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# Advanced load sharing control for roller straightening of long products

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To optimize the utilization of roller straightening machine, achieve an even and controlled distribution of the total load across the drive rollers, avoid over-dimensioning of the drives, and protect the machinery from overload, the required drive torque is distributed specifically across the drives using a control system.

A new, optimized Load Sharing Control (LSC) has been developed by interdisciplinary cooperation within the SMS group. This new LSC features the elimination of master-slave operation. As a result, it enables control when not all rolls are in operation during pulling in and out. It is independent of the process parameters (roll diameter, roll adjustment) and redistributes the total drive torque to the single drives according to a predefined pattern. Initial functional tests were conducted on forces and drive torques calculated with the aid of finite element (FE) simulations of the roller straightening processes and with available measurements. The successful implementation of the newly developed LSC in four industrial Compact Roller Straighteners (CRS®) in the fields of railway rail, medium and heavy section production conclusively demonstrates its effectiveness.

The newly optimized LSC offers benefits such as reduced total drive capacity, decreased roll wear, reduced experimental effort during commissioning and improvement of product quality. Furthermore, it can be implemented on cantilever, horizontal, vertical and combined straightening machines as well.

**KEYWORDS:** ROLLER STRAIGHTENING; DRIVE POWER OPTIMIZATION; DYNAMIC CONTROL SYSTEMS; PROCESS MODELLING; FINITE ELEMENT SIMULATION;

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## INTRODUCTION

Long hot-rolled products such as beams, bars, and rails (hereafter referred to as product) tend to curve after cooling [1-4]. Roller straightening aligns these curved long products by passing them between staggered rollers, inducing controlled, repeated elastic-plastic bending. SMS group technology for roller straightening machines is the CRS® Compact Roller Straightener, typically characterized by nine, individually driven straightening rollers (figure 1).

The product enters the straightening machine on one side (left in figure 1) and is transported and straightened by the straightening rolls. During the straightening process the rolls contact the product to be straightened on two opposite sides. By adjusting the upper rolls towards the product, all straightening rolls exert a bending moment and/or shear force on the product. The repetitive bending cycles aim to reduce the residual stresses and thereby increase the straightness. This principle and the roller straightening machines of this type are well-established in the state of the art.

These high carbon emissions are mainly due to the BF-BOF route: 71% of the global steel production with 2.33 t $CO_2$/t of crude steel. On the contrary, the EAF route produces less than 1 t $CO_2$/t of crude steel (for scrap based) but represents only 29% of the world production (including DRI based) [2].

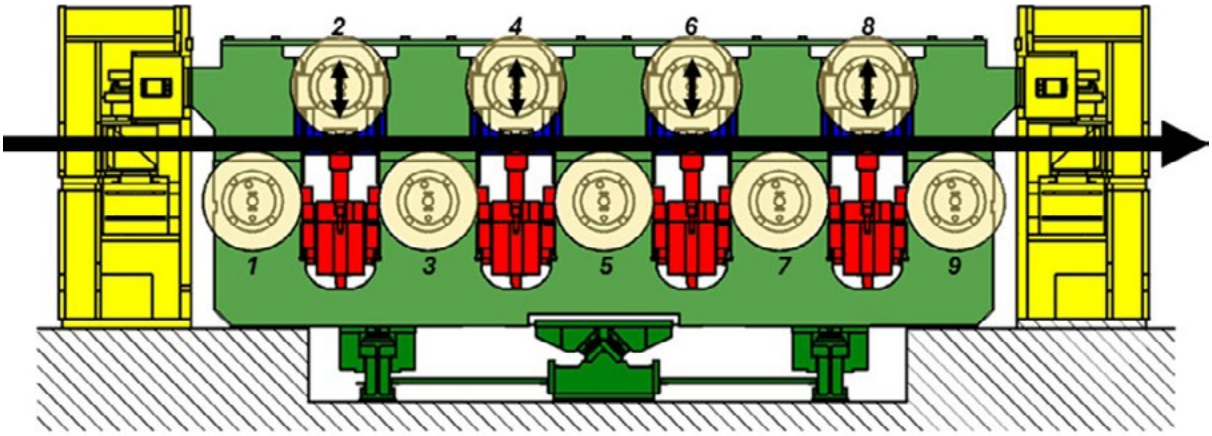

**Fig.1** - SMS group Compact Roller Straightener (CRS®), typically characterized by nine, individually driven straightening rollers. The upper rollers (no. 2,4,6,8) are vertically adjustable to set the amounts of bending.

The technological challenge involves identifying the optimal roll adjustment settings to achieve maximum straightness while avoiding excessive mechanical deformation. These topics have been addressed in numerous research projects, with results reported across the literature. By way of example, without claiming completeness, the following works are briefly noted.

Alpsten's [5] experimental and theoretical investigations showed that roller straightened (rotorized) wide flange sections have a higher resistance than their non-rotorized counterparts as a result of their lower residual stresses and improved straightness. It is suggested to use this research described to optimize the rotorizing operation regarding residual stress, straightness and column strength. Yin et al. [6] set up a theoretical framework by using spring back theory of small curvature plane bending which provides a basis for setting reasonable reduction rules to improve the straightening quality and further increase the adjustment precision as well as the flexibility of the last, adjustable, roller system. The effect of the roll settings - particularly the final roll - on the final shape of equal-leg angles as well as H-beams during roller straightening, while accounting for straightener-frame rigidity, has been investigated using finite element analysis by Hayakawa [7,8]. Żak and Woźniak report comprehensively about research on the subsequent stiff and weak axis roller straightening of vignole railway rail [9-11] aiming for the reduction of the residual stresses in railway rails by changing the technological parameters of the straightening process. Numerical process models and material models were developed and validated by industrial trials. The investigations indicate the possibility of reducing stress levels in the foot down to 120 MPa, well below the maximum 155 MPa allowed by standard. While pulling in and out not all rolls are in operation resulting in considerably different residual stresses and straightness of rail near the ends compared to the straightness in the middle portion [12].

The current work, however, focuses on drive technology optimization during the roller straightening process to ensure drive torque distribution across the rollers, preventing drive over-dimensioning and machinery overload known as Load Sharing Control (LSC).

CRS with multiple individually driven rollers are fundamentally overactuated; this leads to significant torque drift. Traditional approaches to load distribution in such multi-drive systems typically rely on master-slave control architectures [13], where a single roller measured torque serves as the reference for the remaining drives. While functional in steady-state operation, this method suffers from critical deficiencies in dynamic environments such as pulling in and out phases. The master-slave approach often requires complex predefined trajectories or look-up tables [14] based on roll diameters and product geometries; and standard controllers struggle to achieve high-dynamic load redistribution without causing torque peaks that can damage the product surface or the drive train.

To overcome these limitations, this paper presents a new, optimized LSC system that departs from the master-slave paradigm. The primary novelties are threefold. First, a non-sequential, centralized intelligence considers the drive torques of all rollers currently in contact with the material, maintaining stable control even when only a subset of rollers is engaged during pulling in and out phases. Second, the algorithm achieves trajectory-free dynamic control through a speed-offset compensation mechanism that reacts in real-time to the actual total torque, making it robust against varying roll diameters and product types. Third, despite its high dynamics, the controller ensures smooth load redistribution without inducing torque peaks, distributing the total required torque across all engaged drives either evenly or according to a user-predefined distribution, thereby protecting the machinery and improving product quality. The effectiveness of this approach is validated through both 3D finite element simulations and successful industrial implementation in heavy-section and rail production facilities.

## CHALLENGES OF OVERACTUATION AND REQUEST OF CONTROL SYSTEM

The system is overactuated, meaning there are more actuators than necessary to control its degrees of freedom. Specifically, the rigid coupling of the rollers provides one translational degree of freedom for the product, but the system employs nine drives. Overactuation leads to coupling effects, where small deviations in roller radii or contact points create varying transmission ratios. These discrepancies, combined with decentralized speed control, result in torque drift and uneven load distribution.

Figure 2 illustrates the measured drive torques during the straightening process of a wide flange beam HE400M without a mechanism to resolve overactuation. Some rollers operate near their load limits, while others experience minimal load or even work in generator mode, opposing the intended motion. This imbalance can cause inefficiencies, wear, and instability in the system.

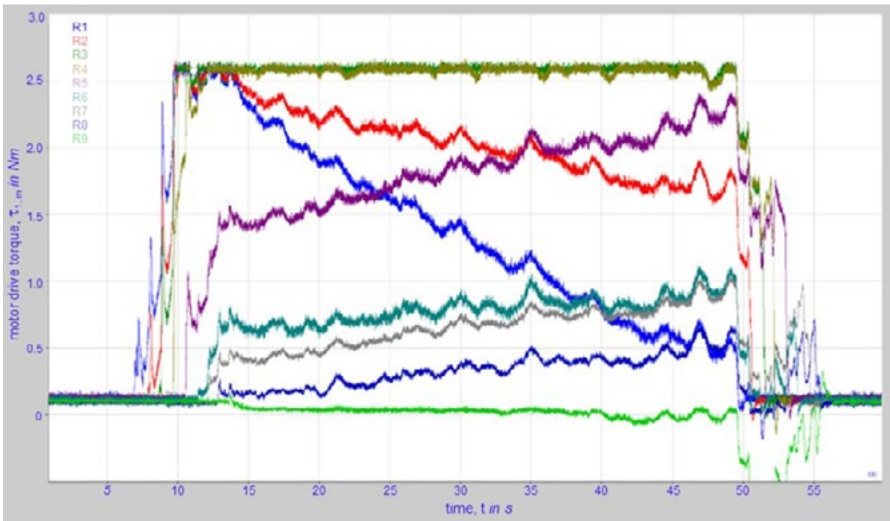

**Fig.2** - Measured drive torques during the straightening of a wide flange beam HE400M without LSC.

The primary objective is to implement a load-balancing control system that ensures uniform utilization of all drives while accounting for their individual nominal torque. Most deformation work occurs in the initial straightening triangles, requiring higher drive power. Conversely, rolls at the exit side typically require less torque, which is often reflected in practice by smaller, lower-power drives.

However, exit-side motors often have a power reserve that can be leveraged to alleviate the load on front drives. Additionally, it is crucial to consider that the transferable power depends on the contact pressure between the material and the straightening roll. The control system must avoid arbitrarily increasing the torque to prevent slippage between the rolls and the material and/or localized deformation of the straightened products.

A common approach to drive torque redistribution involves measuring the torque at one roll, designating it as the master, and using it to guide the distribution of torque to the other rolls as slaves in a master-slave operation. However, this method has several drawbacks, including insufficient drive torque distribution among the rolls, leading to inefficiencies and potential overload of certain drives. Additionally, during the pulling in and out phases, the master roll might not be engaged, resulting in instabilities and uncontrolled behavior that must be managed. Furthermore, underutilization of drive motor converters can lead to unfavorable overdimensioning.

## NEW DEVELOPED CONCEPT FOR LOAD SHARING CONTROL

To address these issues, a centralized load-balancing controller has been developed. This controller adjusts local set speeds to compensate for transmission errors and introduces constraints to prescribe a specific load distribution. By doing so, the overactuation is resolved without altering the static translatoric speed of the product.

The newly developed LSC eliminates the master-slave operation, considering the drive torques of all straightening rolls involved in the process. The LSC is activated when contact is established in the first straightening triangle and ends when the product exits the last triangle. It distributes the total drive torque among individual drives according to a specified pattern, independent of roll diameter or roll adjustment, relying solely on actual drive torques.

Figure 3 illustrates the architecture of the Load Sharing Control system, depicting an LSC unit connected to the decentralized speed controllers of the motors, implemented via motor converters.

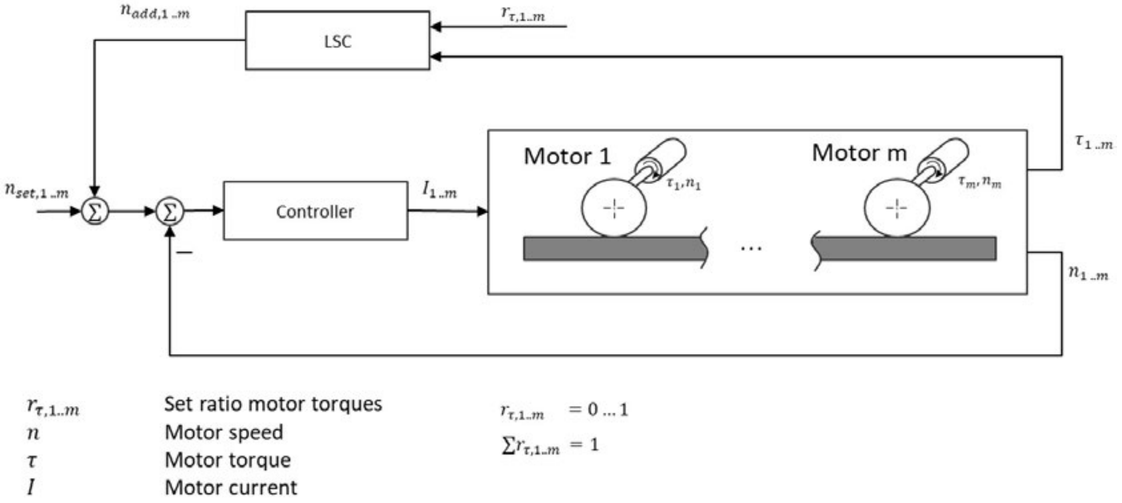

**Fig.3** - Functional diagram of the new developed Load Sharing Control (LSC).

Each controller adjusts its motor speed based on a given set point ($n_{set,\ 1..m}$), without considering the coupling with other controlled rolls. The LSC collects all measured torques from actively engaged drives and adjusts the load distribution to target ratios $r_{\tau,1..m}$ across the individual rolls. Distribution factors determine the percentage share of drive torque allocated to each drive train, representing the desired contribution of each motor to the total drive torque. These factors must sum to 1.0. Numerical process models can assist in pre-determining an appropriate distribution.

To achieve the target distribution, the LSC dynamically applies additional corrections to the speed set points ($n_{add,\ 1..m}$), compensating for transmission deviations. Once the desired distribution is achieved, the correction values stabilize, with minor adjustments ensuring consistent and stable operation.

Main benefits of the newly developed Load Sharing Control (LSC):

- **Optimized drive power:** The approach minimizes the installed drive power for the straightening rolls, effectively protecting the machine from overload while ensuring high product quality for the straightened metallic goods. Energy usage is optimized for efficiency.
- **Improved product property control:** Enhances the prediction and management of product properties, particularly regarding residual stresses.
- **Faster commissioning:** Lowers the time and cost required for machine commissioning.
- **Reduced wear and operating costs:** Minimizes wear on the straightening rolls and reduces load on other components, such as gearboxes and couplings, leading to lower operating costs.

This newly developed LSC has been filed for patent protection.

The required drive torques for predefined roll adjustments can be predicted relatively precisely over the straightening time using numerical or analytical process models, considering the pulling in and out of the product. Based on these calculations, the total drive torque of all straightening rolls can be strategically distributed among the individual rolls, significantly reducing the need for experimental calibration of the straightening machine. If necessary, a catalog of setting parameters can be created and considered in advance. However, the actual drive torques that occur in practice, resulting from the straightening process, often cannot be precisely predetermined. Therefore, the selection of distribution factors can also benefit from expert knowledge.

## PROCESS MODEL

To facilitate initial functional testing of the control system under realistic forces and drive torques, simulations of the roller straightening processes on a CRS®-1600 are performed. The straightening of a product is numerically simulated using a transient, quasi-static, three-dimensional finite element model. The non-linear finite element software Marc, with an implicit solver, is employed [15]. The model calculates, amongst many others, the straightening forces, roll drive torque, displacements, velocities and local magnitudes such as strains and stresses throughout the process duration [16]. This quasi-static process model does not include the dynamic behavior of the drive train. The roll drive torques calculated are the load torques from the process directly at the rollers, multiplication with the gear transmission ratio is required to obtain the motor drive torques.

A half-symmetric model is established, where the straightening rolls are defined as rigid bodies and the product as an elastic-plastic deformable body. The product is meshed with linear 8-node brick elements. The rotational motion of the rollers is transmitted as translational motion to the beam through contact, accounting for deformation (e.g., Hertzian pressure), friction, and, under certain conditions, slip. As in reality, the rollers are interconnected via the beam in the FE model as well. Throughout the process, a constant beam velocity comes into being. When calculating (total) roll drive torques is the primary objective, the rolls are defined as velocity-controlled bodies with pre-defined rotational velocities, and the drive torques are calculated accordingly. Conversely, if the aim is to verify the adequacy of roll drive torque redistribution, the rolls are defined as load-controlled bodies with pre-defined rolling torques, and the rotational velocities of the rolls, along with the translational velocity of the product, result from the calculations.

Hence, the roller adjustments determine the magnitude of the total roll drive torque required to move the beam through the rollers. A redistribution of the roll drive torques does not change the sum of all rollers drive torque, i.e. total roll drive torque.

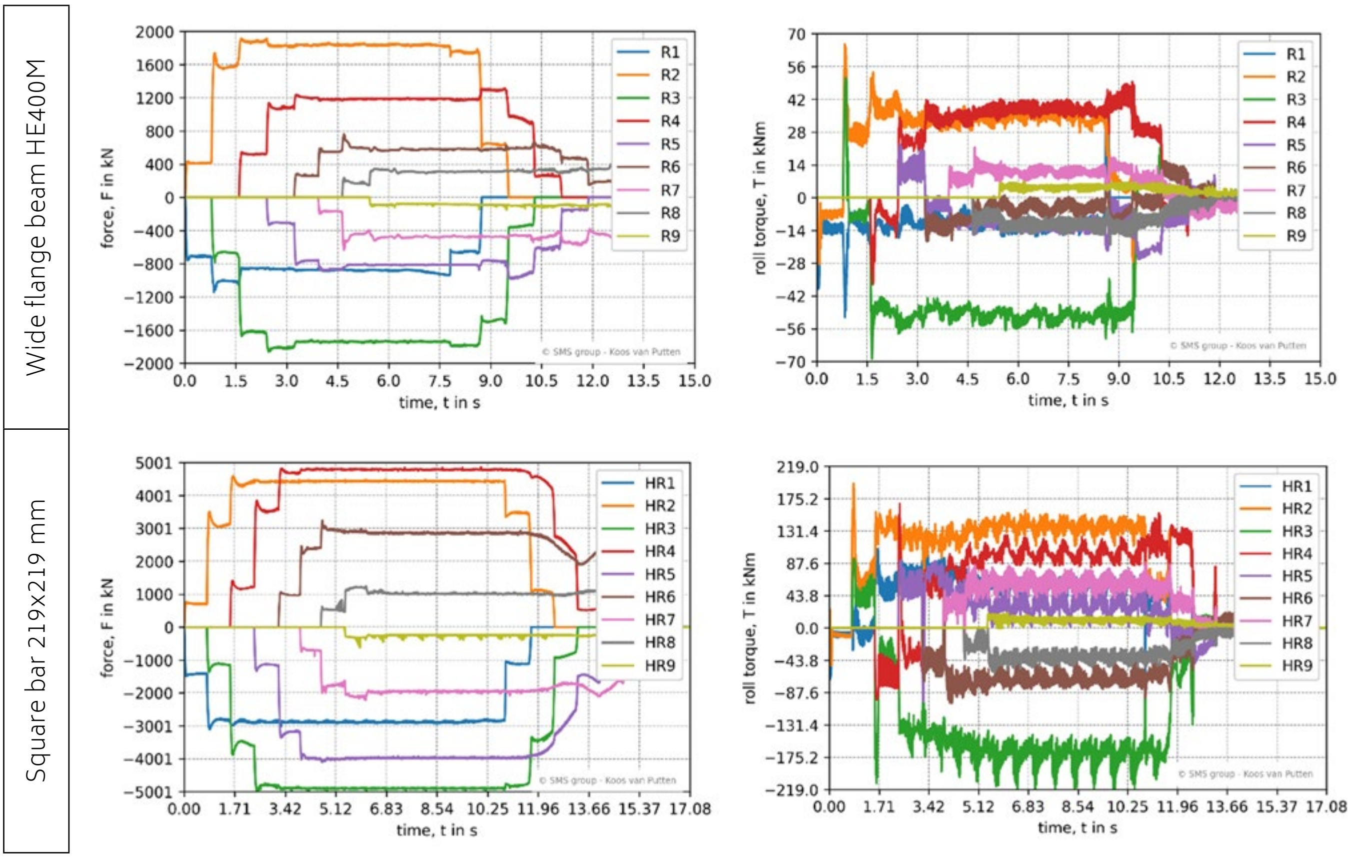

**Fig.4** - In the FE model calculated roller forces and roll drive torques during the straightening.

The roller straightening of a wide flange beam HE400M, with an overstretch factor of 4.5, is simulated. The 9.38-meter beam is meshed with 88012 elements, and the process time of 14.07 seconds is divided into 4221 time increments. Additionally, the roller straightening of a bar with a 219x219 mm square cross-section and a length of 12.4 meters, meshed with 19840 elements, is modeled. The 17.08-second process time is divided into 5124 increments. Figure 4 presents the calculated straightening forces and drive torques throughout the entire straightening process, including the phases of pulling in and out.

The redistribution of the total roll drive torque has, among other methods, been tested using the square bar straightening process model. Figure 5 compares the steady state roll drive torques calculated without and with LSC. In both scenarios, the total roll drive torque is approximately 165 kNm, which is sufficient to move the beam through the rollers at a constant speed, overcoming the resistance caused by bending. Minor deviations, less than 8%, likely arise from different averaging methods during analysis. In the straightening process without LSC, only rolls 2, 3, and 4 contribute to the product's transportation (positive drive torque), resulting in high roll drive torques for these rolls, while the others operate in braking mode (negative drive torque). With LSC active, the prescribed distribution of 8%, 15%, 15%, 15%, 12%, 11%, 8%, 8%, 8% for rolls 1 through 9, respectively, is achieved, ensuring that all rolls contribute to the transportation of the product.

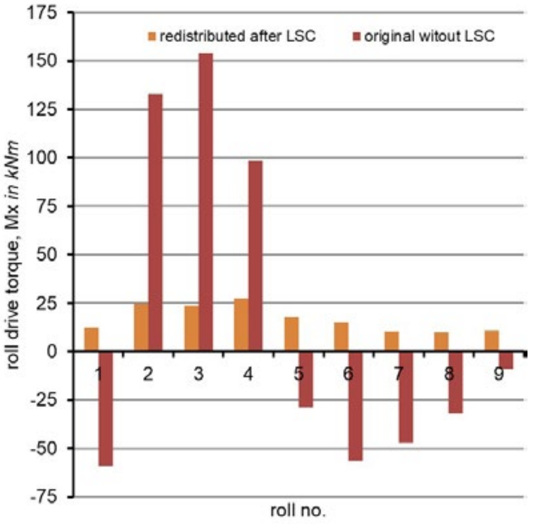

**Fig.5** - Steady state roll drive torque distribution for 219x219 mm square bar straightening without and with LSC.

## INDUSTRIAL IMPLEMENTATION

The effectiveness of the newly developed LSC is conclusively demonstrated through four successful implementations in industrial CRS® systems, particularly in the fields of railway rail, medium, and heavy section production. At this point, the positive impact of LSC on industrial straightening vignole railway rails [17] is highlighted as an example and as representative of its benefits for other profiles.

Figure 6 illustrates the measured motor drive torques during the straightening of a vignole railway rail without LSC active, recorded with the aid of IBA analyzer [18]. In this state, all additional speed setpoints are zero, leading to a heterogeneous distribution of the total motor drive torque across the individual drive axes. Specifically, roll 3 exhibits the highest torque contribution at approximately 1150 Nm. Rolls 2, 4, and 5 contribute around 400 Nm each, while roll 6 adds 200 Nm. Rolls 1, 7, and 8 operate in braking mode, registering torques of approximately -500 Nm, -200 Nm, and -400 Nm, respectively. This suboptimal torque distribution compromises efficiency in terms of both drive power and energy consumption, consequently leading to increased wear and higher operating costs.

Figures 7 and 8 display the measured motor drive torques during the straightening of vignole railway rails with the newly developed LSC active. The primary distinction between the measurements displayed in figure 7 and figure 8 lies in the predefined distribution factors. The straightening process depicted in figure 7 aims to distribute the total motor torque almost equally across all drives. In contrast, the configuration shown in figure 8 assigns a smaller torque share to rolls located at the machine's exit compared to those at the entry.

The roll adjustment settings remain consistent with those used in figure 6. By dynamically adapting the additional motor speed setpoints, the system successfully achieves the predefined target torque distribution. Following this initial adaptation, the additional setpoints largely stabilize, reflecting the inherent transmission deviations between the rolls. This phenomenon is particularly evident in figure 8, where the distribution factors have been intentionally altered. Once the target distribution is achieved, the additional motor speed setpoints converge to similar values for both tested distribution scenarios.

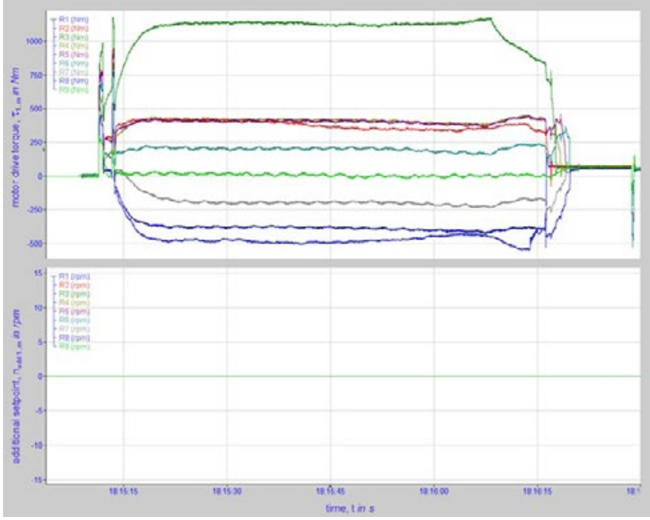

**Fig.6** - Additional setpoints (bottom) and motor drive torque (top) during straightening of vignole railway rails without LSC.

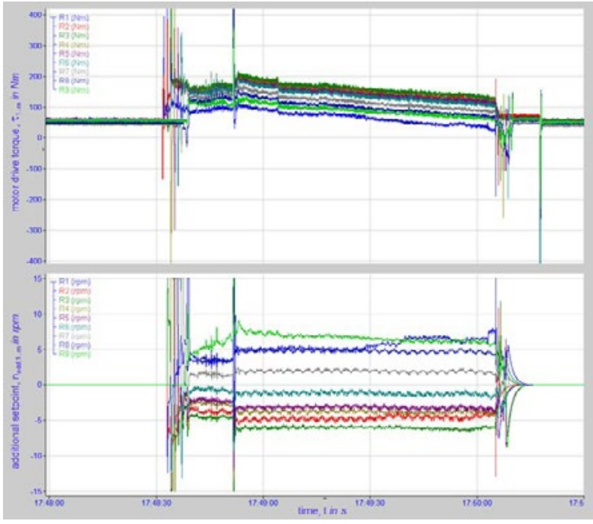

**Fig.7** - Additional setpoints (bottom) and motor drive torque (top) during straightening of vignole railway rails with LSC. Distribution factors 9%, 11%, 11%, 11%, 11%, 11%, 12%, 12%, 12% for rolls 1 through 9, respectively.

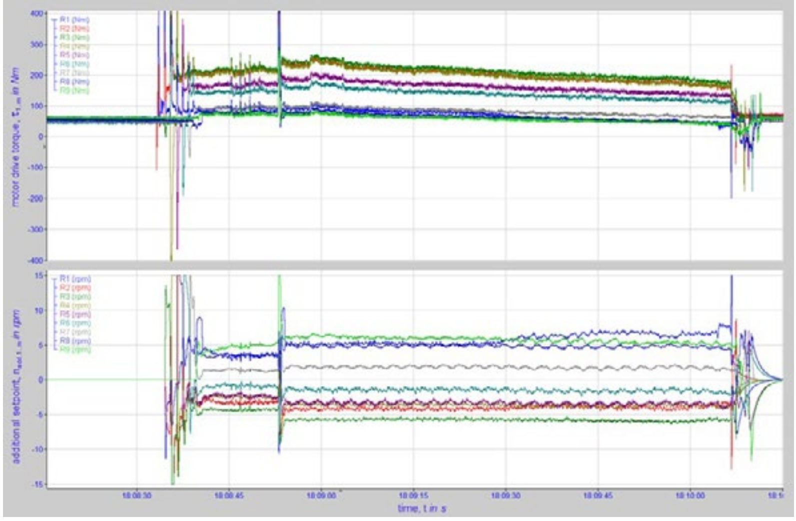

**Fig.8** - Additional setpoints (bottom) and motor drive torque (top) during straightening of vignole railway rails with LSC. Distribution factors 9%, 15%, 15%, 15%, 11%, 11%, 8%, 8%, 8% for rolls 1 through 9, respectively.

## CONCLUSIONS

An advanced Load Sharing Control (LSC) system for roller straightening machines has been developed and successfully implemented in three industrial CRS® in the fields of railway rail, medium and heavy section production. The new LSC ensures uniform utilization of all drives while accounting for their individual nominal torque. It overcomes limitations of traditional master-slave systems by enabling independent control and intelligent torque redistribution across all drive rollers, regardless of process parameters or partial roll engagement during the pulling in and out phases.

Validated through FE simulations and four successful industrial applications in railway rail, medium, and heavy section production, the LSC demonstrably optimizes load distribution. This leads to significantly reduced total drive capacity, decreased roll and component wear, lower operating costs, and enhanced product quality. By ensuring balanced drive utilization, the LSC streamlines commissioning and contributes to more efficient and reliable straightening processes for a wide range of long products.

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