International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075, Volume-8 Issue-4, February 2019

Minimization of Specific Energy of a Belt Conveyor Drive System using Space Vector Modulated Direct Torque Control

N.V. Sarathbabu Goriparti, Ch. S. N. Murthy, M. Aruna

Abstract*: *The main aim of this paper is to model and minimize the specific energy of belt conveyor drive system under different operating conditions such as different loading conditions, different conveyor inclinations, different conveying lengths and lifts, and different capacities using a real time fabricated experimental setup. Further, it demonstrates the advantages of using a variable speed drives (VSDs) for energy savings. Conveyors are designed for transporting goods, ores, minerals, and other such products with maximum rated capacities for any operating sections. But, they operate at a relatively much lower capacity. This is due to the supply and demand side implications of the operating section, they will run at the same constant rated speed causing higher power losses. This behavior will highly degrades the energy efficiency of conveyor. In the present study, an attempt is made to improve the energy efficiency of the conveyor by minimizing the per unit energy consumption using the methodology having combined advantages of energy efficiency modeling with less friction coefficient as per DIN 22101 and superior speed control technique for conveyor kind of high torque loads called space vector based direct torque control. In this paper, specific energies are estimated for the same belt conveyor system, found that with the use of VSDs, specific energies are reduced an amount 10-12% depending upon the capacities at which they have run.

Index Terms*: *Specific energy, Variable speed drives, Energy efficiency

I. INTRODUCTION

Specific energy (kWh/t.km) is an important factor for each organization using belt conveyor drives for transportation system, minimizing the specific energy increases the profit for an organization and reduces pressure on national resources and the environment [1].

The per unit energy consumption for a belt conveyor is a scale measure that can be used to evaluate the conveyor energy efficiency [2]. In underground mines where the main transporting system for ore or mineral is belt conveyor. Increase in demand of electrical energy for transportation has been major cost for any mining operation. The only way to solve this problem is reduce the energy consumption at possible extent.

Designing of conveyor with less friction coefficient provides less wear and tear, no belt stretching, slipping or breaking, benefits prolonged life time, reduced maintenance costs and energy efficient [3].

Speed control is the another important aspect to conserve energy, essential for industrial loads such as pumps, fans, and conveyor belts too, to reduce the power losses and to achieve energy efficiency [4].

Variable speed drive (VSD) is a system that regulates speed and output torque of an electric motor. Further, it facilitates minimum start current, smooth acceleration and deceleration, smooth speed-torque response, soft starting and stopping, per unit energy savings, reverse and breaking operation, less heating problems and prevention of mechanical drive components. Many researchers have been worked on VSDs to achieve the above-mentioned benefits [5-6].

Various authors have investigated on speed control by various techniques like stator voltage control, rotor resistance control, v/f control or frequency control, etc. Most of the studies were carried out on the speed control of asynchronous motors since they are workhorses of any industry [7].

Almost 90\% of the motors used in any industry are asynchronous or induction motors (IMs) because they are highly reliable, less cost, no sparking and commutation problems. However, IMs do not inherently have the capability of adjustable speed operation. Due to this reason, earlier dc motors are used in most of the drives. But the recent progresses in speed control methods of IM have led to their large-scale use in almost all electrical drives. Some of the popular developments are field-oriented control (FOC) and direct torque control (DTC) [8-11].

The variable speed drive, namely, DTC of IM even have its own advantages, using this method for automatic control of belt conveyor, is not so easy [12]. Further, the investigation on specific energy consumption (SEC) of belt conveyor system under adjustable speed control operation is still a precarious work. What kind of simulations and or observations, estimations are required for doing better these works?

Following this question, we tried to formulate some rule of thumb from DIN 22101 standard [13], but also come from our personal experiences with simulation and experimental investigations to model and fabricate the conveyor having less friction coefficient.

Revised Manuscript Received on February 07, 2019.

N.V.Sarathbabu Goriparti, Research Scholar, Department of Mining Engineering, National Institute Technology Karnataka, Surathkal, Surathkal, India.

Ch.S.N.Murthy, Professor, Department of Mining Engineering, National Institute Technology Karnataka, Surathkal, Surathkal, India

M.Aruna, Associate Professor, Department of Mining Engineering, National Institute Technology Karnataka, Surathkal, Surathkal, India.

This paper presents the implementation of energy efficient modeling with less friction coefficient and superior space vector based direct torque control on a belt conveyor drive system for the minimization of per unit energy consumption.

II. MODELLING OF BELT CONVEYOR

In this section, the belt conveyor model with minimum friction is derived from the standard DIN 22101. Based on energy conversion, the energy of a typical belt conveyor, shown in Fig.1, can be classified into four types [2] as follows: the energy required to empty conveyor E_{ec}, the energy required to move the material straight E_h, the energy required to lift the material a certain elevation E_l and an additional energy Es required to overcome skirt friction.

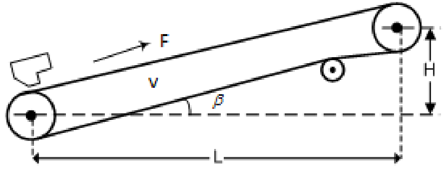

Fig.1. Typical belt conveyor layout

For no skirted belt conveyor, the value of E_s is zero.

The total energy of conveyor is expressed as

$$E_t = E_{ec} + E_h + E_l + E_s \qquad (1)$$

According to [2], E_{ec}, E_h, E_l and E_s are calculated using the following empirical formulae

$$E_{ec} = gCQ(L + L_C)\frac{v}{1000}t \qquad (2)$$

$$E_h = gC(L + L_C)\left(\frac{T}{3.6v}\right)\frac{v}{1000}t \qquad (3)$$

$$E_l = \frac{gTH}{3.6v}\frac{v}{1000}t \qquad (4)$$

$$E_s = 0.2gd^2LM\frac{v}{1000}t \qquad (5)$$

Where g is gravitational acceleration (m/s^2), C is friction factor, Q is mass of the moving parts of the conveyor (kg/m) it is expressed as (Q_r+2Q_b) where Q_r is unit mass of idlers (kg/m) and $Q_b$is unit mass of the belt (kg/m), L is parallelconveyor length (m), Lcreparation length constant due to terminal friction (m), t operating period of conveyor (h), T represents material transfer/flow rate (t/h), d representsload depth (m), M represents material density (kg/m^3).

From reference [2], the friction in belt conveyor depends on several factors such as tension on the belt, speed at which it runs, toughing angle, diameter of the idlers, spacing between idlers and others working conditions.

By considering all the above said variables, an objective function is derived conveyor for the minimum friction with boundary conditions as follows:

The allowable spacing of forward idlersis in between 1 to 1.5 meter, diameter of the idler is in between 108-160mm, spacing of return idlers is in between 2.5 to 3.5mm, belt speed is in between 4- 6 m/s and toughing angle is in between 25-35°.

$$C = \sum_{j=1}^{n} A_i x_i \qquad (6)$$

Where C is the friction coefficient, n represents number of variables, A_iConstant matrix of order nx n, and x_i is state variable matrix of order n x 1.

A 2m length conveyor, shown in Fig.2, is modeled and fabricated with minimum friction coefficient value 0.01 by using the above methodology. And the design values of the fabricated conveyor are listed in Table II.

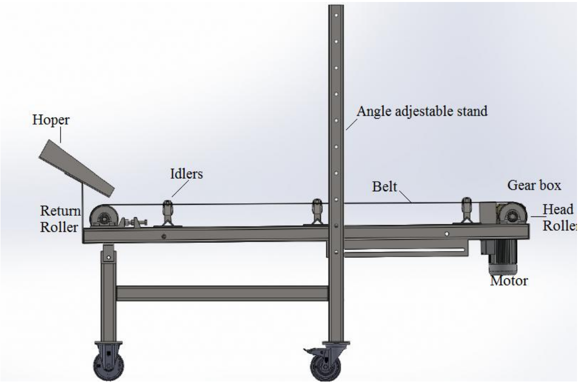

Fig. 2. Fabricated belt conveyor

III. SPECIFIC ENERGY

Specific energy of conveyor is defined as the energy required to transfer one ton of material at a distance of one kilometer [14]. It is calculated by

$$W_s = \frac{P_e}{TS}(kWh/t - km) \qquad (7)$$

Where $W_s$is specific energy of conveyor (kWh/t-km), $P_e$is the electrical power required to run the conveyor, T is the transfer rate (t/h), S is the conveying distance (km). The value of P_e is calculated by dividing the mechanical power P_m with efficiency of the system. The system efficiency is the product of efficiency of belt, efficiency of the drive motor and efficiency of the controller.

The value of $P_m$can be calculated from the total driving force to oppose the friction resistance and belt speed.

IV. SPACE VECTOR BASED DIRECT TORQUE CONTROL

Space vector based direct torque technique was used for energy savings in the current work, since this technique is more suitable for high torque loads.

A. Induction Motor Model

Based on the control phenomena, the three phase induction motor is modelled in the stationary reference frame [11].

$$\frac{d}{dt}\begin{bmatrix} i_\alpha \\ i_\beta \\ \lambda_\alpha \\ \lambda_\beta \end{bmatrix} = \begin{bmatrix} -\frac{r_s}{\sigma l_s} & -\omega_r & \frac{r_r}{\sigma l_s l_r} & \frac{\omega_r}{\sigma l_s} \\ \omega_r & -\frac{r_s}{\sigma l_s} & -\frac{\omega_r}{\sigma l_s} & \frac{r_r}{\sigma l_s l_r} \\ -r_s & 0 & 0 & 0 \\ 0 & -r_s & 0 & 0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ \lambda_\alpha \\ \lambda_\beta \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma l_s} & 0 \\ 0 & \frac{1}{\sigma l_s} \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{v}_\alpha \\ \mathrm{v}_\beta \end{bmatrix} \tag{8}$$

$$\sigma = 1 - l_m^2 / l_s l_r \tag{9}$$

$$T_e = \frac{3}{2} p\left(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\right) \tag{10}$$

$$T_e - T_{load} = \frac{2}{p} J \frac{d\omega_r}{dt} \tag{11}$$

Where i_α and i_β are the current components along α & β axis respectively, v_α and v_β are the voltage components along α & β axis respectively, λ_α and λ_β are the flux components along α & β axis respectively, r_s is stator resistance, l_s is stator inductance, r_r is rotor resistance, l_r is rotor inductance, $_{lm}$ is magnetization inductance $\omega_r$is electrical speed, T_e is electromagnetic torque, T_{load} is load torque, J is rotor inertia constant, p is pair of poles and σ is stray factor.

B. Direct Torque Control Strategy

The basic structure of DTC consist of two hysteresis controllers, torque and flux estimator, a look-up table, and a voltage source inverter [12-14].

In, DTC technique, the output torque and speed are controlled by the use above two mentioned comparators. These comparators provide required voltage to the inverter for motor control [15-19].

From the model of the machine expressed in stationary reference frame the stator flux, torque, and stator flux angle are calculated as follows [20].

$$v_\alpha = \frac{2}{3}(v_a - \frac{1}{2}v_b - \frac{1}{2}v_b) \tag{12}$$

$$v_\beta = \frac{2}{3}(-\frac{\sqrt{3}}{2}v_b - \frac{\sqrt{3}}{2}v_b) \tag{13}$$

$$i_\alpha = \frac{2}{3}(i_a - \frac{1}{2}i_b - \frac{1}{2}i_b) \tag{14}$$

$$i_\beta = \frac{2}{3}(-\frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_b) \tag{15}$$

The stator flux components can be estimated by

$$\lambda_\alpha = \int (v_\alpha - r_s i_\alpha)\, dt \tag{16}$$

$$\lambda_\alpha = \int (v_\alpha - r_s i_\alpha)\, dt \tag{17}$$

The magnitude of the stator flux can then be estimated by

$$\lambda_s = \sqrt{(\lambda_\alpha{}^2 + \lambda_\beta{}^2)} \tag{18}$$

The phase angle of stator flux is estimated by

$$\theta_s = \tan^{-1}\left(\frac{\lambda_\beta}{\lambda_\alpha}\right) \tag{19}$$

And the electromagnetic torque can be estimated by

$$T_e = \frac{3}{2} p\left(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha\right) \tag{20}$$

C. Space Vector based DTC

Two of the major issues which are normally addressed in classical DTC are the variation of the switching frequency of the inverter and torque ripple. Space vector modulation overcome the above mentioned two drawbacks. SVM-DTC uses two proportional plus integral controllers, to compare flux and torque errors and to generate required voltage signals as shown in Fig.3. [21]

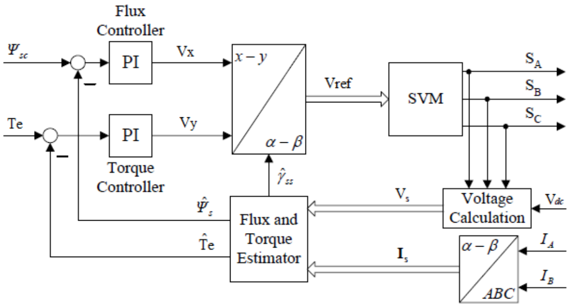

Fig. 3.Block diagram of Space vector DTC

In Space vector DTC, the reference voltage vector (v_{ref}) is synthesized by time averaging of the three nearest vectors around it in the hexagon.

The algorithm for Space vector DTC has the following steps

1. Determination of reference voltage
2. Determination dwell times (ON/OFF state time of chosen switches)

The reference voltage can be estimated by [22]

$$v_{ref} = (v_\alpha + jv_\beta) \tag{21}$$

$$\alpha = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) \tag{22}$$

The dwells can estimated by using the principle called ‘volt-secmatching’. This principle tells thatthe sum of the voltage vectors multiplied by the time interval of chosen space vectors is the product of referencevoltage v_{ref} and sampling period T_s. That means, when v_{ref} falls into Sector-I, it can be synthesized by surrounding vectors v_1, $v_2$and $v_z$as depicted in Fig. 4.

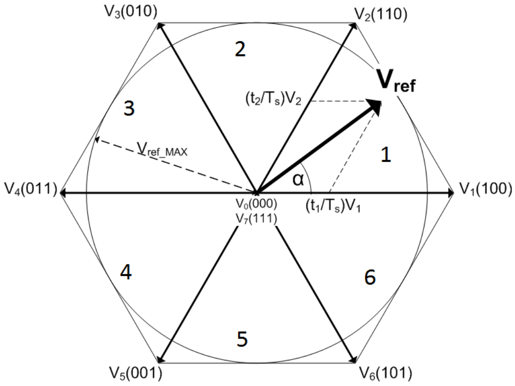

Fig. 4. Hexagon used to synthesize reference voltage vector.

The voltage balance equation is

$$\boldsymbol{v}_{ref}\boldsymbol{T}_s = \boldsymbol{v}_1\boldsymbol{t}_1 + \boldsymbol{v}_2\boldsymbol{t}_2 + \boldsymbol{v}_z\boldsymbol{t}_z \qquad (23)$$

The dwell times can be estimated by [22]

$$\boldsymbol{t}_1 = \frac{\boldsymbol{v}_{ref}\ \sin(60-\alpha)}{\boldsymbol{v}_{dc}\ \sin\alpha}\boldsymbol{T}_s \qquad (24)$$

$$\boldsymbol{t}_2 = \frac{\boldsymbol{v}_{ref}\ \sin\alpha}{\boldsymbol{v}_{dc}\ \sin\alpha}\boldsymbol{T}_s \qquad (25)$$

$$\boldsymbol{t}_z = \boldsymbol{T}_s - \boldsymbol{t}_1 - \boldsymbol{t}_2 \qquad (26)$$

V.EXPERIMENTAL STUDIES

The speed control is implemented in an experimental setup shown in, Fig. 5.The setup consists of 2m belt conveyor which driven by a 0.375kW induction motor (IM).The IM is supplied by an Insulated gate bipolar transistorvoltage source inverter and controlled by a TSM320F28335Digital Signal Processor. The considered belt conveyor in turn acts as a load. The selected sampling frequency is 10 kHz and the DSP board was controlled. An RS 232 cable is used connected to PC.The parameters of the IM is same the motor used in simulation study.

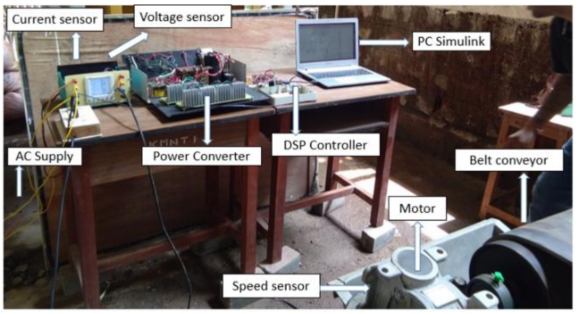

Fig. 5.Photo pic of experimental setup

The conveyor is Simulated and tested for the following cases. Case-I: When the conveyor runs at constant speed. In this case, no speed feedback is connected. This means the conveyor is an open loop system. Hence, No control action in the drive. Therefore, the power losses in the system becomes high causing high per unit energy consumption. Case-II: When the conveyor runs at variable speed. In this case, speed feedback is connected. This means the conveyor is a closed loop control system and the motor is controlled according to the control law. Case-III: When conveyor unloaded (No load condition). Here, no load condition means no material load on the belt. Case-IV: When the conveyor lightly loaded (< 20% of full load). Case-V: When the conveyor fully loaded.

TABLE I SIMULATION PARAMETERS OF IM

Nominal parameters	Values
Rated Power (P)	0.375 kW
Rated Voltage (V)	415 V
Rated Supply Cycles/sec (f)	50 Hz
Stator resistance/ph (r_s)	60 Ω
Stator inductance/ph (l_s)	85 mH
Rotor resistance/ph (r_r)	71 Ω
Rotor inductance/ph (l_r)	85 mH
Magnetizing inductance (l_m)	489 mH
Moment of inertia (J)	0.009 kg m^2
Friction factor (FF)	0
Pole pairs (p)	2

TABLE II SPECIFICATIONS BELT CONVEYOR

Nominal parameters	Unit
Maximum conveying capacity (Q_m)	10 t/h
Belt speed (v)	0.18 m/s
Belt width (B)	300 mm
Conveying length (L)	2 m
Conveying height (H)	0.35 m
Inclination angle (β)	10°
Belt thickness (t_b)	12 mm
Idler weight (m_r)	12 kg/m
Radius of drive pulley (R_d)	7cm

Several tests have been carried out on the test rig i.e. 0.5hp belt conveyor system with and without variable speed drive for various tilt angles, shown in Fig. 6.

Fig. 6. Conveyor at different inclinations (a) 0° inclination (b) 15° inclination (c) 20° inclination

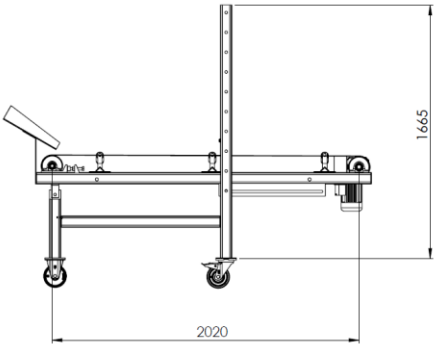

Fig. 7. Conveyor at length 2.2m and lift 0m

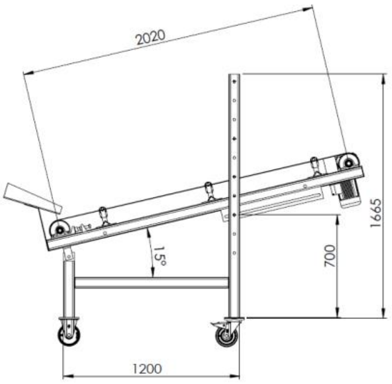

Fig. 8. Conveyor at length 1.2m and lift 0.7m

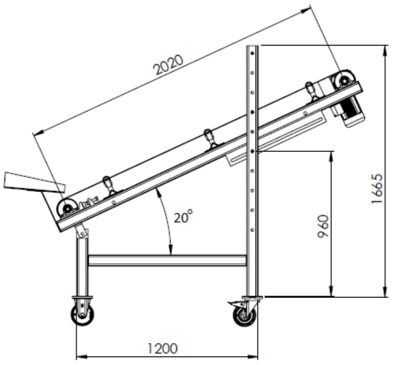

Fig.9 shows the performance characteristics of the conveyor at three different conveyor inclinations, 10°, 15° and 20° against transfer rate.

From Fig.10, the observations are as follows:

- The electrical power and annual energy consumption will increase with the increase of inclination.
- Because of low power factor values, the efficiencies are very low for a given material flow, 2tph.

The specific energy will decrease with the increase of inclination.

V. RESULTS AND DISCUSSION

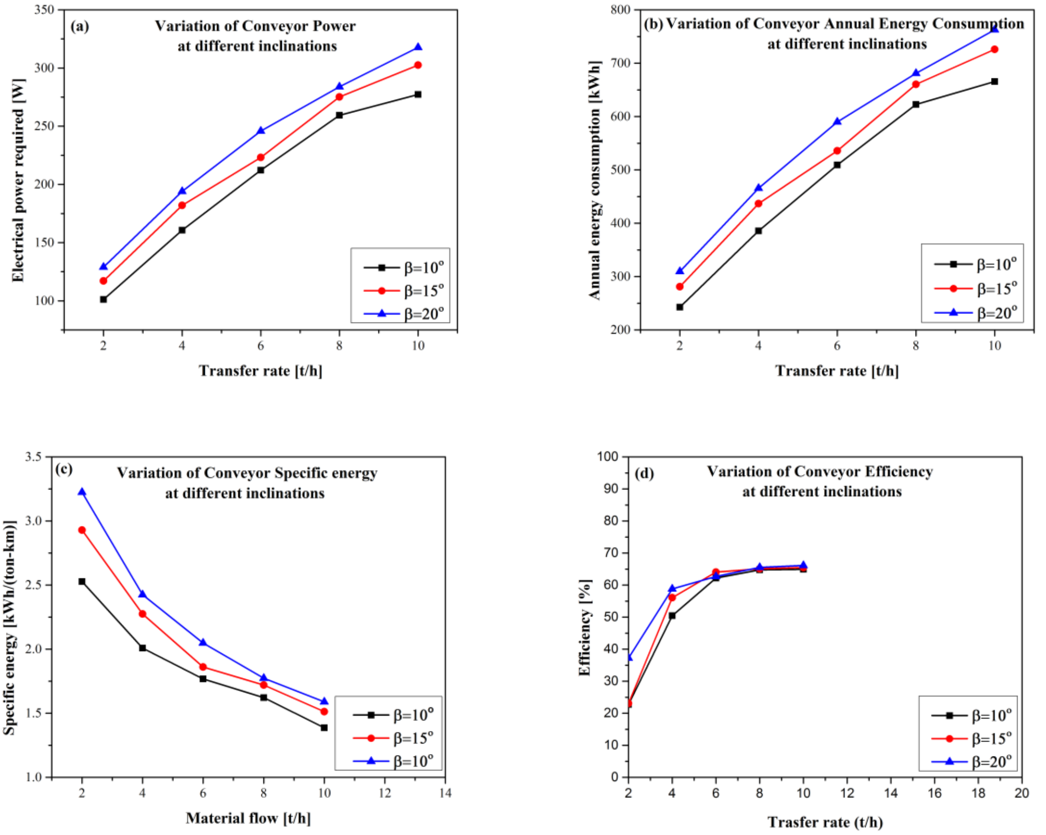

Fig. 10.Experimental proto type resultsat three different inclinations (a) Power waveform (b) Energy waveform (c) Specific energy waveform (d) Efficiency waveform

Fig. 11 shows that the variation in performance characteristics with SVM-DTC. From Fig.11, the observations are as follows:

Fig. 12 describes the percentage reductions of specific energies, by using SVM-DTC. And, the average reduction in specific energy at 10°, 15°, and 20° are 11.5%, 11.3%, and 9.89% respectively by using DTC-SVM.

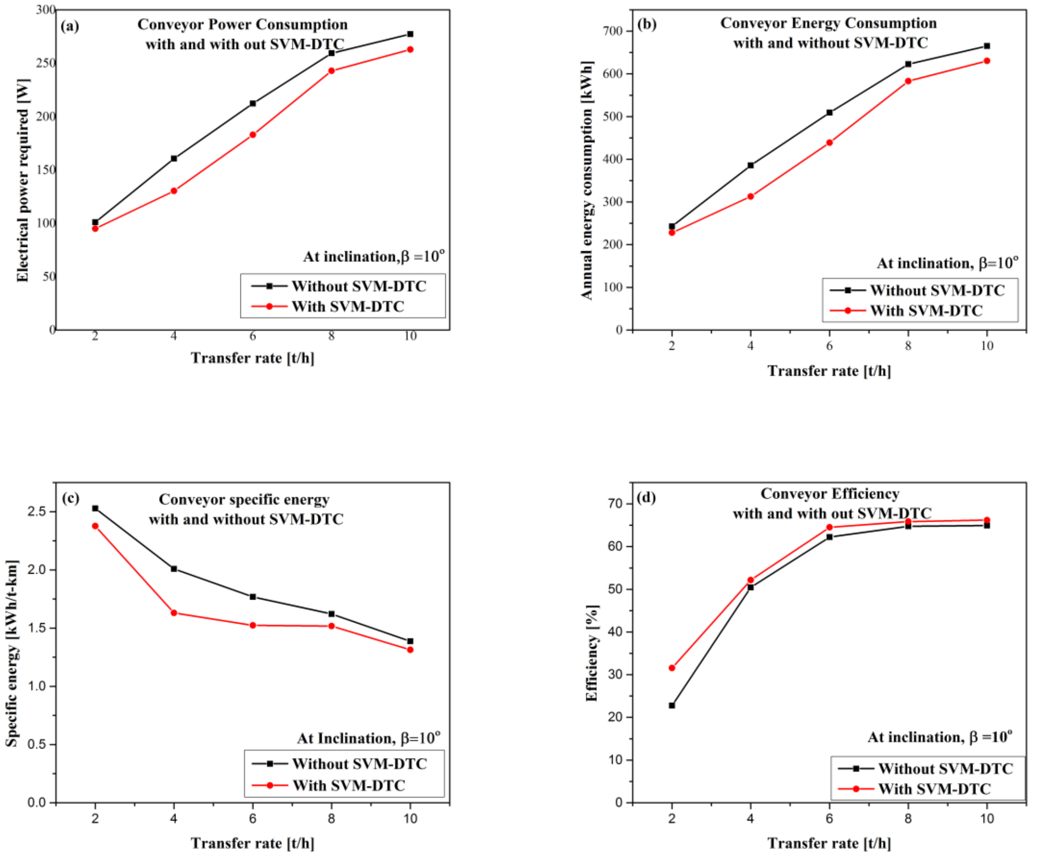

Fig.11.Performance characteristics of conveyor with and without SVM-DTC (a) Power waveform (b) Energy waveform (c) Specific energy waveform (d) Efficiency waveform

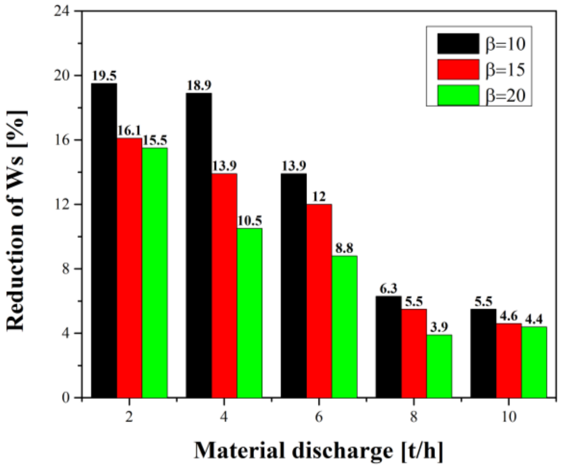

Fig.12. Specific energy Reductions

VI. REGRESSION ANALYSIS

Using Minitab 17, an ANOVA based regression analysis was done to predict the most influencing parameters on the specific energy. The obtained Equation(27) represents specific energy (W_s, kWh/t-km)in terms of conveyor inclination (β in °), material weight (m_l, kg/m), applied force (F, n-m) and belt speed (v, m/s).

$$Ws = 34.9 + 0.0023\,\beta - 0.0722\,ml - 0.002002\,F - 170\,v \quad (27)$$

From the analysis done with Table V, it was observed that the most influencing parameters among the input parameters are applied force and belt speed.

VII. CONCLUSION

A 2m length belt conveyor has been simulated and experimented at different inclinations such as 10°, 15°, and 20° with and without connecting variable frequency drive. With the use of VFDs, the reduction in energy consumption at 10°, 15°, and 20° are 9.6%, 8.55%, and 7.2% respectively. And, the reduction in specific energy at 10°, 15°, and 20° are 11.5%, 11.3%, and 9.89% respectively. The Simulation results are validated with the proto type experimental results. Further, an ANOVA based regression analysis is done for specific energy to find the critical parameters. The obtained R^2 and Adj R^2 from ANOVA are 0.9643 and 0.95 respectively.

TABLE III RESULTS OF ANOVA

Factor	DF	Adj SS	Adj MS	F-value	P
Regression	4	4.40072	1.10018	67.49	0.000
Inclination (β)	1	0.00002	0.00002	0.00	0.970
Unit Mass of Material(m_l)	1	0.00872	0.00872	0.53	0.481
Applied Force (F)	1	0.28704	0.28704	17.61	0.002
Belt Speed (v)	1	0.01807	0.01807	1.11	0.317
Error	10	0.16301	0.01630		
Total	14	4.56372			

TABLE IV MODEL SUMMARY

S	R-sq	R-sq (adj)	R-sq (Pred)
0.127674	96.43%	95%	*

TABLE V SIGNIFICANCE OF MODEL COMPONENTS WITH STUDENT T-TEST

Term	Coef	SE Coef	T-value	P	VIF
Constant	34.9	30.9	1.13	0.285	
Inclination (β)	0.0023	0.0599	0.04	0.970	55.05
Unit Mass of Material (m_l)	-0.0722	0.0987	-0.73	0.481	161.36
Applied Force (F)	-0.002002	0.000477	-4.20	0.002	24.77
Belt Speed (v)	-170	161	-1.05	0.317	238.14

REFERENCES

1. He, Y. Pang, and G. Lodewijks, “Green operations of belt conveyors by means of speed control," Applied Energy, vol. 188, pp. 330-341, 2017.
2. B. Lin, Y. Wu, and L. Zhang, “Estimates of the potential for energy conservation in the Chinese steel industry," Energy Policy, vol. 39, pp. 3680-3689, 2011.
3. S. Zhang and X. Xia, “Modeling and energy efficiency optimization of belt conveyors," Applied Energy, vol. 88, no. 9, pp. 3061-3071, 2011.
4. S. Zhang and X. Xia, “Optimal control of operation efficiency of belt conveyor systems," Applied Energy, vol. 87, no. 6, pp. 1929-1937, 2010.
5. K. Bimal, Modern power electronics and AC drives. Prentice-Hall, 2001.
6. R. Krishnan, Electric motor drives: modeling, analysis, and control, vol. 626. Prentice Hall New Jersey, 2001.
7. P. Vas, Vector control of AC machines, vol. 22. Oxford University Press, USA, 1990.
8. Continuous conveyors – Belt conveyors for loose bulk materials-Basis for calculation and dimensioning, DIN 22101, 2002.
9. Handbook of conveyor & elevator belting, The Good year Tyre and rubber company, Akron, USA, 1975.
10. H.Lauhoff, “Belt conveyor technology, “Speed control of belt conveyors –does it really save energy?” Bulk solid handling, vol.25, pp368-377, 2005.
11. Pimkumwong, Narongrit, Amorn Onkrong, and Tirasak Sapaklom. "Modeling and simulation of direct torque control induction motor drives via constant volt/hertz technique." Procedia Engineering pp.31, 1211-1216, 2011.
12. I. Takahashi and T. Noguchi, “A new quick-response and high-efficiency control strategy of an induction motor," IEEE Transactions on Industry applications, no. 5, pp. 820-827, 1986.
13. M. Depenbrock, “Direct self-control (dsc) of inverter-fed induction machine," IEEE transactions on Power Electronics, vol. 3, no. 4, pp. 420{429, 1988.
14. U. Baader, M. Depenbrock, and G. Gierse, “Direct self control (dsc) of inverter-fed induction machine: A basis for speed control without speed measurement," IEEE transactions on industry applications, vol. 28, no. 3, pp. 581-588, 1992.
15. G. S. Buja and M. P. Kazmierkowski, “Direct torque control of pwm inverter-fed ac motors-a survey," IEEE Transactions on industrial electronics, vol. 51, no. 4, pp. 744-757, 2004.
16. C. Reza, M. D. Islam, and S. Mekhilef, “A review of reliable and energy efficient direct torque controlled induction motor drives," Renewable and Sustainable Energy Reviews, vol. 37, pp. 919-932, 2014.
17. C. Lascu, I. Boldea, and F. Blaabjerg, “A modified direct torque control for induction motor sensorless drive," IEEE Transactions on industry applications, vol. 36, no. 1, pp. 122-130, 2000.
18. P. Marino, M. D'incecco, and N. Visciano, “A comparison of direct torque control methodologies for induction motor," in Power Tech Proceedings, 2001 IEEE Porto, vol. 2, pp. 6-pp, IEEE, 2001.
19. D. Casadei, G. Serra, and A. Tani, “The use of matrix converters in direct torque control of induction machines," IEEE transactions on industrial electronics, vol. 48, no. 6, pp. 1057-1064, 2001.
20. F. Tazerart, Z. Mokrani, D. Rekioua, and T. Rekioua, “Direct torque control implementation with losses minimization of induction motor for electric vehicle applications with high operating life of the battery," International Journal of Hydrogen Energy, vol. 40, no. 39, pp. 13827-13838, 2015.
21. E. Ozkop and H. Okumus, “Direct torque control of induction motor using space vector modulation (SVM-DTC)," 2008 12th International Middle-East Power System Conference, pp. 368-372, 2008.
22. C. Lascu and A. M. Trzynadlowski, “Combining the principles of sliding mode, direct torque control, and space-vector modulation in a high-performance sensorless ac drive," IEEE Transactions on industry applications, vol. 40, no. 1, pp. 170-177,2004.

AUTHORS PROFILE

N.V.Sarathbabu Goripartiwas born in 1984.He received,the B.Tech degree in Electrical and Electronics Engineering and the M.Tech in Control system from the Jawaharlal Nehru Technological University Hyderabad, Hyderabad, in 2006 and 2011 respectively. Currently, he is doing research in Belt conveyor drives in the department of Mining Engineering, Notational Institute of Technology Karnataka, Surathkal.

Ch.S.N.Murthy, Professor, NITK, Surathkal. He received the B.E in Mining Enginering, from the Osmania University, A.P., 1980. He recived M.Tech from the Indian School of Mines, Dhanbad, in 1987.He received the Ph.D degree from Indian Institute of Technology, Kharagpur, in 1999.He has published nearly 150 technical papers in various scientific journals and conferences.

M.Aruna, Associated Professor, NITK, Surathkal. Hereceived the B. E degree in Mining Engineering from the National Institute of Technology Karnataka, Surathkal, in 1993 He obtained the Ph.D in Mining Engineering from the Indian School of Mines, Dhanbad, 2008. He has published nearly 51 technical papers in various scientific journals and 50 papers conference proceedings.