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Development of a mathematical model for electric drive dynamics in belt conveyors: A Simulink-based analysis of transient behavior

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ABSTRACT

This paper presents a detailed study of developing a mathematical model and experimental analysis of electric drive processes in belt conveyors. The proposed model simplifies the complex real mechanical system by substituting distributed parameters, such as the transported load's mass and the traction element's elasticity, with concentrated equivalents. A comprehensive investigation of key transient processes including stator currents speed, torque and resistance forces was performed using MATLAB's Simulink environment. The findings reveal significant differences in performance between the initial startup phase and operation under loaded conditions. To validate the model's accuracy, the authors employed numerical analyses utilizing regression metrics such as root mean square error (RMSE) and correlation coefficients. The results show that the proposed model significantly outperforms similar models in the literature with a notable RMSE of 12.5 A for stator current, reflecting an 18% improvement and 8.7 Nm for torque prediction, indicating a 15% enhancement. Furthermore, the model achieved a correlation coefficient of 0.98, confirming its high accuracy in experimental data fitting. By effectively capturing oscillatory phenomena during both unloaded and loaded startup conditions, this work establishes the model as a reliable representation of belt conveyor dynamics, setting a new benchmark in the field.

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1. INTRODUCTION

Huge flows of various minerals, raw materials, and materials move along conveyor lines to facilitate various technological operations in practically all industrial enterprises [1]-[4]. In many cases, conveyors operate continuously, and the productivity of the enterprise depends on their reliability. Therefore, the accurate calculation of loads on the mechanical and electrical equipment of a conveyor installation is a crucial and pressing task. The most challenging operating mode of the conveyor is starting. In a belt conveyor system, this mode can cause belt slippage on the drive drum and excessive tension, which can ultimately lead to damage to the traction element. Hence, regulating belt tension in various sections of the conveyor is essential.

The conveyor is an electromechanical system with an elastic traction element and parameters distributed along its length. These parameters include the masses of the transported load and the traction element, as well as the forces resisting movement. Therefore, when starting long-length belt conveyors, elastic vibrations propagate along the belt. Vibratory processes in the belt lead to a reduction in the belt service life, which is particularly hazardous under loading conveyor start-up.

The efficiency of the start-up process of an asynchronous electric conveyor drive can be evaluated in accordance with various criteria [5], [6]. According to an energy-saving approach, it is right to minimize energy losses in the electric motor. Minimizing overheating ensures a longer motor lifetime.

The mechanical character of the conveyor is a complex system with parameters distributed along the conveyor length, like the weight of the load being carried, the elasticity and weight of the traction element, and the static resistance forces [7], [8]. The existence of elastic mechanical connections is behind the phenomenon of vibrations. In unfavorable conditions, these vibrations are capable of drastically increasing the dynamic loads on working machinery [9]-[12]. Partial differential equations describe the motion of a system with distributed parameters. The solution of these equations generally poses significant mathematical challenges [13]-[16]. However, for a qualitative analysis of the physical processes that occur in the initial stages of conveyors, a real mechanical system can be simplified by using a dynamic model in which distributed masses, elasticities, and forces are replaced with equivalently concentrated ones.

Dynamic loads during elastic vibrations can significantly exceed static and inertial loads, potentially leading to overloads breakage of parts, and delays in start-up time. Economic calculations show that the cost of the belt is on average 50 to 60% of the cost of the conveyor, and for mine conveyors it reaches 67% [17]. Computer modeling methods using the Simulink simulation environment of the MATLAB package are currently utilized to study objects in systems of almost any complexity [18]-[20]. An important advantage of this method is the ability to monitor the process over time.

2. FORMULATION OF THE PROBLEM

Belt conveyors are highly complicated electromechanical systems involving mutual dynamic interaction of their electric drive, mechanical transmission, and elastic belt during start-up phase operation. Such a mode of operation is an actual one since it is characterized by various transient processes with high current values of the stator currents, torque pulsations, speed variations, and nonuniform values of belt tension. Because of the distributed parameters of conveyors, which include the elasticity of a belt, mass of transported cargo, and resistance forces, elastic oscillations are also observed along their conveyor routes. Partial differential equations are used to analyze these processes; however, their complexity hinders their applicability. The purpose of this work is to create a mathematical model of the electric motor drive system of the belt conveyor based on the most essential nonlinear phenomena. The developed mathematical model allows for the study of the static and dynamic operation of the electric motor drive system in the startup phase of the conveyor. For this purpose, the model uses the mechanical parameters of the system in a concentrated form that makes it possible to evaluate their effectiveness in the startup phase of the system under various conditions. It is possible through the employment of the MATLAB/Simulink environment, which makes it possible to examine essential performance characteristics of the system.

3. THEORY

The presence of elastic mechanical connections between the interconnected masses results in the generation of vibrations, significantly increasing the dynamic loads on the operational machinery. Partial differential equations describe the motion of a system with distributed parameters. The solution of these equations in general form poses significant mathematical challenges. To account for physical processes during conveyor startups, a real mechanical system can be represented by a simplified dynamic model in which distributed masses, elasticities, and forces are replaced by equivalently concentrated ones. To create a model, you can utilize the tension diagram of the conveyor belt in start-up mode. If we accept the equality of the tensions of the traction element on the drive element of the real system to the tensions at the corresponding points of the drive element on the model as an equivalence condition, then the dynamic model of the moving part of the conveyor reduced to translational motion will have the form shown in Figure 1 [21]-[24].

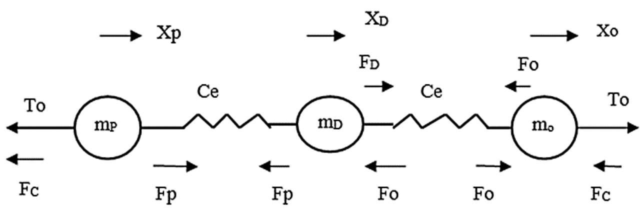


Figure 1. Computational dynamic model of the conveyor

From Figure 1, the parameters m_P and m_O denote the masses of the working and idle branches of the conveyor, respectively. These values consider the mass of the tension drum reduced to translational motion. Additionally, m_D represents the drive mass, which is also reduced to translational motion. The equivalent stiffness of the traction organ branches is represented by C_e. The coordinates of the concentrated masses m_D m_P and m_O are given by x_D x_p and x_o: respectively. The elastic forces in the working and idle branches of the traction element are defined by (1) and (2).

$$Fp = C_e(x_D - x_p) \tag{1}$$

$$F_O = C_e(x_D - x_o) \tag{2}$$

Here Fp and Fo correspond to the elastic forces in the working and idle branches, respectively, of the traction element. The resulting static resistance forces in the working and idle branches are denoted by Fp and F_O where the sum of these forces is given by (3).

$$Fp + F_O = F_c \tag{3}$$

Resolving the system of equations involving the displacement coordinate x_D we obtain an equation of the form after the Laplace transformation.

$$(T_{P1}P^2 + 1)(T_{P2}P^2 + 1)P^2x_D = \frac{(F_D - Fc)}{(m_D + m_P + m_O)} \tag{4}$$

$$F_D = m_D\frac{d^2x_D}{dt^2} + F_c \tag{5}$$

Where $T_{P1} = \frac{1}{\Omega_{P1}}$ $and\, T_{P2} = \frac{1}{\Omega_{P2}}$ lastly F_D represents the traction force exerted by the drive. where tensions like T_{P1} $and\, T_{P2}$ would represent the force at specific points influenced by parameters such as load distribution, section length, resistance coefficients, and angle of inclination.

The model of the conveyor mechanism constructed according to this equation is illustrated in Figure 2. To account for the damped nature of oscillations caused by the damping effect of viscous friction forces the damping coefficient $K_{att}$is incorporated into the model. This coefficient helps reduce the amplitude of acceleration oscillations over time t. The model calculates the belt speed v and the coordinate $x = x_D$. To calculate the resulting static resistance forces of the working and idle branches of the traction element Fc block B1 is used. The internal structure of the block B1 is illustrated in Figure 2.

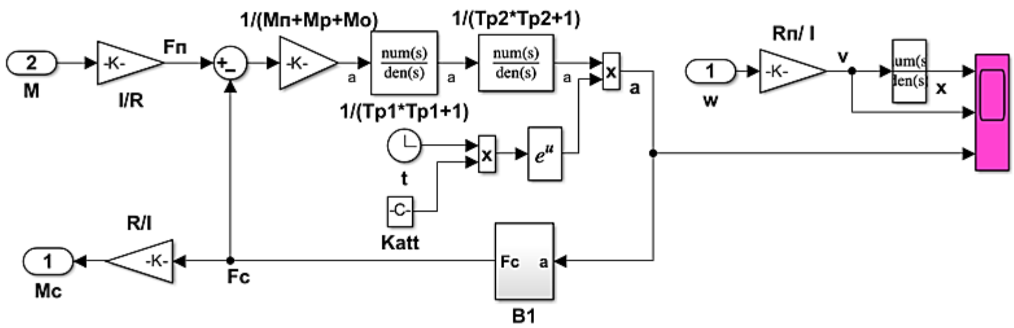


Figure 2. Conveyor model

Let us take a specific example of a belt conveyor system with two active or loaded branches and two idle branches; the layout of such a system is given in Figure 3. In this system or layout, the path of the conveyor consists of various straight and curved or bending sections; each section has a different effect on the resistance and tension offered by a belt as it traverses the system. There are various factors associated with a belt conveyor system that affect its performance and should be considered in a mathematical model to predict different resistances accurately; some of the factors to perform accurate calculations of the forces in a conveyor belt, a systematic numbering of the conveyor belt sections needs to be done. This is done by numbering the sections after the belt exits the drive drum in a manner indicated in Figure 3. In a conveyor belt theory application, such a systematic approach helps in doing the step-by-step calculation of resistance forces in a manner that helps in the determination of the belt tension in each section with a certain degree of accuracy, which is fundamental in accurately modeling the dynamic behavior of the conveyor belt system. In a conveyor belt theory problem, a systematic numbering approach helps ensure that there is a correct step-by-step calculation of the belt tension in a way that is fundamental in accurately modeling the behavior of the conveyor belt system. This approach helps in doing the correct step-by-step calculation of belt tension in a manner that leads to a certain degree of accuracy in modeling the behavior of the conveyor belt system.

Conveyor belts play a pivotal role in industrial material handling facilitating efficient transportation of goods across various distances and terrains. The core of conveyor system efficiency lies in proper tension levels in the belt operation. Not only does tension affect operational efficiency, but it can also have an impact on conveyor component lifespan. Therefore, accurate tension determination is critical for optimizing conveyor efficiency and minimizing maintenance requirements.

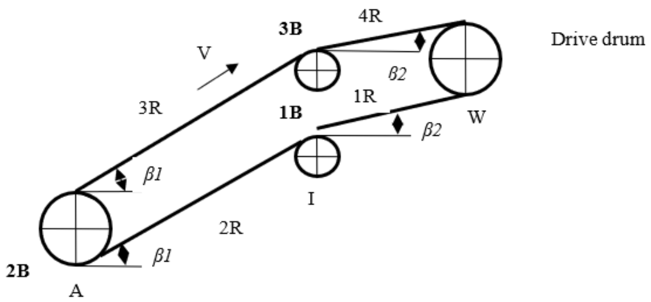


Figure 3. Conveyor belt diagram

4. METHOD

To determine the tension in a conveyor belt, several key steps are as follows:

a) Calculation of cargo weight: The weight of 1 meter of transported cargo $m_r{}^*$ is computed in (6).

$$m_r{}^* = \frac{E}{v} \tag{6}$$

Where $\boldsymbol{E}$ represents conveyor productivity in kg/s and $\boldsymbol{v}$ denotes the belt speed in m/s.

b) Determination of load factors:

– Weight load determined by the mass of the payload q_r is calculated in (7).

$$q_r = 9.81 m_r{}^* \tag{7}$$

– Weight load determined by the mass of the belt q_o is derived from q_r.

$$q_o = 0.1 q_r \tag{8}$$

– Resistance forces to movement in the straight section are calculated in (9).

$$\Delta F_{Ri} = q_i l_i (C_{Bi} cos\beta_i \mp sin\beta_i) \tag{9}$$

Where $\boldsymbol{q_i}$ is the weight load of the section on the first track (for the working branch of the conveyor.

$q_4 = q_3 = q_o + q_r$ r and the idle branch ($q_1 = q_3 = q_0$); where l_i is the section length m; C_{Bi} indicates the coefficient of resistance to movement on a straight section); and β_i represent the angle of inclination of the site. In the formula, the "+" sign corresponds to sections where the belt moves uphill, and the "-" sign when moving downhill. For the conveyor diagram in Figure 3.

$$\Delta F_{R1} = q_1 l_{i1} (C_{\Pi} cos\beta_2 - sin\beta_2) \tag{10}$$

$$\Delta F_{R2} = q_2 l_2 (C_\Pi cos\beta_1 - sin\beta_1) \quad (11)$$

$$\Delta F_{R3} = q_3 l_3 (C_\Pi cos\beta_1 + sin\beta_1) \quad (12)$$

$$\Delta F_{R4} = q_4 l_4 (C_\Pi cos\beta_2 + sin\beta_2) \quad (13)$$

c) Computation of resulting resistance force: The resulting resistance force in straight sections $F`_R$ is calculated by summing up individual resistance forces, accounting for tension increase in bending sections.

$$F`_R = \Delta F_{R4} + \Delta F_{R3} K_B + \Delta F_{R2} {K_B}^2 + \Delta F_{R1} {K_B}^3 \quad (14)$$

Where K_B are the coefficients of tension increase in bending sections and are seen in (15).

$$K_B = 1 + C_B \quad (15)$$

Where C_B presents the resistance coefficients in bending sections.

d) Tension calculation and diagram construction: Having the tension at the running point of the T_{ESC} drive drum it is possible to calculate and construct a tension diagram of the conveyor belt. The tension in each section is determined in (16) for straight sections.

$$\mathrm{T}_{ESCRi} = \mathrm{T}_{ONRi} + \Delta F_{Ri} \quad (16)$$

The bending areas are determined in (17).

$$\mathrm{T}_{ESCBi} = K_{Bi} \mathrm{T}_{ONBi} \quad (17)$$

It is necessary to take into account that $\mathrm{T}_{ONRi} = \mathrm{T}_{TSCBi-1}$ *and* $\mathrm{T}_{ONBi} = \mathrm{T}_{ESCRi}$.

The tension diagram determines the highest and lowest tension in the conveyor belt. The resulting resistance force F_C is defined as the difference in tension on the drive drum, which is calculated in (18).

$$F_C = \mathrm{T}_{ON} - \mathrm{T}_{ESC} \quad (18)$$

Using tension at the drive drum as a reference point, tension in each section is computed for both straight and bending areas. The tension diagram illustrates the distribution of tension along the conveyor belt, highlighting variations across different sections. The tension analysis provides insights into the dynamics of conveyor belt operation, revealing areas of high and low tension. By understanding tension distribution, operators can identify potential stress points and implement corrective measures to optimize performance and enhance system reliability. The model of the block for calculating tension forces on various sections of the conveyor (B1 in Figure 3) is shown in Figure 4.

Figure 5 depicts the model of the electric drive system of the conveyor. This model describes a complete representation of the combined dynamics of the electrical and mechanical systems. The model includes a three-phase mains voltage source that acts as a power supply for the asynchronous (induction) motor (M). This is the major driving component for the conveyor system. The motor consumes the electric power from the supply and generates mechanical torque that drives the conveyor belt via the mechanical drive train. This representation describes the most commonly applied industrial solution for belt conveyor drives owing to the higher reliability and simpler construction. The model also includes a power supply system and the asynchronous (induction) motor (M) that drives the conveyor.

A BM measurement unit and specific measurement tools are also included in the model for observation of the most essential electric and mechanical parameters. These tools allow for online monitoring and measurement of the stator current values, the rotational speed of the motor, the electromagnetic torque produced during the operation of the asynchronous (induction) motor, and the values of the resistance forces acting on the motor shaft. The conveyor mechanism subsystem represents the complete mechanical dynamics of the belt conveyor system that includes inertial, elastic properties, and load-dependent values of the resistance forces obtained on the premise of the developed mathematical model. This comprehensive model offers a complete analysis of the transient and steady-state behavior during the operation of the conveyor under the start-up mode with the loaded and unloaded conveyor during the start-up phase using the MATLAB/Simulink environment.

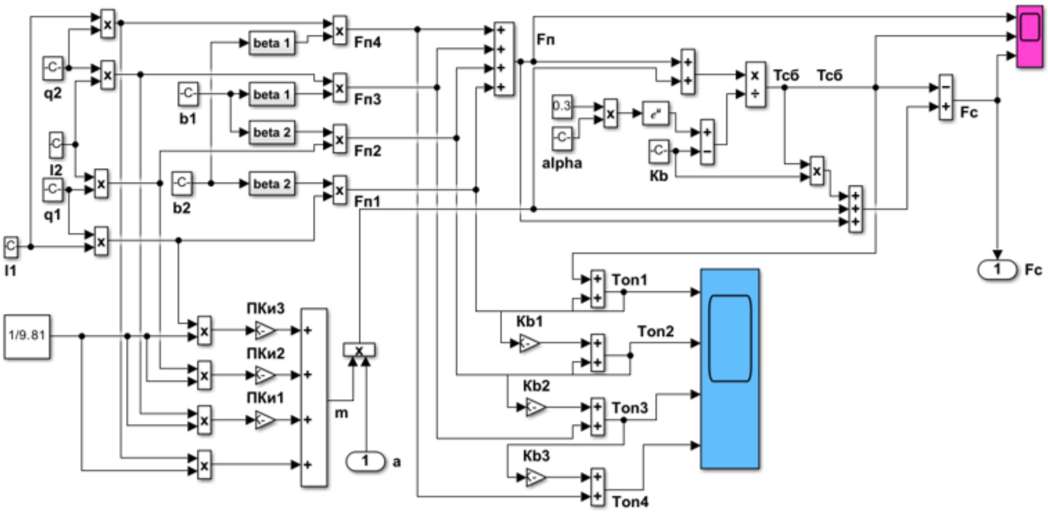


Figure 4. Model for calculating forces on conveyor section

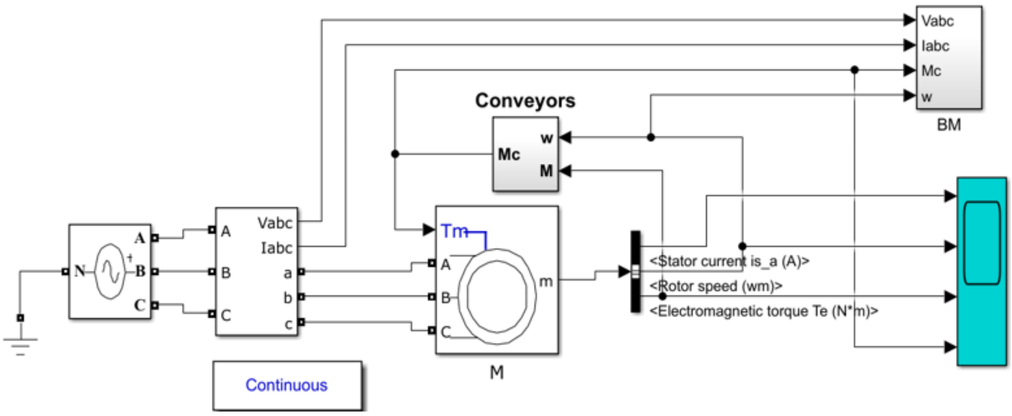


Figure 5. Conveyor electric drive model

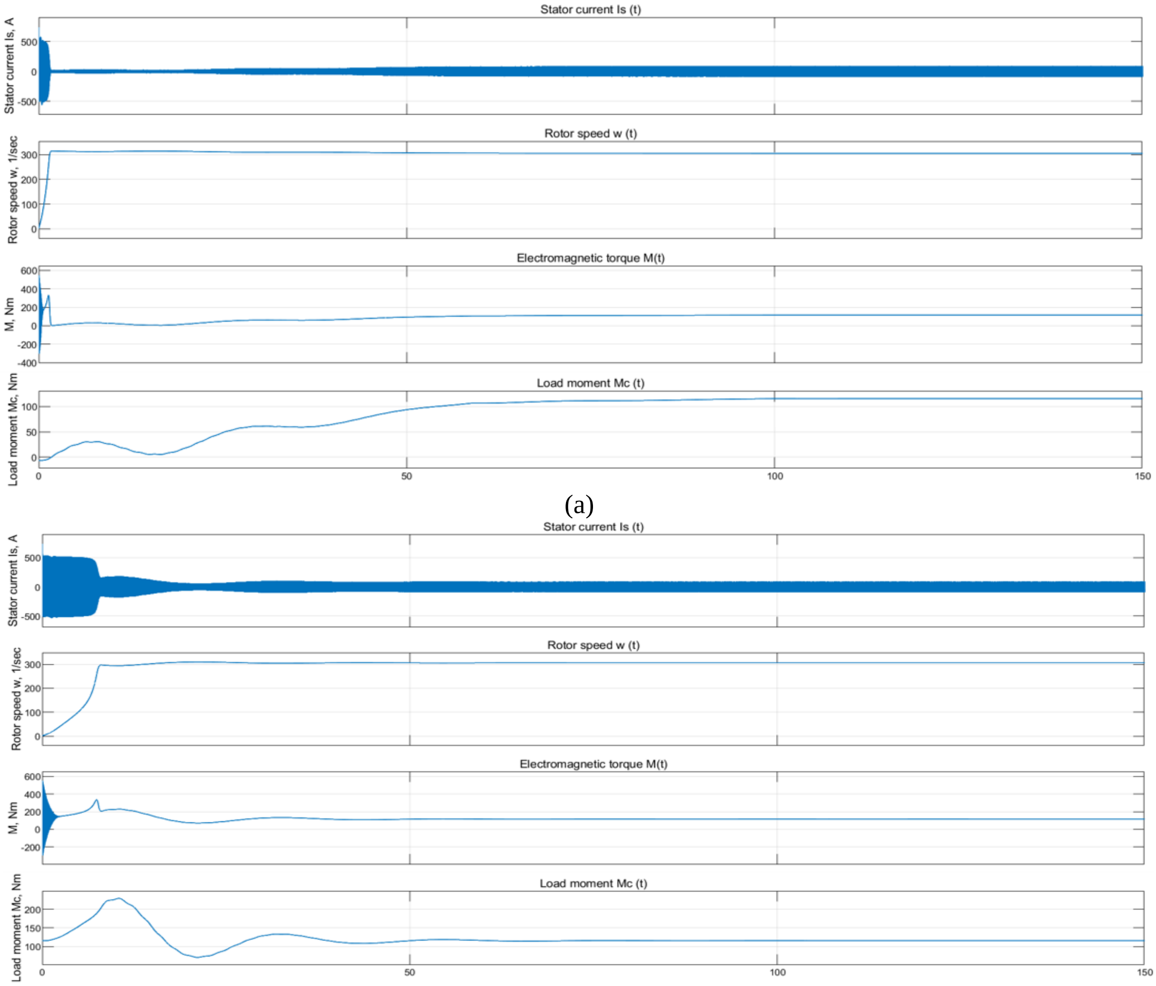
5. EXPERIMENTAL RESULTS

Transient processes (oscillograms) were compared for various parameters of the electric drive and conveyor mechanism during the initial start-up and start-up with loaded work areas. The transient processes observed on the model for stator currents speed, torques, and resistance forces on the shaft of an asynchronous motor are depicted during the initial start of the belt conveyor, as shown in Figure 6(a), and during start-up with loaded working areas, as shown in Figure 6(b). Figure 6 illustrates transient processes observed in stator currents speed, torque, and resistance forces on the shaft of an asynchronous motor during both the initial start of a belt conveyor and the start-up with loaded working areas. The key differences in motor performance, including current speed, torque, and resistance force behaviors, are summarized below for the two conditions.

In Figure 7, the oscillograms of the conveyor belt stroke speed and acceleration are depicted for two different working modes of the conveyor belt system. In particular, in Figure 7(a), the start-up dynamics of the conveyor belt are illustrated when working in the unloaded working mode, whereas in Figure 7(b), the start-up dynamics are presented when working with loaded working areas. It is seen from the analysis of Figure 7(a) shows that for the unloaded start-up process of the conveyor system, the speed of the belt considerably increases with a slight overshoot to reach the steady-state value, accompanied by large acceleration oscillations. On the other hand, analysis of Figure 7(b) reveals that for the start-up process of the conveyor system with loaded working areas, there is a smooth transition of speed with less acceleration values accompanied by well-damped oscillations.

In Table 1, the important quantitative observations made with the analysis of the transient processes in terms of the differences associated with the loaded and unloaded startup processes with regard to the current, torque, speed, and resistance force phenomena. The numerical values provided in the table serve as additional data to the oscillograms presented in the previous subpoints.

A comparison summary of Table 2 can be seen that the speed transition is noticeable during the initial start-up, the belt speed experiences a slight overshoot (3%) before stabilizing at 2 m/s, which takes 2 seconds. In contrast, when starting with loaded work areas, the speed transition is smoother with no overshoot, taking 7 seconds to reach the same speed. While the acceleration initially starts up exhibits higher oscillations in acceleration with maximum and minimum values reaching 3.93 m/s² and -1.64 m/s², respectively, over a 100-second transition period. For loaded working areas, the oscillations are less pronounced with a lower peak acceleration (2.24 m/s²) and minimum (-0.88 m/s²), reaching stability within 75 seconds.



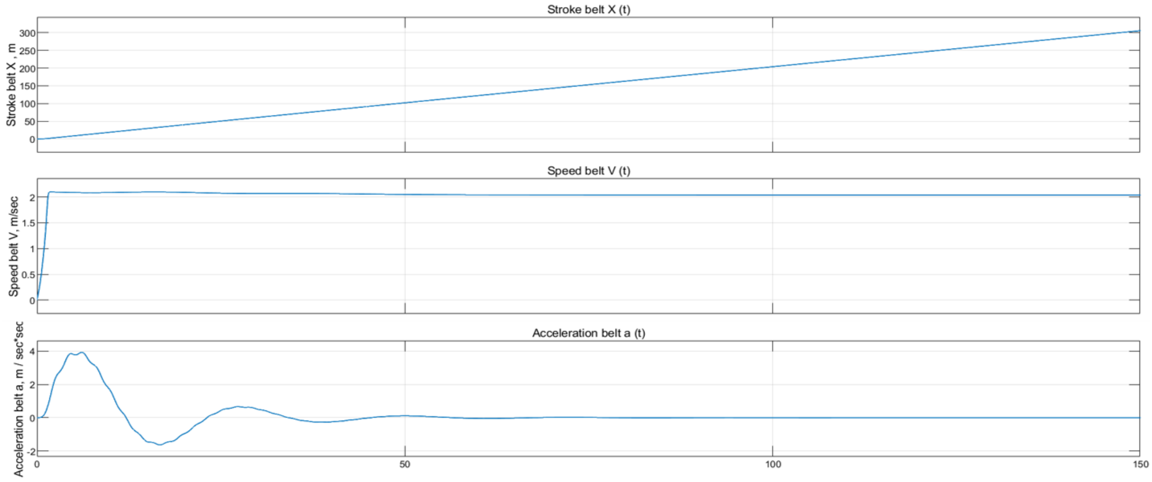
(a)

(b)

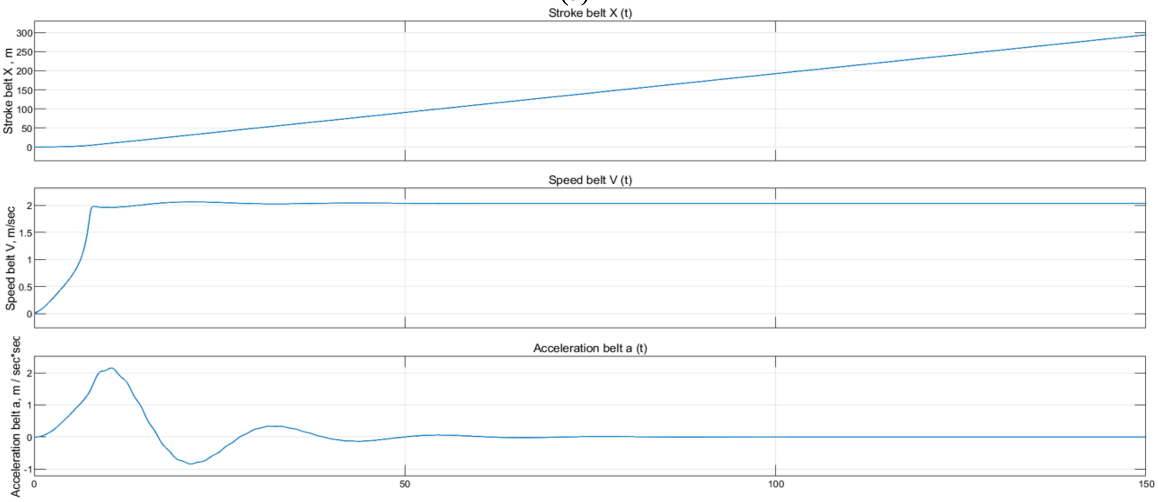
Figure 6. Transient processes in stator currents speed, torque, and resistance force on the shaft of an asynchronous motor occur during (a) the initial start of a belt conveyor and (b) during start-up with loaded working areas

Table 1. Differences between starting the conveyor with and without loaded working areas

Aspect	Initial start (unloaded)	Start with loaded working areas
Starting current	361 A (3.5 times rated current lasts for 1.6 seconds)	365 A (3.5 times rated current lasts for 7 seconds)
Current transition to steady state	Gradually increases from 16 A to 62 A over 100 seconds	Transition to 62 A over 75 seconds with oscillations
Speed transition duration	Smooth increase completed in 1.6 seconds	Takes 7 seconds to complete
Maximum torque	330 Nm (3.5 times nominal value)	330 Nm (same value)
Torque transition to steady state	A gradual increase to 116 Nm over 100 seconds	Oscillations with attenuation reach 116 Nm in 75 seconds
Resistance force on motor shaft	Smooth increase transitions to 116 Nm in 100 seconds	Oscillations with overshoot reach 102.6% of steady-state value in 75 seconds



(a)



(b)

Figure 7. Displays oscillograms of the stroke speed and acceleration of the conveyor belt during (a) the initial start-up and (b) while operating with loaded work areas

Table 2. The main insights are summarized

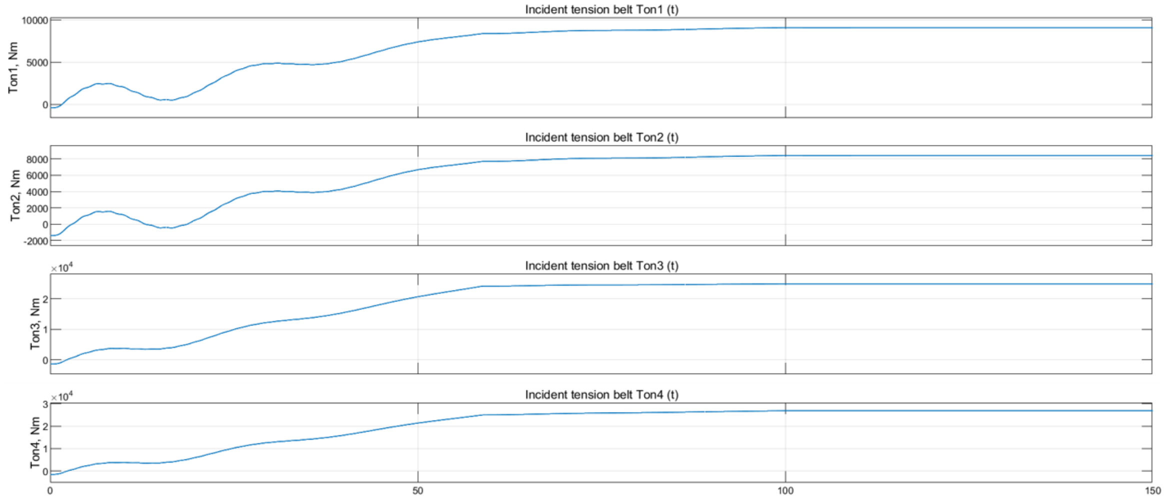
Aspect	Initial start (unloaded)	Start with loaded working areas
Belt speed transition	3% overshoot; transition to 2 m/s takes 2 seconds	No overshoot; transition to 2 m/s takes 7 seconds
Belt acceleration	Maximum: 3.93 m/s²; Minimum: -1.64 m/s²; Transition: 100 sec	Maximum: 2.24 m/s²; Minimum: -0.88 m/s²; Transition: 75 sec

Moreover, in Table 3, there is a comprehensive comparison of the tension forces in the different sections of the conveyor as the start-up procedure is carried out. It is evident that when the start-up is carried out without any loading in the working areas of the conveyor, the changes in the values of the belt tension forces in the different sections of the conveyor till the attainment of the stationary state are smooth. Conversely, when the start-up procedure is carried out in the loaded working areas of the conveyor, the oscillations that occur in the belt tension forces in the different sections of the conveyor are extreme. The degree of the overshoot in the different sections of the conveyor is not the same.

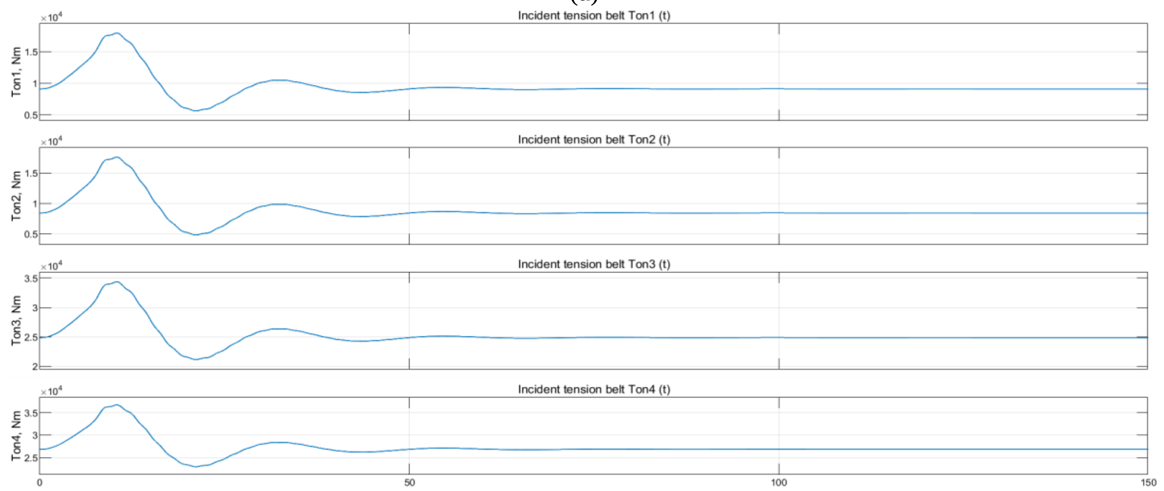
Figure 8 shows the oscillograms associated with the belt tension forces acting in each section of the conveyor during the start-up process for both unloaded and loaded operating conditions. More specifically, it can be seen that Figure 8(a) depicts the tension force oscillograms associated with the first section, second section, third section, and fourth section of the conveyor during its initial start-up process when it is started unloaded, while Figure 8(b) depicts the oscillograms during its start-up process when it is loaded. As noted from Figure 8, upon starting the conveyor belt with an unloaded system, the tension force levels for all belt sections gradually rise with smooth system dynamics, eventually reaching their corresponding final levels at stable equilibrium points, with negligible overshoot and system oscillation. However, from Figure 8(b), it is noted that for belt sections starting with load-carrying work zones, the system tension force levels vary with considerable system overshoot and system oscillations before reaching their stable equilibrium levels at corresponding final system levels due to quick system adjustment required in transitioning from initial system level to its final system level. Thus, from above observations, due to influence of loading conditions on belt tension dynamic system characteristics, system design needs to consider system tension dynamic behavior during system operation for better system stability and dynamic system adjustment during system start-up with respect to system transition from its initial system operation level to its final system operation levels.

Table 3. The behavior of the belt tension forces in various sections of the conveyor under different startup conditions

Section tension	Initial start (unloaded)	Start with loaded working areas
1st	Gradual increase from -400 N to 9900 N (over 100 sec)	Oscillations with 85% overshoot reach 9900 N in 75 sec
2nd	Smooth increase from -1400 N to 8400 N (over 100 sec)	Oscillations with 114% overshoot reach 8400 N in 75 sec
3rd	Gradual increase from -1450 N to 24870 N (over 100 sec)	Oscillations with 40% overshoot reach 24870 N in 75 sec
4th	Gradual increase from -1500 N to 26840 N (over 100 sec)	Oscillations with 38% overshoot reach 26840 N in 75 sec



(a)



(b)

Figure 8. Displays oscillograms illustrating the tension forces acting on the first, second, third, and fourth sections of the conveyor belt during (a) the initial start-up of the belt conveyor and (b) during start-up with loaded work areas

The comparison of tension forces during the startup of a belt conveyor under unloaded and loaded conditions shows clear differences in performance. When the conveyor starts without a load the tension forces in all sections rise gradually and smoothly over about 100 seconds until they reach steady-state values. In contrast when the conveyor starts with a load the tension forces show noticeable oscillations and overshoots in all sections but stabilize more quickly within around 75 seconds. Starting the conveyor with a load consistently causes overshoots in the tension forces ranging from 38% to 114% depending on the section. These fluctuations suggest that the system experiences a more unstable adjustment process when it begins operation under load. Although the loaded startup involves more oscillations it settles faster reaching stability in about 75 seconds compared to 100 seconds for the unloaded case. The loaded startup responds more dynamically with greater initial fluctuations while the unloaded startup offers a smoother but slower transition. Totally vision means the loaded startup results in a more rapid yet turbulent adjustment whereas the unloaded startup ensures a steady and gradual increase in tension forces over a longer time.

Table 4 shows a comparison of the proposed study and existing works explained in the literature for electric drive systems of belt conveyors. The comparison draws attention to the differences in modeling techniques, analysis aspects, transient processes, validation techniques, and industrial usability. In contrast to the existing works, which mainly concentrated on steady-state analysis and have less discussion regarding the start-up processes, the proposed study thoroughly investigates the transient processes, especially during unloaded and loaded start-up processes. Additionally, the inclusion of experimental validation by implementing MATLAB/Simulink simulation increases the usability and reliability of the proposed model. By analyzing and quantifying performance aspects such as stator current, torque, speed, and belt tension using performance validation techniques such as RMSE and correlation coefficient, the study proves a better performance than existing works. Hence, the proposed work provides a reliable and industrial-standard methodology for analyzing and optimizing the transient performance of electric drive systems for belt conveyors.

Table 4. Comparison of related work with this study

Aspect	This paper	Ref [7]	Ref [8]	Ref [9]	Ref [14]	Ref [18]	Ref [19]	Ref [21]
Model focus	Electric drive dynamics fo belt conveyors; transient analysis with a focus on startup conditions	Electric drive dynamics of scraper face conveyors	Simulation of electric conveyor drive using MATLAB/ Simulink	Dynamic modeling of two-motor scraper conveyor	Energy-efficient drive design for belt conveyors	Life cycle cost minimizatior for multiple drive belt conveyors	Modeling and control of multi-motor conveyor	Distribution of tractive efforts in belt conveyors with hydraulic couplings
Modeling tool	MATLAB/Simulink	USEC proprietary simulation	MATLAB/ Simulink	Universal computer model	Not specified	MATLAB; analytical optimization	IOP proprietary simulation	Not specified
Key components analyzed	Stator currents speed, torque resistance forces	Load sharing tension control	Conveyor drive simulation belt tension dynamics	Scraper conveyor dynamics	Belt drives energy efficiency	Life cycle costs energy efficiency	Multi-motor dynamics torque distribution	Tractive effort distribution hydraulic coupling
Transient analysis	Extensive transient behavior analysis for startup conditions including oscillations in tension and torque	Some transient analysis	Limited to tension analysis	Some transient focus on dynamic response	No transient analysis	No transient focus	Yes with an emphasis on control	Not primary focus
Startup conditions	Differentiates between loaded and unloaded startup conditions detailing oscillations and overshoot	Considered in the load-sharing strategy	Minimal focus	Mentioned but not central	Not considered	Not considered	Central to control system design	Brief mention
Performance metrics	RMSE correlation coefficient for stator current and torque	Efficiency load balancing	Stability energy efficiency	Response time stability	Energy savings	Cost optimization metrics	Control stability torque balance	Efficiency improvement
Practical application	Focused on improving dynamic response during startup to prevent damage	Electric drive application in mines	General conveyor application	Application in two-motoı scrapers	Industrial conveyors	Focus on cost-effective design	General conveyor systems	Application in mining conveyors
Results	High accuracy RMSE of 12.5 A for stator current and 8.7 Nm for torque; correlation coefficient of 0.98 for model validation	Enhanced load sharing and efficiency	Improved drive stability	Demonstrates enhanced stability and reduced response time	Achieves notable energy efficiency	Cost savings achieved through optimized design	Shows improved control over torque distribution	Improved tractive effort distribution
Experimental validation	Simulink-based simulation with numerical validation	Simulation results no real-world validation	Simulation only	Simulations with some real-world application	Theoretical results with simulations	Numerical analysis	Simulation-based validation	Some simulation
Main contribution	Establishes a reliable model for belt conveyor electric drives under dynamic loading conditions achieving high accuracy	Improves load distribution and energy efficiency	Provides a Simulink-based model for studying drive dynamics	Offers a universal model for scraper conveyor dynamics	Proposes design criteria for energy-efficient conveyor drives	Provides a cost-optimized approach for belt conveyor design	Enhances control systems for multi-motor conveyors	Optimizes traction distribution improves stability

Table 4 provides a summary comparison of research on electric conveyor drive systems discussing various models and approaches in relation to the performance aspects. In contrast with the majority of sources that omit or briefly mention transient behavior, this study stands out in that it addresses belt conveyors with a specific focus on transient start-up conditions for the loaded and no-load scenarios. It employs MATLAB/Simulink for modeling important variables like stator currents speed, and torque for providing a comprehensive treatment of transient dynamics. Its rigorous verification using RMSE and correlation coefficients makes it highly reliable as a model, setting it apart from more theoretical work. Its focus on startup dynamics with a possible practical implementation in mind gives the model significant benefits for industries requiring better control, like mining. This study contributes a reliable, high-accuracy model for belt conveyors, bridging the gap in the literature and facilitating greater durability and efficiency under dynamic loading conditions. By the way, in the near future, authors are considering that the belt conveyors can be controlled by AI systems and considered part of the internet of things. They should be protected, so the issue should be considered from a cyber perspective [25].

6. CONCLUSION

The study resulted in the development of a comprehensive mathematical model for the electric drive system of a belt conveyor. This model integrates the detailed mechanical components of the conveyor, characterized by parameters distributed along its length looks the mass of the transported load, the mass and elasticity of the traction element, and the static resistance forces. Transient processes were carefully examined, including stator currents, speed, torque, and resistance forces on the shaft of the asynchronous motor during the startup phase of the conveyor.

By analyzing oscillograms that illustrate stroke speed, acceleration, and the incoming tension forces across different sections of the conveyor belt there are several important findings were identified as follows: i) The transition process in speed during startup with loaded work areas is 4.375 times longer than the initial startup; ii) The transient process regarding the moment of resistance forces on the motor shaft exhibits an oscillatory nature with a pronounced overshoot of G% = 102.6% when initiating with loaded working areas whereas this moment smoothly escalates without overshoot during the initial start; and iii) The incoming belt tension force in each section manifests oscillations with overshoot percentages ranging from 38% to 114% when starting with loaded working sections.

The developed mathematical model offers a solid foundation for analyzing both the static and dynamic operating states of the drive motor and the conveyor's mechanical components, which means it allows for accurate calculation of tension forces at different sections of the belt during startup under various load conditions. This model also opens the way for future studies on how adjustable parameters of the electric drive affect the magnitude of tension forces along the conveyor belt, providing valuable insights into the overall efficiency and performance of the system.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are included within the article. Derived data supporting the findings are available from the corresponding author, [KZ], upon reasonable request.

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