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A. TREPPSCHUH*, K. KRUEGER*, R. KUEHN**, H. SCHLIEPHAKE***

THERMAL BASED POWER CONTROL OF A DC-EAF

TERMICZNE STEROWANIE MOCĄ W STAŁOPRĄDOWYM PIECU ŁUKOWYM

The global demand of steel and steel products calls for the enhancement of the productivity in existing steel plants. Automation techniques and closed-loop-controls offer efficient and profitable possibilities to enhance productivity and to decrease specific energy consumption. This examination focuses on the optimisation of the electric power input of a DC electric arc furnace (EAF). All experiments are proceeded at the Georgsmarienhuette steel plant, Germany [1].

The thermal based power control applies as much electric power to the furnace as possible without overheating the water-cooled panels. Thus, the furnace can reach an optimum balance between specific productivity and heat losses. The influence of different variables on the run of the thermal load is investigated by statistic correlation methods. A model is developed to estimate the thermal load of the panels, based on the actual power input, specific energy input, power-off-time and thermal level history. The actual thermal load is compared to the estimated value. If the difference between the two values exceeds certain limits, power control adjusts the electric set point accordingly. This reduces heat losses in the water-cooling system. The slope of the thermal load is extrapolated in order to enable the power controller to react early and quickly.

During the flat bath period, the arc should be covered by foaming slag. If the slag level is not high enough, thermal losses in the water-cooling system increase dramatically. An acoustic signal is used to detect the height of the foaming slag. When the slag covers the arc, the sound level is three to eight times lower compared to the uncovered arc. The power controller increases the power input for good slag conditions and lowers it for poor slag conditions.

The thermal based power input controller increases the productivity of the furnace by 6% – a value that is confirmed by more than 5000 heats that have been processed since 2006.

Keywords: DC-EAF power control, thermal-based power control, foaming slag signal

Światowe tendencje dotyczące produkcji stali zmuszają do podniesienia wydajności. Techniki automatyzacji i sterowania obwodem zamkniętym oferują skuteczne i korzystne możliwości polepszenia wydajności i zmniejszenia zużycia energii. Badanie skupia się na optymalizacji poboru mocy elektrycznego pieca łukowego prądu stałego. Wszystkie doświadczenia odbywały się w stalowni Georgsmarienhuette w Niemczech.

Termiczne sterowanie mocą oparte jest o bilansowanie energii cieplnej w panelach chłodzonych wodą. W ten sposób w piecu można osiągnąć optymalną relację między określoną wydajnością i stratami nagrzewania. Wpływ różnych zmiennych na przebieg obciążenia cieplnego jest zbadany metodami statystycznej korelacji danych. Model jest opracowany w celu oszacowania obciążenia cieplnego paneli, bazując na bieżącym poborze mocy, pobieranej energii właściwej, czasie wyłączenia zasilania mocą, historii poziomu cieplnego paneli. Bieżące obciążenie cieplne jest porównywane z wartością zadaną. Jeśli różnica między tymi dwoma wartościami przewyższa pewną granicę sterowanie mocą dostosowuje odpowiednio żądaną wartość. Redukuje to straty ciepła w systemie chłodzenia. Nachylenie obciążenia cieplnego jest ekstrapolowane, aby umożliwić urządzeniu sterującemu odpowiednio szybką i wczesną reakcję.

Podczas jednostajnego okresu kąpieli, łuk elektryczny powinien zostać przykryty przez pieniący się żużel. Jeżeli poziom żużla nie jest wystarczająco wysoki, dramatycznie rosną starty cieplne w systemie chłodzenia wodnego. Do określenia poziomu spienienia żużla użyty jest sygnał akustyczny. Kiedy łuk jest zakryty przez żużel poziom dźwięku jest niższy trzy do ośmiu razy w porównaniu do przypadku, gdy żużel go nie zakrywa. Urządzenie sterujące zwiększa pobór mocy przy dobrych warunkach żużlowych, a zmniejsza przy słabych.

Termiczny regulator poboru mocy zwiększa wydajność pieca o 6% - wartość ta jest potwierdzona przez około 5000 wytopów przeprowadzanych od 2006 roku.

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* HELMUT-SCHMIDT-UNIVERSITY/UNIVERSITY OF THE GERMAN ARMED FORCES, INSTITUTE OF AUTOMATION TECHNOLOGY, HAMBURG, GERMANY
** SCHMIEDEWERKE GRÖDITZ GMBH, GRÖDITZ, GERMANY
*** GEORGSMARIENHÜTTE GMBH, GEORGSMARIENHÜTTE, GERMANY

1. Introduction

Modern electric arc furnaces require a high degree of automation to achieve a reliable metallurgical process at low production costs. With today's increasing demand of steel, the EAF is utilised aiming at maximum productivity. For efficient furnace operation, water-cooled furnace shells are state of the art. Monitoring the corresponding cooling water temperatures is necessary in order to avoid overheating and excessive wear. The next development step is an automated adaptation of the electric set points corresponding to the thermal status of the furnace. For AC-EAFs, this issue has been addressed since the late 1980ies [2]. As the AC-EAF operates with three electric arcs, the thermal status of three hot spots has to be observed. The DC-EAF operates with only one more or less centrally burning electric arc. Thus, only one hot spot has to be taken into account, which seems to be less complex. But due to the much higher power of the single arc (up to 100 MW), very fast detection and reaction have to be realized. The application of a digital thermal-based power control to an AC-EAF resulted in a productivity increase of 8.1% and energy consumption benefits of 6.2% [3]. Therefore, energy savings and increasing productivity might be expected for DC-EAFs also.

Usually, the electric power is controlled by control diagrams, which define the set points depending on the melting progress. The melting progress is represented by the actual energy input. Certainly, such an open-loop control cannot meet the varying melting and scrap conditions. If the shell temperatures exceed certain limits, the power might first be reduced manually and finally the furnace is switched off automatically. Additionally, the power is reduced automatically if the contracted maximum electric power (¼ hour mean value) might be exceeded.

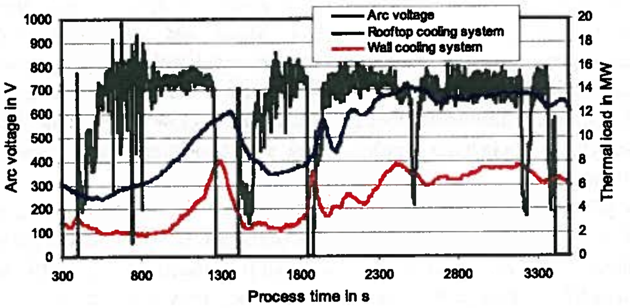

Fig. 1. Run of the thermal load of the main cooling systems, 1 s averaging time

The thermal load of the roof and the sidewall panels during a typical melting process is shown in Fig. 1. At the beginning of the process, the thermal loads of both cooling systems are low. During the following scrap melting, the signal levels increase slowly. As soon as the scrap of the first bucket is melted down, the thermal loads rise steeply because the furnace walls are no longer covered by the scrap bunch. During charging of the second bucket the thermal loads decrease rapidly, even when the arc is ignited again. Obviously, the cooling system exhibits a significant delay time. At $t = 1700$ s, the thermal loads rise again, reaching an almost steady level at $t = 2400$ s. This corresponds to the process, covering effect of the scrap first, cave in of the scrap bunch followed by the formation of foaming slag which covers the arc again. Both cooling systems show similar behaviour.

Figure 2 shows a situation with an excessive increase of the thermal load at the end of the flat bath period. This results in an immediate shut down of the furnace. The power off time of about 90 s causes a disproportionately high increase in process time. During the shutdown, the temperature of the liquid steel decreases. The corresponding energy has to be delivered to crude steel once more. Thus, productivity decreases and energy consumption increases.

Operating the EAF by control diagrams does not regard the varying process conditions during scrap melting as well as during flat bath period. The feasible maximum power input is mainly determined by the thermal status of the system. On the basis of usually given temperature runs it is hardly possible for the operator to define optimum power set point manually.

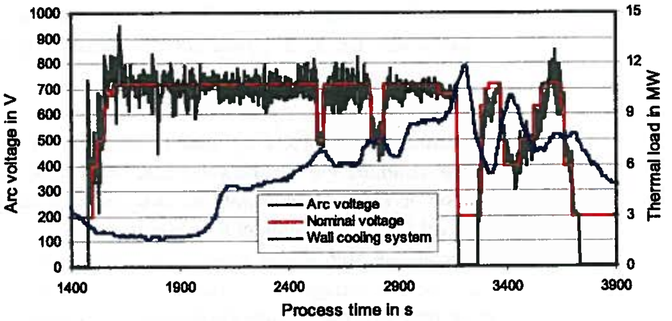

Fig. 2. Excessive increase of the thermal load at the end of the 2nd bucket

Immediate reaction and reliable selection of the electrical set points can only be realized by a closed-loop control. Automated adaptation of the sets points to the thermal status of the system allows for high productivity while limiting furnace shell wear. Consequently, the power input in the EAF is optimised.

2. Design of a thermal load model

The new power controller is based on a model describing the normal thermal level of each process situation. Using this model, it is possible to detect atypical situations in runtime. Thus, the power set point can be adapted to the actual process situation. The electric set points are selected as the control variables for the thermal based power control. The electrical energy accounts for about 80% of the total melting energy, it is not useful to vary the power range of the burners significantly.

The power input control comprises a calculation of the typical run of the thermal load and a short-term forecast. The thermal load run of the rooftop cooling system correlates with the one of the sidewall panel cooling system, but the latter exhibits a higher dynamic. The rooftop cooling system features a significant delay time, caused by an elongated water supply system. In contrast to that, the thermal signals from the sidewall panel cooling system are more dynamic and less sluggish. Therefore, they are usable as a basis for the thermal model.

The panels near to the furnace's hot spot are known for their overheating behaviour. They often trigger the immediate shutdown of the furnace. Two panels are identified as strongly influenced by the thermal radiation of the arc. The average cooling water temperature of these two panels is integrated in a separate prediction model to allow for a precise evaluation of the hot spot's thermal level.

Modelling the thermal load/hot spot's temperature bases on the following actual parameters:

- electric power,
- specific energy input per ton,
- power-off-time and
- thermal history.

Their influence is analysed by a statistic correlation analysis and a Monte-Carlo-Simulation. The influence of the power-off-time on the signals is identified during tapping and charging. The definition of the cooling system's time constant leads to the averaging time for the power-off-time signal. The thermal history signal is also averaged and added to the model calculation applying a fixed weight parameter. All averaging follows a PT_1 algorithm. Thus, actual influences on the thermal load are considered more strongly than older influences. Local minima are avoided by different start parameters of the Monte-Carlo-Simulation. The optimum parameters of 50 heats form the basis for the model. As a result, rugged parameters are achieved and different melting situations can be modelled with adequate quality.

The impact of the specific energy input is approximated by a sigmoid function. A Fermi-function offers adequate parameters and is capable of describing the non-linear influence

$$w_T = \frac{1}{1 + e^{\frac{-(w_{el}-\theta)}{\varepsilon_f}}}. \tag{1}$$

The specific electric energy w_{el} is used as an input parameter to the function. The transformed value w_T allows for a proper modelling of the thermal load in the specific cooling system.

The parameters θ and ε_f are determined by Monte-Carlo-Simulation with start value variation. The specific energy per ton value contains two pieces of information. Firstly, it describes the progress of the heat and the height of the scrap in the furnace shell. Secondly, thermal radiation of crude steel increases with specific power input. Besides the electric arc's direct radiation to the panels, this is the main reason for thermal losses. Both facts are modelled by the Fermi transformation. The mechanism of the transformation is shown schematically in Fig. 3.

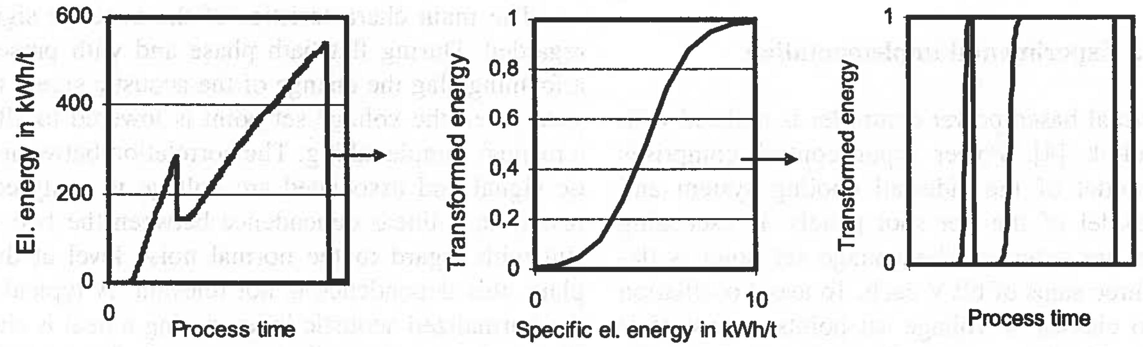

Fig. 3. Mechanism of the Fermi transformation, e.g. with specific energy

Figure 4 shows a typical run of the real and the modelled value during a heat. If the real value exceeds the modelled value, the electric set point is lowered to avoid critical thermal load of the panels. If the modelled value is higher than the real one, the highest set point is selected to optimise productivity. Accuracy of the forecast is not the objective but modelling of a typical run corresponding to the actual process conditions. a better correlation of the modelled to the actual value is achievable with tuned model parameters. However, a rugged model prediction is crucial for the process, especially in anomalous melting situations, e.g. electrode changing, or process interruptions.

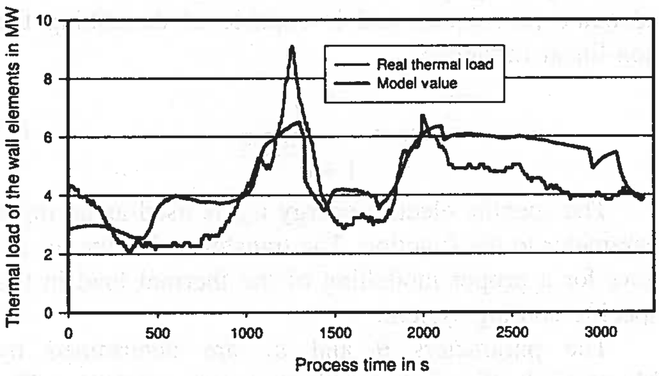

Fig. 4. Thermal load of wall panels and run of model value

To allow for a dynamic reaction to a fast temperature increase, the slope of the thermal load is taken into account. This aims at realizing a fast reaction on rising temperatures. By analysing different critical situations, a suitable extrapolation time is determined. Only the rising run is taken into account. Decreasing thermal load values are not extrapolated. Thus, the moment when the closed loop controller engages set point selection is early enough to avoid overheating.

3. Experimental implementation

The thermal based power controller is realised with Matlab/Simulink [4]. Power input control comprises a thermal model of the sidewall cooling system and a thermal model of the hot spot panels. If exceeding temperatures are detected, the voltage set point is decreased by three steps of 60 V each. To avoid oscillation between two classes of voltage set points, a hysteresis is introduced. The boundaries of this hysteresis are the result of extensive test patterns. At the end of the first basket in Fig. 5, the thermal load of the sidewall cooling system rises. By extrapolation, its increase is amplified. This value is compared to the modelled value and consequently, the voltage set point is decreased by three steps of 60 V each. The controller reacts about 13 s earlier using the described forecast algorithm. As soon as the thermal load is smaller than a defined value, the voltage set point is increased to its maximum.

Supervising the hot spots allows a protection from local overheating which is independent from the main cooling system. The thermal based power control averagely engages three times per heat. By the end of the first bucket normally the main cooling system tends to superheat. During liquid phase the voltage set point is lowered averagely two times, caused by hot spot or main cooling system overheating of 740 V. Overheating and immediate shutdowns are avoided successfully.

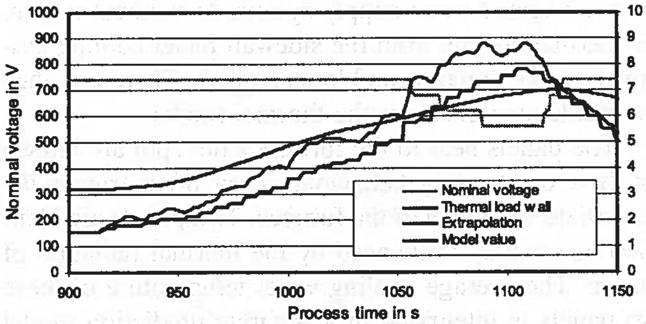

Fig. 5. Increasing thermal load and intervention

4. Embedding a slag height signal

Producing foaming slag during the flat bath phase is an effective practise to enhance the heat transfer between electric arc and crude steel. Therefore, the height of the foaming slag is an interesting parameter for the power control. The goal is to adapt the electric energy input to the actual foaming slag level. The acoustic level of the furnace can be used as an indicating value. An electric arc, covered by slag is much less loud than an uncovered one.

The main characteristics of the acoustic signal are regarded. During flat bath phase and with presence of a foaming slag the change of the acoustic signal is analysed when the voltage set point is lowered to allow for a manual sample taking. The correlation between acoustic signal and associated arc voltage is analysed. This results in a linear dependence between the two values. But with regard to the normal noise level at the steel plant, this dependence is not relevant. A typical run of the normalized acoustic index during a heat is shown in Fig. 6. During the melt down period, the acoustic level is very high. Foaming slag production starts after melting down the second bucket at t = 2000 s. Normalized acoustic level decreases from 0.8 to values around 0.65. Before the last sample is taken, it raises again to 0.75. To better understand this behaviour 10 different heats are analysed. Not later than after the input of 35.000 kWh the acoustic level decreases by typical 0.1 value points. Thus, the signal's dynamic is usable for the power control. As the electric energy input passes 35.000 kWh, the voltage set point is increased by 40 V if the PT_1-averaged acoustic level is lower than 0.66.

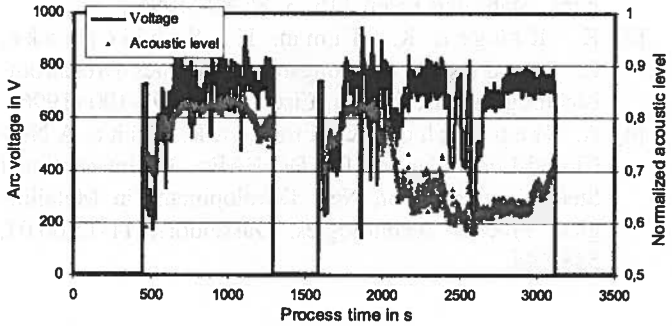

Fig. 6. Run of normalized acoustic level during a heat

The combination 680 V/132 kA is the preferred set point at this stage of the process. If a voltage set point with 740 V is selected, it is not increased to avoid from arc instabilities. When the acoustic level exceeds the value of 0.7, the nominal voltage set point is lowered by 40 V to reduce power losses by arc radiation to the panels. The signals pass hysteresis elements to avoid from oscillations. Figure 7 shows the function of the acoustic based nominal voltage selection during a heat. Shortly after the energy input passes 35.000 kWh nominal voltage is decreased by 40 V as the arc is not properly covered. When the acoustic level passes the limit value, nominal voltage is increased to 720 V. By the end of the heat the furnace gets louder and nominal voltage is decreased again.

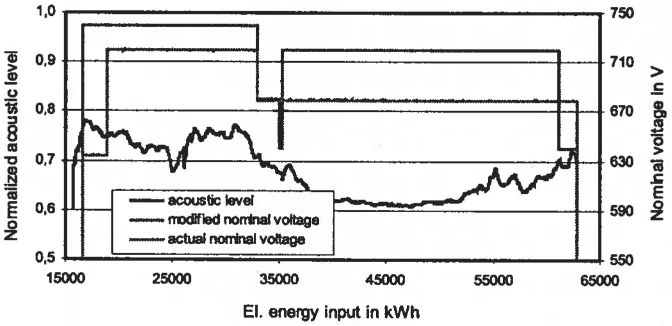

Fig. 7. Adjusting the nominal voltage with regard to acoustic level

5. Results

Figure 8 shows the development of productivity since July 2006 as a result of the thermal based power controller. The control actions influencing nominal voltage have been changed several times. Because of the contracted maximum power consumption per quarter hour, the corresponding controller switched the set point down frequently. Due to that, the benefits in productivity were partially lost. After a new contract with the energy supplying company had been signed, the power controller run at maximum power, arrow A indicates this. Instantly, an increase in productivity by 6% in comparison to the normal production process occurred. In three following campaigns, more than 2200 heats were processed, which means a crude steel production of 280.000 t.

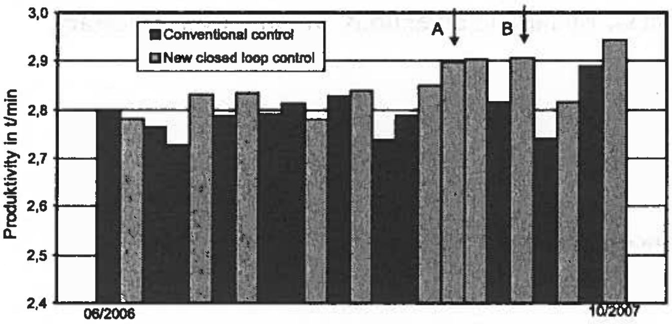

Fig. 8. Run of productivity, A: New energy supply contract, B: Slag height detection

In two trial campaigns, the voltage set points were significantly increased during the flat bath phase. This results in huge specific energy consumption, indicated by arrows **C** and **D** in Fig. 9. The extra electrical power could not be supplied to the molten steel.

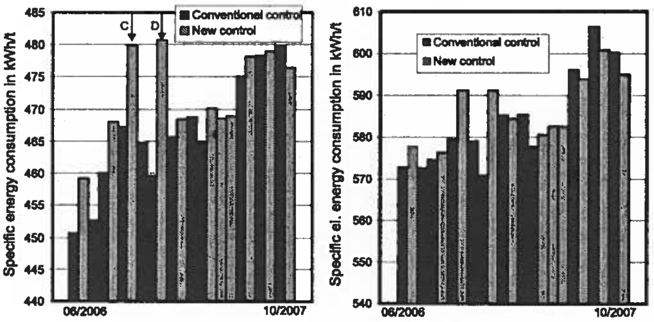

Fig. 9. Run of electric and total energy consumption, C, D: Trials with nominal voltage up to 760 V

Arrow **B** in the productivity plot points to the launch of the acoustic level based foaming slag height detection. A significant increase in productivity and a little less specific energy consumption can be recognised. Anyhow, this does not play an important role with regard to the industrial praxis. It can be expected that the feature has positive impact on the furnace wear. Therefore, the function is in use even if the influence on energy consumption is low.

After three campaigns with a productivity of about 2.9 t/min, a strong decrease follows with normal procedure and the new closed-loop control. During this phase with superordinate process influences, the new set point selection can achieve a benefit in productivity of 3%. The last two beams in all figures hint at major process changes. As a second ladle furnace is applied to the process line, the tapping temperature is decreased by 50°C. Thus, productivity increases and energy consumption is lower than before.

With the new power controller, the productivity is raised under all practical circumstances. It guarantees a full protection from overheating. Voltage set point selection is fully automatic, reliable and matches the process. Manual interventions are no longer necessary.

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