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DEVELOPMENT OF WAYS TO SAVING ENERGY WHEN OPERATING WINDING MACHINES

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Energy efficiency or energy saving is the practical implementation of scientific, technical, economic and industrial measures aimed at the efficient use of energy resources. Therefore, one of the challenges facing the textile industry is energy saving in technological processes in the production of products. To solve this problem, it is proposed to introduce into production advanced technological processes with low energy costs, the use of technological equipment equipped with electric motors with high rates of consumed electrical energy. This problem is also inherent in winders and similar machines equipped with a bobbin changer.

Since most of the time of operation of these devices is wasted and, accordingly, electricity is also wasted. However, to date, these issues have not been given due attention, and studies on this subject have not been conducted. In this work, the operation of the apparatus for changing bobbins in winding and similar machines has been studied in order to reduce power consumption.

As a result of the study, a mathematical model of the relationship between the operating mode and technological parameters of machines and apparatuses was obtained, which makes it possible to identify ways to eliminate shortcomings in their work.

Discontinuous, on signal and sectional methods of operation of the apparatus for changing bobbins have been developed, which make it possible to reduce power consumption on winding machines by 2.8–4.2 times compared to the existing method of operation. And the autonomous method of operation of the device, proposed in the work, completely eliminates the consumption of electricity consumed by the device for changing bobbins. The results of the study can be used in spinning and weaving mills

Keywords: textile industry, energy saving, winding machine, productivity machine, bobbin changer apparatus

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1. Introduction

The textile industry in terms of technological features is one of the important industries, which are characterized by a high technological energy intensity of production and consume significant amounts of energy. An important task facing the textile industry is to find ways of rational ways to ensure energy security, energy efficiency and energy saving in technological processes.

To solve this problem, it is proposed to introduce into production advanced technological processes with low energy costs, the use of technological equipment equipped with electric motors with high rates of consumed electrical energy.

Recite is to reduce the time spent on its production, without compromising the quality of the product and the productivity of the machine. This means that a reduction in the operating time of the used electric motor and, as a result, a decrease in the amount of energy consumed.

One way to save energy is to reduce the time spent on production without sacrificing product quality or machine performance. This means that the operating time of the used electric motor is reduced and, as a result, the amount of energy consumed by these machines is reduced.

This problem becomes even more relevant for winders equipped with bobbin changers, which are used in the weaving and spinning industry. Therefore, research and development of methods to improve energy efficiency or energy saving on these machines is of great importance.

2. Literature review and problem statement

Energy efficiency or energy saving is the practical implementation of scientific-technical, economic and production measures aimed at efficient use of energy resources [1]. There are a number of studies related to some issues related to energy efficiency, energy security and energy saving in various fields of industry. This article discusses with practical data the influence of motors and the process of optimizing their efficiency on energy savings in a textile factory. It is noted that the current focus is on energy consumption on the load side and optimizing the efficiency of the motor [2]. However, the work is of a review nature and does not contain technical solutions. Article [3] discusses with practical data the various factors of energy consumption and the process of optimizing a textile factory for energy saving. It is noted that even cost-effective options are often not implemented in textile enterprises, mainly due to limited information on energy efficiency. It is proposed to involve in the movement for energy efficiency large enterprises of the textile industry, as well as other energy-intensive industries by providing the necessary information.

The issue of energy saving was also addressed in the study [4]. The paper proposes a rational drying mode that reduces the drying time of crushed cotton stalks. It is by reducing the drying time that energy savings are created. However, some factors influencing the drying regime (moisture content of crushed straw, climatic conditions) were not taken into account. The same topic was touched upon in the study of the design of a new grain dryer and drying mode [5]. In this paper, the design of an energy-efficient grain dryer based on thermosiphons has been developed, the energy consumption of which is 3.5…6.8 MJ/kg, depending on the surface temperature and air flow. Energy consumption in the developed design of the grain dryer is lower than in existing convective dryers.

Article [6] provides a brief overview of the world's textile industry, an analysis of the type and share of energy in various textile processes, and highlights the energy efficiency opportunities available in some of the major textile industries, with a brief explanation of each measure. It is shown that for the textile industry there are a large number of energy efficiency measures, and most of them have a low payback period. However, the article does not provide data on the results of specific technical solutions in this area.

The textile industry is one of the most energy-consuming industries, in addition to having a high potential in terms of energy saving due to its technological characteristics. Energy costs are one of the costs that most affect the cost of the product produced in the textile industry. For example, it was shown in [7] that for the production of 1000 m^2 of cotton fabric, 1018 kW/h, 1039 kW/h for linen fabrics, 2394 kW/h for woolen fabrics, and 1292 kW/h for silk fabrics were consumed. In [8], it is noted that in linen textile enterprises, 44.4 % of electricity is consumed in dyeing, 29.2 % in spinning production, and 24.9 % in weaving. The same data on energy costs are given in [9] for dyeing factories for the production of cotton fabrics.

As can be seen from the data presented in these strata, the issues of energy conservation and energy efficiency are also important problems in the textile industry.

The issue of energy security and energy saving in the textile industry is considered in the article [10]. To solve the problems of improving the energy security and efficiency of textile industry enterprises, this paper proposes the use of low-energy-intensive production technologies, the use of alternative energy sources at enterprises, and the reduction of time loss in production processes. Similar suggestions and recommendations were also given in [1, 11]. However, it should be noted that these works, prepared on the basis of the analysis of statistical data, are of a general recommendatory nature, and they do not provide for specific technical or technological measures to address these issues.

One of the ways to save electricity is to reduce the time spent on its production without compromising the quality of the product and the productivity of the machine. This means a reduction in the operating time of the electric motor used and, as a result, a reduction in the amount of energy consumed.

To ensure this, it is important to apply new techniques, advanced technologies, auxiliary materials and accessories in technological processes. An example of this is high efficiency dyeing cartridges [12, 13] and their use in the bleaching and dyeing operations of the yarn dyeing process. As a result of the application of such cartridges, the amount of dye flotte supplied to the coil increases, the processing time is shortened, and therefore the production of one product unit increases and the amount of energy consumed accordingly decreases [14, 15]. With the research carried out regarding the use of the new dyeing tube [16], it has been determined that it is possible to deliver sufficient dye solution to the bobbin by applying lower pump pressure in dyeing. Due to the decrease in the applied pump pressure, the amount of energy consumed by the electric motor that realizes this pressure is reduced. Thanks to the use of high-performance dyeing tube, energy savings of up to 13 % can be achieved compared to existing tubes.

Thus, as a result of the use of high-performance cartridges, energy savings occur for two reasons:

1. By reducing the duration, which led to a decrease in the operating time of the electric motor.
2. By reducing the pressure of the pump during bleaching and yarn dyeing.

However, the combined effect of these two factors on reducing energy consumption in the process of yarn dyeing was not considered. It should be noted that due to the lack of mass production of these cartridges, they have not received wide application.

One of the important factors affecting the loss of electricity in textile enterprises is the frequent stopping and starting of machines and looms for various technological, technical and other reasons. This leads to a decrease in the productivity of the machines and to the consumption of excess energy by the electric motor that drives them.

As it is known, during the start of the electric motor, the current consumed by it is 3–8 times more than the nominal current [17]. This clearly shows how much energy is wasted every year in a weaving shop, where 300 or more machines are installed, each of which stops and starts working at least 3–5 times per hour for various reasons (breakage of warp and weft threads, technical malfunction, removal of goods and etc.). However, unfortunately, this issue has not been given enough space in research.

From the analysis of the literature sources mentioned above, energy saving and energy efficiency in the textile industry are relevant and conducting relevant research in this area is of great importance.

This includes the topic of exploring energy savings and finding solutions for rewinders and similar machines equipped with reel changers. Therefore, the theme of the work on the study of ways to save energy during the operation of winding machines is relevant and has not been studied so far.

This feature also applies to automatic winders and similar machines where each machine head is equipped with an individual electric motor. In these high-speed machines, the motors are also frequently stopped and started, which results in wasted electrical energy. In addition, losses of electrical energy also occur during the operation of special electric motors that perform certain technological operations in these machines (replacement of full bobbins, insertion of full cobs of yarn instead of empty ones, elimination of thread breaks, etc.).

However, these issues have been largely ignored and have not been thoroughly studied until now.

3. The aim and objectives of the study

The aim of this study is to develop ways to save energy when operating winding machines equipped with devices for changing the bobbin. This will provide designers and manufacturers with guidance on the development and improvement of winders and similar machines with low energy consumption.

To achieve this aim, the following objectives are solved:

– to analyze the joint operation of the bobbin changer and the yarn winding process;

– to conduct a theoretical study of the operation of the apparatus in the ideal case of changing bobbins;

– to conduct a theoretical study of the operation of the apparatus with a random variant of changing bobbins;

– to develop ways to operate the bobbin changer to reduce energy consumption.

4. Materials and methods

The aim of this research is to develop ways to save energy during the operation of winding machines equipped with a bobbin changer. To achieve this goal, the relationship between the parameters of the apparatus, the rewinding process and the winding machine is determined theoretically.

To solve the problem, let's use the schematic diagrams of the device operation, according to which a theoretical analysis was carried out and mathematical models of the desired dependence were obtained for the ideal and random variants of the device operation. When analyzing the operation of the apparatus, the principle of the theory of queuing was used. To carry out calculations confirming the significance of the work, according to the obtained research formulas, the practical data of the winding machine of the Murata brand were used.

The study uses a winding machine with 60 winding heads, in which all technological operations are performed automatically, containing one bobbin changer (Doffer) reciprocating on the top of the machine at a speed of 15 m per minute. The winding speed of the yarn on the bobbin is 1000 m/min, the coefficient of useful time is 0.92 of the machines and the length of the movement path of the bobbin changer is 20 meters. For calculations, cotton yarn with a linear density of 18.5 tex and bobbins with a yarn length of 110,000 m were taken. Since the work of replacing the bobbin in all the winding heads of the machine is performed by only one device, this study is inherently in the nature of theoretical studies conducted using the queuing theory. Therefore, elements of the theory of queuing appear here.

5. Results of study on development of ways to saving energy when operating winding machines

5. 1. Results of the study on the relationship between the operation of the bobbin changer and the winding process

The bobbin change operation is carried out in textile enterprises, where yarn is wound on various machines. This operation is carried out manually or automatically when the required length of yarn is wound on the bobbin [18]. Automatic bobbin change is carried out in some winding machines, in rotary and pneumomechanical spinning machines with an open end (OE) [19, 20]. Each of these machines is equipped with one bobbin changer and serves all the winding heads of the machine. The bobbin changer, reciprocating along the machine along the rails at the top of the machine, removes the filled spools from the winder head and replaces them with an empty chuck. After completing the process of replacing the bobbins in all machine heads, the machine continues to move and waits for new full bobbins.

The principle of operation of the bobbin changer on a winding machine is shown schematically in Fig. 1.

The apparatus, moving from the first head 1 to the last one and back, is in constant motion.

As shown in the Fig. 1 the bobbin changer moves to the right starting from head 1, reaches head *n* and returns from there. At this time, the machine stops at the heads with a full bobbin, removes them, replaces them with an empty cartridge, and then continues on its way. Thus, the machine moves continuously along the entire length of the machine to complete the job of changing the bobbins in all heads. After that, the machine waits for the new bobbins to fill up, and when the bobbin is full, it starts the next replacement operation.

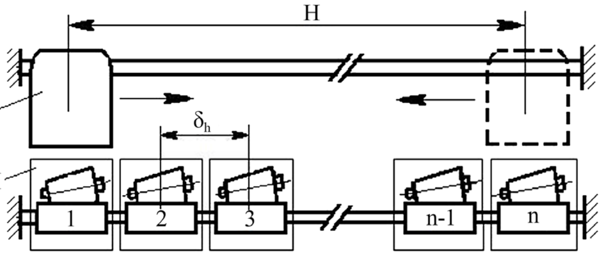


Fig. 1. Schematic representation of the operation of the coil changer apparatus: *D* – Bobbin changing device; *WH* – winding heads; δ_h – distance traveled by the machine between two adjacent heads; *H* is the length of the bobbin changer travel path

The number of bobbin changes per shift depends on the length of the yarn on the bobbin. The number of reel changes per shift is determined by the following formula:

$$k_b = 60T_{sh}/T_b = 60T_{sh}\vartheta R/L_b, \qquad (1)$$

here T_{sh} – shift duration in min. (480 min.); T_b – the filling time of the coil, calculated by the equation $\upsilon\ R/L_b$; L_b – length of yarn in the bobbin, m; ϑ – winding speed of yarn on a bobbin in m/min; R – useful time coefficient.

It has been established that, depending on the linear density (number) of the yarn and the winding speed, the bobbin change operation is performed 3–4 times per shift. A single change of all filled bobbins is carried out in one or more movements of the apparatus moving from one end of the machine to the other and back. It is possible to express the number of apparatus strokes required to change all the bobbins once, as a bobbin change cycle.

The bobbin heads in the machine are filled at different times, and therefore the bobbin replacement process is also carried out at different times. The difference between the filling times of the bobbins depends on the working condition of the machine, its technological parameters and the number of heads in the machine.

In cases when the machine is newly assembled, taken out of repair or is in production with a different yarn, the winding heads of the bobbin are fed sequentially with a time difference τ. In these cases, the winding and filling of the bobbins also takes place sequentially, ideally with a time difference τ. That is, in this case, the replacement of all bobbins is carried out in one stroke of the apparatus, that is, the cycle of changing bobbins is completed in one stroke of the apparatus.

Suppose, in a winding machine with n number of winding heads, the feeding is continued sequentially from the first head to the last head. In this case, the bobbin in the next head will be wound and filled earlier than the time τ than in the previous head (if no malfunction occurs during the machine operation). Conducting the winding process in this way can be considered the ideal case.

In this case, the bobbin change process takes place as shown in Fig. 2.

In Fig. 2 and following figures, the bobbins changer is not shown, and its movement from one head to another is indicated by arrows.

As can be seen in Fig. 2, the apparatus changes all the bobbins in sequence, starting from the coil in the 1st head to the coil in the nth head. Let's consider this as the first ideal bobbin replacement. In this case, the length of the path traveled by the apparatus will be $(n-1)\delta_h = H$.

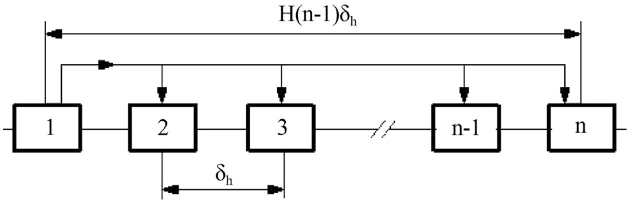


Fig. 2. Schematic representation of the completion of the bobbin change cycle in one pass of the apparatus

In this case, the time spent by the apparatus to change the bobbin is calculated by the formula below:

$$t_{i1}=\left(nt_c+\frac{H}{V_a}\right)\alpha \tag{2}$$

or

$$t_{i1}=\left[nt_c+\frac{(n-1)\delta_h}{V_a}\right]\alpha, \tag{3}$$

here t_{i1} – time spent by the apparatus for coil change in the first ideal case, sec; δ_h – the length of the path traveled by the apparatus between two neighboring heads, m; H – the length of the path traveled by the apparatus on the machine in one run, m; n – the number of winding heads of the machine; α – the coefficient that takes into account the time losses of the apparatus during bobbin changing due to technical reasons (α=1.1–1.2); V_a – movement speed of the apparatus (m/min); t_c – the time spent replacing a bobbin.

In (2) and (3), the first expression in parentheses indicates the replacement time of the bobbins in all heads of the nt_c apparatus, and the second expression shows the time spent on reaching the heads.

Thus, as a result of the analysis of the operating parameters of the bobbin changer and the technological parameters of the yarn winding process, formulas were obtained that make it possible to determine the number of bobbin changes per shift and the duration of one bo bbin change cycle.

5. 2. Results of investigation of the operation of the device for changing bobbins in the ideal change mode

However, in practice, the ideally ordered coil formation (winding process) is almost nonexistent. Because the number of ends down, end connector errors that eliminate ends down, delays in bobbin feeding and other technical faults, the sequential filling of the bobbins can be disrupted during the winding process. For example, due to this or other reasons, the filling of the bobbins in the three heads of the machine 3rd, 10th, 11th and [n–1] took place later than expected. Then the apparatus will leave the bobbin in these three heads and replace the other filled bobbins.

On its return, it will replace the bobbin on the three remaining heads (Fig. 3).

The time spent to change the bobbins in the forward and backward movement directions of the apparatus is determined by the formulas below:

$$t_f=\left[(n-3)t_c+\frac{H}{V_a}\right]\alpha, \tag{4}$$

$$t_r=\left(3t_c+\frac{2H}{V_a}\right)\alpha. \tag{5}$$

Here t_f and t_r – the time the apparatus spends on bobbin replacement in the flow and return.

In this case, the time spent on the bobbin change cycle can be expressed by the formula:

$$T_{ci}=\left(nt_c+\frac{2H}{V_a}\right)\alpha, \tag{6}$$

where T_{ci} – the time, the apparatus spends on the bobbin replacement cycle.

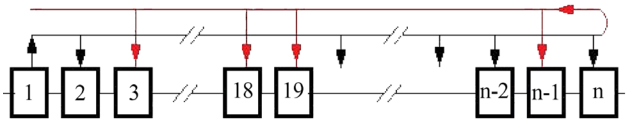


Fig. 3. Schematic representation of the completion of the bobbin change cycle in two passes of the apparatus

The example of the bobbin changing process made in three runs of the apparatus is shown schematically in Fig. 4.

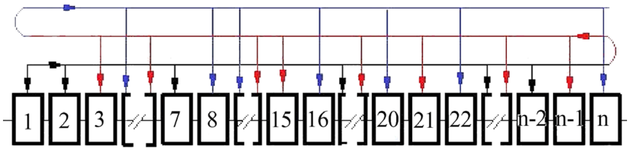


Fig. 4. Scheme of completing the cycle of changing the bobbins in three passes of the apparatus

Even the complete bobbin replacement performed by the apparatus in two runs is close to the ideal situation, but is rare. Based on the studies on the winding processes in winding machines, it has allowed to define the regular winding process as the first, second and third regular process.

Therefore, it is possible to divide the regular bobbin changing process into three operations, such as the first, second and third bobbin changing. In a 60-head winder, the first bobbin change cycle is completed in at least 2 passes, the second in 4 passes, and the third in 6 bobbin changer passes.

In this case, in a cycle of the ideal situation, the average time spent for bobbin changing, T_{cav} is calculated as follows:

$$T_{cav}=\left(nt_c+\frac{4H}{V_a}\right)\alpha. \tag{7}$$

After 3 ideal states, the order in the winding processes gradually deteriorates and finally becomes disordered. That is, the coil heads fill up at different times. For example, the bobbin in head 5 fills first, then the bobbin in head 1, then the bobbins in 8th, then 16th and other heads. Let's define this kind of winding process as a random situation. Undoubtedly, in such a case, the bobbin change takes place randomly.

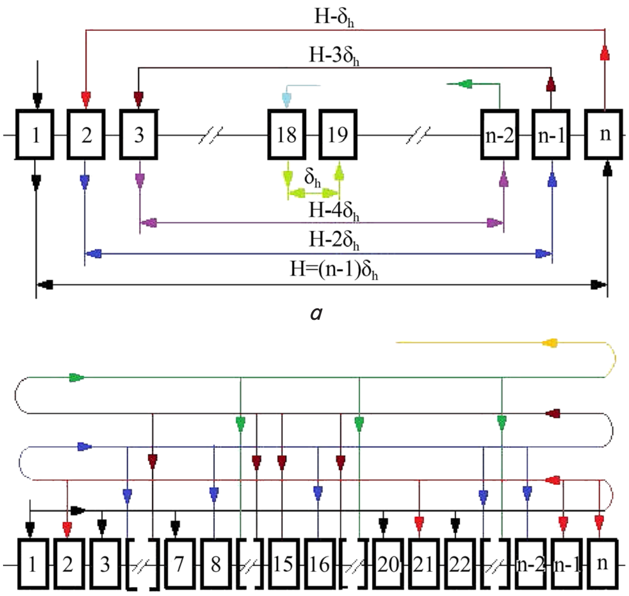
5. 3. Results of study of the operation of the bobbin changer in the random change mode

After the third ideal bobbin change, the order in the winding operations gradually deteriorates and finally becomes irregular. At the same time, the time of filling and changing the reels, respectively, occurs at different times in individual winding heads, which indicates that these processes are random processes. Since the change of all reels is carried out by only one device, this process is random, which is studied using elements of the queuing theory [21]. Undoubtedly, in this case, the spool change process is also random and the length of the path covered by the apparatus will also be different during the complete bobbin change.

As mentioned above, with the exception of the 3rd case, generally the winding and filling of the bobbins in winding machines takes place irregularly. Therefore, depending on the situation, the length of the path traveled by the apparatus during a full coil change will also be different.

The movement of the apparatus in various situations and the length of the path it takes to reach the filled coils are shown schematically in Fig. 5.

As seen in the figures, in the complete bobbin changing process, the apparatus travels the most in the situation shown in Fig. 5, *a*. Let's consider the movement of the apparatus in this state. After the apparatus has changed the coil in the 1st head, it travels a distance of H to reach the filled coil in the last, namely the nth head, and makes the change. After that, the 2nd bobbin fills up. Then the apparatus travels a distance $(H-\delta_h)$ to reach this bobbin and does its job. After that, the bobbin fills at $(n-1)$ and the apparatus travels a distance of $H-\delta_h\cdot 2$ from the 2nd head to reach the bobbin in the $(n-1)$ head. If the filling takes place in the coil in the 3rd head, the apparatus must travel the distance $H-3\cdot\delta_h$ from the $(n-1)$ head to the 3rd head.



a

b

Fig. 5. Schematic representation of the operation of the bobbin changing apparatus with various probabilistic states: *a* — probabilistic operation diagram of the apparatus in the state of maximum travel; *b* — probabilistic operating diagram of the apparatus in the average travel state

At the same time, to determine the total length of the path performed by the apparatus during the change of reels on all machine heads, it is possible to use the combination rule from the connections of various elements [22]. In this case, the problem is reduced to solving combinations C of m elements by n, that is, that is, C_n^2.

According to this, the total length of the path made by the apparatus during the change of bobbins on all heads can be calculated by the formula:

$$\sum H = C_n^2\delta_h = \frac{(n-1)n\delta_h}{2}, \tag{8}$$

where C_n^2 – the binary combination of ΔL from the set n.

Since $(n-1)\delta_h=H$ in this equation, it can be expressed as $\sum H=nH/2$. Moreover, $\sum H$ is the maximum length of the path traveled by the machine in the bobbin change cycle and according to this it is possible to write:

$$\sum H = H_{\max} = \frac{nH}{2}. \tag{9}$$

In this case, the time spent by the apparatus in the coil changing cycle is determined by the following equation:

$$T_{c\max} = \left(nt_c + \frac{nH}{2V_a}\right)\alpha. \tag{10}$$

In fact, the bobbin change cycle takes place with a different number of back and forth movements of the apparatus on the machine according to the diagrams shown in Fig. 3–5, *b*. Therefore, it is more appropriate to consider the length of the path covered by the apparatus in case of random coil change as the average length.

The average length of the path traveled by the apparatus in a bobbin replacement cycle is determined by the equation below:

$$H_{av} = \frac{H_{\min} + H_{\max}}{2}. \tag{11}$$

The minimum length $H_{\min}$ of the path traveled by the apparatus in one cycle is equal to H as seen in Fig. 2.

Substituting the values of $H_{\min}$ and $H_{\max}$ into (10) let's obtain:

$$H_{av} = \frac{H_{\min} + H_{\max}}{2} = \frac{H(n+2)}{4}. \tag{12}$$

In this case, the average time consumed by the machine per bobbin change cycle can be calculated using the following formula:

$$t_{av} = \frac{t_{\max} + t_{\min}}{2} = \left[nt_c + \frac{H(n+2)}{4}\right]\alpha. \tag{13}$$

It has been determined from the researches made on the 60-head winding machine that during probabilistic operation, the bobbin change cycle takes place in approximately 30 runs of the apparatus [23].

As stated, the task of the bobbin changer is to reach the filled bobbins and to replace them. At this time, although the bobbin changing process has been completed, the apparatus is in constant motion throughout the entire shift according to the current operating mode. Therefore, the apparatus wastes most of its work and causes excessive energy consumption. The electrical energy that the apparatus consumes in vain is directly proportional to the time it wastes.

The electrical energy consumed by the apparatus in vain (unnecessary) can be calculated with the following formula:

$$E_m = T_m P_m, \tag{14}$$

where E_{un} – electrical energy that the apparatus consumes in vain during the shift; T_{un} – the time the apparatus wastes in one shift, hours; P_m – the power of the electric motor, kWh.

Wasted time of the apparatus in one shift calculated by the formula:

$$T_m = T_{sh} - T_{us}, \tag{15}$$

where T_{us} – the useful time spent by the apparatus on coil changing during the shift, calculated by the formula $T_{us}=k_b T_{av.us}$.

In this formula, by substituting k_b and $T_{av.us}$ according to equations (1), (7) and (13), the equations that determine the useful time for ideal and random operating states of the apparatus are obtained.

For the ideal working condition of the apparatus:

$$T_{usi} = \frac{T_{sh}\vartheta R}{L_b}\left(nt_c + \frac{4H}{V_a}\right)\alpha. \tag{16}$$

For the probable operating situation of the apparatus:

$$T_{us.r} = \frac{T_{sh}\vartheta R}{L_b}\left(nt_c + \frac{H(n+2)}{4V_a}\right)\alpha. \tag{17}$$

Dividing equations (16) and (17) by 60 and substituting (15) let's determine the useless operating time of the apparatus for both cases during the shift.

For the ideal working condition of the apparatus:

$$T_{un.i} = \frac{T_{sh}}{60}\left[1 - \frac{\vartheta R}{L_b}\left(nt_c + \frac{4H}{V_a}\right)\alpha\right]. \tag{18}$$

For the probable operating situation of the apparatus:

$$T_{un.r} = \frac{T_{sh}}{60}\left[1 - \frac{\vartheta R}{L_b}\left(nt_c + \frac{H(n+2)}{4V_a}\right)\alpha\right]. \tag{19}$$

The electrical energy consumed in vain by the apparatus during this period can be calculated with the following equations for these cases.

For the ideal working condition of the apparatus:

$$E_{un.i} = \frac{T_{sh}}{60}\left[1 - \frac{\vartheta R}{L_b}\left(nt_c + \frac{4H}{V_a}\right)\alpha\right]P_m. \tag{20}$$

For the probable operating situation of the apparatus:

$$E_{un.r} = \frac{T_{sh}}{60}\left[1 - \frac{\vartheta R}{L_b}\left(nt_c + \frac{H(n+2)}{4V_a}\right)\alpha\right]P_m. \tag{21}$$

Let's look at the practical application of this in the example of the bobbin changing apparatus operated on a 60-head bobbin machine. Let's use the values in the literature [23] as the operating parameters of the machine and the bobbin changing apparatus.

Winding speed of the machine υ_w=1000 m/min, efficiency R=0.92 number of heads n=60, movement speed of the apparatus V_a=15 m/min, bobbin change time t_c=0.3 bobbin/min, length of the motion path of the apparatus H=20 m, length of yarn in bobbin L_b=110000 m, shift time 480 min (8 hours) and α=1.1.

Using these values in equations (18) and (19) let's find that $T_{un.i}$=6.28 hours and $T_{un.i}$=5.15 hours.

These values mean that under current conditions, the bobbin changer apparatus wastes 100×6.28/8=78.5 % of the shift time in ideal working condition and 100×5.15/8=64.4 % in probabilistic working condition. Accordingly, 78.5 % and 64.4 % of the electrical energy consumed by the apparatus during the shift will be wasted.

In the case where the engine power is 0.15 kWh, the amount of energy consumed by the apparatus in one shift is as follows for these two operating conditions:

$$E_{uni} = T_{un.i}P_m = 6.28\cdot 0.15 = 0.942\,\text{kWh},$$

$$E_{unr} = T_{un.r}P_m = 5.15\cdot 0.15 = 0.772\,\text{kWh}.$$

As can be seen from here, 1.2–0.942=0.258 and 1.2–0.772= =0.428 out of 1.2 kWh of energy consumed by the device per shift is spent on useful work, and the rest is wasted. This is one of the biggest shortcomings in the operation of the device with the current principle.

5. 4. Results of a study to develop ways to operate a bobbin changer to reduce energy consumption

It is recommended to operate it intermittently in order to eliminate or at least minimize this shortcoming of the apparatus. According to this method, the operation of the apparatus is carried out as follow.

The apparatus is not operated during the period from the beginning of the winding process to the filling of the bobbins. When the bobbins are wrapped and filled, the apparatus is started and the first bobbin replacement process is started. The operation of the apparatus continues until the replacement of all the bobbins (the bobbin replacement cycle) is completed and the apparatus is stopped when the process is finished. After the second bobbin replacement process is finished, the apparatus is stopped again and waits for the next bobbin change. Thus, the bobbin changing apparatus is operated intermittently and the bobbin changing process is continued throughout the shift. In the meantime, the apparatus is started 5 minutes early due to the guarantee of changing the bobbin, and it is stopped 5 minutes after the process is finished. In this case, the time spent by the apparatus for each coil replacement cycle will be 10 minutes more than the normal time, and the waiting time will be 10 minutes less than the filling time of the bobbin.

In this method, described as intermittent, the apparatus spends useful time performing only the coil change cycle during the shift. During the remaining time of the shift, the apparatus does not work and thus saves energy. With this method, the average time spent by the apparatus on useful work during the shift can be determined by considering these 10 minutes in equations (16) and (17) as follows:

– for the regular working condition of the apparatus:

$$T^w_{usi} = \frac{T_{sh}\vartheta R}{L_b}\left[\left(nt_c + \frac{4H}{V_a}\right)\alpha + 10\right]; \tag{22}$$

– for the probabilistic working condition of the apparatus:

$$T^w_{usr} = \frac{T_{sh}\vartheta R}{L_b}\left[\left(nt_c + \frac{H(n+2)}{4V_a}\right)\alpha + 10\right], \tag{23}$$

where $T^w_{us.i}$ and $T^w_{us.i}$ – the average time, the apparatus spends on useful work under regular and probable operation.

The dwell time of the apparatus is adjusted at the start of the shift and between coil change cycles according to the following equation:

$$T_w = T_f - 10 = \frac{L_b}{\vartheta R} - 10. \tag{24}$$

Between coil change cycles, the apparatus switches to the waiting phase 10 minutes after the last coil of the cycle has been changed.

In particular, it should be noted that, as stated above, the ideal, i.e. regular, winding process on the machine lasts up to 3 and at most 4 bobbin change cycles. After that, the winding operation, hence the bobbin changing operation, switches to random operation mode. In this case, regular working status for a 3-shift 5-day workweek constitutes 1/15 of the random situation. Accordingly, it has been deemed appropriate to determine the average time spent by the apparatus for useful work during the operation of the apparatus with the intermittent method by equation (23).

However, when using this method, after the coil replacement cycle is completed, for any reason, one or more of the coils may become wrapped in one or more heads. In this case, these bobbins need to be replaced in the next bobbin replacement cycle, resulting in reduced winder performance.

In order to make up for this deficiency, it is recommended to switch from the intermittent mode to the signal-based operation mode when the regular bobbins replacement is finished. The operation of the apparatus according to the signal is carried out as follows.

When a signal comes to the apparatus from the filled coil head, the apparatus operates and reaches this coil and replaces it. When the change process is finished, the apparatus stops at the head where it is changing the coil and waits for the next signal. When the new signal arrives, it takes action, reaches the filled new coil and performs the coil change. Thus, the operation of the apparatus according to the signal is continuously maintained. In order to carry out the operation regime according to the signal, the mechanism controlling the length of the yarn wound on the bobbin in the winding heads of the machine should be equipped with a signal transmitter, and the bobbin change apparatus with a signal acceptor.

The time spent by the apparatus for the complete bobbin change operation in all heads of the machine in the regime of working with signals has an accidental character. The average value of this time period is determined by the (17).

In this case, the amount of energy consumed by the apparatus for changing the coil during the shift is calculated by the formula below:

$$E_{us.s} = \frac{T_{sh}\vartheta R}{L_b}\left[\left(nt_c + \frac{H(n+2)}{4V_a}\right)\alpha\right]P_m. \tag{25}$$

Here $E_{us.s}$ – the amount of energy that the apparatus consumes during the shift during operation according to the signal.

As can be seen from this equation, in the proposed working method, the apparatus is operated only during the bobbin changing process and consumes energy during this time.

In addition, provided that the machine is running on a signal, the bobbin change process can be completed faster, because when a signal is received, the machine reaches the change head immediately from where it left off. The time it takes for the apparatus to reach the coil waiting to be replaced, under the current principle of operation, depends on the position of the apparatus. For example, if the winding of the bobbin in the head occurred immediately after the passage of the apparatus, then the replacement of this bobbin will occur in the next round of the movement of the apparatus, and, consequently, the winding process in this head will be stopped, thereby reducing the machine's productivity. The operation of the device according to the recommended method also eliminates this drawback and allows to increase productivity to a certain extent.

One of the other possibilities to reduce the duration of the replacement of the bobbins is to reduce the number of bobbins served by the device. This can also be achieved by reducing the number of winding heads served by the apparatus, i. e., by using the sectional method of operation of the apparatus. At the same time, the winding heads of the machine are divided into separate sections with a certain number (for example, 10–20 heads in each section, depending on the power of the machine), each of which is serviced by a separate apparatus. At the same time, each apparatus, making a reciprocating movement in its service area, operates independently of each other. When using this method, the stroke length and the number of heads served by the apparatus are reduced in proportion to the number of apparatuses. The sectional method will be very effective if carried out together with the discontinuous method. The great advantage of this method is that the duration of the reel change is drastically reduced and the energy consumption is reduced.

In addition, winder downtime is significantly reduced by significantly reducing the number of times you have to wait for a bobbin change, which improves machine productivity.

The duration of the change of bobbins per shift with the sectional method can be determined by formula (23) taking into account the number of devices b on the machine. In this case, the number of heads served by one device will be equal to n/b, the movement of the device will become equal to H/b.

In this case, formula (23) will take the following form:

$$T_{us.s} = \frac{T_{sh}\vartheta R}{bL_b}\left[\left(nt_c + \frac{H(n+2)}{4bV_a}\right)\alpha + 10\right]P_m, \tag{26}$$

where $T_{us.s}$ – the duration of the change of bobbin per shift with the sectional method.

To compare the $T_{us.s}$ time and $E_{us.s}$ during the operation of the device with the existing and proposed options, let's calculate using formulas (15) and (30) according to the above example with the number of device $b=3$, $k_b=4$.

As a result of the calculation, it was found that when the machine is operating with three bobbin changers, the duration of the bobbin change is 2.12 hours, and with the existing version, 0.62 hours, which is 4.57 times more compared to the proposed method.

At the same time, the electricity consumed to perform the change of bobbins per shift is:

$$E_{un.s} = T_{us.s}P_m b = 0.62 \cdot 0.15 \cdot 3 = 0.28\,\text{kWh}.$$

Under the existing mode of operation, the apparatus, working for the entire shift, consumes 8·0.15=1.2 kWh. Therefore, it can be argued that as a result of applying the sectional method of the change of bobbins with three apparatus, the power consumption decreases by 1.2/0.28=4.28 times.

It can be seen from the analysis of formula (17) that the minimum time spent on the bobbin change cycle is obtained when the value of the second term is equal to zero, which takes place when the path length of the apparatus is $H=0$. This means that the device serves one head and therefore n becomes equal to one. In this case, the second term becomes equal to zero and, therefore, (17) takes the following form:

$$T_{usr} = \frac{T_{sh}\vartheta R}{L_b} t_c \alpha. \tag{27}$$

The practical meaning of this expression is that the minimum time spent on the reel change cycle will take place if the winder head has its own separate apparatus. Based on this, it can be argued that the most effective among all options is the operation of the apparatus according to this principle, i.e., an autonomous method of operation. In this case, the device operates as follows.

When the diameter of the bobbin reaches the required size automatically the winder head stops. At the same time, the appropriate take-off mechanism of the device removes the bobbin and fills the empty cartridge, after which the winding process begins until the next bobbin change operation.

Since the device is installed motionless, there is no electric motor for movement, as in previous versions. Thus, there is no need to use electricity to change the bobbins. Therefore, the stand-alone operation of the bobbin changer can be considered the most efficient in terms of energy saving.

Another significant advantage of this option is the elimination of the cases of waiting for the bobbins when changing the bobbins, which allows to reduce downtime in the machine, resulting in an increase in the coefficient of useful time, and therefore the productivity o f the machine.

The implementation of the proposed method will require the installation of a bobbin changer on each head, which will entail some increase in the cost of the machine, which is its main drawback. However, the costs associated with the increased cost of the machine can be recouped in the energy saved and increased machine productivity.

6. Discussion of the results of development of ways to saving energy when operating winding machines

As is well known, in winding and similar machines, the bobbin changing apparatus moves back and forth continuously throughout the shift, performing the bobbin changing operation [19, 20]. In this case, the time spent by the device on useful work is a small part of the queue time. During the rest of the shift, the device works in vain and wastes electricity. This is one of the main disadvantages of the coil changer working in the current method. In order to eliminate or minimize this defect, the possibilities of saving electricity in those machines have been investigated.

For this, based on Fig. 1, an analysis of the joint operation of the winding process and the bobbin changing apparatus was carried out, and the interaction between the parameters of the winding process and the operating parameters of the apparatus was studied theoretically.

As a result of the analysis, it was determined that the most appropriate way to save energy in these machines is to reduce the time of operation of the machine by eliminating idle movements without harming the bobbin changing work. A decrease in the operating time of the device means a decrease in the operating time of the electric motor that drives it, and as a result, as noted in [1, 7, 10], a decrease in energy consumption – energy saving.

For this, it is necessary to determine the time that the device spends on useful work. For this purpose, the theoretical formulas (7), (13) were obtained in the research, which determine the average value of the time spent on useful work in one coil change cycle (once changing the coils on all the winding heads of the machine) for ideal and random coil change cases. Based on those formulas, equations (16) and (17) were obtained, which allow to determine the useful work time of the coil changer during one turn by using (1). Formulas (18), (19) were proposed when the apparatus was working unnecessarily during one shift, and formulas (20), (21) were proposed to calculate the energy spent (energy loss) during this time.

However, it is more appropriate to use the formulas (17), (19), (21) used for the random situation, since the ideal bobbin change situation is very short in existing bobbin winding machines. Using these, it is possible to calculate how long the device works unnecessarily in a shift and the amount of electricity loss that occurs during this time. For example, according to the values given in the source [23], for a rewinding machine with 60 winding heads, according to formula (19), it was found that 5.15 hours (64.4 %) of the shift, the bobbin changer is working in vain. That is, 64.4 % of the energy consumed in 8 hours by the bobbin changer operating according to the current method is lost.

The theoretical formulas obtained can be useful in developing new methods for reducing energy consumption and increasing the efficiency of the bobbin changer and improving winding machines. It is these formulas that have played an important role in the emergence of the proposed methods of operation of the reel changer.

In the method of discontinuous reel change, the device break time between reel change cycles is determined by formulas (22) and (23). This method is more efficient in the case of a perfect reel change. However, since this situation is short-term, it is advisable to use formula (23).

Using this method, the useful time of the bobbin changer per shift is 3.51 hours according to formula (23). During this time, the device uses $3.51\times0.15=0.257$ kWh of electricity. Under the existing operating mode, the electrical energy consumed by the device per shift is $8\times0.15=1.2$ kWh.

The proposed method of operation of the device according to signals is more efficient than the intermittent one. Here, the operating time of the device for changing the reels is less than in the discontinuous method. In this method, the bobbin change time per shift is determined by formula (25). As a result of applying this method, the device spends 2.84 hours for useful work per shift and uses 0.423 kWh of electricity during this time. This is $1.2/0.423=2.8$ times less than the electrical energy consumed by the device with the existing mode of operation.

The sectional method of operation of the bobbin changer is more perfect than those proposed above in terms of energy saving and performance of the rewinding process. In this method, the bobbin change time depends on the number of sections and winding heads in each section. The use of the discontinuous method simultaneously with the sectional method enhances the effectiveness of this method. With the sectional method, the time for changing bobbins in one shift is determined by formula (26).

For a rewinder with 60 heads divided into 3 sections, the useful time of the apparatus per shift is 2.12 hours and the amount of energy consumed by it is 0.318 kWh. In the existing method of operation, the device consumes 1.2 kWh of energy during operation for 8 hours. When using this method, the consumed electrical energy is reduced by 3.77 times in comparison with the existing method.

When using this method, the number of idle times in the process of winding yarn is reduced by several times due to the reduction of waiting times for changing bobbins, as a result of which the machine's useful time increases, and, consequently, productivity.

To completely eliminate the consumption of electrical energy spent when changing reels, the proposed autonomous (independent) method of operating the reel changer requires the improvement of winding machines. In this method, since each winding head has its own bobbin changer, the wound bobbin is immediately removed from the head and an empty cone is inserted, and the process continues. In this case, no additional power is required, and the loss of time due to waiting for a reel to change is completely eliminated.

However, to implement this method, it is necessary to upgrade the winding machines. Since, in this case, it will be necessary to install a bobbin changer in each winding head, which will lead to some increase in the cost of its cost. However, these costs can be offset by saving energy and increasing the productivity of machines in operation in enterprises.

It should be noted that the proposed methods are based on the analysis of the formulas obtained in the theoretical part of the study. At the same time, the calculation of the operating parameters of the apparatus for changing bobbin and the amount of electricity consumed for these methods was carried out based on the data in the source [23].

It should be noted that the theoretical results of the study may be valid for determining downtime due to waiting for the execution of some technological operations (tying the ends of broken threads, changing cobs and bobbins, etc.) on winding, spinning and similar machines. The study of which requires extensive experiments and mathematical data processing using the theory of queuing and the laws of mathematical statistics. Also, in the study did not calculate the expected cost-benefit of the study, given that the resulting savings as a result of the work includes also the savings due to the increase in production volume as a result of the increase in machine productivity. Since when using the proposed methods, the time for the device to approach the winding heads for changing the bobbins is reduced, which leads to a decrease in downtime in the rewinding process, resulting in an increase in the useful time factor and, consequently, the machine's productivity. Therefore, the question of the influence of the methods of operation of the reel-to-reel machine on the performance of winding machines and the efficiency of the yarn rewinding process is planned to be considered in subsequent work.

7. Conclusions

1. A formula has been obtained for determining the number of bobbin changes per shift and it has been found that it is 3–4 depending on the length of the thread in it and the machine's productivity. A formula is obtained for determining the duration of one bobbin change cycle, which depends on the number of winding heads, the speed of the apparatus and the length of its stroke on the machine, as well as on the time it takes to change one bobbin.

2. The analysis of the operation of the bobbin changer in an ideal situation is carried out and an equation is obtained that determines the average time of one cycle of bobbin change. This period consists of the sum of the time required to change the bobbins in all heads and the time to reach the apparatus to the heads, and depends on the number of heads, the speed of the apparatus and the norm of time for changing one bobbin.

3. Theoretical formulas have been obtained to determine the average value of the operating time of the bobbin changer for one shift with ideal and random variants of bobbin change. This time depends on the number of bobbin changes per shift, on the number of apparatus strokes made in one bobbin change cycle and on the number of winding heads. With a decrease in the number of moves of the apparatus, the time of its movement decreases with constant values of the remaining parameters and, consequently, the consumption of electricity decreases.

4. The following options for the operation of the bobbin changer on winding machines are proposed, which make it possible to reduce the amount of electricity consumed and increase the productivity of the machine:

– operation of the device with interruptions – with this method, during the shift, time is spent only on the execution of the cycle of changing the reels, in the remaining time the device does not work, which saves energy;

– operation of the apparatus according to signals from the winding heads. In this method, the machine operates the bobbin change only on signals from the winding heads, and consumes energy at this time. Thanks to this, it is possible to save energy by 2.82 times compared to the existing method;

– sectional operation of the apparatus – while the winding heads of the machine are divided into separate sections with a certain number depending on the power of the machine, each of which is serviced by a separate device. As a result of using the sectional method of working with, for example, three devices, it is possible to reduce the power consumption by 4.2 times with a machine power of 60 winding heads;

– autonomous mode of operation of the apparatus – with this method, each winding head is served by its own separate bobbin changer, which operates without an electric motor. The implementation of this method can completely eliminate the consumption of electricity for changing the bobbins and will significantly increase the performance of the winding machine.

Conflict of interest

The author declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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