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DIAGNOSIS OF THE ELECTRIC DRIVE OF THE DISCHARGE ROLLER CONVEYOR OF A WIDE-STRIP HOT MILL

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Abstract. The purpose of the study is to develop an automated system for technical diagnostics of the state and regulation of the electric drive of the rollers of the collector roller table at a wide hot rolling mill based on change in the load currents of the rollers electric motors. The system allows the quality of finished rolled products and the productivity of the mill to be enhanced due to the timely detection of faulty equipment and its rapid replacement based on the results of diagnostics. The following methods of diagnostics of the electric drive of the diverting roller table and its possible malfunctions which can negatively affect the quality of the finished rolled products were analyzed: experimental identification of the relation of the forms of change in the load currents of the electric motors of the rollers with specific types of malfunctions; determination of diagnostic signs of malfunctions in the values of change in the load currents of the electric motors of the rollers; creation of a mathematical model for calculating the forces of strip transportation; development of methods and algorithms for technical diagnostics of the electric drive of the collector roller table based on characteristics of change in the load currents of the electric motors of the rollers; development of a generalized algorithm for the operation of the automated technical diagnostics system; experimental evaluation of the effectiveness of the proposed methods and algorithms for diagnostics on the operating mill. Analytical methods of solving algebraic and differential equations and systems were used in the study. As a result of the research, the technical effectiveness of the methods and algorithms developed to diagnose the eccentricity of the roller barrel of the diverting roller table, malfunctioning of the brush-collector device of the roller electric motor, the destruction of the couplings in the roller electric drive line, malfunctioning of the bearing units in the roller electric drive line or the roller sides, the correct alignment of the roller relative to the technological plane of the diverting roller was experimentally confirmed. The diagnostic methods and algorithms developed can be used to create diagnostic systems for electric drives of diverting roller table at operating mills during their reconstruction, as well as at newly built mills. The system thus developed was installed at the industrial plant's 2000 hot rolling mill.

Keywords: electric drive of the rollers of the diverting roller table, broadband hot rolling mill, faults of the electric drive, diagnostic signs, diagnostic system

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ДИАГНОСТИРОВАНИЕ ЭЛЕКТРОПРИВОДА ОТВОДЯЩЕГО РОЛЬГАНГА ТЯНУЩИХ РОЛИКОВ ШИРОКОПОЛОСНОГО СТАНА ГОРЯЧЕЙ ПРОКАТКИ

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Аннотация. Целью исследования является разработка автоматизированной системы технического диагностирования состояния и настройки электропривода роликов отводящего рольганга широкополосного стана горячей прокатки по характеристикам изменения токов нагрузки электродвигателей роликов. Система позволяет за счет своевременного выявления неисправного оборудования и его оперативной замены по результатам диагностирования повысить качество готового проката и производительность стана. В работе выполнены: анализ способов диагностирования электропривода отводящего рольганга и возможных его неисправностей, негативно влияющих на качество готового проката; экспериментальное определение соответствия форм изменения токов нагрузки электродвигателей роликов конкретным видам неисправности; определение диагностических признаков проявления неисправностей в показателях изменения токов нагрузки электродвигателей роликов; создание математической модели расчёта усилий транспортирования полосы; разработка методик и алгоритмов технического диагностирования электропривода отводящего рольганга по характеристикам изменения токов нагрузки электродвигателей роликов; разработка обобщённого алгоритма работы автоматизированной системы технического диагностирования; экспериментальная оценка эффективности предложенных методик и алгоритмов диагностирования на действующем стане. При исследовании применялись аналитические методы решения алгебраических и дифференциальных уравнений и систем. В результате исследований экспериментально подтверждена техническая эффективность разработанных методик и алгоритмов диагностирования эксцентриситета бочки ролика отводящего рольганга, неисправности щёточно-коллекторного устройства электродвигателя ролика, разрушения соединительных муфт в линии электропривода ролика, неисправности подшипниковых узлов в линии электропривода ролика или касания роликом бортов рольганга, правильности выставки ролика относительно технологической плоскости отводящего рольганга. Разработанные методики и алгоритмы диагностирования могут быть использованы для создания систем диагностирования электроприводов отводящих рольгангов на действующих станах при их реконструкции, а также на вновь строящихся станах. Разработанная система внедрена на широкополосном стане 2000 горячей прокатки промышленного предприятия.

Ключевые слова: электропривод роликов отводящего рольганга, широкополосный стан горячей прокатки, неисправности электропривода, диагностические признаки, система диагностирования

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Introduction

The main method of producing rolled sheets in the world at the present time is by means of pressure treatment of slabs on wide hot rolling mills (WHRM). The technology of pressure treatment is constantly being improved, in order to enhance the quality of finished products [1–3] and the productivity of mills [4–6].

At the end of 2019, Russian metallurgical enterprises that produce rolled metal were rated. The leaders of the rating were: Novo-Lipetsk Iron and Steel Works – 17.493 million tons; Evraz – 13.019 million tons; Magnitogorsk Iron and Steel Works – 12.664 million tons [7]. As of 18.12.2020, the consolidated price index for black rolled steel is growing rapidly: +96.8 points to a record level of 827.4.

Many studies on the issues of rolled metal production consider the technological features of the process as a whole and on individual steel grades [8–11]. They also assess the state of equipment [12–15], surface quality of finished rolled products [16–19], as well as the processing and consolidation of information in the technological process [20, 21]. One of the main areas of technological improvement is improvement to the electric drives in mill units, as well as control and diagnostic systems [22–24].

One of the most important technological units of WHRM (Wide hot rolling mills) is the collector roller table (CR). The reliability of operation and the extent to which the technological requirements are fulfilled determine the quality of rolled products and productivity of the mill. The timely replacement of CR rollers based on the results of diagnostics of failed electric drive equipment is one of the ways to improving the quality of rolled products and the performance of the WHRM.

The operational equipment of the CR electric drive is installed directly in the technological zone of the mill. This, however, does not allow the state of the electric drive of the CR rollers to be monitored visually or metrologically during the process. Metrological monitoring requires the installation of a large number of measuring sensors. An alternative method for diagnosing the electric drive of the CR is based on analysis of the change in the load currents of the roller motors. This method allows conclusions to be made about the technical condition of the equipment in real time.

Russian WHRM are not equipped with automated systems for technical diagnostics of the state of the electric drive of the CR rollers. Diagnostic systems used to collect data of the load currents of the electric motors of the rollers of the roller table are limited by the list of detected drive faults, and the diagnostic results are insufficiently reliable [22–24].

The creation of an effective automated technical diagnostics system relating to the state and regulation of the electric drive of the CR rollers, based on changes to the load currents of the electric motors of the rollers, will identify the electric drive faults during the rolling process. It will also enable repair work to be prepared in advance, thus reducing the time required for their implementation. The quality of the finished rolled products and the productivity of the WHRM will also be enhanced.

Taking into account the above, the authors have set out the objective of this study: to improve the quality of rolled products and increase WHRM productivity by means of the timely replacement of faulty electric drive equipment of the CR rollers. This is based on reliable diagnosis of faults identified by a system for the technical diagnosis of the state and regulations of the electric drive of the CR rollers of the WHRM.

In order to achieve this objective, the following main stages were identified:

– analysis of the existing methods of diagnostics of the CR electric drive and possible malfunctions of the CR electric drive which may negatively affect the quality of the finished rolled products;

– experimental identification of the compliance of the form of load current change in the roller electric drive, in relation to the type of specific malfunction in the electric drive line of the CR roller;

– identification of diagnostic signs shown by the CR electric drive malfunctions in terms of changes to the load currents of the roller electric drive;

– construction of a mathematical model for calculating belt transportation forces;

– development of methods and algorithms allowing technical diagnostics of the DR electric drive based on the characteristics of changes to load currents in the roller electric drive;

– development of a general algorithm for the operation of the automated system for technical diagnostics of the state and regulation of the CDR electric drive;

– experimental assessment of the effectiveness of the proposed methods and algorithms for diagnosing the CR electric drive.

Analysis of defects in the electric drive of rollers and the functional capabilities of the data collection system operating at the WHRM

A typical structural diagram of the process line of a continuous wide strip hot rolling mill is shown in Fig. 1.

Slabs heated to the required temperature in the furnaces (1) are transported by the receiving roller table to the vertical breaker (2), at which the surface of the slab is cleaned. The workpiece passes through roughing stands (3) and is transported by the intermediate roller table (4) to flying shears (5). After alignment of the head and tail parts of the strip, the rolled product passes through a group of finishing stands (6). Then the strip enters the collector roller table (7). During transportation it is subjected to cooling with water from above and below from showering devices, and then wound into a roll by one of the coilers (8).

The collector roller table is divided into several sections according to rolling process conditions. Each section has a separate electric drive control circuit which allows the speed and direction of rotation of the rollers to be changed.

A typical solution for the CR at WHRM is the roller table installed at the hot rolling mill 2000 (HRM) used in large metallurgical enterprises of the Russian Federation with an individual gearless electric drive (Fig. 2). Fig. 2 designations: 1 – roller, 2 – electric motor, 3 – coupling, 4 – intermediate shaft).

The collector roller table at the mill consists of nine roller sections. Each CR section is equipped with 58–60 rollers with diameter D = 300 mm. In the case of rolling strips with a thickness of 1.2…4.0 mm, coiling is carried out at first group of coilers (1, 2 and 3), located in the third section of the roller table. Thick strips (thickness 4.0…16 mm) are transported to the second group of coilers (4 and 5) located in the ninth section of the CR. Strip transportation is carried out at a speed of 4…20 m/s.

The electric drive of each roller table section (Fig. 3) is carried out according to the group scheme for the power supply to electric motors from a single thyristor converter. The excitation windings of the electric motors in each section are powered by a separate uncontrolled DC voltage source of 220 V. A subsystem for collecting information on the instantaneous values of the load currents of the electric motors of the CR rollers is provided in the APC (Automatic Process Control) system of mill 2000 GP.

Fig. 3 shows the designations: VR – Voltage regulator; CR – Current regulator; CS – Current sensor; VS – Voltage sensor; TC – Thyristor converter;

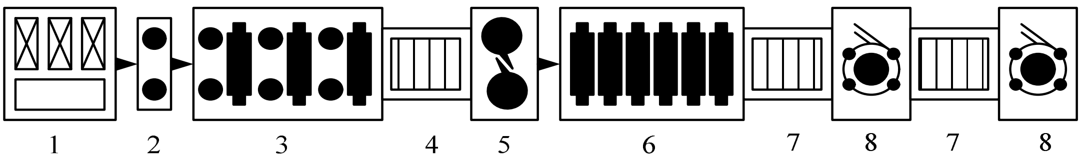

Fig. 1. Typical Structural Diagram of Continuous Wide Strip Hot Rolling Mill Process Line

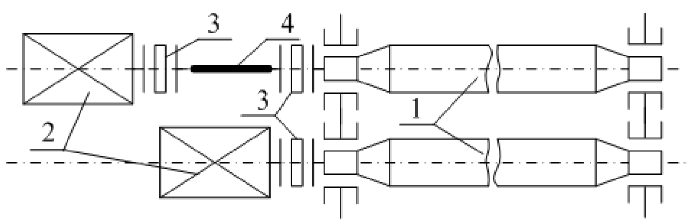

Fig. 2. Typical Solution of CR at WHRM

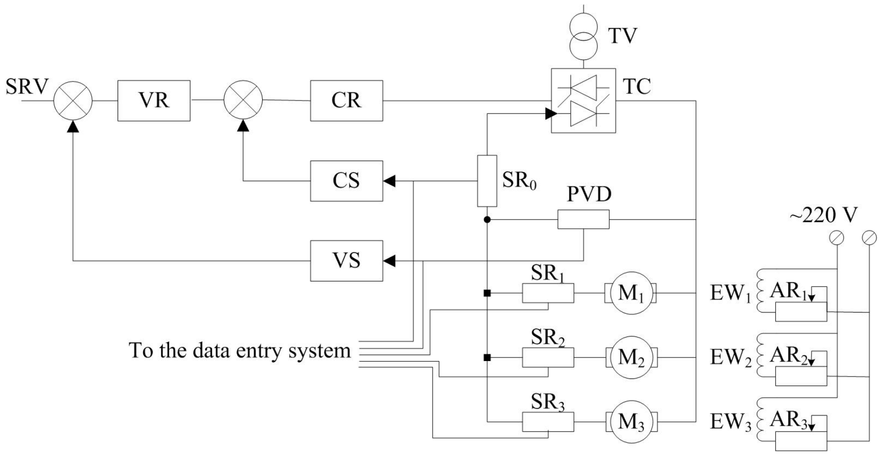

Fig. 3. Structural diagram of the electric drive of each section of the collector roller table

PVD – Power voltage divider; EW – Excitation winding; SR – Shunt resistance, Ohm; Ohm (AR – Additional resistance); SRV – Speed reference voltage; TV – Transformer ; (M – Electric motor.

The CR electric drives are subject to the following process requirements:

1. When the CR electric drive is operating in transportation mode of the head part of the strip, in order to prevent looping and to ensure the reliable transportation of the sheet to the receiving coiler, the roller table rollers must form longitudinal tensile forces in the strip in the direction of strip movement.

2. When operating in the strip tracking mode, the linear speed of the roller table barrel generating rollers must be equal to the linear speed of the strip. This is in order to prevent excessive wear of the roller barrels and deterioration of the strip surface quality.

3. When transporting the tail part of the strip, in order to prevent looping and to ensure the coiling end speed, the CR electric drive must generate longitudinal tensile forces in the strip in the direction opposed to the strip movement direction.

The main malfunctions of the electric drive of the CR rollers which may lead to a decrease in the quality of the finished rolled products and the productivity of the mill, are as follows: eccentricity of the roller barrel; malfunction of the brush-collector device of the roller electric motor; destruction of the couplings in the line of the electric drive of the roller; malfunction of bearing units in the line of the electric drive of the roller or contact between the rollers with the roller table sides; roller deflection relative to the CR technological plane; failure of the CR electric drive to perform the technological requirements.

The following methods of diagnostics of CR electric drive state exist:

– metrological control during scheduled repair works;

– vibration and acoustic diagnostics;

– diagnostics of change in the load currents of the roller motors.

Analysis of the diagnostic methods revealed the following weaknesses:

– the first method does not allow the malfunction to be identified directly during rolling and, accordingly, does not allow for repair work to be carried out in advance, thus increasing their implementation time;

– the second method requires the installation of a large number (in terms of the number of electric rollers) of measuring sensors directly in the technological zone of the mill. This is associated with significant capital costs and the costs of their maintenance;

– the data acquisition system used at the mill 2000 GP only identifies the number of the faulty electric drive of the roller without specifying the type of fault.

The third method is preferable to the first two in that faults can be directly identified during the metal rolling process. It also enables the use of the load current meters already available. However, there are no diagnostic methods that identify the entire specified list of possible defects of the CR electric drive. Therefore, the objective is to develop an effective automated system for technical diagnostics of the state and regulations of the electric drive of the CR rollers, based on the characteristics of the change in the load currents of the electric motors of the rollers.

Correspondence between the various changes to the instantaneous values of the load currents in the electric drive motors has been experimentally established (Fig. 4) as well as the individual faults occurring in the roller electric drive lines.

It has been shown that the current variation form Fig. 4a corresponds to eccentricity of the roller barrel; the form in Fig. 4b – to faults of the brush-collector device of the roller electric motor; the form of Fig. 4c – destruction of one coupling in the roller electric drive line; the form of Fig. 4d – destruction of two couplings; the forms of Fig. 4e, f – the simultaneous appearance of roller barrel eccentricity and destruction of one and two couplings, respectively.

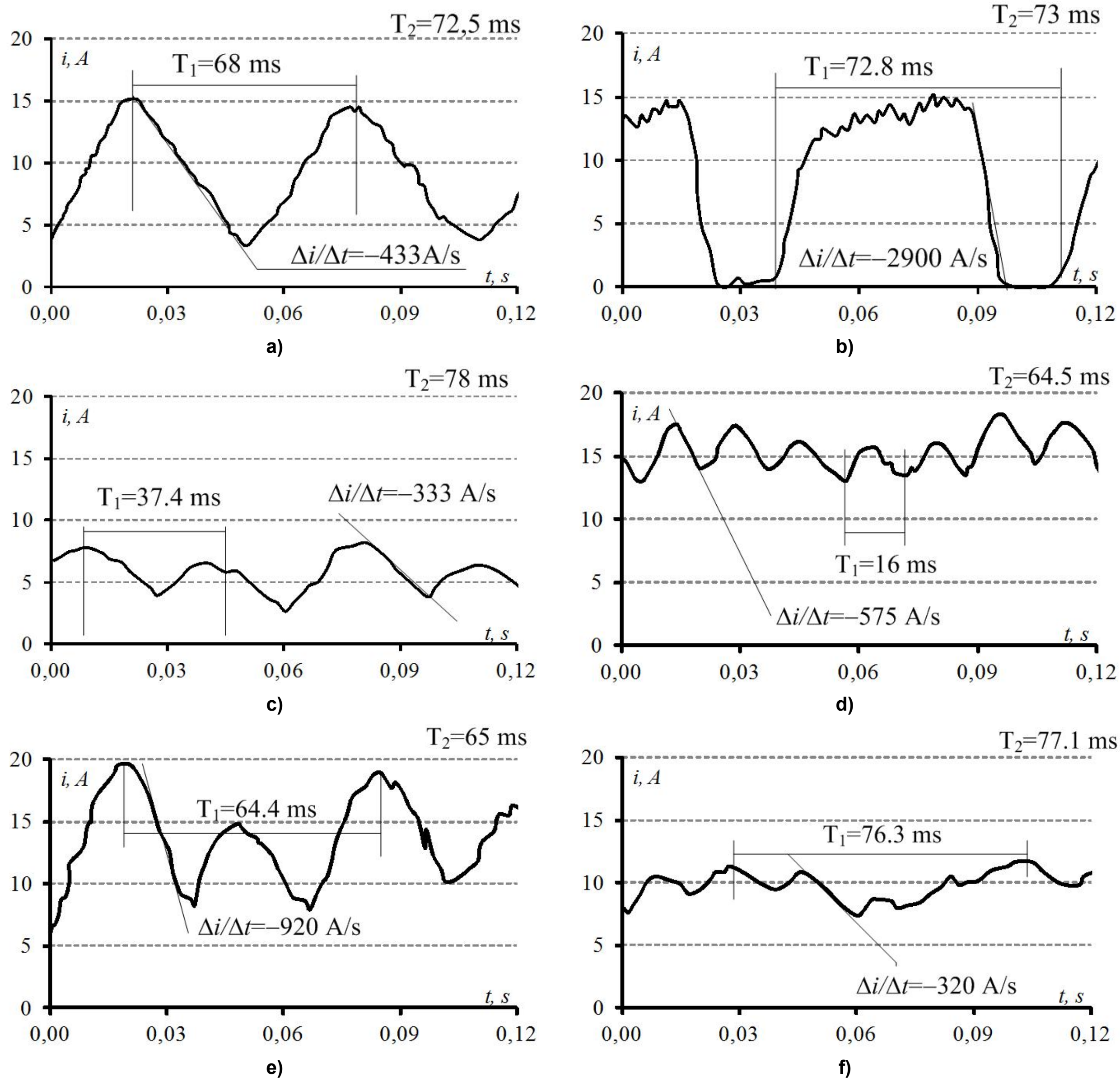

Fig. 4. Time diagrams of load current changes of CR roller motors

As a result of metrological processing of oscillograms, Fig. 4 shows that the maximum rate of load current reduction $\Delta i/\Delta t$, the ratio of the period of change in the load current of the roller electric motor of the roller table (T_1) compared to the calculated period of roller rotation (T_2) can be used as diagnostic signs for the eccentricity of the roller barrel, faults in the brush collector device of the electric drive, and destruction of the couplings (Fig. 4) at the current rolling speed V, the frequency characteristics of the load current change and the presence in the time diagram of the current i_k (Fig. 4b) time intervals equal to zero load current ($i_k = 0$).

We propose the proposed diagnostic functions be divided into two groups:

1. Diagnostics of the condition of the roller barrel, brush-collector device of the motor and the coupling shall be performed according to the characteristics of changes in the instantaneous values of the load currents.

2. Diagnostics of bearing assemblies, deviations in the roller alignment and distribution of transportation forces along the roller electric drives should be performed according to the parameters of changes in the average values of load currents calculated for a fixed time interval.

Diagnostic method for the electric drive of the rollers of the collector roller table according to the characteristics of changes in the instantaneous values of the load currents of the electric motors

For each form of change in the instantaneous values of load currents Fig. 4, samples were created. Based on these samples, the confidence intervals of individual observations of diagnostic signs at a significance level of $q = 0.05$ were calculated.

The values of diagnostic signs were calculated by the following expressions:

1) maximum load current reduction rate:

$$\frac{\Delta i}{\Delta t} = \min\left[\frac{i_{k+1} - i_k}{\Delta t}\right],$$

where i_{k+1}, i_k are the values of the roller motor load current in the data base of current values of the load currents of the CR roller motors; $\Delta t = 0.002$ s is the temporary discrete reading of the instantaneous load current values;

2) estimated roller rotation period:

$$T_2 = \frac{\pi \cdot D}{V_r},$$

where D is the diameter of the roller barrel, m; V_r is the current rolling speed of the strip, m/s.

The value of T_1 was determined by the autocorrelation function of the temporary diagram of the current change:

$$R(\tau) = \sum_{k=1}^{N_r} \frac{\left(i_k - \overline{I}\right)\left(i_{k+\tau} - \overline{I}_\tau\right) \cdot S_\tau}{S},$$

where τ is the time offset relative to the beginning of the temporary diagram of the change in the load current of the electric motor; i_k, $i_{k+\tau}$ are the instantaneous values of the load current of the electric motor of the CR roller; $N_r =]T_1/\Delta[$ is the number of instantaneous values of the load current in the calculated period of the roller rotation for the temporary discrete reading Δ (][is the integer rounding operator). The arithmetic mean values of the instantaneous values of the load currents of the electric motor in the time intervals $[0;\ \Delta \cdot N_r]$ and $[\tau;\ \tau + \Delta \cdot N_r]$ are respectively calculated by the formulae:

$$\overline{I} = \frac{1}{N_r}\sum_{j=1}^{N_r} i\left(j \cdot \Delta\right)$$

and

$$\overline{I}_\tau = \frac{1}{N_r}\sum_{j=1}^{N_r} i\left(j \cdot \Delta + \tau\right);$$

average square deviations of the instantaneous values of the motor load current in the time intervals $[0;\ \Delta \cdot N_r]$ and $[\tau;\ \tau + \Delta \cdot N_r]$ are calculated according to the formulae:

$$S = \sqrt{\frac{1}{N_r - 1}\sum_{j=1}^{N_r}\left(i\left(j \cdot \Delta\right) - \overline{I}\right)^2}$$

and

$$S_\tau = \sqrt{\frac{1}{N_r - 1}\sum_{j=1}^{N_r}\left(i\left(j \cdot \Delta + \tau\right) - \overline{I}_\tau\right)^2};$$

3) the ratio of amplitude values of the second A_2/A_1 and the fourth A_4/A_1 harmonics to amplitude value of the first harmonic in the frequency spectrum of electric motor load current variation.

As a result of statistical analysis of time diagrams of load currents Fig. 4, the numerical characteristics of the diagnostic signs for the specified malfunctions of the electric drive of the rollers and their combinations were determined (Table. 1).

A methodology for diagnosing the state of the electric drive of the CR rollers based on the characteristics of changes to the instantaneous values of the load currents of the electric motors was thus developed. It consists of the following main stages:

1. From the total range of changes in the instantaneous values of the load currents of the roller motors, a range with a duration of $t = 0.5$ s can be determined.

2. The values were determined as a result of correlation, differential and frequency analysis of the above expressions and decomposition in the Fourier series,

$$\frac{\Delta i}{\Delta t},\ \frac{T_1}{T_2},\ \frac{A_2}{A_1},\ \frac{A_4}{A_1} \text{ и } i = 0,$$

in which A_1, A_2, A_4 are the amplitudes of the first, second and fourth harmonics in the frequency spectrum of the load current variation of the electric motors.

Table 1

Diagnostic signs of malfunctions of the electric drive of CR rollers

Type of malfunction	Diagnostic Conditions
Destruction of two couplings	$T_1/T_2 < 0.369$
Collapse of one coupling	$T_1/T_2 \in (0.387; 0.633)$
Malfunction of the brush-collector device of the electric motor	$(T_1/T_2 \in (0.752; 1.0763)) \vee (\Delta i/\Delta t < -978.8) \wedge (i_k = 0)$
Roller barrel eccentricity	$(T_1/T_2 \in (0.752; 1.0763)) \vee (\Delta i/\Delta t > -978.8) \vee$ $\vee (A_2/A_1 \in (0; 0.487)) \vee (A_4/A_1 \in (0; 0.276))$
Simultaneous presence of roller barrel eccentricity and destruction of one coupling	$(T_1/T_2 \in (0.752; 1.0763)) \vee (\Delta i/\Delta t > -978.8) \vee$ $\vee (A_2/A_1 > 0.537) \vee (A_4/A_1 < 0.276)$
Simultaneous presence of roller barrel eccentricity and destruction of two couplings	$(T_1/T_2 \in (0.752; 1.0763)) \vee (\Delta i/\Delta t > -978.8) \vee$ $\vee (A_2/A_1 < 0.487) \vee (A_4/A_1 > 0.276)$

3. Analysis was also performed of the conditions of relativity of the values calculated in paragraph 2 to the conditions of diagnostic features of Table. 1.

When performing the conditions of table 1, it can be concluded that there is a malfunction in the CR roller drive line. Otherwise, it can be concluded that there is no defect in the electric drive line of the *k* roller.

An algorithm for diagnosing the fault of the brush-collector device of the roller electric motor, the eccentricity of the roller barrel and the destruction of the couplings in the electric drive line of the roller, based on the correlation, frequency and differential analysis of the change in the instantaneous load currents of the electric motors of the CR rollers, has been developed.

Diagnostic methods of the electric drive of the rollers of the collecting roller table based on the characteristics of changes in the average values of the load currents of the electric motors

Based on the condition for calculating the average values of the load currents I_{AVk} with an error of not more than 5%, the time interval for averaging the instantaneous values of the load currents can be statistically determined – $\Delta t = 0.14$ s.

As a result of the dispersion and regression analysis of the change in the values of the idling currents of the electric motors of the I_{0k} of the CR rollers (56 electric motors were studied) during the overhaul period of the mill, it was established:

– The “linear rolling speed” factor V significantly influences the change in the idling currents of the electric motors. Each electric motor corresponds to its own law of change $\hat{I}_{0k} = f(V)$. It is impossible to obtain a single regression model $\hat{I}_{0k} = f(V)$ which corresponds simultaneously to the change in I_{0k} of all 56 electric motors studied.

– The time factor within the overhaul period does not have a significant effect on the change in the values of the no-load currents. In the absence of a malfunction in the bearing units of the electric drive lines of the rollers or contact between rollers and the roller table sides, the confidence interval of I_{0k} change is ±13% of its value at a fixed speed V.

– In the case of a malfunction in the bearing units of the roller drive lines or in the case of contact between the roller and the roller table, the value of the idling current of the electric motor increases several times.

Bearing this in mind, the following technique is proposed for diagnosing the failure of bearing units in the electric drive line of the roller or the roller touching the roller tables sides:

1. With the mill equipment at idle, after performing scheduled repair works, a range of values of the idle currents I_{0k} of the electric motors of the roller of the roller table can be created within the working range of rolling speeds $V = 4…20$ m/s with a step of speed change $\Delta V = 1$ m/s.

2. During mill operation, in the absence of metal on the CR rollers and given a fixed level of the rolling speed setting V', the current values of the no-load currents of the electric motors of the CR $\hat{I}_{0_k}$ *rollers* are recorded.

3. The value of the idling current I'_{0_k} for the *k* electric motor, corresponding to the value of the speed V', is extracted from idle currents’ value range. Based on this expression

$$\Delta I^*_{0_k} = \left(1 - \frac{\hat{I}_{0_k}}{I'_{0_k}}\right) \cdot 100\ \%$$

a calculation of the relative change of the idle current is performed.

4. If the value of $\Delta I^*_{0_k}$ exceeds 13%, it can be concluded that there is a malfunction of the bearing units in the electric drive line of the roller or that roller has touched the sides of the roller table.

In order to determine the quality of the electric drive of the CR rollers in terms of the technological requirements for strip transportation, we propose a diagnostic method related to the effort of strip transportation by CR rollers:

1. Based on the current range of changes to the average values of the load currents I_{AV_k} of the electric motors of the rollers of the roller table, a range of average values of the load currents I_{AV} is selected, preceding the moment when the strip is gripped by the coiler.

2. The values of the resistance force to transportation of the strip in each interroll space are calculated according to the established mathematical ratios:

$$F_{C_k} = F_{C_1} + F_{C_2} = h \cdot d \cdot B \cdot \rho \cdot g \cdot \mu + \left(F_T + F_B\right) \cdot \mu,$$

where F_{C_1} is the resistance force due to the gravity of the part of the strip in the interroll space; F_{C_2} is the resistance force due to the pressure on the strip from above F_T and from below F_B of the laminar cooling water jet; B, h are the width and thickness of the strip, respectively; d is the distance between the CR rollers; ρ is the density of the strip material; μ is the friction coefficient in the bearings of the CR rollers) [25].

3. Calculation is made of the transport forces F_k communicated by the roller drive motors to the strip in each space between the roller:

$$F_k = \frac{2 \cdot c\Phi_n \cdot \left(I_{AV_k} - I_{0_k}\right)}{D} - F_{C_k},$$

where $c\Phi_n$ is the product of the design constant of the electric motor and the rated excitation flux.

4. The results of the calculation are presented in the form of Fig. 5 and transferred to the mill APCs.

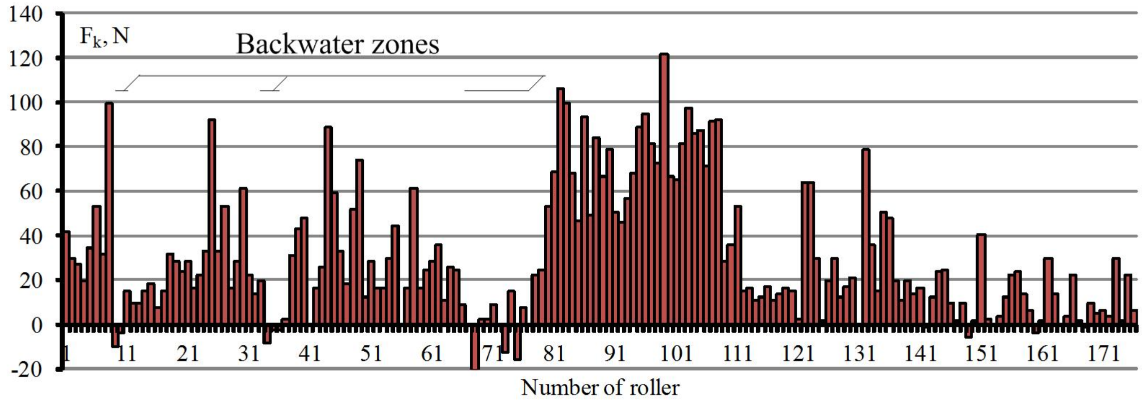

Fig. 5. Diagram of strip transportation forces distribution on CR rollers

There is uneven distribution of the transporting forces of the strip F_k on the CR rollers. Not only do some of the rollers not meet the technological requirement for transporting the head of the strip ($F_k > 0$), but also apply braking forces to the strip ($F_k < 0$), thus forming resistance zones on the collecting roller table (Fig. 5).

We propose a method for monitoring roller alignment relative to the CR technological plane. The procedure includes the following stages:

1. During rolling of thin strips with thickness h = 1.2…3.0 mm at rolling speed V_l, two data lines are extracted from the range of average values of load currents of electric motors of CR rollers: $I_k(t_1)$ and $I_k(t_2)$ at the moments before (t_1) and after (t_2) the sheet is gripped by receiving coiler, respectively.

2. The values of the idle currents $I_{0_k}(V_l)$ of the electric motors of the CR rollers are based on data from the idle currents' value range.

3. The correct fulfilment of the inequality $0.87 \cdot I_k(t_1) < I_{0_k}(V_l) < 1.13 \cdot I_k(t_1)$ is checked for the electric motor of the k CR roller. If the inequality is met, then the mark M1 is added to the range of diagnoses for the k electric motor.

4. The correctness of the inequality is also checked:

$$0.87 \cdot I_k(t_2) < I_{0_k}(V_l) < 1.13 \cdot I_k(t_2).$$

Should it be achieved, the mark M2 is added to the k electric motor.

5. An analysis of the presence of M1 and M2 marks for electric motors ($k-1$), k and ($k+1$) rollers is performed. If M1 mark is missing for all rollers, and M2 mark is missing only for electric motor of the k roller of the roller table, it can be concluded that this CR roller is higher than the process plane of the roller table.

6. When rolling of strips with a thickness of h = 6.0…16.0 mm at a rolling speed V_m, row $I_k(t_3)$ is extracted from the range of average values of load currents of electric motors of CR rollers. This corresponds to time moment t_3 prior to sheet gripping by receiving coiler.

7. The values of the idle currents $I_{0_k}(V_m)$ of the electric motors of the CR rollers are based on data from the idle currents' values range.

8. The correctness of the inequality is checked for the electric motor of the k CR roller:

$$0.87 \cdot I_k(t_3) < I_{0_k}(V_m) < 1.13 \cdot I_k(t_3).$$

If the inequality is met, then the mark M3 is added to the range of diagnoses for the k electric motor.

9. In the absence of M1 mark and the presence of an M3 mark for the k CR roller, it can be concluded that this roller is installed below the CR process plane.

Algorithms have been developed to diagnose the failure of the bearing units of the electric drive line of the CR roller or in the case of the roller touching the sides of the roller table; the correct alignment of the rollers relative to the technological plane of the CR; and the distribution of transportation forces along the rollers of the collector roller table.

A general algorithm of the diagnostic system for the electric drive of CR rollers has also been developed. It shows the sequence for creating diagnostic ranges; calculating diagnostic signs; performing diagnostic functions; and outputting the diagnostic results to the mill APC system. This takes into account the change in the operating modes of the electric drive of CR.

Results of experimental testing of diagnostic algorithms

Prior to the implementation of the automated system for technical diagnostics of the electric drive of the CR rollers at mill 2000, the reliability of the diagnostic algorithms was checked jointly with workshop personnel.

In order to verify the reliability of diagnostics at the initial stage of implementation in the Borland Delphi software environment, a generalized algorithm of the diagnostic system and algorithms for performing the developed diagnostic functions was used. The digitization of the sig.0nals for instantaneous values of the load currents of the electric motors of the CR rollers was carried out using a 12-bit analog-to-digital

Table 2

Assessment of the efficiency of diagnostics of faults in the electric drive lines of roller table rollers based on instantaneous values of the load currents of the electric motors

Malfunction type of the roller electric drive line	N	N_{id}	ΔN, %
Correctly functioning electric drive lines	23	23	100
Malfunction of brush-collector assembly of CR roller motor	20	16	80
Destruction of one or two couplings in the roller electric drive line	47	17	36
Roller barrel eccentricity	33	21	64
Eccentricity of roller barrels and destruction of one or two couplings in the roller electric drive line	16	5	31
Overall effectiveness	139	82	59

Table 3

Assessment of correctness of roller alignment diagnostics relative to CR process plane

Parameter	Roller number						
	61	59	30	33	69	18	46
Deviation value, mm	–5,0	–4.0	–3.5	–3.0	–3.0	–0,5	+6,0

converter with a time discrete reading of the current values Δ = 0.001 s.

The reliability results for detecting faults in the electric drive lines based on change to the instantaneous values of the load currents are shown in Table 2, where N is the number of diagnosable drive lines with a malfunction of this type; N_{id} is the number of detected drive lines of rollers with a malfunction of this type; $\Delta N = N_{id}$ 100 %/N is the efficiency of detecting a malfunction of this type.

Based on the results of the experimental assessment of the reliability of diagnosis, a report on the testing of the diagnostic system was drafted. The report noted that the "software allows with a degree of accuracy the type of malfunction in the electric drive of the CR of the mill 2000 GP" to be diagnosed and specified.

The reason for the relatively low efficiency of identifying faults associated with the destruction of the couplings is that the appearance of this fault at the initial stage of the destruction of the coupling does not always lead to the corresponding Fig. 4 change of load currents of CR rollers electric motors.

When diagnosing the failure of the bearing units in the electric drive line of the roller or in the case of the roller touching the roller table edge, three rollers with specified failures were identified. The reliability of diagnostic information was confirmed by the personnel of the mechanics workshop.

As a result of checking the diagnostic algorithm for the correctness of the rollers alignment relative to the CR technological plane, the program determined that the rollers No. 61, 59, 30, 33, 69 are installed below, and the rollers No. 18, 46 are above the technological plane. The metrological check performed by the personnel of the shop mechanic service confirmed the reliability of diagnoses (Table 3).

An automated system of technical diagnostics of the state and settings of the electric drive of the CR rollers has been installed at an active hot rolling mill 2000. The expected economic effect of the implementation of the system was $22,000 per year.

Conclusion

We established that the application of the period of change, rate and frequency indicators of the change in the load current of the CR roller electric motor, can be used as diagnostic signs of eccentricity of the CR roller barrel, failure of the brush-collector device of the roller electric motor and destruction of one or two couplings in the line of the electric drive of the roller. We defined the numerical characteristics of the diagnostic features of these defects in the case of their separate and joint manifestation in the load currents of the roller motors.

A method was developed to diagnose malfunctioning of the brush-collector device of the roller electric motor; roller barrel eccentricity; and destruction of one or two couplings in the roller electric drive line. The method is based on the results of statistical, differential and correlation analysis of the characteristics of change to the instantaneous values of the load current of the CR roller electric motor.

A method was developed to diagnose the correctness of the roller alignment relative to the CR technological plane. The method is based on the nature of changes to the average values of the load currents of the roller electric motors in various operating modes of the CR electric drive.

We also propose a technique diagnosing strip transportation forces distribution as per the electric drives of CR rollers. The method is based on the mathematical model of the calculation of forces applied to the strip by the electric motors of the CR rollers. This method was developed for the technological conditions of rolling the sheet at the operating wide-band hot rolling mill 2000.

We also propose a technique for the diagnosis of failure of bearing assemblies in the electric drive line of the roller or contact with roller table edges. This is based on the nature of the change in the idling current of the electric motor.

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Diagnostic algorithms have been developed: malfunctioning of the brush-collector device of the roller electric motor; destruction of the couplings in the electric drive line of the roller; eccentricity of the roller barrel; malfunction of the bearing units in the electric drive line of the roller or contact with the roller table edges; correctness of the roller alignment relative to the CR technological plane; distribution of the strip transportation force along the CR rollers.

A functional diagram and a general algorithm of the automated system for technical diagnostics of the state and settings of the electric drive of the CR rollers have also been developed. They take into account the technological features of metal rolling at the hot rolling mill.

Experiments were performed to verify the reliability and efficiency of the algorithms and methods for diagnosing the eccentricity of the roller barrel, malfunctioning of the brush-collector device of the roller electric motor, the destruction of the couplings in the electric drive line of the roller, the malfunction of the bearing units in the electric drive line of the roller or the roller touching the roller table edge, the correctness of the roller alignment relative to the technological plane of the CR.

An automated system of technical diagnostics of the state and regulations of the electric drive of the CR rollers has been installed at a wide hot rolling mill 2000. The expected economic effect of the implementation is 585 thousand rubles per year.

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