

CIRCULATING CURRENTS IN THE DELTA CONNECTION, FEASIBILITY OF SKEW TAPPING IN THE OPERATION OF SUBMERGED-ARC FURNACES¹Gudrun Saevarsdottir, ¹Petre Manolescu, ²Thordur Magnússon, ¹Kristinn Sigurjónsson¹ School of science and engineering, Reykjavik University, Iceland, e-mail: gudrunsa@ru.is² ELKEM Iceland**ABSTRACT**

Ferrosilicon is produced in submerged electric arc furnaces. Good process control requires an optimal heat distribution in the furnace. This is controlled by managing the power dissipation in the furnace as well as the current appropriately for the given raw material mix. The current in the furnace can be adjusted by raising/lowering the electrodes which in turn adjusts the impedance. For a three phase AC furnace the current in each electrode should be equal. In rare cases of extreme asymmetry in operation, electrodes are in the top or bottom position, there is no room for adjusting the impedance and the furnace goes off balance. In this paper the feasibility of separately adjusting the voltage provided by three single-phase tap transformers in order to compensate for the furnace unbalance. The transformers are connected in Δ and normally operate with the same tap position. In order to adjust the voltage for one electrode the tap number must be lowered / raised on two transformers. During this skew tapping circulating currents arise in the Δ connected circuit, at a risk of overloading the transformers. An estimate of the impedance within the transformers and the electrical circuit is done for a 75MVA submerged arc furnace. The goal is to find the size of the circular currents in order to evaluate their influence.

KEYWORDS: *Submerged arc furnace, control, furnace operation, skew tapping, asymmetric operation.*

1. INTRODUCTION

Two of the main control parameters in the Silicon or FerroSilicon production process are the electric power load and the current passing through the furnace. Metallurgists and furnace operators strive to maintain balanced and symmetric conditions in the furnace, as that is a precondition for good Silicon yield and efficient power usage in the furnace. Under rare circumstances the furnace will be very asymmetric so that moving the electrodes within the holders' range will not produce impedance consistent with a phase current within acceptable limits. Stepping down the voltage over the whole furnace will result in reduced production, and therefore it may be tempting to adjust the furnace transformers differently in order to get a symmetric load in the furnace under asymmetric metallurgical conditions. This paper provides an analysis of this option and the precautions that must be made along with possible consequences for the furnace equipment. A 75 MVA furnace at Elkem Iceland is used as a case in the calculations.

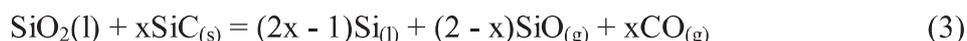
2. THE ELECTRIC FURNACE OPERATION**2.1. The chemical process and furnace operation**

The production of ferrosilicon takes place in submerged-arc furnaces of up to 50 MW, most frequently running on three phase AC current. The raw materials consist mainly of quartz or quartzite (SiO_2) and carbon materials such as coke, coal, char or wood chips. The production of

silicon is achieved by carbothermic reduction of silicon oxide. Ideally the overall reaction can be written (Schei et.al. 1998):



In reality the reaction is more complex and is split into a number of sub-processes, that can be simplified and presented at two process steps that occur at different temperatures:



The reaction given by equation 2 takes place at above 1512°C. The parameter x in equation 3 depends on the temperature of the reaction zone. In order to obtain an acceptable Si recovery the temperature must be well above 1800 °C, preferably close to 2000°C (Schei et.al. 1998). In a three phase AC furnace as treated in this paper, three electrodes protrude into the furnace and supply the current which partially passes through the charge and partially forms the electric arc which dissipates heat in a concentrated volume which is necessary to reach sufficient temperature. One of the most important concepts in FeSi process operation is the silicon recovery.

Silicon recovery

The silicon recovery is a key concept in one of the most important parameters in Si and FeSi production. It is defined in the following manner:

$$\text{Si recovery} = \frac{\text{Si in metal}}{\text{Si in rawmaterials}} \quad (4)$$

There are a number of factors that influence the silicon recovery. The most important are:

- Reactivity of carbon materials
- Fix – C
- Tapping of the furnace
- Stoking of the furnace
- Segregation and particle size of raw materials
- Temperature distribution in the furnace
- Stable symmetric operation in the furnace

The products of the process are: high silicon alloy, condensed silica fume and recoverable heat. There are a number of mechanisms used to control the submerged arc furnace for optimal silicon yield. Selection and feeding of raw materials along with stoking and mixing of the furnace charge are important to control the chemistry of the furnace. Regular and successful tapping is necessary as untapped metal may react back to SiO gas and contribute to fume production. Electric operation of the furnace controls the load distribution for optimal heat distribution for the given furnace design, but preventing equipment overload. The furnace is controlled for power dissipation by selecting the transformer tap positions, and the current in each electrode is controlled by moving the electrode up and down in the furnace and thereby altering the resistance in the respective phases. Changes in the electrical conditions in the charge are compensated by moving the electrodes in order to maintain a target resistance and current through the electrode.

The current distribution in the furnace determines the modes of heat dissipation and therefore temperatures, thermodynamic conditions and consequently the stoichiometry and rates for the process reactions. For optimal silicon recovery is important that the balance between the two thermal zones is maintained (Sævarsdottir 2010, Schei et.al. 1998). Ideally the conditions in the

three phase industrial furnace are symmetrical. Even distribution of raw materials as well as symmetric level of maturity in the furnace charge should ensure that conditions for electric current conduction in all three phases are similar, thus providing similar phase resistance and phase reactance for all three electrodes. Deviation from such conditions have however been known to occur in furnace operation for a range of reasons. On rare occasions the deviation from symmetry can be so severe that raising the electrode holder position to its highest level will not increase the resistance sufficiently to maintain the current within the design limits. In this case the transformer tap positions have to be changed and less power delivered to prevent damage to the electric equipment. Changes in furnace conditions may cause the phase resistance to rise so much for one phase that even though the electrode is lowered to its lowest position, the power released in this phase is significantly lower than in the other phases. This reduces the overall performance and production for the furnace and a colder region can cause tapping problems. These two types of operational situation are categorized as severe furnace asymmetry and strategies for reacting to this type of problems are the topic for this paper. Skew tapping of the furnace transformers are pursued as an option and the consequences discussed. This requires a thorough discussion of the electric configuration of the furnace.

3. ELECTRIC CONFIGURATION

The electric power is supplied to ELKEM Iceland by 220 kV lines. The voltage is stepped down to 33 kV in a three phase transformer. At this voltage step capacitor banks are applied in order to produce capacitive reactive power for phase correction, as the electric furnace is a heavy inductive load in the system. In this way the powerfactor as seen from the distribution utility is close to unity. Also phase currents for the furnace are accurately measured at this voltage step using a specialized arrangement. The electric current is transformed to the lower furnace voltage though a second set of transformers. For furnace 3 at ELKEM Iceland, which is the case for this study, the second transformer step is by three one phase 25 MVA transformers.

3.1. Furnace transformers

The furnace runs on 300 V voltage supplied by three single phase transformers, one for each phase. On the primary side they can be connected in Y or Δ by means of a switch. On the secondary side they are connected to the electrodes in Δ by a Knapsack-connection, as shown in figure 1 (Valderhaug 1997, Sævarsdottir 2002).

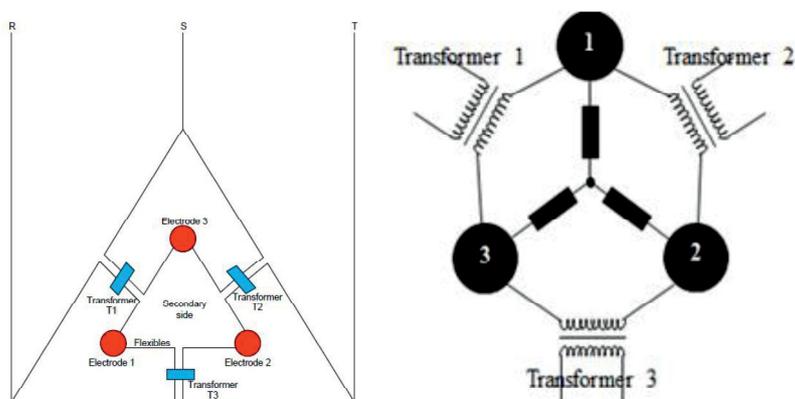


Figure 1: Diagram showing the electrical arrangement for a three-phase furnace (left) and the Knapsack connection (right)

This type of connection minimizes reactance in the secondary bus system. Conductors are aligned in such a way that conductor carrying current in opposite direction are aligned next to one another minimizing the area for magnetic flux and thereby the induction.

3.2. Voltage drop in Δ due to skew tapping

The transformers are of a load tap changer type, which means that they permit tap changing and thus voltage regulation while the transformer is in operation. The tap changing is done on the high voltage side. Since the currents are lower the tap changer contacts, leads etc. can be smaller. As the high voltage winding is wound outside the low voltage winding it is easier to get the tapping connections out to the tap changer. The three single-phase transformers are connected in Y while the furnace is started up and then changed to Δ in order to deliver higher current to the electrodes. Normally the transformers are simultaneously switched to the same tap-number. The voltages obtained from each tap number are included in the technical specifications for the transformers and need not be revealed in this paper. Since single-phase transformers are used for each phase individually it also means that the transformers can be manipulated individually. However in a Δ connection there is no common.

Zero point. If two transformers are on a tap number lower or higher than the third one and the phase shift between the three phases as delivered by the transformers is 120° degrees, a voltage difference will appear inducing circular currents in the system. This is schematically illustrated in figure 2.

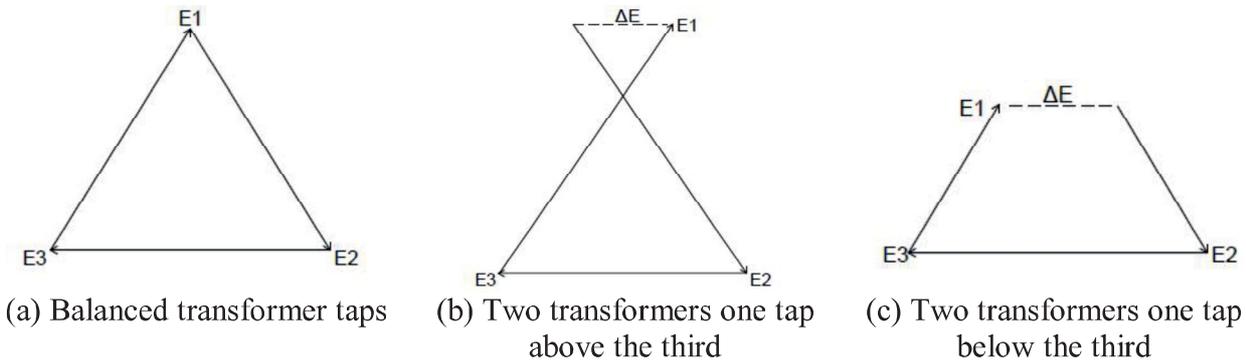


Figure 2: Complex number representation of the voltages delivered by transformer in the delta connection illustrating the voltage difference occurring in the delta connection on the secondary side. In case a all transformers have the same tap positions, but in cases b and c the tap positions for one transformer is different from that of the others

The voltage difference is spread throughout the system. A simplified graphical representation is shown in figure 2, where E1, E2, E3 are the voltages given by the furnace transformers and ΔE is the voltage difference that occurs when selecting different taps. During normal operation the transformers operate between taps 13 and 19. When all transformers are balanced and operating (for example) at tap number 15, then the voltage difference ΔE will be zero. From the transformers' data sheet the voltage on the secondary side at tap 15 is 285.7 V. There are 120° between phases so by assigning each voltage a phase the sum would be zero.

$$\Delta E = E1 + E2 + E3 = 285.7V\angle 0^\circ + 285.7V\angle 120^\circ + 285.7V\angle 240^\circ = 0$$

If two transformers are raised by one tap a voltage difference will appear

$$E = E1 + E2 + E3 = 285.7V\angle 0^\circ + 289.5V\angle 120^\circ + 289.5V\angle 240^\circ = 3.8V\angle 0^\circ$$

which is equal to the voltage difference between the two taps. The same happens when the two transformers are lowered by one tap

$$E = E1 + E2 + E3 = 285.7V\angle 0^\circ + 283.3V\angle 120^\circ + 283.3V\angle 240^\circ = 2.4V\angle 0^\circ$$

The voltage difference between each is from 2.4 to 4 V. This voltage drop distributed through the components in the Δ connection will give rise to circulating currents that will not affect the phase current. The size of the current depends on the impedance in the Δ connection. In order to estimate the magnitude of the circular currents an assessment of the impedance of the system must be made.

3.3. Transformer inner impedance

From the data sheet (ABB 1998) the following information can be obtained:

- Impedance at 25 MVA and at position 22:
 - T1 = 2:12%
 - T2 = 2:12%
 - T3 = 2:09%
- Impedance at 25 MVA and at position 34:
 - T1 = 1:98%
 - T2 = 1:98%
 - T3 = 1:96%

The transformers have 34 tap positions, further information from the data sheet do not need to be revealed. By using tap number 22 as reference the phase-null voltage will be $E_{LN}=307$ V:

At tap number 22 and 25 MVA the percentage impedance will be 2.12% for transformers A and B and 2.09% for transformer C. This means that the “per unit” impedance, Z_{pu} , for transformers A and B will be 0.0212 and for transformer C will be 0.0209. The base impedance is given by:

$$Z_B = \frac{E_{LN}^2}{S} = \frac{307^2}{25MVA} = 3.78m\Omega \quad (5)$$

The inner impedance of the transformers (Z_i) can be calculated according to $Z_{pu} = Z_i / Z_B$

The per unit impedance of transformers A and B is the same and so will the inner impedance

$$Z_{iA,B} = Z_{puA,B} * Z_B = 0.0212 * 3.78 * 10^{-3} \Omega = 80\mu\Omega \quad (6)$$

For transformer C the per unit impedance is a bit lower which affects the total inner impedance:

$$Z_{iC} = Z_{puC} * Z_B = 0.0209 * 3.78 * 10^{-3} \Omega = 79\mu\Omega \quad (7)$$

The impedances are given in the per unit system and so only the magnitude is obtained. However within the transformers the resistance is about five times smaller than the reactance (Wildi, 2006). The inner impedance of the transformers can thus be split up in resistance and reactance.

$$Z = \sqrt{(X^2 + R^2)} = \sqrt{(5R)^2 + R^2} \quad (8)$$

By substituting the result in equation 6 for Z in equation 8 results that the inner resistance of the transformers A and B is $R_{iA,B} = 15.7 \mu\Omega$, and $X_{iA,B} = 5 * R_{iA,B} = 78.4 \mu\Omega$.

Similarly the resistance and reactance within the transformer C is $R_{iC} = 15.4 \mu\Omega$ and $X_{iC} = 5 * R_{iC} = 77.4 \mu\Omega$. Thus obtained the impedance for the transformers A, B and C is:

$$Z_{i_{A,B}} = (15.7 + j78.4) \mu\Omega, \quad Z_{i_C} = (15.4 + j77.4) \mu\Omega \quad (9)$$

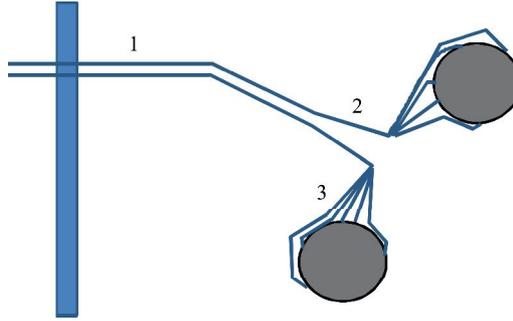


Figure 3: Simplified illustration of the Δ connection between electrodes and transformers

3.4. Bus impedance

The current flows from the transformers to the electrodes by means of busses and flexibles, all water cooled. In order to get a picture of the magnitude of the circulating current in the Δ impedance estimation is necessary. Figure 3 is a simplified illustration of the system modeled here. The resistance is calculated by splitting the lines from each transformer in 3 separate parts as indicated in figure 3. The bus lines are denoted by 1, flexibles by 2 and bus lines attached to the electrode contact clamps. The resistance is then calculated for each part and then summed up. The reactance is calculated in a similar fashion, by splitting the system up. Firstly the bus lines are treated as parallel plates and the inductance between them calculated accordingly. The flexibles have an increasing distance between them. Since only an estimation is needed they can also be treated as parallel lines while using the average of the distance between them. The secondary bus lines split up in order to distribute the current in an evenly fashion through the electrode. An easy approach at estimating the inductance in these lines is to calculate the magnetic flux within the area spanned by them.

Resistance

The electrical resistivity of copper is $\rho_{Cu} = 1.68 * 10^{-8} \Omega * m$ at $20^\circ C$. The temperature coefficient is $\alpha = 0.0039$. Since the temperature within the lines is of about $60^\circ C$ the electrical coefficient will change according to the equation $\Delta\rho = \alpha\Delta T * \rho_0$, where ρ_0 is the electrical resistivity of copper at 20 degrees Celsius. Thus we obtain an operating Copper conductivity of $\rho_{Cu}(60^\circ C) = \rho_0 + \Delta\rho = 1.94 * 10^{-8} \Omega * m$.

The first bus lines (A) before the flexibles are composed of 10 lines going out of the transformers and 10 lines going into the transformers. Their length is different for each transformer so the resistance has to be calculated for each of them separately. In order to simplify the calculations it is possible to treat each 10 lines as a single cable with 10 times the cross-sectional area.

The resistance can be calculated according to the equation $R = \rho_{Cu} * L/A$ where L is the length of the line and A is the circular area. Since the length of the first bus bars are different between transformers so will the resistance. Therefore the resistances will be denoted as R^i_1 where $i=1,2,3$ according to the transformer in question. The circular area of the copper tube is given by the difference between the outer and inner areas of the tube.

The combined resistances for all the busbars and flexes in the delta is calculated as:

$$R_{tot} = 2 * (R^1_1 + R_{flex} + R_3) + 2 * (R^2_1 + R_{flex} + R_3) + 2 * (R^3_1 + R_{flex} + R_3) = 47.6 \mu\Omega \quad (10)$$

Inductance

In order to find the inductance of the system it is easiest to use a similar approach as for the resistance. The arrangement of the lines gives the possibility for them to be treated as parallel plates, with each plate consisting of 10 lines. $L = \mu d/w$ where w is the width of the plates and d the distance between plates. The permeability of air is similar to the permeability of vacuum so $\mu = \mu_0$. This gives an inductance of $L_{prlength} = 5.98 * 10^{-8} H/m$ pr. unit length of this configuration. The length of this configuration is different for each transformer and is denoted by L^i_1 with $i=1,2$ or 3 .

$$L^1_1 = 2.19 * 10^{-7} \mu H, L^2_1 = 3.27 * 10^{-7} \mu H \text{ and } L^3_1 = 3.22 * 10^{-7} \mu H.$$

The same approach is used for the flexibles, but the distance between them is not constant. This is accounted for by dividing the length of the flexibles into sections and calculating average values. The resulting value is the same for all transformers and is equal to $L_{flex} = 4.03 * 10^{-7} H$. After the flexibles the lines split up so a different approach must be used to estimate the inductance. Their geometry is a bit more complicated in order to distribute the current evenly through the electrodes. One method to evaluate the reactance is by calculating the magnetic flux through the area spanned by the lines. Because of the arrangement of the electrodes and busbars the area is approximated to a triangle with the sides equal to twice the average length of the lines. The flux through the triangle was approximated to (Ulabý, 2007):

$$\Phi = L_3 * I = \int B dS \approx 1.08 * 10^{-6} I [Wb] \quad (11)$$

which gives an inductance of $L_3 = 1.08 \mu H$.

The overall inductance in the buses and flexibles is then:

$$L_{tot} = L^1_1 + L^2_1 + L^3_1 + 3 * L_{flex} + L_3 = 3.16 \mu H \quad (12)$$

The reactive impedance is $X_L = \omega L = 2\pi f L = 991 \mu\Omega$ and the overall impedance from the busses and flexibles will be

$$Z_{bus} = R + jX_L = (47 + j991) \mu\Omega = 993 \mu\Omega \angle 87^\circ \quad (13)$$

Total impedance for the Δ is then a combination of the impedance in the transformers, buses and flexes:

$$Z_{tot} = Z_{transformers} + Z_{bus} = (0.172 + j1.148) m\Omega = 1.16 m\Omega \angle 82^\circ \quad (14)$$

3.5. Circulating currents

In order for the transformer to operate at an acceptable temperature the current must not exceed the upper limit for total current through the transformers. The nominal current can be found by dividing the power rating of the transformer by its nominal voltage. The furnace 3 transformers have a power rating of 25 MVA and the nominal voltage on the secondary side is 305 V.

$$I_n = \frac{S_n}{V_n} = 82kA \quad (15)$$

The circular current going through the circuit due to different tap positions in addition to the applied current for the furnace load may exceed the nominal current. If the furnace transformers are operated with different tap positions, the voltage difference to be swallowed by the Δ is between 2.5 and 4 Volts as shown in section 3.2. The circulating current associated with this voltage drop is

$$I_c = \frac{4V}{1.16m\Omega} = 3.45kA \quad (16)$$

which is around 4% of the nominal current.

4. CONCLUSIONS AND FURTHER WORK

In this paper it is shown that using a different tap position for one of the three one phase furnace transformers serving a submerged arc furnace will lead to a voltage difference in the Δ connection on the secondary side of the furnace circuit. This will lead to a circulating current which is quantified based on an estimate of the impedance in the Δ connection. The estimate indicates that the resulting circulating current for a difference of one step in the transformer setting is up to 4% of the nominal maximum current. This current, which comes in addition to the load current will not show up on any measurements routinely made on the furnace, but will nevertheless represent a stress on equipment. The phase current is measured with a special arrangement on the primary side of the furnace and the current in the Δ is never measured directly. Therefore there will be no flag in the system warning of such a current component. Due to this extreme care must be taken when applying skew tapping in order to compensate for asymmetric current, and can only be safely applied when the estimated transformer current is below the design value by a good margin.

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6. REFERENCES

- [1] Anders Schei, Johan Kr. Tuset, Halvard Tveit (1998). Production of High Silicon Alloys. Trondheim: Tapir Forlag.
- [2] Fawwaz T. Ulaby(2007), Fundamentals of Applied Electromagnetics. Pearson Education, Inc.
- [3] Saevarsdottir, G.(2002). High-current AC arcs in silicon and ferrosilicon Furnaces, Dr. Thesis no. 2002:56, IME-report 2002:36, NTNU, Trondheim, p. 95-185.

- [4] Saevarsdottir G., Bakken J.A. (2010), Current distribution in submerged arc furnaces for silicon metal, Proc. Conf. INFACON-XII, Helsinki, Finland, p. 717-728.
- [5] Valderhaug Aa. M. (1992), Modelling and control of submerged-arc ferrosilicon furnaces, Dr.Ing thesis 1992. Norwegian Institute of Technology, Trondheim.
- [6] ABB 1998, Name plate, Icelandic Alloys/furnace 3. ABB Kraft National Transformer Division. Drawing number 1ZXX 460013-AGS.
- [7] Theodore Wildi(2006). Electrical Machines, Drives, and Power Systems. New Jersey:Pearson Education, Inc.

