ELECTRIC ARC ON A COKE BED IN A SUBMERGED ARC FURNACE

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ABSTRACT

This paper describes measurements of current and voltage done on submerged arc furnaces. The aim is to focus on and attempt to separate from one another the electric arc current and the current bypassing the arc through the charge. Toward this goal two measurement campaigns on AC-arcs burning on coke beds are accounted for. The first was done on a 150 kVA pilot furnace at SINTEF in Trondheim Norway, and the second one was done on a 48 MVA industrial furnace run by Icelandic Alloys in Iceland. The measurements were compared to simulations employing an advanced MFD arc model. The main results are that a coke bed does not necessarily behave as a linear conductor. However the warmer chemically transformed part of an operating Si-metal or FeSi furnace probably exhibits linear behaviour and passes a considerable fraction of the phase current, perhaps on some operating conditions, as much as 50%.

1. INTRODUCTION

Two sets of measurements are accounted for in this paper. The first measurement campaign was done on a 48 MVA submerged arc ferrosilicon furnace at Icelandic Alloys in Iceland, during the start-up period following a relining of the furnace. Current and voltage waveforms were measured while the furnace was run on a coke bed at reduced power. The MFD (Magneto-Fluid-Dynamic) AC arc simulations for Si and FeSi furnaces previously reported by two of the authors of this paper, have been compared to measurements, but comparison is somewhat complicated by the uncertainty involved in estimating the fraction of the phase current bypassing the arc through the charge. The main argument for doing measurements during the start-up period is that the electrode is slightly dipped into the coke bed and lifting the electrode just a few cm. should ensure that no current bypasses the arc through direct contact with the bed. The main problem when comparing modelling results with measurements is the increased uncertainty in determining the gas composition in the arc region, which is open to infiltration of air.

The second measurement campaign was done on a SINTEF pilot furnace in Trondheim, Norway. The measurements were carried out while starting up the furnace on a coke bed, the electrode submerged in coke. In this case, a measure of charge current bypassing the arc is present, and could be estimated with some degree of accuracy. As Si-metal was produced, the current and voltage waveforms were monitored and evaluated. At the end of the campaign, after a period of silicon-production, measurements were made during melting down in the furnace, so that there was hardly any charge conduction. These measurements were compared with simulations.

2. PILOT FURNACE MEASUREMENTS

SINTEF Process Metallurgy conducted a smelting experiment in order to evaluate the reactivity of a selection of carbon materials. Silicon metal was produced in a 150 kVA single phase pilot furnace. During this experiment**,** current and voltage waveforms were measured for comparison with simulation results obtained from the MFD model. At the end of the experiment, the furnace was run without adding raw materials and pure electric arc conduction was obtained.

The electrode current in the pilot furnace was measured with a high frequency-response Hall effect measuring device. The voltage was measured between the connection at the top of the electrode and the bottom contact of the furnace. The current and voltage waveforms were recorded using a digital oscilloscope.

The experiment was started by heating up the pilot furnace by short-circuiting the electrode against a coke bed. Table 1 lists RMS current and voltage along with the contents of harmonics including a DC component during two AC-periods separated by several minutes. In between, coke was added to the bed. The current and voltage waveforms for the cases listed in the table are displayed in Figure 1. During this period, voltage waveforms were almost sinusoidal, but the current displayed substantial contents of harmonics. The voltage is sinusoidal as the transformer voltage is practically imposed on the arc because of the relatively small reactance of the system. It is seen that after adding coke to the bed the current becomes more sinusoidal, but still shows the same kind of behaviour with the resistivity increasing with current although the phase resistance is lower as the contact area between coke bed and electrode is increased. The high level of harmonics in the current, and the associated deviation from sinusoidal current waveform as seen in Figure 1, caused speculation as furnace charge in general and carbon materials in particular have been considered to display linear electrical behaviour, as opposed to the arc. It is, however, well known that detoriated metal-to-metal contacts generate harmonics, and in fact measuring harmonics is a method to monitor contacts [1].

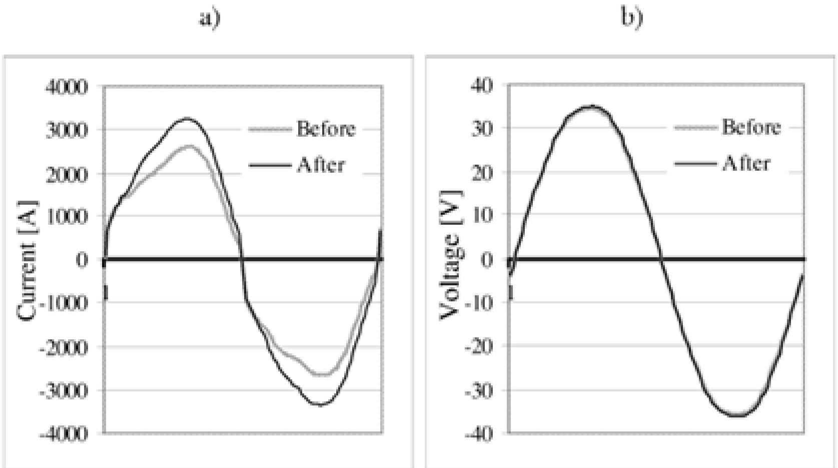

Figure 1: Current a) and voltage b) waveforms as a function of time during the heating-up of the furnace, when the electrode is in direct contact with a coke bed. The figures compare the waveforms before and after the addition of coke to the bed. As the power source is 50Hz AC, the span of the timescale is up to 20 ms

Table 1: Typical RMS current and voltage levels during the start-up period of the pilot furnace. The values in the table pertain to the curves in Figure 1

	Before addition of coke		*After addition of coke*	
	Current [kA]	*Voltage [V]*	*Current [kA]*	*Voltage [V]*
RMS-value	1.9	25.9	2.4	25.3
%OH	14.5	2.4	11.1	2.0
%DC	1.6	1.1	1.7	1.1

The current in a bed of carbon particles is conducted through a large number of particle-to-particle contact points as seen in Figure 2. A plausible explanation for the nonlinear behaviour is that the current that flows between the carbon pieces contracts due to the small contact area. The result is a strong oscillating ohmic heat source that causes high local temperatures. For some qualities of carbon materials, the electrical conductivity decreases with increasing temperature, meaning that a high temperature gives a high resistivity.

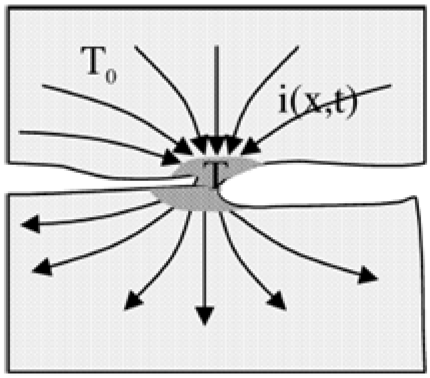

Figure 2: Contact points between particles

Considering the heat capacity per unit volume ρc_p and the thermal conductivity k of carbon materials and the small size of the contact area, the thermal time constant $\rho c_p l^2/k$ is less than the time scale of 50 Hz [2]. This implies that the contact temperature could oscillate in pace with the 50 Hz current. That would lead to a current dependent charge resistivity, which implies higher resistivity at higher currents and lower resistivity at lower currents. This is indeed consistent with the observation of a current that rises fast in the beginning of the half-period, but then flattens out as the voltage increases. When the furnace is operated with a coke bed current transport is by solid conduction through the particles and by particle-to-particle contacts [3] although invisible short arcs or sparks cannot be excluded.

2.1 Normal charge for Si production

After the heating-up period, the coke bed was replaced by a normal *charge for Silicon production*. After the furnace had been running for a while and the operation was quite stable, the current contained considerable amount of harmonics. The current waveform was characterized by a fast rise in the beginning of the half-period followed by a slower increase and then again a fast increase when the current again rises and reaches its maximum. It subsequently decreases and crosses zero. This is shown in Figure 4 and does not agree well with an arc burning in parallel with a *linear* charge, as depicted in Figure 3. The sudden rise in current after passing through zero cannot be attributed to the arc as no such behaviour was registered at the end of the experiment when the charge was melted down and pure arc conduction was obtained. This is shown in Figure 6. It is therefore logical to assume that the phase current can be divided into two. First, there is a charge current going

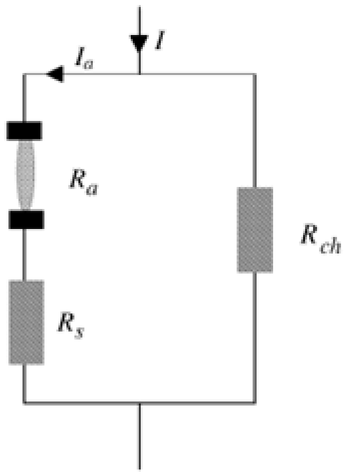

Figure 3: Schematic drawing of a configuration with a conducting charge resistance in parallel to the arc

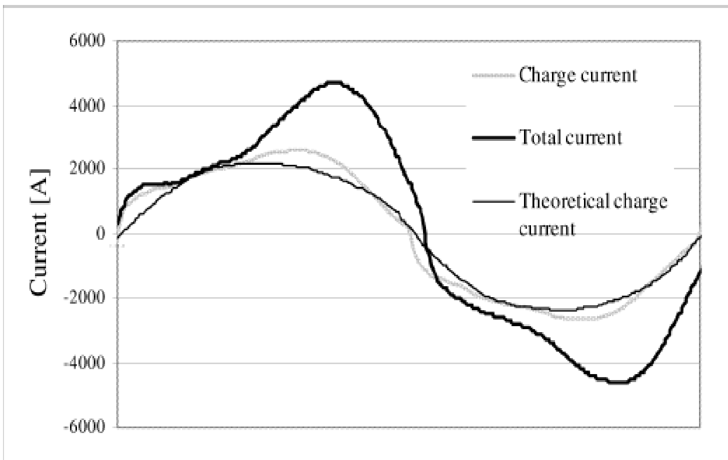

Figure 4: Current waveform during the early part of Si-metal production in the pilot furnace. The time span is one AC period = 20 ms. For comparison, the maximum linear charge current in parallel to the arc is drawn into the figure. This current is proportional to the phase voltage. In addition a similar parallel current proportional to the coke bed current as shown in Figure 1 is drawn into the figure

through the charge which shows non-linear behaviour similar to that of the coke bed in Figure 4. Second, there is a highly non-linear arc current. The arc current is small in the beginning of each half period, as the plasma cools immediately below 7000K when there is no current and the resistance is much higher than that after the arc has been ignited and the current in the arc heats it to ~20000K. Therefore, the arc current is low in the beginning of the half-period, grows as the plasma gets hotter and reaches a maximum shortly after a quarter of the period and falls more linearly with voltage in the second quarter of the period.

After some hours of Si-metal production, the current waveforms had taken on a form shown in Figure 5. The current rises almost linearly with voltage until the arc starts conducting well and the current rises to a maximum before decreasing again. This indicates that when the chemical reactions in the furnace are at steady state, the raw materials in the lower and warmer regions of the burden contain sintered and well conducting SiC. Here, the charge appears to be a good linear conductor as opposed to the situation just after fresh charge materials were added to the furnace. An upper limit for a parallel charge current is drawn in Figure 5, which is obtained by assuming no arc conduction just after the current crosses zero. This is a simplification,

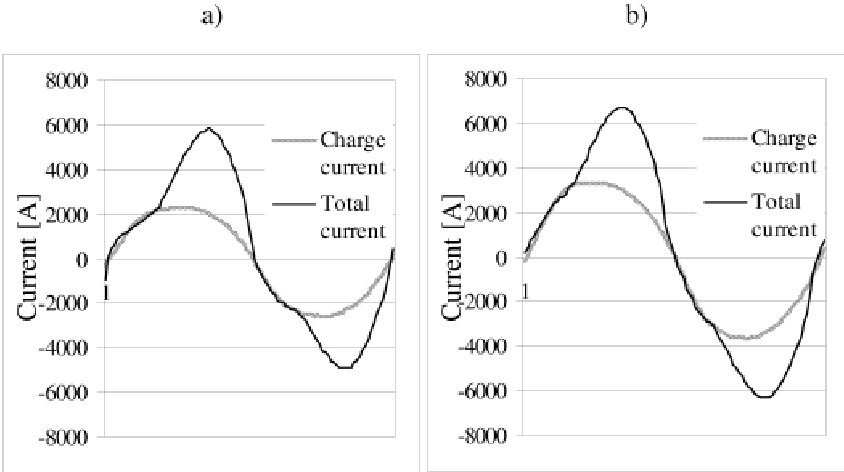

Figure 5: Current waveforms as a function of time for 20 ms at two different instances of time compared to charge current assumed to be proportional to the voltage waveforms. The upper limit of the charge current shown in these figures (53% for a) and 60% for b)), are obtained by assuming that there is no arc conduction close to zero current

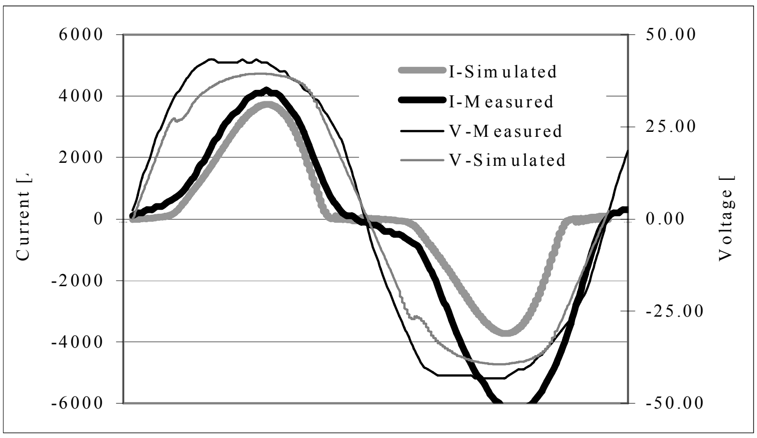

Figure 6: Current and voltage waveforms measured on the pilot furnace after the charge was melted, compared to MFD simulations for a 2 cm long arc. The time span is one AC period = 20 ms for a 50 Hz AC power source

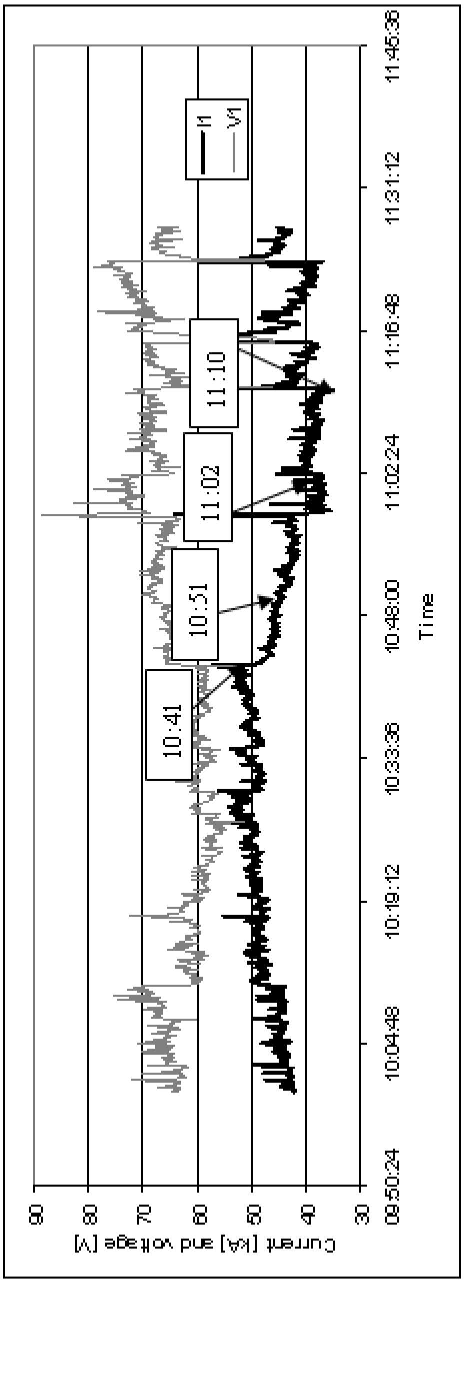

Figure 7: Development of current and voltage over time for phase 1 in the three-phase industrial furnace during furnace manipulation when electrode 1 was raised gradually above a coke bed. Marked on the figure are the instants of time forr snapshots of the current and voltage waveforms

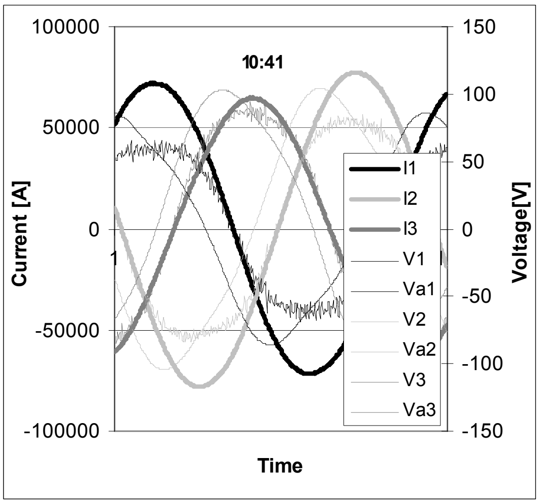

Figure 8: Snapshots of current and voltage waveforms at the start of the manual operating period. The time span is just over one AC period = 20 ms

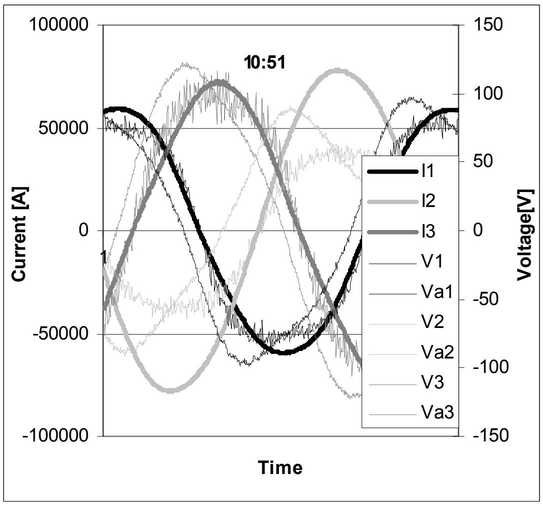

Figure 9: Electrode 1 has been raised, the current in phase 1 (black thick line) has decreased and voltage increased

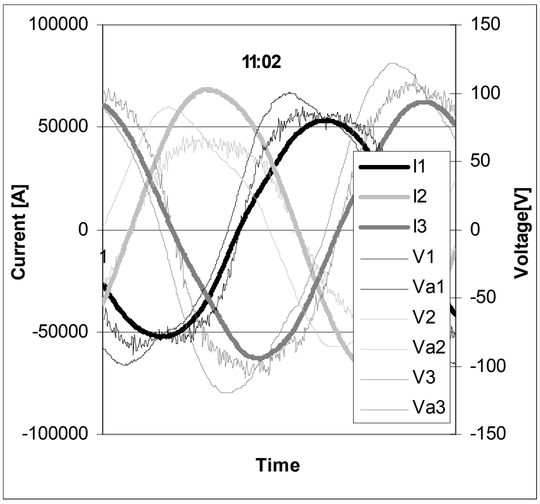

Figure 10: Electrode 1 has been raised again, the current has decreased further and the voltage increased correspondingly. The time span is one AC period = 20 ms

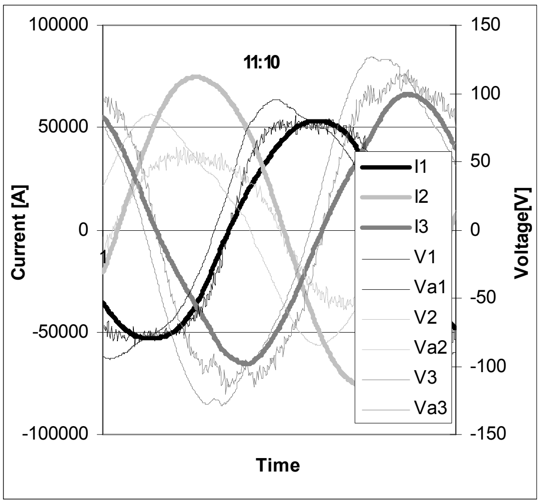

Figure 11: The same as Figure 10, after further raising of the electrode. The time span is one AC period = 20 ms

which is shown not to be valid for an industrial arc with 10x the current in the pilot furnace. In the industrial measurements also accounted for in this paper. Figure 6 shows that in the pilot furnace, there is some conductivity in the arc while passing through zero. However, Figure 6 indicates that the error involved in this assumption is less than 20%, so for the conditions in the Si-metal producing pilot furnace, we can confidently state that the charge current was in the region of 40-50%. Finally, the material in the furnace was melted down without further charging. Before shutting the furnace off, the current and voltage waveforms shown in Figure 6 were obtained. After shut-down the electrode could be lowered by 2 cm before landing on the conducting furnace bottom. The recorded waveforms were therefore compared with a MFD simulation of a 2 cm long arc, using a model based on that described in [4,5], the results being shown in the same figure. It is seen that in the positive half period, the difference between measurement and simulation is acceptable, but in the negative half period, the difference is considerable. This means that in the one-phase AC furnace there is a DC component that is not accounted for in the mathematical model. This may be due to either geometry or material difference in the anode / cathode surfaces between half periods giving rise to a rectifying effect.

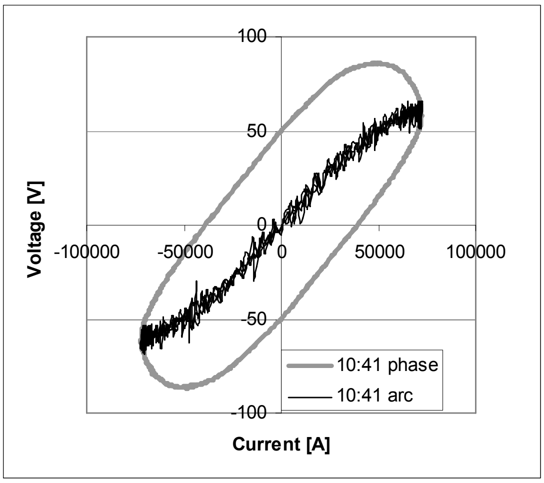

Figure 12: Lissajous figure from the first snapshot of electrode 1. The oval figure is the measured current as a function of measured voltage, while the black curve in the centre is the corrected arc voltage Va as a function of current

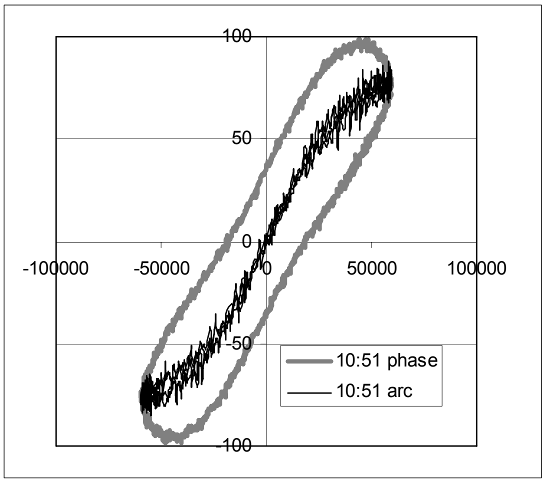

Figure 13: Same as Figure 12, 2nd snapshot

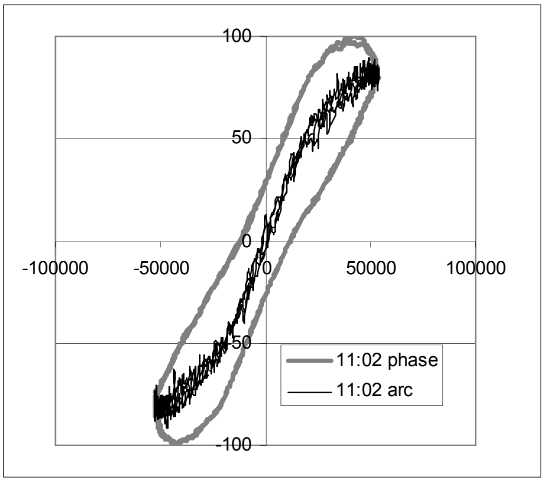

Figure 14: Same as Figures 12-13: 3rd snapshot

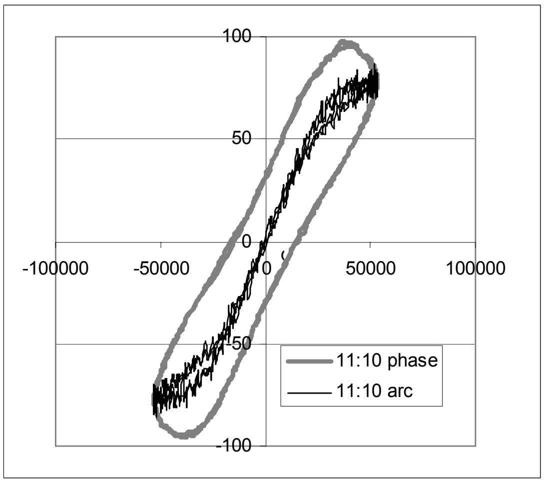

Figure 15: Same as Figures 12-14: 4th snapshot

3. INDUSTRIAL FURNACE MEASUREMENTS

3.1 Start-up of an industrial furnace using coke bed

The measurements were performed on an industrial furnace during *start-up on a coke bed*. During the start-up period a coke bed is surrounding the electrode tip, and the electrode tip is only about ~10 cm deep in the bed. When the electrode is elevated there will probably be very little material in contact with the electrode, so it is plausible that the charge resistance R_{ch} as defined in Figure 3 is very large and consequently the entire phase current goes through the arc. At the time of measurements, the load on the furnace was only about 15 MW. This gave the operators the freedom to indulge in the authors´ wishes for electrode manipulation.

Figure 7 shows the current and voltage development over a period when electrode 1 was gradually raised by 8 cm without changing the transformer settings. This caused a decrease in phase current from 50 kA to 34 kA. Four snapshots showing current and voltage waveforms are shown from this period, and the time at which the snapshots were taken is marked on Figure 7.

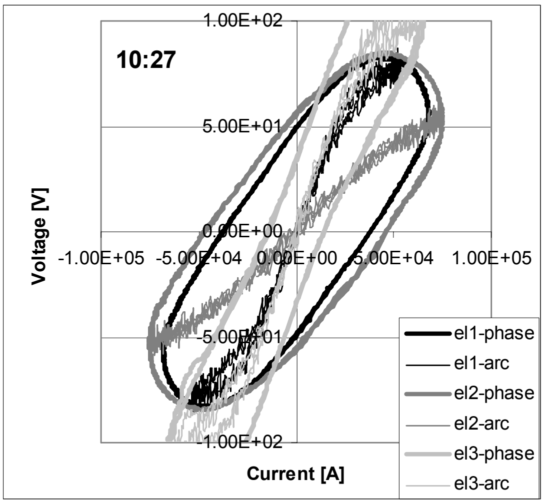

Figure 16: Lissajous curves for all three phases measured at random

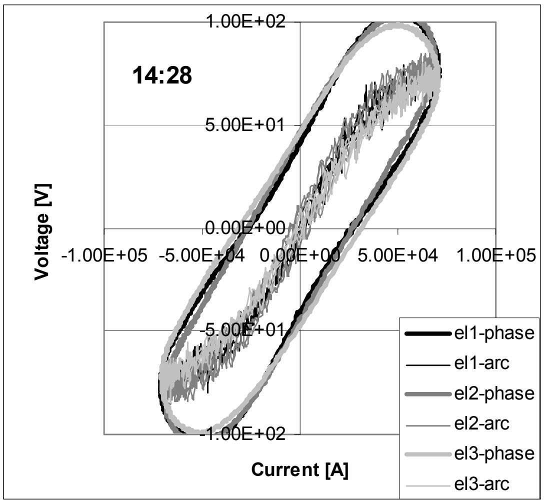

Figure 17: Lissajous curves for all three phases measured at random

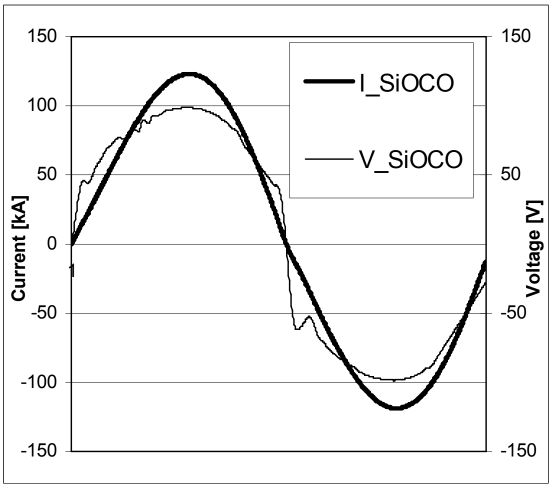

Figure 18: Current and voltage waveforms obtained from MFD simulations with SiO-CO

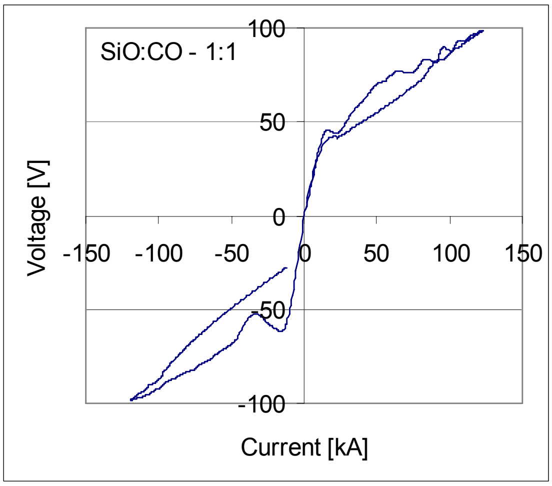

Figure 19: Lissajous figure for a simulated 5 cm long arc in SiO-CO atmosphere

Table 2: Arc resistance at current zero derived from random snapshot measurements on an arc burning on a coke bed in a FeSi furnace

$R_a + R_s$ [mΩ]– when passing zero			
	Phase 1	*Phase 2*	*Phase 3*
Snapshot 09:17	0.9	2.0	2.5
Snapshot 10:00	1.9	1.3	2.6
Snapshot 10:27	2.7	0.9	2.7
Snapshot 12:25	1.9	1.0	1.9
Snapshot 14:03	1.7	1.7	1.7
Snapshot 14:28	1.7	1.7	1.7

The current waveform is derived from current measurements on the primary side of the transformers, while the voltage is measured using a Bøckmann setup. The snapshots plotted in Figures 8-11, show current and voltage waveforms for each of the three phases, and a corrected arc voltage Va obtained by subtracting the voltage drop due to the inductance from the measured voltage. In this correction, it has not been attempted to separate the voltage drop over a resistance R_s in series with the arc, and such voltage drop is lumped into Va.

Plotting voltage as a function of current gives so-called Lissajous figures. Figures 12-15 show such figures for phase 1 at these four instances in time, using both the measured Bøckmann voltage and the estimated arc voltage Va. In general the figures show that when the electrode was raised, the phase resistance increased, the phase current decreased and the slope of the curves when passing through zero voltage increased.

This slope of the Lissajous curve gives the phase resistance at zero current. Several current – voltage wave-form snapshots were taken at random in an attempt to separate the voltage drop over the arc, and the voltage drop in the coke bed and furnace bottom. It was observed that the resistance when passing through zero varied between ~0.9 and 2.7 mΩ. When the resistance was at a minimum, the Lissajous figure was a straight line, exhibiting linear electric behaviour as shown for phase 2 in Figure 16. In those cases, the current probably was passing directly from the electrode through the coke bed without forming an electric arc. The non-linear coke bed behaviour observed in the pilot furnace was not found here, but there was some scrap iron present in the bed as well as iron from the electrode mantel. Linear behaviour was therefore expected. In other cases, the curvature and hysteresis of the Lissajous figure indicated the presence of an arc. From these estimates, given in Table 2, we assume that the resistance of the coke bed and furnace bottom is approximately 1mΩ, and the rest of the phase voltage drop is due to the arc.

Similar resistance measurements during furnace manipulation were obtained and are shown in Table 3 along with the result of a MFD arc simulation discussed in the next section. Before electrode 1 was elevated, the phase resistance was 1.2 mΩ, so there was relatively little arcing, which is supported by the relatively linear Lissajous diagram in Figure 12, with just a hint of arcing. This means that when the electrode had been elevated by 4 cm, the arc was probably not longer than 4cm, and further elevation of the electrode meant that the arc had moved to the edge of the electrode burning to the edge of the hole in the coke bed, and it probably was only moderately longer when the electrode had been moved by 8cm. Raising the electrode further almost extinguished the arc.

3.2 Numerical simulation

The authors of this paper have previously reported simulation models for AC electric arcs, where the MFD (Magneto- Fluid-Dynamic) equations are solved for the geometric and electric parameters of the furnace[4]. In the case of an arc burning on a coke bed, the largest uncertainty involved in these simulations is the plasma gas composition. The previously reported simulations pertain to electric arcs in Si-metal or FeSi furnaces, where the plasma gas in the crater is composed of SiO and CO. The simulations were thus made using physical transport coefficients and radiation data for a 1:1 and 2:1 SiO-CO mixtures [4]. One of the results was that the calculated temperature field and current and voltage waveforms were not very sensitive to the SiO:CO ratio. Arcs have also been simulated with gas data including traces of Al and Ca [4,5]. The plasma composition above the coke bed is probably much richer in carbon species, and hardly includes any Si. As the normal chemical reactions involving the condensed phases SiO_2(l), Si(l) and SiC(s) and the gaseous phase (SiO + CO) have not yet started, there must also be *nitrogen* species from infiltrated air present. In addition, iron species are probably also present in the arc region above the coke bed. Iron tends to increase the electric conductivity of the arc plasma. However, as the required physical data for nitrogen and iron containing plasmas were not available, the present arc simulations are based on SiO:CO = 1:1 as we have used in our previous simulations of arcs in the Si-metal furnace. The results should therefore be interpreted bearing in mind that the arc plasma composition is not correct. Where there is a considerable charge current, bypassing the arc its effect on the current voltage waveform should be most pronounced as the current crosses zero and the arc resistance R_a is the largest as compared to the assumed constant charge resistance R_{ch}. Therefore, it is interesting to examine the Lissajous figures for the simulated waveforms and compare them with the measured waveforms of an arc burning on a coke bed in the FeSi furnace. The slope of the Lissajous curve after passing through zero for the simulated 5 cm SiO-CO arc is compared to that of the measured curves in Table 3. It is seen that the measured resistance (R_a + R_s) at zero current is comparable to the resistance of the simulated SiO-CO arc when the electrode has been raised by 6-8 cm above the coke bed. The arc extinguished shortly after this and the electrode was lowered in order to maintain the current.

Table 3: Arc resistance at current zero derived from the snapshot measurements on an arc burning on a coke bed in a FeSi furnace and from MFD arc simulations of a 5 cm long arc in SiO-CO atmosphere

	$R_a + R_s$ *[mΩ]– when passing zero*
Snapshot 10:41	1.2
Snapshot 10:51	2.1
Snapshot 11:02	2.8
Snapshot 11:10	3.5
5cm SiO-CO arc	3.0 (+R_s ~ 1 mΩ)

4. CONCLUSIONS

The paper describes measurements of current and voltage waveforms on a coke bed for two furnaces, a laboratory pilot furnace and an industrial FeSi furnace. These measurements are compared with MFD arc simulations and are interpreted in terms of current passing through an electric arc versus a fraction of the current bypassing the arc through the charge. Results from the pilot furnace indicate that a coke charge does not necessarily behave as a linear conductor, possibly due to heating up of contact points between the particles. When the coke bed had been replaced with raw materials for Si-metal production, the current and voltage waveforms were consistent with an arc in parallel to a non-linear charge resistance through which a moderate fraction of the current bypassed the arc. At later stages of the experiment when the furnace was producing silicon, the warm lower region of the burden in a running Si-metal or FeSi furnace acts as a linear resistance. This was particularly true for the crater walls that consisted of melted quartz and silicon metal and solid silicon carbide. There, the measured waveforms indicated that as much as 50% of the current in fact was bypassing the arc through the charge. In fact, the extreme assumption of no arc conduction when the current passed through zero gave an upper limit of up to 60% charge current. Deviation from this upper limit because of conduction in the arc at zero current, reduces this fraction by up to 20%. This meant that the fraction of the phase current that passes through the charge without going through an arc, still was in the interval of 40-50% in the case of the Si-metal producing pilot furnace.

Measurements were made on an industrial furnace on a coke bed, where it could be ascertained that there was no current bypassing the arc through the charge when the electrode was elevated. The resistance when the current is passing through zero is used to estimate the error involved in assuming that the total phase current passes through the charge around current zero. The phase resistance at current zero for an arc on a coke bed in the industrial furnace was estimated to be 1-3.5 mΩ, including electrode, coke-bed and furnace bottom resistance R_s of ~ 1 mΩ. Results from the industrial furnace indicate that arc modelling based on SiO-CO plasma data for a 5 cm long arc is in reasonable agreement with measurements for an arc of similar length. Considering the uncertainty in the gas composition, the accordance with measurements is acceptable for the resistance when the current passes through zero.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Runde , A. Gjelsvik , A. Rein.,"Method for Detecting Degraded Contacts in Gas Insulated Substations", 17th Int. Conf. Electrical Contacts, Nagaya Japan 1994, Proceedings pp 699-704

[2] G. A. Saevarsdottir, "*High current AC-Arcs in Silicon and Ferrosilicon Furnaces*", Ph.D thesis, IME-rapport 2002:36, NTNU

[3] P.A.Eidem, M.Tangstad, J.A.Bakken, "Measurements of material resistivities and contact resistance of metallurgical coke", this conference.

[4] G.A.Sævarsdottir, J.A.Bakken, V.G. Sevastyanenco, Liping Gu," High-Power AC Arcs in Metallurgical Furnaces", Journal of High Temp. Material Processes, Sep. 2001

[5] G.A.Sævarsdottir, J.A.Bakken, V.G. Sevastyanenko, Liping Gu, "Arc Simulation Model for Three-Phase Electro-Metallurgical Furnaces", INFACON 9, June2001, Quebec City, Canada. Proceedings pp.253-263.