Inductive reactance, and the operation of large submerged-arc furnaces

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SYNOPSIS

Traditionally it has commonly been believed that the only problem with inductive reactance in a submerged-arc furnace is that it leads to difficulties with the electricity supply as a result of the low power factor. This paper sets out to show that inductive reactance can also give rise to the following problems in the metallurgical operation of a furnace:
(i) dead and live phases (fairly well known in open-arc furnaces),
(ii) lack of sensitivity to electrode movement,
(iii) interactions between electrodes.

These problems increase with increasing inductive reactance relative to resistance, and thus they increase with furnace size. Each of these effects is discussed in detail, and suggestions are made for their alleviation.

SAMEVATTING

Daar is tradisioneel algemeen geglo dat die enigste probleem met induktiewe reaktansie in 'n dompelboogoond is dat dit lei tot probleme met die elektrisiteitsvoorsiening as gevolg van die lae arbeidsfaktor. Die doel van hierdie referaat is om te toon dat induktiewe reaktansie ook tot die volgende probleme in verband met die metallurgiese bedryf van 'n oond aanleiding kan gee:
(i) dooie en lewendige fases (redelik goed bekend in oopboogoonde),
(ii) gebrek aan gevoeligheid vir elektrodebeweging,
(iii) wisselwerking tussen elektrodes.

Hierdie probleme neem toe met toenemende induktiewe reaktansie relatief tot weerstand en gevolglik neem hulle toe met die oondgrootte. Elkeen van hierdie effekte word in besonderhede bespreek en voorstelle vir die verligting daarvan word aan die hand gedoen.

Introduction

Electric-arc furnaces have been used for many years both for the melting of scrap iron (open-arc furnaces) and for reduction processes (submerged-arc furnaces). In the latter type of furnace, ore and reducing agent are fed to the furnace continuously from the top so that the electrodes are buried in the mix and the arc is submerged; hence the term *submerged-arc* furnace. The most common physical arrangement consists of a circular bath with three vertical electrodes arranged in a triangle. Six-electrode furnaces with circular or rectangular baths, although also used, are less common.

The economic benefits of reduced running costs with larger furnaces has resulted in a proliferation of the larger types, while the older, smaller furnaces are phased out of operation. With increasing size of furnace, the ratio between the reactance and the resistance of the furnace increases, resulting in a lower power factor. This is shown in Table I, where the resistances and reactances of two sizes of furnace are compared. It is generally assumed that a low power factor can be corrected for by the inclusion of capacitors across the high-voltage section of the circuit and that, apart from the added capital cost of the capacitors and larger transformers, the problem can be solved. However, this is not correct, since a high relative reactance in the circuit also has a significant effect on its operation and control. This problem is aggravated by the difficulty of measuring the individual phase resistances and reactances of the circuit[1, 2].

Because the effects of inductive reactance are really significant only on large submerged-arc furnaces, it is only in recent years that they have given rise to difficulties. Consequently, there are many furnace operators today who are unaware of the cause of these difficulties. A reactance problem (an imbalance for example) is often diagnosed as a purely metallurgical problem, and the remedial action taken is therefore of very little beneficial effect. Because such problems appear to be stubbornly resistant to treatment, an understanding of their causes and how they can effect the metallurgical operation of the furnace is essential.

The Furnace Circuit

The electrical energy fed to a furnace is dissipated as a combination of arc and resistive heating and, since these are low-voltage mechanisms, high currents must be used for the introduction of sufficient energy into the furnace. The high-voltage, low-current power provided by the supply authority is transformed to a low-voltage, high-current form close to the furnace, and busbars of high-current capacity carry the current between the transformers and the electrodes.

The most common configuration is the so-called 'knapsack' connection, in which the secondary busbars from each transformer that carry the 'go' and 'return' current are kept close together (usually they are interleaved) until they are close to the electrodes, where they open up and are connected in delta to the electrodes. An example of the connection arrangement for a large furnace is shown in Fig. 1, in which three single-phase transformers are placed on one side of the furnace building. Sometimes the three transformers are placed

TABLE I

COMPARISON OF TYPICAL RESISTANCES AND REACTANCES FOR SUBMERGED-ARC FURNACES PRODUCING SIMILAR PRODUCTS

Parameter	12 MVA furnace	48 MVA furnace
Resistance, mΩ	1,8	1,2
Reactance, mΩ	0,7	1,1
Power factor	0,93	0,74

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*National Institute for Metallurgy, Randburg, Transvaal.

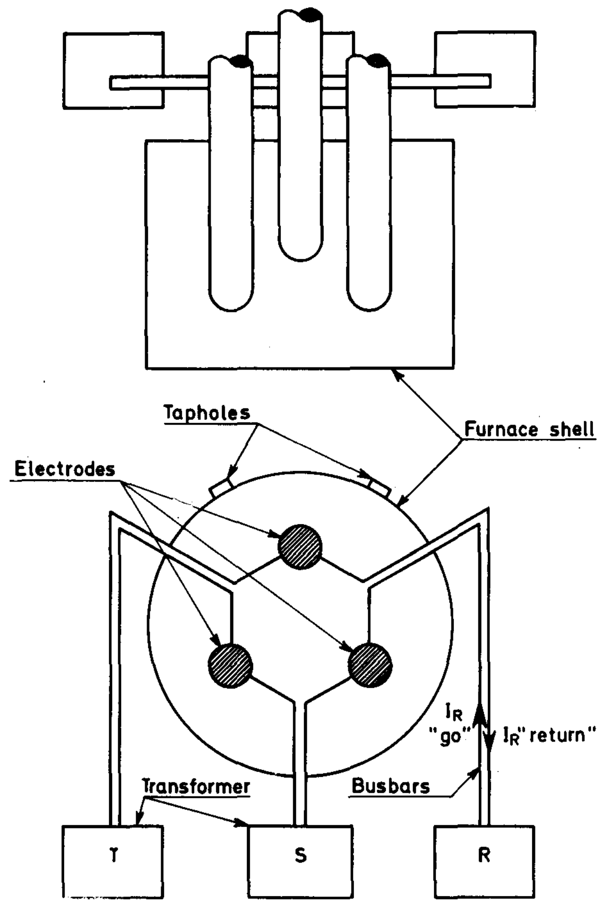


Fig. 1—Typical layout of the electrical circuit of a submerged-arc furnace

symmetrically round the furnace so that the busbars are shorter and equal in length, and this provides a more balanced circuit. On smaller furnaces a single three-phase transformer is used.

In the bath of a furnace, conduction occurs mainly between the tips of the electrodes and the metal pool[3, 4]. The bath thus forms a star circuit, with the metal pool as the star point. Although a small portion of the current flows directly between the electrodes, little error is caused in the modelling of the furnace if this current is regarded as part of the star conduction. The raising or lowering of an electrode affects the resistance between the tip and the bath in that phase.

When the transformers and busbars are connected in delta to the electrodes, which together with the furnace bath form a star circuit, the equivalent circuit should be represented in combined delta-star form. Fortunately, the delta parts of the circuit are constant; they can therefore be represented in their transformed star form, and the equivalent circuit reduces to the simple star representation shown in Fig. 2. The total resistance and reactance in each phase are lumped together and fed in delta from a three-phase a.c. supply.

Reactance

Reactance, generally denoted by the symbol X is always associated with a.c. circuits, and the majority of the reactance in a furnace is caused simply by magnetic inductance; that is, the current in the conductors creates a magnetic flux round them and, as this flux changes, so it induces a voltage along the conductor. In addition, arcing in the furnace makes a minor contribution to the reactance.

The reactance due to magnetic inductance depends only upon the geometry of the conductors and the degree of magnetic saturation of any iron (or similar material) in the vicinity; the reactance of the furnace is thus reasonably constant. This reactance can be calculated, although the geometry of a furnace tends to make the calculation rather complicated. If a conductor carrying a current is placed next to the return conductor carrying the same current in the opposite direction, the magnetic fluxes cancel each other, and the induced

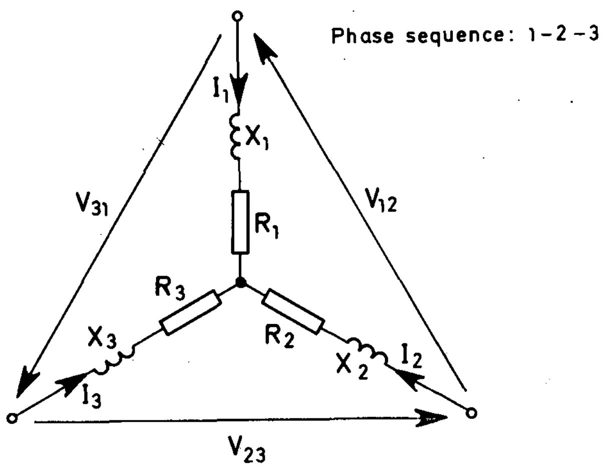


Fig. 2—Equivalent circuit of a submerged-arc furnace

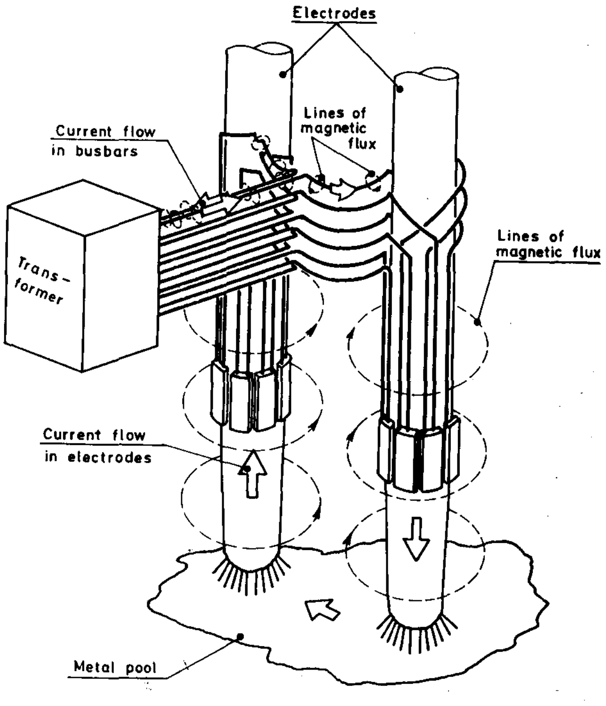


Fig. 3—Cut-away view of one circuit of a submerged-arc furnace, showing the location of the magnetic fields that cause inductance (structural detail and burden not shown)

voltage (and hence the reactance) is decreased. The reduction of busbar reactance in a knapsack connection is based on this fact. Because the electrodes are spaced relatively far from one another, the major portion of the reactance in the circuit, generally called the 'reactance window', occurs after the busbar opening. This window (shown in Fig. 3) includes the flexible connections to the electrodes, the electrodes themselves, and the metal bath beneath them. For this reactance to be as small as possible, the busbar opening point must be close to the electrodes, the distance between the flexible connection to the electrodes and the metal bath must be as short as possible, and the electrodes must be close together.

Reactance should not be confused with resistance, although they are measured in the same units. Reactance also obeys an Ohm's-law type of relationship:

$$X=E_{\mathrm{rms}}/I_{\mathrm{rms}}, \tag{1}$$

where E_{rms} is the voltage induced in the circuit by the current I_{rms}. With inductive reactance, the phase of the waveform of the induced voltage leads that of the current by 90° ($=\pi/2$ radians), whereas with a resistor the two phases are the same. As a result of this, the phasor of the voltage across the reactance lies 90° anticlockwise from the phasor of the current through the reactance. With a resistor, the phasors of the current and the voltages are parallel.

Problems Caused by Reactance

Reactance problems are associated with large furnaces, for in small furnaces the effects are usually insignificant. The reason for this can easily be seen from an examination of the effects of furnace size on the average resistance, R, and reactance, X. From Kelly and Andreae type of formulae[5], R varies inversely with electrode diameter, D, for a given specific electrode resistance:

$$R \propto D^{-1}. \tag{2}$$

For a fixed ratio of electrode diameter to electrode spacing, X is proportional to the electrode length (if the effects of arcing are ignored), which is related to electrode diameter, so that

$$X \propto D^{+1} \tag{3}$$

and thus

$$X/R \propto D^{2}. \tag{4}$$

Obviously, as D increases, a point is reached where the reactance becomes noticeable, and the problem then rapidly becomes worse with increasing D.

The term *low power factor* is synonymous with *high reactance relative to the resistance*. Problems caused by a low power factor can be divided into two groups:

(i) problems with the power supply, i.e., transformer size, phase-correction capacitors, and the supply authority;
(ii) problems with the operation and control of the furnace.

The problems with the power supply are relatively well known and well understood, and were often believed to be the only trouble arising from high reactance. The problems with operation and control are more difficult, and there are three main problems:

(a) the dead-phase and live-phase phenomenon,
(b) the lack of sensitivity to electrode movement, and
(c) the interaction effects between electrodes.

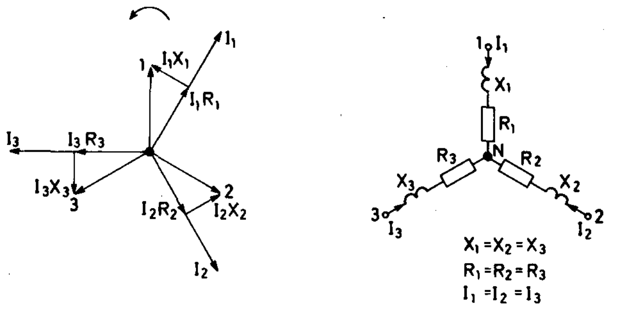
Dead and Live Phases

Dead and live phases are caused by imbalances in the reactances and are better known in open-arc steelmaking furnaces, where they cause uneven erosion of the refractories. They also occur in submerged-arc furnaces but tend to be misinterpreted under normal operation.

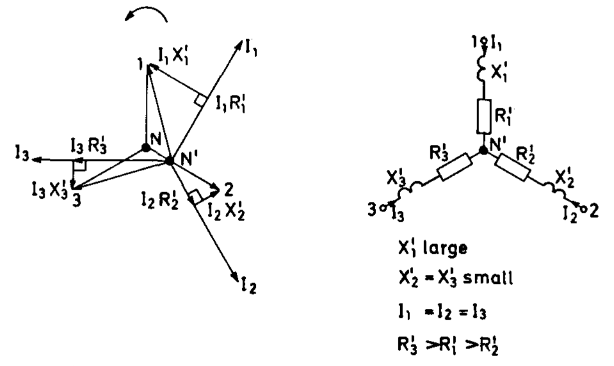
In the circuit arrangement shown in Fig. 1, the busbar connections for the R and T transformers are longer than that of the S phase and, even though the reactance in the busbars is minimized by interleaving of the 'go' and 'return' conductors, there is an asymmetry in the reactance. The asymmetry could be avoided if the transformers were placed in a triangular arrangement round the furnace so that the busbars were of equal length, but this could make access to the electrode structure difficult. An additional asymmetry occurs if the furnace is tapped from one side, since the metal tends to flow downwards towards the taphole from the rear electrodes so that the current path for the front electrode tends to be longer than that for the other two electrodes. A third source of asymmetry in reactance results from an imbalance in the relative amount of arcing in each phase.

When a furnace is run with equal currents in the phases, the resistances must be unbalanced to compensate for the unequal reactances. If the phase rotation is 1–2–3 and electrode one has a higher reactance than the other two phases, then the power in phase two (dead phase) will be lower than the power in phase one, and phase three (live phase) will have a higher power.

This phenomenon can be seen from the phasor diagrams shown in Fig. 4, which are based on a simple star-equivalent circuit. In Fig. 4(a) the furnace is shown as completely balanced, with the reactances equal and



(a) Balanced furnace



(b) Unbalanced furnace
(dead and live phases)

Fig. 4—Phasor diagrams demonstrating dead and live phases

the resistances equal, the result being equal currents in each phase. If there is an increase of reactance in phase one at the same time as the reactances in the other two phases are reduced, the reactances become asymmetrical. The resistances in phases two and three are adjusted so that the currents remain equal. This is shown in Fig. 4(b), where the neutral has shifted from the centre, N, to N′ and the resistances are unbalanced so that

$I_1R'_1=I_1R_1$ (no change)
$I_2R'_2<I_2R_2$ (dead phase)
$I_3R'_3>I_3R_3$ (live phase)

and, since the currents are the same, $R'_3>R'_1>R'_2$. Consequently, with the power in each phase, $P'_3>P'_1>P'_2$.

In a submerged-arc furnace, dead and live phases usually result in a consistent imbalance in the consumption of raw materials as a direct result of the differing amounts of power being dissipated in the phases. Another effect of unbalanced resistances is that one electrode will consistently ride higher in the furnace than the other two. In extreme cases, such an electrode may be so far out that the metal bath freezes up and causes difficulties in tapping. If this occurs, that electrode should be run at a lower resistance. The main danger with dead and live phases is that they easily lead to gross imbalances on large furnaces, and this is most undesirable as is shown below.

Lack of Sensitivity to Electrode Movement

The lack of sensitivity resulting from high reactance can be seen from the circuit shown in Fig. 5 and the equation for one phase of a three-electrode furnace:

$$I=\frac{V}{\sqrt{R^2+X^2}} \quad \dots\dots\dots\dots\dots \quad (5)$$

Equation (5) is plotted graphically in Fig. 6, with $I_{\text{max}}=V/X$. It should be noted that the slope of the curve becomes less as R/X becomes smaller. This means that the current is relatively less sensitive to changes in resistance in a furnace where X is large than in a furnace where X is small. This means that, with a furnace under current control, the electrodes have to move further to correct for changes in the currents.

By far the most serious problem with this sensitivity occurs during a bad imbalance of the furnace. During such an imbalance, it can happen that the current in an electrode cannot be maintained, even though the electrode is so far down that the variable resistance in that phase has been reduced to zero. This is because the reactance in that phase is limiting the current. In Fig. 6, the cases can be compared where R/X is normally around 1,0 ($I/I_{\text{max}}=0,7$) and where R/X is normally around 2,0 ($I/X_{\text{max}}=0,45$).

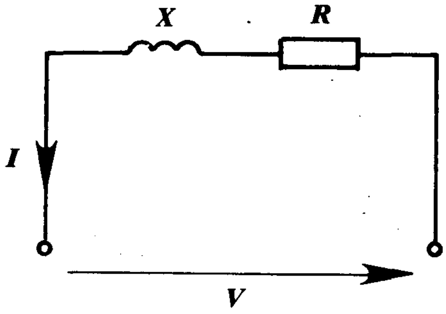


Fig. 5—Circuit for one phase of a three-electrode furnace — see equation (5)

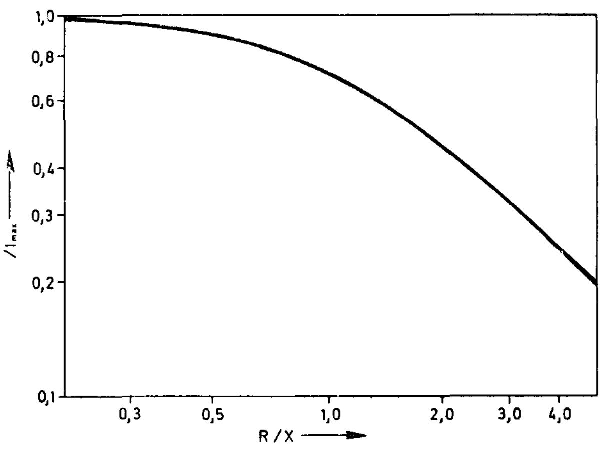


Fig. 6—Sensitivity of current to ratio between resistance and reactance

In the first case a reduction of resistance from its normal value to zero results in a current increase (i.e., I to I_{max}) of only 43 per cent, whereas in the second case an increase in current of 122 per cent will occur. With a furnace under current control during unbalanced conditions, the low ratio of resistance to reactance results in a situation in which a small imbalance in the currents can cause relatively large changes in the resistances (and hence powers) in each phase, thus aggravating the unbalanced conditions.

Interaction Effect

The interaction effect is the somewhat unexpected interaction between the movement of one electrode and the currents and powers in the other electrodes. In the most common furnace arrangement, three-phase power is fed through three electrodes to a bath of molten metal, which forms the neutral point for the circuit. With only three connections to the neutral point, changes in one phase have a significant effect on the other two phases, particularly when the ratio of reactance to resistance is high. This interaction can be seen on a furnace when one of the electrodes is moved deliberately. If the electrode is raised (thus increasing the resistance), the current in that phase drops as expected. However, at the same time, the current in the previous phase in the phasor rotation also drops, but the third phase remains almost unaffected. This is illustrated in Table II. The interaction with the powers in each phase (as shown) is even more difficult to predict intuitively.

To show how the amount of interaction increases with reactance, the following example can be considered.

Assume that the furnace circuit can be represented by the star-equivalent circuit shown in Fig. 2, that the circuit is driven by live voltages V_{12}, V_{23}, and V_{31}, which remain constant at 300 V, and that the normal operating current for the furnace is 100 kA in each phase. The circuit is then deliberately unbalanced by the forcible reduction of the current in phase two to 80 kA while the currents in the other two phases remain at 100 kA. Now consider the effect of an increase in the relative reactance in the circuit by setting $X_1=X_2=X_3=X$, changing X from 0,0 to 1,4 mΩ, and calculating the power in each phase as a percentage of the total circuit power. The results are summarized in Fig. 7.

At low reactances the current imbalance has little effect on the power balance. However, as the reactance is increased, the power imbalance becomes increasingly more severe until, at a reactance of about 1,35 mΩ, there is no power at all in phase one and a large amount of power in phase three. It should also be noted that the phase with the low current is not the phase with the lowest power, and in fact this phase is relatively insensitive to changes in reactance.

The basic trouble with interactions is that, if one electrode is abnormal, it affects the other two phases, and these phases in turn may become abnormal.

Unfortunately, in the day-to-day operation of a furnace, the effects of interactions are difficult to predict without fairly sophisticated calculating facilities. Because of this difficulty, it is better to try to keep a large furnace as balanced as possible, thereby avoiding the difficulty. However, if an imbalance does occur, it must be carefully handled to avoid any subsequent troubles, and the following is a convenient rule of thumb that works satisfactorily. If an electrode is short so that the resistance in that phase is high, the current for that electrode will be lower than normal. If this lower current persists, then the current setpoint in the previous phase in the phasor rotation should be set to about midway between the normal current and the current in the low-current phase. This will keep the resistances under the two normal electrodes reasonably balanced, and therefore should not introduce any further troubles through these electrodes in turn becoming abnormal.

TABLE II

AN EXAMPLE OF INTERACTION BETWEEN PHASES

Parameter	Phase 1	Phase 2	Phase 3
*Balanced furnace (calculated)**			
Resistance, mΩ	1,2	1,2	1,2
Current, kA	100,0	100,0	100,0
Power, MW	12,0	12,0	12,0
*High resistance in phase three (calculated)**			
Resistance, mΩ	1,2	1,2	2,0
Current, kA	102,0	88,7	81,1
Power, MW	12,5	9,5	13,1
Thus;			
Changes in current from balanced state, kA	2,0	−11,2	−18,9
Comparable changes on an actual furnace (measured and averaged†);			
Current before change, kA	103,4	97,5	96,8
Current after change, kA	103,8	88,2	78,0
Thus;			
Change in currents, kA	0,4	−9,3	−18,8

*Standard conditions: 300 V phase ot phase, X=1,25 mΩ.

†The values were recorded on a 48 MVA ferrochromium furnace under conditions close to those used for the calculations above. Electrode three was twice raised and lowered to achieve changes comparable to the calculated changes, and the effects were averaged to obtain the results shown here.

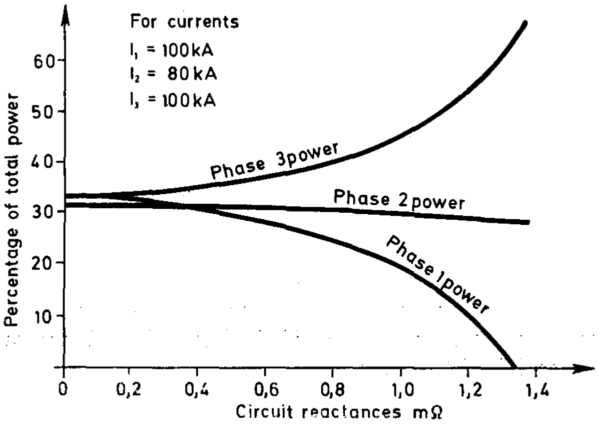


Fig. 7—Relative power in each phase versus circuit resistance for unbalanced circuits

Discussion

With all the problems outlined above, increase of the reactance relative to the resistance in a furnace increases the severity of the problem. This is aggravated by the fact that on large furnaces measurements of the voltages between the electrodes and the furnace bath are severely distorted by induced voltages in the measuring leads as a result of the high currents flowing in the circuit. This affects the measurement of the resistances and powers in each phase so that, during unbalanced operating conditions in the furnace, the furnace operator (and the electrode controllers if they are working on resistance or impedance control) receive a distorted measurement of the power distribution. The control action to rectify the imbalance is therefore generally incorrect, and can lead to a more unbalanced situation. In practice, operators are generally well aware of the inaccuracies of the measurements of resistance (and hence of power), and tend to ignore these measurements and rely solely on current measurements for control of the furnace. On a large furnace with a high ratio of reactance to resistance, this can have disastrous consequences.

One way of physically overcoming the reactance problem in the design of a furnace is the use of series capacitors on the supply to the furnace. In an a.c. circuit, a capacitor behaves in the opposite way to an inductor, in that the phase of the voltage across the capacitor lags (instead of leads) the current by 90° and the inductive reactance is therefore cancelled by the capacitive reactance. This is irrespective of the state of balance of the furnace.

An alternative way of overcoming the reactance problem in the operation of a furnace is to use d.c. or low-frequency a.c. instead of mains-frequency a.c. in the feeding of power to the furnace. With the recent developments in high power a.c. to d.c. converters, this alternative has become an economic possibility. However, the use of d.c. energy affects other aspects of furnace operation that can cancel out the advantage gained.

Conclusions

(1) Inductive reactance is a phenomenon that becomes more significant with increasing size of furnace. The problems arising from reactance extend beyond the problems arising from power supply, for they also affect the metallurgical operation of the furnace. The three main problems with reactance are dead and

live phases, insensitivity to electrode movement, and interaction between phases. All these problems become aggravated by increasing reactance.

(2) Dead and live phases are the result of a fundamental imbalance in the inductive reactance in each phase. The effect is that, at balanced currents, the resistances, and hence the powers in each phase, are unbalanced. Although the phenomenon is well known in open-arc furnaces, it tends to be misinterpreted in submerged-arc furnaces.

(3) Insensitivity to electrode movement, or insensitivity of the currents to changes in resistance, worsens as the reactance becomes more significant. In the extreme case, the achievement of the current set-point desired by the electrode controllers may not be possible, even though the electrode has been pushed so far down that it is in direct contact with the metal bath.

(4) Interaction between phases, or the effect that the movement of one electrode has on the currents and powers in the other two phases, is particularly significant during furnace imbalances, and is very difficult to handle effectively. It is not well understood, and frequently other unrelated factors are blamed for its effects.

(5) If inductive reactance problems are to be overcome, large furnaces should be designed with as low an average reactance as possible. In addition, efforts should be made to balance the reactances at the design stage. Capacitors in series with the power supply help by cancelling out the effects of the inductive reactances on the operation of a furnace. Given an existing furnace with a high reactance problem, special attention should be paid to the maintenance of the balance of the furnace whenever possible. If it becomes unbalanced, it must be handled correctly with due regard to the interaction effects.

Acknowledgement

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  measurement techniques for the above processes; use and design of sensors, data acquisition and telemetery systems.
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