Electrode Voltage Measurement in Electric Furnaces: Analysis of Error in Measurement and Calculation

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ABSTRACT

Efficient control of the power input to an electric furnace is a critical operational success factor that requires accurate measurements of the electrode currents and voltages. These are the key measured values for control of furnace power as they are required to calculate electrode resistance, used by most control systems in deciding when to raise or lower an electrode or change the tap position. The method of electrode current measurement is generally considered adequate; however, there is debate over how to most accurately determine electrode voltage. There is a belief in the industry that direct voltage measurement between an electrode and the furnace bath suffers from an induced voltage error caused by the very high currents in the electrode. An alternative method calculates the electrode voltages from measurements on the primary of the furnace transformer where the induced voltage is negligible. It is demonstrated in this paper, however, that the accuracy of this alternative method depends on accurate knowledge of the reactance in the furnace power supply circuit. Any error in the estimated reactance will produce errors in the calculated voltages. This paper also includes calculations showing that the induced voltage error affecting the direct measurement is often less than what is commonly believed and that this method is a viable option for furnace power control. The choice between the two methods may be influenced by furnace geometry, e.g. the calculation method is not applicable to six-electrode furnaces, or by maintenance concerns. The furnace process will also be a factor in determining the preferred method, giving consideration to electrode current levels and furnace power factor. Hatch is developing a PLC-based Electrode Regulator with a selectable source for electrode voltage, allowing either method to be used for control and the possibility to compare the two in real-time.

1 Background

The power delivered to an electric furnace is controlled by raising or lowering the electrodes to adjust the electrode-to-bath resistance as well as changing the transformer tap position to alter the voltage applied to the electrodes. Control of this equipment is usually provided by a computerized control system, typically a PLC (programmable logic controller). The main inputs for control are measurements of electrode-to-bath voltage and electrode current. Potential transformers (PTs) and current transformers (CTs) reduce the electrode voltages and currents to a level suitable for transducers to provide the signals to the control system. The accuracy of these measurements has a direct impact on the control of power delivered to the furnace.

The electrode-to-bath voltage measurement is the focus of this paper. As illustrated in Figure 3, there are two common methods for voltage measurement in a furnace: 1) secondary, or direct, measurement and 2) primary voltage measurement, so named because the measurements occur, respectively, on the secondary and primary side of the furnace transformer.

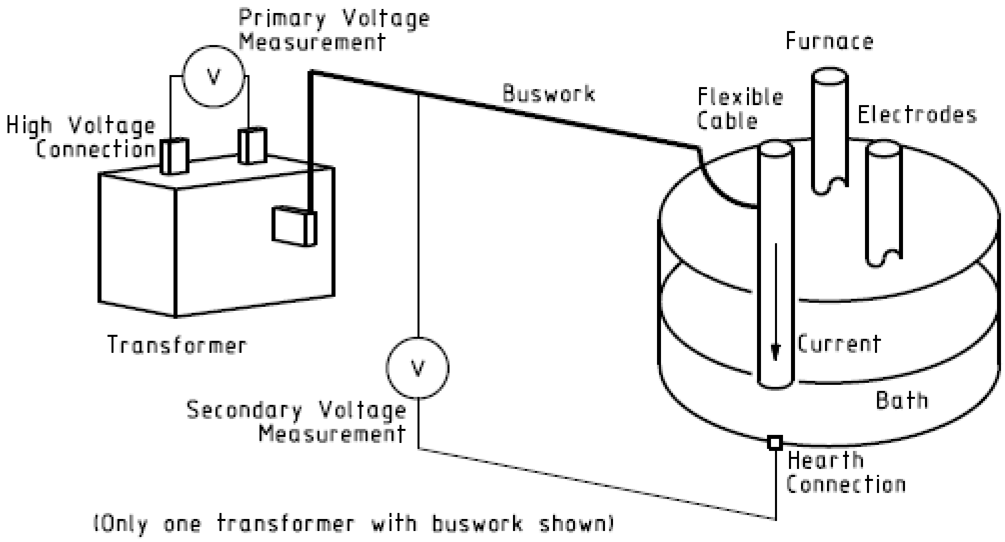

Figure 3: Primary and secondary voltage measurements on an electric furnace

For the secondary measurement a PT is connected between each of the electrodes' buswork and the furnace bath. The measurement is nearly a direct measurement of electrode-to-bath voltage, but also includes voltage drops across the electrodes and flexible cables, as well as a portion of the buswork (the connection to the buswork is often made at the transformer, however this component can be reduced by connecting the PT closer to the electrode).

The primary measurement is the line-to-line voltage at the primary side of the furnace transformers. In addition to the voltage drops listed above the primary measurement also includes a drop across the furnace transformer. Because the primary voltage measurement does not have a connection to the furnace bath, a calculation is used to estimate the electrode-to-bath voltage; this paper refers to this method as the *primary calculation method*.

2 Secondary Measurement of Electrode-to-Bath Voltage

The measurement of electrode-to-bath voltage on the transformer secondary has the advantage of being a direct measurement not requiring additional calculations. It does, however, require electrical connections in the harsh environment near the furnace. The bath connection is typically a metal control strap woven between courses of refractory in the furnace bottom, or hearth. As the straps are difficult to inspect and replace, several are typically installed under each electrode. Thermal expansion and contraction of the hearth can sever the connections and in some instances the connection may be relying solely on metal penetration through the refractory to complete the circuit. The focus of this paper, however, is the existence of an inherent error in the voltage measurement. This error is due to the close proximity of the measurement to the high electric current in the electrode.

2.1 Measurement Error

Faraday's Law describes how a changing magnetic field, such as that caused by AC current, can induce a voltage in a coil of wire. Figure 4 highlights the measurement loop created by the secondary voltage measurement. As illustrated in the figure, this measurement loop is tantamount to a coil in the presence of a changing magnetic field caused by the high electrode current; a voltage is therefore induced in the measurement leads. The transducer reports the total voltage – the sum of electrode-to-bath voltage and induced error – to the control system. This error can impact both furnace control and reporting.

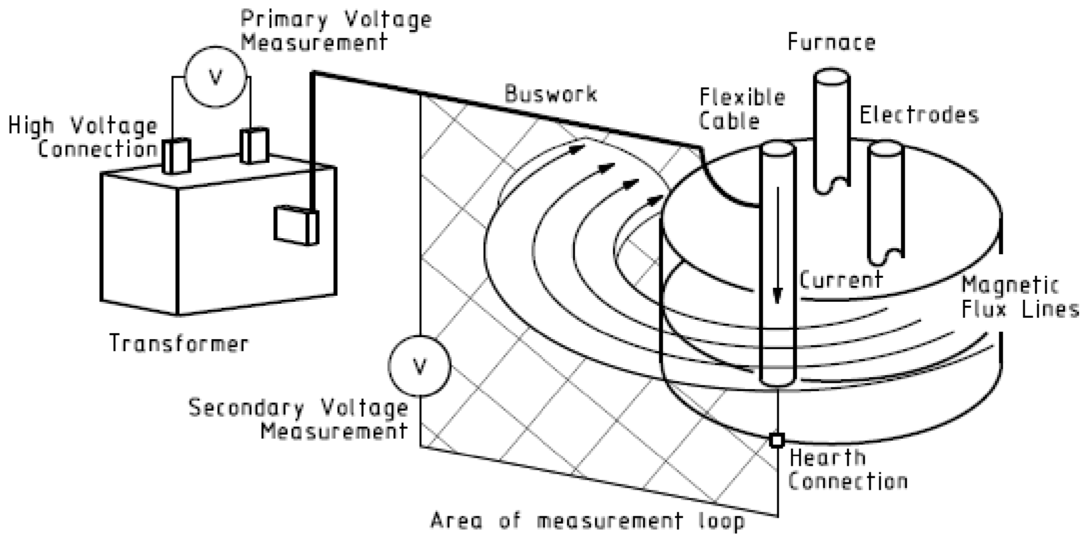

Figure 4: Measurement loop and the magnetic field created by the electrode current

The magnitude of the induced voltage error, labelled U_{RMS}, can be estimated from a calculation provided by Bretthauer and Timm [2]:

Equation 4: $$U_{RMS} = \mu \cdot b \cdot f \cdot I \cdot \ln\left[1 + \left(\frac{a}{r}\right)\right]$$

where:

μ = magnetic permeability of the medium
b = height of the measurement loop
f = alternating current frequency
a = distance from the electrode to the voltage transducer
r = radius of electrode
I = RMS electrode current

An example from Stewart [1] demonstrates that on an actual electrode-to-bath voltage of 180V, with electrode current of 100kA, the induced voltage, U_{RMS}, as determined from Equation 4 is 21V[2]; this corresponds to a rather significant 12% error. This result would suggest direct measurement of electrode-to-bath voltage is not useful for control. The example given, however, only examines a specific set of furnace operating conditions – one with very high electrode current and relatively low electrode-to-bath voltage – and different furnace operations should be examined. Moreover, note that Equation 4 only considers a single electrode. The other electrodes in the furnace form the current return path and will produce an induced voltage which counteracts that from the first electrode.

In the following sections, the magnitude of the induced voltage error is investigated for different furnace operations and is extended to an approximate two and three-electrode model to further examine the net effect of the induced voltage.

2.2 Error Analysis for Different Operating Parameters

It was shown that the induced voltage error created by an electrode carrying a high current may be large enough to affect the control and reporting of furnace operation. While some ferroalloy operations will have electrode currents in the range of 100kA or more, other furnaces, particularly those processing ferronickel or PGM-type materials, typically operate with electrode currents below 50kA. As well, the electrode-to-bath voltage could range anywhere from 100V to 1000V or more. The induced voltage should, therefore, be examined at different operating points for a variety of furnaces to understand the extent of the error. Considering Equation 4 as the worst-case scenario before considering the effect of multiple electrodes, Table 21 presents the induced voltage error calculated for a selection of furnaces with electrode currents and voltages in their typical operating regions. The data was taken from a variety of furnaces with which Hatch has been involved, including those producing ferronickel, lead, ferroalloys, etc.

[2] The example uses the following parameters:
$\mu = 4\pi * 10^{-7}$ V·s/A·m
b = 3 m
f = 50 Hz
a = 2 m
r = 1 m

Table 21: Induced voltage on various furnaces

Description	Electrode Current, I	Electrode Voltage, V	Induced Voltage, U_{RMS}	Error
Furnace #1	120 kA	225 V	25 V	11 %
Furnace #2	75 kA	150 V	16 V	10 %
Furnace #3	38 kA	120 V	8 V	7 %
Furnace #4	20 kA	100 V	4 V	4 %
Furnace #5	31 kA	275 V	6 V	2 %
Furnace #6	8 kA	215 V	2 V	1 %
Furnace #7	40 kA	850 V	8 V	1 %
Furnace #8	41 kA	738 V	8 V	1 %

The error calculated for certain submerged-arc furnaces is shown to be in the range of the example given previously. The other furnaces examined, however, have lower electrode currents and correspondingly lower errors. Thus, although significant error may be possible for furnaces with very high electrode currents, there are many furnaces where the error is negligible, including most nickel and platinum furnaces, or other arcing operations.

2.3 Error Analysis using a Multiple-electrode model

As mentioned, Bretthauer and Timm's equation for the induced voltage [2] considers only the voltage induced by a single electrode. In the common three-electrode furnace there are two other electrodes which will contribute to, and in fact decrease, the induced voltage error. Discussion of the complicated geometry in the three-electrode model will be deferred to consider the simpler two-electrode model presented in Figure 5.

The model considers a second electrode located at a centre-to-centre distance, d, from the original. The current flowing into the first electrode flows out of the second. As the current is travelling in opposite directions, the magnetic flux from the second electrode will be in opposition to that generated by the first. The reduced strength of the magnetic field will therefore decrease the induced voltage in the measurement loop.

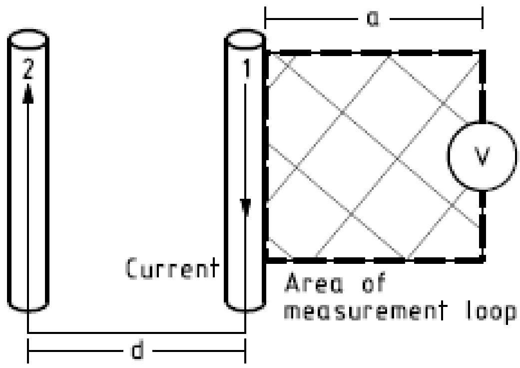

Figure 11: **Figure 5:** Two-electrode arrangement for analysis of induced voltage error

Maintaining the variables of Equation 4, the induced voltage due to each electrode can be derived as:

Equation 5: $$U_{1\ RMS} = \mu \cdot b \cdot f \cdot I_1 \cdot \ln\left[1 + \left(\frac{a}{r}\right)\right]$$

Equation 6: $$U_{2\ RMS} = \mu \cdot b \cdot f \cdot I_2 \cdot \ln\left[1 + \left(\frac{a}{d + r}\right)\right]$$

Equation 5 for the value of U_{1RMS} comes directly from Equation 4. The induced voltage from the second electrode, U_{2RMS} given in Equation 6, considers the additional distance between the electrode and the measurement loop, d. The resulting induced voltage is a sum of that from each electrode. Recalculating Stewart's example, using $I_2 = -I_1 = -100$kA and choosing a typical electrode spacing of 3m, reveals an overall induced voltage, U_{RMS}, of 13V. This corresponds to an error nearly half that of the single electrode model, at approximately 7%.

The two-electrode analysis is extended to the common three-electrode configuration. The calculation is complicated by the geometry of the magnetic flux lines passing through the measurement loop and also by the different phase angle of the current in each electrode. Figure 6 presents a top-view of the three-electrode system for a geometric analysis. The magnetic flux through each measurement loop will be the vector sum of the flux generated by all three electrodes.

Considering the measurement loop highlighted in the figure, the component of the induced voltage from Electrode 1 is unchanged from the single and two-electrode models. The other electrodes, however, have a diminished effect as they are no longer in the same plane as the measurement loop (magnetic flux induces the highest voltage when the lines of flux are perpendicular to the induction loop). The flux lines from electrodes 2 and 3 no longer meet the loop at right angles, and therefore the induced voltage is less.

Recalculating Stewart's example for the three-electrode model, again assuming a 3m centre-to-centre distance between electrodes, yields an induced voltage, U_{RMS}, of 13V, similar to the 7% error determined by the two-electrode model.

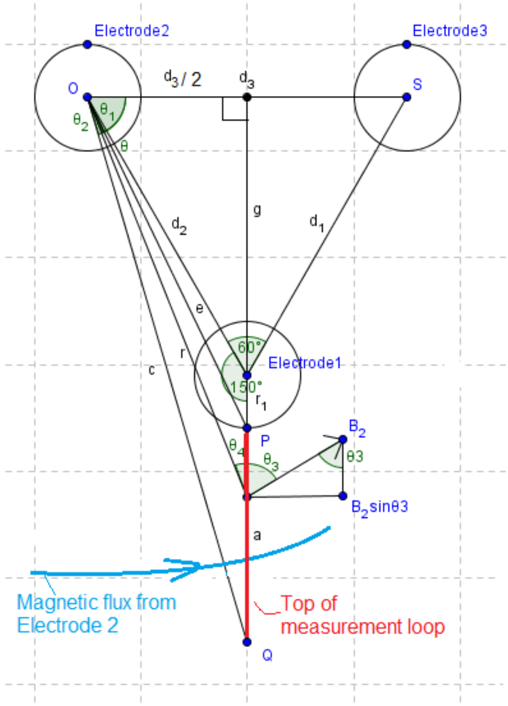

Figure 12: **Figure 6:** Geometric model of the magnetic flux from electrodes in a three-electrode system

2.4 Summary of Direct Electrode-to-Bath Voltage Measurement

Although preliminary analysis of induced voltage casts doubt on the validity of direct electrode-to-bath voltage measurements, expanding the analysis to include all electrodes reveals the error is not as large as initially expected. It is also worth noting that the error is only significant on a subset of furnaces with very high electrode currents and relatively low electrode-to-bath voltages. Furnaces with electrode currents less than 50kA can expect less than 5% error due to induced voltage. Table 22 summarizes the results of the different models applied to the example furnaces. These results are still only an approximation as it is extremely difficult to consider every angle of the furnace geometry, or the effect of the material inside the furnace and the building steel framing the entire circuit.

Table 22: Induced voltage error as determined by the single and multiple-electrode models

Description	Electrode Current, I	Electrode Voltage, V	Single-electrode calculation		Two or Three-electrode calculation	
			Induced Voltage	Error	Induced Voltage	Error
Stewart [1]	100 kA	180 V	21 V	12 %	13 V	7 %
Furnace #1	120 kA	225 V	25 V	11%	16 V	7 %
Furnace #2	75 kA	150 V	16 V	10%	10 V	7 %
Furnace #3	38 kA	120 V	8 V	7%	5 V	4 %
Furnace #4	20 kA	100 V	4 V	4%	3 V	3 %
Furnace #5	31 kA	275 V	6 V	2%	4 V	1 %
Furnace #6	8 kA	215 V	2 V	1%	1 V	0 %
Furnace #7	40 kA	850 V	8 V	1%	5 V	1 %
Furnace #8	41 kA	738 V	8 V	1%	5 V	1 %

3 Electrode-to-Bath Voltage from Primary Calculations

Stewart [3] introduced a method to estimate electrode-to-bath voltage from measurements performed on the primary side of the furnace transformer; in this paper the method is referred to as the *primary calculation method*. The method avoids the induced voltages that affect the direct measurement of electrode-to-bath voltage discussed in the previous section. The calculation, however, must be specifically calibrated for each furnace. This paper discusses the primary calculation method, the information required to calibrate the calculation, and the accuracy that can be expected if the calibration is not exact.

The complete electrical circuit for the furnace introduced in Figure 3 is provided schematically in Figure 7. The diagram includes all three furnace transformers, T_i, all sources of reactance for each electrode including the buswork, flexible cables and electrode itself, $X_{source-i}$, and the electrode-to-bath resistance, R_{bath-i}. The primary calculation method estimates the electrode-to-bath voltage for each electrode, V_{1n}, V_{2n}, and V_{3n}, from measurements of:

- the furnace transformer primary voltage, V_{12}, V_{23}, and V_{31};
- the electrode currents, I_1, I_2, and I_3;
- and the total furnace power, P, measured separately by a dedicated meter.

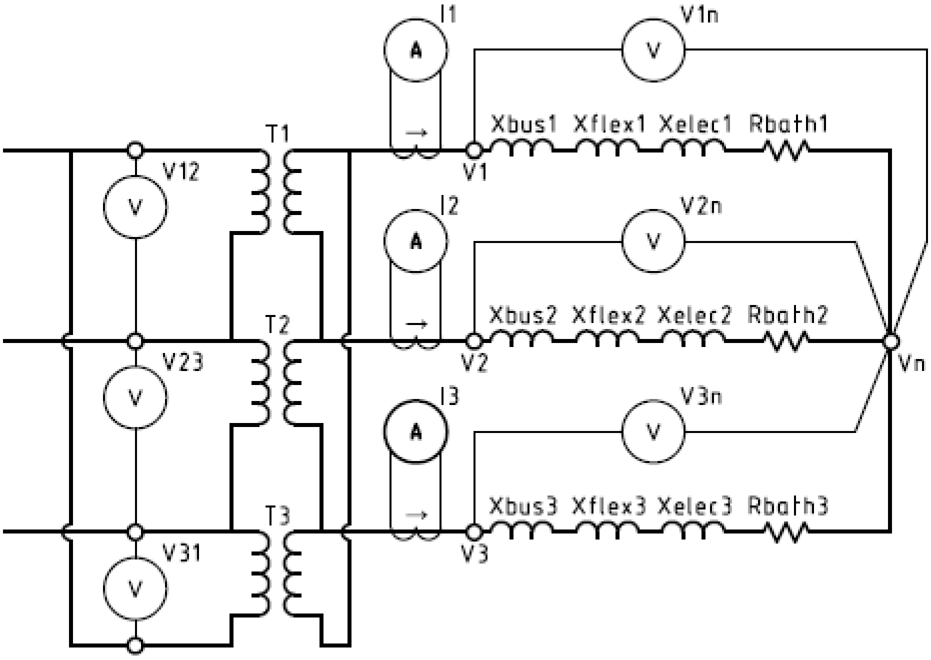

Figure 7: Complete circuit diagram for the three-electrode, three-transformer furnace

The accuracy of the primary calculation method relies on the assumption that the reactance in each phase is related by a fixed ratio and, moreover, that the ratio is known. The reactance per phase is a subset of the total furnace reactance which can often only be estimated and may change over time. There are several known methods used to estimate the phase reactance [4], however, these will not be discussed in this paper. The result of the primary calculations must be considered an approximation and in the next sections the expected accuracy of the method is considered.

3.1 Validity of the Primary Calculations

The complete three phase furnace circuit shown in Figure 7 can be simplified by considering only the secondary side of the furnace transformers. As well, the reactance values for the transformer, buswork, flexible cables and electrode can be combined into a single value for each phase, known as the *total phase reactance*, X_i. The simplified circuit is shown in Figure 8. The available measurements are shown on the figure, as well as the actual value of electrode-to-bath voltage, which the primary calculation method is meant to calculate.

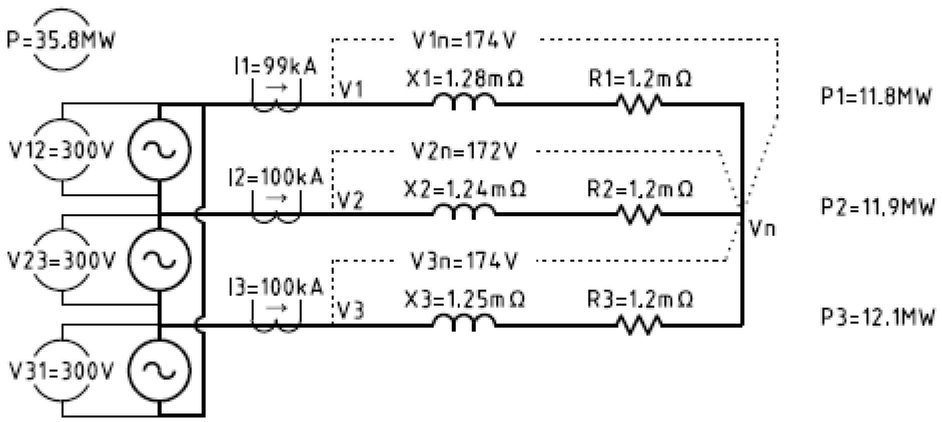

Figure 8: Simplified furnace circuit model with sample values

Figure 8 provides sample data for furnace resistance and reactance, and the corresponding electrode current, electrode-to-bath voltage and power at each electrode. Although the electrode-to-bath resistance for each electrode is equal, note that the current, voltage and power for each electrode are not. This unbalance occurs because the total phase reactance for each electrode differs slightly, as provided in the figure.

To demonstrate the validity of the primary calculation method it is applied to the example of Figure 8. The calculation is performed assuming accurate measurement of the required values as well as exact calibration of the total phase reactance. The results, presented in Table 23, are equal to the actual values provided in the Figure. This demonstrates the accuracy of the primary calculation method when the calculation is perfectly calibrated.

Table 23: Primary calculation method applied to the circuit of Figure 8

Primary Calculation Method Inputs		**Primary Calculation Method Outputs**	
Transformer Secondary Voltages (measured)	V_{12} = 300 V V_{23} = 300 V V_{31} = 300 V	Electrode-to-Bath Voltages	V_{1n} = 174 V V_{2n} = 172 V V_{3n} = 174 V
Electrode Currents (measured)	I_1 = 99 kA I_2 = 100 kA I_3 = 100 kA	Bath Resistances	R_1 = 1.2 mΩ R_2 = 1.2 mΩ R_3 = 1.2 mΩ
Total Phase Reactance (calibration values)	X_1 = 1.28 mΩ X_2 = 1.24 mΩ X_3 = 1.25 mΩ	Electrode Powers	P_1 = 11.8 MW P_2 = 11.9 MW P_3 = 12.1 MW
Total Furnace Power (measured)	P = 35.8 MW		

3.2 Error in the Calculation

As noted for Figure 8, the reactance values for each phase are similar but not identical. In a real system it may often be assumed, for lack of better information, that these values are the same. Employing this assumption in the primary calculation method, however, results in an error in the calculated electrode-to-bath voltages. Table 24 presents the results of the primary calculation method when reactance is assumed to be equal for the example of Figure 8.

Table 24: Primary calculation method applied to Figure 8, assuming equal reactance

Primary Calculation Inputs		Primary Calculation Outputs		Actual	Error
Secondary Voltage (measured)	V_{12} = 300 V	Electrode-to-Bath Voltage	V_{1n} = 173 V	174 V	-1%
	V_{23} = 300 V		V_{2n} = 174 V	172 V	+1%
	V_{31} = 300 V		V_{3n} = 173 V	174 V	-1%
Electrode Current (measured)	I_1 = 99 kA	Bath Resistance	R_1 = 1.2 mΩ	1.2 mΩ	0%
	I_2 = 100 kA		R_2 = 1.2 mΩ	1.2 mΩ	0%
	I_3 = 100 kA		R_3 = 1.2 mΩ	1.2 mΩ	0%
Total Phase Reactance* (calibration)	X_1 = **1.25** mΩ	Electrode Power	P_1 = 11.8 MW	11.8 MW	0%
	X_2 = **1.25** mΩ		P_2 = 12.1 MW	11.9 MW	+2%
	X_3 = **1.25** mΩ		P_3 = 11.8 MW	12.1 MW	-2%
Total Power (measured)	P = 35.8 MW	*Actual X_i, per the figure: 1.28 mΩ, 1.24 mΩ, 1.25 mΩ			

Although the errors in the calculated electrode-to-bath voltage are small – less than 2% – considering a circuit with different parameters shows how easily the error can increase. The circuit presented in Figure 9 has a wider range of total phase reactance, although they are all still within three-tenths of a milliohm. The primary calculation method will be applied to the circuit, again assuming accurate measurements but using equal values of total phase reactance as default calibration values. The results are provided in Table 25.

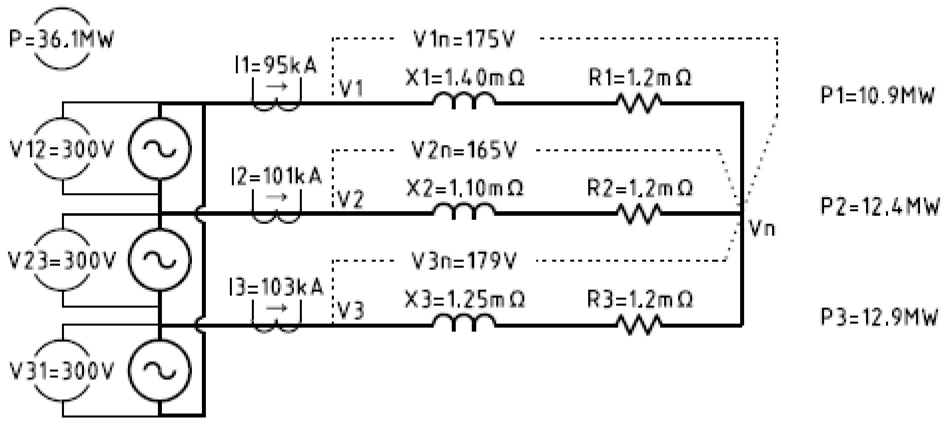

Figure 9: Circuit model with unequal total phase reactance values (actual electrode-to-bath voltages shown)

Table 25: Primary calculation method applied to Figure 9, assuming equal reactance

Primary Calculation Inputs		Primary Calculation Outputs		Actual	Error
Secondary Voltage (measured)	V_{12} = 300 V	Electrode-to-Bath Voltage	V_{1n} = 171 V	175 V	-2%
	V_{23} = 300 V		V_{2n} = 182 V	165 V	+10%
	V_{31} = 300 V		V_{3n} = 167 V	179 V	-7%
Electrode Current (measured)	I_1 = 95 kA	Bath Resistance	R_1 = 1.3 mΩ	1.2 mΩ	+8%
	I_2 = 101 kA		R_2 = 1.3 mΩ	1.2 mΩ	+8%
	I_3 = 103 kA		R_3 = 1.0 mΩ	1.2 mΩ	-16%
Total Phase Reactance* (calibration)	X_1 = **1.25** mΩ	Electrode Power	P_1 = 11.7 MW	10.9 MW	+7%
	X_2 = **1.25** mΩ		P_2 = 13.3 MW	12.4 MW	+7%
	X_3 = **1.25** mΩ		P_3 = 11.1 MW	12.9 MW	-14%
Total Power (measured)	P = 36.1 MW	*Actual X_i values, per the figure: 1.40 mΩ, 1.10 mΩ, 1.25 mΩ			

As demonstrated in Table 25, a larger, but still conceivable error in the total phase reactance calibration has increased the error in electrode-to-bath voltage to 10% on Electrode 2. An even larger error is observed in the electrode power calculations. Considering typical furnace operation where power is meant to be balanced on all electrodes, the primary calculation method would result in an unbalance, with electrode 3 compensating for the calculation and actually drawing too much power.

3.3 Error Analysis with Different Operating Parameters

As in the analysis of error in the secondary, or direct, measurement in Section 2, it is worth examining the error in the primary calculation method for different operating parameters. The next example, provided in Figure 10, considers a furnace operating with a higher resistance than that in Figure 9, with a power factor of 0.9 compared to 0.7 in the previous example. The results of the primary calculation method, presented in Table 26, demonstrate that a furnace with a higher power factor will have less error, and in fact doubling the resistance in the circuit effectively reduces the error by half.

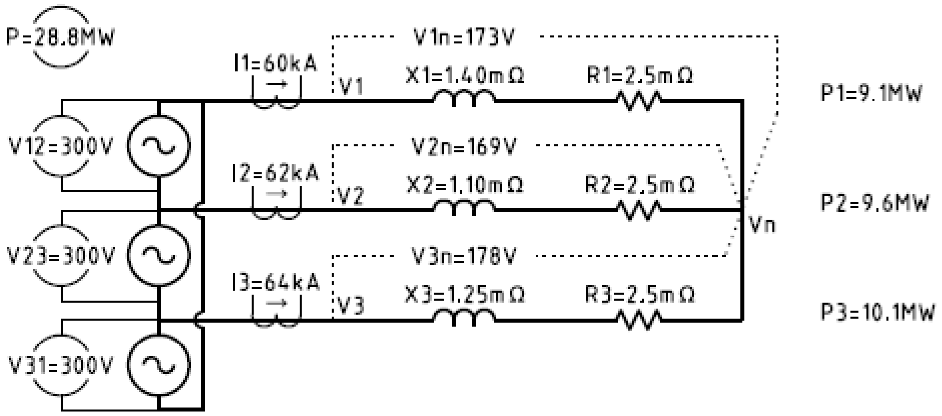

Figure 10: Circuit model with higher power factor

Table 26: Primary calculation method applied to **Figure 10**, assuming equal reactance

Primary Calculation Inputs				Primary Calculation Outputs				Actual		Error
Secondary Voltage (measured)	V_{12} =	300	V	Electrode-to-Bath Voltage	V_{1n} =	174	V	173	V	+1%
	V_{23} =	300	V		V_{2n} =	178	V	169	V	+5%
	V_{31} =	300	V		V_{3n} =	168	V	178	V	-6%
Electrode Current (measured)	I_1 =	60	kA	Bath Resistance	R_1 =	2.6	mΩ	2.5	mΩ	+4%
	I_2 =	62	kA		R_2 =	2.6	mΩ	2.5	mΩ	+4%
	I_3 =	64	kA		R_3 =	2.3	mΩ	2.5	mΩ	-8%
Total Phase Reactance* (calibration)	X_1 =	**1.25**	mΩ	Electrode Power	P_1 =	9.4	MW	9.1	MW	3%
	X_2 =	**1.25**	mΩ		P_2 =	9.9	MW	9.6	MW	3%
	X_3 =	**1.25**	mΩ		P_3 =	9.4	MW	10.1	MW	-7%
Total Power (measured)	P =	28.8	MW	*Actual X_i values, per the figure: 1.40 mΩ, 1.10 mΩ, 1.25 mΩ						

3.4 Loss of Arc and Six-Electrode Furnaces

Loss of arc is a special case which should also be examined in discussing the primary calculation method. In some arcing operations arc loss occurs frequently, often caused by interruptions from feed material, changing bath level or an electrode break. A representative circuit diagram during arc loss is presented in Figure 11.

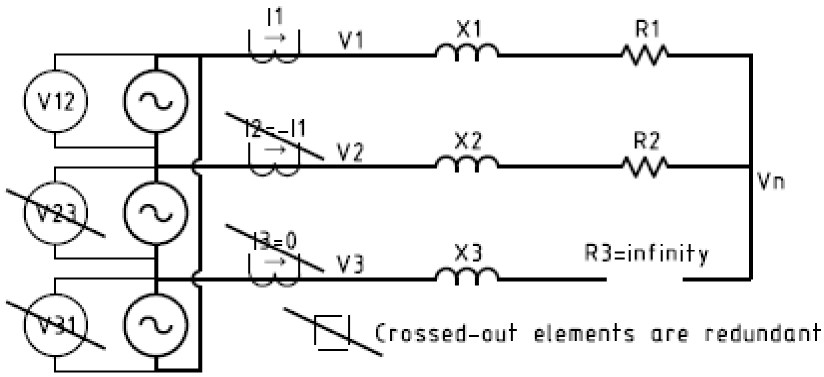

Figure 11: Circuit model for a loss of arc on Electrode 3

During arc loss the three-phase furnace circuit temporarily becomes a single-phase loop. With I_3 equal to zero, it is given that I_2 is now equal and opposite to I_1. In this configuration, the solution to the primary calculation is undefined as there is no longer enough information to determine the electrode-to-bath voltages, V_{1n} and V_{2n}.

The problem stems from the available measurements used in the primary calculation method. As indicated in Figure 11, the measurements include the line-line voltage, V_{12}, and the electrode current, I_1. The other measurements are trivial, in that $V_{23} + V_{31} = V_{12}$, $I_2 = -I_1$, and $I_3 = 0$. The circuit impedance of the loop formed by electrodes 1 and 2 is the sum of that for the two phases, i.e. $R = R_1 + R_2$ and $X = X_1 + X_2$. Given any combination of resistances that sum to the same value (e.g. $R_1 = 2.5m\Omega$ and $R_2 = 2.5m\Omega$, or $R_1 = 1.0m\Omega$ and $R_2 = 4.0m\Omega$, which both sum to $5.0m\Omega$) the measurements at V_{12} and I_1 will remain the same. Consequently, it is impossible to know the electrode voltages, V_{1n} and V_{2n}.

A six-electrode furnace consists of three single-phase loops, as the furnace circuit diagram demonstrates in Figure 12. By extension of the single-loop analysis for loss of arc, it is evident that measurements of line-line voltage and electrode current will not be sufficient to determine the individual electrode voltages. It is thus necessary for six-electrode furnace control systems to use direct measurement of electrode-to-bath voltages.

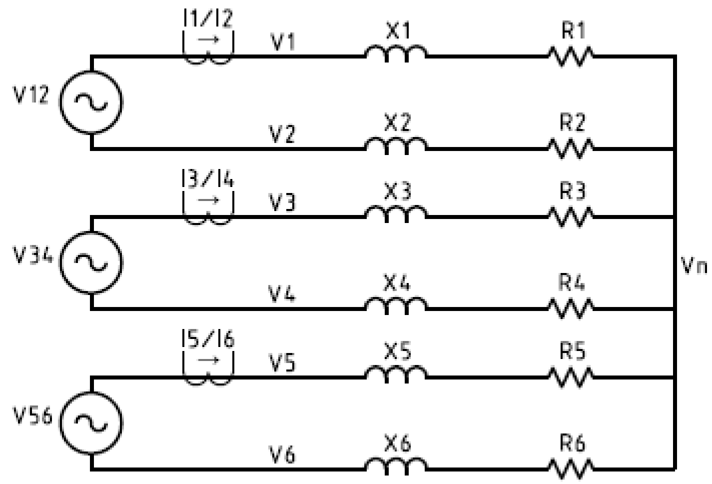

Figure 12: Six-electrode furnace model

4 Conclusion

In an electric furnace there are two methods of obtaining the electrode voltages needed for control: direct measurement from electrode-to-bath on the secondary side of the furnace transformer, or calculation using measurements from the primary or high-voltage side. The former method is affected by an induced voltage error caused by the high currents in the electrodes. Because of this error the latter is often cited as the preferred choice. However, the accuracy of the primary calculation method quickly falters when the reactance of the system is not known precisely.

A practical implication of an error in electrode voltage measurement is the possibility of unequal power distribution within the furnace. Assuming balanced heat under each electrode is desired, an operator would enter an equal resistance setpoint for each electrode. If the measurement of electrode voltage is not accurate, however, what the control system presumes is equal resistance will actually be unbalanced. This will result in uneven heating of the furnace and increased wear and maintenance requirements. Choosing the best option is thus important, and will depend on the furnace and the preferred operating point. Hatch has prepared furnace control software that offers both methods with the desired method selectable from the operator screen which allows the user to determine and test the best method for their furnace.

Considering direct electrode-to-bath voltage measurement, a calculation of the induced voltage caused by 100 kA in a single electrode suggests that errors in the direct electrode-to-bath voltage measurement can be as high as 12%. However, expanding the analysis to account for the other electrodes in the system demonstrates that the induced voltage error may actually be as low as 7%. Further, an error this large is possible only on a subset of furnaces with very high electrode currents and low voltages. Furnaces with electrode currents less than 50kA can expect less than 5% error from induced voltage.

As discussed in this paper, the primary calculation method can be used to estimate the electrode-to-bath voltages using measurements from the primary of the furnace transformer, where induced voltage is not a significant issue. The primary calculation method has been shown to be very accurate, assuming that the reactances of each phase are known precisely. However, estimating reactance is not straight-forward, and errors of only a few tenths of a milliohm can cause greater than 10% error in the calculated electrode-to-bath voltage.

The percentage error in the primary calculation method is reduced in furnaces with higher power factor, but these furnaces tend also to have lower currents and would thus experience less error in a direct measurement as well – choosing between the two methods remains unclear. The primary calculation method does fail, however, when there is a loss of arc, and is never applicable to six-electrode furnaces. In these cases, only the direct measurement offers valid measurements. In three-electrode furnaces where arc loss is not frequent, though, consideration can be given to both options.

5 References

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