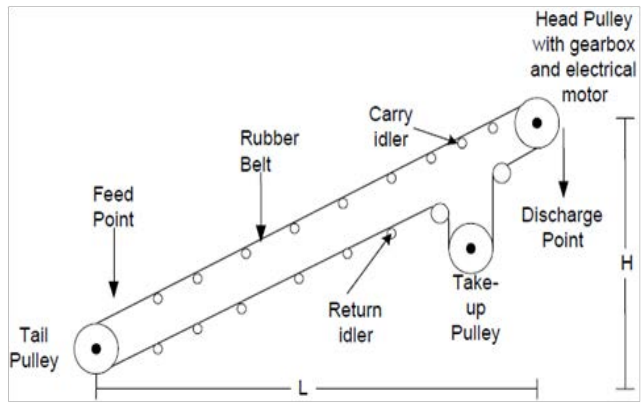

Figure 1. Typical conveyor belt.

3. Conveyor Start-up System Modeling

Considering the application of energy efficient conveyor system, the minimum power required to operate and run the conveyor system and move the conveyor load in required direction can be categorized into three dimensions subject to minimum power required to 1. Run the empty conveyor under no load conditions, 2. Move the conveyor load horizontally and 3. Move the conveyor load vertically. For the energy efficient conveyor, the most important parameter is the start-up of the conveyor[4] which is baseline reason of generating the motor torque in comparison to rated voltage. In this work, different conveyor belt start-up methods have been proposed and evaluated to develop an energy efficient conveyor system. These methods are used energy management tools so that an optimized relationship between the power consumption, conveyor belt speed and belt loading dynamics can be developed. To get started, a squirrel cage motor is employed and controlled which is directly coupled to the head pulley through a gearbox using direct on line method[5]. During the start-up, the motor breakaway torque is rated at almost 2.3 times more at full load torque for smaller motors in the region of 74 kW and 1.1 times more for motors in the region of 630 kW. At rated voltage, the breakdown torque (pull out torque) is the maximum rated torque which a motor can develop. This parameter value is 2.5 times more than a rated torque for small motors and 2.8 times more for large four pole motors. Thus it can establish that during start-up phase, the conveyor system will experience a high jerk or abnormal rate of change (mostly very high peaks) that can cause resonance on the conveyor. As the conveyor operational speed increases, the developed torque also increases until the breakdown torque reaches to its peak limit, where afterwards the developed motor torque decreases until the net acceleration torque is reduced to minimum potentially zero. The criteria for small values of jerk cannot be realized. Long acceleration times cannot be tolerated. Starting currents is seven times more than the full load current during start-up and 3.5 times more when breakaway torque speed is reached. As a result the motor's temperature level increases. To cancel out the temperature effect, the standard starting time of the motor is defined and tried to keep in permitted vicinity, e.g., for a pole motor with rated value of 75 kW, the start-up time should not exceed to 18 seconds. With the squirrel cage motor, the starting length of a conveyor is very short. Reduced stator voltage starter of a squirrel cage motor is another method of starting the conveyor. In this method star/delta, reactor or reactor resistor starting equipment can be used. Hence the starting- torque and current is reduced; e.g., a star/delta is one third of direct on line starting. Slipring motor with rotor control equipment is a third method of starting that can be used to control the torque and starting current. The fourth method of starting is mechanical soft starters or variable speed units located across the motor and the gearbox.

In this work, an electronic Variable Speed Drive (VSD) method is used as the start-up and controlling of conveyor which utilizes the vector control pulse wide modulation control philosophy or direct torque control philosophy. In a downhill conveyor application, the VSD is capable of breaking the load on a continuous basis. The VSD allows energy flow from the DC busbar towards the supply network, thus helping to reduce overall energy cost[6]. With a VSD there is no limited start-up time per hour. A conveyor can be restarted while in motion without comprising the ideal conveyor starting requirements. The same is not valid for a fluid coupling application. VSD's on conveyor belts reduce maintenance cost. Belts speeds can be varied to operate at a constant speed; hence reducing the fluctuations. Running and capital costs of VSD's are noticeably lower than that of fluid couplings. It is important to identify drive efficiencies in a conveyor system. The power that is measured at the terminals of the electrical motor is not always the power that is consumed by the conveyor. The efficiency of the electrical motor, as well as that of the gearbox, must be taken into account in order to determine what the conveyor power consumption is. VSD efficiencies are rated at 98% and the power factor is more than 0.93 across the standard operating speed range. Harmonics current is one of the major disadvantages that are injected into the network by a VSD. Larger belts require more power and this has brought the need for larger individual drives and for multiple drives such as four drive units of 1000 kW each on one belt. After the power on a conveyor belt is calculated, a decision can be taken whether the belt should be fitted with single or multiple drives. VSD's are more efficient than the usual fix speed drives. Half the power consumed by motors before the belt reaches its rated speed is converted into heat in the resistors or couplings. Applied to the operating period, these starting losses represent an equivalent power loss of between roughly 1 and 2% of the rated output of the motor. Losses are present in every power transfer element in the entire conveyor system. Different drives experience-varying efficiencies. Today there are highly efficient motors available where efficiencies of up to 96% are available against the usual type of efficiency between 89 and 92%. Mechanical losses in the gearboxes and conveyor components contribute to a total loss of about 10%. The physical properties of the conveyor belt cover plates manufactured from rubber influence the level of conveying systems' energy consumption.

4. Modeling Conveyor Belt Energy Requirements and Loading Dynamics

A conveyor belt is used to transfer material from one place another or from one process to next, as a process in which primary electrical energy is converted into potential and movement energy. Such type of energy conversion mechanism formulates the relationship between energy consumption, conveyor physical parameters like speed and loading dynamics. The energy, in terms of the conveyor parameters, is the power integrated over a certain period of time[7]. The minimum energy requires running conveyor belt can be categorized as:

- The minimum energy required to run the empty conveyor under no load condition.
- The minimum energy required to move the material horizontally over certain defined distance under load conditions.
- The minimum energy required to uplift the material a certain defined height under load conditions.

4.1 Modeling the Energy Requirements to Run the Empty Conveyor

In order to run the empty conveyor under no load condition, the energy is required to move the different parts of the conveyor and to overcome friction in the conveyor system. The empty conveyor friction force can be calculated as follows:

$$F_1 = gCQ(L + L_O) \tag{1}$$

Where;

$F_1 = empty\ conveyor\ friction\ force\ (N)$

$g = gravitational\ acceleration = \frac{9.8m}{s^2}$

$c = conveyor\ friction\ factor$

$Q = factors\ representing\ conveyor\ moving$

$parts\ mass\ for\ center - to - center\ distance\ \left(\frac{kg}{m}\right)$

$L = horizontal\ projection\ of\ center - to -$

$center\ distance\ for\ incline\ or\ decline\ belts\ (m)$

$L_o = compensation\ length\ constant\ indepedent$

$of\ conveyor\ length\ (m)$

The power to overcome this friction force is:

$$P_{ec} = F_1 \times \frac{s}{1000} \quad or \quad P_{ec} = \frac{gCQ(L + L_O)S}{1000} \tag{2}$$

The energy consumption to run the empty conveyor under no load conditions is then the integral of the power over the period of time:

$$E_{ec} = \int_0^1 P_{ec}\, dt \quad \text{or} \quad E_{ec} = \int_0^1 \frac{gCQ(L + L_O)S}{1000} dt \quad \text{or}$$

$$E_{ec} = \int_0^1 \frac{gCQ(L + L_O)}{1000} S dt \tag{3}$$

Where;

$E_{ec} = power\ to\ run\ the\ empty\ convyor (kW)$

$t = time\ period\ where\ in\ the\ belt\ operated\ \left(\frac{mins}{hours}\right)$

4.2 Modeling the Energy Requirements to Move Conveyor Material Horizontally

A loaded conveyor belt whether it is marginally or fully loaded experiences an additional friction force due to the load on the belt. This friction force can be calculated as follows:

$$F_2 = gCQ(L + L_O)\left(\frac{T}{3.6S}\right) \tag{4}$$

Where; $F_2 = load\ friction\ force\ (N)$

$T = transfer\ rate\ in\ tons\ per\ hours\ \left(\frac{t}{h}\right)$

The power to transfer material horizontally can be obtained by the following Equation:

$$P_h = F_2 \times \frac{s}{1000} \quad \text{or} \quad P_h = gC(L + L_O)\left(\frac{T}{3.6S}\right) \times \frac{S}{1000}$$

$$P_h = gC\left(\frac{L + L_O}{3600}\right)T \tag{5}$$

The energy is then again the result of the integral of the power and results in the following:

$$E_h = \frac{gC(L + L_O)}{1000} t \tag{6}$$

Where;

$E_h = energy\ to\ transfer\ material\ on\ the$

$horizontally\ (kW)$

4.3 Modeling the Energy Requirements to Elevate or Lower Conveyor Material

The vertical component of force along the incline to lift or lower the load can be calculated as follows:

$$F_3 = \frac{gTH}{3.6S} \tag{7}$$

Where;

$F_3 = component\ of\ force\ along\ the\ incline\ (N)$

$H = the\ net\ change\ in\ elevation\ (m)$

The power required to elevate of lower the conveyor material can be calculated as:

$$P_l = \frac{gTH}{3600} \tag{8}$$

Where;

$P_l = power\ to\ lift\ load\ or\ power\ generated\ in\ lowering\ the\ load\ (kW)$

The energy applicable can be obtained by:

$$E_l = \frac{gTH}{3600}t \quad (9)$$

Where;

$P_l = power\ to\ raise\ load\ or\ generated\ in\ lowering\ the\ load\ (kWh)$

The conveyor system's total energy consumption is the sum of the energy consumption components and can be represented as follows:

$$E_t = E_{ec} + E_h + E_l \quad (10)$$

Where; $E_t = total\ energy\ consumption (kWh)$

5. Impact of Conveyor Speed on Conveyor Energy Consumption

In order to add value to the existing conveyor power models it is necessary to consider the effects of the conveyor speed in more detail. The conveying rate of a conveyor can be determined from the following parameters: 1. Loading of the belt (kg/m) and 2. Speed of the belt (m/s). The relationship between the transfer rate in tons per hour, the loading on the belt and the speed of the belt is the following:

$$T = 3.6MS \quad (11)$$

Where;

$T = transfer\ rate\ of\ the\ conveyot\ \left(\frac{t}{h}\right)$

$M = mass\ of\ the\ material\ one\ one\ meter\ conveyor\ (kg)$

$S = conveyor\ speed\ \left(\frac{m}{s}\right)$

If all parameters are kept constant then only the energy consumption of the empty conveyor system is affected. From the above it can be seen that the energy to move the material horizontally, as well as to elevate the material $(E_h\ and\ E_L)$ is independent of the speed. However, one of the parameters, the conveying rate (T), will change if the material is fed through a normal channel or static gate; this is due to the resultant change of speed. This concept should be considered in the conveyor energy study. When the material is fed onto the belt through a channel or static gate, the material forms a constant profile. If the speed of the conveyor belt is increased, the profile on the belt stays more or less the same, but the rate in which the material is fed onto the belt increases. When the cross sectional load area is taken at any given speed it will be the same. The area is a function of the belt design, for example, for a 300mm belt with 20^o rolls, the area for slumping material is $0.003m^2$ and for 30^o degree rolls it is $0.004m^2$. The relationship between material mass per meter, the speed of the conveyor and the transfer rate can be obtained from the following Equation:

$$T = \frac{1000}{60} M \times S \quad (12)$$

From the above discussion it is possible to change the energy conversion model of the conveyor in order to reflect the influence of the speed of the conveyor on the conveyor power. Figure 2 shows the influence of belt speed on the different power components if the transfer rate (tons per hour) is kept constant. The speed variation influence can be recognized in the component P_{ec} which represents the power necessary to run the empty conveyor, and which is proportional to the speed of the conveyor. The other components P_h and P_l (power required to move load horizontally and vertically) have no influence on the conveyor speed. This observation characterize that when conveyor is running under full load conditions it is more energy efficient as compared to when conveyor is running under marginally or unloaded conditions. This fact should be taken into consideration when conveyor cost efficiency is required to be investigated. In Figure 3 illustrate the case of power consumption of the same conveyor when running at constant speed for the one scenario and at adapted speed to match the conveyor material load in the other scenario. The closer the conveyor running to full load condition, the smaller is the difference between the constant speed scenario and the adapted speed scenario. In practice the speed of the conveyor will have a bottom limit due to conveyor operation characteristics. The speed will thus be adapted only to these values in cases of very low flow rate. In many applications, conveyor belts are running empty for long periods of time, by using our proposed model the energy losses can be calculated and quantified. In cases where the conveyor belt is over-designed, the same principle is valid. The power to run the empty conveyor makes provision for a larger load than is needed in the application and therefore the material transfer via the conveyor is not as efficient as it could be. This problem can be overcome by implementation of methods to ensure that the belt is equally loaded, in other words, to ensure that the kilogram per meter on the belt is constant. This can be done by either implementing speed control on the conveyor belt or by installing a buffer in front of the conveyor to take up all the fluctuations of the feed and discharge at a constant loading on the conveyor. The conveyor belt can even be stopped and started when the bin reaches a specific level in order to run the conveyor fully loaded.

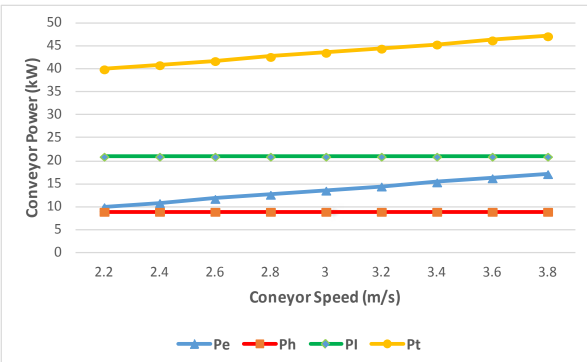

Figure 2. Influence of conveyor speed on power with constant transfer rate.

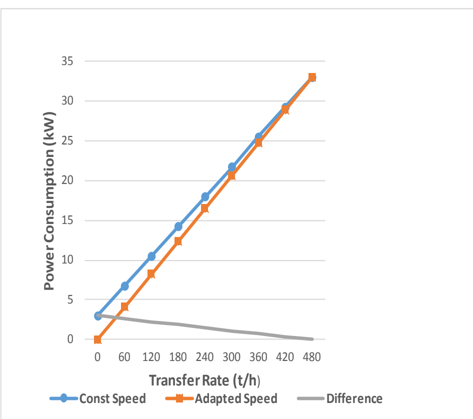

Figure 3. Influence of transfer rate adapted speed on conveyor power.

6. Conclusion

Conveyor belts are the material handling equipment that is widely used in industry to move the material from the one place to another or from one process to next process. The manufacturing companies are continuously looking for to reduce the operating expenditure by reducing the electricity cost by developing the energy efficient products. The concept of improving the energy consumption and system efficiencies by controlling multiple drive units is of great interest recently. In this work, efficiency of a conveyor system is evaluated by integrating all the factors that have an influence on the electricity costs of the conveyor system. Using VSD mechanism, an energy efficient conveyor system is developed by physically modeling the conveyor belt speed and loading dynamics mechanism. For the energy efficient conveyor system, different start-up of conveyor methods are evaluated as a baseline reason of generating the motor torque in comparison to rated voltage as an optimal energy management tool to develop a relationship across the power consumption, conveyor belt speed and belt loading dynamics.

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