NEW OPTIMIZATION MODULES FOR ELECTRODE CONTROL SYSTEMS OF AC ELECTRIC ARC FURNACES[1]

Björn Dittmer[2]
Detlef Rieger[3]
Thomas Matschullat[4]
Arno Döbbeler[5]
Klaus Krüger[6]

Abstract

Next steps towards maximum performance are done by systems that can measure and detect the conditions inside the furnace in order to adapt the setpoints of the melting profile accordingly. By using structure-borne sound sensors, the SonArc modules CSM and FSM measure the state of the melting process inside the furnace shell. In combination with the evaluation of the panel temperatures the optimal impedance respectively current setpoint is defined for each phase separately. Also the overall setpoint regarding transformer tap and reactor tap is controlled and optimized. In this way specific energy consumption, power-on time and furnace wear can be significantly reduced. Furthermore, during flat bath operation the foaming slag level can be automatically controlled in order to achieve a permanently high level of foaming slag. By detecting the foaming slag levels for each phase's hot-spot separately, the carbon and oxygen injection into the furnace are optimized. This results in lower carbon consumption and increased energy efficiency. The most important system for control of an AC Electric Arc Furnace (AC-EAF) is the electrode control system. Firstly, the electrode control needs to achieve a smooth melting with absolutely lowest disturbances of the electrical values. By using state of the art impedance control adapted to the characteristics of the actuation system, optimal melting can be achieved. In this way stress and wear of the mechanical and electrical parts of the furnace are reduced.

Keywords: AC-EAF; Furnace optimization; Foaming slag; Structure-borne sound.

---

[1] *Technical contribution to the 16th Automation and Industrial IT Seminar, September 24th to 27th, 2013, Vitória, ES, Brasil.*

[2] *Sales Manager, Siemens AG, Metals Technologies, Erlangen, Germany*

[3] *Senior Key Expert, Siemens AG, Corporate Technology, Munich, Germany*

[4] *Process Senior Key Expert, Siemens AG, Metals Technologies, Erlangen, Germany*

[5] *Head of Sales Group, Siemens AG, Metals Technologies, Erlangen, Germany*

[6] *Chair for Process Data Processing and Systems Analysis, Helmut Schmidt University – University of the Federal Armed Forces, Hamburg, Germany*

1 INTRODUCTION

Nowadays, electric arc furnaces (EAFs) are operated with increased arc voltages and secondary currents in order to enhance productivity. Power inputs of up to 300 MVA are achieved for AC-EAFs.(1) Operating such a high arc power requires an accurate control of the meltdown process. An arc that radiates its high power towards the furnace walls will cause tremendous damage. By preventing such an undesired behavior, downtimes are kept at a low rate and high furnace productivity is maintained. In order to achieve this goal, a closed-loop power control has to be set up. Such a power control needs to react to occurring events in the meltdown progress, in especially to furnace walls that are not covered by scrap or suitable foaming slag practice. The crucial point is to achieve this kind of information about the process.

The key control system for AC-EAFs is a closed-loop electrode control system. The basic task is to control the position of the electrodes, more specific to maintain the electrical operating point. The performance of this very basic task is first of all affecting many key performance indicators (KPIs) of a meltshop, such as specific electrical energy consumption, electrode consumption and productivity resp. power-on time of the furnace. Second, its performance is crucial for reducing stress of the mechanical and hydraulic systems as well as for limitation of power grid disturbances. It is common sense that best performance of this basic task is achieved by impedance based electrode control.(2) Basic additional functions for reducing overcurrent, short-circuits and electrode breakages are state-of-the-art and keep downtimes to a minimum. Adaptation to the characteristics of the actuation system is needed for best performance, i.e. the characteristics of the hydraulic valves.

The above mentioned basic functions of an electrode control definitely influence the performance of an AC-EAF. Nevertheless, performance of the furnace depends largely on selection of the electrical operating points. By taking the overall design of the furnace into consideration, operational diagrams are set up, also called melting profiles or power programmes. They are used for providing the electrical setpoint of the furnace, i.e. the transformer tap, reactor tap and impedance setpoints. These diagrams are usually depending on total energy input.(3) This functionality is covered by Level 2 systems or similar solutions. The selection and sequence of setpoints in this operational diagram has direct impact on the KPIs of an AC-EAF.

Nowadays, add-on modules for the electrode control are in use to adapt the setpoints provided by the operational diagrams in order to meet the actual melting conditions inside the furnace, i.e. by evaluating the thermal load of the water-cooled panels.(2,4) Optimization modules can be used to increase the power input into the furnace by dynamically adjusting the impedance setpoints to the melting progress.(2) Usually, the furnace operator is still responsible for taking further control actions based on his subjective perception of sound emissions and his visual impression of the furnace. Approaches towards a further automated power control usually rely on evaluations of the arc current and voltage. Other measurement techniques are often not applicable due to the extreme conditions in the furnace environment. However, several approaches exist that use sound measurements, mostly for automated foaming slag operation.(5)

In this background, Siemens does successful research in electric arc furnace technology on the base of structure-borne sound sensors since years. The research program started with a feasibility study at EAF #1 of Lech-Stahlwerke in Meitingen, in the south of Germany. After proven feasibility – by means that structure-borne sound signals are applicable to evaluate the foaming slag level and distribution – a carbon injection control was developed and commissioned. Up today it operates very successfully. The time period to develop such a carbon control from feasibility study to a running system at the arc furnace took 1½ years. One year later the second arc furnace at Lech-Stahlwerke was also equipped with the foaming slag control (SonArc FSM). The FSM system ensures that slag foaming levels are uniformly high throughout the foaming process. Consequently, the energy efficiency of the arcs is increased while at the same time the amount of injected carbon is reduced. The operating results of furnace no. 1 were reported already at the AISTech Conference 2007.(6)

Since this time Siemens Metals Technologies started a four years research project together with the Helmut Schmidt University Hamburg and Siemens Corporate Technology, to investigate the applicability of structure-borne sound signals during the scrap melt-down phase. It is shown that the melting conditions inside the furnace can be monitored and a closed-loop power control can be set up in order to achieve best melting results during main melting. The development work was reported at the AISTech Conference 2010.(7)

In the meanwhile four references with SonArc FSM exist and two pilot installations with the condition-based scrap melt-down control (SonArc CSM) are in operation. This paper reports for both modules about the functionality, the hardware installation, the control strategy and last but not least the operating results.

2 MATERIAL AND METHODS OF SONARC SYSTEM

2.1 Common System Structure of Sonarc CSM / FSM System

Three structure-borne sound sensors, each assigned to one electrode segment, are used to record signals. They are mounted to the furnace shell by welding three adapter plates onto the panels opposite to the respective phase/electrode. The adapter plate is positioned approximately 800 mm above the steel bath level. The sensors are connected using temperature shielded signal cables, which have to be protected from excessive heat and mechanical destruction, as shown in Figure 1. In order to enable an easy change of the furnace vessel, the cables are connected using Harting sockets or connector boxes which are mounted at or close to the furnace vessel.

Figure 1: Example of a heat protected sensor mount at the furnace panel.

The following Figure 2 schematically shows the complete system setup at an AC-EAF. In addition to the structure-borne sound signals, the current signals are recorded by using Rogowski coils. The high-speed sampled signals are forwarded to the data acquisition and computation module.

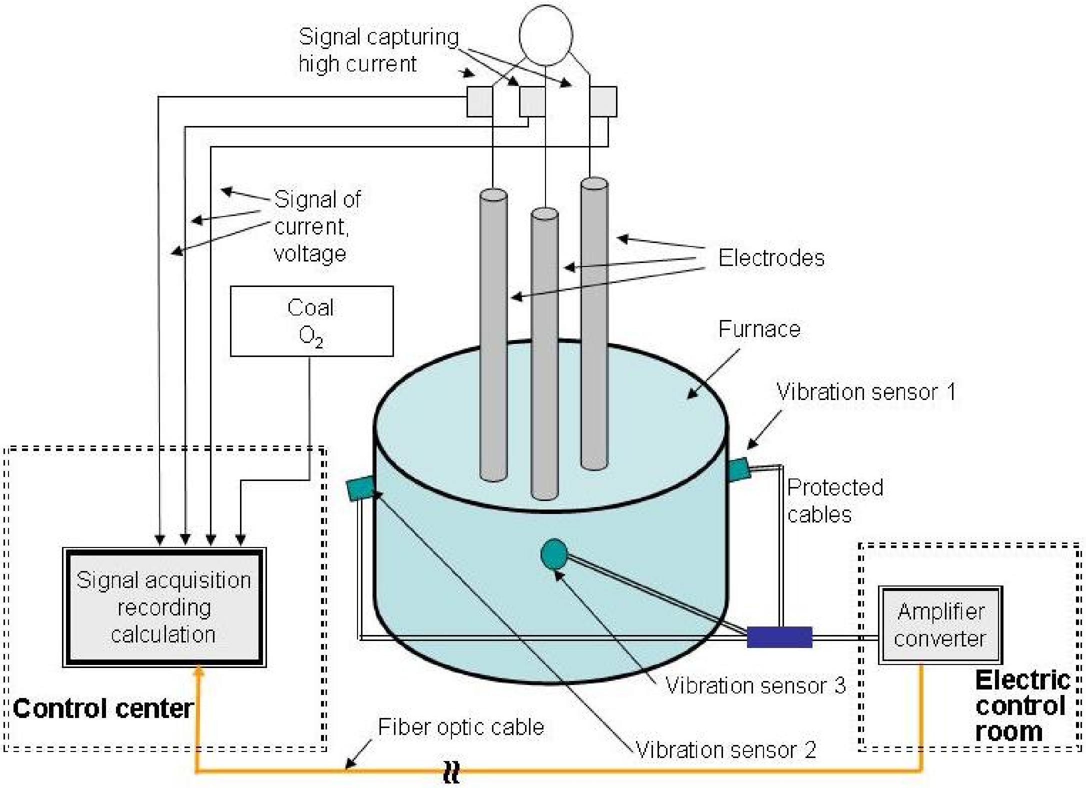


Figure 2: Overview of the overall arrangement for the SonArc FSM and CSM

2.2 PRINCIPLE OF FOAMING SLAG CONTROL

The SonArc FSM system evaluates the sound propagation from the electric arcs, where the sound is created, to the furnace shell, where the resulting vibration is detected by the acceleration sensors, also called structure-borne sound sensors. The electric arcs serve as acoustic sources. By calculating the damping of the sound propagation, the height of the foaming slag is determined.

The great advantage of this method is to determine not just an average slag height around the electrodes, but particularly a specific height in the complete area between each electrode and the furnace shell. The one-dimensional view is actually extended by the FSM to a two-dimensional measurement of the slag height distribution. Due to the mounting of three sensors opposite to the corresponding electrodes, the slag height can be determined independently in three zones of the furnace, as outlined in Figure 3. Thus the spatial distribution of the slag height can be evaluated and displayed in the visualization.

The outstanding chance of the correct spatial measurement of the slag height is to regulate the carbon injection by an individual control of the carbon valves in order to achieve an uniform slag distribution.

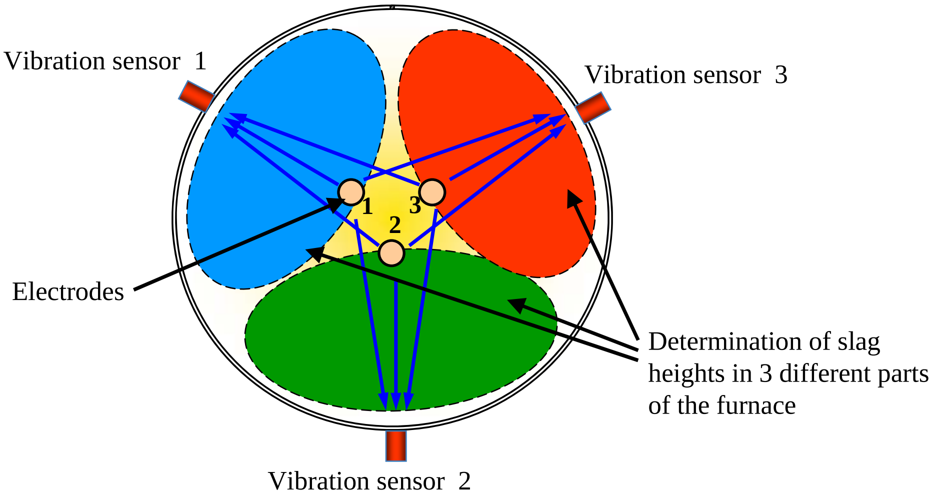


Figure 3: Determination of the spatial distribution of the foaming slag height in three different regions by using three sensors.

For the regulation of the carbon injection a control system based on Fuzzy algorithms was developed. This allows for implementing easily appropriate rules for the carbon injection which can be adapted to the specific situations of the particular customer's furnace configuration. As the carbon valves are usually not designed for a continuous analog control, the output signal is transformed into a pulsed width modulation, which yields in an appropriate carbon supply. On the time scale the slag foaming is divided into different periods, as schematically shown in Figure 4. The periods are determined by the specific energy input. They are characterized by different reference slag height settings.

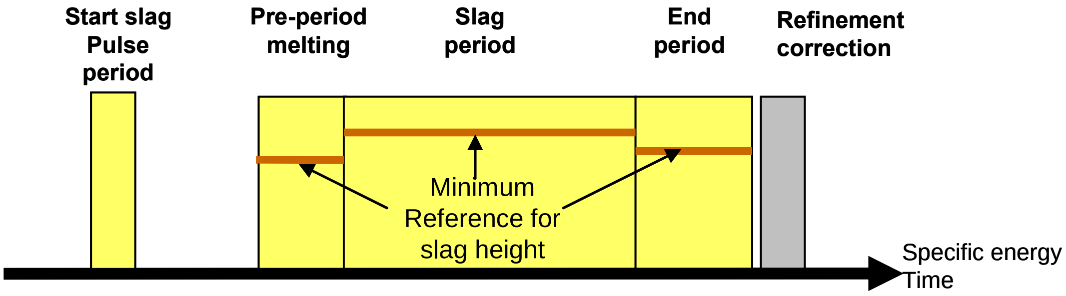


Figure 4: Defined periods of the carbon control.

The carbon is injected in a pulsed modulation mode, where pulse width and frequency are controlled by the FSM in order to inject the right quantity of carbon for each of the three valves. This enables the FSM to apply exactly the needed amount of carbon for each valve in order to achieve a most uniform, sufficient and stable slag height. During the end period, where the foamy slag is partly poured out, the slag height is lowered and fluctuates. An example of FSM operation during second basket melting, including overheating until tapping is shown in Figure 5. It shows the measured slag heights, the (minimum) reference slag height at the three phases and the pulsed injection of carbon in order to achieve best foaming slag.

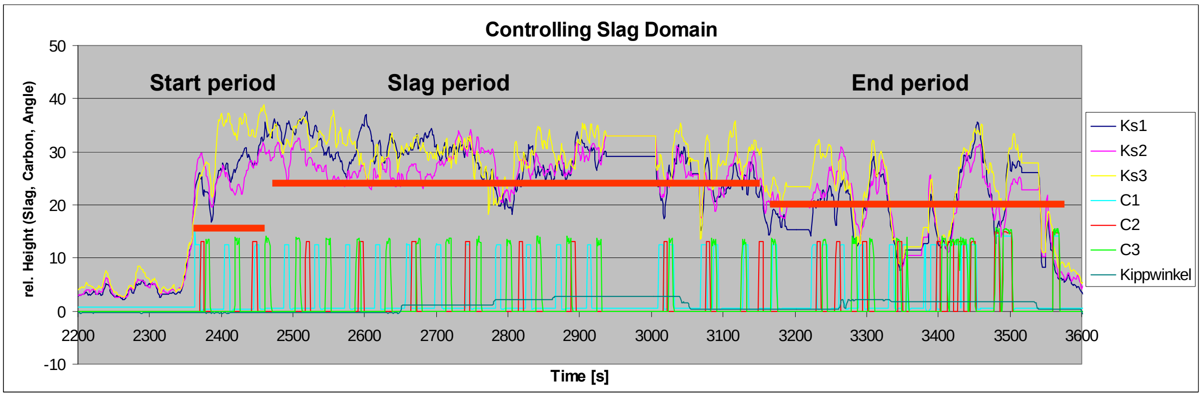


Figure 5: Example of a uniform slag height control by using the FSM.

2.3 Principle Of Condition Based Scrap Melting

The SonArc CSM system dynamically controls the electrical energy input during the scrap melt-down period and partly also during the flat bath period by immediately reacting upon the state of the scrap and the melt. This yields in a condition-based optimization of the melting process.
The CSM uses the same hardware as described before for the FSM. Similar to the FSM, the CSM measures the sound propagation from the electric arcs, where the sound is created, to the furnace shell, where the resulting vibration is detected by acceleration sensors. By measuring the current of the three arcs and the wall vibration opposite to the electrodes, two different condition-based status signals are calculated dynamically:

- the shielding of the panels by scrap or slag
- scrap state at the arc base, especially the appearance of “cold” heavy scrap.

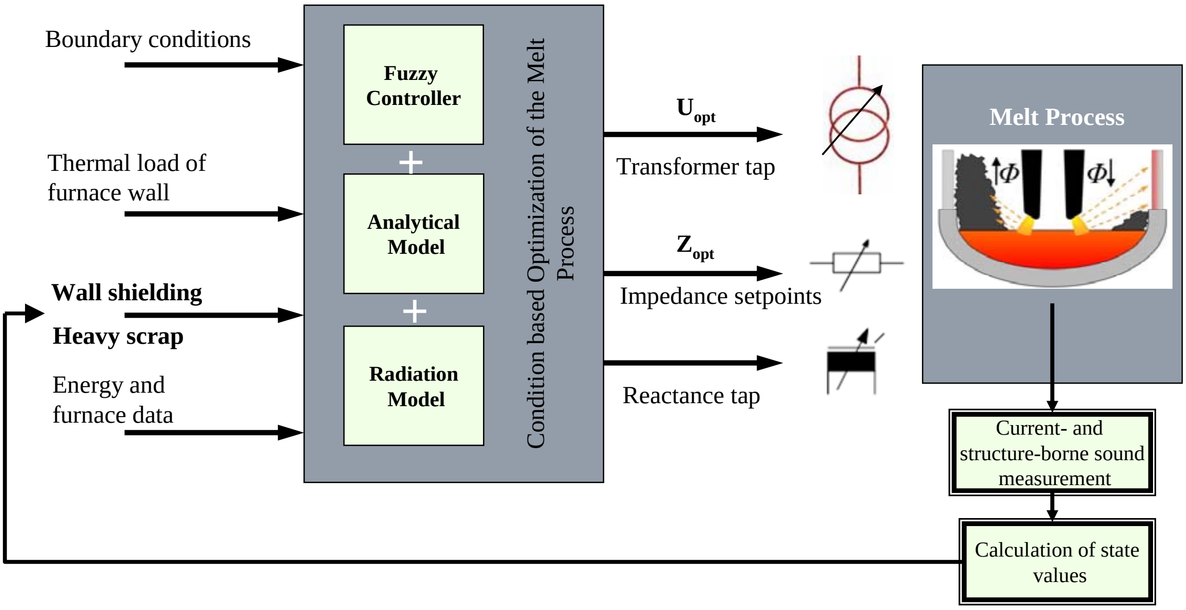


Figure 6: Schematic outline of the SonArc CSM operation.

These two signals support characterizing the melting process. Combined with additional information about the furnace, a new condition-based control of the electrical energy input is realized. The additional information include the thermal load of the furnace panels, the specific energy input, electrical data and further boundary conditions of the process.

As schematically shown in Figure 6, the new designed controller regulates the secondary voltage by switching the transformer tap, calculates new individual impedance set points for the three phases and switches the series reactance. The controller maximizes the power input by taking into account the actual wall shielding and the thermal load.

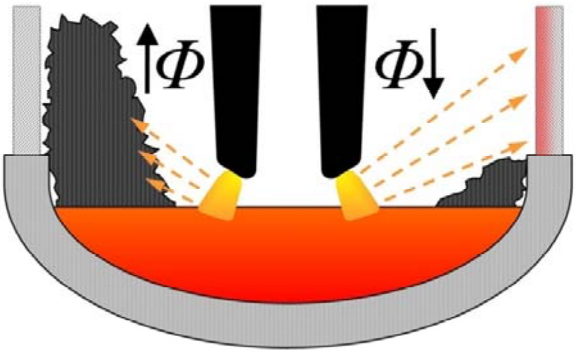


Figure 7: Illustration of an asymmetric loss of wall shielding and lowering of the radiation.

The main feature and advantage of the CSM is its ability to detect a loss of wall shielding much earlier compared to the resulting temperature rise of the panels, which results from the increased radiation impact. This time lead of approximately 60 s enables the CSM to react by redistributing the power respectively the radiation of the three arcs. This immediate redistribution moderates or avoids the thermal impact of the corresponding panels. In Figure 7 a schematic drawing illustrates the described situation.

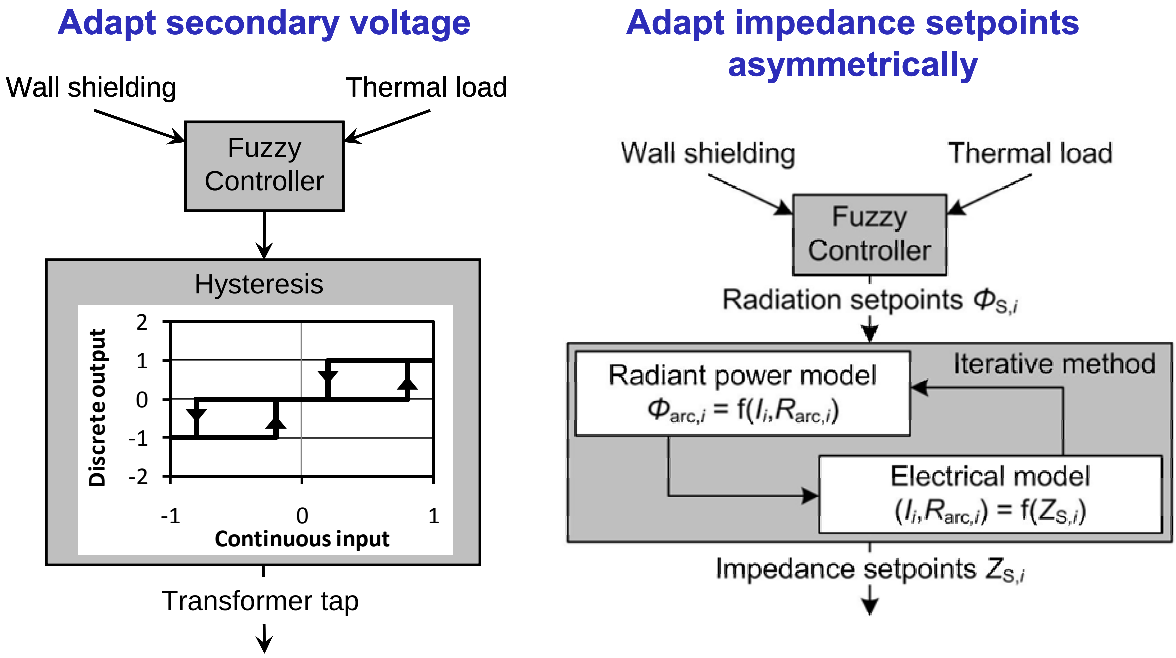
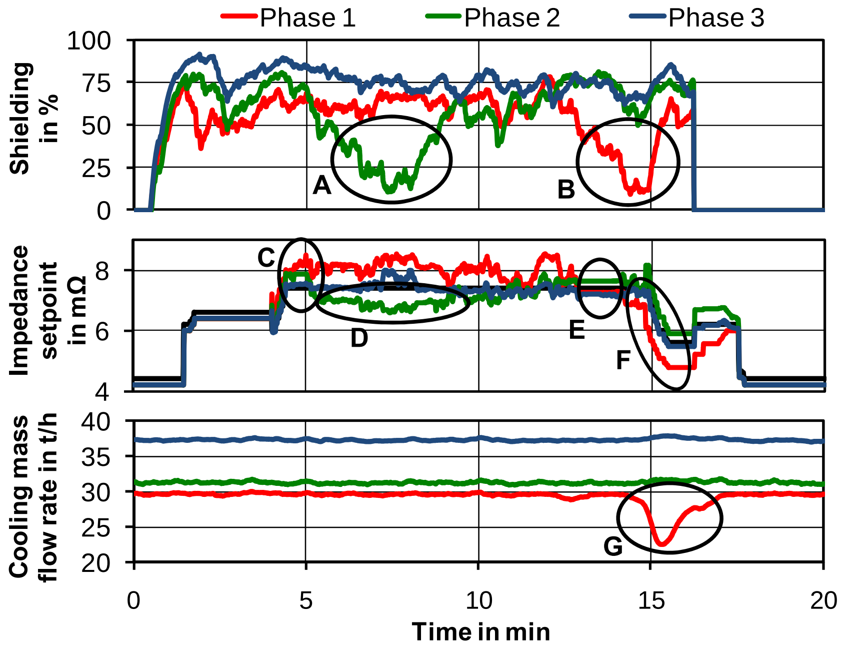


Figure 8: Power control strategy by controlling the transformer tap and the impedances setpoints.

The CSM controller reacts in two different ways on the loss of wall shielding and the thermal load of the panels, as explained in Figure 8. First of all, on a long time scale when the loss of shielding and the expected or measured temperature increase last for a longer time or is very distinct, the transformer is tapped down. Thus the secondary voltage is adapted. On the other hand, transformer tap is increased when the melt conditions allow for, e.g. at high arc shielding and low panel temperatures. The transformer tap switching is activated by a hysteresis loop to avoid unnecessary switching operations. Second, on a short time scale the same input signals are evaluated to control the impedance set-points of the three phases individually, which yields in an asymmetric electrical furnace operation. Based on the calculated shielding and panel temperature prediction or measurement, a fuzzy controller calculates an optimal radiation power distribution. Using a new developed radiation model(8) and an analytical electric model, the corresponding impedance set-points are calculated in an iterative loop in order to fulfill best the optimum radiation distribution. So an almost immediate redistribution of the radiation power can be achieved to moderate or avoid the thermal impact instantaneously. A more detailed description is given in the literature.(7)



Low shielding of the furnace walls is detected before thermal load occurs

Low shielding is compensated by asymmetrical power control

Excessive thermal load needs for lowering the transformer tap

Figure 9: Avoiding thermal load of the furnace walls by asymmetrical power control.

In Figure 9 an example is displayed for an evaporation cooled furnace showing the described effects and the reaction of the CSM. At the marked areas A and B a sharp decay of the wall shielding at phase 2 and later at phase 1 is detected by the CSM. As a fast reaction the radiation of the arcs is redistributed by lowering the impedance set-points of the affected phases and increasing the impedances of the well shielded phases (D and E, F). In the case of A this fast redistribution is sufficient to avoid a thermal heating of the affected panels, the cooling rate remains constant. In the case B this radiation redistribution cannot avoid a thermal panel heating, seen at G. Thus the redistribution is enhanced and additionally the transformer tap is lowered, yielding in a decrease of the impedances and power (F). After a short time the heat impact automatically diminishes.

This example exhibits the main advantage of the CSM yielding in a smoother and more stable operation with less transformer tap switching operations and an increased energy input whenever it is permitted by the melt situation.

3 OPERATION RESULTS OF INSTALLATIONS

The SonArc FSM is installed at four furnaces. Further projects are in the planning phase, like for example the application at an arc furnace with DRI feeding. The SonArc CSM is installed at two totally different types of furnaces. One is used for the production of stainless steel, with a special cooling on the base of saturated steam. This kind of cooling is used to produce steam with the heat losses. The second furnace produces special bar qualities. Here the CSM is installed on the same platform as the SonArc FSM. In the following Table 1 the main data of the furnaces are described.

Table 1: Arc furnaces equipped with SonArc FSM/CSM

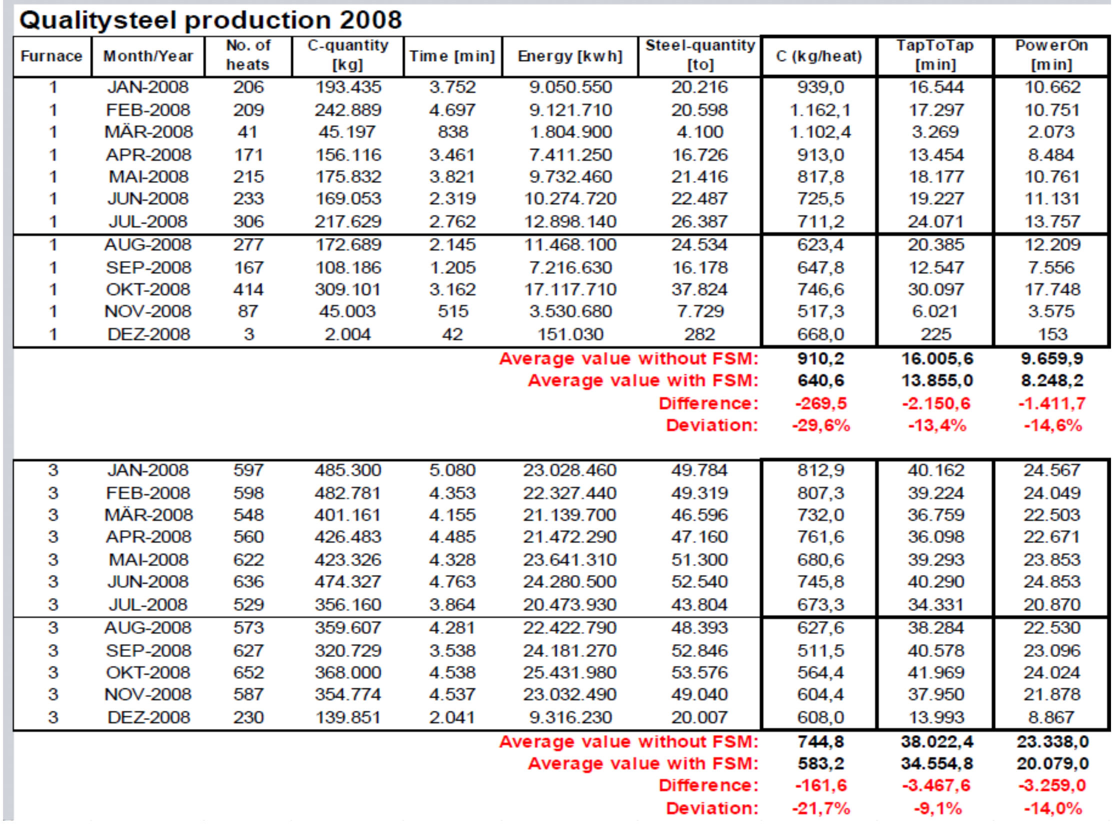
Steelworks	**Lech-Stahlwerke**	**Lech-Stahlwerke**	**BMZ**	**Outokumpu Nirosta**	**BMZ**
Location	Meitingen, Germany	Meitingen, Germany	Slobin, Belarus	Bochum, Germany	Slobin, Belarus
Steel grades	Rebar SBQ	SBQ	Rebar SBQ	Stainless Ferritic Austenitic	Rebar SBQ
Furnace No.	1	3	3	1	2
SonArc FSM Commissioning	2007	2008	2009		2011
SonArc CSM Commissioning	Planned for 2013	2011		2010	
Electrode Control	Simelt AC	Simelt AC	Simelt AC	Simelt AC	Simelt AC
Tapping weight	100 mt	80 – 100 mt	110 mt	155 mt	110 mt
Tapping system	EBT	EBT	EBT	Spout	EBT
Transformer power	75 MVA	87 MVA	95 MVA	135 MVA	95 MVA
cooling	Water	Water	Water	Saturated steam	Water
Coherent jet burner for O2	3	3	3	0	3
Carbon injection points	3	3	3	0	3
Further plants in steelworks	LF VD 4 Str Caster	LF VD 4 Str Caster	LF 4 Str Caster	AOD Slab Caster	LF 4 Str Caster

The following chapters show an excerpt of the operation results of the SonArc CSM and FSM systems. For a more detailed view on all achieved results, we refer to the recent publication of results at the Conference AISTech 2012.(9)

3.1 Results of Sonarc FSM Operation

At the two furnaces of the Lech-Stahlwerke the following results for the special bar qualities were achieved as shown in Table 2. Upon using the FSM a remarkably large reduction in several operating figures is revealed, compared to the time before. These are the savings in injection carbon, which are in the range of 21 % up to 29 %, and the reduction in power-on time which is around 14 %. The productivity is increased, reflected by the tap-to-tap time, which is about 9-13 % better than without FSM. For the rebar qualities (see table III) the benefits are also remarkably well, but on a lower level compared to the SBQ grades.

Table 2. Results in special bar quality production for the two furnaces at the Lech-Stahlwerke: Comparison of operation periods with and without FSM



Qualitysteel production 2008

Furnace	Month/Year	No. of heats	C-quantity [kg]	Time [min]	Energy [kwh]	Steel-quantity [to]	C (kg/heat)	TapToTap [min]	PowerOn [min]
1	JAN-2008	206	193.435	3.752	9.050.550	20.216	939,0	16.544	10.662
1	FEB-2008	209	242.889	4.697	9.121.710	20.598	1.162,1	17.297	10.751
1	MÄR-2008	41	45.197	838	1.804.900	4.100	1.102,4	3.269	2.073
1	APR-2008	171	156.116	3.461	7.411.250	16.726	913,0	13.454	8.484
1	MAI-2008	215	175.832	3.821	9.732.460	21.416	817,8	18.177	10.761
1	JUN-2008	233	169.053	2.319	10.274.720	22.487	725,5	19.227	11.131
1	JUL-2008	306	217.629	2.762	12.898.140	26.387	711,2	24.071	13.757
1	AUG-2008	277	172.689	2.145	11.468.100	24.534	623,4	20.385	12.209
1	SEP-2008	167	108.186	1.205	7.216.630	16.178	647,8	12.547	7.556
1	OKT-2008	414	309.101	3.162	17.117.710	37.824	746,6	30.097	17.748
1	NOV-2008	87	45.003	515	3.530.680	7.729	517,3	6.021	3.575
1	DEZ-2008	3	2.004	42	151.030	282	668,0	225	153
						Average value without FSM:	**910,2**	**16.005,6**	**9.659,9**
						Average value with FSM:	**640,6**	**13.855,0**	**8.248,2**
						Difference:	**-269,5**	**-2.150,6**	**-1.411,7**
						Deviation:	**-29,6%**	**-13,4%**	**-14,6%**
3	JAN-2008	597	485.300	5.080	23.028.460	49.784	812,9	40.162	24.567
3	FEB-2008	598	482.781	4.353	22.327.440	49.319	807,3	39.224	24.049
3	MÄR-2008	548	401.161	4.155	21.139.700	46.596	732,0	36.759	22.503
3	APR-2008	560	426.483	4.485	21.472.290	47.160	761,6	36.098	22.671
3	MAI-2008	622	423.326	4.328	23.641.310	51.300	680,6	39.293	23.853
3	JUN-2008	636	474.327	4.763	24.280.500	52.540	745,8	40.290	24.853
3	JUL-2008	529	356.160	3.864	20.473.930	43.804	673,3	34.331	20.870
3	AUG-2008	573	359.607	4.281	22.422.790	48.393	627,6	38.284	22.530
3	SEP-2008	627	320.729	3.538	24.181.270	52.846	511,5	40.578	23.096
3	OKT-2008	652	368.000	4.538	25.431.980	53.576	564,4	41.969	24.024
3	NOV-2008	587	354.774	4.537	23.032.490	49.040	604,4	37.950	21.878
3	DEZ-2008	230	139.851	2.041	9.316.230	20.007	608,0	13.993	8.867
						Average value without FSM:	**744,8**	**38.022,4**	**23.338,0**
						Average value with FSM:	**583,2**	**34.554,8**	**20.079,0**
						Difference:	**-161,6**	**-3.467,6**	**-3.259,0**
						Deviation:	**-21,7%**	**-9,1%**	**-14,0%**

After the successful installation of two systems at very well known furnaces, it had to be proofed that the system can operate at different furnaces as well and can yield comparable savings. So it was a great success to get such results also at two arc furnaces in Belarus, which are different from the mechanics of the furnaces above. They are characterized in the columns 3 and 5 of table I.

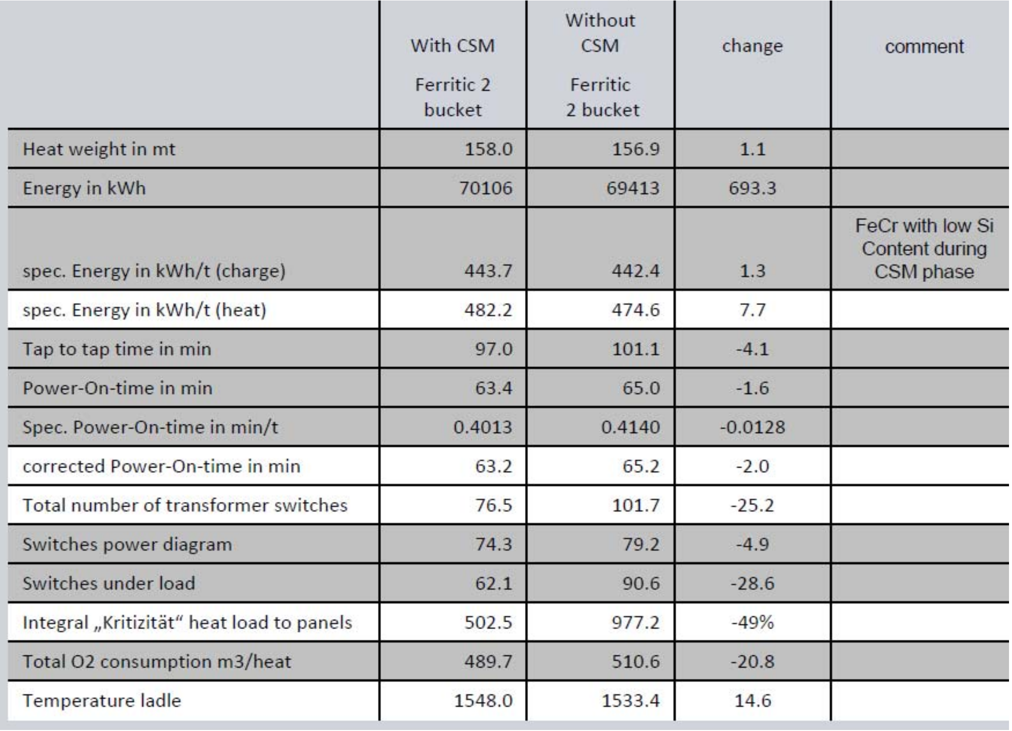
Summarizing, it is shown that the main benefit of applying the SonArc FSM system results in a remarkably high reduction of carbon injection in the range of 25 %. This is due to the directed and demand oriented input of the blow carbon and ensures that only the needed amount is used. The reduction in specific electric energy consumption is about 2 %.

3.2 Results of Sonarc CSM Operation

The piloting phase of SonArc CSM proved sustainable benefits. The early detection of a loss of panel shielding and the fast reaction by redistributing the radiation power resulted in a high reduction of the general heat load of the furnace walls. As displayed in Table 3, the so called “integral heat transmission criticity”, which is the measured quantity, is reduced by 33 % - 49 %. This forward-looking operation mode also yielded in a pronounced reduction of the transformer tap switching operations of about 16 to 25 %. Especially the transformer tap changes under load, which create the most wear, are reduced by 21 to 29 tap changes, respectively 22 to 32 %. Hence the transformers tap changer maintenance cycles can be extended, productivity is enhanced and conversion costs are reduced.

A significant reduction in the power-on time could be achieved as well, as a result of the forward-looking and smoother operation mode. Table 3 shows that the power-on time decreased by 2 respectively 3 %.

Table 3: Results of SonArc CSM for 2 bucket ferritic grades



	With CSM Ferritic 2 bucket	Without CSM Ferritic 2 bucket	change	comment
Heat weight in mt	158.0	156.9	1.1	
Energy in kWh	70106	69413	693.3	
spec. Energy in kWh/t (charge)	443.7	442.4	1.3	FeCr with low Si Content during CSM phase
spec. Energy in kWh/t (heat)	482.2	474.6	7.7	
Tap to tap time in min	97.0	101.1	-4.1	
Power-On-time in min	63.4	65.0	-1.6	
Spec. Power-On-time in min/t	0.4013	0.4140	-0.0128	
corrected Power-On-time in min	63.2	65.2	-2.0	
Total number of transformer switches	76.5	101.7	-25.2	
Switches power diagram	74.3	79.2	-4.9	
Switches under load	62.1	90.6	-28.6	
Integral „Kritizität“ heat load to panels	502.5	977.2	-49%	
Total O2 consumption m3/heat	489.7	510.6	-20.8	
Temperature ladle	1548.0	1533.4	14.6	

The operational data exhibit that the energy consumption is more or less on the same level or even a bit higher. The reason for this phenomena is the simultaneously change in ferro chromium quality during the commissioning of the SonArc CSM. The silicon content during operation with the CSM was much lower then before, explaining the slight increase in the specific energy consumption. Further on tapping temperature increased by 15 to 20 °C, which comes ahead with higher energy demand. More detailed operational data can be found in the literature.(9)

In general, the utilization of the CSM leads to a smoother and forward-looking operation yielding in a significantly reduced heat load to the panels and a large reduction of transformer tap changes. Further on a slight decrease in power-on time can be realized. All three savings exhibit the enormous potential of the CSM. The expected reduction in electric energy consumption due to the early detection of a loss of panel shielding and the according radiation redistribution has not been observed yet and might be obscured by other effects.

4 CONCLUSIONS

The achieved results of operating the SonArc FSM and CSM system at different types of AC electric arc furnaces are outstanding. This new product family opens the way for holistic furnace automation. The great potential for further development is much higher then assumed before. New modules are underway to get part of the SonArc family, like the ”next bucket charging signal”, a signal that indicates the optimal time for charging the next bucket, or the “detailed optimization of scrap melt down” by additionally detecting scrap size and scrap type and as well other topics.

Utilizing these further condition based modules instead of fixed schemes, additional potential for savings can be raised.

Acknowledgements

We would like to thank Lech-Stahlwerke GmbH, BMZ - Byelorussian Steel Works and Outokumpu Nirosta GmbH for their outstanding support during commissioning the SonArc CSM/FSM system. We also thank Mr. Wolfgang Wichert and Mrs. Monika Boh, both former melt shop managers at Lech-Stahlwerke GmbH. Special thanks go to Mr. Jürgen Höhl and Dr. Helge Mees for their encouragement and support during installation at Outokumpu Nirosta GmbH.

REFERENCES

1 SELLAN, R.; FABBRO, M.: The 300-ton 'Jumbo-size' FastArc EAF at MMK Iskenderun New Danieli Minimill Complex (Turkey). *Proceedings Conference on Innovation in EAF and Steelmaking Processes*, AIM, Milan, Italy, May 2009

2 BOWMAN, B.; KRÜGER, K.: Arc Furnace Physics. *Verlag Stahleisen*, Düsseldorf, Germany, 2009

3 SCHLIEPHAKE, H.; TIMM, K.; BANDUSCH, L.: Computer controlled optimization of the productivity of ISPAT-Hamburger Stahlwerke's AC-UHP-EAF. *Proceedings 5th European Electric Steel Congress*, Paris, France 1995

4 KNOOP, M.; LICHTERBECK, R.; KÖHLE, S.; Siig, J.: Steuerung des Einschmelzens im Drehstrom-Lichtbogenofen zum Schutz der Wandkühlelemente. *Stahl u. Eisen* 117 (1997), no. 2, pp. 91-96

5 HOMEYER, K.-O.: Automatisierung der Kohlezugabe zur Schaumschlackenbildung im Lichtbogenofen. *Fortschr.-Ber. VDI Reihe 8 Nr. 862. VDI Verlag*, Düsseldorf, Germany, 2001

6 WICHERT, W.; MATSCHULLAT, T.; RIEGER, D.: Foaming slag in more dimensions – A new detection method with carbon control. *Proceedings AISTech May 2007,* Indianapolis, USA

7 DITTMER, B.; KRÜGER, K.; RIEGER, D.; MATSCHULLAT, T.; DÖBBELER, A.: Asymmetrical power control of AC EAFs by structure-borne sound evaluation. *Proceedings AISTech May 2010*, Pittsburgh, USA (Also published in: *Iron and Steel Technology*, Feb. 2011, pp. 49-55)

8 DITTMER, B.; KRÜGER, K.: Modelltheoretische Untersuchungen zur thermischen Strahlungsleistung in Lichtbogenöfen. *elektrowärme international*, Vol. 67, No. 4, December 2009, pp. 274-278

9 MATSCHULLAT, T.; RIEGER, D.; DITTMER, B.; KRÜGER, K.; DÖBBELER, A.; MEES, H.: Results of Foaming Slag and Scrap Melt Down Control SIMELT CSM/FSM Based on Structure-Borne Sound in Electric Arc Furnace Operation. *Proceedings AISTech May 2012*, Atlanta, USA