MASTERING MOLD LEVEL CONTROL FOR ALL CONTINUOUS CASTERS USING ADVANCED CONTROLLER SOLUTIONS WITH A NOVEL TECHNOLOGICAL PACKAGE[1]

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Abstract
Nowadays the productivity and high quality products of continuous casting machines are major driving forces in the development of casting technology. A stable and reliable mold level control is one crucial part within the casting process. The latest caster solutions from Siemens Metals Technologies are answering these requirements in terms of mold level control with the technological package Simetal LevCon. Mastering the mold level control with utmost precision to ensure homogeneous shell growth is done by LevCon. The advanced controller has several process models implemented to overcome the different situations during casting. Improved auto-start, the clogging compensation model and the anti bulging model for slab casters are only a few models within. The powerful controller, designed with modern control theory, automatically adapts reliably and extremely quickly to any changing casting condition. Of course, the LevCon can operate with all major electromagnetic or radiometric mold level measurements systems. Furthermore the actuation of the stopper is done precisely by a very compact, fast and accurate inline attached electromechanical linear servo actuator, controlled via LevCon. Moreover, the inline attached drive provides best force transmission as well as being operator friendly during handling, due to the actuator weight of only 9 kg and its ergonomic position. In addition the tundish stopper control mechanism is improved with reduced weight (down to 40%) by higher stiffness compared to former generations.
Key words: Mold level control; Anti bulging; Model based controller; Electromechanical linear servo actuator; Tundish stopper control mechanism.

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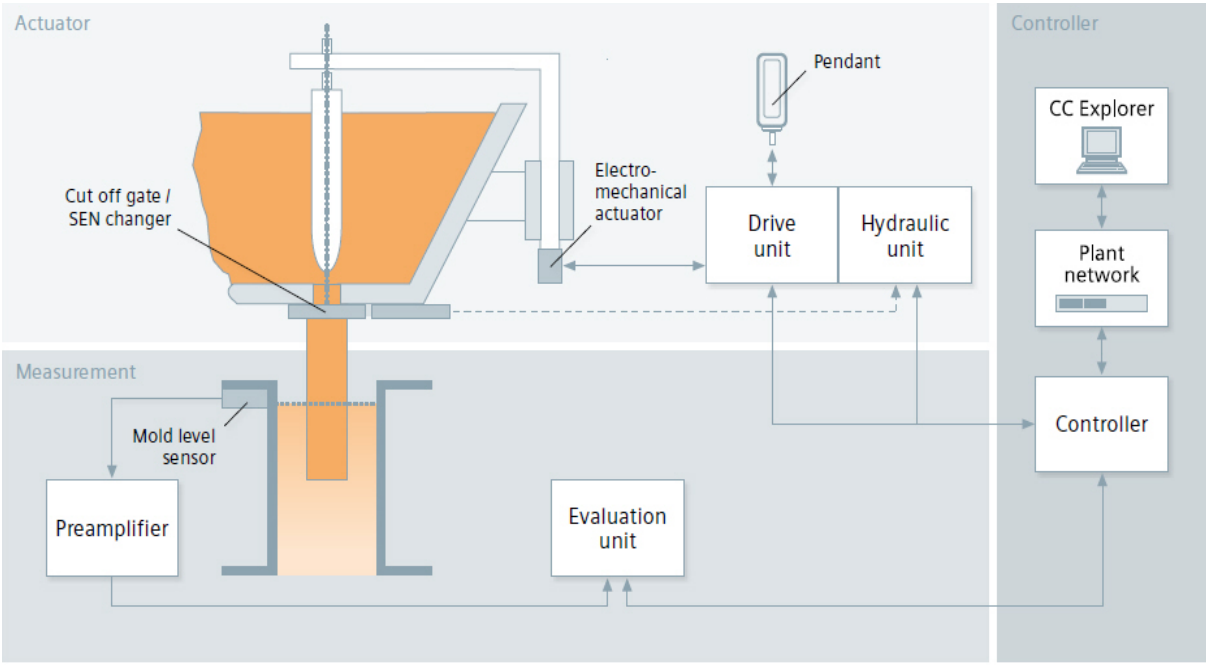
1 INTRODUCTION

The precise control of the mold level is a core function in continuous casting due to the fact that the mold level fluctuations have a major impact on product quality and productivity. These variations have to be reduced to a minimum, thus plant operators need a control system capable of adapting automatically to varying casting conditions. Casting disturbances such as submerged entry nozzle (SEN) clogging, unsteady bulging effects (especially with critical steel grades like peritectic carbon steel and ferritic stainless steel), surface waves in the mold or type-specific limitations in mold level measurement have extensive consequences. Furthermore dead time in the control cycle, due to the channel from the stopper or slide gate to the mold level confront plant operators with additional challenges. As do manual start-up procedures which require human interaction in a dangerous environment. In addition rising demands on steel quality, plant productivity, increased safety standard, operator- and maintenance friendly equipment require an innovative product.
Mastering these challenges for all types of continuous casters can only be achieved with the latest innovation of the technological package Simetal LevCon. It consists of a mechatronic solution with parameterized, pre-configured and pre-tested software and equipment correspondent to the high quality Connect & Cast ®[(1)] philosophy. The LevCon adapts reliably and extremely quickly to mold level fluctuations and changing casting conditions. This is made possible by advanced model-based control algorithms that can actually predict the mold level behavior to avoid disturbances in the control loop. Unsteady bulging is actively suppressed by a powerful algorithm based on modern control theory. SEN flow can be regulated swiftly and reliably by means of a stiff but lightweight stopper rod mechanism driven by a fast and accurate electromechanical linear servo actuator or a hydraulic cylinder. The intelligent interaction between the advanced controller and highly robust mechanical components improves safety and brings plant operators one step closer to fully automatic casting operation. Furthermore LevCon controller also handles the precise control of withdrawal drives for a stable mold level with open stream operation in long product casting machines.
The typical configuration from the latest release of Simetal LevCon mold level control is shown in Figure 1. It consists of three main parts as the powerful mold level controller software with its HMI, the stopper rod mechanism with an inline attached electromechanical linear servo actuator (including the drive unit cabinet on the tundish car) and the mold level measurement. All major measurement systems regardless electromagnetic or radiometric are fully applicable to LevCon.



SIMETAL LevCon configuration

Figure 1. Typical Simetal LevCon configuration, consisting of controller, actuator and measurement.

2 LEVCON CONTROLLER

A reliable combination of proven controller concepts which are implemented in LevCon for many years and new modern control theory build the philosophy behind Simetal LevCon. Mold level control has to cope with a variety of challenges over all types of actuation and level measurement which are handled by a bunch of different integrated process models as shown in Figure 2. All these mathematical models determine the dynamic behavior of stopper (or slide gate) and influence thereby the reaction of steel bath in different casting situations. In general feedback and feed forward concepts are combined.

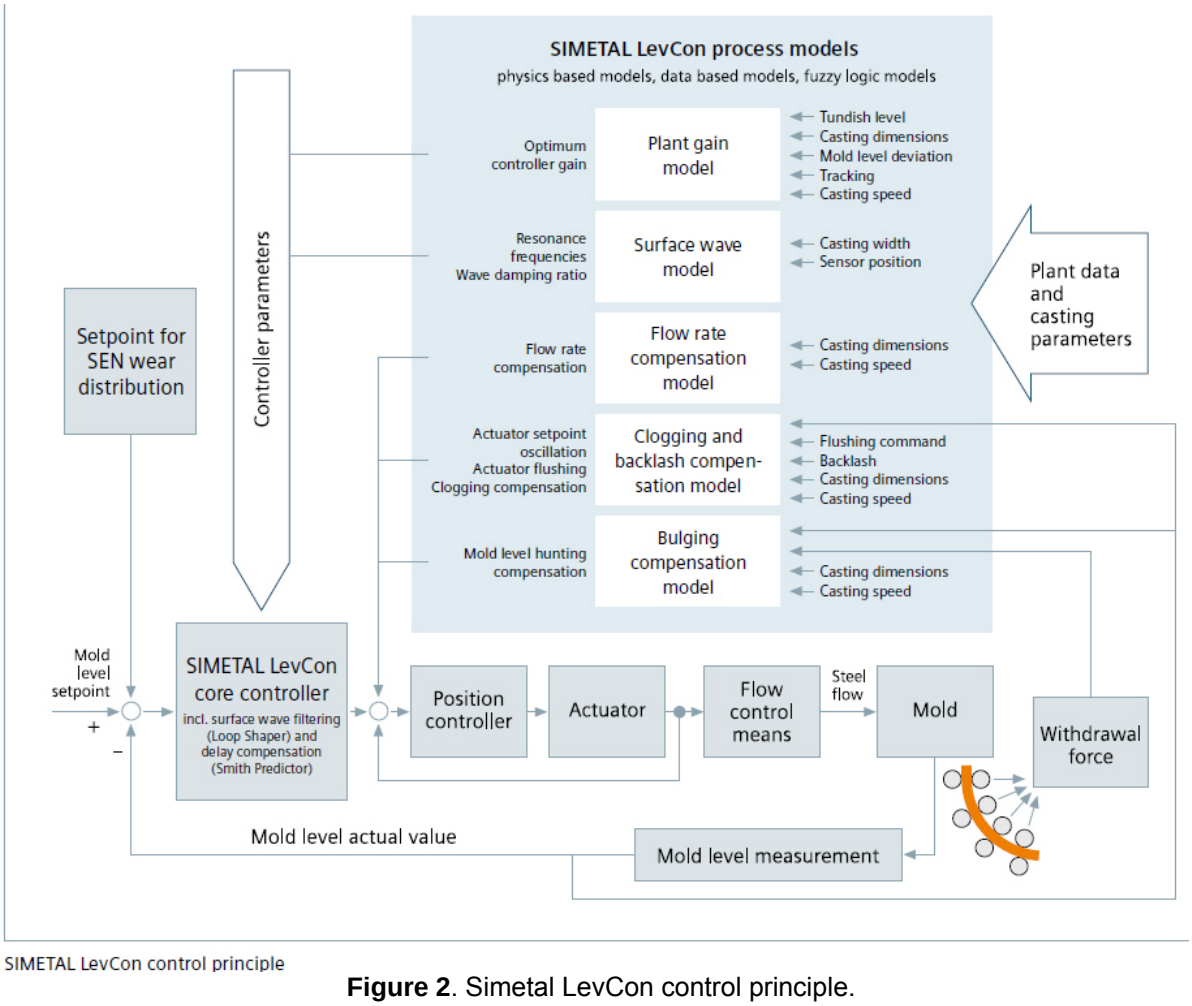


Figure 2. Simetal LevCon control principle.

The core controller is responsible for a stable control circuit in all casting conditions when automatic level control is enabled. A change in casting conditions results in a different dynamic plant response (actuator → mold level). By considering these changes in the controller (by means of the plant gain model), the dynamic of the closed loop keeps similar also with new casting conditions. These conditions are mainly defined by mold dimensions, tundish level and casting speed. The plant gain model is calculating the gain of core controller based on physical models.
By means of the “flow rate compensation” model, which is realized as feed forward control, mold level is stabilized during changes in casting speed and mold width. A simplified version of the physical model used for the plant gain model and flow rate compensation is

$$y(t) = \frac{1}{A_M} \int_0^t \left(k_{st} u(\tau) - A_M v_c(\tau) \right) \mathrm{d}\tau$$

This formula describes the mold level $y(t)$ depending on stopper position $u(t)$, casting speed $v_c(t)$, linearized stopper gain k_{st} and mold cross section A_M.
Surface resonance waves in the mold can lead to instabilities of steel bath if the controller feeds them back. So it is of a high importance that the controller does not react on the resonance frequency which is defined by:

$$f_{SW} = \sqrt{\frac{mg}{4\pi W}}$$

depending on earth acceleration g, mold width W and number of nodes m. Typical flow characteristics show $m=1$ to $m=6$, where $m=2$ is the most frequent situation. The Loop Shaper model,[2,3] based on H_∞ controller design approach, ensures that the LevCon controller is not exciting the critical frequency by appropriate signal filtering. According to Figure 3 the Loop Shaper is able to minimize disturbances in case of surface resonance waves.

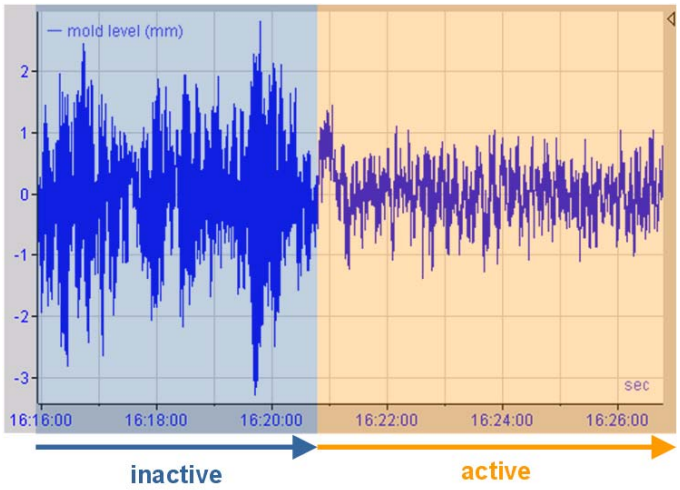


Figure 3. Reduction of surface waves by the Loop Shaper model (measured data from a slab caster).

Clogging of nozzle and SEN are a common phenomenon which induces irregular mold level fluctuations. In case of unclogging, the stopper has to react fast to avoid an abrupt increase of steel flow. By means of a physical based process model for clogging compensation, the necessary stopper position is estimated in order to keep the steel flow constant. In case of unclogging LevCon is able to react faster with activated compensation which reduces the resulting peak in mold level behavior as shown in Figure 4.

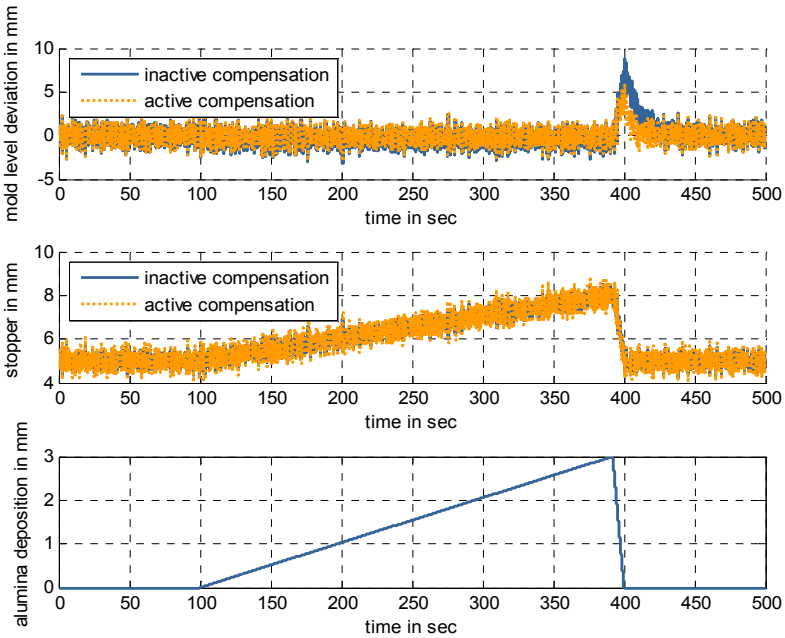


Figure 4. Reduced peak with activated clogging compensation.

3 LEVCON BULGING COMPENSATION

In case of a non uniform strand shell, (especially at peritectic carbon steel and ferritic stainless steel) bulging between rollers is varying over time and creates an oscillating steel flow in the liquid core. Thus, mold level fluctuations are generated which have additional influence on irregular shell growth according to Figure 5. This self amplifying effect can cause severe periodical mold level fluctuations.

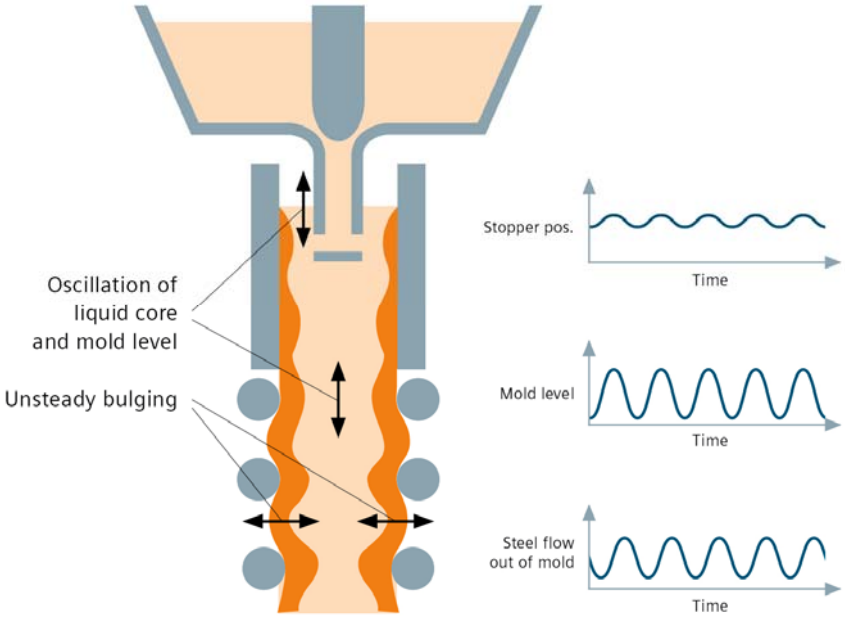


Figure 5. Self amplifying effect of unsteady bulging of strand shell.

Sometimes bulging can be reduced by increasing secondary cooling to thicken the strand shell. Otherwise casting speed must be reduced to stabilize the situation, which leads subsequently to decreased production and often downgrading of the slabs. In extreme cases casting even has to be stopped.
To cope with this situation a new algorithm based on modern control theory has been developed. The flow oscillations from the liquid core are compensated with an adequate steel flow modulation in the SEN by means of stopper movements. LevCon Bulging Compensation includes a mathematical model of the level disturbance generated by unsteady bulging which is depending on casting speed and the roller pitches of the bulging sensitive zone. The bulging frequencies $f_{B,i}$ depending on casting speed v_c and wave lengths λ_i can be calculated by

$$f_{B,i} = \frac{v_c}{\lambda_i}$$

Bulging disturbance consists in general of several wave lengths which appear at the same time. Each wave length is related to a roller pitch p_i and can be a harmonic of the base pitch as well ($n_i \neq 1$):

$$\lambda_i = \frac{p_i}{n_i}$$

Due to the oscillating liquid core, bulging frequencies are also affecting withdrawal forces and actual casting speed. Based on frequency analyses of these signals the

controller is able to differentiate bulging frequencies from other disturbances. Such a frequency analysis of an unsteady bulging case is shown in Figure 6.

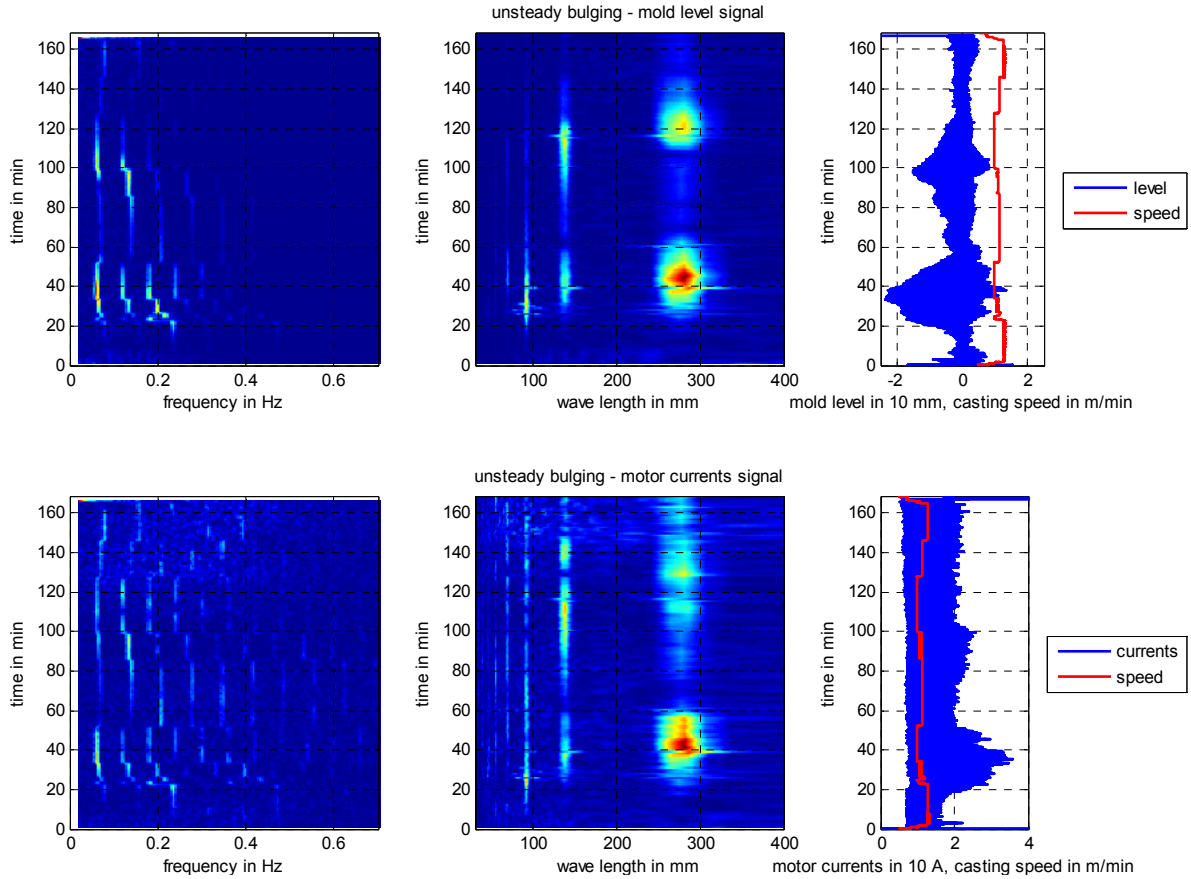


Figure 6. Frequency analysis of mold level and motor currents (measured data from a slab caster).

The accurate determination of bulging frequencies is the basis for an effective compensation. LevCon controller is able to work with fixed wave lengths based on long term analyses of data recordings or to use adaptive wave length detection. Which type is implemented depends on the bulging behavior of the casting machine.
A complex differential equations model (of 19^{th} order in last installations) implemented in the controller (Simatic S7-400) allows a simultaneous compensation of all frequencies (7 frequencies in last installations). Due to this reliable estimation of the disturbance an effective compensation is possible as shown in Figure 7 (selected references from Brazil and PR China).

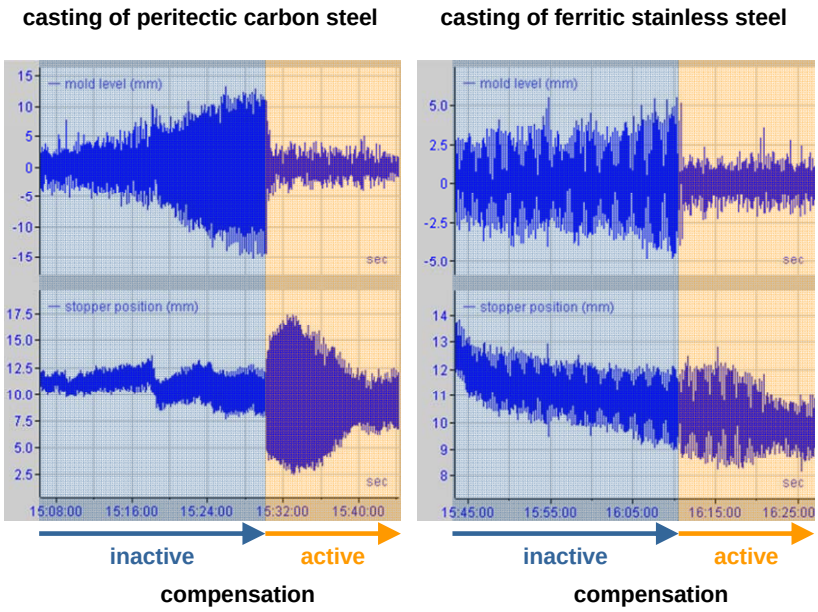


Figure 7. Reduction of mold level fluctuations by Bulging Compensation (measured data from slab casters).

By means of this new feature, mold level fluctuations, due to unsteady bulging, are reproducibly suppressed and a smoother strand shell is produced. Therefore also the oscillation of liquid steel is measurably improved, which means that the bulging effect itself is reduced. This can be observed in the decreasing stopper movement after activation of compensation, when the smooth shell enters the bulging sensitive zone within the strand containment.

4 ACTUATOR

The Simetal LevCon actuator controls the flow of liquid metal from the tundish into the mold. This actuator equipment consists of stopper, stopper rod mechanism, electromechanical linear servo drive and the drive unit. Manual operation of the flow can be done either by pendant which controls the drive or manually via lever. The latest stopper rod mechanism design is an enhancement on the proven Siemens VAI equipment. In an emergency case a hydraulic SEN changer, cut off gate or nozzle changer will be actuated as a back-up safety function for the stopper, slide gate or nozzle. Thus the hydraulic cylinder and the correspondent hoses are only in emergency situations or short periods of operation under pressure. The actuation is done by the controller via interface to the drive unit. As no flammable fluids are required for the electromechanical linear stopper drive, the system increases safety on the casting platform.

The previous design of stopper rod mechanism (for slab casters) was up to 700 kg in weight compared to the latest design, with massive reduction to about 280 kg. Although the weight is decreased by 60%, the stiffness is maintained in all load cases. Moreover the stopper rod mechanism type for long product casters has been reduced by about 60 kg (~ 25%). Due to the differences in dimension of tundish from slab and long product casters, two types of stopper rod mechanism with analogue design are released by Siemens VAI.

The stiff, yet lightweight, stopper mechanisms facilitate the use of a compact electromechanical linear servo actuator. To overcome the different moving loads with only one type of drive, a partly weight compensation done by a spring is applied in

the slab type. This design ensures reliable and accurate position control with the lowest energy consumption. Due to our concept the actuator is in parking position on the tundish car while the stopper rod mechanism keeps with the tundish, less actuators and therefore less investment cost are necessary. Moreover the weight of only 9 kg and the low mounting height of the electromechanical actuator enable operator-friendly coupling and decoupling. In addition best force transmission for fast and precise stopper movement is achieved by the inline attached electromechanical servo actuator, which is connected to a standardized drive unit from the Siemens Sinamics family.
Operator and maintenance friendliness is supported by condition monitoring of the electromechanical actuator. Such as tracking of operation hours or greasing intervals are triggered by the LevCon controller. Each actuator is tracked separately and has its own history, which is dynamically saved in operation. The strand modular design of each drive unit ensures maximum process availability. Furthermore, the standardized mechanical design ensures a low variety of different (spare) parts. An additional benefit is the identical electric, automation and hydraulic equipment for flat and long product casting machines.
Figure 8 shows the typical arrangement of a slab caster with the main parts of the actuator system on the tundish and tundish car.

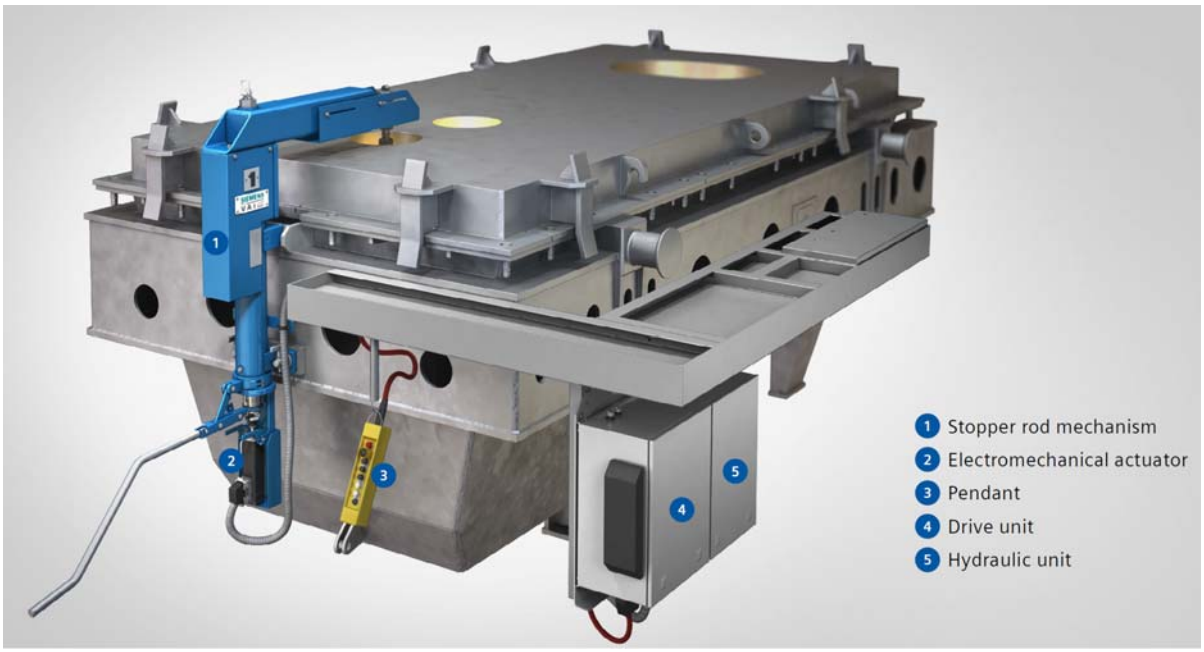


Figure 8. Typical configuration for a single strand slab caster.

5 AUTOSTART

Another powerful feature is the proven auto-start by Simetal LevCon, applied with

- stopper / slide gate;
- slab / billet / bloom / beam blank;
- single / twin / triple casting;
- flow / speed control.

As a result, the latest development of stopper rod mechanism with the compact electromechanical linear servo drive enables access to a significantly more precise flow control already at start casting. Position and force is controlled as well as the data from elastic deformation of the arm is used to evaluate the exact opening

position of the stopper. The reference movement of the stopper is done in preheating position after the drive is coupled into the stopper rod mechanism and the installed stopper is in correct position. This confirms the mounted position of the stopper to ensure enough space for proper closing, even if the stopper or refractory of the tundish is worn. On the other hand the full stroke movement of the stopper rod mechanism is checked, which ensures proper function.
To guarantee the correct and defined opening, the preheated stopper and tundish refractory is calibrated in casting position. The calibration procedure starts before the ladle is opened. First movement is upwards to unlock the position lock mechanism and then downwards until the tundish is closed. The closed position is detected by a defined procedure while moving downwards. Afterwards the force is increased to a nominal force and then decreased while waiting for filling the tundish and start casting.
Consequently using the dimensions of the mold, tundish weight and SEN configuration, the mold is filled smoothly even though the mold level measurement is not available at start casting. After reaching a defined mold level, the controller switches to feedback mode and the actual mold level is following a setpoint curve as do the withdrawal drives. Subsequently casting speed is ramped up to nominal speed (Figure 9).
Thanks to the LevCon technological package the performance of the system is given already from the first heat on.

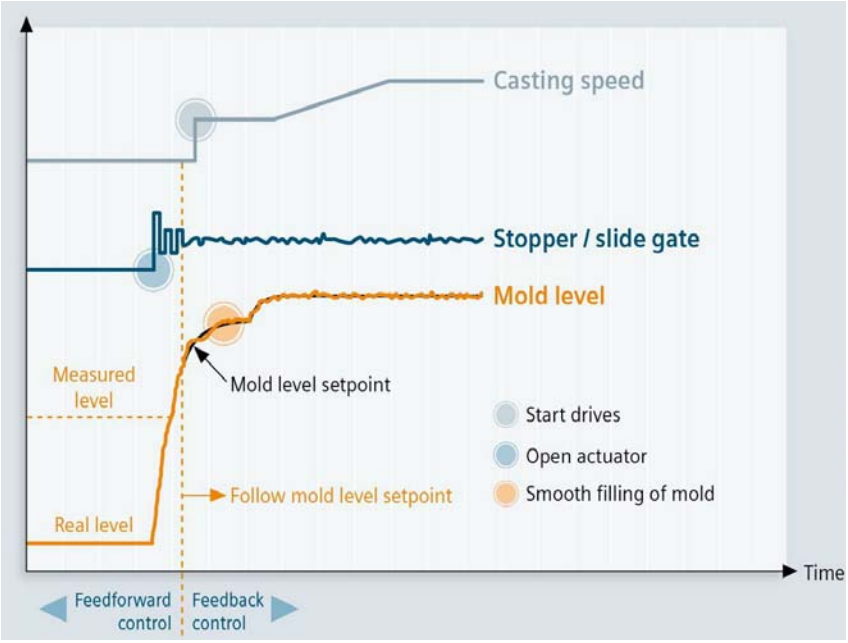


Figure 9. Auto start of casting.

6 CONCLUSION

As a result of the latest improvements of Simetal LevCon a variety of casting disturbances can be compensated in a better way, the safety on casting floor is increased and more operator friendliness is achieved. A reliable anti bulging model as well as new clogging compensation are implemented. By means of the bulging compensation model oscillations in liquid core are compensated to keep the steel bath stable and creating smooth shell growth in the mold. The new simplified, modular and yet lightweight stopper rod mechanism in combination with the latest

linear electromechanical linear servo actuator enables a well defined stopper calibration procedure for an improved auto-start and precise stopper position control. All these measurements contribute to the steady rise in quality of the cast products.

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