A SOLUTION TO MEASUREMENT PROBLEMS AND INTERACTION EFFECTS IN THE CONTROL OF SUBMERGED-ARC FURNACES

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(presented by Dr. Stewart)

SYNOPSIS

This paper describes a new type of microprocessor-based electrode controller that was specifically designed to overcome problems with the measurement and control of the variables in large submerged-arc furnaces. The nature of these problems is discussed, and the *modus operandi* of the new controller is explained.

Introduction

In another of the papers presented at this congress, Sommer *et al.* describe the research work conducted by the National Institute for Metallurgy (NIM) on the computer-aided control of submerged-arc furnaces[1]. One aspect of this work was the identification of a problem area in the control of electrodes on large furnaces and the subsequent development of a controller, based on a microprocessor, to overcome these problems.

Over the past decade, the need for increased economy and the improvements in technology have resulted in a dramatic increase in the size of submerged arc-furnaces. As the furnace sizes have increased, so the typical power-factors have decreased, and this evolution has led (among other things) to the emergence of subtle problems in the behaviour of the high-power circuit of the furnace and in the control of the electrodes. Unfortunately, these problems are not detectable in themselves but cause troublesome secondary effects, with the result that many furnace operators are unaware that the source of their troubles lies in the electrical circuit and the control of the electrodes.

Furnace size

The effect of furnace size on the nature of the electrical circuit is illustrated in Table 1, in which some typical operating parameters on a small (9 MVA) furnace are compared with the same parameters on a large (48 MVA) furnace producing the same product. The ratios in the last two columns summarize the major electrical difference between large and small furnaces. A high reactance-to-resistance ratio (such as that on the large furnace) is significant since it gives rise to problems in the operation of the furnace because of a phenomenon called the interaction effect, while an increase in the current-to-voltage ratio (also associated with increased

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furnace size) causes larger errors in the measurements of electrode-to-bath voltages, and these errors seriously affect the accuracy of the measurements of real power and resistance in each phase.

Equivalent circuit

The electrical energy for a submerged-arc furnace is taken from a three-phase high-voltage supply and converted to a low voltage by transformers situated close to the furnace. The most common wiring arrangement is the "knapsack" connection, in which the secondary windings of the transformer are connected in delta (by way of interleaved busbars to reduce the reactance) to the electrodes, which then form a star connection to the molten bath in the furnace. The circuit is usually represented by the star equivalent-circuit shown in Figure 1, in which all the elements of the circuit are lumped into a reactance and a resistance in each phase of the star as shown[2]. All delta elements in the circuit are converted to their equivalent star form, and the driving voltages from the three-phase supply are assumed to have negligible source impedances. The molten bath of the furnace is represented by the neutral point N and is not connected to the supply. The potential of this point thus floats to a value such that the phasor sum of the resulting currents in the three electrodes is zero.

Measurements on a furnace

The accurate measurement of the electrical variables in the secondary circuit of a furnace is difficult owing to the error voltages that are induced magnetically in the voltage-measurement leads to the electrodes and the bath by the high currents flowing in the electrodes[3]. This problem is worse on large furnaces (which, as shown in Table 1, have a higher current-to-voltage ratio than smaller furnaces), and errors of up to 20 per cent of the values measured are possible. With inaccurate values for electrode-to-bath voltages, it is not possible to obtain accurate values for phase powers or resistances, so that control of the electrodes from resistance or power is unsatisfactory. This has resulted in the widespread use of current control, particularly on large furnaces.

Various techniques have been developed to reduce errors in the measurement of electrode-to-bath voltages in a furnace so that accurate phase powers and phase resistances can be determined[4,5]. However, these methods depend on reliable connections to the furnace bath, and these are not always possible. Neutral connections to the furnace bath are usually made by the imbedding of a metal (copper or stainless-steel) conductor in the carbon lining of the furnace and leading this out through the refractory lining and furnace shell to a terminal on the outside. During normal furnace operation, the carbon lining is usually extremely hot (900 to 1400° C), and it is thus difficult to ensure a reliable neutral connection particularly over the entire life of the furnace lining (which is usually about five to ten years). It has also been found that, if the lowest error is to be obtained in the values for electrode-to-bath voltages, separate neutrals have to be installed for each phase directly under each electrode, which, unfortunately, is the hottest region of the carbon lining.

Interaction effect

Because the neutral point in a furnace circuit is not connected to the supply, a variation in the resistance in one of the phases (as might result from the movement of an electrode) causes the potential of the neutral point to change, and consequently affects the currents and powers in all three phases[4,6,7]. This interaction between the movement of one electrode and the currents and powers in all three phases is not balanced, and this imbalance becomes worse as the reactance-to-resistance ratio increases, which results in this effect being more pronounced on larger furnaces.

Consider a condition in which electrode 2 of a furnace is short so that it operates on the "bottom stop" of its hoist, and its current is only 80 per cent of the set-point current. If the other two electrodes are operating under error-free resistance control, they will not be affected by this short electrode, but, if they are under current control, they will have been moved so that their currents are equal to the set-point current. The extent of this resulting imbalance under current control is shown in Figure 2 for seven different sizes of furnace producing the same product. For each furnace, the relative power in each phase expressed as a percentage of the total power is computed for a current in Phase 2 set at 80 per cent of the rated current, whereas the other two phases carry rated current. For the smallest furnace (9 MVA), the low current in Phase 2 has little effect on the power distribution, since each phase has approximately 33 per cent of the power. However, as the furnace size increases, the same percentage imbalance of current results in a progressively more unbalanced furnace, and on the largest furnace (78 MVA) the imbalance is fairly severe. It should also be noted that the phase with the least current (Phase 2) is not the phase with the least power (Phase 1).

Highly unbalanced conditions in the furnace can lead to problems in the operation of the furnace, such as difficulties in tapping, broken electrodes, high rates of electrode erosion, and similar troubles. Unfortunately, the imbalance caused by the interaction effect is not obvious from the conventional instruments in the control room, so that the imbalance often goes unnoticed until the problems start to appear. Also, the extent of the imbalance increases as the reactance-to-resistance ratio increases, which is why large furnaces are more prone to these problems than are small furnaces.

Reactance assumptions

It would be most desirable to be able to determine the resistances (and related variables) in each phase of a furnace circuit without the inherent inaccuracies associated with the connection to the furnace bath. A voltage balance between each pair of electrodes in the equivalent circuit shown in Figure 1 gives the following expressions :

$$R_1 i_1 + jX_1 i_1 - R_2 i_2 - jX_2 i_2 = V_{12} \quad \ldots\ldots\ldots\ldots (1)$$

$$R_2 i_2 + jX_2 i_2 - R_3 i_3 - jX_3 i_3 = V_{23} \quad \ldots\ldots\ldots\ldots (2)$$

$$R_3 i_3 + jX_3 i_3 - R_1 i_1 - jX_1 i_1 = V_{31} \quad \ldots\ldots\ldots\ldots (3)$$

It should be noted that the line voltages V_{12}, V_{23}, V_{31} can be determined accurately since their measurement does not involve the formation of a measurement loop round which a voltage can be induced. These voltages can, in fact, be determined accurately from primary measurements if the transformer turns-ratios are known. In a similar manner, the secondary currents i_1, i_2, i_3 can be determined from measurements of the primary current. Therefore, all the voltages and currents in equations (1), (2) and (3) can be determined accurately from primary measurements. The sum of equations (1), (2) and (3) shows that

$$V_{12} + V_{23} + V_{31} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

This means that the equations are not independent and therefore cannot be solved for R_1, R_2, R_3 and X_1, X_2, X_3, even though all the voltages and currents are known. If, however, some assumption is made about the interrelationship between the reactances, i.e.,

$$aX_1 = bX_2 = cX_3 = X \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where a, b and c are constants or known functions, then equations (1), (2), and (3) can be solved for R_1, R_2, R_3 and X.

This method of determining the resistance and powers for each electrode is based solely on primary measurements that are accurate and easy to maintain; however, it depends on the reliability of the reactance assumption (equation (5)).

Electrode controller

As a result of the problems associated with the direct control of the electrodes on a furnace either by current control (in which case interaction effects will give rise to operational problems) or by resistance or impedance control (that incur the effects of large errors in measurement), an electrode controller was developed that controls the furnace on resistance control based on values calculated from the primary measurements by means of the reactance assumption method[8]. This type of controller has become feasible with the advent of microprocessor technology.

In the prototype unit, the assumption used was simply that the reactances are equal to one another (but not necessarily constant), i.e. a=b=c in equation (5). Each reactance in the circuit is the sum of the reactances caused by two separate phenomena : the response of the magnetic inductance to the a.c. supply, and the non-linear behaviour of the arcs in the a.c. circuit[4,9]. The magnetic inductances depend on the geometry of the conductors that make up the circuit, and consequently remain relatively constant. The arcs, on the other hand, tend to fluctuate, but, as their contribution to the total reactances is no more than about 5 to 10 per cent, these fluctuations are relatively insignificant. Thus, provided the design of the furnace is reasonably symmetrical, the reactance assumption is reasonably justified.

More recent models of the controller include a facility that compensates for consistent imbalances in the reactances; for example, in some furnaces the electrode closest to the tapholes has a higher reactance than the other two electrodes, which under balanced current control causes a "live" and "dead" phase effect[4].

Limits of operations

In addition to controlling the electrode hoists on the basis of the calculated resistances, the electrode controller controls the tap-changers on the transformers. This provides an additional degree of freedom in that the controller is able to maximize the power input to the furnace within the constraints imposed by the limits of operation of the furnace equipment.

The control is based on the well-known power-current operating characteristics for a furnace[10] as shown in Figure 3. If the furnace is operated at constant resistance, the operating point in Figure 3 will lie on the parabolic line shown, and, if the transformer secondary voltage is increased by a change in the taps, both the electrode current and the furnace power will increase. Eventually one of four limits will be reached : maximum electrode current (vertical broken line), maximum transformer volt-ampere limit (MVA limit), maximum transformer voltage, maximum real power (horizontal line). The first three of these limits depends on the furnace equipment and is usually fixed for a particular operation, although the electrode controller permits all the limits to be set individually by the operator. The curves in Figure 3 apply to single-phase operation but the concepts can easily be extended to three-phase operation. The controller operates on the basis of maintaining the resistances as close as possible to the resistance setpoints and then adjusting the transformer-tap position so that the furnace operates against one of the limits of operation, although the actual limiting factor may change from one variable to another as the state of the furnace changes.

Operation of the electrode controller

The electrode controller consists of a cabinet the size of a small control desk and is completely self-contained[11]. The input signals are the three primary a.c. line-voltages, the three primary a.c. currents, the transformer-tap position, and the hoist-position signals for the three electrodes. The voltages and currents are converted to d.c. signals in the controller, and the total real power is measured and converted to a d.c. signal. These signals are read in by the computer, which then computes the phasor relationship between the voltages and the currents as shown in the appendix. The resistances are then determined by the use of the reactance assumption, and any control action needed on the electrode hoists to correct these resistances is performed accordingly. The four factors that may limit the operation are also examined and, if necessary, control action is taken on the transformer taps. The output signals are raise and lower signals for each hoist-position actuator and raise and lower signals for the actuators on the transformer tapchangers. The resistance setpoints and limits of operation are set by the operator via thumbwheel switches on the controller panel, and are read into the computer and stored in the memory. The controller also provides for several variables of interest to the operator to be displayed on a display panel, and this information is supplied by the computer system. A complete scan sequence, calculation of resistances and other variables, and control action (if any) are repeated at one-second intervals, although the display panel is updated less often to make it easier to read. To avoid unnecessary control actions, the resistances and limits of operation are allowed to vary within small dead bands round the set points without control action being taken, and the signals are filtered digitally to remove short-term variations.

Electrode baking control

The electrodes used on most submerged-arc furnaces are self-baking Söderberg electrodes. The situation sometimes arises (typically when the furnace is switched on again after a long shutdown or after a long slip has been taken) that one or more of the electrodes must be "baked-in" while the rest of the furnace is operating relatively normally. This baking process requires that the electrode must not be moved, and the current is held at a low value until the electrode has had sufficient time to heat up again.

The electrode controller includes a facility for the baking of electrodes. When a baking-in period is initiated by means of a push-button, the unit automatically blocks all the control signals that go out to that electrode so that the electrode is not moved, and simultaneously it lowers the current in that electrode (by means of the transformer tap-changers) to the specified baking-in current. This facility enables the electrode controller to be used during periods when the furnace is upset and thereby avoids further trouble that might otherwise occur under manual control.

Results

As discussed in the paper by Sommer *et al.*[1], a prototype electrode controller has been operating successfully on a large 48 MVA furnace producing high-carbon ferrochromium since February 1978, and has contributed significantly towards a large increase in furnace production. There has also been an improvement in the stability of operation, and the incidence of electrode breaks has been reduced. The operation of the prototype unit has also been very satisfactory in that only a few minor hardware failures have occurred over a three-year period, and the availability of the unit has been virtually 100 per cent. The technology for the manufacture of the unit has now been licensed to a commercial firm, and two units are due to be installed shortly on two 75 MVA ferromanganese furnaces.

The major advantages of the electrode controller are as follows :

1. It overcomes the measurement problem on large submerged-arc furnaces in that it avoids the measurement of electrode-to-bath voltages. When checked against a direct-measurement system[4], the reactance assumption was found to be sufficiently accurate over a wide variety of furnace conditions.

2. The electrode controller provides a solution to the interaction problem in that it is a resistance controller.

3. Because the controller continuously drives the furnace against some limit of operation, the maximum possible power is fed to the furnace within the constraints of the operating equipment, and this results in maximum production from the furnace.

4. It is a self-contained unit that is easy to operate, and has been well accepted by the furnace operators.

5. Being computer-based, it is relatively easy for the unit to be incorporated into a distributed computer system. Such features as maximum demand control could be implemented merely by inclusion of the maximum demand as a limit of operation in the unit.

APPENDIX

The inputs for the electrode controller are the scalor quantities

V'_{12} V'_{23} V'_{31}	Primary line voltages
I'_1 I'_2 I'_3	Primary star currents
P	Total real power
k	Transformer tap position.

The secondary voltages and currents are determined from the corresponding primary variable by scaling them by the constants f(k) for transformer turns-ratio, i.e.,

$$V_{12} = f(k) \quad V_{12}$$

$$I_1 = \frac{I'_1}{f\ (k)} .$$

The phasor relationship between the voltages and the currents can be determined from the fact that the phasor sums of both the line voltages and the star currents are zero. These phasors can therefore be represented by closed triangles as shown in Figure 4 (a), and the angles ϕ_1, ϕ_2, ϕ_3 and θ_1, θ_2, θ_3 in this diagram can be determined by the cosine rule. This leads to the phasor diagram shown in Figure 4 (b). The angle β in Figure 4 (b), which relates the voltage and current triangles to each other, can be determined from the equation for the two wattmeter method of determining power :

$$|V_{12}| . |I_1| . \cos \beta + |V_{32}| . |I_3| . \cos \left[\pi - (\beta + \phi_3 + \theta_2) \right] = P$$

In this equation all the variables except β are known, and β can thus be calculated.

TABLE 1 Comparison of the electrical parameters between small and large submerged-arc furnaces

Size of furnace MVA	Typical electrode current kA	Typical electrode-to-bath voltage V	Reactance mΩ	Current-to-voltage ratio	Reactance-to-resistance ratio
9 (small)	30	85	0,5	353	0,18
48 (large)	100	170	1,1	588	0,85

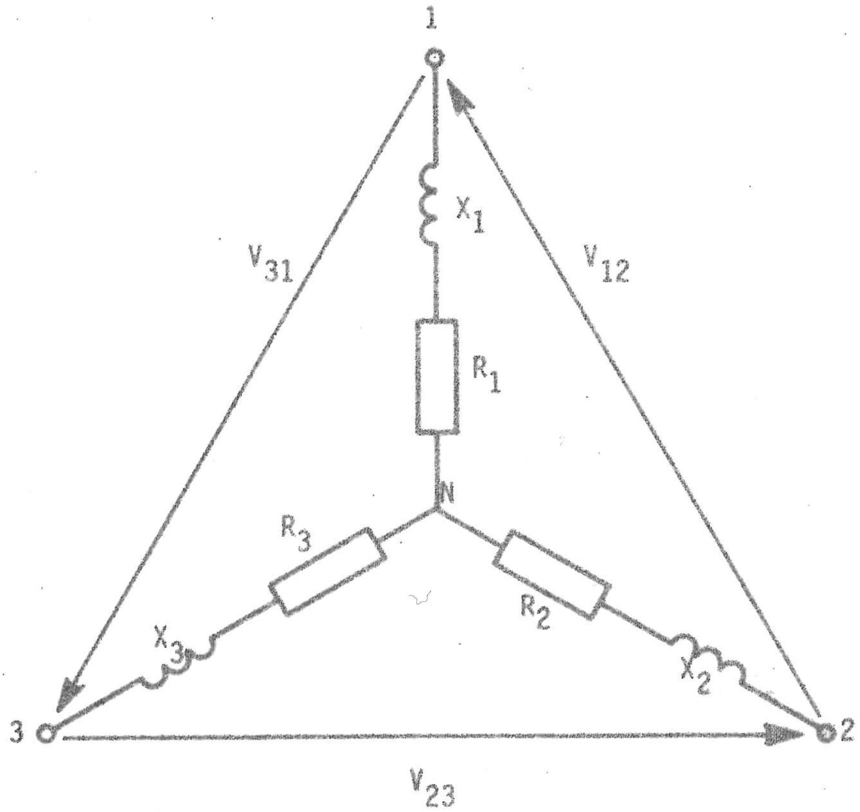

FIGURE 1 Star Equivalent-circuit of the Furnace

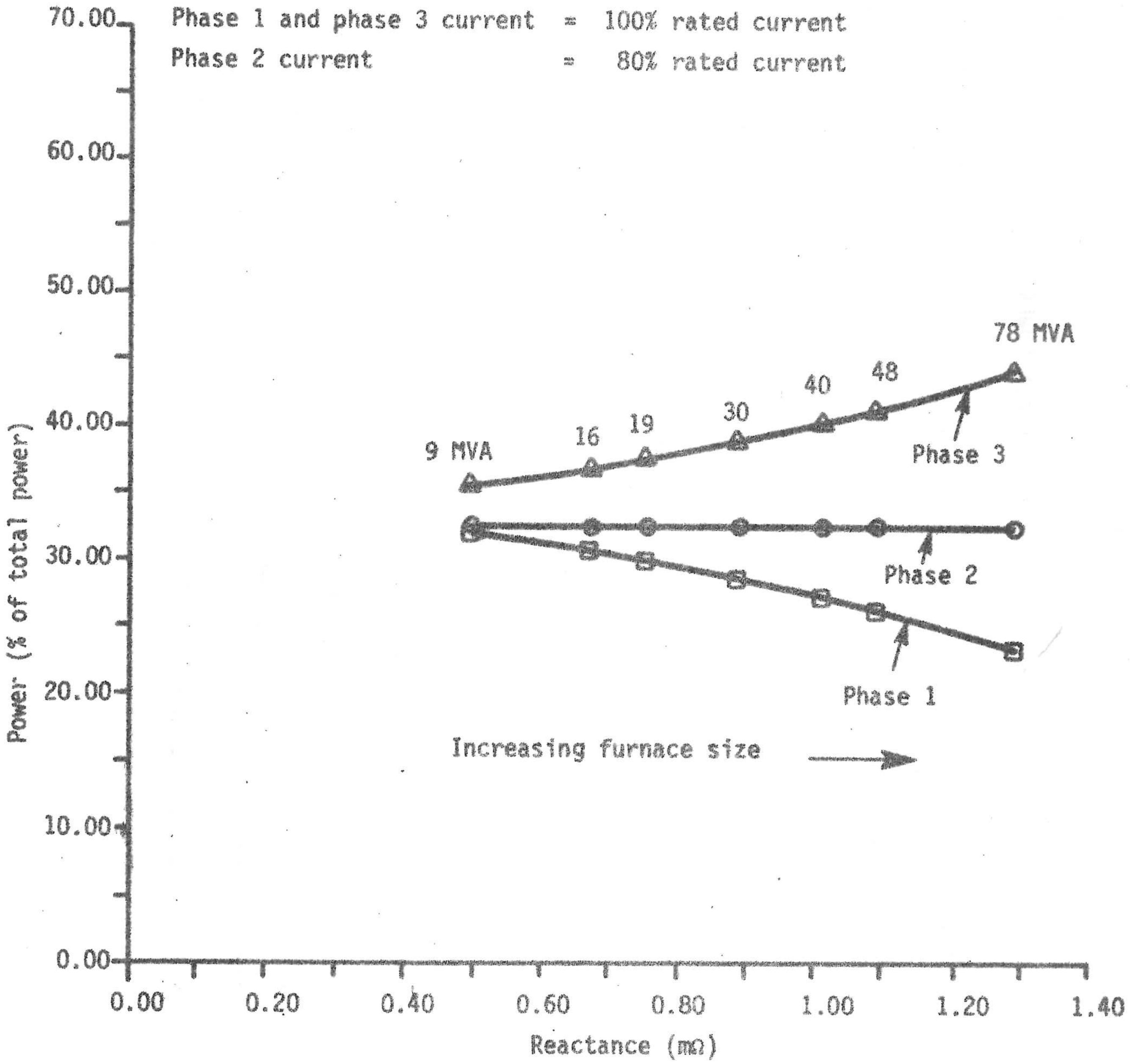

FIGURE 2 Effect of Reactance on Power Imbalance in a Furnace during Unbalanced Current Conditions

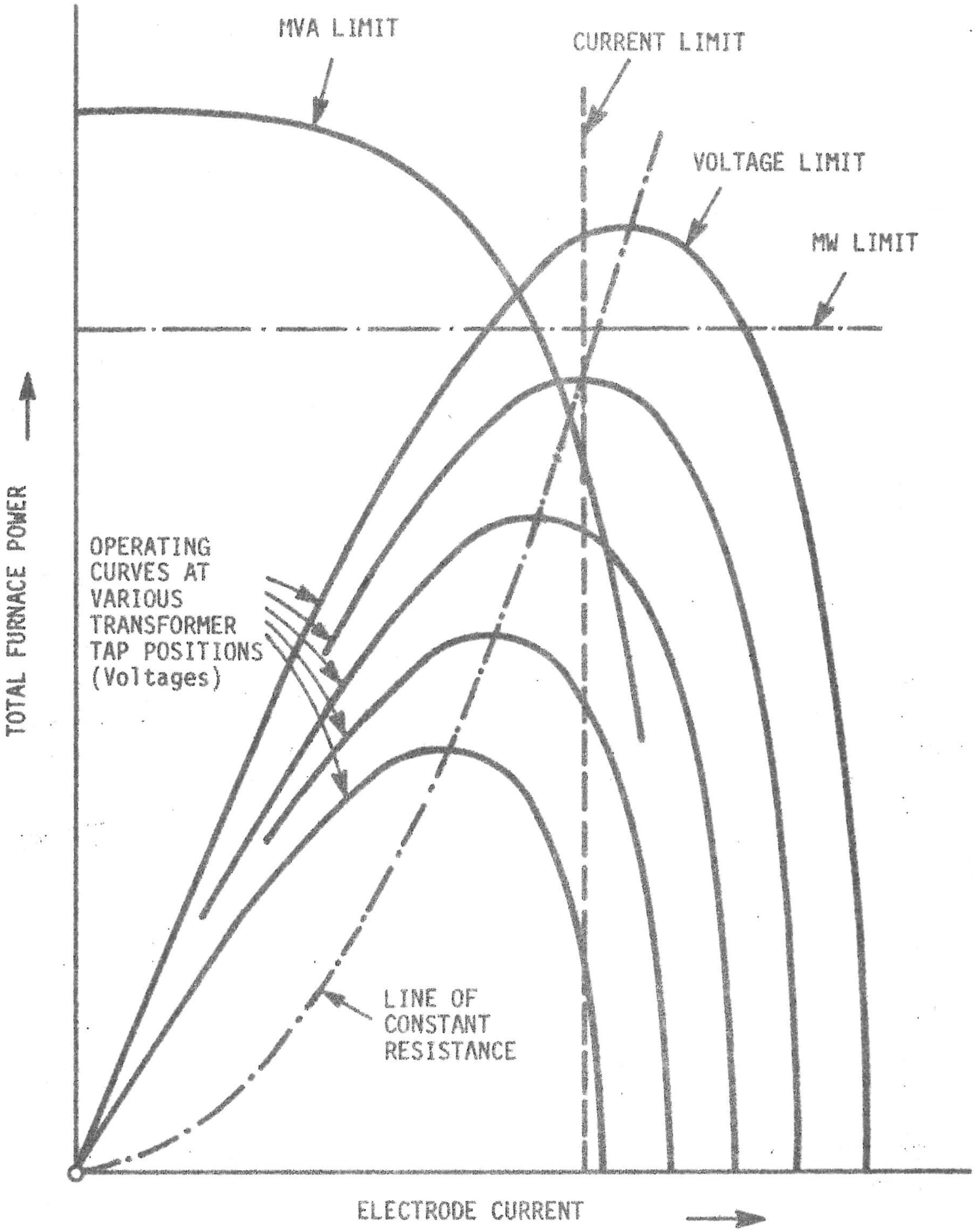

FIGURE 3 Curves of Power against Current, showing Limits of Operation

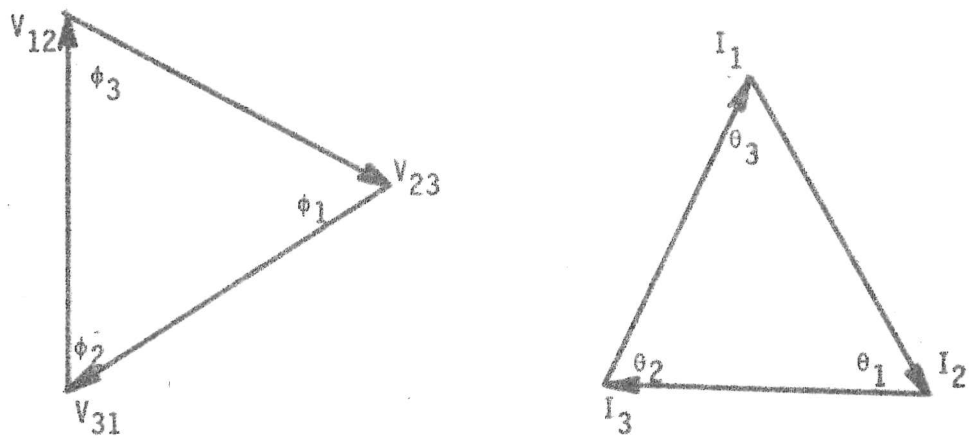

FIGURE 4(a) Phasor Triangles for Voltages and Currents

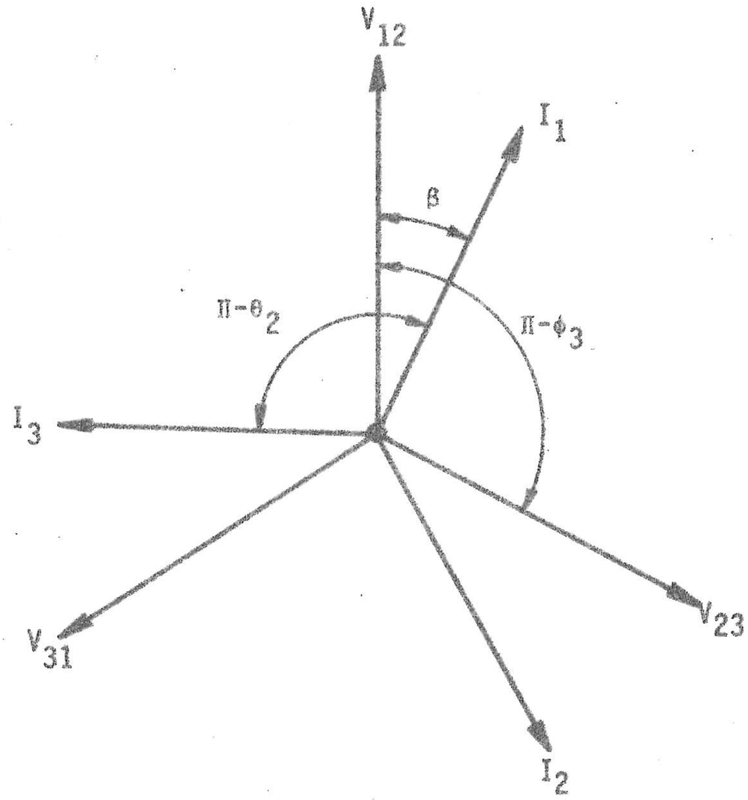

FIGURE 4(b) Angles between Voltage and Current Phasors (drawn in star form)

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DISCUSSION

(Joint discussion of Messrs. Sommer's & Stewart's papers)

Mr. H. Tuovinen*

I would like to thank and congratulate Messrs. Sommer and Stewart for their clear and interesting presentation. I would like to ask one question: You are optimizing the power input of the furnace based on the material balance and the attitude of the electrodes in the future. How is it about the metallurgy of the process; how do you take into account chemistry and thermodynamics of the process to optimize the operation with various feed materials and products?

Mr. G. Sommer:

To change from one raw-material recipe to another or to change from one product to another, one uses the design mass balance. Having obtained this from the background operation in the computer one can then select the raw-material setpoints for the dedicated microcomputer of the raw-material feeding system. At the same time one can obtain a mass flow model which will provide a measure of the production rate within the furnace. It is assumed that with maximum real power one will obtain maximum production. The prediction of the output is, however, influenced by the possible hold-up of metal in the furnace as I explained in my paper.

Mr. T. Magnussen**

I would appreciate some further comments upon the calculation of the electrode length. You mentioned an electrode consumption factor, and the expression 'arc factor' was used.

Concerning the electrode regulator, it is certainly very interesting to have a procedure by which you are not dependent on the electrode to hearth voltage. But I am somewhat suspicious regarding the principle of assuming the reactance. It seems to me that the calculated resistance is a function of the assumed value of the reactance.

Dr. A.B. Stewart:

First of all, in connection with the electrode-length model, as mentioned, there are a number of models which are running. The classical one is the consumption model and one can improve the accuracy of the consumption model by better power measurements and including a factor for the effect of arcing. For the other two models: one is based on raw materials consumption around an electrode and arcing and the other is based on arcing, reactance and resistance. Now the arcing measurement itself is based on an analysis of the harmonics in the electrode-to-bath voltage. The variables (arcing, reactance, resistance and raw materials consumption) are averaged over a day using a computer. These variables are compared with the results from measuring the lengths of the electrodes using standard sounding techniques, and linear regression models relating electrode lengths to the variables are developed.

In connection with the second question, the whole resistance measurement is entirely based on the assumption as to whether reactances are related by the equation shown. Our experience has shown that this is actually a fairly good

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approximation. It does actually work well. I think that this is related to the fact that you have got a fairly well-defined current part in the system and it is stable. Even though the metal bath might rise and fall a certain amount, it does not affect the inter-relationship between the phase reactances. It affects the global reactance quite considerably. I admit that the system is not perfect but then the direct measurement technique is also not perfect. We have found that the estimated resistance measurement and the resistance control relate to what is happening underneath the particular electrode, whereas before, on standard resistance control, there was always the problem that the resistance control did not work satisfactorily.

Mr. P.E. Streicher*

Just as a practical man, not as a theoretician, I wish to give you the background of this particular furnace. Originally it is an Elkem 48 MVA furnace. It has been completely redesigned in many respects and together with the experience we have gained with the computer control, it is a completely new furnace now. The details of the changes I will not go into at the moment. Originally the design was for a production of 50 000 tons of charge chrome per year. The furnace has been producing under this particular system up to 7 700 tons of charge chrome per month. In other words from the original designed capacity and still with the 48 MVA transformers (in fact, it is 52 MVA if you take the transformers to their limit), it has now produced 92 400 tons per annum, and this was not a one off situation. We have decided, in view of the aid we obtained with the computer control system, to install bigger transformers in this furnace and some other proprietary changes in the future, when alloy markets are better again. I do not know when that is going to be, but we should then be producing 100 000 tons of charge chrome per year on this unit. I think this should substantiate the claim of the success of this operation.

Mr. A.G. Arnesen**

I will start to enquire about several same things that Mr. Streicher commented on, namely the substantial increase in production from this furnace. Now, you, Mr. Sommer, were very careful to stress that you felt that one thing was the automatic control, another thing was the increased attention around this furnace in order to try to get a deeper understanding of the operation. I have one question: Do you think there is a third element in this, an element of increased learning? We have seen this in many places in the world that, when people go from one generation of small furnaces to larger furnaces, it takes quite some time to learn to operate them. Secondly, regarding the electrode model, electrode length model. Of course, electrode length to know at all times where your electrode position is in the furnace is a dream of all operating metallurgists. Have you actually tested your models against practice and what is the reliability of your models? Could you comment on that?

Mr. G. Sommer:

In my lecture I said that, as a result of the better understanding that was gained of the process, the rebuilding of the furnace and the achievement of automatic control of the raw materials and electrodes, the furnace production was increased to 125 per cent of the designed capacity. I personally believe

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that, with the data-logging facilities available and the interpretation of this data, the furnace production could also have been increased substantially.

Electrode-length models were tested over a period of nine months and a total of 15 soundings were made during that period. The difference between the length predicted by the models and the actual length measured on the furnace was no more than ± 5 centimeters with a confidence limit of 95 per cent.

We believe that with the success obtained from the models, there is some fundamental relationship between length and the measurements used (arc factor, material consumption per electrode, reactance and resistance measurements). Therefore, we have confidence that we will obtain reasonable results on other furnaces and hopefully in other operations.

Mr. H. Parsons*

Dr. Stewart mentioned that there was a reduction in the electrode breakage on the furnace. The question is: What percentage improvement did you have and, secondly, with such a fine controller on the furnace, why do you think you still have electrode breakage?

Dr. A.B. Stewart:

With regard to your first question, I do not have the figures on me so I cannot really off hand give you an answer, but there was over a period of time, a substantial reduction in electrode breakages. Now, I believe that some of that can be attributed to this controller, not a large amount of it, but nevertheless, some of it can be. Obviously there are many other factors that come into this as well. It is very difficult to give you a straight answer. In fact this answers your second question. The electrode controller being completely automatic provides a stabilizing influence on the operation of the furnace. The operators are less prone to trying out their own particular control strategies which vary from shift to shift and upset stable operation. Also, during unbalanced conditions, say after a tip break, the controller avoids the highly unbalanced power situation which can occur if current control is being used. However, electrode breaks can still occur due to other factors.

Question from India

It is interesting to note the large increase in production for the Elkem 48 MVA charge chrome furnace. By rough mental calculations I find that for a design of 50 000 tons per year, the power factor must be around 60 per cent of that load to give you a 50 000 tons a year, and by the introduction of the computer you have raised it to 100 000 tons a year. Does that mean that, assuming the power consumption for the raw materials remains the same, you have increased the power factor from 60 per cent to 120 per cent by the mere introduction of the computer or are there some other changes? Could you kindly elaborate on this?

Mr. G. Sommer:

I do not believe we claimed that a computer can change the power factor. However, one can influence the resistance of the burden by changing particle size or by using different raw materials. The change in resistance will influence the power factor as the reactance is relatively fixed in the construction.

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Mr. P.J. Nienaber*

Being the operator of that so-called No. 4 furnace, I would like to answer the first part of Mr. Parsons' question. For the last two years we did not even take a long slip on any of the electrodes, which implies virtually no breakages worth mentioning.

As far as electrode breakages are concerned, obviously most of the electrode problems, or at least 80% thereof, do result from operators' errors, i.e. wrong slipping rates or underestimations of some of the characteristics or variables on the furnace. By installing an electrode controller and thereby eliminating at least some of the operators' errors, would prevent breakages. I think that our results confirmed the above reasoning.

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