Application of Resistance Energy Model to Optimising Electric Power Consumption of a Belt Conveyor System

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Abstract: - Driven by constantly increasing energy demands, prices, environmental impact caused by carbon dioxide emissions and global warming, efficient use of energy is gaining grounds in both public and private enterprises. The energy consumption of belt conveyors can be lowered using energy modelling techniques. In this research, a resistance-based mathematical energy model was utilised in the electrical energy efficiency optimisation of the troughed, inclined belt conveyor system taking into account indentation rolling resistance, bulk solid flexure resistance and secondary resistance as they together contribute 89% resistance to motion. An optimisation problem was formulated to optimise the electrical energy efficiency of the belt conveyor system and subsequently solved using the "fmincon" solver and interior point algorithm of the MATLAB optimisation toolbox. Verification results of the utilised model showed that it performed quite better as compared to the more recent analytical energy model for long belt conveyors. Analysis of simulation results showed that for the same given operating capacities, an average energy saving of about 7.42% and an annual total cost savings of Gh¢ 5, 852, 669.00 (USD 1, 083, 827.59) for a 2592-hour operation can be achieved when the used model and optimisation technique are employed over the constant speed operation.

Keywords: - Belt conveyor system; Energy model; Optimising energy efficiency; Modelling; Simulation

1. Introduction

The rising cost of doing business has necessitated companies to search for better ways of minimising expenses that affect competitiveness and the bottom line. Automating certain functions in manufacturing and material handling does improve productivity and efficiency creating some cost savings [1]. A growing area of concern is the increasing energy cost. Cost of energy forms a large part of the operational cost of belt conveyor systems and according to [2], this constitutes 40% of the operational cost. Conveyor equipment, aside of gravity conveyors, require motors and other equipment that use electricity for power [1]. Saving energy of belt conveyor systems offers a lot of benefits aside of the cost savings. It increases the energy reserves and curbs emissions of carbon dioxide [3].

A belt conveyor is a piece of equipment used to transport materials or products from one place to another. It converts electrical energy into mechanical motion [4], [5]. Belt conveyors are widely used for handling bulk material over short to medium conveying distances because of their high efficiency of transportation as compared to other methods of transportation [5], [6]. They are largely used in the mining industry, in manufacturing, at bulk terminals, in cement plants, power plants and chemical production industries for the transportation of goods and services [7]. A typical conveyor system consists of the tail pulley, idler, belt, take-up and drive pulley [6], [7], [8].

Material handling is one of the important phenomena in industry. Belt conveyors are being preferred in most parts of material handling systems because of their high efficiency of transportation. However, they come with their own problems of electrical energy consumption. According to [1], conveying equipment consume up to 50% of a facility's energy usage and account for nearly 70% of electrical load in an industrial facility [1]. This presents both a challenge and an opportunity for energy savings. Driven by constantly increasing energy demands, prices, environmental impact caused by carbon dioxide emissions and global warming, efficient use of energy is gaining grounds in both public and private enterprises [9]. The material handling industry and for that matter, a belt conveyor system is no exception. The electrical energy consumption of a belt conveyor is dependent on the drive's speed and the resistances to motion. The resistances to motion include indentation rolling resistance, bulk solid flexure resistance, secondary resistance, idler roll rotating resistance and belt flexure resistance [10], [11]. Fig. 1 gives a diagram of a belt conveyor system with corresponding values of motion resistances [11], [12], [13].

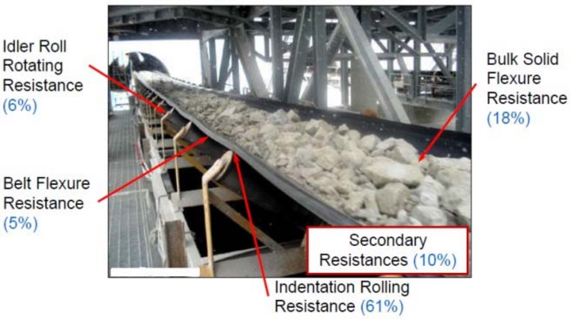

Fig. 1. A Belt Conveyor System with Critical Values of Motion Resistances

According to research conducted by [13], the number of publications considering material handling efficiency with relevance to energy management and savings is increasing rapidly [3], [13]. Fig. 2 shows the literature dedicated to energy savings measures over 17 years [13].

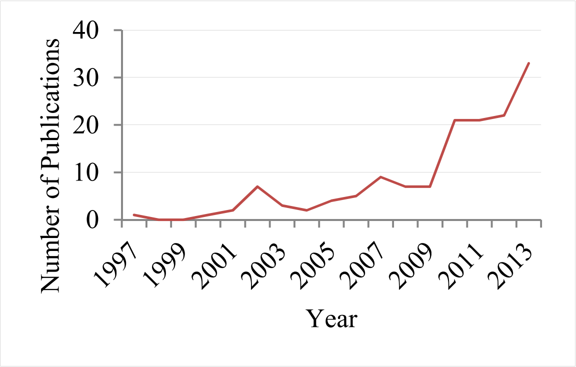

Fig. 2. A Graph of Energy Efficiency Publications over Time

There are two main types of energy models for belt conveyor systems: the resistance-based energy model and the energy conversion-based model. The resistance-based energy model is based on more accurate and complex calculations meant for electrical energy consumption optimization while the energy conversion-based model methodology is based on simple and less accurate calculations. An analytical energy model tries to lump all parameters of the resistance energy model into four coefficients, which results in less accuracy. These energy models originate from well-known standards or specifications, such as ISO 5048, DIN 22101, JIS B 8805 and CEMA. The existing energy models are suitable for design purposes and can hardly be used for optimisation calculation [5], [6], [8], [14], [15], [16].

Steady state operation energy models have been developed by some researchers and are reported in the literature. [14] presented a new energy calculation model characterised by two compensation length variables, along with a comparative study of the existing energy models. [5] adopted the analytical energy model to develop a model-based optimisation approach to improving the energy efficiency of belt conveyors at the operational level. [15] developed a new energy model of a DC motor driven belt conveyor based on an adaptive observer where a parameter estimation algorithm was derived. [16] developed a parametric energy model for energy management of long belt conveyors which use two-parameter power equation and a partial differential equation to capture the variable amount of material mass per unit length throughout the belt length.

These existing energy models are mostly built under design conditions. When a belt conveyor operates away from its design condition, inevitably, these models will result in large differences in energy calculation. In practice, most belt conveyors are not working under the design conditions and some of them are working far away from their design conditions, as for instance, some belt conveyors even operate under no load.

Dynamic models of belt conveyors are also studied in the literature. [17] developed a dynamic model of belt conveyors with multiple drives. [18] investigated the modelling of long belt conveyors. They presented a mathematical model that allows analysis of the dynamic states of a belt conveyor. Another dynamic model based on the spring-mass model, was built by [19]. These dynamic models focus mainly on the analysis of transient behaviour of belt conveyors, i.e. they are typically not used for energy optimisation.

Use of improved belt equipment, proper maintenance culture, and energy efficiency based on indentation rolling resistance reduction have been reported in the literature to increase energy efficiency of belt conveyor systems [2], [5], [11].

Switching control and Variable Speed Drive (VSD) based controls are also proposed to improve energy efficiency of belt conveyors [2], [5], [10].

The implemented projects of the energy saving methods focus only on lower level control loops or an individual belt conveyor without operational considerations at the system level.

This research paper gives focus to utilisation of resistance energy model taking into account indentation rolling resistance, bulk solid flexure resistance and secondary resistance as they together contribute 89% resistance to motion. Field studies and model development approach for the drive system are given consideration.

The rest of the paper is organised as follows:

2. Field studies

A number of belt conveyors at the operations of a mining company were studied. During the studies, the electric power consumed, belt speed, and feed rate of the 12-conveyor system of the mine were recorded at different time intervals with the aid of the field instruments. The electric power consumed was measured against the belt speed when the feed rate was held constant at T = 65.4 t/h. Also, the electric power consumed was measured against the feed rate when the speed was held constant at v = 3.7 m/s.

3. Data collection and analysis

Data on the belt conveyor system of a mining company located in the Tarkwa-Nsuaem municipality of the Western region of Ghana were collected and analysed. The various conveyors studied were grouped into two as overland conveyors and crusher conveyors. The data collected on each conveyor are tabulated as shown in Table 1. The collected data aided the calculation of model parameters C_1 and C_2 as indicated in Table 2. Also, instruments such as electrical energy meter, belt motion monitor and belt weightometer were employed to aid in the determination of the electric motor output power (P_M), belt speed (v) and belt load carrying capacity (T), respectively.

4. Resistance energy model

Our focus is to utilise a resistance-based energy model and also a model for the energy cost of a belt conveyor system in order to minimise electrical energy consumption and operating cost of the belt conveyor system. The resistance- based energy model is obtained from mathematical calculations of mechanical resistances of the belt conveyor. Under stationary operating conditions, the energy consumption of belt conveyors is mainly determined by the resistances to motion of the belt conveyor. With nominal values of system settings, resistance of the belt conveyor can be calculated. ISO 5048, DIN 22101 and CEMA [20], [21], [22] distinguish four components that make up the total mechanical resistance.

The primary or main resistance component, F_H consists of various resistances including flexing resistances of the conveyor belt as well as the bulk solid material and the indentation rolling resistance of the idlers.

The secondary resistance, F_N is the resistance force that is due mainly to frictional and acceleration forces in the feeding area.

The slope/gradient resistance, F_{St} is the resistance due to inclination of the belt conveyor.

The special resistance component, F_S is the resistance for special designed belt conveyors, e.g. situations where, special curves are involved. The resistance energy model is given by Equation (1) [10-17].

$$F_U = F_H + F_N + F_{St} + F_S \qquad (1)$$

The diagrammatic model of a troughed, inclined belt conveyor system modified after [16], is shown in Fig. 3. It is powered by an electric motor-driven system and supported by a system of pulleys. It carries the bulk material on top of the troughed surface of the belt. The troughed structure of the belt is maintained by sets of evenly spaced carrying and return idlers. The appropriate idler spacing is determined during the design stage as recommended by international standards such as CEMA, JIS, ISO and DIN 22101 [21], [22] to avoid excessive belt sag and potential spillages. This ensures that the cross-sectional area of the belt is fairly constant. The belt is usually fitted with accessories such as a feed chute at the tail end and a scraper below the head end.

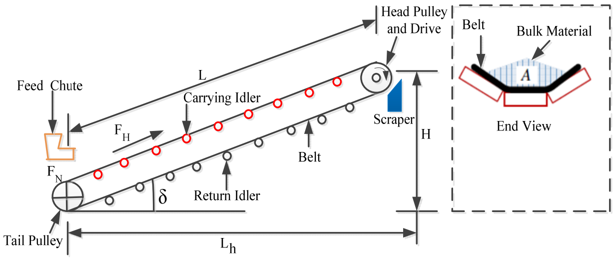

Fig. 3. Model of the troughed inclined belt conveyor system

The main focus is to utilise a resistance energy model taking into account indentation rolling resistance and bulk solid flexure resistance which together largely form the main resistance, F_H and secondary resistance, F_N but since the belt conveyor system under study is inclined, the slope/gradient resistance component must be considered as well.

The free body diagram illustrated by the primary resista- nce of the belt conveyor is given by Fig. 4.

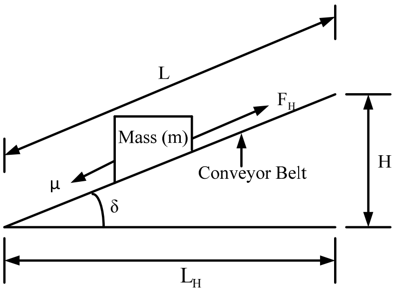

Fig. 4. Illustration of Primary Resistance

The resistance energy model is obtained as follows:

$$F_H = \mu.m.g \qquad (2)$$

$$m = \mathrm{L\,g}\left[Q_{\mathrm{R0}} + Q_{\mathrm{RU}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] \quad (3)$$

$Q_{\mathrm{RR}}$and Q_B represent the unit mass of rotating rolls and the unit mass of the belt respectively.

In the belt conveyor world, the friction coefficient μ is replaced by the letter f [23]. Therefore, the main resistance is given in Equation (4) [20], [22], [23] as:

$$F_H = \mathrm{f\,L\,g}\left[Q_{\mathrm{R0}} + Q_{\mathrm{RU}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] \quad (4)$$

Let: $Q_{\mathrm{RR}} = Q_{\mathrm{R0}} + Q_{\mathrm{RU}}$

Then, $\mathrm{F_H}$ is expressed as in Equation (5).

$$F_H = \mathrm{f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] \quad (5)$$

According to experiments [10], [22], [23], the secondary resistance can be expressed with adequate correctness for belt conveyors with L > 80 m by Equation (6).

$$F_N = (\mathrm{C}\text{-}1)\,\mathrm{F}_H \quad (6)$$

where, C = conveyor length coefficient

Now, by adding Equation (5) and Equation (6), we obtain Equation (7) as follows:

$$\begin{aligned} F_H + F_N &= \mathrm{f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] + (\mathrm{C}\text{-}1)\,\mathrm{F}_H \\ &= \mathrm{f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] + (\mathrm{C}\text{-}1)\left(\mathrm{f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right]\right) \\ &= \mathrm{f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] + \mathrm{C\,f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] - \mathrm{f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] \\ &= \mathrm{C\,f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] \end{aligned} \quad (7)$$

The coefficient, C in Equation (7) depends on the length of the conveyor and can be found in either graphs or in tables.

Neglecting the special resistance component, $\mathrm{F_S}$ since it is too small, the total resistance to motion can be found by adding the slope resistance, $\mathrm{F_{St}}$ to Equation (7) to give Equation (8).

$$F_T = F_H + F_N + F_{\mathrm{St}} = \mathrm{C\,f\,L\,g}\left[Q_{\mathrm{RR}} + \left(2\mathrm{Q}_B + Q_G\right)\mathrm{Cos}\,\delta\right] + \mathrm{g\,H\,Q}_G \quad (8)$$

The unit mass of transporting material, Q_G can also be calculated using Equation (9) [20], [22].

$$Q_G = \frac{T}{3.6 \times v} \quad (9)$$

Q_G is obtained from the product of the cross-sectional area (A) of the material conveyed and the material density (ρ). It is therefore right for one to say that the total resistances to motion of the belt conveyor are dependent on the amount of material that the conveyor belt is carrying, specified as Q_G since $Q_{\mathrm{RR}}$and Q_B which represent the unit mass of rotating rolls and the unit mass of the belt respectively remain fairly constant whiles the conveyor system is installed. Therefore, $\mathrm{F_T}$ can be written as in Equation (10).

$$F_T = \mathrm{f}\,(Q_G) = \mathrm{C\,f\,L\,g}\,(Q_{\mathrm{RR}} + 2\mathrm{Q}_B\mathrm{Cos}\,\delta\,) + (\mathrm{C\,f\,L\,g\,Cos}\,\delta + \mathrm{g\,H})Q_G \quad (10)$$

The mechanical power of the belt conveyor can be calculated using Equation (11) [20], [22].

$$P_T = \mathrm{F}_U \times \mathrm{v} \quad (11)$$

Now, based on the mechanical power of the conveyor it is possible to calculate the electric power of the drive motor which sets the belt into motion using Equation (12) [20], [22].

$$P_M = \frac{P_T}{\eta} \quad (12)$$

where, $\mathrm{P_M}$ = electric power drawn by the drive motor in kW

From Equation (12) the electric power of the drive motor is given as:

$$P_M = \frac{P_T}{\eta} = \frac{F_T.\mathrm{v}}{\eta} = \frac{\mathrm{C\,f\,L\,g}\,(Q_{\mathrm{RR}} + 2\mathrm{Q}_B\mathrm{Cos}\,\delta\,).\mathrm{v}}{\eta} + \frac{(\mathrm{C\,f\,L\,g\,Cos}\,\delta + \mathrm{g\,H})\,Q_G.\mathrm{v}}{\eta} \quad (13)$$

Let: $C_1 = \frac{\mathrm{C\,f\,L\,g}\,(Q_{\mathrm{RR}} + 2\mathrm{Q}_B\mathrm{Cos}\,\delta\,)}{\eta}$ and $C_2 = \frac{(\mathrm{C\,f\,L\,g\,Cos}\,\delta + \mathrm{g\,H})}{\eta}$

then Equation (13) reduces to Equation (14). $\mathrm{C_1}$ and $\mathrm{C_2}$ are physical parameters that can be calculated for a given belt conveyor system [14], [15], [16].

$$P_M = C_I v + C_2\,\mathrm{v}\,\mathrm{Q}_G = C_I\,\mathrm{v} + C_2\,\mathrm{v}\frac{T}{3.6 \times v} = C_I\,\mathrm{v} + C_2\frac{T}{3.6} \quad (14)$$

Therefore, the belt conveyor's electric power consumption can be expressed as a function of ν and T as given in Equation (15).

$$P_M = \mathrm{f}\,(\mathrm{v}\,,\mathrm{T}) = C_1\,\mathrm{v} + C_2\frac{T}{3.6} \quad (15)$$

Thus, the total electrical energy consumed can be calculated by integrating Equation (15) over a given time interval t_0 to t_1. This is given in Equation (16).

$$E_{\mathrm{ec}}(t_0, \mathrm{t_1}) = \int_{t_0}^{t_1} \mathrm{f}\,(\mathrm{v}\,(t), \mathrm{T}\,(t))\mathrm{dt} = C_1 \int_{t_0}^{t_1} \mathrm{v}\,(t)\mathrm{dt} + \frac{C_2}{3.6}\int_{t_0}^{t_1} \mathrm{T}\,(t)\mathrm{dt} \qquad (16)$$

The total energy cost can therefore, be obtained by multiplying the total electrical energy consumed by the TOU tariff function, U (t) as given in Equation (17).

$$E_c(t_0, \mathrm{t_1}) = \int_{t_0}^{t_1} \mathrm{f}\,(\mathrm{v}\,(t), \mathrm{T}\,(t))\ \ (\mathrm{U}\,(t))\mathrm{dt} = C_1 \int_{t_0}^{t_1} \mathrm{v}\,(t)\ \mathrm{U}\,(t)\mathrm{dt} + \frac{C_2}{3.6}\int_{t_0}^{t_1} \mathrm{T}\,(t)\ \mathrm{U}\,(t)\mathrm{dt} \quad (17)$$

For ease of discrete-time numerical analysis, the energy consumption function of Equation (16) and the cost function Equation (17) are discretised.
Let the sampling time be given as in Equation (18).

$$t_s = \frac{t_1 - t_0}{N} \qquad (18)$$

where, N = number of samples
Now, the discrete form of the total energy consumption and total energy cost can be obtained as in Equation (19) and Equation (20).

$$E_{\mathrm{ec}} = \sum_{j=1}^{N} \mathrm{f}\,(\nu_j, \mathrm{T}_j) t_s$$

(19)

$$E_c = \sum_{j=1}^{N} \mathrm{f}\,(\nu_j, \mathrm{T}_j) P_j t_s$$

(20)

E_{ec} and E_c are performance indicators, which are to be employed as the objective functions for optimisation.

5. Optimisation of the electrical energy efficiency of the belt conveyor system

Many a time, belt conveyors work under reduced or minimal feed rates. Sometimes, they even run on no load due to mismatched feeds. The mismatch between speed and the feed rate exists because in practice, conveyors tend to operate at slightly below full capacity. They are usually oversized during design in anticipation of capacity expansions and sometimes to standardise component sizes in an effort to lower maintenance costs [24]. It could also be due to material blockages. In mining applications, conveyors are at times loaded by an excavator resulting in an uneven loading of the belt, so that the overall material flow rate is 50% to 70% of full capacity [25]. In this research therefore, we try to optimise the electrical energy efficiency of the belt conveyor by matching belt speed to the input material feed rate in order to maximise the mass of material conveyed per unit length and, consequently, per unit of energy. To achieve this, the electric power is employed as the objective function for minimisation formulated as follows:

$$\begin{array}{ll} \text{Min} & P_M = \mathrm{f}\,(\nu, \mathrm{T}) \\ \text{Subject to} & \mathrm{T_{min}} \le \mathrm{T} \le \mathrm{T_{max}} \\ & \nu_{\mathrm{min}} \le \nu \le \nu_{\mathrm{max}} \end{array}$$

where, f (v, T) = function of electric power drawn by the
drive motor
ν_{min}= minimum belt speed in m/s
ν_{max}= maximum belt speed in m/s
$\mathrm{T_{min}}$ = minimum belt feed rate in t/h
$\mathrm{T_{max}}$ = maximum belt feed rate in t/h

5.1. Computer simulations of the belt conveyor system

Simulations of the optimisation problem were carried out in MATLAB environment using the optimisation toolbox. It provides functions for finding parameters that minimise or maximise objectives while satisfying constraints. The toolbox includes solvers for linear programming, mixed-integer linear programming, quadratic programming, nonlinear optimisation, and nonlinear least squares. These solvers can be used to find optimal solutions to continuous and discrete problems, perform trade-off analyses, and incorporate optimisation methods into algorithms and applications. The “fmincon” solver finds a minimum of a constrained multivariable function using the interior point algorithm. It finds the minimum of a problem specified by:

$$\min_{\mathrm{x}} \mathrm{f(x)}\ \text{such that} \begin{cases} \mathrm{c(x)} \le 0 \\ \mathrm{ceq(x)} = 0 \\ \mathrm{A} \bullet \mathrm{x} \le \mathrm{b} \\ \mathrm{Aeq} \bullet \mathrm{x} = \mathrm{beq} \\ \mathrm{lb} \le \mathrm{x} \le \mathrm{ub} \end{cases}$$

where, b and beq = vectors
A and Aeq = matrices
c(x) and ceq(x) = functions that return vectors
f(x) = function that returns a scalar
lb and ub = the lower boundary and upper
boundary and can be passed as vectors
or matrices.

f(x), c(x), and ceq(x) can be linear or nonlinear functions of x.

6. Results and discussions

This section presents the results and discussions of the research. The results from field studies and computer simulations of the belt conveyor system are discussed.

6.1. Field study results

The results from the field studies are presented in Fig. 5 and Fig. 6.

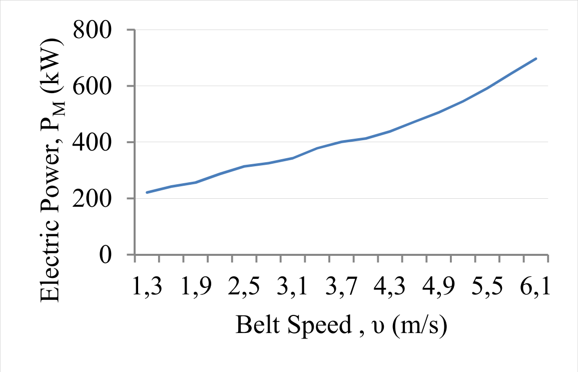

Fig.5 Graph of Electric Power Consumption against Belt Speed at Constant Feed Rate of T = 65.4 t/h

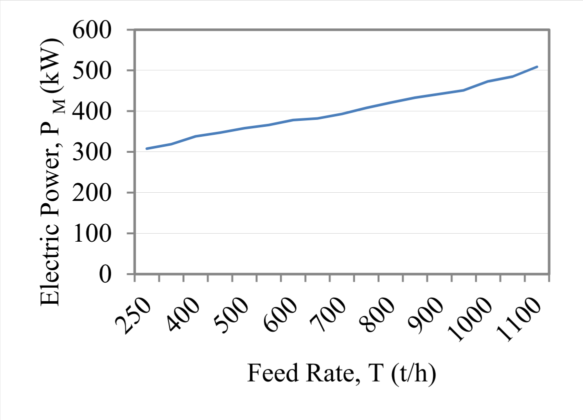

Fig. 6 Graph of Electric Power Consumption against Feed Rate at Constant Belt Speed of v = 3.7 m/s

6.2. Results of computer simulations for optimisation

The computer simulations were meant to find the optimal solutions of the system of belt conveyors for belt speed and feed rate both varying from minimum to maximum values i.e., $v_{\min} \le v \le v_{\max}$ and $T_{\min} \le T \le T_{\max}$ respectively. This was necessary to improve the operation efficiency of the belt conveyors by matching belt speed to the input material feed rate in order to maximise the mass of material conveyed per unit length and, consequently, per unit of energy.

The optimisation problem was solved repeatedly for each of the twelve conveyors when the feed rate was varied from 100 t/h to 2000 t/h. Results of the plot of the feed rate at conveyor base case operating speed of 4.5 m/s which is constant and at the optimised speed, v varying from 2 m/s to 6 m/s against electric power consumption on the same graph for the twelve conveyors are given in Fig. 7 to Fig. 18. The minimum and maximum speed values selected here were based on belt conveyors manufacturer's manual.

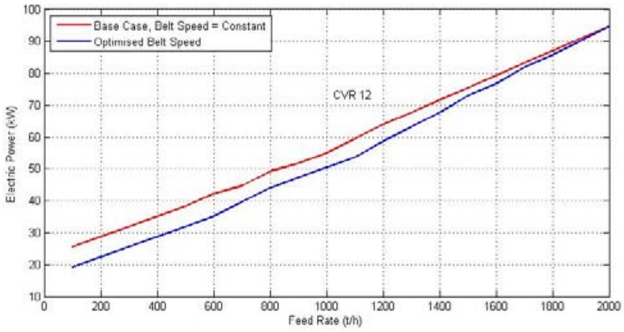

Fig. 7 Computer simulation results of optimisation for the crusher conveyor CVR 12

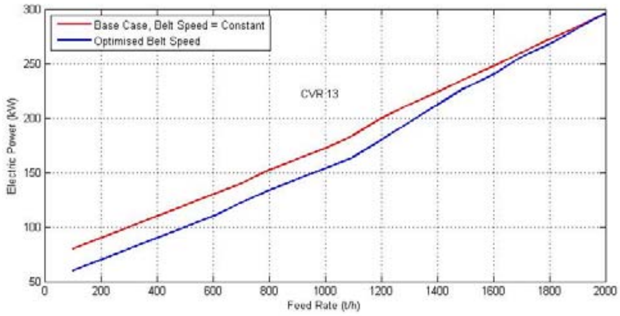

Fig. 8 Computer simulation results of optimisation for the crusher conveyor CVR 13

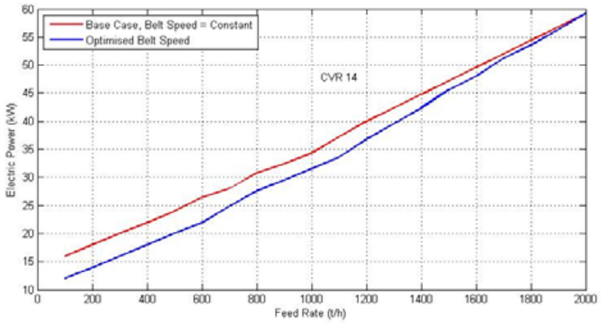

Fig. 9 Computer simulation results of optimisation for the crusher conveyor CVR 14

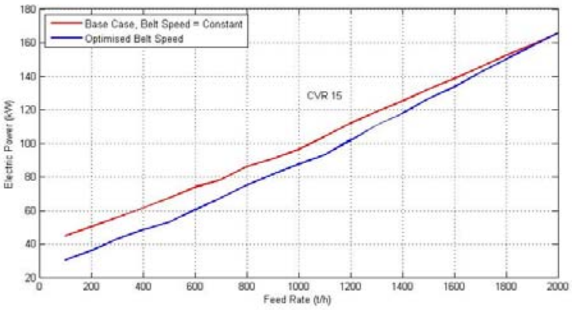

Fig. 10 Computer simulation results of optimisation for the crusher conveyor CVR 15

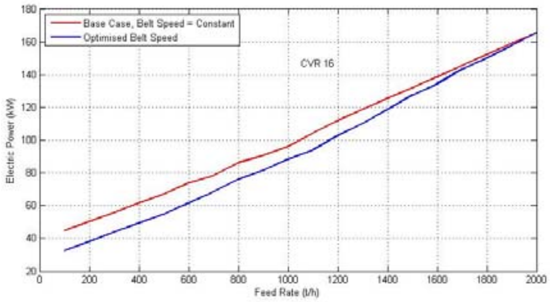

Fig. 11 Computer simulation results of optimisation for the crusher conveyor CVR 16

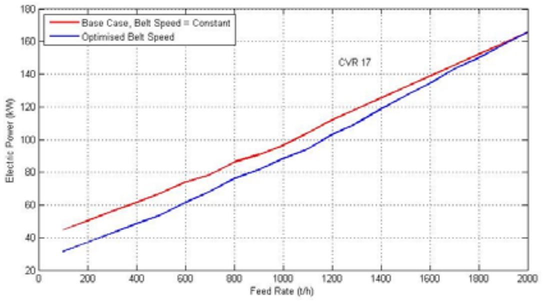

Fig. 12 Computer simulation results of optimisation for the crusher conveyor CVR 17

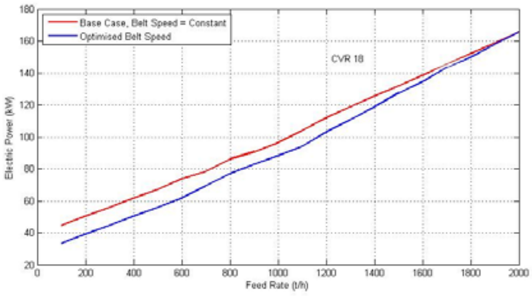

Fig. 13 Computer simulation results of optimisation for the crusher conveyor CVR 18

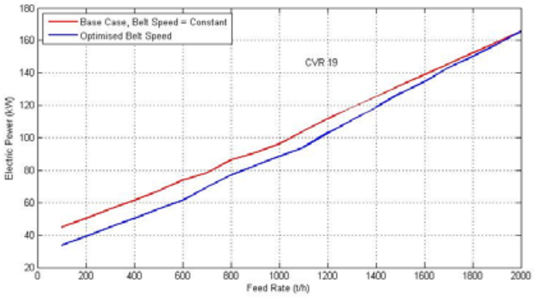

Fig. 14 Computer simulation results of optimisation for the crusher conveyor CVR 19

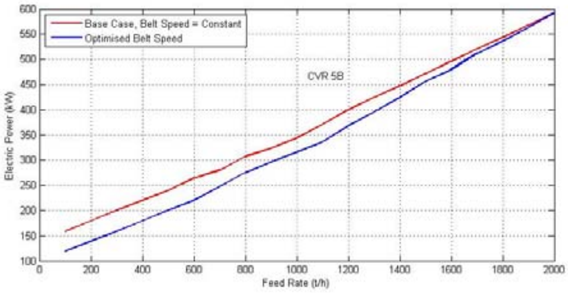

Fig. 15 Computer simulation results of optimisation for the overland conveyor CVR 5B

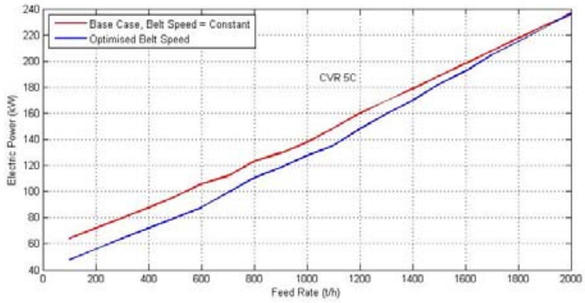

Fig. 16 Computer simulation results of optimisation for the overland conveyor CVR 5C

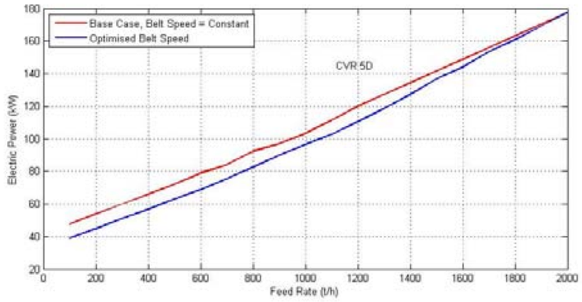

Fig. 17 Computer simulation results of optimisation for the overland conveyor CVR 5D

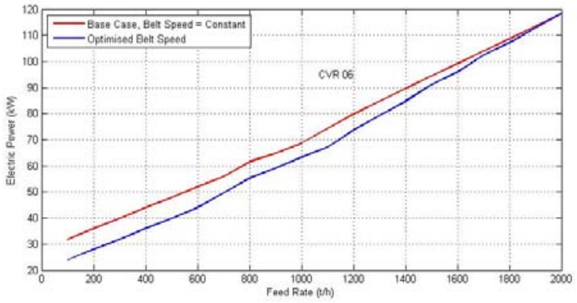

Fig. 18 Computer simulation results of optimisation for the overland conveyor CVR 06

6.3. Electrical energy and cost savings analyses

The power savings for each conveyor for given operating capacities were calculated by summing the differences in power consumption between the optimised case and the base case at each feed rate point. The percentage savings were calculated using Equation (17).

$$\%\,\mathrm{kW} = \frac{\sum(\text{Base case power} - \text{Optimised case power at each feed rate point})}{\sum \text{Base case power at each feed rate point}} \times 100 \quad (17)$$

The results of the calculations for each of the twelve conveyors are given in Table 3.

Table 3 Power Savings for the Twelve Conveyors

SN	**Conveyors**	**Power Savings (kW)**	**%Power Savings**
1	CVR 12	85.96	7.31
2	CVR 13	286.00	7.79
3	CVR 14	53.60	7.29
4	CVR 15	176.20	8.56
5	CVR 16	159.16	7.73
6	CVR 17	164.68	8.00
7	CVR 18	150.00	7.28
8	CVR 19	150.20	7.29
9	CVR 5B	536.60	7.30
10	CVR 5C	208.50	7.09
11	CVR 5D	136.40	6.18
12	CVR 06	106.40	7.24
Average % Savings			**7.42**

Given that the belt conveyor is operated 30% of the available time of 360 days per year at 24 hours per day, the production time per year can be computed using Equation Production time per year,

$$t = \frac{30}{100} \times 360 \times 24 \text{ hrs} = 2592 \text{ hrs} \qquad (18)$$

The electrical energy savings per year can therefore be calculated using Equation (18).

Electrical energy savings per year = kW x t

Given the current electricity tariff of Gh¢ 1.02 per kWh [26], the cost of electricity savings of each conveyor can be found by multiplying the electrical energy savings by the tariff. Calculations of the electrical energy savings and the corresponding cost savings per year of each conveyor are tabulated in Table 4.

Table 4 Electrical Energy and Cost Savings for the Twelve Conveyors

SN	**Conveyors**	**Power Savings (kW)**	**Electrical Energy Savings/Year (kWh)**	**Cost Savings/Year (Gh¢)**
1	CVR 12	85.96	222808.30	227264.50
2	CVR 13	286.00	741312.00	756138.20
3	CVR 14	53.60	138931.20	141709.80
4	CVR 15	176.20	456710.40	465844.60
5	CVR 16	159.16	412542.70	420793.60
6	CVR 17	164.68	426850.60	435387.60
7	CVR 18	150.00	388800.00	396576.00
8	CVR 19	150.20	389318.40	397104.80
9	CVR 5B	536.60	1390867.00	14186850
10	CVR 5C	208.50	540432.00	551240.60
11	CVR 5D	136.40	353548.80	360619.8
12	CVR 06	106.40	275788.80	281304.60
Total Savings		**31104.00**	**5737910.00**	**5 852 669.00**

6.4. Discussions

This section of the paper discusses the following: field study results, the results of computer simulations for optimisation and cost savings.

6.4.1 Discussions of field study results

Field studies results revealed that at a constant feed rate of 65.4 t/h, the belt speed and the electric power consumption of the conveyor maintain a fairly linear relationship shown by the graph in Fig. 6. Moreover, given a constant speed of 3.7 m/s of the belt conveyor, the electric power consumption and the feed rate show a more linear correlation compared to the case of constant feed rate. Running the belt conveyor at a reduced speed while achieving the same purpose can give significant energy savings. From these analyses, it is important to note that running the belt conveyor at a fixed speed whiles the feed rate is varying can waste electric power. It becomes imperative therefore, to match belt speed to the feed rate in order to save energy.

6.4.2. Discussions of results of computer simulations for optimisation

From Fig. 7 to Fig. 18, it is clear that the belt conveyors consume less power when running at optimised belt speed from 2 m/s to 6 m/s than when operated at the constant belt speed of 4.5 m/s. It is also clearly shown that the further the feed rate is reduced; the more energy can be saved through the optimisation of the belt speed. The graphs look similar though, but analyses of the results show that each of the conveyors has slightly different power improvement levels. Conveyor CVR 15 for example, appears to have performed quite better than all the other conveyors with power savings of 8.56%. This is quite obvious due to its high effective efficiency which is 0.86 coupled with its relatively low friction coefficient value of 0.023. Conveyors CVR 5C and CVR 5D gave quite low power savings of 7.09% and 6.18% respectively as compared to the rest. This was attributed to low effective efficiencies which are 0.76

and 0.73 respectively and high coefficients of friction 0.026 each. For low power requirements, a typical overland conveyor requires efficiency values ranging from 0.80 to 0.98 and a friction coefficient ranging from 0.022 to 0.025 [10].

6.4.3. Discussions of results of cost savings

The cost savings analysis of each of the twelve conveyors given a total production time of 2592 hours per year and a current electricity tariff of Gh¢ 1.02 per kW for non-residential consumers who fall in the range of 600 kWh and above have been presented in Table 2. The analysis showed that AGA Iduapriem Mine will be saving a total electrical energy of 5737910.00 kWh and a corresponding cost of Gh¢ 5 852 669.00 when the twelve conveyors are optimally operated in terms of belt speed matching to feed rate for 2592 hours over a period of one year.

7. Conclusion

A mathematical energy model for electrical energy efficiency optimisation of belt conveyor system was successfully utilised. It was established that to improve the operation efficiency of the belt conveyor, it is necessary to operationally match belt speed to the feed rate. Furthermore, from the findings the following conclusions hold valid:

1. Belt conveyors consume a considerable amount of the total electrical energy supply and can be lowered using energy models and optimisation techniques.
2. For optimal performance of the belt conveyors with regard to electric power consumption, the belt speed should be varied within the maximum and minimum limits commensurate with the feed rate.
3. Electric power consumption and operational cost of belt conveyors highly depend on the belt speed, feed rate, effective efficiency and length of the belt conveyor.
4. The analytical energy model is more appropriate for short belt conveyor analyses while the proposed model is desirable for long belt conveyors.
5. A considerable amount of power and cost savings for all the twelve belt conveyors are achievable when the used model and optimisation technique are employed over the fixed speed operation.

8. Future work directions

The following constitute future work as an extension to this research:

1. The used model should be improved to perform better at shorter lengths. This approach is likely to improve the calculation of the primary and secondary resistances' contributions to the overall power requirement of belt conveyors.
2. A comparative electricity consumption and operational cost analyses of belt conveyor against haulage truck systems in mining operations should be conducted for possible optimisation.

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Table 1 Data on Belt Conveyors

Parameter	**Crusher Conveyors**								**Overland Conveyors**			
	CVR 12	**CVR 13**	**CVR 14**	**CVR 15**	**CVR 16**	**CVR 17**	**CVR 18**	**CVR 19**	**CVR 5B**	**CVR 5C**	**CVR 5D**	**CVR 06**
Motor kW	45	160	160	160	160	160	160	160	200	160	160	160
Motor rpm	1475	1485	1485	1485	1485	1485	1485	1485	1485	1485	1485	1485
Motor efficiency (η_m)	0.95	0.91	0.89	0.94	0.89	0.95	0.89	0.89	0.88	0.91	0.87	0.89
Drive efficiency (η_d)	0.85	0.90	0.89	0.92	0.90	0.86	0.85	0.87	0.90	0.83	0.84	0.90
$\eta = \eta_m \times \eta_d$	0.81	0.82	0.79	0.86	0.80	0.82	0.76	0.77	0.79	0.76	0.73	0.80
Belt Length (m)	150	400	95	253	253	253	253	253	900	350	300	200
Conveyor height (m)	26.05	103.52	40.15	43.93	65.48	86.53	43.93	65.48	156.28	90.58	77.64	34.72
Belt Width (mm)	1200	1400	1200	1400	1400	1400	1400	1400	1400	1400	1400	1400
Belt inclination (degrees)	10	15	15	10	15	20	10	15	10	15	15	10
Belt speed (m/s)	4.35	4.49	4.38	4.34	4.44	4.50	4.44	4.34	4.49	4.45	4.50	4.50
Idler spacing (mm)	900	1000	900	1000	1000	1000	1000	1000	1000	1000	1000	1000
Idler diameter (mm)	35	45	35	45	45	45	45	45	45	45	45	45
load capacity (t/h)	923	969	918	989	989	989	989	989	989	989	989	989

(Source: AGA, 2016)

Table 2 Calculation of Model Parameters

Parameter	**Crusher Conveyors**	**Overland Conveyors**

	CVR 12	**CVR 13**	**CVR 14**	**CVR 15**	**CVR 16**	**CVR 17**	**CVR 18**	**CVR 19**	**CVR 5B**	**CVR 5C**	**CVR 5D**	**CVR 06**
L (m)	150	400	95	253	253	253	253	253	900	350	300	200
C	1.60	1.25	1.89	1.37	1.37	1.37	1.37	1.37	1.10	1.27	1.31	1.45
f	0.023	0.024	0.026	0.023	0.024	0.023	0.024	0.024	0.023	0.026	0.026	0.024
g (m/s^2)	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Q_{RR} (kg/m)	30.3	30.9	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3
Q_B (kg/m)	13.5	15.3	13.5	12.5	13.5	13.5	13.5	13.5	13.5	13.5	15.5	13.5
H (m)	26.05	103.52	40.15	43.93	65.48	86.53	43.93	65.48	156.28	90.58	77.64	34.72
δ (degrees)	10	15	15	10	15	20	10	15	10	15	15	10
Cos δ	0.98	0.97	0.97	0.98	0.97	0.94	0.98	0.97	0.98	0.97	0.97	0.98
Motor efficiency (η_m)	0.95	0.91	0.89	0.94	0.89	0.95	0.89	0.89	0.88	0.91	0.87	0.89
Drive efficiency (η_d)	0.85	0.90	0.89	0.92	0.90	0.86	0.85	0.87	0.90	0.83	0.84	0.90
$\eta = \eta_m \times \eta_d$	0.81	0.82	0.79	0.86	0.80	0.82	0.76	0.77	0.79	0.76	0.73	0.80
C_1	3790.73	5074.92	2510.27	5156.32	5675.21	5535.41	6088.46	6312.01	16032.62	8418.39	7748.88	4637.71
C_2	321.97	1162.62	497.15	519.54	936.08	1127.59	671.59	952.73	2215.48	1312.56	1167.13	505.39