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SKEW CONTROL OF RAIL MOUNTED WIDE SPAN MULTI-MOTOR DRIVES

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Vojkan Kostić, Nebojša Mitrović, Milutin Petronijević, Bojan Banković, Filip Filipović

University of Niš, Faculty of Electronic Engineering, Department of Power Engineering, Republic of Serbia

ORCID iDs: Vojkan Kostić https://orcid.org/0000-0002-7714-469X
Nebojša Mitrović https://orcid.org/0000-0003-3767-3244
Milutin Petronijević https://orcid.org/0000-0003-2396-0891
Bojan Banković https://orcid.org/0000-0002-5504-599X
Filip Filipović https://orcid.org/0000-0002-1930-9273

Abstract. *In this paper, the construction skewing problem of rail mounted wide span multi-motor drives is considered. A new skew control algorithm is proposed, and the controller design is analyzed in detail. Additionally, a PLC program algorithm for the practical implementation of the proposed solution is presented. The practical implementation of the skew control is described as a concrete example from an industrial environment. Subsequently, in order to determine performance, the characteristic time dependencies were recorded.*

Key words: *Skew control, rail mounted wide span multi-motor drive, gantry crane.*

1. INTRODUCTION

The application of controlled multi-motor drives is very common in the industry [1]. Motor operation control of multi-motor drives is realized at the control level of the entire multi-motor drive, usually utilizing programmable logic controllers (PLCs) and industrial communication networks. As a rule, high control performance is achieved by employing controlled electric motor drives that utilize various vector control methods for precise speed/torque regulation. A comparison of different control structures for controlled multi-

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Corresponding author: Vojkan Kostić
University of Niš, Faculty of Electronic Engineering, Department of Power Engineering, Aleksandra Medvedeva 4, 18000 Niš, Republic of Serbia
E-mail: vojkan.kostic@elfak.ni.ac.rs

motor drives is presented in [2,3]. Examples of electric motor drive applications in different branches of industry (metallurgy, mining, sugar industry) are shown in [4-6].

In the industry, wide span multi-motor drives, used for the transportation of goods and materials, are often encountered. Structurally, these drives consist of two movable legs connected by a bridge, which as a whole form a gantry [3,6,7]. In the case of drives with a wide span, a very common practical problem is the occurrence of construction skewing. The most common causes of skewing are the geometrical imperfection of the construction, elasticity of construction, skidding of one side in relation to the other, uneven loading of individual sides due to the position of the load, as well as the influence of wind on drives located outdoors [7]. The impermissibly large skewing can result in the damage to the construction, and in the worst case, its destruction [8]. Bearing in mind the above, the fundamental technical requirement for a controlled multi-motor drive with a wide span is the synchronous movement of both sides. Accordingly, finding a practical solution that solves the skew control problem in a simple manner is very significant.

Skew control analysis, although of great importance for the operation of controlled multi-motor drives with a wide span, is not sufficiently represented in the literature. The skewing problem of cranes, primarily from the standpoint of mechanical construction, but also control, is analyzed in [7]. The specific problem of container skewing in container cranes has been analyzed in [9,10]. The author of this paper has considered the construction skewing problem of rail mounted wide span multi-motor drives in [6,8,11-13].

In this paper, in Section 2, a new skew control algorithm for rail mounted wide span multi-motor drive is proposed. Additionally, the design of the skew controller is analyzed in detail. In the appropriate hardware environment typical for controlled multi-motor drives, which implies the application of frequency converters and PLC systems interconnected by one of the industrial communication networks, the implementation of the proposed skew control algorithm is simple with a minimal hardware upgrade. The necessary additional hardware consists of two absolute encoders and two inductive proximity switches with appropriate markers, the number of which is determined by calculation. By designing the skew controller as described and verifying it experimentally, desired drive performances can be achieved. In Section 3 of this paper, the PLC program algorithm for the practical implementation of the proposed skew control algorithm is presented in detail. The practical implementation of skew control in the industry, on the gantry crane installed at a sugar beet open storage in the TE-TO Senta sugar factory, is presented in Section 4. Upon commissioning the gantry crane, time dependencies of characteristic quantities were recorded to determine the performance of the described skew control algorithm. These dependencies were recorded in a similar manner to that described in [14]. Characteristic results are shown in Section 5.

2. SKEW CONTROL

The principle block diagram for the skew control between two induction motors (IM_i and IM_k) supplied by frequency converters (FC_i and FC_k) is shown in Fig. 1. Given that the two movable legs are connected by a bridge which represents an elastic connection, the motors are not rigidly coupled.

Elastically coupled induction motors drive the wide span construction and they are speed-controlled by the appropriate frequency converters. The frequency converters operate in the speed mode, utilizing their own speed controllers. Depending on the required drive performance, the motor speed, n_i and n_k, can be estimated or measured using appropriate encoders. The controlled multi-motor drive is speed-controlled and the main speed reference is n^*.

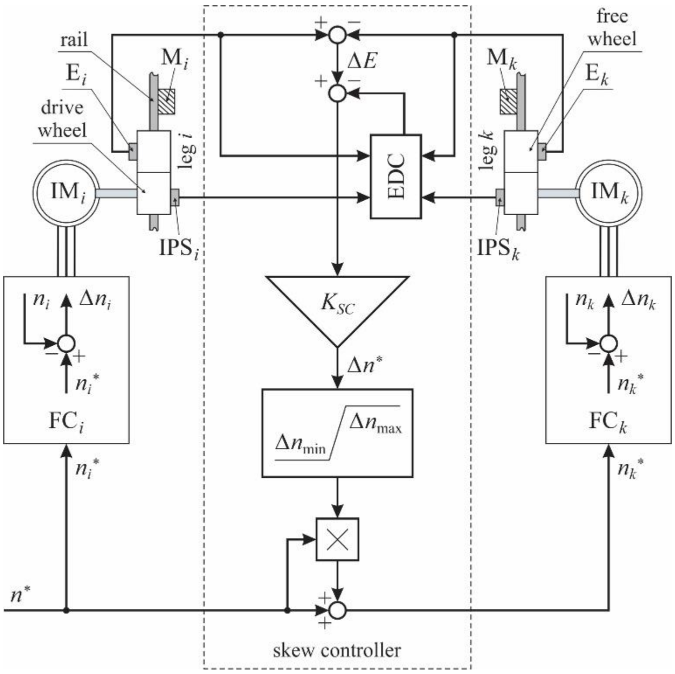

Fig. 1 The principle block diagram for skew control

Skew control between two movable legs connected by a bridge is realized by a skew controller, which is designed in the PLC system and it is a superior controller to the speed controller of the follower (slave) frequency converter, FC_k. Since high performance is not required from the PLC system, it is possible to use the existing PLC for the drive control. The operation principle of the skew controller is based on the fact that the motor driving the leg which lags by position needs to accelerate to reduce the lagging, while the motor driving the leg which leads by position needs to decelerate to reduce leading. In this way, the skew is reduced.

In the skew control algorithm, whose principle block diagram is shown in Fig. 1, the desired speed reference for one frequency converter (FC_i) is set to the main speed reference, $n_i^*=n^*$. For the second frequency converter (FC_k), the desired speed reference is obtained after correction of the main speed reference by the skew controller, $n_k^*=n^*+\Delta n^*\cdot n^*$. The reference correction, Δn^*, is proportional to the algebraic difference of absolute encoder positions, $\Delta E=E_i-E_k$, corrected by the external disturbances compensator, EDC. The reference correction is calculated in relative units, and the conversion to absolute units is achieved by multiplying by the main speed reference, $\Delta n^*\cdot n^*$. The proportional gain of the skew controller, K_{SC}, can be calculated by:

$$K_{SC} = \frac{\Delta n_d^*}{\Delta E_g} \ , \qquad (1)$$

where Δn_d^* is the desired reference correction for the given encoder positions difference ΔE_g.

To ensure the stable drive operation under large external disturbances, it is desirable to limit the reference correction, Δn^*, by a limiter within the range of $\Delta n_{\min} \div \Delta n_{\max}$.

The encoder positions difference, ΔE, can deviate from the actual skew value for several reasons, such as differences in wheel circumferences where encoders are mounted, slippage of those wheels, differences in clearances of gearboxes, etc. The external disturbances compensator, EDC, takes into account and compensates all external influences on the position difference of two encoders by measuring the actual skew when inductive proximity switches, IPS_i and IPS_k, are above markers, M_i and M_k, symmetrically mounted along the construction runway. The slippage of drive wheels, as the biggest external disturbance, can be eliminated by mounting encoders on free wheels, as shown in Fig. 1.

The operation principle of the external disturbances compensator is illustrated in Fig. 2.

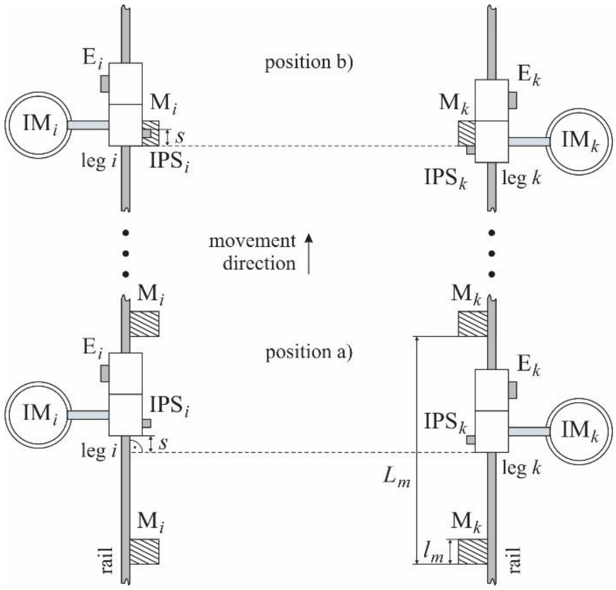

Fig. 2 The operation principle illustration of the external disturbances compensator

Position a) in Fig. 2 illustrates the controlled multi-motor drive with a wide span whose construction is skewed by the value s. The skew value represents the distance between the construction reference point on the motor side IM_i and the normal to the movement direction drawn from the construction reference point on the motor side IM_k.

Position b) in Fig. 2 illustrates the operation principle of the external disturbances compensator. The actual skew of the construction, s, is measured by encoders, and it is the distance travelled by the first activated inductive proximity switch over the associated marker until the activation moment of the second inductive proximity switch. The output from the external disturbances compensator, i.e. the compensation value, is the difference between the difference of absolute encoder positions and the actual skew, $EDC = \Delta E - s$, and it corresponds to the influence of external disturbances on the construction skewing. In this way, with each passage over the markers, the influence of all external disturbances, accumulated between two pairs of markers, is eliminated.

For each wide span construction, the value of critical skew, s_{cr}, which can compromise its stability, is known. The skew controller is designed according to the allowable maximum skew, $s_{\max}$, which must be less than the critical skew, $s_{\max} < s_{cr}$. Depending on the technical requirements, the value of the allowable maximum skew in practice should be chosen from the range of (0.4÷0.8) s_{cr}.

The length of all markers along the runway should be the same and equal to the allowable maximum skew, $l_m = s_{\max}$, to enable the skew control in the manner explained in Section 3.

The distance between each pair of markers along the runway, L_m, must be such that, during the movement of the drive between markers, external influences on the position difference of two encoders cause the construction skewing less than the allowable maximum skew. Let the drive move at a constant linear speed v. The distance between the markers will be covered in time:

$$t_m = \frac{L_m}{v} \; . \tag{2}$$

Also, let us assume that during the movement of the drive, due to external disturbances (such as differences in wheel circumferences where encoders are mounted, slippage of those wheels, differences in clearances of gearboxes, etc.), the maximum expected difference between linear speeds of leg i and leg k of the drive is Δv. To ensure that during the movement of the drive between markers external influences on the position difference of two encoders cause construction skewing less than the allowable maximum skew, the following must be met:

$$t_m \le \frac{s_{\max}}{\Delta v} \; . \tag{3}$$

The distance between each pair of markers, based on equations 2 and 3, is:

$$L_m \le \frac{s_{\max}}{\Delta v / v} \; . \tag{4}$$

Finally, the expression for calculating the distance between each pair of markers, L_m, can be written as follows:

$$L_m \le \frac{s_{\max}}{\Delta v_{\%}} \cdot 100\% \; , \tag{5}$$

where $\Delta v_{\%}$ is the maximum expected difference between linear speeds of the leg i and leg k of the drive, expressed in percentages.

The number of marker pairs, N_m, for a runway of the length L, can be calculated using the following expression:

$$N_m \ge \frac{L}{L_m} \; . \tag{6}$$

In practice, the maximum expected difference between linear speeds of the leg *i* and leg *k* of the drive, $\Delta v_{\%}$, is a few percent at most. When adopting this value, one should consider the fact that a higher value increases safety, but it also increases the number of markers, so a compromise solution needs to be found.

To ensure stable drive operation under large external disturbances, it is desirable to limit the reference correction, Δn^*, by a limiter within the range of $\Delta n_{min} \div \Delta n_{max}$, where $\Delta n_{min} = -\Delta n_{max}$. Limiter saturation values should be adopted assuming irregular operation of the skew control (e.g., failure of one encoder), with the condition that the allowable maximum skew, s_{max}, is reached within the desired time, t_d. In the case of irregular operation of the skew control, the worst-case scenario is when the limiter operates at its saturation value, e.g. Δn_{max}. Then there is the maximum difference between linear speeds of leg *i* and leg *k* of the drive, Δv_{max}, which amounts to:

$$\Delta v_{max} = \Delta n_{max} \cdot \frac{1}{I_{dw}} \cdot \frac{\pi}{60} \cdot D_{dw} \ , \tag{7}$$

where I_{dw} is the drive wheel gearbox ratio, and D_{dw} is the drive wheel diameter.
Under the above conditions, the following applies:

$$\Delta v_{max} = \frac{s_{max}}{t_d} \ . \tag{8}$$

The limiter saturation value, based on equations 7 and 8, is:

$$\Delta n_{max} = I_{dw} \cdot \frac{60}{\pi \cdot D_{dw}} \cdot \frac{s_{max}}{t_d} \ . \tag{9}$$

Finally, the expression for calculating the limiter saturation value, Δn_{max}, in percentages of the drive maximum main speed reference, n_{max}^*, can be written as follows:

$$\Delta n_{max,\%} = \frac{1}{n_{max}^*} \cdot I_{dw} \cdot \frac{60}{\pi \cdot D_{dw}} \cdot \frac{s_{max}}{t_d} \cdot 100\% \ . \tag{10}$$

The desired time, t_d, is adopted depending on the required drive performance. It should be noted that a smaller value provides a wider limiter range and faster skew controller response, but it can cause control instability. The typical limiter saturation value is in the range of (5÷15) %.

If it is adopted that the desired reference correction is equal to the limiter saturation value in relative units, $\Delta n_d^* = \Delta n_{max,\%} / 100\ \%$, for the given encoder positions difference corresponding to the encoder position increment for the distance travelled in the length of the allowable maximum skew, $\Delta E_g = E_{p,max}$, the proportional gain of the skew controller, K_{SC}, can be calculated using the expression:

$$K_{SC} = \frac{\Delta n_{max,\%}}{E_{p,max}} \cdot \frac{1}{100\%} \ . \tag{11}$$

The encoder position increment for the distance travelled in the length of the allowable maximum skew, $E_{p,max}$, is:

$$E_{p,\max} = E_{p,1\text{m}} \cdot s_{\max} \ , \tag{12}$$

where $E_{p,1\text{m}}$ is the encoder position increment per meter of travel.
The encoder position increment per meter of travel, $E_{p,1\text{m}}$, can be calculated as follows:

$$E_{p,1\text{m}} = E_{p,rev} \cdot I_{fw} \cdot \frac{1}{\pi \cdot D_{fw}} \ , \tag{13}$$

where $E_{p,rev}$ is the encoder position increment per revolution, I_{fw} is the free wheel gearbox ratio, and D_{fw} is the free wheel diameter.
Finally, for the proportional gain of the skew controller, K_{SC}, by substituting expressions 10, 12, and 13 into expression 11, is obtained:

$$K_{SC} = \frac{1}{n^{*}_{\max}} \cdot \frac{I_{dw}}{I_{fw}} \cdot \frac{D_{fw}}{D_{dw}} \cdot \frac{60}{t_d} \cdot \frac{1}{E_{p,rev}} \ . \tag{14}$$

The designed skew controller should be experimentally verified upon commissioning the drive, and that in accordance with the desired performance.

In the appropriate hardware environment typical for controlled multi-motor drives, which implies the application of frequency converters and PLC systems interconnected by one of the industrial communication networks, the implementation of the proposed skew control algorithm is simple with minimal hardware upgrade. The necessary additional hardware consists of two absolute encoders and two inductive proximity switches with appropriate markers, the number of which is determined by calculation. By designing the skew controller as described and verifying it experimentally, desired drive performances can be achieved.

3. PLC PROGRAM ALGORITHM FOR SKEW CONTROLLER

Skew control is realized by the skew controller, which is designed in the PLC system by writing the appropriate program code. The PLC program algorithm for the proposed skew controller from Fig. 1 is shown in Fig. 3.

In the “skew check (M)” block, shown in Fig. 4, the fact that the length of all markers along the runway is the same and equal to the allowable maximum skew, $l_m = s_{\max}$, is utilized. Based on information from inductive proximity switches obtained when passing over the markers, this block checks the skew. If the skew exceeds the length of the markers, it sends a signal to stop the drive operation. Skew control by this block is independent of encoder functionality and any external disturbances, and it is active when the drive passes over the markers.

The “position difference (M)” block, whose PLC program algorithm is shown in Fig. 5, measures the difference in positions of the leg i and leg k of the drive, i.e. the actual skew of construction, s, as the difference of absolute encoder positions at the moment of inductive proximity switches activation upon passing over the markers. The actual skew of the construction, s, is taken into account when the inductive proximity switches become inactive, i.e. when the drive passes over the markers.

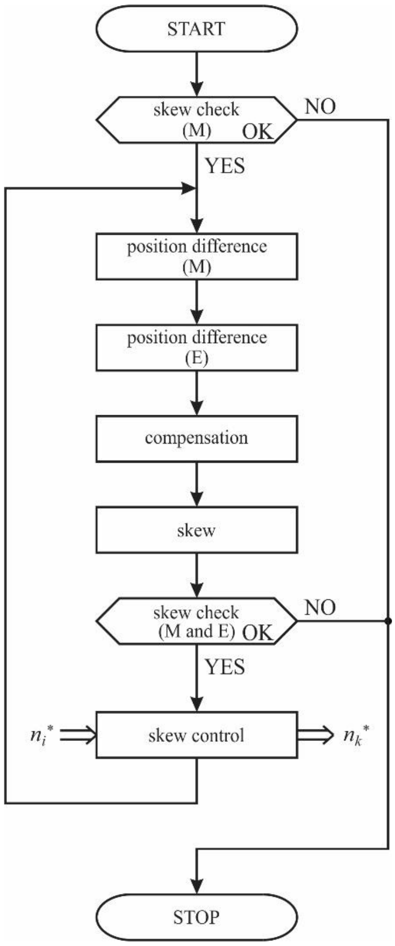

Fig. 3 The PLC program algorithm for the proposed skew controller

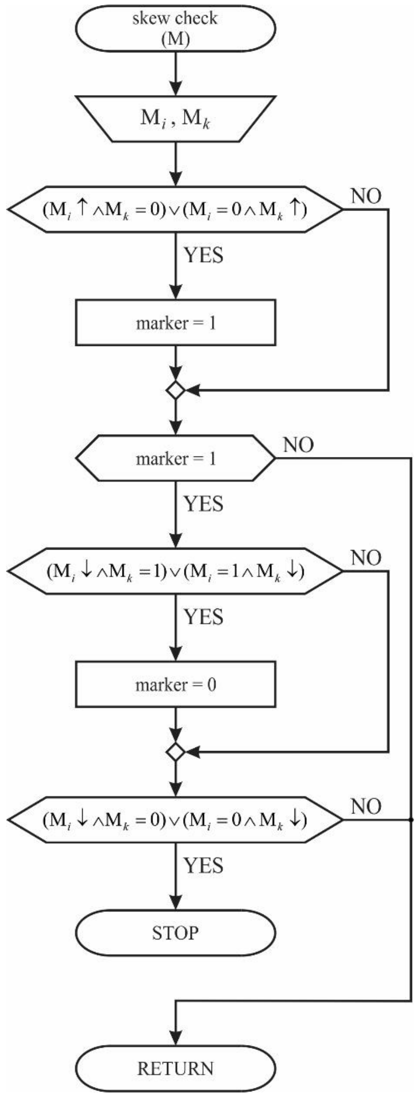

Fig. 4 The PLC program algorithm for the "skew check (M)" block

The "position difference (E)" block, shown in Fig. 6, measures the difference between the absolute positions of two encoders, ΔE, mounted on the free wheels of the leg *i* and leg *k* of the drive, in each processor cycle.

The "compensation" block, whose PLC program algorithm is shown in Fig. 7, calculates the compensation value as the difference between the difference of absolute encoder positions and the actual skew, $EDC=\Delta E-s$. Compensation, *EDC*, is calculated when the inductive proximity switches become inactive, i.e. when the drive passes over the markers.

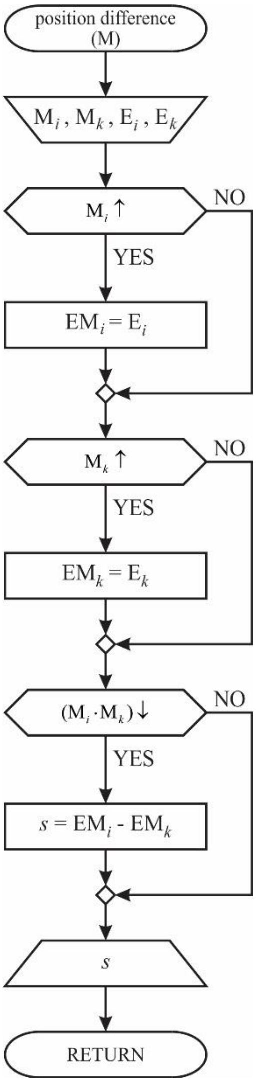

Fig. 5 The PLC program algorithm for the "position difference (M)" block

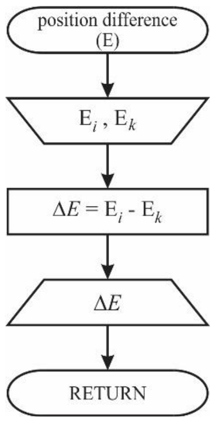

Fig. 6 The PLC program algorithm for the "position difference (E)" block

The "skew" block, shown in Fig. 8, calculates the skew value as the difference between the difference of absolute positions of two encoders and the compensation, $s_{calc} = \Delta E - EDC$, in each processor cycle. The calculated skew value is equal to the actual skew, $s_{calc} = s$, when the drive passes over the markers, i.e. when the compensation is performed. Between two compensation calculations, the calculated skew value may deviate from the actual skew due to the influence of external disturbances.

The "skew check (M and E)" block, shown in Fig. 9, checks the skew by comparing the calculated skew value with the allowable maximum skew in each processor cycle. If the calculated skew exceeds the allowable maximum skew, $s_{calc} > s_{\max}$, the block sends a signal to stop the drive operation.

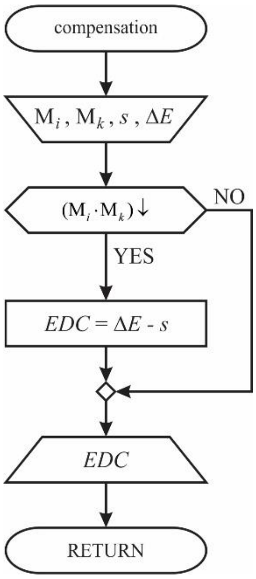

Fig. 7 The PLC program algorithm for the "compensation" block

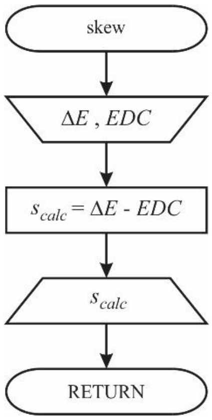

Fig. 8 The PLC program algorithm for the "skew" block

The PLC program algorithm for the "skew control" block is shown in Fig. 10. This block ensures the skew control by calculating the speed reference for one frequency converter, n_k^*, in each processor cycle. The calculation is based on the speed reference of the second frequency converter, n_i^*, and the calculated skew value, s_{calc}. The reference correction, $\Delta n^* = s_{calc} \cdot K_{SC}$, is limited by the limiter within the range of $\Delta n_{\min} \div \Delta n_{\max}$ to ensure stable drive operation under large external disturbances. The calculated speed reference in absolute units is $n_k^* = n_i^* + \Delta n^* \cdot n_i^*$.

The proposed PLC program algorithm for the skew control is primarily intended to control the skew in rail mounted wide span multi-motor drives. Additionally, the proposed algorithm also checks skew in two independent ways. This ensures the safe operation of wide span multi-motor drives, alongside designing the skew controller as previously described.

4. Practical Implementation

The proposed skew control algorithm has been implemented in the industry on the gantry crane installed at a sugar beet open storage in the TE-TO Senta sugar factory. Skew control is implemented for the gantry motion drive, whose main structural elements are shown in Fig. 11.

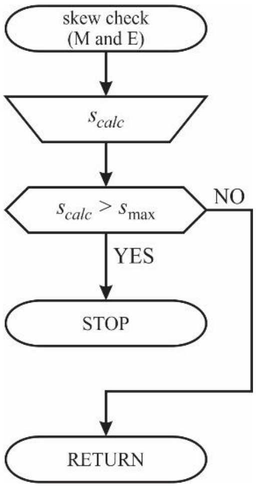

Fig. 9 The PLC program algorithm for the “skew check (M and E)” block

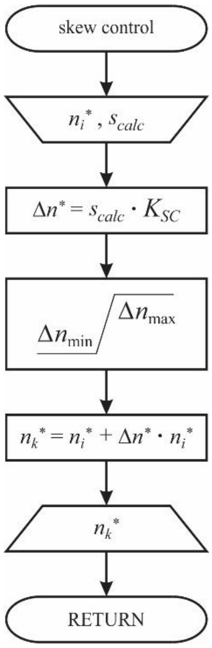

Fig. 10 The PLC program algorithm for the “skew control” block

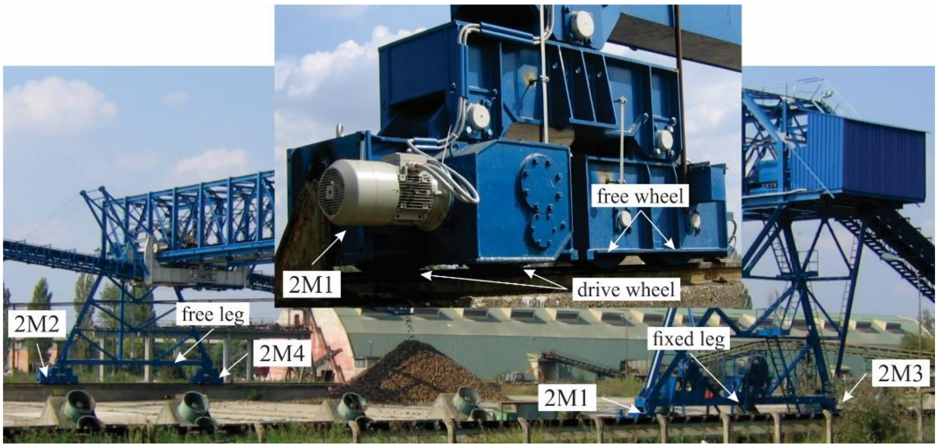

Fig. 11 The gantry motion drive – main structural elements

The gantry motion drive is a controlled multi-motor drive with four three-phase induction motors, 2M1 to 2M4, two per leg, supplied from frequency converters, 2U1 to 2U4, respectively. The operation of the gantry motion drive is controlled by the PLC system, which manages the entire gantry crane operation.

The structure of the gantry is lattice, to decrease the influence of wind. The distance between the fixed leg and the free leg of the gantry crane is 64.5 m. It is evident that this is the wide span construction where two movable legs are connected by a bridge which represents an elastic connection. The fundamental technical requirement for such a construction is the synchronous movement of both sides.

The induction motors 2M1 to 2M4 drive the common load, the gantry crane, and are speed-controlled by appropriate frequency converters. The frequency converters operate in the speed mode, utilizing their own speed controllers. Since high drive performance is not required, the motor speed is estimated.

The skew control between the fixed leg and the free leg of the gantry crane is realized by the skew controller between frequency converters 2U1 and 2U2. The speed reference for frequency converter 2U1 is set to the main speed reference, $n_{2U1}^*=n^*$. For frequency converter 2U2, the speed reference is obtained after the correction of the main speed reference by the skew controller, $n_{2U2}^*=n^*+\Delta n^*\cdot n^*$. In accordance with the theoretical analysis from Section 2, the reference correction, Δn^*, is proportional to the algebraic difference of absolute encoder positions, corrected by the external disturbances compensator, and limited within the set range. The external disturbances compensator takes into account and compensates all external influences on the position difference of two encoders by measuring the actual skew when inductive proximity switches are above markers, symmetrically mounted along the crane runway. The slippage of drive wheels, as the biggest external disturbance, is eliminated by mounting encoders on free wheels.

The following data about the gantry motion drive are known:

- three phase induction motors: 5.5 kW, 1455 rpm;
- transmission mechanism – drive wheel: I_{dw}=394.7368, D_{dw}=0.5 m;
- transmission mechanism – free wheel: I_{fw}=15.6466, D_{fw}=0.5 m;
- length of the crane runway: L=300 m;
- critical skew: s_{cr}=1 m;
- absolute encoders: multiturn, resolution 12 bits per revolution, 2^{12} revolutions.

For the chosen encoders, the position increment per revolution is $E_{p,rev}=2^{12}=4096$. The encoder position increment per meter of travel, calculated using expression 13, has a value of $E_{p,1m}$=40800. The maximum encoder position increment is $(2^{12}\cdot 2^{12})-1=16777215$, meaning the encoder can map the travelled distance of 411.2064 m. Considering the length of the crane runway to be mapped and an appropriate degree of security, it is clear that two absolute encoders have been well chosen.

In accordance with the theoretical analysis from Section 2, and considering the critical skew value, the allowable maximum skew of s_{max}=0.5 m was adopted. Also, in line with the theoretical analysis from Sections 2 and 3, the length of all markers along the crane runway is the same and equal to the allowable maximum skew, $l_m=s_{max}$=0.5 m.

For the adopted value of the maximum expected difference between linear speeds of the fixed leg and the free leg of the gantry crane $\Delta v_{\%}$=1 %, the distance between each pair of markers, based on expression 5, should satisfy the condition $L_m\leq 50$ m. Also, the number of marker pairs, according to expression 6, should meet the condition $N_m\geq 6$. Considering the obtained values, 6 marker pairs along the crane runway have been adopted, mounted at a maximum distance of 50 m.

The adopted value of the desired time to reach the allowable maximum skew, assuming irregular skew control operation (e.g. failure of one encoder), is t_d=60 s. Also, considering the nominal motor speed, the adopted drive maximum main speed reference has a value of n_{max}^*=1455 rpm. Now, the saturation value of the skew controller limiter in percentages of the drive maximum main speed reference, based on equation 10, is $\Delta n_{max,\%}$=8.6356 %.

The proportional gain of the skew controller, calculated using expression 14, has a value of K_{SC}=1/236230.

Based on the calculated values for the proportional gain of the skew controller and for the saturation value of the skew controller limiter, the following values have been adopted: K_{SC}=1/236230 and $\Delta n_{max,\%}$=10 %. Now, the limiter setting is ± 10 %. The designed skew controller was experimentally verified upon commissioning the drive.

5. EXPERIMENTAL RESULTS

Upon commissioning the gantry crane installed at a sugar beet open storage in the TE-TO Senta sugar factory, to determine the performance of the described skew control algorithm implemented in the gantry motion drive, time dependencies of characteristic quantities were recorded using frequency converters (ASC550 series) and PLC system (90 series, CPU 07 KT 98), utilizing the "907 AC 1131" software, all manufactured by ABB.

The time dependencies of motor speeds and the calculated skew value were recorded, with a sampling time of 20 ms. The PLC system retrieves motor speeds from the frequency converters via the PROFIBUS DP industrial communication network. Motor speeds are estimated quantities, expressed as integer values in [rpm]. The calculated skew value is computed in the PLC system and expressed as an integer value in [cm].

Characteristic time dependencies for the gantry motion drive, for the movement direction that is adopted as positive, are shown in Fig. 12 to Fig. 14.

The desired speed reference for frequency converter 2U1 is set to the main speed reference of the drive, $n_{2U1}^*=n^*$, and has a value of 1000 rpm. From Fig. 12, it can be concluded that the motor speed n_{2U1} "well" follows the speed reference, with a certain ripple that is a consequence of various external disturbances.

The time dependence of the calculated skew value, s_{calc}, is shown in Fig. 14. The gantry crane moved between two pairs of markers for some time, and the skew controller reduced the skew (s_{calc}) to a value of 0 cm. At the moment $t \approx 0.1$ s the inductive proximity switches become inactive, i.e. they passed over the markers. External disturbances compensation was performed. The calculated skew value is now equal to the actual skew and has a value of $s_{calc} = -2$ cm. The "minus" sign indicates that, relative to the direction of the gantry crane movement, the free leg lags behind the fixed leg.

So, while the gantry crane was moving between two pairs of markers, the skew controller reduced the skew (s_{calc}) to a value of 0 cm. However, due to various external influences on the position difference of two encoders, the calculated skew value differs from the actual skew by – 2 cm. This difference is compensated when the inductive proximity switches pass over the markers ($t \approx 0.1$ s).

After the moment $t \approx 0.1$ s, to reduce the skew, for frequency converter 2U2, the speed reference is obtained after correction of the main speed reference, $n^*=n_{2U1}^*$, by the skew controller, $n_{2U2}^*=n^*+\Delta n^* \cdot n^*$. Considering that the free leg lags behind the fixed leg, it should hold true that $n_{2U2}^* > n_{2U1}^*$. By analyzing Fig. 13, it is clear that the motor speeds difference n_{2U1}-n_{2U2} varies within the range of about – 22 rpm to 10 rpm, with the mean value certainly being less than zero, consistent with the previous conclusion.

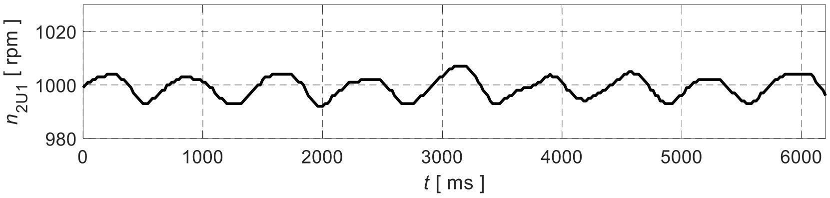

Fig. 12 The motor speed of 2M1, n_{2U1}

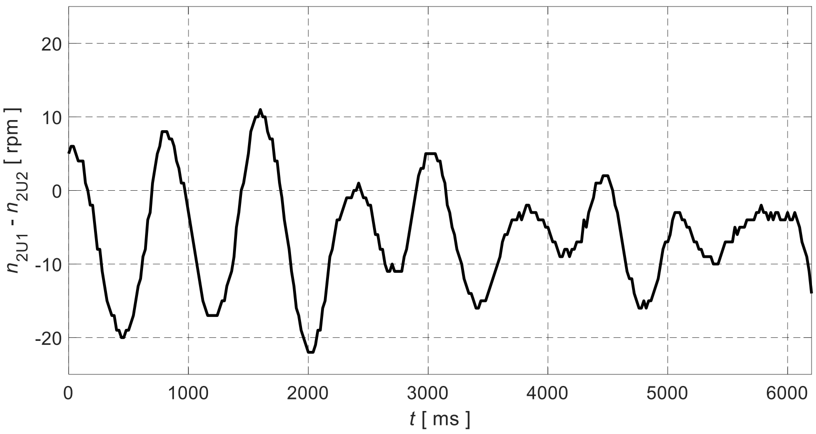

Fig. 13 Motor speeds difference between 2M1 and 2M2, n_{2U1}-n_{2U2}

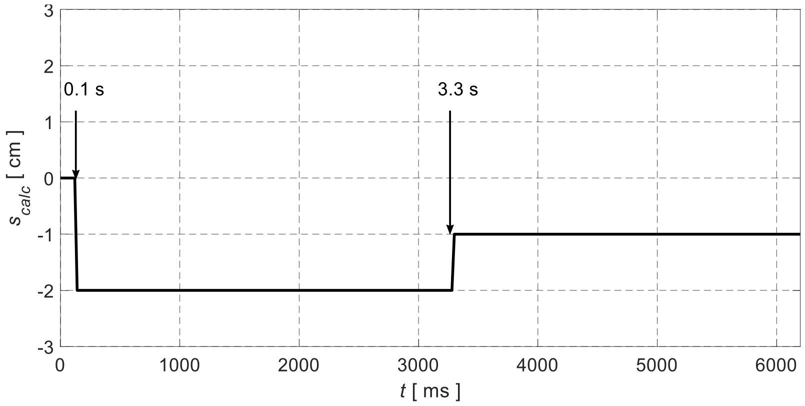

Fig. 14 The calculated skew value, s_{calc}

As a consequence of the skew controller operation, at the moment $t \approx 3.3$ s the skew decreases, and the calculated skew value is $s_{calc} = -1$ cm. Considering that the free leg lags behind the fixed leg, it should hold true that $n_{2U2}^* > n_{2U1}^*$. By analyzing Fig. 13, it is clear that the motor speeds difference n_{2U1}-n_{2U2} varies within the range of about – 16 rpm to 2 rpm, with the mean value certainly being less than zero, consistent with the previous conclusion.

If the gantry crane continues to move, as a consequence of the skew controller operation, the skew will continue to decrease, and the calculated skew value will reach the value of

$s_{calc} = 0$ cm. Due to the limited number of points in recording the time dependencies, that moment is not shown in Fig. 12 to Fig. 14.

Based on the presented analysis, it can be concluded that during the operation of the gantry motion drive, the calculated skew value changes within narrow limits, far less than the allowable maximum skew. Additionally, it is clear that as a consequence of the skew controller operation, the calculated skew value decreases. Since the calculated skew value may differ from the actual skew due to various external influences on the position difference of two encoders, special attention is paid to analyzing the operation of the external disturbances compensator. It is clear that when the inductive proximity switches pass over the markers, all external disturbances compensation is realized. Due to various external disturbances, and as a consequence of the skew controller operation, a difference in motor speeds occurs, which is limited by the limiter to ensure stable drive operation.

Considering the above, as well as the experimental results shown in Fig. 12 to Fig. 14, the conclusion is that the implementation of the skew control algorithm in the gantry motion drive is necessary, and that the proposed algorithm, whose principle block diagram is shown in Fig. 1, has satisfactory performance.

6. Conclusion

In this paper, a simple and practical method for skew control of rail mounted wide span multi-motor drives is proposed. The design of the skew controller is analyzed in detail, and the PLC program algorithm for the practical implementation of the proposed solution is presented. This innovative skew control algorithm is suitable for implementation in existing drives. In the appropriate hardware environment typical for controlled multi-motor drives, which implies the application of frequency converters and PLC systems interconnected by one of the industrial communication networks, the implementation of the proposed skew control algorithm is simple with minimal hardware upgrade. The necessary additional hardware consists of two absolute encoders and two inductive proximity switches with appropriate markers, the number of which is determined by calculation.

An unavoidable requirement in forming the skew control algorithm is maintaining safety and functionality in specific situations, such as the failure of key components, occurrences of wear, skidding of one side in relation to the other, uneven loading of individual sides due to the position of the load, and the influence of wind on drives located outdoors. For this reason, the external disturbances compensator is formed as a separate structure in the control algorithm. This compensator, based on the additional system of markers, corrects potential skew calculation errors and ensures the reliable operation of the skew controller. By designing the skew controller as described and verifying it experimentally, desired drive performances can be achieved.

Additionally, the practical implementation of the proposed skew control algorithm in the industry, on the gantry crane installed at a sugar beet open storage in the TE-TO Senta sugar factory, is presented. Upon commissioning the gantry crane, time dependencies of characteristic quantities were recorded in order to determine the performance of the described solution. In this paper, part of the detailed performance analysis results is shown, which confirmed good control characteristics.

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