The study of continuous rolling mill inter-stand tension inferential control systems

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Abstract

The inter-stand tension inferential control systems are used to stabilize the rolling motor torque. To stabilize the motor torque the electric drive system with the properties of the rolling motor torque supply may also be used. An alternate option may include torque stabilization by to the effect on speed of the previous, further or controlled mill stand. The tension control accuracy depends on how exact the unhindered rolling torque is determined. Nevertheless, a change in tension due to this factor may result in improving gauge accuracy in some systems. Using the model of the continuous rolling mill, the paper considers the force interaction between the stand electric drives for different technological conditions of rolling. It analyses the operation of the rolling mill using different system for tension inferential control. The finished studies prove that size alignment is provided with the tension control system affecting speed of the further stands. The paper verifies that the characteristics of the rolling mill including aligning ability depend on the rolling speed. It is a good practice to apply those results during the selection and calculation of the inferential tension controllers.

Keywords: electric drive, rolling mill, tension control, simulation, stand force interaction, size alignment.

1. Introduction

On the modern bar and wire mills inter-stand tension is controlled at rolling [1, 2]. For a variety of reasons, it is impossible to use tension direct control systems that is why tension value is inferred by the rolling motor torque. The rolling motor torque is defined with the torque of unhindered rolling that at a first approximation can be specified as

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constant during rolling and torques affected by the front and back tensions. If there is no back tension for the first stand, so after the torque of unhindered rolling of the stands has been estimated with one of the possible methods, we can evaluate torque components from tension effect for each stand of the rolling mill. With these values, we can develop the systems for inter-stand tension control while stabilizing the torque of the rolling motor.

2. Relevance

To stabilize the motor torque the electric drive system with properties of the rolling motor torque supply may be used. An alternate variant may include torque stabilization due to the effect on speed of the previous, further or controlled mill stand. A disadvantage of such systems is sensitivity of the unhindered rolling torque to fluctuating technological conditions of rolling. It ultimately affects accuracy of the tension control. In some cases, however, resulting tension deviations at rolling with such systems may have a beneficial effect on size alignment. Because of the need to increase gauge accuracy and provide stability of continuous rolling it is relevant to study and compare different tension control systems.

3. Problem statement

According to the studies [4–7], when the rolling motor torque is controlled by effecting the roll speed of the further stand this system can adjust tension as well as align sizes at measuring technological conditions of rolling. It is associated with elastic expansion of the stand at changing rolling conditions. Specifically, when increasing the original size of rolled products, yield stress and friction coefficient in the deformation zone that should result in gain of the motor torque; rolling product size in the reduction direction due to the stand elastic expansion the front tension for the stand will also grow. It will influence size reduction as at raising tension the roll pressure and stand elastic expansion are decreased. As a result, changing roll product size occurs to a lesser extent, that is, gauge alignment is enabled [8].

The study aims to determine effect of the fluctuating technological conditions of rolling on distribution of inter-stand tensions and loads of rolling motors for three variants of the continuous rolling mill: with the speed control system only, for electric drive of the rolling mill with properties of the torque supply as well as for the system stabilizing the torque due to the effect on speed of the following stand of the inter-stand gap.

4. Theory

We consider the wire mill with four-roll passes that uses a variable frequency electric drive with the asynchronous vector speed control motor [9-12].

The rolling mill is simulated by means of MATLAB environment and SIMULINK application [13, 14]. Structural diagrams of the asynchronous motor with frequency converter and vector speed control have been developed, the structural diagram of strip within the inter-stand gap is also provided.

Equations describing operation of the asynchronous motor in the rotating coordinates are offered in [9]. According to these equations, the structural diagram of the asynchronous electric motor at alignment of the rotating \(\alpha-\beta\) coordinates due to the vector of rotor's flux linkage (Fig. 1) is provided. Inputs of this model are \(U_{1\alpha}\) and \(U_{1\beta}\) projections of the voltage space vector, the Ms value of static torque of the electric drive. Output variables are the \(\omega\) rotor speed of the asynchronous motor and value of the flux linkage of \(\psi_2\) rotor. The model relies on saturation of the motor magnetic system [15, 16].

The structure of the automatic speed and motor torque control system accounts for the principle of the subordinate coordinate adjustment (Fig. 2). Flux linkage is controlled with double-circuit; speed is controlled with two-circuits for control of the current component in \(\beta\)-direction, motor torque and speed [8, 9]. Inputs of this model are signals setting motor speed and rotor flux linkage, feedback signals of the \(i_{1\beta}\) and \(i_{1\alpha}\) current components, rotor flux linkage and motor speed. Outputs are \(U_{1\alpha}\) and \(U_{1\beta}\) projections of the voltage space vector.
For simulation of strip behavior within the inter-stand gap the known tension expression in the integral form, proposed first by D.P. Morozov [17, 18], is used. Speed calculation considers the values of leads and lags of the metal speed related to the roll speed in the deformation zones. Strip behavior model is shown in Fig. 3. Input variables of this model are rotation speed of rolls of the adjacent stands; an output variable is the value of tension within the inter-stand gap.
\[ T_{i,i+1} = \frac{E Q_i}{l_{i,i+1}} \int_{0}^{t} (v_{i+1} - v_i) dt + T_{i,i+1}(0). \]

where \( E \) – elasticity modulus of the rolled material; \( Q_i \) – cross-section of strip between \( i \) and \( i+1 \) stands; \( l_{i,i+1} \) – length of the inter-stand gap; \( v_i, v_{i+1} \) – speed of metal output from rolls of the stand with \( i \) order number and metal entry to the stand with \( i+1 \) order number.

Fig. 3. Structural diagram of the strip model in the inter-stand gap.

At simulation, each model has the form of subsystem with input and output parameters. It enables a relatively easy simulating the multi-stand mill with stand electric drives correlated through the rolled strip.

The established model of the continuous three-stand rolling mill is shown in Fig. 4.

Fig. 4. Model of the continuous three-stand mill

(ASCS – automatic speed control systems of the 1st, 2nd and 3rd stands; AM – models of asynchronous motors of the 1st, 2nd and 3rd stands; \( M \) – torques of motors of the 1st, 2nd and 3rd stands, \( M_{\text{rol}} \) – torques of rolling of the 1st, 2nd and 3rd stands; \( v \) – peripheral speed of rollers of the 1st, 2nd and 3rd stands; \( F_{12}, F_{23} \) – tensions in the first and second inter-stand gaps).
Torques of the stand motors change due to the variations of the rolling technological conditions. So, the torques at rolling are effected by the origin size of the rolled products, friction coefficient in the deformation zone and yield stress of the rolled strip. During investigations, such changes were simulated by setting a deviation of the rolling torque to 10% in one of the stands and changing values of the inter-stand tensions and motor torques of every stand was calculated. Investigation results are provided in Table 1 and 2.

| Specified Conditions | Change of $T_{rol}$ in the stand by 10% | Inter-stand Tension Alteration, $T$ |
|----------------------|----------------------------------------|--------------------------------------|
| ASCS                 | Rate of the output stand 178 1/s       | Stand 1 – 2                          |
|                      | in the 1.                              | 117.7                                |
|                      | in the 2.                              | -79                                  |
|                      | in the 3.                              | -67.3                                |
|                      | Rate of the output stand 17.8 1/s      | Stand 2 – 3                          |
|                      | in the 1.                              | 472                                  |
|                      | in the 2.                              | -219                                 |
|                      | in the 3.                              | -102                                 |
|                      | Rate of the output stand 17.8 1/s      |                                    |
|                      | in the 1.                              | 0                                    |
|                      | in the 2.                              | -1000                                |
|                      | in the 3.                              | -1000                                |
|                      | Rate of the output stand 17.8 1/s      |                                    |
|                      | in the 1.                              | 0                                    |
|                      | in the 2.                              | -1000                                |
|                      | in the 3.                              | -1000                                |
| Tm3=const Tm2=const (ED-torque source) | Rate of the output stand 178 1/s       |                                    |
|                      | in the 1.                              | 464                                  |
|                      | in the 2.                              | -32.8                                |
|                      | in the 3.                              | -3                                   |
| Torque stabilization Tm1 , Tm2 due to the front tension | Rate of the output stand 17.8 1/s |                                    |
|                      | in the 1.                              | 870                                  |
|                      | in the 2.                              | -30                                  |
|                      | in the 3.                              | -10                                  |

| Specified Conditions | Change of $T_{rol}$ in the stand by 10% | Motor torque alteration, $Tm$ |
|----------------------|----------------------------------------|-------------------------------|
| ASCS                 | Rate of the output stand 178 1/s       | 1                             |
|                      | in the 1.                              | 88.8                          |
|                      | in the 2.                              | 8.5                           |
|                      | in the 3.                              | 0.4                           |
|                      | Rate of the output stand 17.8 1/s      | 2                             |
|                      | in the 1.                              | 52.6                          |
|                      | in the 2.                              | 21.9                          |
|                      | in the 3.                              | 10.4                          |
|                      | Rate of the output stand 17.8 1/s      | 3                             |
|                      | in the 1.                              | 100                           |
|                      | in the 2.                              | 99.8                          |
|                      | in the 3.                              | 99.9                          |
| Tm3=const Tm2=const (ED-torque source) | Rate of the output stand 178 1/s       | 2                             |
|                      | in the 1.                              | 53.6                          |
|                      | in the 2.                              | 3.3                           |
|                      | in the 3.                              | 0.3                           |
| Torque stabilization Tm1 , Tm2 due to teh front tension | Rate of the output stand 17.8 1/s | 3                             |
|                      | in the 1.                              | 10                            |
|                      | in the 2.                              | 2                             |
|                      | in the 3.                              | 2                             |
At low speeds and the same deviation of the rolling torque, that is, similar changes of rolling conditions, variations of inter-stand tensions and motor torques are established to increase significantly.

For instance, when rolling conditions in the first stand are changed at high speed the deviation of tension in the first inter-stand gap is 117.7 N, at low speed– 472 N; here, tension variations in the second gap amount 10.7 N and 181 N, correspondingly. At this, the most essential motor torque changes take place in those stands where rolling conditions vary while motor torques of other stands alter due to the changing inter-stand tensions.

For electric drive with properties of the torque supply [19] all alternations of rolling conditions in the second and third stand are proven to result in changing motor torque of the first stand. As we can see, changes of the rolling conditions in the mill stands of such system spread against rolling direction and may significantly load motors of the first mill stands. Furthermore, the value of the rolling speed with the use of the system considered does not effect on the value of variations of inter-stand tension and rolling motor torques.

In the systems stabilizing motor torque due to the front tension alterations of the rolling torques in the stands lead to substantial changing front tension enabling alignment of the rolled product sizes. In this case changes of the rolling conditions in the mill stands spread in the rolling direction increasing loads of the further motors. Here, when rolling conditions undergo changes in the third stand only the motor torque of this stand will essentially raise.

It should be noted that the system stabilizing inter-stand tensions cannot promote alignment of the rolled product size as at constant tension elastic expansion of the stand does not depend on this factor.

The results provided prove that properties of the mill depend on rolling speed. To estimate dynamic characteristics of the continuous mill with different speeds the frequency response characteristics of the three-stand mill (Fig.5) were determined that associate tension alternations in the inter-stand gaps and changes of the signal setting speed for the first stand at different rolling speed.

![Graph](image)  
**Fig.5.** Frequency response characteristics of the rolling mill at change of the speed setting for the first stand  
(1,2- for rolling speed 1.78 m/s, 3,4- for rolling speed 17.8 m/s; 1,3- for the first inter-stand gap, 2,4- for the second inter-stand gap).

The analyses of characteristics show that dynamic properties of the strip have the main influence on the frequency bandwidth in the case under consideration. At the change of rolling speed, the strip speed ratio and its time constant will significantly vary in the inter-stand gap. Coefficients connecting speed alterations in the first stand and inter-stand tensions have the highest values at low speeds. Speed alterations in the first stand have more pronounced influence on the tension change in the first inter-stand gap when compared to the second. This is due to the impact of the second (intermediate) stand acting here as a kind of damper. At low rates, the phase delay is shifted towards the lower side under influence of the strip properties.

The frequency response characteristics obtained testify that at the use of the system stabilizing motor torque with change of the further stand speed the rolling mill will have the best alignment capacity at lower speeds; at raising speed the size alignment will be less efficient. However, even in that case when technological rolling conditions are changed at higher speeds it will have less effect on the tension alteration, so improve the operation of the rolling mill, too [20-24].

To maintain dynamic properties of the control system at change of the rolling speed one should consider a significant alteration of speed ratios connecting the stand speed setting and values of the inter-stand tensions [25-28].
5. Conclusion

1. It is a good practice to use the principle of the three-stand mill modeling developed at investigation of rolling mills with different number of the continuous stands.
2. The actual rolling mill has been quantitatively evaluated with regard to the force interaction of the electric drives at fluct-uations of the rolling conditions.
3. The finished studies prove that gauge alignment is provided with the tension control system effecting on speed of the following stands. It verifies that the characteristics of the rolling mill including aligning ability depend on the rolling speed.
4. At higher speeds the alignment property is reduced but at the same time the inter-stand tensions undergo less alterations at fluctuations of the rolling conditions, that is, rolling operation is improved.
5. It is advisable to apply modeling methods and obtained findings to selection and calculation of the tensions regulators for continuous rolling mills.

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