Multi-Motor Drives for Crane Application

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Abstract—**This paper focuses on the application of adjustable speed induction motor drives for gantry cranes. Modern solution considers application of frequency converters for all drives. Multi-motor drives are standard solutions in crane application and requirements of load sharing are present. Presented algorithm provides load sharing proportional to the rated motor power on the simple and practically applicable method on the basis of estimated torques by frequency converters, and controller realized in PLC. Special attention is devoted to wide span gantry drive and algorithm for skew elimination. Solutions for load distribution in multi-motor drive, as well as mode of gantry drive skew elimination, are described. Suggested solution concept is confirmed by the experimental results.**

Index Terms—**frequency converter, multi motor drive, load sharing, skew controller**

I. INTRODUCTION

A Rail Mounted Gantry Crane is typically used for the movement of containers, loading of trucks or material storage. This crane type usually consists of three separate motions for material transportation. The first motion is the hoist, which raises and lowers the material. The second is the trolley, which allows the hoist to be positioned directly above the material for placement. The third is the gantry, which allows the entire crane to be moved along the working area. Very often, in industrial applications additional drives as auxiliary hoist, power cable reel and conveyer belt are needed. Therefore, cranes represent complex machinery. Each of the mentioned drives, depending on the crane capacity, can be realized as multi-motor.

The electrical technology for crane control has undergone a significant change during the last few decades. Conventional AC operated crane drives use slip ring induction motor whose rotor windings are connected to power resistance in 4 to 5 steps by power contactors. Reversing is done by changing the phase sequence of the stator supply through line contactors. Braking is achieved by plugging operation. The main disadvantage is that the actual speed depends on the load. Nowadays, these systems are replaced by frequency converter supplied squirrel-cage induction motors for all types of motion [1]-[3]. Control concept, based on application of Programmable Logic Controllers (PLCs) and industrial communication network, represents the standard solution, which is used in complex applications [4].

Reason for writing the paper is wide span gantry crane accident in sugar factory, as a consequence of skewing. Authors of this paper had an assignment to design all electrical drives on the crane and especially to solve the problem of gantry drives as cause of breakdown. For that reasons, characteristic drives of crane movement are considered. In the first part of the paper, control topologies for multi-motor load sharing are presented.

In the second part of the paper, specific application of wide span gantry crane drives serves for reloading the sugar beet is shown. Solution for load distribution in multi-motor drive, as well as mode of skew elimination for gantry drive, is described. Suggested solution concept is confirmed by the experimental results.

II. LOAD SHARING CONFIGURATIONS

With respect to the power supply of the motor, the following cases are possible [5]:

- multiple motors-single converter;
- multiple motors-multiple converters.

In crane applications multi-motor drives and proportional share of power between motors are often used. Load sharing is a term used to describe system where multiple converters and motors are coupled and used to run one mechanical load [6], [7]. In the strictest sense, load sharing means that the amount of torque applied to the load from each motor is prescribed and carried out by each converter and motor set. Therefore, multiple motors and converters powering the same process must contribute in proportional share of power to the total driven load.

Multiple motors that are run by a single converter are not load sharing because torque control of individual motors is not possible. Motors that are controlled by separate converters without any interconnection are not sharing the load, either. The lack of interconnection defeats any possible comparison and error signal generation that is required to compensate for differences in the load that is applied to any single drive and motor set.

Control topologies for load sharing consider the presence of interconnection, i.e. information knowledge about load (motor current or torque). There are three categories of load sharing techniques: common speed reference, torque follower and speed trim follower.

The common speed reference is the simplest form of load sharing to set up, least precise and less flexible. The precision of this control is dependent on drive control algorithm, the motor characteristics and the type of load to be controlled [7].

Torque follower type of load sharing requires the frequency converter to have the operation capability in "torque mode". If speed regulation is required, one of the converters ("master") may be in "speed mode". In speed mode controller provides a torque command at output, which can be distributed, to the other converters ("slaves" or "torque followers"). The second converter operates in torque

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regulation mode with the torque reference of the master as command. This torque signal may be scaled to divide load sharing in any desired ratio.

In speed trim follower configuration, all converters are operated in speed regulation mode and receive the same speed reference. The torque reference of the master is sent to the follower converters. Each follower converter compares its own torque reference with that of master. The output of the comparator is an error signal that trims the speed of the follower. Alternative configuration cascades the torque reference comparison, as in Figure 1. The first follower compares the master to its internal value. The second follower compares foregoing follower to its internal value, etc.

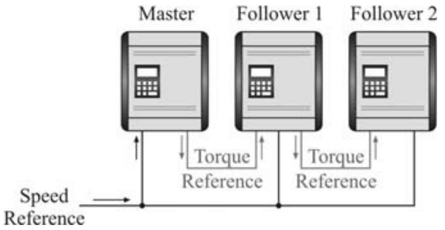

Figure 1. Speed trim follower configuration.

III. PRACTICAL IMPLEMENTATION OF WIDE SPAN GANTRY CRANE DRIVES

The experimental behavior analysis of some drives is considered in the case of a crane with wide span, which in sugar factory serves for continuous transport of sugar beet from the reception position to the factory storage.

The crane with the following details has been taken for experimentation with adjustable frequency drive:

- Handling capacity: 500t/h;
- Gantry span: 64.5m;
- Hoist height: 18m;
- Working conditions: outdoor.

Gantry crane for sugar beet storage comprises the following functional parts:

1. Gantry drive (16m/min) with four induction motors of 5.5kW, two per leg.
2. System conveyor belts (2m/s) with "battered" (30kW), horizontal (30kW) and "butterfly" conveyor (11kW).
3. Trolley drive (12m/min) with four motors of 1.1kW.
4. "Butterfly" hoist (3kW).
5. Motor driven cable reel (1.1kW).
6. Decentralized crane control system with appropriate PLC, Profibus communication between converters and other intelligent devices (for example: encoders, operator panels etc.), Figure 2.

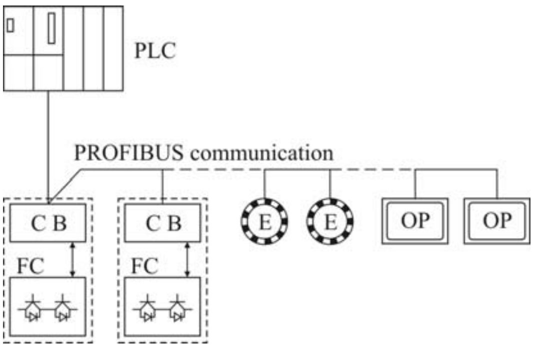

Figure 2. Decentralized crane drive control.

All motors are three phase fed by frequency converters. Certainly, the most complicated is the gantry drive, for the following reasons:

- that is a multi motor drive which consists of two motors on each side;
- the span is wide;
- construction is lattice, therefore it is elastic;
- plant is located outdoor so the influence of the wind may be considerable;
- the length of runway rail path is 300m.

Basic requirements set in front of this drive are: equal load distribution between motors located on the same side, as well as skew elimination between fixed and free gantry leg.

A. Load sharing controller design

Although the motors have the same power, there are few necessary reasons to do the load distribution: different wheel diameter, unequal adhesion, geometrical imperfection of the construction, slipping of the pinion wheel due to wet or frozen rails. Load distribution is resolved by using speed trim load sharing configuration, Figure 1. Load distribution controller is realized by PLC.

In Figure 3, the principle block scheme for load distribution between two rail coupled induction motors (IM_1 and IM_2) fed by frequency converters (FC1 and FC2) is shown. The starting point in the design of load sharing controller is that the less loaded motor should accelerate in order to take over the part of load from the more loaded motor. Information about the load can be obtained in different ways. The easiest one is by motor current. Modern converters used in drives, enable to obtain information about the motor torque in percentage in relation to rated torque.

As we can see in the Figure 3, the speed reference of only one motor (n^*_2) is updated in relation to the main speed reference ($n^*=n^*_1$). Reference correction Δn^* is proportional to the difference of estimated electromagnetic torque ($\Delta T_e=T_{e1}-T_{e2}$). Proportional gain of load sharing regulators K_{LS} can be calculated:

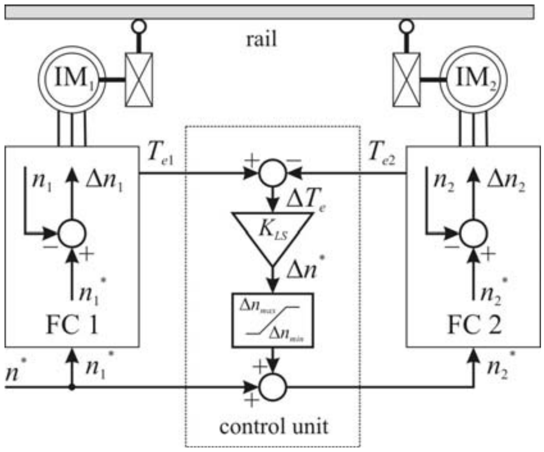

Figure 3. The principle of load sharing based on estimated torques.

$$K_{LS} = \frac{\Delta n^*{}_d}{\Delta T_{eg}} \tag{1}$$

where $n^*{}_d$ is the desired reference speed correction in relation to main speed reference for given electromagnetic torque differences ΔT_{eg}.

In order to ensure stabile motor operation during the large external disturbances, especially at low speed, when estimation of electromagnetic torque in speed sensorless drives looses in accuracy, it is necessary to limit the correction value Δn^*, as shown in Figure 3.

For the purpose of suggested algorithm verification, the trolley load sharing is analyzed. Because of the short distance between left and right side, the skew may be neglected. Trolley drive consists of four motors, two on each side (IM_1-IM_2 on left and IM_3-IM_4 on right side). Frequency converters are set on speed sensorless vector control mode. Motors have the common reference speed. In Figure 4, motors torque and speed without load distribution is shown. At reference speed, in steady state, one can see that even if the motors have the same rated power, load torques are different. Estimated motor torque is not applied in control algorithm. Speed between left and right side is different because it depends of motor characteristics and load, as shown in Figure 4.

Effect of load sharing is shown in Figure 5. The approximately equal motor torque on the same leg can be easily seen. Used system enables that the speed of every motor is regulated, but also the load difference is controlled. In this way, the load difference is being maintained accurate.

Depending on the purpose of drives and needed accuracy of maintaining load distribution, load controller can be with only proportional effect, but also with proportional integrated effect. In our case only proportional controller with $K_{LS}=10$ is used. Output from the load controller is restricted on only several percentages of maximum speed reference (in our example $\Delta n_{\text{min-max}}=2\%$). That is quite enough to provide necessary load regulation and not to "break" the drive speed regulation by too big effect on the speed reference. This solution can be applied for all kinds of multi motor drives on cranes.

B. Skew controller design

Rail mounted gantry cranes frequently skew due to poor rail conditions, uneven wheel wear, wheel slippage or unequal load conditions when the trolley is operating at one end of the crane bridge. Skewing of the crane can cause excessive wheel wear and stress, especially to the wheel flanges. It can also produce horizontal forces at right angles to the rail, which can result in unusual stresses to the crane runway beams and building structure. This often results in differing diameters of drive wheels, which subsequently cause the crane to skew.

Skew elimination is realized by suitable PLC, two absolute encoders, two proximity sensors (with six pairs of markers 50cm length) and four frequency converters for motor supply of gantry drives, as shown in Figure 6. On each leg, one of the converters is master and the other one is slave. Their reference difference is consequence of load sharing between the motors on that leg. The principle of load sharing on the same leg is described in previous subsection and shown in Figure 3.

Based on travelled paths difference, the skew controller generates the total reference speed component, as the consequence of skew. Control scheme for skew elimination between the master and slave motor of gantry drive is shown in Figure 7. The starting point in designing the skew controller is that the motor, whose lag should be accelerated to overtake the motor on the other side in order to eliminate the skew. As shown in Figure 7, the speed reference of only one motor ($n^*{}_2$) is updated, in relation to the main speed reference ($n^*=n^*{}_1$). Reference correction Δn^* is proportional to the difference of absolute encoder position ΔE. Regulator

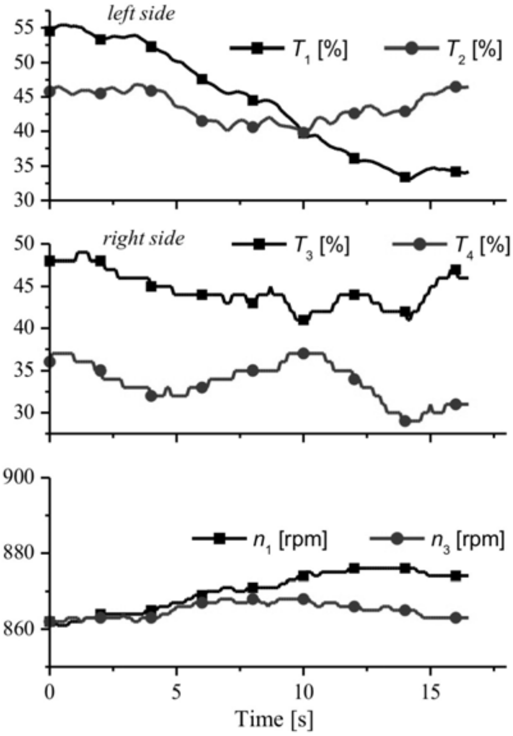

Figure 4. Motors torque and speed without load sharing.

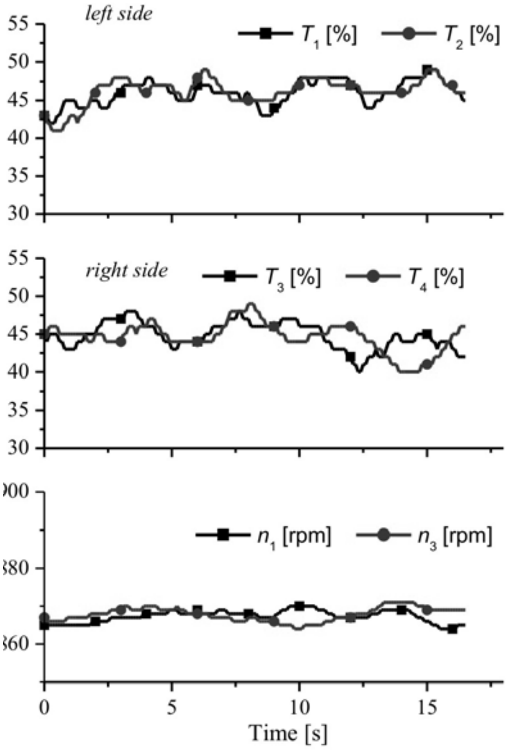

Figure 5. Motors torque and speed with load sharing.

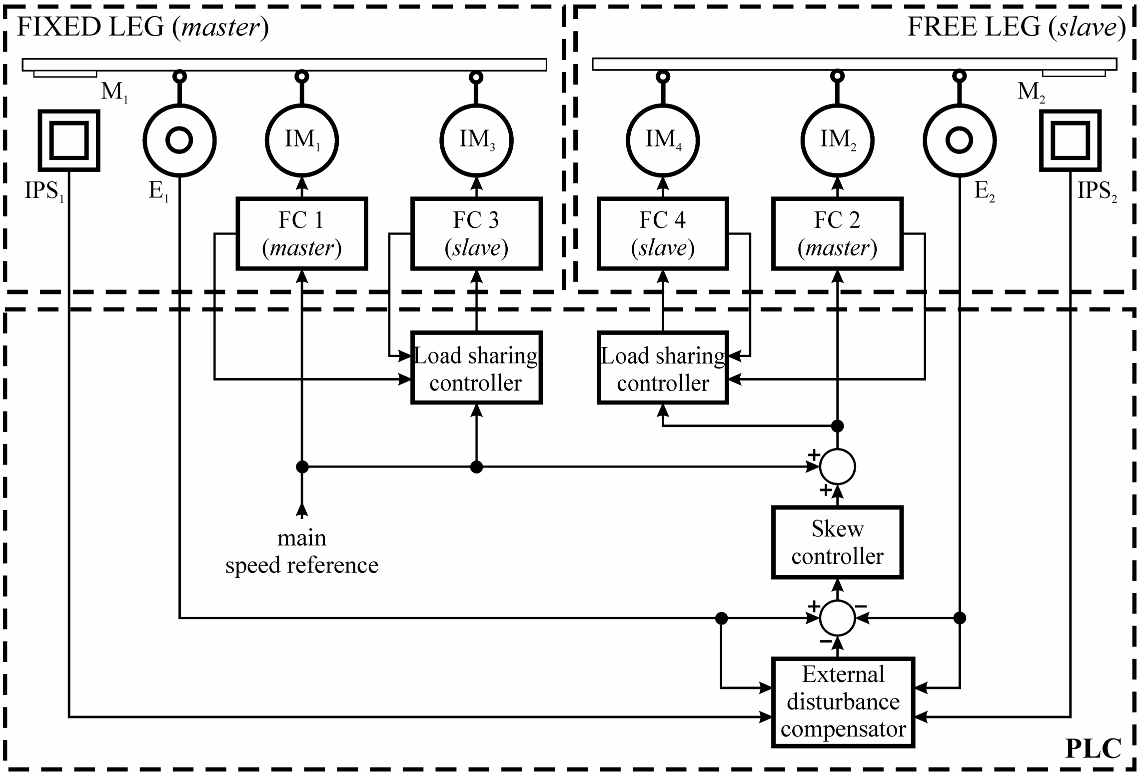

Figure 6. Block scheme of gantry drive.

gain K_{SC} can be calculated by (2):

$$K_{SC} = \frac{\Delta n^*{}_d}{\Delta E_g} \tag{2}$$

where $\Delta n^*{}_d$ is the desired reference speed correction in relation to main speed reference for given absolute encoder position differences ΔE_g.

In order to ensure stable motor operation during the large external disturbances, especially at low speed, when estimation of electromagnetic torque in speed sensorless drives looses in accuracy, it is necessary to limit the correction value Δn^*.

Currently, skew is achieved as the difference of position between two encoders with respect of the correction from the external disturbance compensator. External disturbances compensator (EDC) respects all external influences on the position difference of two encoders: the difference in the wheel diameter, wheel and joint encoders slipping.

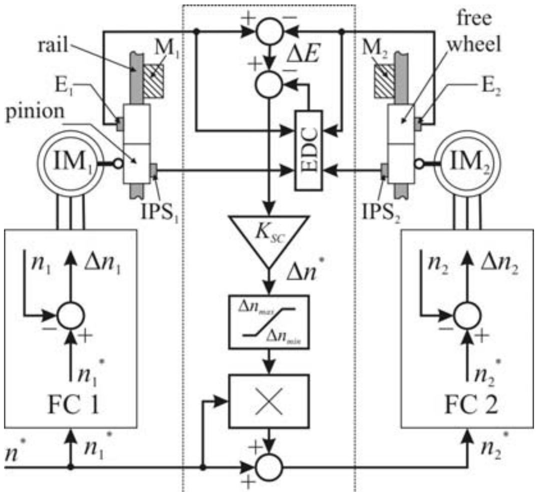

Figure 7. The principle block diagram of skew controller.

The biggest external disturbance, slipping of driving wheels, is eliminated by mounting encoders on free wheels. Position "**a**" in Figure 8, represent term of skew (*s*) as distance between reference point and normal on movement direction. Pairs of markers (M) and proximity sensors (IPS) are needed for the realization of the disturbance compensator. Proximity sensors are fitted on legs, while the markers are mounted and equidistantly disposed along the rails. During the movement of the crane, proximity sensors serve to detect the markers presence and to register the moment when fixed (or free) leg passes above markers. In the general case, crossing over the markers of the fixed and free leg is not simultaneous. By absolute encoders, the trajectory difference is measured till the moment when both legs are positioned on the markers, as shown in Figure 8 position "**b**". In fact, this difference is the real skew of the crane, determined at each crossing over the markers, and represents the output of the external disturbance compensator. If the difference is greater than the length of markers that means the crane skew is more than allowed. For this reason it is required that the length of markers matches allowed skew of the crane. Number of markers that should be mounted along runway is estimated on the basis of the static speed accuracy of the drive (especially for speed sensorless drives) and maximum wheel diameter deviation (geometrical imperfection of the construction). In our case, the distance between markers is 50m.

Distance between successive markers (l_{ms}), for adopted length of marker l_m, can be calculated by the following expression:

$$l_{ms} \le \frac{l_m}{e_{\%} / 100} \tag{3}$$

where $e_{\%}$ is maximum expected linear speed difference between the legs in percent. Number of marker pairs n_m for the length of runway rail path l can be estimated by:

$$n_m \ge \frac{l}{l_{ms} + l_m} \tag{4}$$

Per unit upper and lower limiter saturation value in Figure 7, $\Delta n_{\min-\max}$, is adjusted by:

$$\Delta n_{\min-\max} = \pm \frac{1}{n^*_{\max}} \cdot I_p \cdot \frac{l_m}{\pi \cdot D_p} \cdot \frac{1}{t_m} \tag{5}$$

where:

$n^*_{\max}$ - maximum speed reference [rpm],

I_p - pinion wheel gearbox ratio,

D_p - diameter of pinion wheel [m],

t_m - maximum allowed skew correction desired time [min].

Assuming that $\Delta n^*_d = \left|\Delta n_{\min-\max}\right|$ and ΔE_g as number of encoder pulses which represent the length of marker, controller proportional gain K_{SC} is easily obtained by (2).

In the Figure 9, the behaviour of gantry drives without skew controller is shown. Therefore, in this case, load sharing regulators for fixed and free gantry leg are included. Initial crane skew is near 10cm. From the load sharing aspect, motors torque, and torque difference on the same side should be observed. Estimated motors torque is obtained from the frequency converter. Mechanical computation performed by SAP software package, shows that the skew influence is manifested differently on the motors torque on fixed and free leg. Skew influences on the motors torque is shown in the Table I. Increasing tendency of skew is noticed, Figure 9. In this case, skew is a value that cannot be controlled.

TABLE I. TORQUES DURING THE SKEW

Skew [m]	Free leg torque [Nm]	Fixed lag torque [Nm]
0.1832	5.33	152.55
0.3664	10.66	305.102
0.549	15.99	457.65
0.732	21.32	610.2
0.915	26.65	762.75

Figure 9 confirms the data given in the Table I. During crane skew, motors (IM1 and IM3) on fixed leg are more loaded than the motors (IM2 and IM4) on the free leg. In addition, the effects of the load sharing controller can be noticed because the motors on the same leg approximately share loads, i.e. torque difference oscillates about zero value. The amplitude oscillation depends on load sharing gain controller and its limiter settings, as in previous subsection explained, Figure 3.

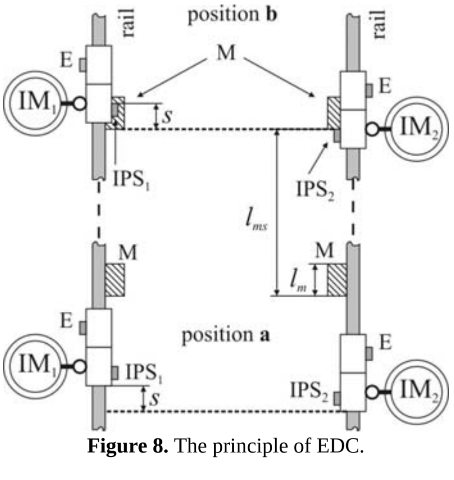

Figure 8. The principle of EDC.

Figure 10 shows experimental results including the skew controller. Gantry drive relevant parameter and controller set-up values are shown in Table II. Three working sections are noticeable: I) crane acceleration, II) steady state operation and III) crane deceleration. Observed variables are: master motor speed, estimated speed difference between master motor on fixed leg and master motor on free leg, estimated torque differences between motors on the same leg and actually skew.

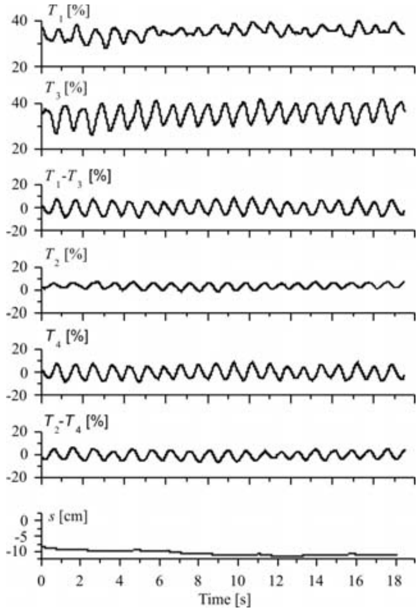

Figure 9. Behavior of gantry drives without skew controller.

In the first section, during crane acceleration due to different load between the fixed and free leg (trolley position, conveyor belts ballast) skew in transient is noticeable. According to absolute encoder position difference, there is regulating tendency to cut down or eliminate skew. Simultaneously, with the action of skew regulator, the effect of load sharing controller is active.

In the second section, drive operates at constant speed. During this fixed speed operation, trolley travelling between fixed and free leg is active. Efficiency of algorithm can be seen from several aspects:

- skew accumulated during the acceleration is rapidly eliminated, regardless of the variable load as function of trolley position and load of conveyor;
- load sharing controller provides equal load distribution with respect to adjusted proportional gain and limiters value.

In the third section, during crane deceleration, similar statements are valid. It is evident that before final crane stop, fine position adjustment between legs was conducted. Extended field measurement and customer data feedback during long period confirmed satisfactory performance of proposed skew controller of crane motion.

TABLE II. PARAMETER AND CONTROLLER SET-UP VALUES

parameter values			
$n^*_{\max}$	1455rpm	$E_{p,rev}$	4096pulses
I_p	394.7368	D_p	0.5m
I_{fw}	15.6466	D_{fw}	0.5m
l	300m	l_m	50cm
t_m	1min	$e_{\%}$	1%
load sharing controller		skew controller	
K_{LS}	10	K_{SC}	1/236230
$\Delta n_{\min-\max}$	$\pm 0.02 \cdot n^*_{\max}$	$\Delta n_{\min-\max}$	±0.1
$E_{p,rev}$ - encoder pulses per revolution [pulses/rev], I_{fw} - free wheel gearbox ratio, D_{fw} - diameter of free wheel [m].			

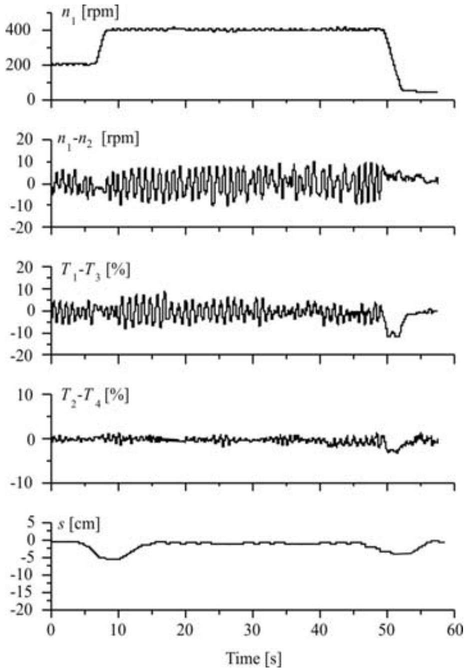

Figure 10. Behavior of gantry drives with skew controller.

IV. CONCLUSION

Presented results show how the delicate problems of controlled multimotor drives, which call into question the stability of the whole system and its work in general, can be overcome in simple and inexpensive ways. In the concrete example of wide span gantry crane, the considered problems are load sharing and skew elimination.

- Applying modern converters and the appropriate algorithm, realized in the PLC, as a reliable solution for load sharing is shown. The solution is applicable in speed sensorless drives where information about the speed and load torque is estimated from frequency converters. Load distribution between several motors is realized by using speed trim configuration with vector controlled frequency converters. The proportional load sharing controller is used to compare the actual torque signals of the drives and generate an error signal used for speed trim. The proposed system allows that the speed of every motor to be regulated with approximately equal torque on appropriate motors, therefore the load difference i.e. load sharing is controlled. Efficiency of load sharing controller is demonstrated experimentally by comparison of the trolley multi-motor drives behaviour with and without controller. In the presented crane drive example, the load sharing is applied to the trolley and gantry drives.
- The skew problem is solved by software coding, and two encoders are necessary for hardware implementation. Proposed skew controller is designed for reliable and satisfactory performance drive control of crane motion. The control system keeps the motion of the crane centred, eliminating its skew at the same time. A proportional controller in outer compensation loop, subordinated to the speed controller, realizes the centring and elimination of the skew. The measurement of the travelled path difference in relation to the master leg, which could be done in the proposed system by means of only two absolute encoders, plays a key role in the described system. This configuration also request realization of external disturbance compensator, which has the role of skew supervisor. On exactly predefined positions, the main task is to provide skew monitoring and adjustment of controlled variable according to real skew value. Efficiency of skew controller is experimentally demonstrated by comparison of the gantry multi-motor drives with and without controller.

The core of the system is mid-range PLC as master unit that communicates with the frequency converters and other slave devices using Profibus DP protocol. Information interchange among PLC, frequency converters and encoders enables simple realization of suggested algorithms, system performance monitoring and parameters tuning. Described algorithms can be applied to various multi-motor drives configuration, for example common DC bus drives that will be the theme of our further research.

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