ELECTRODE CONTROLLER — LEADING TO ENERGY EFFICIENCY

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ABSTRACT:

This paper describes the Electrode Control philosophy of Submerged Electric Arc Furnace (SAF). It begins with explanation of different types of electrode control existing worldwide, e.g. Current Control, C3 Control, Impedance Control, Resistance Control based on Secondary Data and Resistance Control based on Primary Data. The limitations of different controls as compared with Resistance Control based on Primary Data are described. This is demonstrated through examples of interaction effect. Advantages of Resistance Control have been discussed in details. Since the electrical & metallurgical effects are decoupled under resistance control the operating staff will be able to treat the source of metallurgical problem without fearing that the electrical side influences their observations. The aim of this paper is to acquaint the readers with resistance control based on Electrical model of Submerged Arc Furnaces and how it helps in energy efficiency. Finally, characteristic graphs of 28.5MVA Ferro Silicon furnace of Bhutan have been drawn with derivation of all the equations from electrical considerations of the furnace.

The algorithm for calculation of furnace resistances (secondary resistances) based on primary data of furnace transformers is not presented here. The Resistance Control based on Primary Data completely depends on this algorithm and the algorithm can be obtained from the author, which can be implemented in any running PLC/DCS system used for electrode control or can be implemented anew in SAF.

KEY WORDS: *Electrode control, specific energy consumption, C3 control, interaction effect, interaction coefficients, perpetual imbalances, insensitivity effect, dead and live phases, chronic imbalance, characteristic graph, density distribution diagram, PID controller.*

1. INTRODUCTION

The required electrode control system for least specific energy consumption should be

1. To control electrode penetration based on a patented algorithm for calculation of individual electrode resistances based on primary data [not using any secondary data].
2. To enable electrical optimization at higher power levels.
3. To ensure more stable furnace operations & providing relevant and accurate electrical variables to make rational metallurgical decisions.
4. To improve electrical power consumption, furnace production and metallurgical performance of furnace.

Under balanced metallurgical conditions, trends in the holder position will be an excellent indication of electrode length and combined with ampere-hour consumption per electrode can be used to determine & maintain the required slip rate of each electrode. Metallurgical condition will however change regularly for a variety of reasons resulting in an unstable furnace operation. Since the electrical & metallurgical effects are decoupled under resistance control the operating staff will be able to treat the source of metallurgical problem without fearing that the electrical side influences their observations. It is also possible for the operating staff to adjust the individual resistance set points to limit the electrode traveling if metallurgical condition causes an electrode to lose penetration. Deep electrode penetration is essential for high reaction temperature & good recoveries. The optimal operating conditions will depend on setting of correct resistance for the type & size of reductant, carbon balance & particular blend of materials & fines.

2.1 CURRENT PHILOSOPHY IN FURNACE CONTROL

2.1 Current Control

In manual mode of operation fixed electrode penetration is maintained on the basis of current of individual electrode. Furnace power is maintained by changing the tap position of the Furnace transformer/s. In a PLC/DCS based operation, electrode wise current set points & furnace power set points are fed to PLC/DCS. The required current of individual electrode is maintained by electrode regulation through command from PLC/DCS & power of furnace is maintained by tap changing of furnace transformer through command from PLC/DCS. In some places only current is maintained as per set point in PLC/DCS & tap changing is performed manually to avoid excess operation of tap changer. For different loads, different current set points are applied. The actual electrode current is fed to the PLC/DCS by any of the following four means.

(i) By converting the primary current to corresponding secondary line/electrode current through putting physical interposing CTs, furnace transformer Dial Switches (Auxiliary tap changer) & furnace transformer Star Delta connection status feedback. (ii) By converting the primary current to corresponding secondary line/electrode current by programming interposing CTs in PLC/DCS & by feeding furnace transformer Star Delta connection status feedback to PLC/DCS. However, in this method in case of problem in PLC/DCS it is not possible to know the electrode current. (iii) By taking reflection of secondary current through putting a single ratio CT in the main transformer of an Auto Transformer type Furnace Transformer. (iv) By introducing CTs/ Rogowski Coils into Furnace Transformer Secondary. It is not always physically possible to put secondary CTs/ Rogowski Coils, moreover, the secondary leads would be suffering from high electromagnetic induction due to high magnetic field.

2.2 C3 Control

This is another version of Current Control. In this philosophy of electrode control, fixed electrode penetration is maintained by PLC/DCS/ manually based on C3 factor and power input to furnace is regulated by operating transformer tap changer manually/by PLC/by DCS. According to Mr. W.M. Kelly & Mr. J.A. Person, the electrode periphery resistance decreases as the power density in the electrode increases. On the basis of this theory Mr. J.Westly of Elkem suggested the formula

$$\frac{I}{P^{2/3}} = \text{Constant} = C3,\ I = \text{Electrode Current},\ P = \text{Furnace power}$$

Where ‘I’ is in KA & ‘P’ is in MW. Hence, the current ‘I’ is changed by the electrode regulation so as to reach the set value of ‘C3’. Sometimes if ‘C3’ set value is not reached then the tap position has to be changed to change ‘P’ and again the ‘I’ is adjusted by traveling of electrode to reach at the set value of ‘C3’. Normally, this ‘I’ is calculated from the primary current of furnace transformers and ‘P’ is measured from the primary as well. There are also some fluctuations in the supply primary voltage. This also leads to inconsistent electrode penetration. As the electrode movement is based on electrode current, hence decision cannot be made fast when furnace is at full load & hence no stability would be available.

It is not easy to have a better recovery through ‘C3’ control or current control as metallurgical problems and electrical parameters are coupled with each other (explained in interaction effect). But in case of resistance control the recovery becomes good.

2.3 Impedance Control

In this control method, electrode-wise impedance set point and total power set points are fed to PLC/DCS which calculates the electrode-wise impedance either from furnace transformer primary voltage and current or from electrode to hearth voltage and from electrode current (which is calculated by any of the four methods described in current control). Impedence is controlled by electrode regulation by PLC/DCS and power is controlled by changing the tap position of furnace transformer. This is a little bit similar to Resistance Control, but the method is not accurate. Electrode movement directly changes the resistance of secondary circuit and indirectly changes the reactance of secondary circuit due to change of current. So a better option is to control directly the resistance of secondary circuit.

3. ADVANTAGES OF RESISTANCE CONTROL

In case of current or ‘C3’ control the trends in metal composition become clear only after several taps, but changes in electrode position under resistance control can indicate the need for immediate corrective action. This may involve changing the resistance set point or adding more carbon. During wet season controlling the carbon balance by ‘C3’ control system is difficult that leads to a variable carbon balance within the furnace. Hence, the improvement in furnace efficiency is possible by means of resistance control. This process also helps us to achieve higher load than the rated value as the process is more stable. If we have to increase the load beyond the rated value, then we have to ensure the following:

(a) The gas plant should be able to handle the additional gas flow. (b) The furnace burden is sufficiently permeable to minimize blows. (c) The metal / slag can be tapped & transmitted away from the furnace quickly & efficiently. (d) The batching system can handle increased capacity. (e) Sufficient raw materials. (f) All cooling water circuits are regularly monitored and water leaks are minimized. (g) Transformer temperatures are regularly monitored & oil to be replaced/ filtered at recommended intervals. (h) The furnace shell is large enough & lining is good. (i) The furnace roof lining is in good condition, etc.

If the resistance set point is not properly fixed the furnace may behave abnormally. If high resistance is set then consequences are the following:

- Slag formation which gives rise to problems in tapping & plugging of furnace.

- The electrical instrument shows little or only temporary response to raising and lowering of the electrodes with subsequent problems in balancing the furnace load & excessive electrode travel.
- An abnormal wear on the electrodes i.e. reduced wear on the electrode tip and increased wear on the side of the electrodes. Above all, wear on the slits of the fins may result in channel formation and splitting up of the electrodes.

Actually the slagging condition is frequently related to a deficiency of carbon in the charge, but with higher resistance set point, the slaggy condition cannot be avoided even with a surplus of carbon in the charge. The reason for such a condition may be a lack of heat in the inner zone as the heat evolution from I^2R is decreased when the furnace is operated on high resistance. In case of a Ferro Silicon furnace, the SiO in the gas will increase with lower temperature in the inner zone followed by increase of lava or slag in the outer zone.

With a slaggy condition a lifting or lowering will result in a small and temporary change in resistance indicating that the current finds other ways to travel, for instance from the side of the electrode to charge. This may again limit the heat to inner zone and the consequences of too high resistance are accelerated. So for proper control of the furnace operation, both metallurgical and electrical considerations have to be taken into account. In case of ‘C3’ factor or current control this is not easy to solve the situations as ‘C3’ or current is a dependent parameter.

Besides increasing production and reducing electricity cost, the resistance control of the electrodes results in a more stable & more balanced operation. This leads to:

(a) Reduced thermal strain on super structure; (b) Accurate logging and reporting of data; (c) Resolving of operational issues before they become major problems; (d) Reduced damage to electrodes and hoisting devices; (e) Easier tapping.

These advantages yield further benefits such as increased safety, reduced operating costs, reduced variable costs & reduced maintenance costs.

4. LIMITATIONS OF CONVENTIONAL RESISTANCE CONTROL TECHNIQUES [RESISTANCE CALCULATED FROM FURNACE TRANSFORMER SECONDARY DATA]

If the resistance r1, r2, r3 are calculated using the electrode voltages measured from electrode to hearth [or to a calculated star point], then inaccuracy increases. Electrode to hearth [or to a calculated star point] voltage measurement is not correct, as induced voltages in the measurement cause large inaccuracies. Furthermore, these induced measurement errors become progressively worse since the power factor decreases as the magnetically induced voltages increase resulted from higher current to voltage ratios. The measurement also rely on a reliable electrical connection to the hearth of the furnace [or to a calculated star point] that is difficult to maintain in practice. The accuracy of electrode to hearth voltage measurement is affected as neutral point [the physical location where the three electrode currents vectorically add to zero] moves around as the magnitude of electrode currents vary [if the star point is not calculated by Bockman method]. The connections to the hearth need to be provided exactly at this point to accurately measure the voltage. Hence, the inaccuracy in measured resistance would skew the penetration of individual electrodes. The results may be superheating of bath or excessive losses in off-gas. The resulting effect is substantial increase in specific energy consumption. Hence resistances measured from primary parameters are to be taken into account.

The Bockman method is characterized by the three measuring conductors from contacts in the furnace bottom to a junction box placed above the furnace current supply. In this junction box three conductors are star connected by three adjustable resistors (adjusted to the value calculated by this method). The star point will then represent the exact potential of melted metal.

5. CONSEQUENCES OF CURRENT-BASED CONTROLS

In three phase star equivalent circuits one will find the effect that if one of three currents changes, the remaining two currents will change as well. This interaction between three currents is known as the interaction effect.

For electrical consideration the furnace can be taken as a star connected load as it can be shown that when an electrode is moved the resistance in that phase is affected while the resistances of other two phases remain unaffected. Electrode currents are three line currents of the star circuit. Vectorically, where these 3 line currents mix to zero resultant, it is called the star point. In the balanced condition the star point to electrode resistances is same. Let the electrodes be electrode 1, 2 & 3, the currents be I1, I2, and I3 for the electrodes, respectively. Electrode 1 has the charge resistance of r1 up to the star point, electrode 2 has r2 & electrode 3 has r3. In a balanced condition I1 = I2 = I3 & r1 = r2 = r3. Suppose the charge resistance under electrode 1 changes, say to r11, then I1 definitely changes. As the furnace is a star equivalent load, though r2 & r3 do not change, I2, I3 still deviate from their normal value. Actually when r1 is disturbed, Electrode 1 should move up or down to restore the balance but as the system is working in the principle of current balancing [not resistance balancing], hence there would be movement of every electrode as all currents deviate from their normal value. This results in excessive movement of electrodes and balancing time increases as the balancing parameter is a dependent quantity ‘I’ but not an independent quantity ‘r’.

Example [of interaction effect]:

CONDITION	PARAMETERS	ELECTRODE 1	ELECTRODE 2	ELECTRODE 3
Balance	Primary Current	610A	610A	610A
	Electrode Current	81.0KA	81.0KA	81.0KA
	Resistance	1.4 m-Ohm	1.4 m-Ohm	1.4 m-Ohm
	Tap Position	23	23	23
Unbalance	Electrode Current	71.7KA	75.7KA	81.5KA
	Resistance	1.8m-Ohm	1.4m-Ohm	1.4m-Ohm
Percentage	Electrode Current	-11.5%	-6.5%	+0.6%
Change	Resistance	+28.6%	0%	0%

Owing to invisibility of interaction effect, many operators will dispute that it is a part of their problem. Instead they try to interpret the cause in more physically observable terms and they typically point to the problems with the electrode paste or raw materials or broken electrodes or water leakages as the source of the trouble. Of course such problems do occur as well but they are not the exclusive cause of poor operation, particularly in the case of large furnaces that seems to suffer from perpetual imbalances.

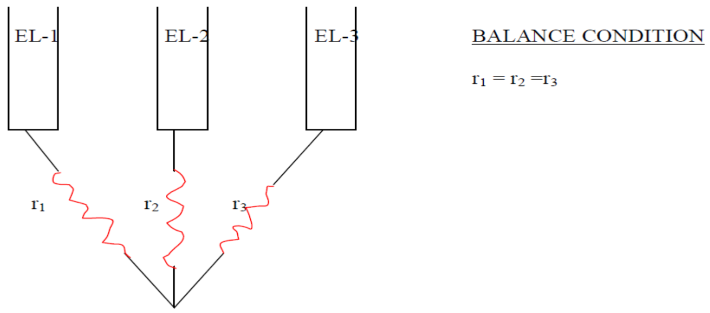


Figure 1: Electrodes and per phase charge resistance

It is convenient to introduce the concept of interaction coefficients G1, G2, G3 to quantify these functional dependences.

$G1 = -(2/3)\ \mathrm{Cos}^2\Phi$, $G2 = (1/3)(-0.5\ \mathrm{Cos}^2\Phi + 0.866\ \mathrm{Sin}\Phi\ \mathrm{Cos}\Phi)$,

$G3 = (1/3)(-0.5\ \mathrm{Cos}^2\Phi - 0.866\ \mathrm{Sin}\Phi\ \mathrm{Cos}\Phi)$, where $\mathrm{Cos}\Phi$ is the power factor of furnace.

The change ΔIi in current Ii of an electrode [i= 1, 2, 3] as a result of a change ΔRj in resistance Rj [j=1, 2, 3] can then be determined from ΔIi = ΔRj [Ii / Rj] Gk, where k = 1, 2, 3. Here G1 refers to the electrode in which the resistance was changed, G2 is the following one in phase sequence and G3 is the preceding one in phase sequence. The larger the value of G the greater will be the change in current corresponding to G coefficient as a result of one electrode movement. An analysis based on a linearization around a balanced furnace shows that these coefficients are functions of power factor only.

Please refer to the figure showing interaction coefficient as function of furnace power factor. From the figure, G1 drops in proportion to the square of power factor down to zero. This means that in large furnaces where the power factor is lower, the sensitivity of current to movements of the electrode is relatively less than on small furnaces where the power factor is higher. This phenomenon is called insensitivity effect and results in large movements of an electrode being needed to achieve small changes in electrode current.

The graph of G3 crosses that of G1 at a power factor of 0.5. This means that in a furnace with a power factor of less than 0.5 the movement of any electrode will cause a greater change to the current in another electrode than to the current in itself. Clearly this has major consequences for electrode control based on current. In practice the skewness of interaction problem associated with current control getting progressively worse as the power factor decreases, and does not suddenly appear at power factors below 0.5. At power factor exceeding 0.9 the problem is seldom. At 0.8 the problem becomes noticeable. At 0.7 it is significant and affects the operation of the furnace. At 0.6 it is a major problem and likely to contribute to major production losses. At power factor of 0.5 and below the system becomes unstable and the furnace is likely to suffer perpetual operating problems. In the interaction effect the changes in the currents are not strictly linear functions of the changes in the resistance, but they can be approximated as linear functions around any chosen operating point. This makes it easier to draw generalized conclusions about the important trends.

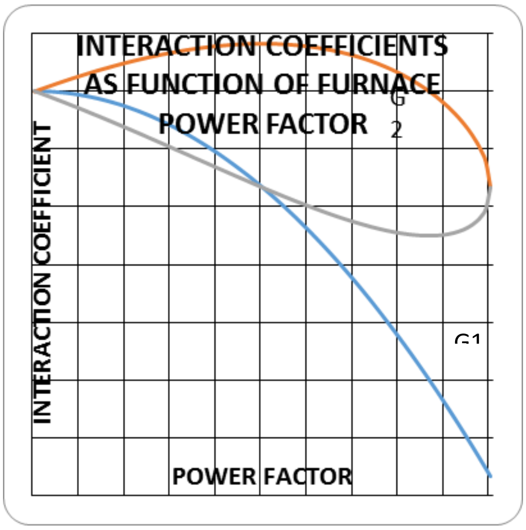


Figure 2: Interaction Coefficient as a function of Furnace Power Factor

A combination of interaction and insensitivity effect during an unbalance on a large furnace can result in a low voltage across a phase. In an attempt to keep the current at a normal level, the operator may push the electrode right into the metal bath. It is almost impossible for the usual instruments in the control room to detect this extremely dangerous situation. This is called the effect of DEAD AND LIVE PHASES.

The interaction effect has two consequences in furnace operation based on current or C3 control.

5.1 Excessive movement of electrode

5.1 For efficient metallurgical reductions to take place the correct electrode penetration needs to be maintained. If the electrode is moved excessively the arcing & the reduction condition will be disturbed. Frequent movement of electrodes can also lead to pumping of burden [charge]. Pumping of colder charge into the reaction zone causes the current density to drop off as colder mix is more resistive. There is also the possibility that the new colder mix will displace some existing mix from reaction zone, thus shortening the reduction time and hence inhibiting metallurgical reactions. Excessive movement of electrodes also causes electrode breakage and accelerates wear on hoist mechanism and other mechanical parts.

In furnaces with higher power factor the interaction effect is minimal. In the furnaces with lower power factors these phenomena can be a major problem that cause excessive and endless operating troubles.

5.2 Excessive movement of electrode

When the electrode is on lower limit & current is low, the electrode cannot be slipped since it needs to be baked to avoid fractures and breaks. The operator has now very few options available. If a long slip is taken the power limit will have to be reduced to allow baking. This will affect production. If normal slipping is maintained an unbalanced condition for an extended period of time will cause metallurgical and ultimately production problem.

Let’s consider initially the case where there is one short electrode [electrode 1] in the furnace & two undamaged electrodes. The short electrode will be running on the bottom stops of the hoist with a low current. Due to interaction effect, the current in the preceding phase [electrode 3] in the phase direction [say 1-2-3] will decrease while the current in the following phase [electrode 2] will increase. [The current in the preceding phase in terms of phase sequence drops by an amount comparable to that drop in a particular electrode current, while the current in the following phase rises by a smaller amount] The operator tries to rectify this unbalance by lowering the electrode in preceding phase [electrode 3] and raising the electrode in the following phase [electrode 2]. In doing this he will cause the current in the short electrode [electrode 1] to decrease still further that aggravates the problem of recovering this short electrode. The electrode currents may be balanced now, but the penetrations are unbalanced. One of the first consequences of the above is that the molten pool beneath the raised undamaged electrode [Electrode 2] will start to cool & solidify. A few hours later this will lead to difficulties in tapping the material out from beneath this electrode, as well as from beneath the original short electrode. The operators at tap hole are unable to judge what is actually happening within the furnace and may think the problem roots to some other cause, e.g. a pieced broken electrode blocking the tap hole.

Another possible consequence is an increase in temperature above the burden in the region of electrodes that are riding high, while the remaining electrode that has penetration has a cooler top. If this type of problem persists over a period of time, the heat may accelerate the rate of structural damage to the roof and to the electrode contact shoe assemblies. This loss of heat will also adversely affect the consumption of electrical energy per ton of production. Yet another effect may be a difference in the rate of raw material consumption between the electrode zones. Unfortunately this can be rather difficult to interpret in a way that can be used to diagnose and correct the situation.

In a furnace with a very low power factor specifically around 0.5 and lower the penetrations of two undamaged electrodes may actually be so disturbed that they are far from the desired penetration than the original short electrode was. Indeed the required current may actually be unattainable in the deep-penetrating electrode even with the electrode in direct contact with the hearth. The damage caused during such operation can be considerable and can include breakage [particularly green breaks] of the electrode, damage to hearth and other structures apart.

If the two undamaged electrodes were initially of similar lengths, then driving them into an unbalance in penetration will obviously result in an unbalance in the hoist position too. If the short electrode persists for more than a day or two, it is likely that the rates of slipping of the electrodes will be adjusted to bring the range of travel of the hoists back to more normal limits [in the example slipping electrode 3 is longer & electrode 2 is shorter]. The electrode with good penetration [El 3] will therefore be encouraged to grow longer, while the electrode with poor penetration [El 2] will become shorter. When the original short electrode finally recovers, the new short electrode will in turn throw the furnace into an unbalance, and the cycle will begin again. When the unbalance moves from one electrode to another in this way, the operators are often surprised at the lengths of electrodes that they thought were operating properly. They may even treat the new short electrode as as a broken one.

Table 7: Interaction Effect

63MVA, 45MW, P.F. 0.71, Secondary line Voltage = 300V, Phase Seq. = 1-2-3

CASES	r1	r2	r3	I1	I2	I3
Base Case	1.0 m-Ohm	1.0 m-Ohm	1.0 m-Ohm	122.5KA	122.5KA	122.5KA
Raise El 1	1.1 m-Ohm	1.0 m-Ohm	1.0 m-Ohm	118.5KA	123.2KA	119.9KA
Differences	0.1 m-Ohm [+10%]	0 m-Ohm [0%]	0 m-Ohm [0%]	(-)4.0KA [-3.3%]	+0.7KA [+0.6%]	(-)2.6KA [-2.1%]
With short electrode 1 electrode 2&3 are moved to return to their normal current	1.1 m-Ohm	1.057m-Ohm	0.945 m-Ohm	116.6KA	122.5KA	122.5KA

5.2 Variation in Supply Voltage

In case of change of supplied voltage to furnace transformers, the electrode currents change, though the resistances r1, r2, r3 are unchanged. Furnace operation based on current or C3 control would operate the electrode regulation to maintain the same current. Actually the tap position of the furnace transformers should be operated differently to maintain the same current.

6 6. ELECTRICAL CONSIDERATIONS OF FURNACE

P = Total active power of furnace [measured at furnace transformer primary]
Q = Total reactive power of furnace [measured at furnace transformer primary]
I = Electrode current [calculated from primary line current & tap position]
X = Furnace reactance [calculated at primary]
V = Secondary phase voltage [calculated from primary voltage & tap position]
= Electrode to star point voltage
R = Furnace resistance [calculated at primary]
Z = Furnace impedance [calculated at primary] = + $(r^2 + X^2)^{0.5}$ = V/I
K = Arcing factor [max. value = 1]
VA = Apparent power of furnace [measured at furnace transformer primary] = 3VI = + $(P^2 + Q^2)^{0.5}$
MVA max. = Furnace designed MVA
I max. = Max. Electrode current as per design
D = Diameter of casing in meter

The inductance of a furnace and hence the furnace reactance 'X' is fixed for a particular furnace. It normally depends on the physical layout of electrodes, bus bars, transformer inductance etc. The resistance 'r' is a variable one & is the power dissipating unit. It is approximated when there is not too much arcing below the electrode. When arcing takes place, there is a nonlinear inductive effect in power dissipation, which affects the analysis. This affect can be taken into account in the circuit analysis by using a special arcing factor.

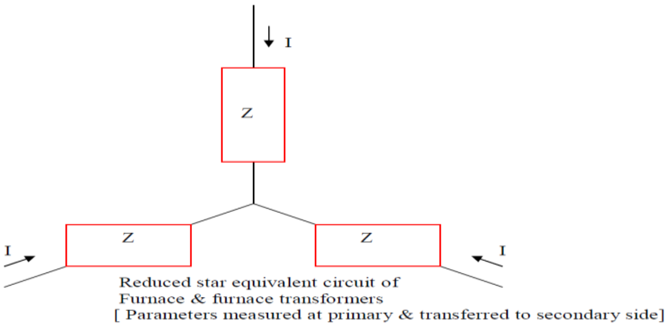


Figure 3: Star Equivalent Circuit of Furnace and Furnace Transformer

From the fundamentals $P = 3I^2r$ (1)

$= 3I^2 (Z^2\text{-}X^2)^{0.5} = 3I^2 [(V/I)^2\text{-}X^2]^{0.5}$

$= 3IX (V^2/X^2\text{-}I^2)^{0.5}$ (2)

For all furnaces maximum safe (peak) electrode current Imax. = 55 x $d^{1.5}$ KA 3)

From the fundamentals $Q = 3I^2X,\ X = Q/(3I^2)$ (4)

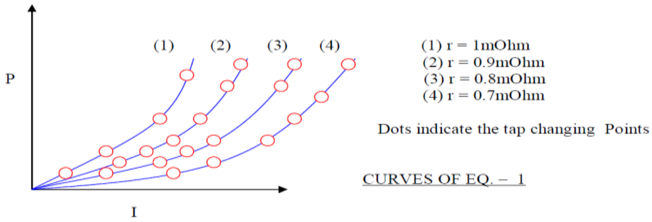
$P = +[(VA)^2 – Q^2]^{0.5}$

If we take arcing factor (K) into consideration

$P = K [(VA)^2 – (3I^2X)^2]^{0.5}$ (5)

$P\text{max.} = K [(VA\text{max.})^2 – (3I^2X)^2]^{0.5}$ (6)

The curves of equation 1 are obtained by changing P & I at constant ‘r’. This is done if the electrode position and the mix in the furnace stay constant and P&I are varied by changing the tap position of furnace transformers. As the changes are in step, so we can get only certain points not a continuous curve. Then curves for different ‘r’ are drawn in the same manner. But for each curve ‘r’ has a constant value.



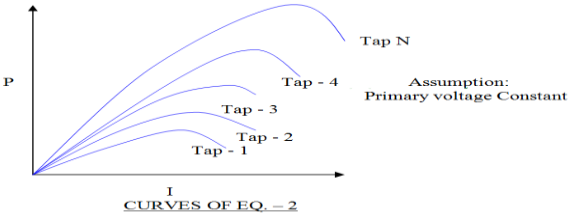


Figure 4: Curves of Eq.1 **Figure 5:** Curves of Eq.2

Curves of equation 2 are obtained by changing P & I keeping ‘V’ constant i.e. by movement of electrodes keeping tap position of transformers constant. So we can get total nos. of curves equal to nos. of tap positions.

Increasing the current beyond corresponding peak value of ‘P’ results in only over heating of hearth and overheating of electrode with less production and more specific power consumption.

The curve of Eq.3 is a straight line parallel to ‘P’ axis.

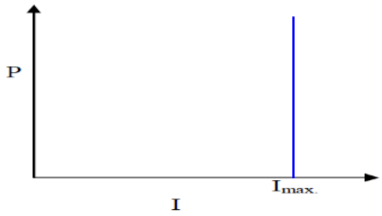


Figure 6: Curves of Eq.3

Curve of Eq.6 is drawn between ‘P’& ‘I’ taking MVAmax. and ‘X’ as constants. For analysis ‘K’ is taken as 1. This curve is called as MVA Limit Curve. When all these four types of curves are drawn on a single graph sheet the total graph is named as ‘Characteristic Graph’ for a furnace or ‘Density Distribution Diagram’. The intersection of curve of Eq. 6 with curves of Eq. 2 gives the max. allowable current for that particular tap position. The operating point of the furnace lies below MVA limit curve & left to Imax. curve.

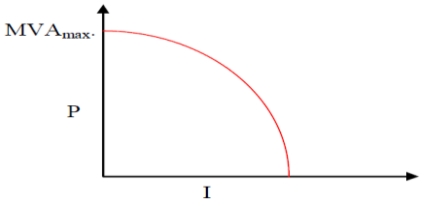


Figure 7: Curves of Eq.6

It has been mentioned above that C3 = I/($P^{2/3}$) = Constant, which implies that $rP^{1/3}$ = Constant as I = +√[P/(3r)]

This indicates that r α [1/$P^{1/3}$], but for larger furnaces the resistance decreases relatively less with higher power or with higher electrode current. Hence taking r = constant in resistance control will not make any difference even if power density is changed.

Controlling 'r' is done according to the flow diagram below.

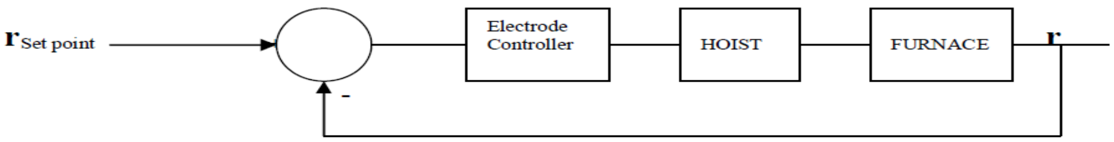


Figure 8: Closed Loop Control System for Electrode Control

For a closed loop PID controller, generally the following set points are provided.

1. $r_{set point}$ 2. Hysteresis band for $r_{set point}$ Upper 3. Hysteresis band for $r_{set point}$ Lower 4. Power set point

The controller moves the electrode to get the $r_{set point}$. The movement of electrode is restrained when

($r_{set point}$ - Lower hysteresis band) ≤ r ≤ ($r_{set point}$ + Upper hysteresis band)

Beyond these values of 'r' the movement of electrodes starts and it finishes when r = $r_{set point}$ is reached. With this value of 'r' the PLC/DCS reads the power at any existing tap. If power does not match with 'Pset', then it gives command to change the transformer taps [all transformers at a time] so that the measured power reaches approximately to 'Pset'. It should be understood that when 'P' is changing due to changing of taps the electrode does not travel as 'r' is constant. Hence the PLC/DCS maintains the resistance set point by movement of electrodes (Electrode Regulation) and maintains the power by changing transformer taps.

It should be kept in mind that auto system based on resistance control should only be tried when

(a) Furnace is stable (b) There is no abnormality of electrodes (c) Furnace has not been just started.

In the above cases manual control of electrodes should be tried.

7 7. CALCULATIONS FOR CHARACTERISTIC GRAPH OF 28.5MVA Fe-Si FURNACE OF BHUTAN FERRO ALLOYS LTD., BHUTAN

The following readings were taken.

Set value C3 = 10.8, Pset = 12.4MW, actual P = 12.7MW, C3 = 10.9, Q = 9.8MVAR, Tap position = 5,

I1 = 59.1KA, I2 = 60.4KA, I3 = 58.5KA, Primary Voltage [line] = 21.5KV [balance],

Primary current [line] = 430A, Diameter of the casing = d = 1.32m

Iav = [59.1 + 60.4 + 58.5]/3 = 59.3KA, If we calculate from tap ratio & primary current Iav [from primary] = (22000/160) x 430 = 59.13KA ≅ 59.3KA [tap ratio at Tap 5 = 22000/160], we will use the value of 59.3KA for calculation purpose.

X = Furnace per phase reactance = $Q/(3I^2)$ = 0.92896 mΩ

Imax. = 55 $d^{1.5}$ = 55 x $1.32^{1.5}$ = 83.4KA (a)

From Eq. 1 $P = 3I^2r$ (b)

'P' is from 0 to 35MW, 'I' is from 0 to 86KA, 'r' is from 0.6 to 1.5 mΩ (0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1.0, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3, 1.35, 1.4, 1.45, and 1.5)

MVAmax. = 28.5 x 1.2 = 34.2MVA, 28.5MVA is transformer rating with 20% continuous overload capacity,

X = 0.92896 mΩ

From Eq. 6 Pmax.[in MW] = $\sqrt{[34.2^2 - (3I^2)^2(0.92896)^2/10^6]}$ (c) ('I' from 0 to 86KA)

From Eq. 2 $P = 3IX\sqrt{(V^2/X^2 - I^2)}$ Putting value of 'X' the equation becomes

$P = 3I \times 0.92896 \times 10^{-3} \sqrt{[V^2/(0.92896 \times 10^{-3})^2 - I^2]}$ (d) Here 'I' varies from 0 to 86KA

V = Secondary phase voltage when primary line voltage is 22KV and √3V = 140.1, 145.2, 150.2, 154.9, 160, 164.8, 169.9, 175.3, 180.3, 184.9, 189.7, 194.7, 200, 204.7, 209.5, 214.6, 220, 224.5, 229.2, 234, 239.1, 244.4 volts at different taps

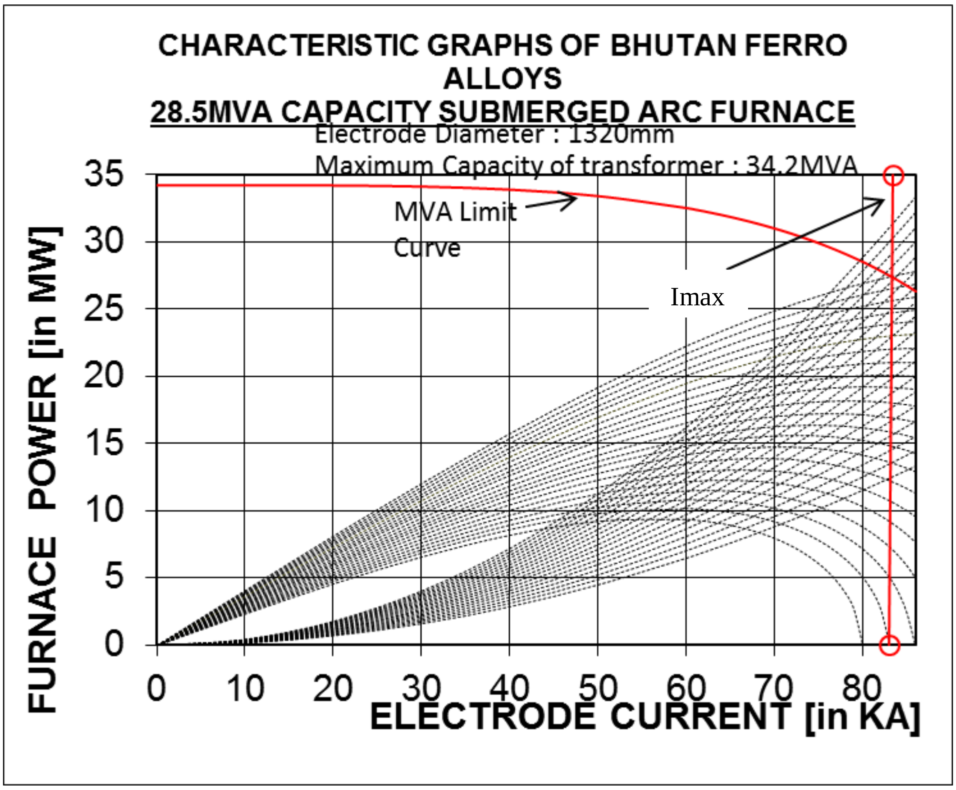


Figure 9: Characteristic Graphs

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