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Characterization of electrode currents
A basis for current control without electrode interaction

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Abstract – The power distribution in submerged arc furnaces is controlled either with current or with resistance control. Current control only requires current measurements and is widely used for small furnaces. For larger furnaces, the current interaction effect is large. Alternatively, furnaces can run on resistance control, which requires unreliable voltage measurements.

We propose a novel way of characterizing transformer and electrode currents that gives information about circulating current and imbalance, and outline how this characterization can be used to design current control that can neutralize the interaction effect. Our method is based on high-frequency measurements, enabling us to compute both phase and magnitude of each transformer current. The currents can then be decomposed into a circulating current that will not enter the furnace, a balanced three-phase current, which is the desired current, and an unbalanced single-phase current, which we want to minimize. This decomposition into effective balanced current and unbalanced current can be used to propose synchronized electrode movements. To correct for the imbalance, one electrode must be moved down and the other two moved up, or vice versa. Provided correctly calibrated movements, the interaction effect will be reduced or neutralized. To correct for a too high or too low total current, all electrodes are moved up or down simultaneously. This paper details the theoretical foundations. Further investigation and testing are required to develop a robust control strategy.

1. INTRODUCTION

Electrical control of submerged arc furnaces has two objectives, to maintain a stable and high power and to maintain a suitable power distribution around each electrode. The total power is normally controlled by adjusting the transformer tap positions and the power distribution is normally controlled by individually adjusting the vertical position of each electrode (Stewart, 1980), where raising an electrode increases the resistance and lowering it decreases the resistance. This is implemented either as current control, where an electrode is moved to maintain a given current, or resistance control, where the electrode is moved to maintain a given electrode resistance (Valderhaug, 1992).

Both current and resistance control have their own set of advantages and challenges. For resistance control, both voltage and current measurements are needed to find the electrode resistances. This is a weakness, since measuring electrode voltage is complicated and uncertain (Reuter *et al*., 1995). However, if the resistances are known they can each easily be adjusted independently by moving a single electrode. Current control only requires electrode current measurements, which are more accurate, and having direct control over the current is useful for making sure we stay inside the operational constraints (Valderhaug, 1992). But this method poses its own challenges. Moving one electrode changes the current distribution inside the furnace, thus affecting the current of all three electrodes (Barker *et al*., 1991). This is called the interaction effect and is most prevalent in larger furnaces with low power factors (Barker *et al*., 1991). This means that current control on large furnaces can create the need for new adjustments, which in turn creates the need for even new adjustments, and so on. Therefore, a current control algorithm should ideally take the interaction effect into account and make coordinated electrode movements. For example, a decoupling strategy where all three electrodes are moved synchronously so that they only change one current for current control has been suggested (Valderhaug, 1992).

In this paper, we propose a basis for an alternative method for current control that counteracts the interaction effect. Instead of measuring only current magnitudes, we propose using high-frequency current measurements to obtain information about both the magnitude and phase of the currents. This is used to decompose the transformer currents into a net balanced positive rotation current, with equal magnitude and 120° phase shifts, a circulating current, and a single-phase current imbalance. We can then adjust for current imbalance and total delivered current separately by using synchronous electrode movements instead of individual adjustments. The method does require non-standard measurements, but the added phase information can be useful for more than a control algorithm, since it, for example, gives information about circulating current and a direct way of quantifying imbalance in the furnace (Monsen, 2025). We first explain the theory of symmetrical components and the needed measurements, before presenting the current decomposition that the control scheme is based on. Then we outline the suggested control strategy and discuss its possible advantages and challenges.

2. THEORY

2.1 Simplified furnace model

We will be working on a simplified, linear circuit model of the furnace, where the secondary side transformers are modelled as voltage sources connected in a delta-star to impedance elements representing the electrodes (Barker and Stewart, 1980). We assume that there is no mutual inductance between the elements and no current paths inside the furnace other than those going down through the electrodes and connecting to the charge material. In particular, this means that we disregard arcing, mutual inductance between the electrodes, and complicated current paths. The simplified circuit model is shown in Figure 1, where the transformers are labelled A, B, and C and the electrodes are labelled 1, 2, and 3. The simplified model is suitable for analysing current distribution between the electrodes, but more advanced models are needed for other studies.

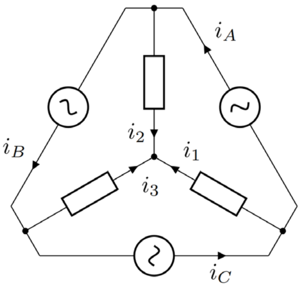


Figure 1: Simplified equivalent circuit for a submerged arc furnace.

Normally in furnaces, only current and voltage magnitudes are measured and presented. However, both magnitudes and phase angles are needed to fully specify systems with alternating currents like this one. This can be done with phasors, complex numbers that contain information about both phase and magnitude. The phasor $A \exp(\theta j)$, where j is the imaginary unit, has magnitude A and phase θ. Going forward, we will assume currents and voltages are given as phasors unless otherwise specified.

Assuming the simplified equivalent circuit in Figure 1, it is possible to calculate electrode currents from transformer currents, but we cannot calculate transformer currents from electrode currents. Similarly, it is possible to calculate transformer voltages from electrode voltages, but not the other way around. In general, we say that the model has three degrees of freedom for both current and voltage. This means that if we know the value of three independent currents, we can determine all currents, and similarly for voltages.

2.2 Symmetrical components

Instead of specifying the three transformer currents directly as three current phasors, we will use a combination of three different basis vectors. This method is known as symmetrical components (Anderson, 1995). The first basis vector is $[1, \alpha^2, \alpha]^T$, where $\alpha = \exp(2\pi j/3)$ and j is the imaginary unit. This vector contains three phasors with magnitude 1 and phase angles $0°$, $240°$, and $120°$, in that order. It has a positive rotation, which for the circuit in Figure 1 means that the current reaches its peak value in the transformers A, B, and C, in that order. The vector $[1, \alpha^2, \alpha]^T$ is therefore called the positive sequence. The second basis vector is $[1, \alpha, \alpha^2]^T$, which has opposite rotation of $0°$, $120°$, and $240°$ and is called the negative sequence. This current will reach its peak value in the transformers in the order A, C, and B. The third basis vector is called the zero sequence and has three equal phasors with magnitude 1 and phase angle $0°$, namely $[1,1,1]^T$. In linear systems like this one, decomposing the currents into symmetrical components has the benefit that calculations can be done on the different sequences separately and added together in the end, which can simplify calculations.

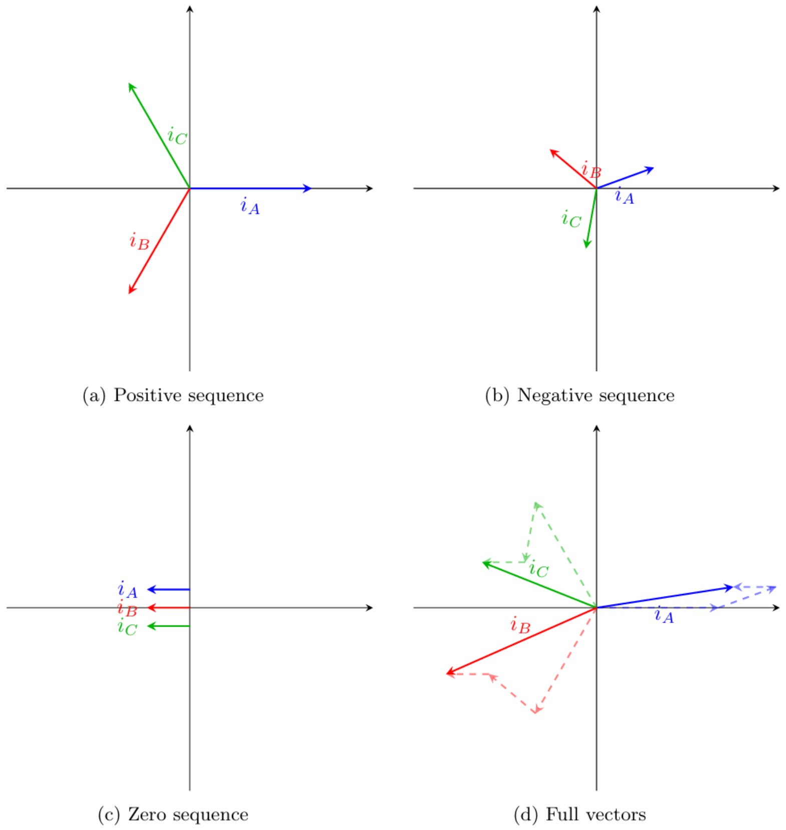
Let $[i_A, i_B, i_C]^T$ be the three transformer current phasors. Symmetrical decomposition consists of determining how much of each of the three basis vector currents are present, that is, we need to find the three complex numbers $[i_0, i_+, i_-]^T$ such that the transformer currents can be written as a linear combination of the basis vectors. Then, we can write the currents as

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} i_0 \\ i_+ \\ i_- \end{bmatrix}. \qquad [1]$$

Any three-phase current system can be similarly decomposed using symmetrical components (Anderson, 1995).

The phasor i_+ specifies the magnitude and phase angle for a balanced three-phase current. Ideally, this should be the only component. The phasor i_- specifies the magnitude and phase angle of a balanced three-phase current with negative rotation, which will introduce current imbalance. The phasor i_0 specifies the amount and phase angle for a common component. The decomposition is illustrated in Figure 2, where we can see the positive sequence, the negative sequence, the zero sequence, and how they add up.

For the furnace circuit in Figure 1, the different sequences have different physical interpretations. Both for the transformers and electrodes, the positive sequence is the current we want, a perfectly balanced three-phase current with positive rotation. The negative sequence introduces imbalance. It is a three-phase current with negative rotation, which added to the positive sequence gives an unbalanced current. The larger the negative sequence is relative to the positive sequence, the greater the imbalance. The zero sequence is mathematically defined as one third of the sum of the phasors. For the transformers, this means that the zero sequence coincides with the definition of circulating current (Monsen, 2025). In other words, the zero sequence is a measure of circulating current in the transformer delta. The current must sum to zero in the star connection between the electrodes due to charge conservation, which means that the zero sequence component will always be zero for the electrode currents.



(a) Positive sequence (b) Negative sequence

(c) Zero sequence (d) Full vectors

Figure 2: Decomposition of the three current phasors i_A, i_B, and i_C by symmetrical components. The different graphs show the positive sequence, the negative sequence, the zero sequence, and lastly how they add up to the full vectors.

2.3 Electrode currents

When the transformer currents are known, the electrode currents are given by

$$\begin{aligned} i_1 &= i_C - i_A, \\ i_2 &= i_A - i_B, \\ i_3 &= i_B - i_C. \end{aligned} \qquad [2]$$

The electrode currents can also be written as a linear combination of the symmetrical components of the transformer currents, as

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} \alpha - 1 \\ 1 - \alpha^2 \\ \alpha^2 - \alpha \end{bmatrix} i_+ + \begin{bmatrix} \alpha^2 - 1 \\ 1 - \alpha \\ \alpha - \alpha^2 \end{bmatrix} i_-. \qquad [3]$$

The vector $[\alpha - 1, 1 - \alpha^2, \alpha^2 - \alpha]^T$ represents a balanced set of three current phasors, with magnitude $\sqrt{3}$ and phase angles 150°, 30°, and 270°, respectively, that is a positive rotation. Similarly, the vector $[\alpha^2 - 1, 1 - \alpha, \alpha - \alpha^2]^T$ is a set of currents with magnitude $\sqrt{3}$ and the negative rotation 210°, 330°, and 90°. This is in accordance with theory for a balanced delta-star system, where the currents entering the star connection will be $\sqrt{3}$ times larger than those in the delta connection and with a phase angle shift of 30°.

2.4 Measurement equipment

To have access to phase information, we need equipment that can measure and log currents with sufficiently high frequency to resolve the sinusoidal current waveform, not just RMS values, and from that extract the phase and amplitude of the signal. The sampling frequency must therefore be many times higher than the current frequency. As explained previously, it is possible to calculate electrode currents if we know the transformer currents. Thus, either measuring the transformer currents or the electrode currents will work.

Measurements of secondary side transformer currents are not standard in submerged arc furnaces but can for example be done with Rogowski coils (Monsen, 2025). Alternatively, one can make high-frequency measurements of the electrode currents, but this will not give access to information about the circulating current in the transformer delta. Measuring electrode current is a standard process (Sævarsdóttir, 2013), the difference being that one will need to log high-frequency measurements. More work is needed to identify typical errors for the high-frequency measurements and how to best mitigate them, regardless of which method is used. For example, care must be taken to synchronize the three measurements to obtain the correct phases.

Given high-frequency measurements, a Fourier transform can be used to estimate the phases and amplitude of the signal frequencies (Monsen, 2025). The simplified circuit in Figure 1 will have a perfect sinusoidal signal and thus only one frequency, but higher harmonics of the fundamental frequency can be present in a real furnace (Reuter *et al.*, 1995; Stewart, 1980). This needs to be taken into account when designing the full control algorithm, but will not be further considered here.

3. RESULTS AND DISCUSSION

We first present the mathematical results, detailing the calculations that need to be done on the high-frequency current measurements. Then we explain its potential application, by describing how it can be used to design a practical control scheme.

3.1 Decomposition of transformer currents

Let $[i_A, i_B, i_C]^{\mathrm{T}}$ be the secondary side transformer currents in a furnace, and choose the global phase such that $i_+/M = 1$ and $i_-/M = r\exp(j\beta)$, where M and r are real numbers. In other words, i_+ has phase angle 0 and i_- has phase angle β. The currents can then be decomposed with symmetrical components as

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} i_0 + \begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} i_+ + \begin{bmatrix} 1 \\ \alpha \\ \alpha^2 \end{bmatrix} i_-. \qquad [4]$$

From this, we add and subtract a vector with the same phase as i_+ and the same magnitude as i_-, that is $[1, \alpha^2, \alpha]^T rM$. We then get

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} i_0 + \begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} i_+ + \begin{bmatrix} 1 \\ \alpha \\ \alpha^2 \end{bmatrix} i_- = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} i_0 + \begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} (i_+ - rM) + \begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} rM + \begin{bmatrix} 1 \\ \alpha \\ \alpha^2 \end{bmatrix} i_-. \qquad [5]$$

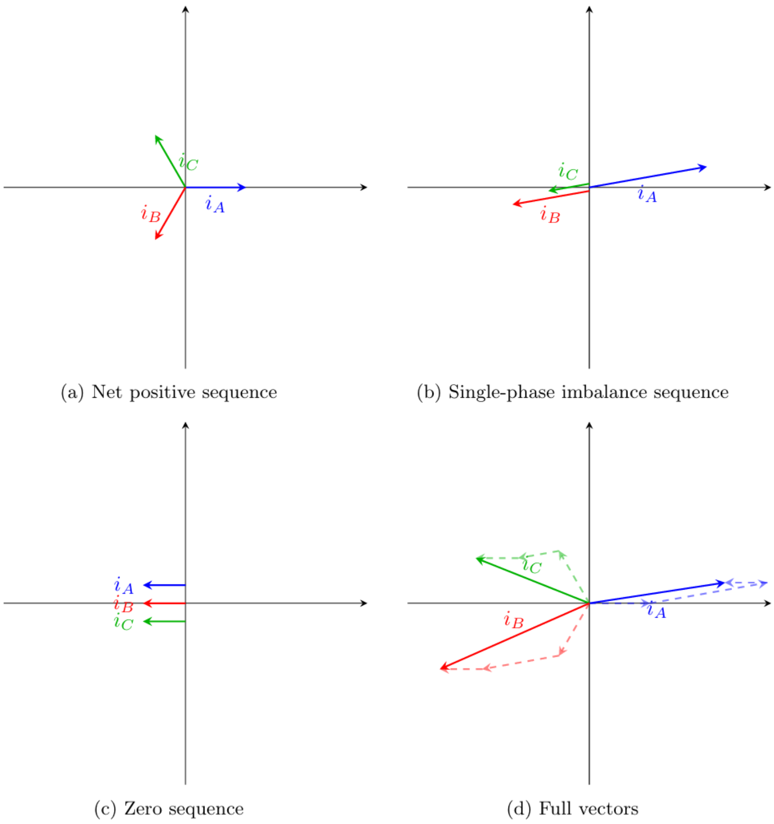
The first term is the zero sequence, which can be interpreted as the circulating current in the transformer delta (Monsen, 2025). The second term, with amplitude $i_+ - rM = M(1-r)$ is the net transformer currents having the desired behaviour, namely a balanced three-phase current in positive rotation. We will call this the net positive sequence. The last two terms constitute the unbalanced part. Denoting the unbalanced components of the transformer currents as $[i'_{\mathrm{A}}, i'_B, i'_{\mathrm{C}}]$, the unbalanced components can be written out as

$$
\begin{aligned}
i'_{\mathrm{A}} &= rM + i_{-} = rM\big(1+\exp(j\beta)\big) = 2rM\cos\left(\frac{\beta}{2}\right)\exp\left(\frac{j\beta}{2}\right),\\
i'_{\mathrm{B}} &= \alpha^{2}rM + \alpha i_{-} = \alpha rM\big(\alpha+\exp(j\beta)\big) = 2rM\cos\left(\frac{\pi}{3}-\frac{\beta}{2}\right)\exp\left(j\left(\pi+\frac{\beta}{2}\right)\right),\\
i'_{\mathrm{C}} &= \alpha rM + \alpha^{2} i_{-} = \alpha^{2}rM\left(\frac{1}{\alpha}+\exp(j\beta)\right) = 2rM\cos\left(\frac{\pi}{3}+\frac{\beta}{2}\right)\exp\left(j\left(\pi+\frac{\beta}{2}\right)\right),
\end{aligned}
\qquad [6]
$$

where $2\cos\phi = \exp(j\phi)+\exp(-j\phi)$. The arguments, or angles, of the unbalanced components are then

$$
\begin{aligned}
\arg(i'_{\mathrm{A}}) &= \frac{\beta}{2},\\
\arg(i'_{\mathrm{B}}) &= \pi+\frac{\beta}{2},\\
\arg(i'_{\mathrm{C}}) &= \pi+\frac{\beta}{2}.
\end{aligned}
\qquad [7]
$$

This means that the unbalanced part of the current has the same phase for all three transformers, just with different signs. The decomposition is shown visually in Figure 3, where we see how the net positive sequence, the single-phase imbalance sequence, and the zero sequence add up to the full vectors. Note the main difference to the symmetrical decomposition shown in Figure 2, that we have a single-phase unbalance instead of a negative rotation sequence.



(a) Net positive sequence

(b) Single-phase imbalance sequence

(c) Zero sequence

(d) Full vectors

Figure 3: Decomposition of the three current phasors i_A, i_B, and i_C into a net positive rotation, a single-phase unbalance and the zero sequence. The bottom right graph shows how they sum to the full vectors.

3.2 Implications for electrode currents

We take advantage of the fact that we have a linear system and look at each part of the decomposed transformer currents separately. For a balanced delta-star system, the currents entering the star connection will be $\sqrt{3}$ times larger than those in the delta connection and with a phase angle shift of 30°, as previously explained. This applies to the net positive sequence. The circulating current, i.e. the zero sequence component of the transformer current, does not enter the electrodes, and the electrode current will have no zero sequence component.

Looking at the single-phase unbalanced transformer currents, we find that the unbalanced electrode currents are

$$\begin{aligned} i_1' &= i_C' - i_A' = 2rM\left(-\cos\left(\frac{\pi}{3}+\frac{\beta}{2}\right)-\cos\left(\frac{\beta}{2}\right)\right)\exp\left(\frac{j\beta}{2}\right), \\ i_2' &= i_A' - i_B' = 2rM\left(\cos\left(\frac{\beta}{2}\right)+\cos\left(\frac{\pi}{3}-\frac{\beta}{2}\right)\right)\exp\left(\frac{j\beta}{2}\right), \\ i_3' &= i_B' - i_C' = 2rM\left(\cos\left(\frac{\pi}{3}+\frac{\beta}{2}\right)-\cos\left(\frac{\pi}{3}-\frac{\beta}{2}\right)\right)\exp\left(\frac{j\beta}{2}\right). \end{aligned} \quad [8]$$

The unbalanced currents can all be written on the form

$$i_n' = 2rM \cdot x_n \cdot \exp\left(\frac{j\beta}{2}\right), \quad [9]$$

where $n = 1,2,3$ and

$$\begin{aligned} x_1 &= -\cos\left(\frac{\pi}{3}+\frac{\beta}{2}\right)-\cos\left(\frac{\beta}{2}\right), \\ x_2 &= \cos\left(\frac{\beta}{2}\right)+\cos\left(\frac{\pi}{3}-\frac{\beta}{2}\right), \\ x_3 &= \cos\left(\frac{\pi}{3}+\frac{\beta}{2}\right)-\cos\left(\frac{\pi}{3}-\frac{\beta}{2}\right). \end{aligned} \quad [10]$$

The absolute values of x_1, x_2, and x_3 determine the distribution of the unbalanced current between the three electrodes. The larger the absolute value of x_n, the more unbalanced current passes through electrode n. x_1, x_2, and x_3 always adds up to zero, but their individual values vary as a function of β, where $\beta/2$ is the phase angle of the unbalanced current. The behaviour of x_1, x_2, and x_3 is plotted in Figure 4.

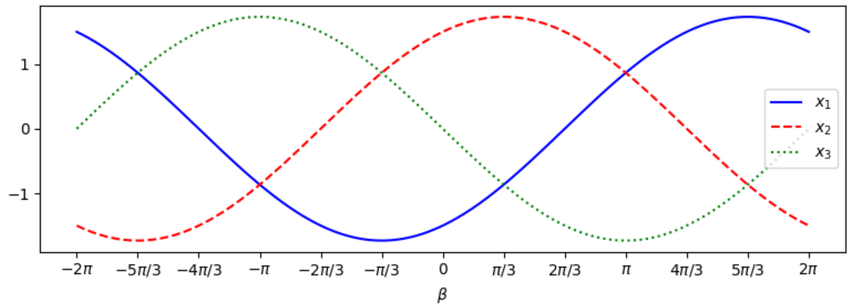


Figure 4: x_1, x_2, and x_3, representing the distribution of the single-phase unbalanced electrode currents, as functions of beta.

3.3 Control scheme outline

We can use the mathematical results from the previous section to outline a practical control scheme. Suppose we have measurement equipment that can measure the high-frequency secondary side transformer currents and extract phases and amplitudes. We can then give information on circulating current, the desired current entering the furnace, the unbalanced current, and how it is distributed between the electrodes.

Specifically, suppose we have a program that uses these measurements to calculate the unbalanced electrode currents as explained in the previous section, particularly to calculate x_1, x_2, and x_3, which represents the amount of unbalanced current in electrode 1, 2, and 3, respectively. We can now control for total current and current imbalance separately. To increase the total current, which is the balanced plus the unbalanced parts, all electrodes can be moved down. Or vice versa, all electrodes can be moved up to decrease the total current.

For the single-phase unbalanced current, since we know how this current is distributed in the electrodes, we can move the electrodes synchronously to counteract the imbalance. Suppose we are in the case of $\beta = \pi$ as shown in Figure 4, where $x_1 = x_2$ and $x_1 + x_2 = -x_3$. This can be interpreted as an unbalanced current going down into electrode 3 and divided equally to go up through electrodes 1 and 2. To counteract the imbalance, we then need to increase the resistance of electrode 3 and decrease the resistances of electrodes 1 and 2. Physically, this means raising electrode 3 and lowering electrodes 1 and 2.

As another example, suppose $\beta = -2\pi$, such that $x_1 = -x_2$ and $x_3 = 0$. Then there is no unbalanced current in electrode 3, all of it is oscillating between electrodes 1 and 2. This means that the resistances of electrodes 1 and 2 must be increased compared to the resistance of electrode 3. So, electrodes 1 and 2 should be raised. But the current going through electrode 3 will also be affected by these increased resistances, and electrode 3 should be lowered to compensate.

The conditions around each electrode are likely to differ, and if all electrodes are moved by the same amount, the currents are not necessarily changed equally. For control of the total current, we recommend establishing a running estimate on the relative change in electrode positions needed to change all three currents by the same amount. Such an estimate can be checked, and possibly updated, after each total current correction. Similarly, we recommend running estimates for the situations where all the unbalanced current is oscillation between two electrodes. The estimate would then be on the relative change in the three electrode positions required to change two currents while keeping the third one unchanged. The running estimates, one for the balanced current and three for the unbalanced cases, are probably closely linked, and constitutes a topic for further research.

The general case where the unbalanced current enters one electrode and is distributed to the two others, can be written as the sum of two currents, each with zero unbalanced current in one electrode. The total correction will then be the sum of two corrections, following the method previously outlined.

Some thought must be offered to the absolute value of the imbalance. This can for example be to only make adjustments when the magnitude of the imbalance is outside of some deadband, or to move more quickly if the absolute value is larger. Questions about the step size of electrode movements, relative step size for each electrode, and time between steps also need to be addressed. Specific algorithms should be simulated on a model of the furnace to get a good understanding of how it will behave under various conditions and to test it against other control strategies.

3.4 Higher harmonics

There might be higher harmonics of the fundamental frequency present in the furnace, which will complicate the symmetrical components analysis. High-frequency measurements previously done on a silicon submerged-arc furnace indicate that the current harmonics are small compared to the imbalance of the fundamental, even though the electrode voltage is clearly distorted due to arcing (Monsen, 2025). Further study is needed to determine whether this is applicable in general, and how much higher harmonics will affect the performance of a control strategy like the one we have proposed. It is not difficult to do the calculations and adjustments presented here only based on the fundamental frequency, but the presence of higher harmonics might still influence the performance of the control strategy. If necessary, the method should therefore be extended to account for the effect of higher harmonics.

3.5 Further work

Our characterization of electrode currents constitutes a sound theoretical basis for a current control without electrode interaction, but more studies are needed to develop and test robust control algorithms. While our simple model is sufficient for analysing current distributions, a more realistic model is required for properly studying the control strategy. Such a model should include typical induction effects, non-linearities, and changes in the furnace conditions. The latter is needed to study robustness against changes due to variation in raw material properties and uneven material flow.

For further research, we propose at least the following. A first step would be to investigate the behaviour of the running estimates described above and to test the control strategy on a simple furnace model. Then, it should be tested on more complex and realistic models. Measurements should also be performed on real furnaces, and the behaviour of the symmetrical components should be studied regarding variations, typical time constants and so on. Lastly, a successfully developed control strategy should be tested on real furnaces. If successfully implemented, the current interaction effect will be properly counteracted. If not, we assume that the novel strategy at least will substantially reduce current interaction effects.

4. CONCLUSIONS

We have shown that the electrode currents can be decomposed into one perfectly balanced three phase system in positive rotation and one single-phase imbalanced current. This lays the theoretical foundation for a novel current control method which effectively eliminates, or substantially reduces, the interaction effect. The single-phase imbalance can be counteracted by moving one electrode down and the other two up, or vice versa, while the total current shows whether all electrodes should be moved up or down to maintain the set point for the electric current.

The method requires high-frequency current measurements, to compute magnitude and phase for each transformer current. In addition, decomposition of transformer currents shows the amount and phase of a current circulating between the transformers without entering the furnace. Further studies are needed to design a proper control algorithm and to investigate the effect of higher harmonics in the current. Simulating and testing the method are important next steps to validate the proposed method and to compare its performance with those of other control strategies.

5. ACKNOWLEDGEMENTS

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