LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

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MASTER'S THESIS

BELT CONVEYOR ENERGY EFFICIENCY ANALYSIS AND ENERGY MODEL DEVELOPMENT

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ABSTRACT

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Belt conveyor energy efficiency analysis and energy model development

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An energy model of a belt conveyor was designed. Operation of a belt conveyor was researched. Operational indexes were calculated. Energy optimization process and recommendations were presented.

Keywords: belt conveyor, energy model

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List of symbols and abbreviations

A_{m}—unit mechanical work

b_1 — width between the skirt boards

$\mathrm{C_{Ft}}$ — introduced artificial constant

d— driving wheel diameter

dens —material density

effM—motor efficiency

effR—gearbox efficiency

f —artificial resistance coefficient

F_{bA} —inertia and frictional resistance at the loading point and in the acceleration area between the material and the belt

F_{c} —frictional resistance due to the belt cleaners

F_{f} —frictional resistance between the skirt boards and the material in the accelerating area

F_{fr} —resistance due to idler tilting

F_{H}—main mechanical resistance

F_{N}—secondary mechanical resistance

F_{p} —resistance from the material ploughs

F_{S}—special mechanical resistance

F_{sb} —resistance due to friction between the material, handled and the skirt boards

F_{St} —gradient mechanical resistance

F_{t} —pulley bearing resistance

F_{U} — total mechanical resistance

F_{W}— total mechanical resistance

F_{w} —wrap resistance between the belt and the pulley

g—gravitational acceleration

H—total conveyor height

k_1 , k_2 , k_3—constant coefficients, reflecting the geometry of the object

L—total conveyor length

L_{h} —total distance of transportation

L_0 —compensating constant of length

$money$—electrical power price per 1kWh

M—reference motor torque

n—motor reference speed

P—motor mechanical power

P_{Acs} —introduced constant, reflecting minor power factors

P_{ec} —power to run the empty conveyor

P_{el}—conveyor electrical power

P_{h} —power to move the material horizontally over a certain distance

P_{l} —power to lift the material a certain height

P_{M}—motor electrical power

P_{T}—conveyor mechanical power

Q—total unit mass of conveyor parts

Q_{R0}—unit mass of moving part of holding idlers

Q_{RU} —unit mass of moving parts of returning idlers

Q_{B} —unit mass of the belt

Q_{G} —unit mass of transporting material

$redr$—gearbox ratio

S_{h}—price of 1 hour conveyor operation

S_{m}—price of 1kg transportation

t—load switching time

T—conveyor belt load

V—belt speed

δ—conveyor inclination angle

η—efficiency coefficient of the drive system

θ_1,θ_2, θ_3,θ_4—artificial variables, simplifying the calculation

π—mathematical constant

ρ-material density

ω—motor rotational speed

1 Introduction

1.1 Background of the study

Problem of energy efficiency improving is an urgent issue worldwide. Rise of energy resources prices bring new challenges, which can be solved only by developing efficient technical solutions. At the same time each scope of activity has own specific features, that have to be taken into account. These scoped form the total amount of electrical energy consumption, expressed by electrical power. To state effective measures for consuming resources more efficiently analysis of vital factors, determining electrical energy consumption level, should be carried out. Energy market analysis can reveal main consumers, therefore first priority fields of technology, which should be developed. Belt conveyors stand in the focus of the current paper, as conveyors consume 2% of electrical energy in industrial sector and 11% in service sector [1]. Meanwhile, sector of conveyors is not homogeneous. Wide range of applications and wide range of used technical solutions make it inappropriate to look for uniform solutions for the whole industry. Total efficiency of introduced measures depends on installed equipment and at the end is defined by economical estimation. Efficiency of electrical energy consumption in general can be improved by introducing equipment with higher technological level of efficiency, IE3 motor instead of IE2 or IE1 e.g.. Nevertheless, considering certain system economical benefits of reducing electrical energy consumption should exceed costs of new equipment and its maintenance during life cycle.

This fact make it reasonable, to choose a real object of research and build an energy model, based on its constructional and operational data. Proper approach to building a model makes it possible to adjust it to real operational measures, as constructional and actual measures tend to differ.

A choice of approach to building an energy model is an important initial step, which defines the whole research process. Two basic approaches can be named – energy model, based on resistances calculation and energy model, based on energy consumption principle. Two approaches stand for two main groups of international standards, which regulate the process of conveyor constructing. ISO 5048, DIN 22101 and CEMA are based on the first approach and JIS B 8805 is based on the second [2]. There can be mentioned the third approach, analytical. This approach is based on resistances calculation, but also

uses artificial coefficients, to simplify calculation. First approach is the most precise, nevertheless calculations are complex. Second approach is not precise, but is easier to implement. Third approach is a compromise solution.

Any approach to energy model constructing requires constructional measures of the object. In the current calculation parameters of the real object were used and then obtained results were compared to operational measures from the object. This principle makes it possible to adjust the model and make it more precise.

Energy model make it possible to define main factors, which have the biggest role in electrical energy consumption and energy efficiency of the object. This approach helps to focus only on important aspects, casting away insignificant measures. As an index of energy efficiency it makes sense to use price of consumed energy or a ratio between wasted money and conveyed material mass.

Along other aspects it is also significant to choose a proper control algorithm for the object. In the field of belt conveyors series of experiments were held and results were sometimes conflicting. Modern technical literature still compares two main measures of control – belt speed and loading factor. Following stated principle of this paper, this aspect was tested on a real object model. Summing up, it can be stated that all found technical solutions should be considered suitable for the defined object, not for the wide range of applications.

1.2 Objective of the work and limits

The main objective of the work is belt conveyor efficiency analysis and developing technical measures to increase energy efficiency. The analysis is based on an energy model of a belt conveyor, which was developed during the research process. The model is based on a real object; therefore technological parameters of the object were used as reference parameters for the model. The objective of the analysis is stating recommendations and measures for increasing energy efficiency of a belt conveyor. As the analysis is based on a model, final recommendations refer to a real object, used for model development. Therefore, obtained results are not designed to be used in a variety of systems and conditions. Moreover, designed measures were also tested on the model of a real object; therefore potential benefits may vary if used in other applications. Analysis, based on an

energy model does not consider work schedule, desired level of daily productivity, volume of raw material supply etc., focusing on technical equipment, used in the source object and parameters of handling material.

1.3 Methods, used to achieve the objective

Work starts from analysis of electrical energy consumption and energy efficiency in general. These introductions chapters serve to state main aspects, which are researched in the following chapters. This theoretical part is vital to exclude excessive work at ineffective measures. Moreover, it is used as substantiation for a developed model. The energy model is based on an analytical approach and uses available data of the conveyor, transporting wood chips on a Finnish forest integrated plant. Model and analysis, based on it are the main objectives of the work. As it will be discussed in the following chapters, analytical approach to energy modeling was used to develop a model of a belt conveyor. A real technological object was used to provide energy model with reference parameters. As far as analytical approach is more flexible in comparison with other approaches (chapter 4) it includes also operational indexes of the object in order to adjust artificial constants, used in the developed model. As adjustment of constants increased precision of the developed model (model indexes approached nearly real object indexes), analysis of model operation provides more reliable results. Stated measures and recommendations refer to a real object and are based on equipment and parameters of the raw material, handled by the real conveyor system.

1.4 Structure of the work

The work consists of 9 chapters, which reflect various aspects of the research. The objective of the work is belt conveyor efficiency analysis. Work is designed so research starts from a broad overview of main terms and then focuses on the main objective. This principle serves several purposes: it allows introduction of all necessary terms and methods, which serves as a substantiation for following model development and system analysis.

The work begins with an introduction chapter; it reflects background of the work, main objective, principles and methods used to achieve the objective and limits of the work. Next chapters, such as “Electrical energy consumption” and “Energy efficiency” introduce

main terms, studied in the work. Moreover, modern energy market, up-to-date conveyor technologies and widespread methods of energy efficiency optimization are described. Moreover, these chapters also give a short analysis technologies and their applicability in the studied scope. Following chapter “Developing a model” describes modern approaches to energy models development. This chapter introduces mathematical expressions, reflecting specific features of energy models. This chapter also introduces mathematical tool, used for developing a belt conveyor energy models, which is studied and analyzed in the current work.

Following chapter “Source object description” introduces the original technological object and its operating equipment and parameters. These parameters are used as a reference for developing an energy model. The main objective of the chapter is to show the process of the model development and describe its vital elements. It also shows user interface of the model, algorithms of parameters setting and dependencies between all model parameters. In such a way, starting from a description of the source object and general overview of the developed model the chapter comes to description of the model operation and tools for energy analysis.

Next chapters “Calculation results with nominal input values” and “Experiments” represent process of operating a model with operating setting of equipment on the real object. Calculation represents technological and economical indexes, which reflect electrical energy consumption, production and energy efficiency level of the object. Experiments, described in the following chapter describe series of experiments. Reference parameters, used for setting the equipment were varied in order to find a better operational point with a higher level of energy efficiency. The objective was to consume less electrical energy with saving the same production volume. Results were shown with diagrams to ease demonstration of different approaches of setting.

Last chapters, “Conclusion” and “Summary” introduce short summary of analysis and proposed technological measures for rise of energy efficiency.

2 Electrical energy consumption

2.1Total distribution of energy consumers

A question of improving electrical energy consumption in general should be researched on a basis of consumers' distribution. As technical improvements in one field can reach high levels, total consumption level of the sector can have insignificant reduction. It is vital to distinguish two main sectors – industrial sector and service sector, as distribution of consumers vary. Not only these sectors have specific consumers, but also common ones have different total role.

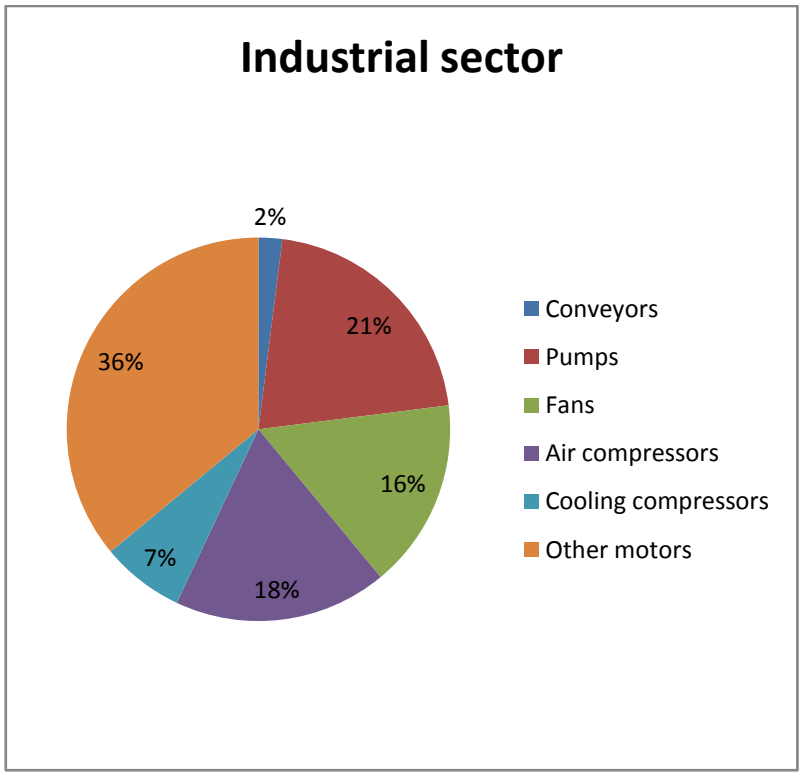

Fig. 1. Distribution of consumers in industrial sector in EU [1]

Note: Other motors include various loads, mainly of material processing sector (mills, cutters, laminators, extruders, mixers etc.) and material handling sector (conveyors, hoists, packers etc.)

Part of fans and pumps in both sectors is almost equal, while part of conveyors varies heavily. Each type of consumer requires certain algorithm of control and has a certain border of energy efficiency improving. Motors are often controlled by electrical drives, which are used for various technical applications and are highly developed nowadays.

Centrifugal loads, on the contrary, are controlled by managing material flow density, not the power source. For example, decreasing material flow density by 20% can decrease power consumption by 50%.

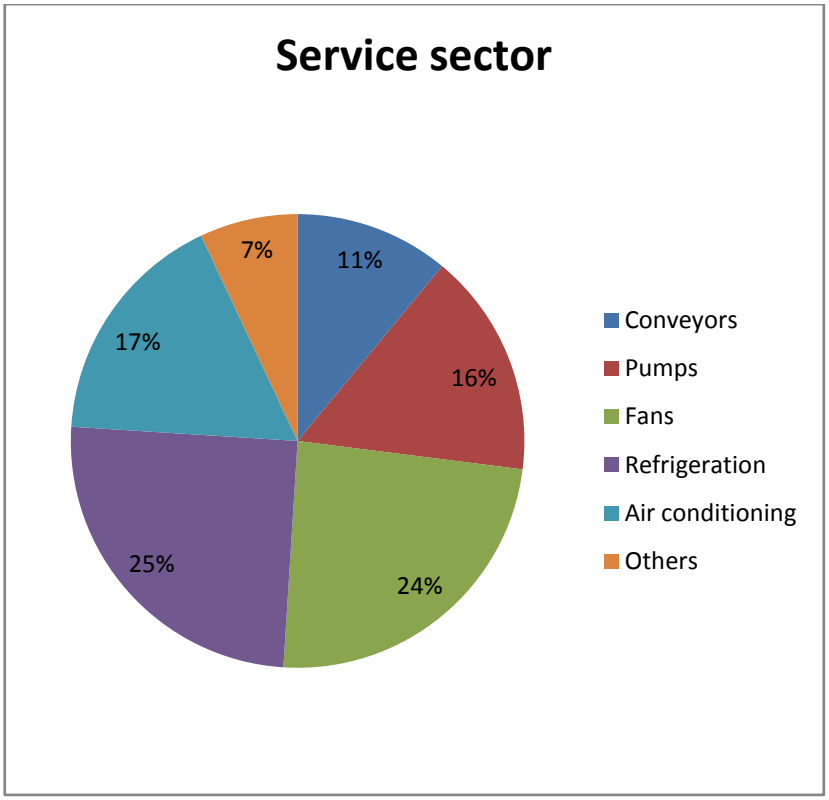

Fig. 2. Distribution of consumers in service sector in EU [1]

As types of consumers vary, different technical applications demand personal approach for increasing energy efficiency. Common measures are not numerous – integration of modern equipment and controlled loads, efficient management, professional development.

Previous data correspond to European Union and can differ for certain states and regions. This fact leads to a known conclusion, that a solution should be based on a defined field and be specific.

2.2 Conveyor systems

Conveying systems play a noticeable role in technical sectors, as it is shown above. Belt conveyors represent most important parts of material handling systems because of high efficiency of transportation [2]. The task of reduction of handling costs involves developing conveying system and all its components, from motor to idlers. Decreasing cost of transportation decreases the total price of production.

Belt conveyor is in fact a typical system of transforming electrical power into mechanical. Nevertheless it sounds simple; the process is complex and involves numerous components, efficiency of each makes up the total efficiency of the whole system. Process of improving efficiency of conveyor has several levels – productivity, operational schedule, equipment level and technology.

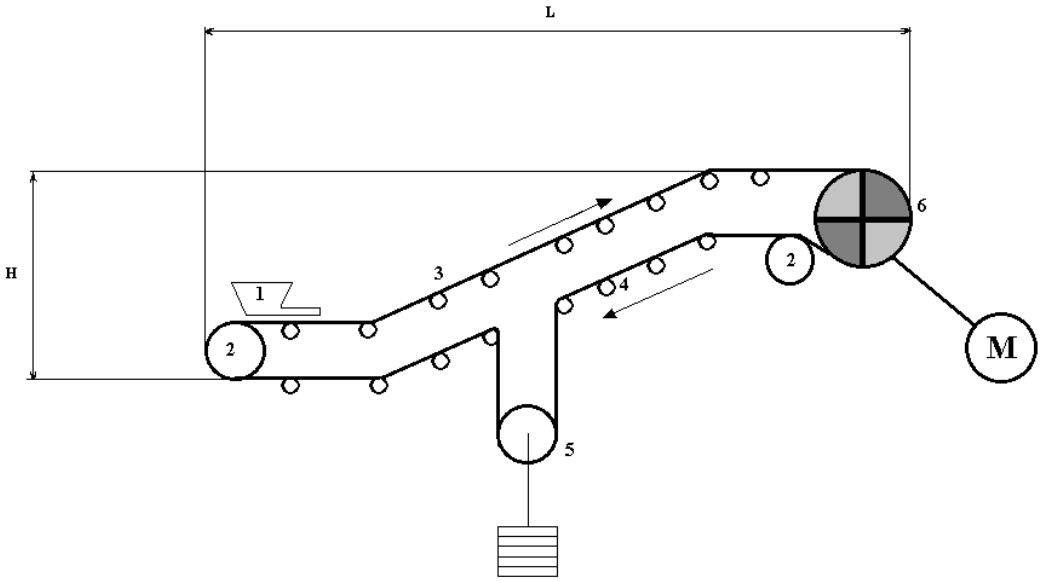

Fig.3 Simplified diagram of a belt conveyor. 1. Material loader 2.Idler pulley 3.Top rollers 4. Return rollers 5.Tightener 6. Drive wheel; M-electrical motor, driving system; H-total height, L-total length

Practically, energy efficiency improving demands integrations of modern technical equipment. Idlers, belt and driving system are stated as main subjects of such work. Various research papers state different components and factors, which influence on conveyor efficiency [3]:

- Idlers - construction, design, lubrication, bearing, sealing and inspection.
- Conveyor belts – structure, material and reliability
- Motors, used in the conveyor system

Also level of productivity was researched:

- Variation of load level
- Belt speed regulation with constant material loading
- Material loading regulation with constant belt speed
- Electrical drive options

Nevertheless, every possible technical solution should be tested on a proper energy model prior to implementing it on a real technical object. Specific application has special components and factors, which can be evaluated with an energy model.

Energy model construction involves well known standards, such as ISO 5048, ISO 22101, JIS B 8805 and CEMA. Important to bear in mind, that any approach to modeling has benefits and disadvantages[3]. Approach should be chosen based on a specific application. Precise results demand complex calculations; in some cases it is not essential. A compromise solution with relatively simple mathematical basis and relatively high precision can be a good option. Energy model of a conveyor more or less represents a common construction of conveyor system. Varying parameters it is possible to adjust a model to represent a certain conveying object. Inclusion of operational measures can significantly increase precision of results and can make analytical conclusions more reliable and specific. Nevertheless, the process of adjusting a model can be relatively easy, while constructing a precise model can demand a long period of time [3].

2.3 Latest developments in belt conveyor development

Considering latest tendencies in the field of belt conveyors it can be seen, that the majority if new technologies are in fact already known and remade. The key component is the approach to integrating these technologies and wide usage of energy models for testing purposes. Conveyor modeling plays a great role, as it makes possible to test basic object measures before commissioning [3].

Main directions of technology development can be named [4]:

- Energy efficiency optimization
- Transportation route optimization
- Electrical power distribution decentralization (intermediate drives)
- Analysis and optimization

These directions are closely connected. All these aspects are usually worked at during development of the project. Object specificity determines applicability of technologies and approaches. That means that quality of results and analytics depends on the range of research. Wide research area demands wider approach and average analytical conclusion can be irrational in some applications.

Basic directions of technologies development are closely examined in the following chapter.

3 Energy efficiency

3.1 Generic description

Total electrical energy consumption minimization is a key aspect of any technical project and belt conveyors are not exclusion. Though belt conveyor is a powerful tool for transporting goods and materials and is applicable for transporting heavy loads, there are several options for efficiency increasing. Electrical energy consumption depends on mechanical forces in the conveyor system. As it was stated earlier, a belt conveyor is a system, converting electrical power into mechanical. Mechanical power in its turn depends on mechanical forces which resist setting the belt into motion. These forces are already known and can be named [4]:

- Idlers resistances
- Resistances of unevenness of material covering carrying idlers
- Resistances, specified by material/belt flexibility on rolling idlers
- Resistances, specified by mechanical imperfection of system adjustment

These resistances in combination with secondary forces, needed for hoisting material, form the needed amount of electrical power [1]. Nevertheless, distribution of resistances varies in different applications.

A standard industrial belt conveyor with 400m length can be considered as an example. Power, setting in motion, can be divided in several components [4]. As it can be seen on Fig. 3 the majority of power is spent for lifting the material. It was also established, that running resistance of idlers and therefore needed amount of electrical power to drive the conveyor is determined by type and amount of grease used in the labyrinths and roller bearings. Moreover, environmental temperature and humidity are also parameters, which determine grease density behavior and therefore idler resistance. Choice of grease for mechanical elements should consider ambient conditions. [9] Analysis of belt resistance also established dependency on ambient temperature. Important to say, that differences of resistances with various temperatures depend on belt material. Nevertheless, general conclusion is that with lower ambient temperature belt resistance is higher. [9]

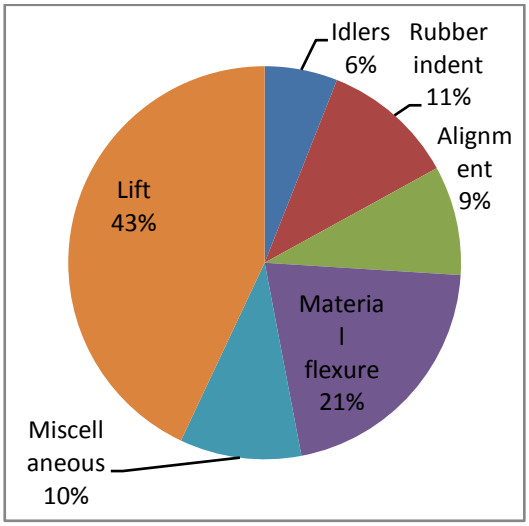

Fig. 4. Conveyor electrical energy consumption. Horizontal length 412 m, vertical lift 12 m [4]

In a conveying system with a higher angle of lifting, in a mine, for example, power distribution has a different structure. It can be seen on the following picture. Role of the lifting component is evidently bigger. As it is impossible to decrease the height of the system, the potential of efficiency increasing is bordered.

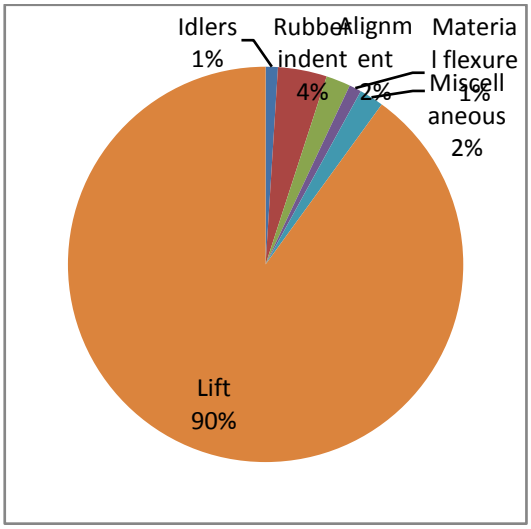

Fig. 5. Conveyor electrical energy consumption. Horizontal length 686 m, vertical lift 199 m[4]

Considering a long land conveyor it is evident, that power distribution is differs from the previous results. It is also seen on a diagram. Main part of consumed energy is spent on overcoming mechanical resistances. Therefore this component is examined as the main aspect of efficiency increasing.

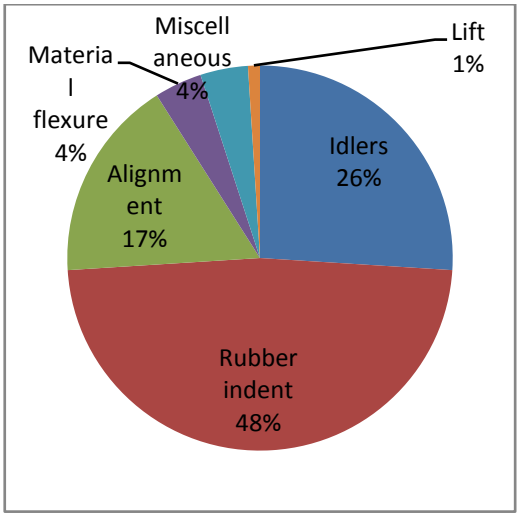

Fig. 6. Conveyor electrical energy consumption. Horizontal length 19139 m, vertical lift 3 m [4]

As it was stated earlier, main technologies in the field of belt conveyors are well known. Previous diagrams show that different applications ask for specific approaches, as components, determining the total amount of consumed electrical power, are different in each case.

3.2 Route optimization

Route optimization involves changing the transportation route for shorting it and decreasing the consumed amount of energy. Evidently, the shortest line between two points is mostly preferred. Unfortunately, it is not always possible due to specific of territory, occupied by the technical object. Possibilities of shortening and optimization of existing route is examined in the following chapter.

3.2.1 Horizontal route optimization

Practically, nature specifics of territory not always guarantee the shortness of the transportation route. Rugged topography is often an obstacle, which demands new approach to constructing a conveying system. In such cases, tunnels are often used. This approach can significantly shorten the transportation route, nevertheless, the cost of a tunnel project demands proper economical analysis of the application [5].

Another option of horizontal optimization is changing the geometry of the conveyor belt. Practically it means usage of tube belts, in which the plane belt is rolled into the tube and unrolled at the end point of the route. This approach makes sense in applications with bulk materials transportation.

Fig. 7. Tube belt conveying system [4]

There is series of other technical approaches, which change geometry of belt. They include solutions of changing the tension of the belt and changing the angle between conveyor belt

and earth. Inclined conveyor belts are used in systems mostly on rugged topography with a large sum of turns during the route.

3.2.2 Vertical route optimization

This group of technical solutions is used in conveyor systems with significant lifting or lowering heights . Traditional conveying applications involve angles lower than 18°, therefore new technologies can afford higher inclination angles.

A group of solutions are named High Angle Conveyor [4]. Construction of these conveyors is called “sandwich”, as the material is transferred between two belts. Technology involves changing the geometry of the belt and usage of additional pressure component, which presses the belts and the material together and prevents caving of the material inside the “sandwich” during the route.

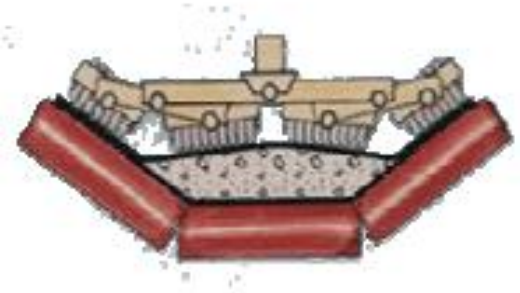

Fig 8. High angle conveyor (HAC®) [4]

Another solution should be mentioned, so called Pocketlift® [4]. It affords vertical lifting and lowering of materials. The material is brought on the belt divided by equal portions which are loaded in the separate pockets of the conveyor. Such construction uses separate holding equipment for each pocket. This technology is used in mines. As an example of usage, application Pattiki 2 [6] can be examined.

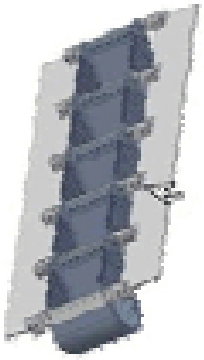

Fig 9. Constructional principle of Pocketlift® [4]

Fig 10. Pocketlift® conveyor at Pattiki 2 [4]

3.3 Power decentralization

A separate group of solutions is aimed on optimization the way the object is powered and set in motion. Earlier electrical drives usually were installed at the end point of the route, nevertheless. Nowadays this approach is not a common rule. A tendency can be seen, following it manufacturers and developers optimize the application by decentralizing power supply and installing drives along the transportation route. This approach is beneficial is several aspects, which will be examined later.

The idea to decentralize driving system is not new. The first application, based on this principle was built in 1974 in USA. That application was built for use by American miners

[4]. The reasons to choose this method were numerous. Firstly, such approach guarantees more reliability, as material transportation will not stop after breakage of one of the drives. Besides, this method guarantees higher permissible load. One aspect is field specified. Mines have a limitation of free space; hence several drives of smaller size were more convenient for installing, than one large machine.

One more feature of decentralized drives should be mentioned. This feature is minimizing tension of the belt. Due to this benefit decentralized drives are used not only by miners, but also in tunnel applications [7].

A common demonstration of this principle is shown on the diagram. This diagram shows tension dependence on the number of drives. The peak level of tension refers to the end point of belt, where the drive is installed. First part refers to the holding part of the belt; the second part refers to the returning part. Red line refers to application with one intermediate drive; green line refers to two intermediate drives. Each drive excites a peak of tension near itself. Nevertheless, the total level of tension decreases with increasing of drives number.

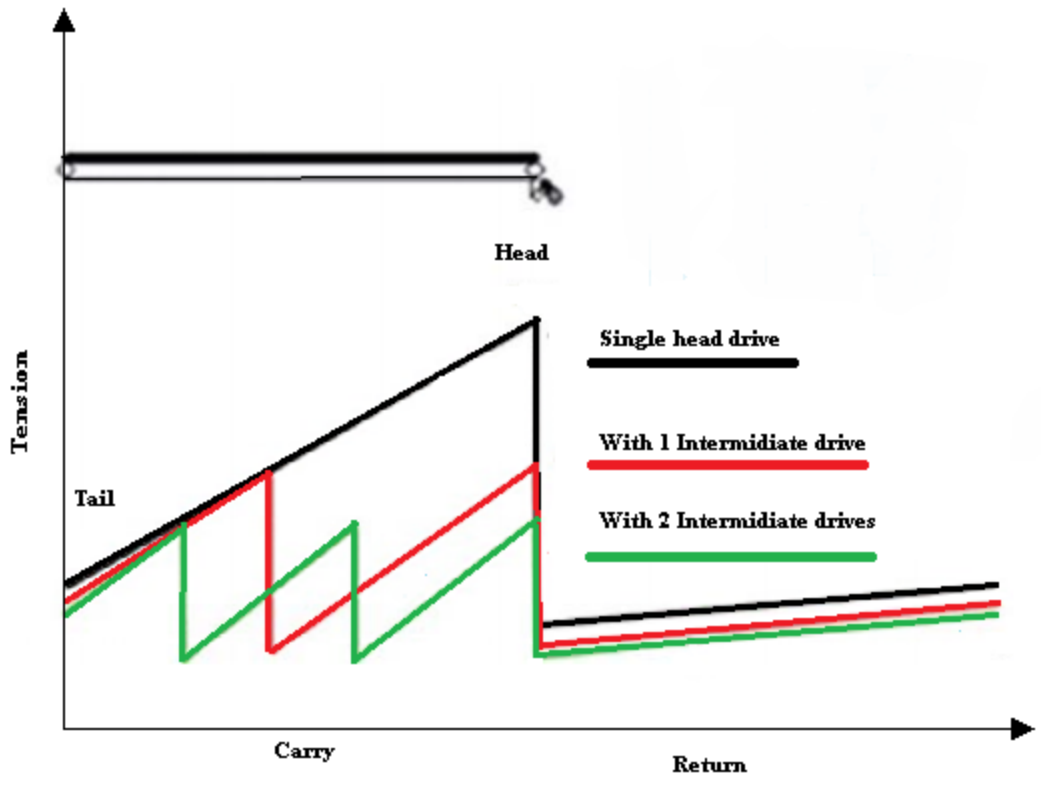

Fig 11. Tension dependence on the number of intermediate drives [4]

The technology of installing intermediate drives became convenient and reliable. It guarantees continuous transportation with needed level of production. As additional equipment has a certain financial cost a balance should be held between maintainability and reliability benefits and financial investments. Therefore, upgrading the application with intermediate drives should be rational due to economical analysis.

3.4 Analysis and simulations

No matter which way of optimization was chosen, developers are commonly using simulation tools to test their concepts, before commissioning [8].

Conveyor modeling involves several aspects. The wideness of analysis determines complexity of calculation and modeling. One approach to conveyor modeling is focused on studying the belt behavior under different conditions. Main aspects of this behavior were mentioned earlier, they refer to mechanical forces in the conveyor system. Proper evaluation of these aspects will lead to declination of consumed energy. Another approach is focused on analysis of the material transported on the conveyor. Such models analyze certain material, it's structure and behavior during transportation process, not only on the belt, but also in the feeding tubes. Particles of the material, their speed and motion trajectory are studied. Such approach can show a detailed picture of feeding process, describe mechanical forces influencing particles and dynamics of the material flow.

It is possible to combine different approaches in one model. Nevertheless, number of studied measures defines the complexity of work, process of developing the model and also the studying process itself. This aspect is studied beforehand, during economical evaluation of the modeling project.

3.5 Control algorithms

Stability and energy efficiency of the object is mostly determined by the control system of the object, its principle, settings and equipment. As it was stated before, in a wide range of questions regarding belt conveyors it is needed to examine specific features of the application examine environment. Nevertheless, a certain number of principles exist. These principles are regularly under analysis and discussion in technical literature, their applicability is always a question of interest. Every examination should be based on experimental measures.

Lately, mostly in German technical literature, a number of recommendations regarding speed control have been published [9]. According these recommendations, 100% level of load should be kept constant. Under 100% level, the maximum level of load on the belt (depending on the material and conveyor features) is taken. This means, that varying speed of the belt, the load level should be kept the same [10]. This approach, according to description, should decrease electrical energy consumption. It should be stated, that this approach is quite controversial. Using modern tools of computer simulation and modeling, group of researchers studied key factors, which define the total level of electrical energy consumption [11]. They mostly focused on mechanical resistances of the system. Researchers concluded that the total electrical energy consumption is determined mostly by level of load, not by the speed of the belt. Method of calculation involved 60% and 80% of nominal values [9].

3.6 Theoretical basis of calculation.

Mentioned experiments were based on standard DIN 22101, which involves following definitions of resistances [12]:

- Main resistance F_{H}
- Secondary resistanceF_{N}
- Gradient resistanceF_{St}
- Special resistance F_{S}

Total mechanical resistance of the system can be calculated as follows:

$$F_{\mathrm{W}} = F_{\mathrm{H}} + F_{\mathrm{N}} + F_{\mathrm{St}} + F_{\mathrm{S}} \qquad (1)$$

This approach will be discussed later. Theoretical basis refers to calculation of resistances. It should be stated, that this is not the only approach to energy modeling. A key factor here is applicability.

Applicability of DIN 22101

Standard DIN 22101 describes fundamental principles for calculation and construction of belt conveyors for bulk materials [13]. For calculation of main resistance component Coulomb’s law is used.

Mechanical mass of transporting material, conveyor belt and idlers, multiplied by artificial component f forms main resistance of the system. Definition of the f value is quite important, especially if the main component has a great role in total resistances distribution. This coefficient has certain rules of definition and is set based on system measures. Besides this coefficient, a number of other parameters is set during calculation – unit mass of load material, unit mass of idlers etc. Set parameters reflect a set condition of the system, its setting and are not changed.

Nevertheless, known studies, work by Alles R. show a certain fluctuation in the f coefficient during changes in operational conditions [14]. Dependence of this coefficient on the load level was examined by Alles R. The result can be seen on the following diagram:

Fig.12 shows a certain behavior of resistance coefficient during fluctuation of nominal load. In the phase of 0-16% of nominal load coefficient decreases, but after a negative peak it starts to increase. Nevertheless, following the studies method used by researches, Alles R particularly, only second kind of dynamic can be examined. This approach is a compromise to some extent. Nevertheless, involving this aspect in modeling project can increase reliability of the final results. As load level is inversely proportional to speed, the dynamic of resistance coefficient is opposite when speed is varied. This means that with growth of speed coefficient increases to a peak and after this peak value it decreases [9].

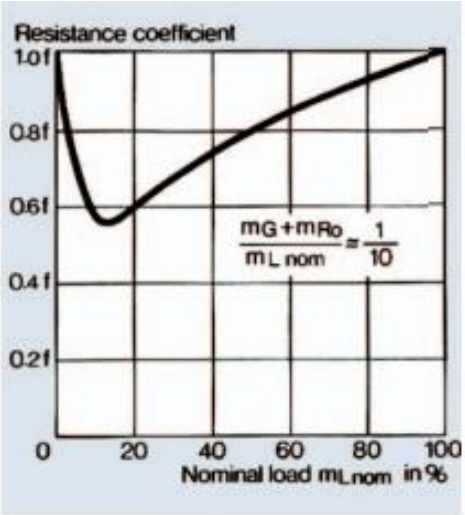

Fig 12. Dependence of resistance coefficient on nominal load level [14]

4 Developing a model

The process of developing an energy model of a belt conveyor begins with a choice of approach. As it was mentioned before, approaches to energy models developing are based on international standards. First group of standards which includes ISO 5048, DIN 22101 and CEMA is based on approach of resistances calculation. Second group, which includes JIS B 8805 and Goodyear's model, is using an approach of energy conversion principle [2]. Both types of models have advantages and disadvantages, which should be closely analyzed. Applicability of each method depends on application features.

4.1 Resistance based energy models

This type of models is based on calculation of mechanical resistances of the belt conveyor. With nominal values of system setting, resistance of belt is calculated. ISO 5048 and DIN 22101 [12,15] distinguish four components of total mechanical resistance: main resistance F_{H}, secondary resistance F_{N}, gradient resistance F_{St} and special resistance F_{S}.Hence, the total mechanical resistance of the conveyor belt can be written the following way:

$$F_{\mathrm{U}} = F_{\mathrm{H}} + F_{\mathrm{N}} + F_{\mathrm{St}} + F_{\mathrm{S}} \quad (2)$$

After definition of all four components and calculation of the total resistance, the mechanical power of the conveyor can be calculated:

$$P_{\mathrm{T}} = F_{\mathrm{U}} * V \quad (3)$$

,where V – is the speed of the belt (m/s).

Basing on mechanical power of the conveyor it is possible to calculate electrical power of motor, which sets the belt into motion. It can be done with the following formula:

$$P_{\mathrm{M}} = \frac{P_{\mathrm{T}}}{\eta} \quad (4)$$

,where η is efficiency coefficient of the driving system, which includes motor and gearbox.

Considering four resistance components main formulas should be expressed. These formulas are based on definitions from ISO 5048 and DIN 22101. Main resistance can be calculated with the following formula:

$$F_{\mathrm{H}} = \mathrm{fLg}[Q_{\mathrm{R0}} + Q_{\mathrm{RU}} + (2Q_{\mathrm{B}} + Q_{\mathrm{G}})\cos\delta] \quad (5)$$

In this expression f is an artificial coefficient of resistance, it was considered earlier. L is the total length of the belt, Q_{R0} is the unit mass of moving part of holding idlers (kg/m), Q_{RU} is unit mass of moving parts of returning idlers (kg/m), Q_{B} is unit mass of the belt (kg/m), δ is the inclination angle of the belt ( ), Q_{G} is the unit mass of transporting material (kg/m). Also Q_{G} is defined by the following expression

$$Q_{\mathrm{G}} = \frac{T}{3.6V} \quad (6)$$

,where *T* is the load of the belt (t/h).

Secondary resistance, according to ISO 5048 and DIN 22101 [11,15]can be divided in four components:

1. The inertia and frictional resistance at the loading point and in the acceleration area between the material and the belt, F_{bA}
2. The frictional resistance between the skirt boards and the material in the accelerating area, F_{f}
3. The wrap resistance between the belt and the pulley, F_{w}
4. The pulley bearing resistance, F_{t}.

Similarly, the special resistance is further divided into four parts:

1. Resistance due to idler tilting, F_{fr}
2. Resistance due to friction between the material, handled and the skirt boards, F_{sb}
3. The frictional resistance due to the belt cleaners, F_{c}
4. The resistance from the material ploughs, F_{p}

Gradient resistance if determined by incline of the conveyor system and can be calculated with the following formula:

$$F_{\mathrm{St}} = Q_{\mathrm{G}} * \mathrm{H} * \mathrm{g} \quad (7)$$

H – is the total height of conveyor, difference in heights between starting point and end point.

4.2 Energy based models

Considering principle of energy conversion, it can be stated, that power, consumed by conveyor can be divided into 3 components:

1. Power to run the empty conveyor, P_{ec}
2. Power to move the material horizontally over a certain distance, P_{h}
3. Power to lift the material a certain height, P_{l}

Separate components also contribute to the energy balance of the conveyor system. This part can be expressed by P_{Acs}. Total power, needed to drive the conveyor belt is expressed by the following formula:

$$P_{\mathrm{T}} = P_{\mathrm{ec}} + P_{\mathrm{h}} + P_{\mathrm{l}} + P_{\mathrm{Acs}} \quad (8)$$

P_{ec}, P_{h}, P_{l} are calculated by appropriate formulas:

$$P_{\mathrm{ec}} = \mathrm{gf}(L_{\mathrm{h}} + L_0)\mathrm{Q}V \quad (9)$$

$$P_{\mathrm{h}} = \mathrm{gf}(L_{\mathrm{h}} + L_0)\frac{T}{3.6} \quad (10)$$

$$P_{\mathrm{l}} = \mathrm{gH}\frac{T}{3.6} \quad (11)$$

where L_{h} is a total distance of transportation (m), $L_0$is a compensating constant of length (m) and $\mathrm{Q} = Q_{\mathrm{R0}} + Q_{\mathrm{RU}} + 2 * Q_{\mathrm{B}}$ (12)

Most components of resistances change, depending on the conveyor length. Nevertheless, several components don't depend on the belt length. $\mathrm{L}_0$is used for compensation of these components. JIS B 8805 is based on these definitions, nevertheless, determination of L_0 for various models can vary.

Remarks on the existing models

Models, based on resistance calculation take into account a large number of aspects, defining total electrical energy consumption [16]. Hence, resistance based models are believed to be more accurate. Nevertheless, more complex mathematical expressions are used for parameters definition and calculation of the model [17]. This fact is vital, hence it makes the study process more complicated. On the other hand, energy based models are

using less complex calculations, integrating compensative constants. This approach of using artificial constants leads to decreasing of accuracy. Therefore, a compromise takes place – more comprehensive and accurate model is more complicated to be developed and calculated and ease of calculation and development decreases accuracy. Moreover, existing models use constructional parameters of objects, while constructional and factual measures differ to some extent. This difference also decreases accuracy of model calculation.

During development process, carried by the author, actual measures of the object were used to adjust the model by varying artificial constants [18]. An opportunity of comparison actual and theoretical results is crucial, as it makes possible to make a model, similar to the prototype. Accuracy of the model can guarantee reliability of recommendations for increasing total energy efficiency of the object.

4.4 Analytical energy model

Analytical energy model can be a compromise between accuracy of the model and complexity of calculation. Moreover, analytical model in comparison with resistance based models is based on a less amount of parameters and is beneficial, when initial data is limited. Routes of this approach originate in the ISO 5048 standard [15]. Nevertheless, analytical form provides necessary parameters setting and electrical energy consumption optimization.

According to ISO 5048 and DIN 22101 [12] secondary resistance of the belt can be expressed by the following formula:

$$F_{\mathrm{N}} = F_{\mathrm{bA}} + F_{\mathrm{f}} + F_{\mathrm{w}} + F_{\mathrm{t}} \qquad (13)$$

F_{t} has a relatively small value, hence it can be cut out

F_{w} also has relatively small value and varies a little, so it is replaced by a constant C_{ft}

If the initial speed of material in the direction of belt movement is taken as zero and the frictional factor between the material and the belt is taken as the same as that between the material and the skirt boards, F_{bA} and F_{f} can be calculated through the following formulas:

$$F_{\mathrm{bA}} = \frac{TV}{3.6} \qquad (14)$$

$$F_{\mathrm{f}} = \frac{T^2}{6.48\rho b_1^2} \quad (15)$$

where ρ is the bulk density of material (kg/m3) and b_1 is the width between the skirt boards (m). Now, $\mathrm{F_N}$ can be rewritten:

$$F_{\mathrm{N}} = \frac{TV}{3.6} + \frac{T^2}{6.48\rho b_1^2} + \mathrm{C_{Ft}} \quad (16)$$

Special resistance $\mathrm{F_S}$ for existing conveyor, including $F_{\mathrm{fr}}, F_{\mathrm{sb}}, F_{\mathrm{C}}$ and F_{p} has a certain expression with *V* and *T*:

$$F_{\mathrm{S}} = k_1 \frac{T^2}{V^2} + k_2 \frac{T}{V} + k_3 \quad (17)$$

,where k_1 , k_2, k_3 are constant coefficients, reflecting the geometry of the object.

Combining mathematical expressions of components following formula can be written:

$$P_{\mathrm{T}} = \frac{V^2 T}{3.6} + \frac{VT^2}{6.48\rho b_1^2} + \{\mathrm{gfQ}\left[\mathrm{L}\cos\delta + \mathrm{L}(1-\cos\delta)\left(1 - \frac{2Q_{\mathrm{B}}}{\mathrm{Q}}\right] + k_3 + \mathrm{C_{Ft}}\right\} V +$$

$$+ k_1 \frac{T^2}{V} + (\frac{\mathrm{gLsin\ \delta + gfLcos\ \delta}}{3.6} + k_2)T \quad (18)$$

Hence, it can be stated:

$$\theta_1 = \frac{1}{6.48\rho b_1^2} \quad (19)$$

$$\theta_2 = \mathrm{gfQ}[\mathrm{L}\cos\delta + \mathrm{L}(1-\cos\delta)\left(1 - \frac{2Q_{\mathrm{B}}}{\mathrm{Q}}\right] + k_3 + \mathrm{C_{Ft}} \quad (20)$$

$$\theta_3 = k_1 \quad (21)$$

$$\theta_4 = \frac{\mathrm{gLsin\ \delta + gfLcos\ \delta}}{3.6} + k_2 \quad (22)$$

We obtain analytical energy model of the object:

$$P_{\mathrm{T}} - \frac{V^2 T}{3.6} = \theta_1 T^2 V + \theta_2 V + \theta_3 \frac{T^2}{V} + \theta_4 T \qquad (23)$$

$\theta_1, \theta_2, \theta_3, \theta_4$ are defined by structural parameters and components of the belt conveyor, by the operational regime and by the characteristic of material. Therefore, these parameters are nearly constant for a certain conveyor. This way it can be stated, that contractual or operational change of the object will change these parameters. To increase accuracy of calculation it is beneficial to use experimental measures of the object. As it was stated before, experimental values differ from contractual values of the object.

5 Source object description

5.1 Object description

In the current paper a forest integrated plant in south Finland was considered. Energy model is simulating a belt conveyor, installed in this technological object. The source conveyor is transporting wood chips.

Fig. 13. Image of the wood chips conveyor

The model is based both contractual and actual measures of the conveyor system. Based on these measures, introduced artificial coefficients and model parameters were chosen. Measures of the source object are given in the following table:

Table 1.Parameteres of the source object

Motor	Stroemberg HZUR743B3
	95 kW 990 rpm

Gearbox	Valmet B-80
	i=18,62:1
Drive wheel	VR1200x1000x140
Returning wheel	TR1200x800x70
Tension mechanism	TR1200x630x70
Length	295 m
Height	34,6 m
Holding idlers	RR5430
	702 p.
Electrical power	Min. 11,4 kW
	Max 39,2 kW
	Mean value 24,3 kW

Main system parameters were used as given. On the basis of these values, parameters of the belt and material were chosen, according to technical directories. Given levels of electrical energy consumption were used as oriental measures; they were used during model adjustment process.

5.2 Approach to modeling

Analytical approach was used for modeling the belt conveyor. As it was mentioned earlier, this approach is based on resistance calculation and involves artificial parameters. Along modeling of the conveyor itself (belt conveyor, idlers, transporting material etc), electrical drive was modeled. This drive includes motor, inverter and gearbox. Results, obtained during calculation of the model, were used to calculate operational economical indexes.

Important to mention, that during carried work, actual (experimental) measures of the object were considered, hence it was possible to adjust model by varying introduced coefficients and constants. This adjustment leads to increasing of accuracy and reliability of results. Developed model is close in operation to the source object, as calculation results are close to experimental.

5.3 General view of the model

In the left part of the scheme a logical block of electrical drive is situated. This block includes motor and inverter of set parameters. Inverter is receiving reference values of speed and load – from blocks “Speed reference” and “Load reference”. These values

reflect rotational speed of rotor and electromagnetic load torque. Setting of the blocks reflects amplitudes of parameters changing. As initial speed of rotor is equal to zero, setting of speed defines the end value. Changing of speed can be seen on acceleration ramp. Ramp parameters can also be set in the drive block. Deceleration of the motor can also be set. Nevertheless, as object is intended for working for a long period of time, deceleration phase is not considered in the calculation. Acceleration is set to 450 rpm/s .

On the output of the logical block main parameters can be obtained – stator current, rotor speed, electromagnetic torque and DC bus voltage. These parameters reflect the output of the motor, hence the system includes gearbox the conveyor receives changed values.

The goal of motor control is setting of the output speed, or the rotor speed. This aspect is also set in the drive settings. Other option is to control output torque. Output speed is measured in rad/s. Output speed in sent into a subsystem, which models gearbox and driving wheel of the belt. To convert angular speed to linear, gearbox ratio and wheel size are used. Mathematically, logic of this subsystem can be expressed by the following formula:

$$V = \frac{\frac{1}{2} * d * \omega}{redr} \quad (24)$$

, where d is the drive wheel diameter (m), ω is the angular speed of the shaft (rad/s), *redr* is the gearbox ratio. The output of the block transmits linear speed value.

This linear speed is used in all four components of mechanical resistance, which defines output measures of the object (including economical).

First component is main resistance:

$$F_{\mathrm{H}} = \mathrm{fLg}[Q_{\mathrm{R0}} + Q_{\mathrm{RU}} + (2Q_{\mathrm{B}} + Q_{\mathrm{G}})\cos\delta] \quad (5)$$

In this expression f is an artificial coefficient of resistance, it was considered earlier. L is the total length of the belt, Q_{R0} is the unit mass of moving part of holding idlers (kg/m), Q_{RU} is unit mass of moving parts of returning idlers (kg/m), Q_{B} is unit mass of the belt (kg/m), δ is the inclination angle of the belt ( ), Q_{G} is the unit mass of transporting material (kg/m). Also Q_{G} is defined by the following expression

$$Q_{\mathrm{G}} = \frac{T}{3.6V} \quad (6)$$

where T is the load of the belt (t/h).

Second component is secondary resistance:

$$F_{\mathrm{N}} = \frac{TV}{3.6} + \frac{T^2}{6.48\rho b_1^2} + \mathrm{C_{Ft}} \quad (16)$$

where ρ is the bulk density of material (kg/m3) and b_1 is the width between the skirt boards (m). $\mathrm{C_{Ft}}$ is and introduced artificial constant, reflecting minor resistance components.

Third component is gradient resistance:

$$F_{\mathrm{St}} = Q_{\mathrm{G}} * \mathrm{H} * \mathrm{g} \quad (7)$$

H – is the total height of conveyor, difference in heights between starting point and end point.

Fourth component is special resistance:

$$F_{\mathrm{S}} = k_1 \frac{T^2}{V^2} + k_2 \frac{T}{V} + k_3 \quad (17)$$

,where k_1 , k_2, k_3 are constant coefficients, reflecting the geometry of the object.

Components of resistance make up the total resistance of conveyor system, F_{U}.Multiplied by linear speed of belt it forms mechanical power of conveyor:

$$P_{\mathrm{T}} = F_{\mathrm{U}} * V \quad (3)$$

As the goal of modeling was determination of consumption measures, it is vital to transform mechanical power to electrical. Electrical energy consumption is determined by efficiency parameters of the system. In the considered object it is efficiency of motor and gearbox. In the model this principle is implemented is the logical block. Mathematically it can be represented by the formula:

$$P_{\mathrm{el}} = \frac{P_{\mathrm{T}}}{\mathrm{effM} * \mathrm{effR}} \quad (25)$$

,where effM and effR reflect efficiency coefficients of motor and gearbox.

After this operation, it is needed to calculate unit mechanical work, spent to transport one kilo of material. Therefore, electrical power (kW) is converted to unit work per kilo (J/kg). A formula is used for this operation:

$$A_{\mathrm{m}} = \frac{3.6\ P\mathrm{el}}{\mathrm{T}} \qquad (26)$$

Unit work is then transformed in economical index – money spent, to transport one kilo of material. A formula is used:

$$S_{\mathrm{m}} = \frac{money\ * A_{\mathrm{m}}}{3.6{*}10^{6}} \qquad (27)$$

, where *money* is price of one kWh (Eur)

After this, cost of operation is calculated. In the model price of one hour of conveyor is considered. In mathematical form it is:

$$S_{\mathrm{h}} = \frac{money\ * P\mathrm{el}}{1000} \qquad (28)$$

Pel is used from the first transmission line.

Results of calculations are transmitted to a graphical block, where they are represented for the user. User can analyze dynamics of economical parameters via this block.

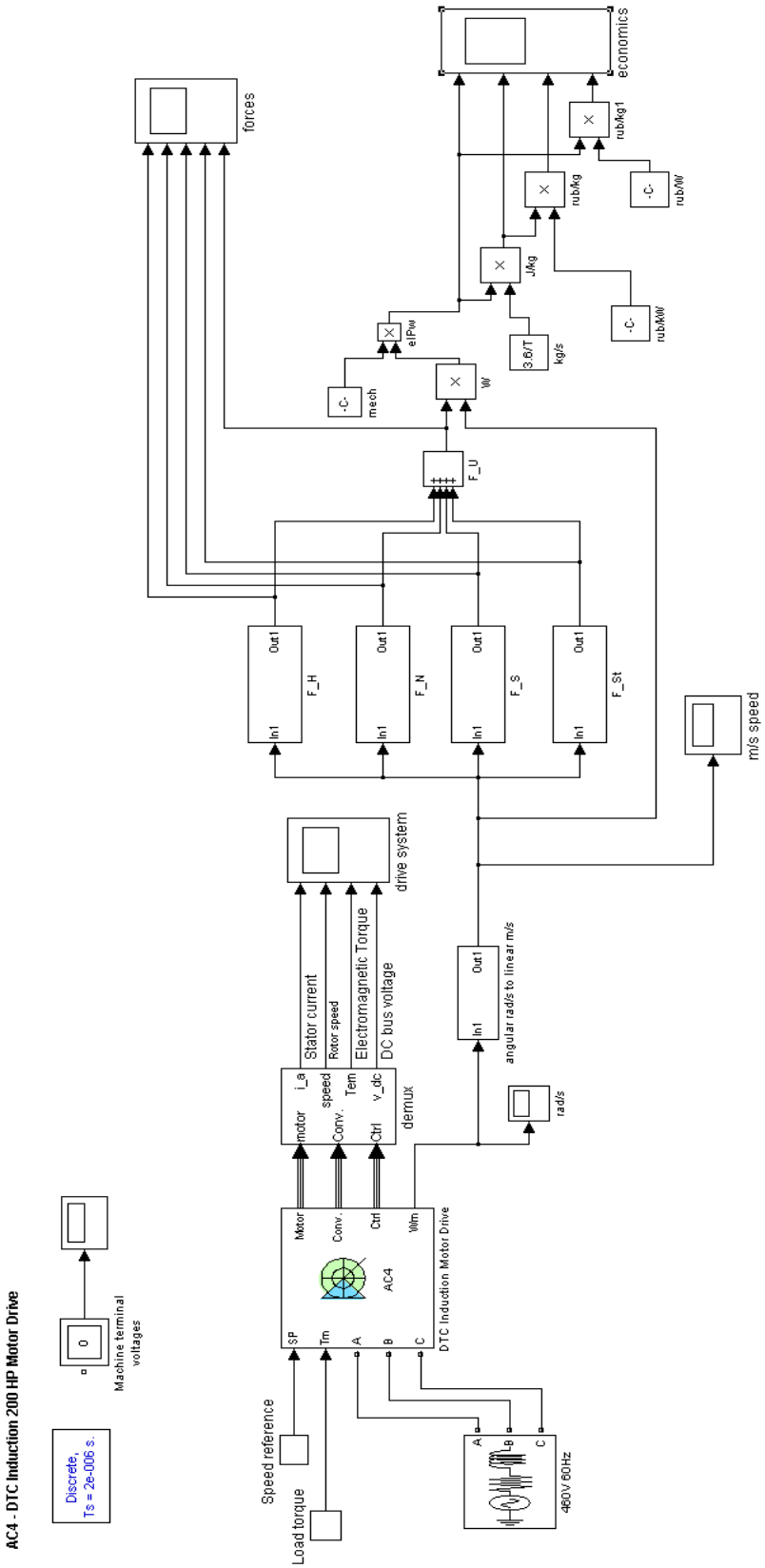

Fig.14. General view of the model, developed in MatLab Simulink.

5.4 Drive setting

Drive system is based on a 200 hp AC motor. Interface of the model is built such way, that user sets a preferable speed of belt, and according to this value a calculation takes place. As a result, a drive sets to proper values of rotor speed and load torque.

5.4.1 Setting speed

Considering setting of parameters it is relevant to examine speed setting. By speed, rotational rotor speed is meant. The value is received from the reference speed logical block by the drive block. Setting of speed block is shown on the next image:

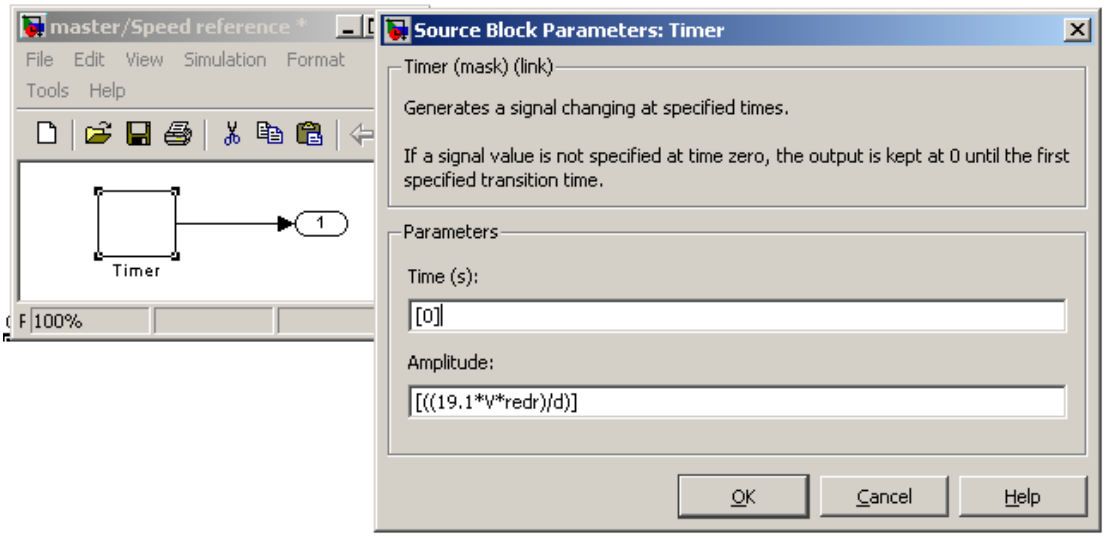

Fig.15. Subsystem of reference speed setting

Formula of setting is based on connection between rotor speed and drive wheel. Gearbox ratio is set by the user. Using size of the wheel, angular speed is conversed into linear. Following formula is used:

$$n = \frac{60 * V * redr}{\pi * d} \qquad (29)$$

, where V (m/s) is linear speed of conveyor belt, *redr* is gearbox ratio, d (m) is wheel diameter.

All parameters of this formula are set by the user. Experimental measures from the plant were used as initial values for the model.

4.4.2 Load torque setting

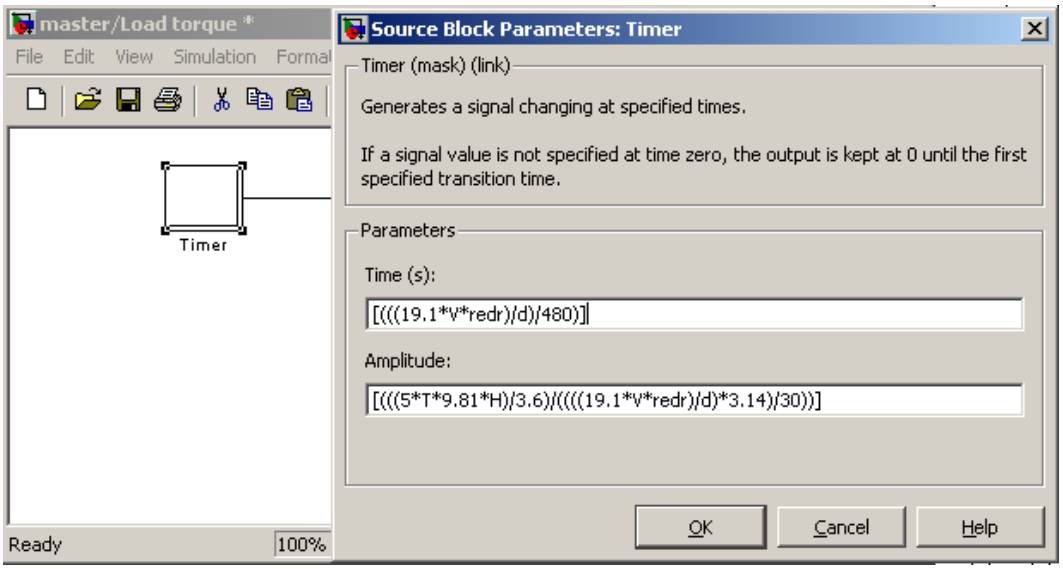

Fig.16. Subsystem of load torque setting

Load torque is determined by mechanical power and rotational speed. It can be expressed the following way:

$$\omega = \frac{\pi * n}{30} \tag{30}$$

$$\mathrm{P} = \frac{5 * T * \mathrm{g} * \mathrm{H}}{3.6} \tag{31}$$

$$\mathrm{M} = \frac{\mathrm{P}}{\omega} \tag{32}$$

$$\mathrm{M} = \frac{5 * T * \mathrm{g} * \mathrm{H}}{3.6} * \frac{30}{\pi * n} = \frac{T * \mathrm{g} * \mathrm{H}}{3.6} * \frac{30}{\pi * \frac{60 * V * redr}{\pi * d}} =$$

$$= \frac{5 * T * \mathrm{g} * \mathrm{H}}{3.6} * \frac{30 * d}{19.1 * V * redr * \pi} \tag{33}$$

Load torque has a certain timer, which sets the time of switching the torque on. Time is determined by formula:

$$\mathrm{t} = \frac{n}{480} \tag{34}$$

480 rpm is used by certain purpose – as acceleration ramp is set to 450 rpm/s, setting of 480 rpm makes a switching right after reaching the reference speed.

5.4.3 Drive block setting

Window of drive setting has three tabs with basic motor and inverter settings. General settings are set independently from the user and depend on the motor data. Mutual dependency of all parameters requires accuracy in settings.

Three tabs are presented on the following images:

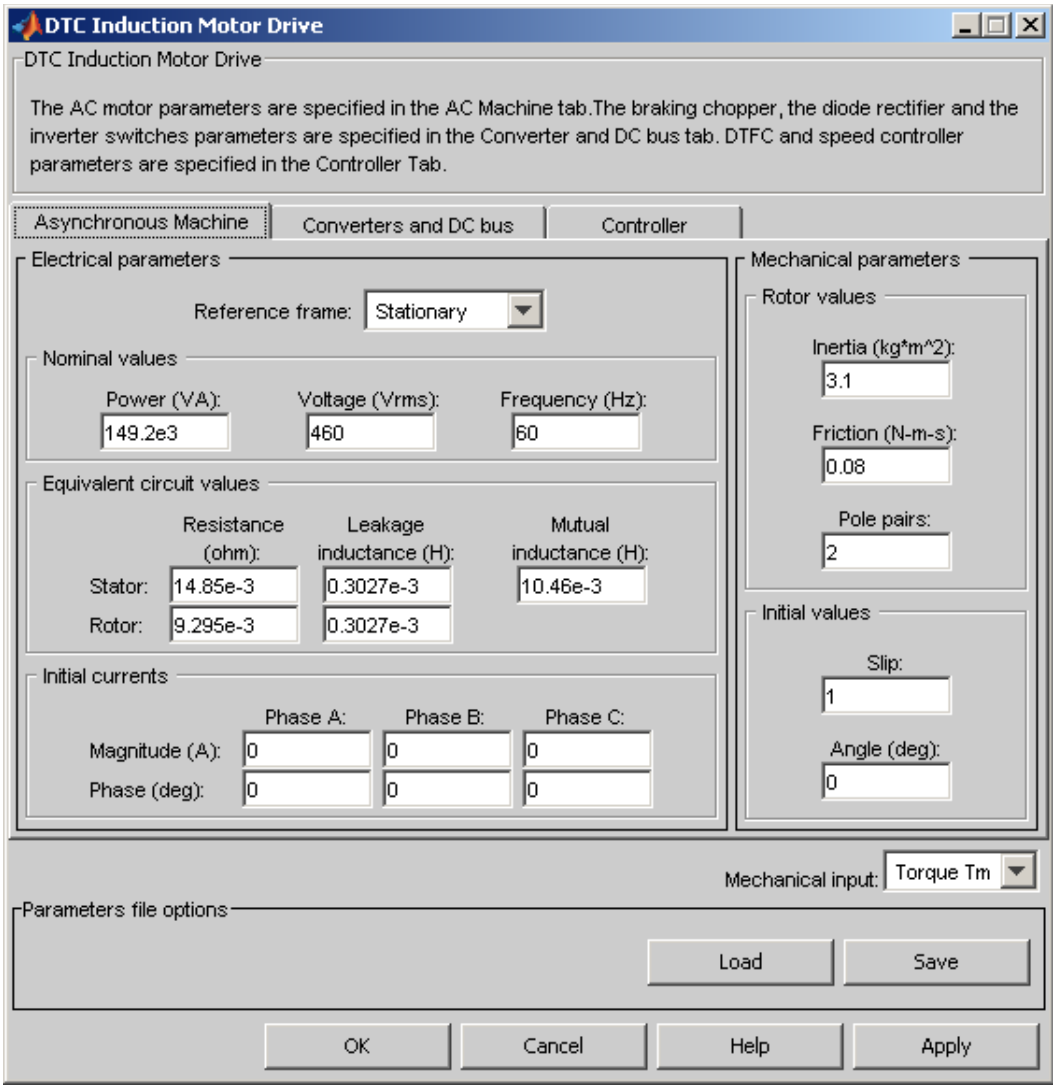

Fig.17. AC motor settings tab

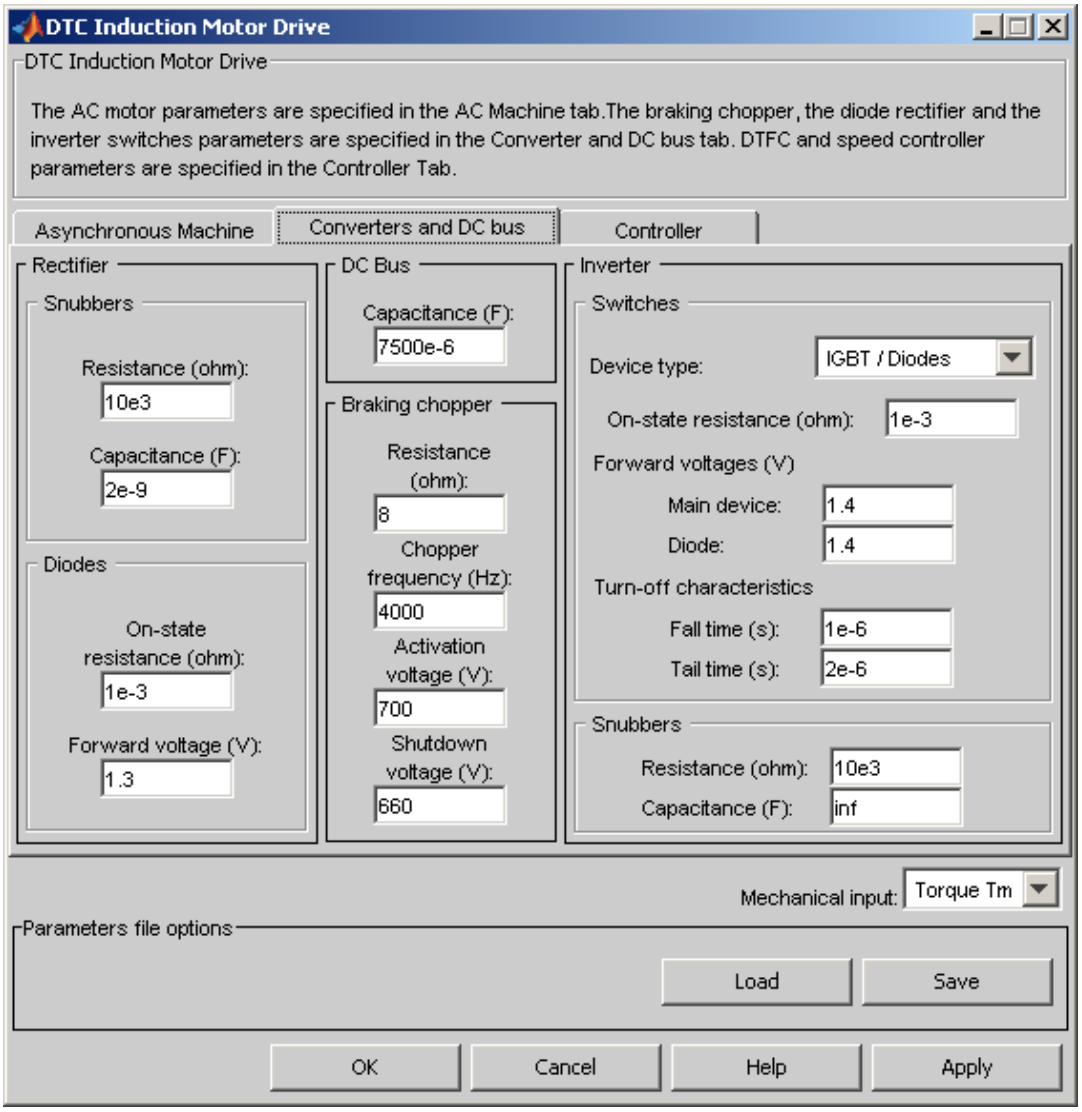

Fig.18. Converter and DC bus settings tab

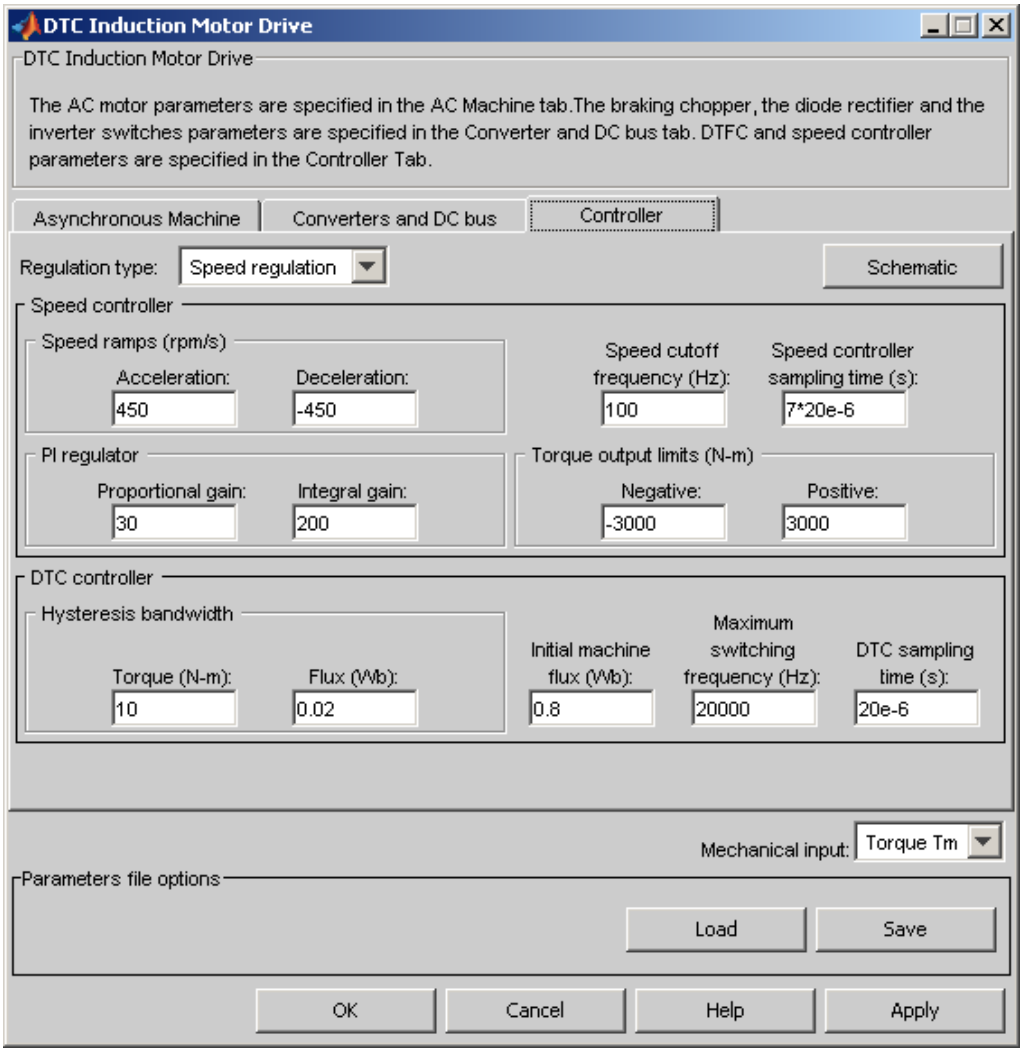

Fig.19. Controller settings tab

5.5 Resistances subsystems

Total mechanical resistance of the conveyor system involves four components. Mathematical formulas for calculation of these components are given. These formulas are presented via logical blocks in subsystems of the considering model. The principle is following:

$$F_{\mathrm{U}} = F_{\mathrm{H}} + F_{\mathrm{N}} + F_{\mathrm{St}} + F_{\mathrm{S}} \quad (2)$$

$$F_{\mathrm{H}} = \mathrm{fLg}[Q_{\mathrm{R0}} + Q_{\mathrm{RU}} + (2Q_{\mathrm{B}} + Q_{\mathrm{G}})\cos\delta] \quad (5)$$

$$F_{\mathrm{N}} = \frac{TV}{3.6} + \frac{T^2}{6.48\rho b_1^2} + \mathrm{C_{Ft}} \quad (16)$$

$$F_{\mathrm{St}} = Q_{\mathrm{G}} * \mathrm{H} * \mathrm{g} \quad (7)$$

$$F_{\mathrm{S}} = k_1 \frac{T^2}{V^2} + k_2 \frac{T}{V} + k_3 \quad (17)$$

On the basis of total mechanical force of resistance, the total mechanical power is calculated.

Detailed description of each formula was examined earlier. Subsystems, representing these components are presented on the following images:

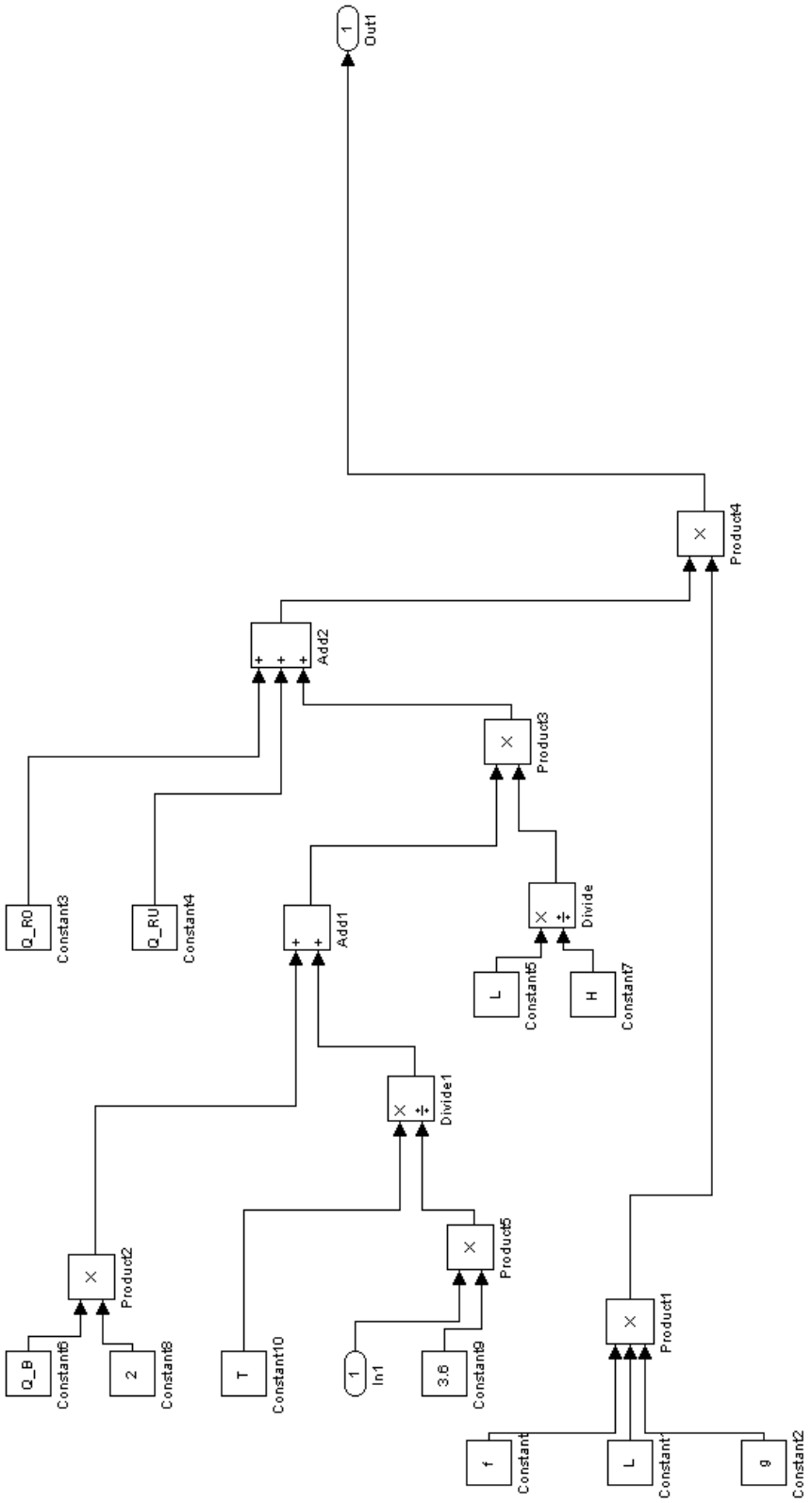

Fig. 20. Main resistance subsystem

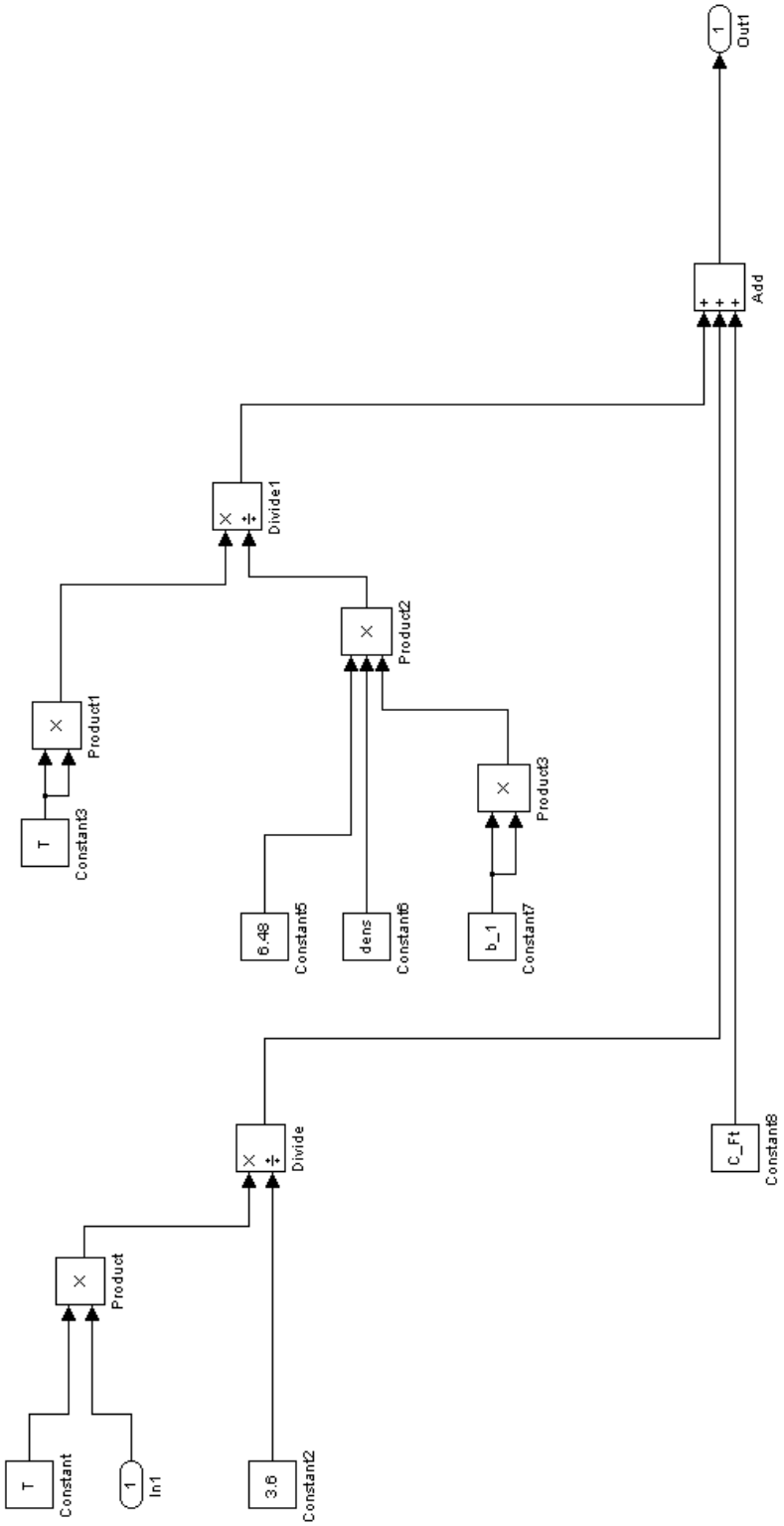

Fig. 21. Secondary resistance subsystem

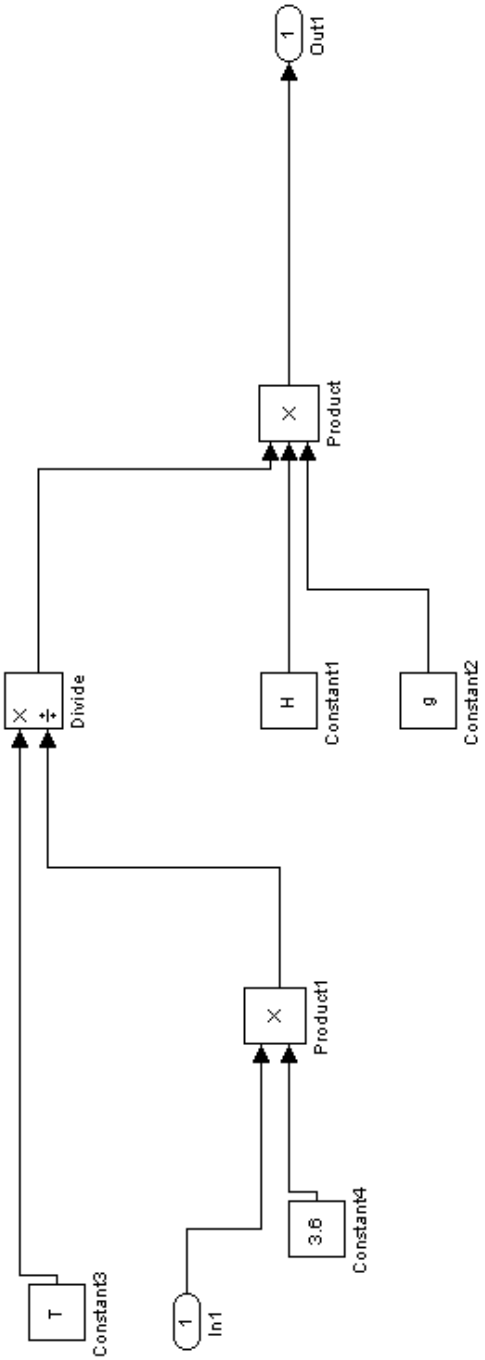

Fig. 22. Gradient resistance subsystem

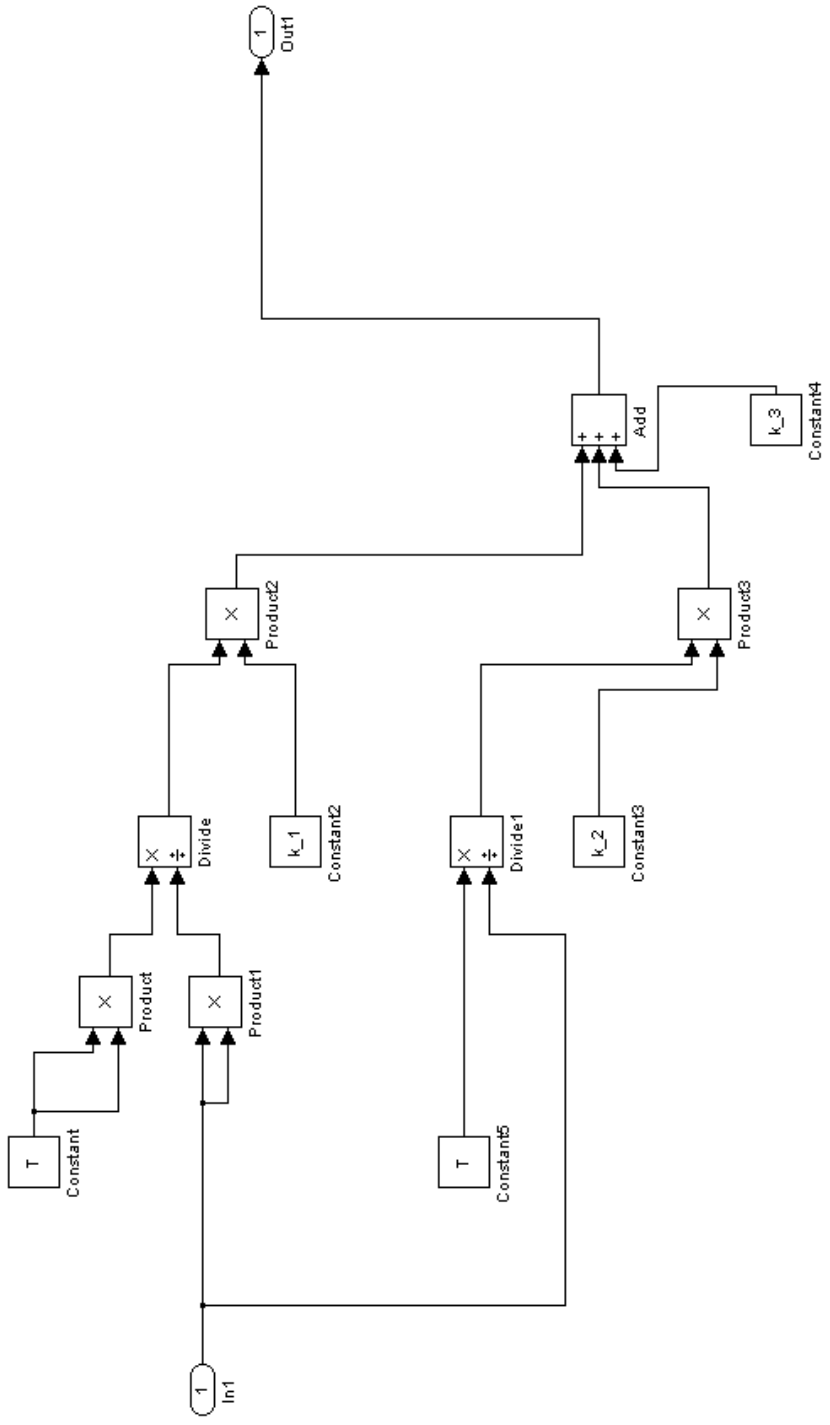

Fig. 23. Special resistance subsystem

5.6 System settings

Interface of the model gives and opportunity to set all required parameters in a centralized manner– in the pad of MatLab. Parameters are divided into six groups for convenience.

Fist group involves parameters for main resistance calculation:

f – artificial resistance coefficient (-)
L – total conveyor length (m)
g – acceleration of gravity (m/s2)
Q_R0 – unit mass of rotational parts of holding idlers (kg/m)
Q_RU – unit mass of rotational parts of returning idlers (kg/m)
Q_B –unit mass of the belt (kg/m)

Second block involves parameters for secondary resistance calculation:

b_1 – width between skirt boards (m)
dens – bulk density of material (kg/m3)
C_Ft – compensating constant

Third block is needed for calculation of special resistance:

k_1, k_2 and k_3 are artificial coefficients.

Fourth block is needed for gradient resistance calculation:

H – total height of conveyor (m)
Other components are set earlier

Fifth block is needed for general parameters:

d – drive wheel diameter (m)
effM – motor efficiency coefficient (-)
effR - gearbox efficiency coefficient (-)
redr – gearbox ratio (-)
money – price of 1 kW*h of electrical energy

Last block involves main parameters::

T – production(hour load) of conveyor (t/h)

V – linear conveyor belt speed (m/s)

```
f=0.009;
L=295;
g=9.81;
Q_RO=18;
Q_RU=15.2;
Q_B=13;

b_1=1.05;
dens=312.5;
C_Ft=0.5;

k_1=0.2;
k_2=0.2;
k_3=0.01;

H=34.6;

d=1.2;
effM=0.95;
effR=0.93;
redr=18.62;
money=0.1;


V=3.5;
T=62.5;

```

Fig.24 MatLab tab with set system parameters

6 Calculation results with nominal input values

6.1 Nominal values

Nominal values term reflects actual measures from the plant, experimental values. These parameters cannot be changed during calculation:

L – total length of the conveyor (m)

b_1 – total width between skirt boards (m)

dens – material bulk density (kg/m3)

H – total height of the conveyor (m)

d – driving wheel diameter (m)

redr – gearbox ratio (-)

T – load level (t/h)

V – linear belt speed (m/s)

These parameters were obtained by measurements during conveyor operation. On the basis of these values, artificial coefficients and conveyor constants are determined. These values depend on conveyor construction and operational characteristics. On the basis of the current model, a set of economical indexes was obtained, which were used to adjust the model.

After setting all parameters and all logical blocks it is possible to hold a calculation and consider results.

6.2 Electrical drive

Electrical drive results are reflected on Fig.25. First diagram considers stator current. First point reflects starting current. Frequency increases according to speed increasing. An amplitude surge can be seen as the speed reaches reference value.

Second diagram reflects rotor speed. It represents speed ramp of the motor. Inclination of the ramp was set in the drive settings window. Speed reference values were set in a logical block, basing on user's choice of belt speed.

Third diagram reflects electromagnetic torque behavior. Rapid surge can be seen after switching the motor, after it the value stays constant. This value reflects acceleration torque. At certain moment (calculated on the basis of entered parameters) load torque is switched on. After short period of constant value, torque decreases till the level of nominal value.

The fourth diagram reflects DC bus voltage. In the initial moment of switching the motor surges can be seen, after it voltage comes to a certain level. After switching the load, voltage rapidly decreases then reaches a constant level.

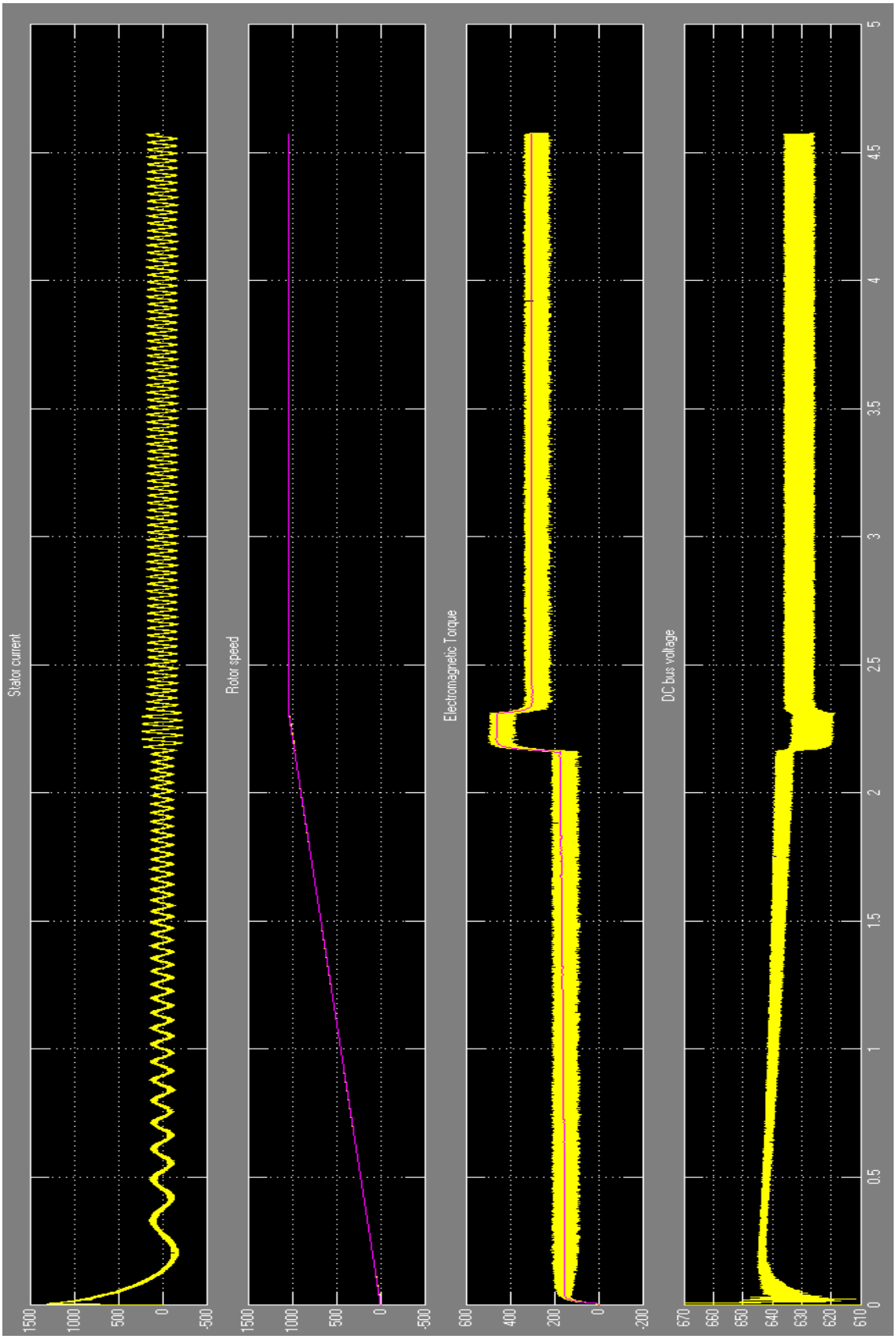

Fig. 25. Electrical drive calculation results

6.3 Mechanical forces calculation results

Next phase considers mechanical forces and calculation of resistance components.

First diagram on Fig.27 reflects main resistance component. First points should be excluded from analysis, as in the initial moment of zero speed, resistance goes to infinity. With increasing speed main resistance decreases and sets the constant level of 7760 N.

Secondary resistance, second diagram on Fig.27, has a relatively law value. Besides that dynamics of secondary resistance is opposite. With zero initial speed its value is equal to introduced constantC_{Ft}. With increasing of speed, secondary resistance increases and after speed reaches reference value, resistance keeps level of 63 N.

Special resistance has the same dynamic, as main resistance. Besides that, initial points with zero speed should be also excluded. With increasing speed resistance reaches the level of 67 N.

Gradient resistance has the same initial extreme points. After it values decrease and set constant line of 1700 N.

Total resistance is mainly determined by main resistance. Therefore it has the same dynamics and extreme points. After the system reaches reference level total resistance obtains a level of 9590 N.

Roles of each resistance component can be seen on Fig.26.

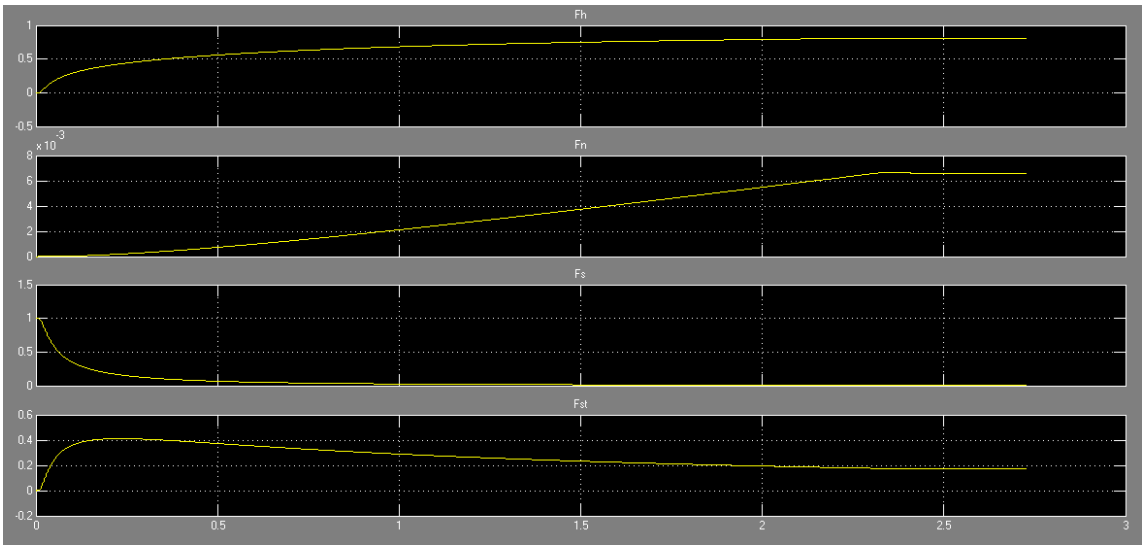

Fig. 26. Ratios between each component and the total resistance.

It is vital to consider, that roles of each component change during operation phases. In the initial moment total resistance is determined by special component. Main resistance role increases and reaches 80% part after reaching reference speed. Secondary resistance also increases its role, but even after reference speed is reached, its value is only 0.7%. Special resistance part decreases and reaches 1% level at the end. Gradient resistance increases with the speed and reaches 40% part after reaching reference speed. Nevertheless afterwards it decreases to 18% level.

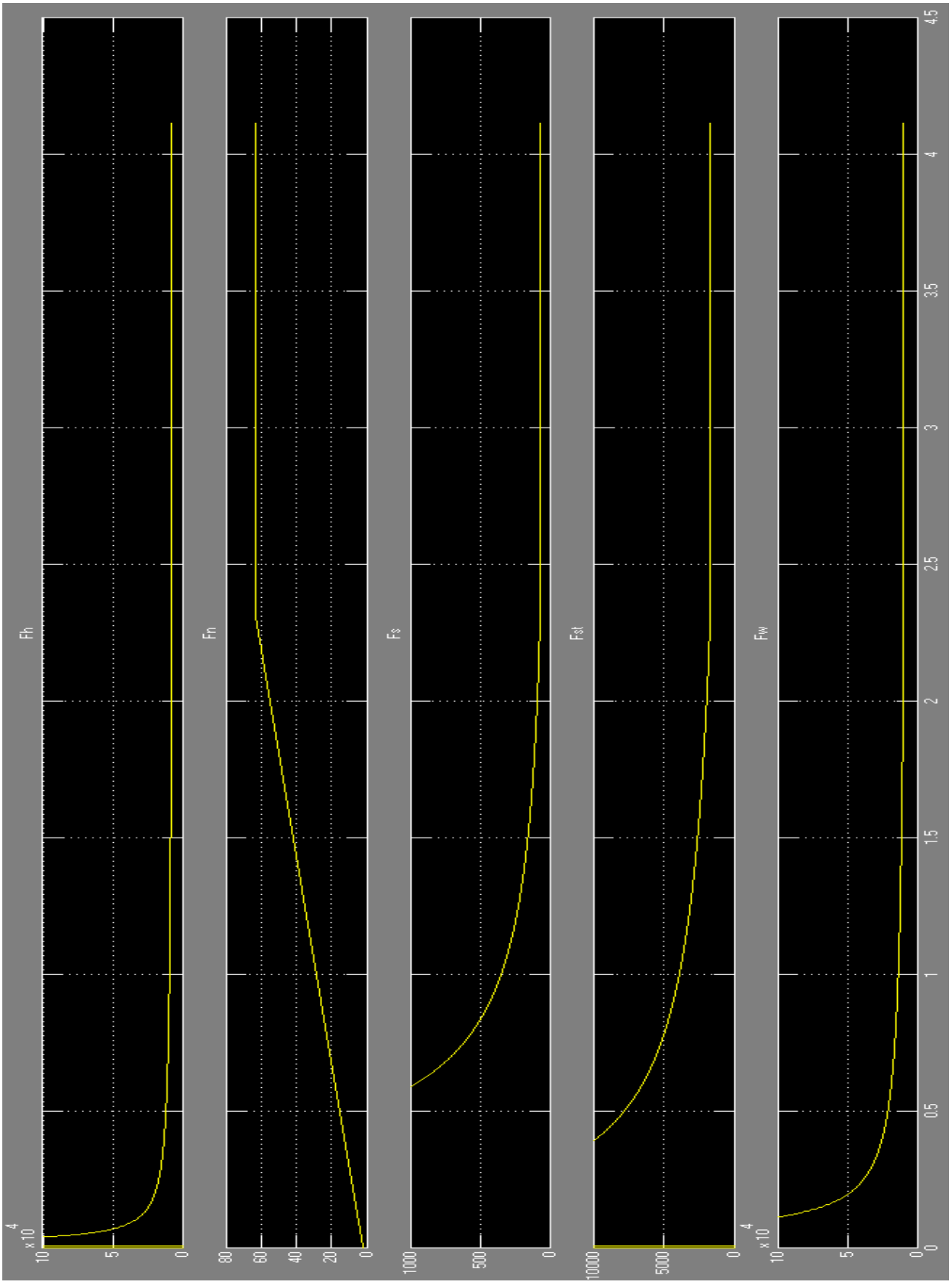

Fig.27. Resistance components calculation

6.4 Economical indexes

Economical measures of conveyor operational process are calculated basing on previously calculated mechanical forces. Mechanical power of the conveyor is calculated via the following formula:

$$P_{\mathrm{T}} = F_{\mathrm{U}} * V \quad (3)$$

F_{U}- total mechanical resistance force, N

V- inear belt speed,m/s

Consumed electrical energy can be calculated afterwards:

$$P_{\mathrm{M}} = \frac{P_{\mathrm{T}}}{\eta} \quad (4)$$

η-drive system efficiency coefficient, %

Combination of two formulas gives an equation of:

$$P_{\mathrm{el}} = \frac{F_{\mathrm{U}} * V}{\mathrm{effM} * \mathrm{effR}} \quad (25)$$

effM and effR are efficiency coefficients of motor and gearbox respectively. These values are entered by the user.

Obtaining consuming electrical power makes possible to calculate unit mechanical work for material transportation, J/kg.

$$A_{\mathrm{m}} = \frac{3.6 * P_{\mathrm{el}}}{T} \quad (26)$$

T-load level of conveyor, t/h, set by user.

Mechanical work can be converted into financial equivalent. Price for electrical power is used for this purpose. Price("*money*") for 1kWh is entered by user. Calculation is based on equation:

$$S_{\mathrm{M}} = \frac{A_{\mathrm{m}} * money}{3.6 * 10^6} \quad (27)$$

Final index is price of one hour of operation. This index is based on current level of mechanical power. Following equation is used:

$$S_{\mathrm{h}} = \frac{P_{\mathrm{el}} * money}{1000} \tag{28}$$

All indexes are represented in diagrams – this way economical indexes dependence on time is shown. Calculated measures are close to experimental values, measured on the plant.

Diagrams show, that on stable operational phase transporting one ton of material requires 6 euro cents and one hour of operation requires four euro. Consideration of acceleration process and technical service influences the result.

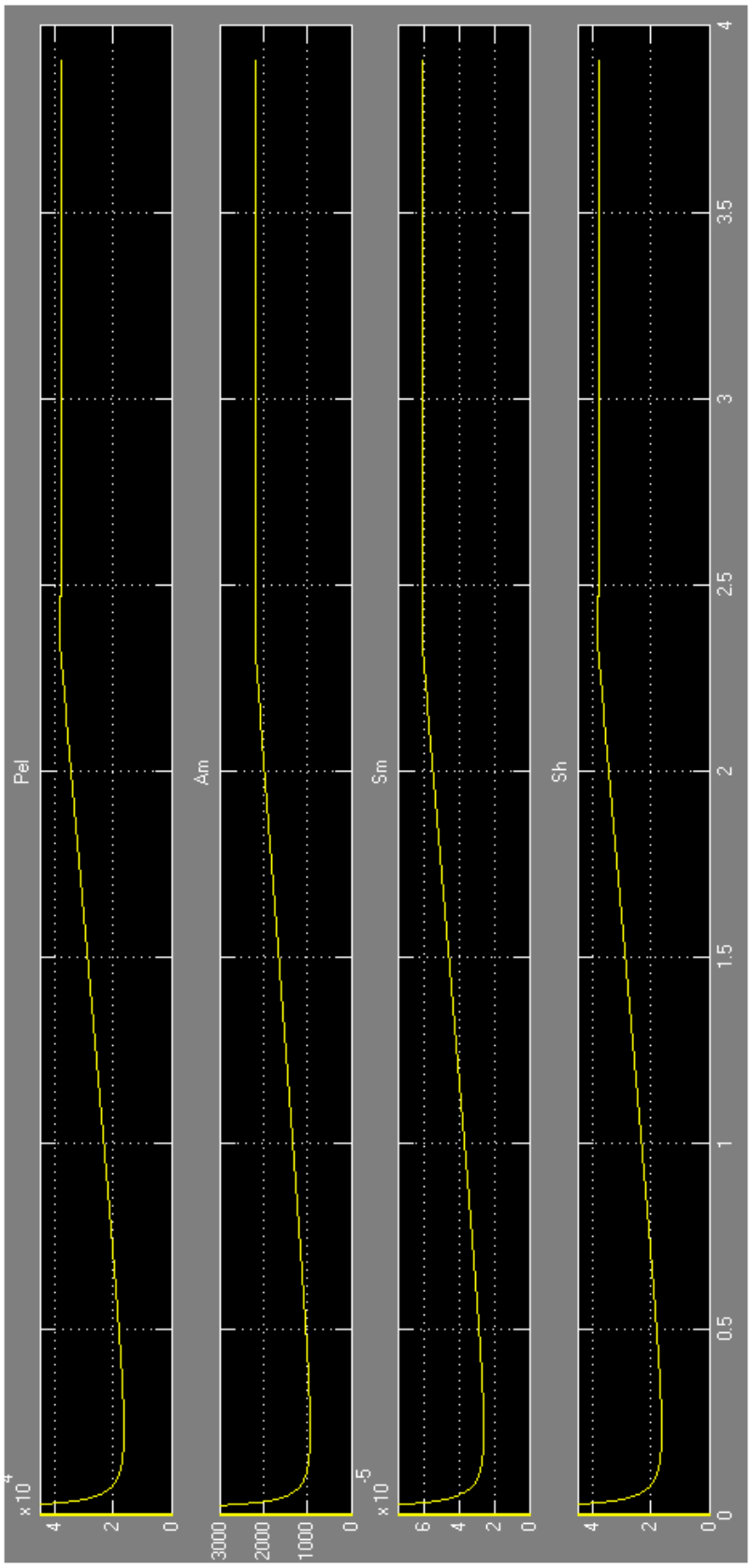

Fig. 28 Economical indexes of the model with nominal parameters

7 Experiments

7.1 Method of holding experiments

After certain results for nominal input parameters were obtained a series of experiments was held. This series aimed to evaluate energy efficiency borders, stability of the system, borders of control and economical indexes with different combinations of input parameters.

As it was stated before, two main ways of controlling conveyor applications can be figured out – variation of speed with constant load and variation of load with constant speed.

In the first phase of experiments linear belt speed of conveyor was varied, as the load of the conveyor was kept constant – nominal value of 62.5 t/h/ Obtained results shown transportation price linear dependency on belt speed. The Lower the speed is, the cheaper the transportation. Nevertheless, developed model stated two borders of 1.2 m/s and 6 m/s speeds. Trespassing of these speeds is not possible due to mechanical features of the object. Mechanical torque on these speeds occurs to be too high and the motor is not suitable for it.

Second phase of experiments was based on variation of load with constant speed. Diagram shows certain price dependency on load level. With increasing load the price decreases. Moreover, dependency has a quadratic character. Therefore besides mechanical borders for load, economical borders take place. The inclination of line decreases, so economical benefits also decrease.

7.2 Results analysis

As it is clearly seen during modulation and represented on diagrams, nominal values of load and belt speed represent centric values of robustness ranges for both parameters. In each case a shift in parameters is possible in both directions.

Considering energy efficiency strictly by varying speed and load settings of the system it can be stated, that the most relevant option is to increase the conveyor load. According to plant actual measures, top level of load reached 100 t/h. Theoretical calculation stated highest level of 150 t/h. According to model calculation, this level of load is mechanically possible on considered equipment. Therefore, the path of load increasing is the easiest one. Accurate value of highest possible load can be obtained on a plant. Though increasing the load level of the belt can decrease unit price of transportation up to 30%, hourly cost of transportation will increase up to 20%. This aspect shows that actual operational measures depend on plant environmental conditions and timetable of operation.

According to result of mechanical resistances calculation the most important aspect is main resistance. Nevertheless, this aspect is highly dependable on material and constructional features. To decrease main resistance, total weight of holding components and weight of belt should be decreased; nevertheless, mechanical characteristics should be kept constant.

Optimization of object control seems to be a more relevant option. This option involves more precise settings of control equipment and setting of control algorithm. This approach to energy optimization doesn't involve constructional changes in the conveyor system, consisting mainly of software measures.

Table 2. Experimental results. Variation of belt speed, belt load is constant T=62.5 t/h

V	**1,40**	**1,70**	**2,00**	**2,30**	**2,60**	**2,90**	**3,20**	**3,50**
Pel	22240,00	24403,00	26600,00	28800,00	31500,00	33320,00	35590,00	37850,00
Am	1281,02	1405,61	1532,16	1658,88	1814,40	1919,23	2049,98	2180,16
Sm	0,00160	0,00176	0,00192	0,00207	0,00227	0,00240	0,00256	0,00273
Sh	100,08	109,81	119,70	129,60	141,75	149,94	160,16	170,33
	3,80	**4,10**	**4,40**	**4,70**	**5,00**	**5,50**		
	40130,00	42400,00	44700,00	47000,00	49300,00	52150,00		
	2311,49	2442,24	2574,72	2707,20	2839,68	3003,84		

0,00289	0,00305	0,00322	0,00338	0,00355	0,00375
180,59	190,80	201,15	211,50	221,85	234,68

Table 3. Experimental results. Variation of belt load, belt speed is constant V=3.5 m/s

T	**25,00**	**32,50**	**40,00**	**47,50**	**55,00**	**62,50**	**70,00**	**77,50**
Pel	30860,00	32240,00	33630,00	35000,00	36490,00	37850,00	39270,00	40700,00
Am	4443,84	3571,20	3026,70	2652,63	2388,44	2180,16	2019,60	1890,58
Sm	0,00555	0,00446	0,00378	0,00332	0,00299	0,00273	0,00252	0,00236
Sh	138,87	145,08	151,34	157,50	164,21	170,33	176,72	183,15
	85,00	**92,50**	**100,00**	**107,50**	**115,00**	**122,50**	**130,00**	
	42130,00	43580,00	45030,00	46480,00	47950,00	49430,00	50910,00	
	1784,33	1696,09	1621,08	1556,54	1501,04	1452,64	1409,82	
	0,00223	0,00212	0,00203	0,00195	0,00188	0,00182	0,00176	
	189,59	196,11	202,64	209,16	215,78	222,44	229,10	

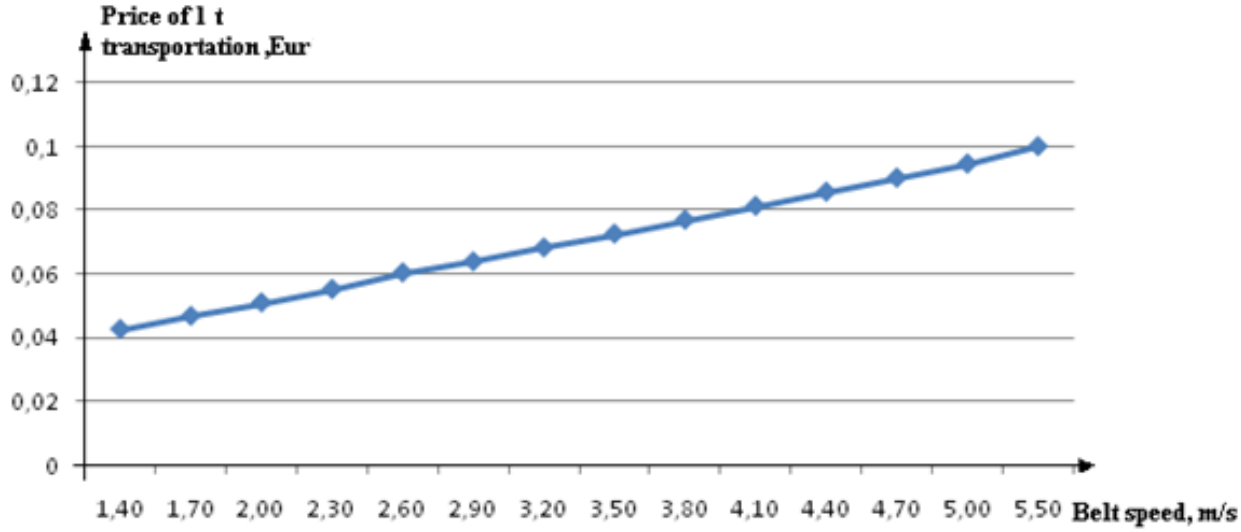

Fig.29 Price of transportation of 1 ton of material depending on belt speed.

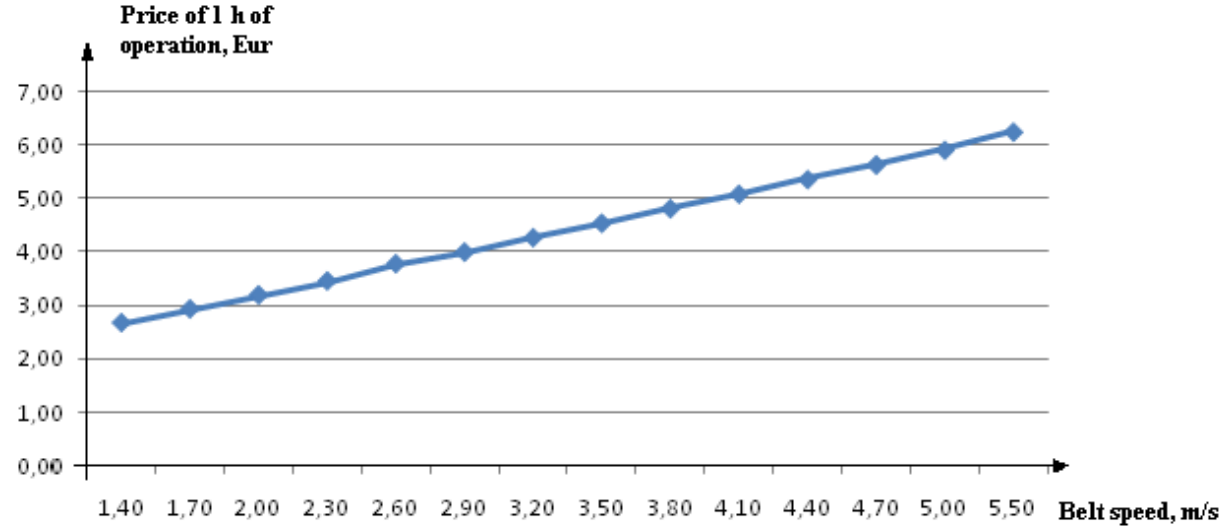

Fig.30 Price of one hour of conveyor operation depending on belt speed

The choice of calculation interval is based on physical abilities of equipment. Slow belt speed factually increases price of transportation, though diagram shows opposite statement. Nevertheless, lower belt speed is out of possible speed range and the belt cannot be driven with that speed with current setting. Mechanical power of motor in that case is not sufficient to handle the load.

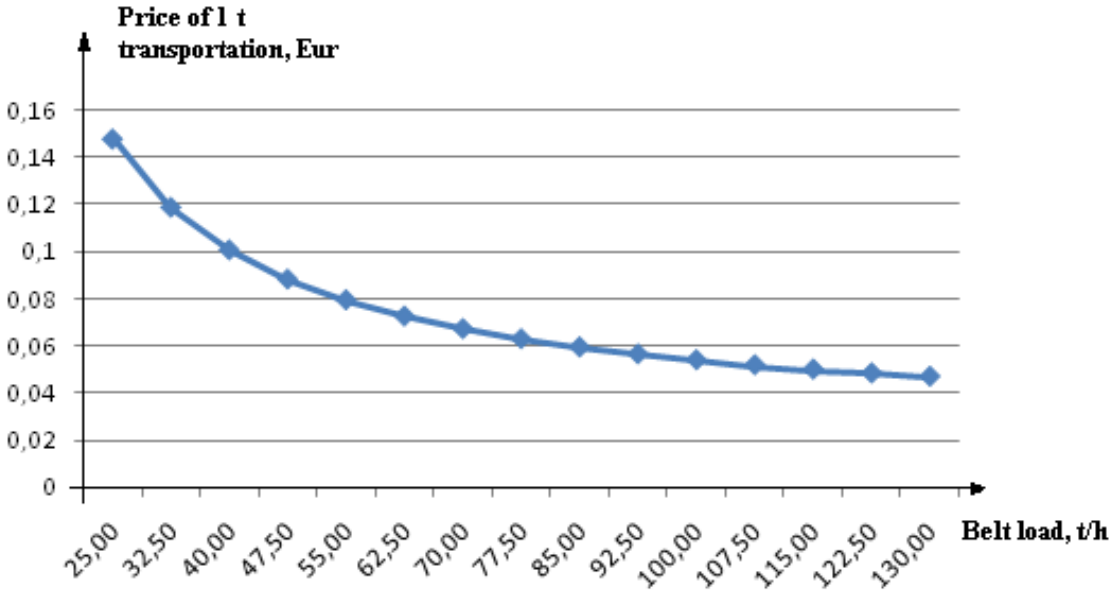

Fig.31 Price of transportation of 1 ton of material depending on belt load.

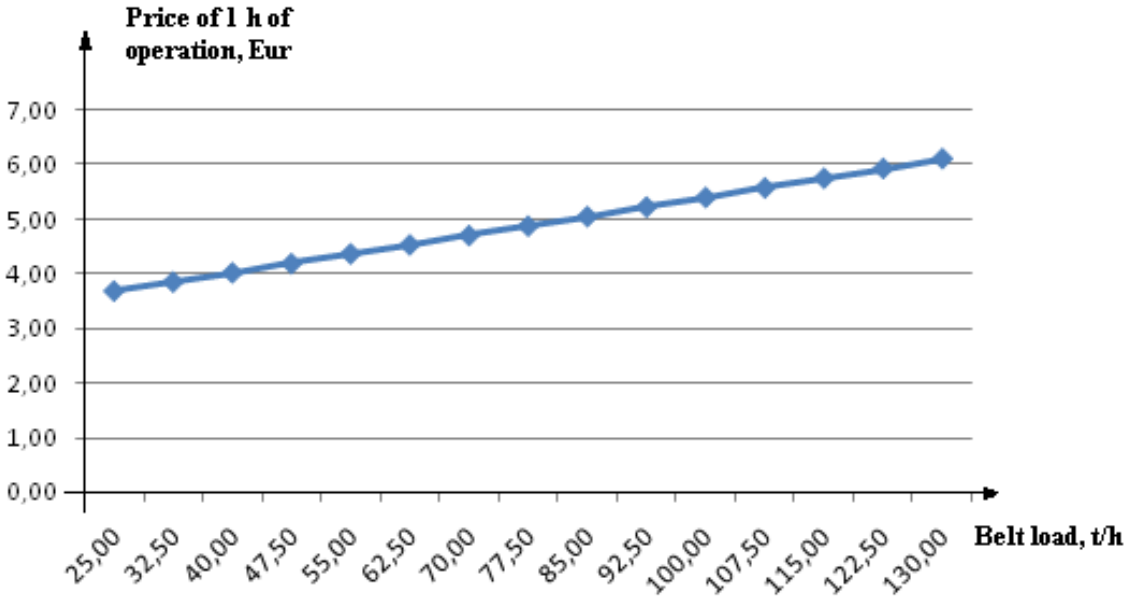

Fig.32 Price of one hour of conveyor operation depending on belt load.

8 Conclusion

An energy model of a belt conveyor was designed. The model is based on a real object and both contractual and operational indexes of the object were used. Analytical approach to modeling was chosen and operational indexes from the object were used to adjust the model. Beside economical values, obtained during the calculation, which depend on the price of energy and can widely vary, total presentation of the belt conveyor made it possible to analyze it's operational behavior and energy efficiency potential.

Operational behavior of the conveyor was presented by diagrams, based on the model calculation. These diagrams show certain role of object parameters and their variation during conveyor operation. Diagrams show not only certain values, but also dynamics of their changing.

Economical calculation presented needed costs for conveyor operation. Obtained results can be used for economical analysis, which can determine what contractual or management measures are economically viable. Results are also presented by diagrams, which reflect actual values and dynamics of their changing.

Analysis of conveyor operational behavior was implemented by series of experiments. A goal to determine best control algorithm and reference values was set. Obtained results showed that real object operational parameters, which were set as reference values are situated in the middle of robustness interval and thus can be changed. This series of experiments proved that energy efficiency of the conveyor can be significantly (by 30%) improved by using of alternative reference values, higher load level to be precise. Though certain reference values depend on used equipment, obtained results can be used as a vector of object optimization. The model itself can be used for deeper analysis of the object, testing of proposed innovations and economical calculation of their affects.

9 Summary

Within the limits of the current study, electrical energy consumption market was considered and conveyor sector was closely examined. Modern technologies in this sector and recommendations for energy efficiency increasing were studied.

For specification of stated problem of conveyor energy efficiency optimization, wood plant in Finland was taken as a test object. Constructional and actual measures of the object were used to develop and adjust energy model of a belt conveyor.

In the limits of the study, possible approaches to modeling were considered. Analytical approach was chosen to develop an energy model of a belt conveyor. Parameters of the object were integrated in the model and after calculation of all necessary values the model was set.

Calculation of the developed energy model gave necessary data for analysis of the conveyor system. Electrical energy consumption factor were examined. As actual measures of the object were known, the adjustment of the model was held and artificial coefficients and constant were adjusted. Developed energy model showed operational indexes close to actual plant indexes.

After calculation of model with nominal operational values of parameters, series of experiments were held. Two phases of experiments involved variation of speed with constant load level and variation of load level with constant speed. Results were analyzes and certain recommendations for energy efficiency optimizations were given. Obtained data gives description of object dynamics, robustness and economical indexes.

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