

ARC FURNACE LOADS VOLTAGE STABILITY

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The use of the arc furnace and its influence on the power system is being studied. A set of models that allows for the evaluation of the electrical behavior during steady state is presented in this paper. The results are presented and used to validate them. Detection of steady-state voltage instabilities is performed through certain mathematical criteria. Among those arc furnace load criteria (dE_s/dV_p) criterion, L -indicator criterion, and (Z_{Th}/Z_{Load}) criterion. The result of those criteria has been checked using the critical voltage value of arc furnace load node, which represents criterion quantities.

KEY WORDS: *Power Quality, Arc Furnace, Voltage Stability.*

1. INTRODUCTION

It is recognized that one of the main sources of harmonics, flickers and three-phase load unbalance are found in arc furnace. These three phenomena are problems of power quality that affect our daily lives. These problems have their origins in the non linear linking of the load that is connected to the power system. The utilities and their potential users that have this type of equipment should have a method that permits the evaluation of those problems. As the behavior of the arc furnace from the electromagnetic view point is not strictly periodic, it cannot be analyzed with precision using the Fourier series and harmonics [1-5]. Sometimes they can be considered as non-periodic loads for which the flicker is a greater problem than the harmonics [6-8]. The arc furnace load suffers from voltage stability [9-12] problems. It can cause serious voltage instabilities.

This paper will attempt to study the arc furnace from the power quality point of view through three derived models. First, the complete model is presented. In this model, the most important non-linearities of the arc furnace systems are represented. These are the saturation and hysteresis effect on the transformer, the power cable, and the arc phenomenon inside the furnace. A second model possesses some approximations are presented. An iterative method is needed to aggregate a random signal (resistance parameter) in this a second model. A third model in which simplifications are made, in which the wave-shape of the arc voltage-current is supposed to be piece-wise linear and the resistance of the arc furnace circuit impedance is neglected.

In those models special attention is paid to the current and power in the arc because they are closely related to the flicker voltage instability phenomenon. The results for each model are compared with a real arc furnace [12-15] recorded values in order to validate the results. In an arc furnace it is normally possible to control both the voltage and the current, and these quantities can be controlled independently of each other. To obtain the highest possible power, it is generally necessary to utilize the highest voltage setting and the highest current from the furnace transformer. Reducing the power can be accomplished by decreasing the voltage or current or both. For the more possible economy to be achieved, it is important that the correct settings to be chosen. For this problem to be properly understood, characteristic curves or load curves for the furnace are to be prepared for each furnace.

2. ARC FURNACES STUDIED MODELS

An arc furnace for manufacture of steel is essentially a steel shell with a spheroid bottom, lined with refractory material. It has a tilting mechanism and lip for pouring, as shown in fig. (1). The diameter of large furnaces now being installed is between (6 and 10) m. The roof is arched and is lined with refractory material, three holes admit the graphic electrodes, one for each phase. Roof electrodes and superstructure can be lifted up and swing to one side so that the furnace can be charged. The electrodes are typically about 60cm in diameter. They are usually molded in sections (2 to 3) m long and threaded at each end so that a new section can be screwed on the other end wastes away, thus allowing the electrodes to continuously fed to the arc. Electrodes are raised or lowered by remote automatic control that adjusts each electrode position to hold circuit impedance constant and thus, as possible maintain constant current.

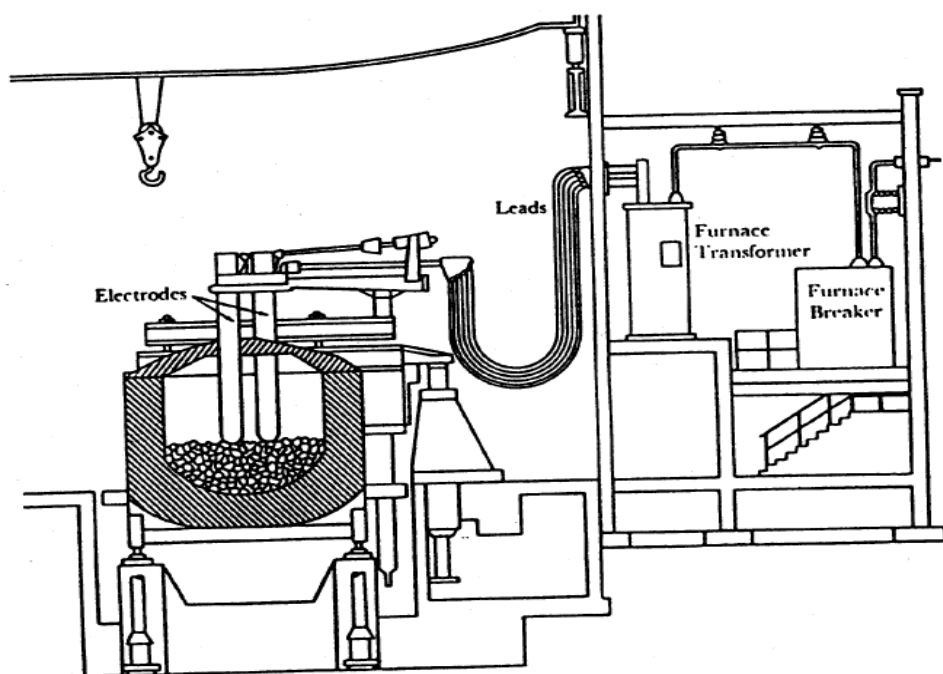


Fig. (1) Arc furnace elements

A furnace transformer connected to the electrodes by a number of conductors, who are water-cooled for the largest furnaces, supplies power. Their reactance does suffer from unbalance. It was observed that a certain apparent power is fed into the furnace at a certain power factor with a lower voltage across the arc, if the phase reactance is lower, the arc then becomes shorter, and heat radiation is concentrated more on the charge. After the furnace has been charged, usually with steel scrap, the operator energizes the circuit with the electrodes in the drawn position. They are then lowered under automatic control until they contact the charge and an arc is ignited, the control then attempts to maintain constant impedance in the circuit.

2.1 Arc Furnaces Equivalent Circuit:

The main furnace elements are shown in Fig. (2), these are: Transformer reactance, power cable and arc source (the electrodes). In that circuit of the arc furnace, V is the secondary furnace transformer line voltage, I = electrode current (assumed to be sinusoidal); X = phase reactance (including the reactance of the reactor and transformer recalculated to the secondary side, the phase reactance of the bus bars ahead of the delta connection point and the reactance of the electrodes); r = loss resistance; ρ = arc resistance (assumed to be constant over the arc cycle), R is the total circuit and arc resistance.

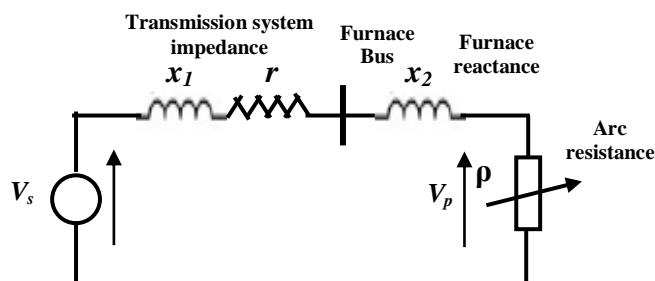


Fig. (2) Equivalent circuit arc furnace

2.2 Arc Furnaces Analysis Equations:

The furnace powers, currents, losses, arc voltages and power factors can be calculated using its equivalent circuit of fig. (2) as follows: with $(R=r+\rho)$, $(X=x_1+x_2)$. R is the circuit resistance, ρ is the arc resistance, x_1 is the circuit reactance and x_2 is the furnace circuit reactance, the furnace current I is given by assuming the input voltage is V as:

$$I = \frac{V}{\sqrt{3(R^2 + X^2)}} \quad (1)$$

The apparent power is given by:

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

While the input reactive power is given by:

$$Q = \frac{3XV^2}{R^2 + X^2} \quad (3)$$

The input power is given by:

$$P_r = \sqrt{S^2 - Q^2} \quad (4)$$

The losses power is:

$$P_l = 3rI^2 \quad (5)$$

The useful arc power is found from:

$$P_\rho = P_r - P_l \quad (6)$$

The arc voltage is given by:

$$V_\rho = \frac{P}{3I} \quad (7)$$

The efficiency is calculated from:

$$\eta = \frac{\rho}{R} \quad (8)$$

The load power factor is given by:

$$\cos\phi = \frac{R}{\sqrt{R^2 + X^2}} \quad (9)$$

2.3 Maximum Current Corresponding to Maximum Power:

The arc power is expressed by:

$$\begin{aligned} P_\rho &= P_r - P_l = \sqrt{S^2 - Q^2} - 3I^2r \\ &= \sqrt{3I^2V^2 - 9I^4X^2} - 3I^2r \end{aligned} \quad (10)$$

The maximum arc power with respect to the arc furnace current is obtained from:

At $(dP_\rho/dI)=0$:

$$\frac{6IV^2 - 36I^3X^2}{2\sqrt{3I^2V^2 - 9I^4X^2}} - 6Ir = 0 \quad (11)$$

Then:

$$r = \frac{V^2 - 6I^2X^2}{2\sqrt{3I}\sqrt{V^2 - 3I^2X^2}} \quad (12)$$

Or:

$$36X^2I^4(r^2 + X^2) - 12V^2I^2(r^2 + X^2) + V^4 = 0 \quad (13)$$

$$aI^4 + bI^2 + c = 0 \quad (14)$$

Where: $a = 36X^2(r^2 + X^2)$

$$b = 12V^2(r^2 + X^2)$$

$$c = V^4$$

Then, the current at maximum power operating point is given by:

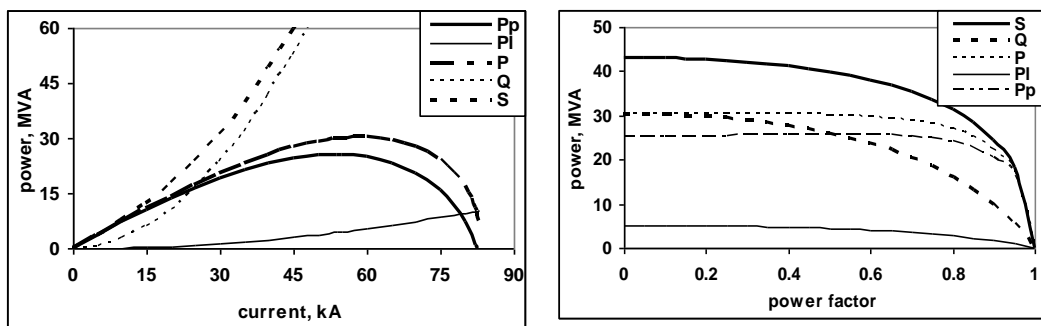
$$I_M = \sqrt{\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}} \tag{15}$$

Neglecting the power losses, the current at the maximum power point is found from:

$$I_M = \frac{V}{\sqrt{6X}} \tag{16}$$

2.4 Load Curves of Balanced Arc Furnaces:

Load curves furnaces are plotted in fig. (3) with the aid of equation (1) to (9) as a function of the electrode current and the load power factor. The furnace data are $X=2.9$ m.ohm/phase, supply voltage $V=420$ volt, $r=0.5$ m.ohm/phase, arc resistance is variable, $I=$ furnace current ranging from (0 to 80) kA. If the current is more than maximum value power, the arc power will decay. While the losses will still increase further. If the electrical efficiency is taken into account, it is clear that one must keep to the left of this point. Load power factor at that point is usually around 0.75. After power factor of 0.6 nearly furnace power become constants only the reactive powers are variable in values. This will influence the load voltage stability.



(a) (b)
 Fig. (3) Arc furnace power characteristic curves
 (a) Arc current, kA (b) Arc power factor, pf

2.5 Studied Load Characteristics:

Assuming the arc furnace load is the arc resistance (ρ) node (n), then the studied load will be represented by the circuit shown in fig. (4).

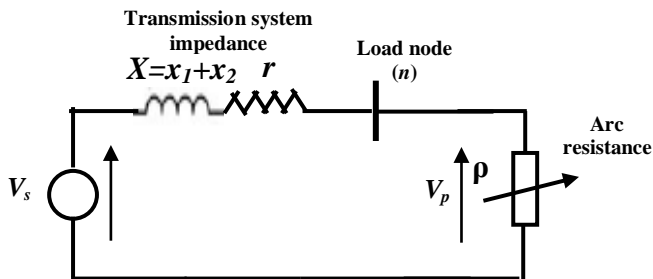


Fig. (4) Studied system circuit

The load resistance ρ characteristic with the furnace current I and with the furnace operating power factor and with the arc voltage are shown in fig. (5).

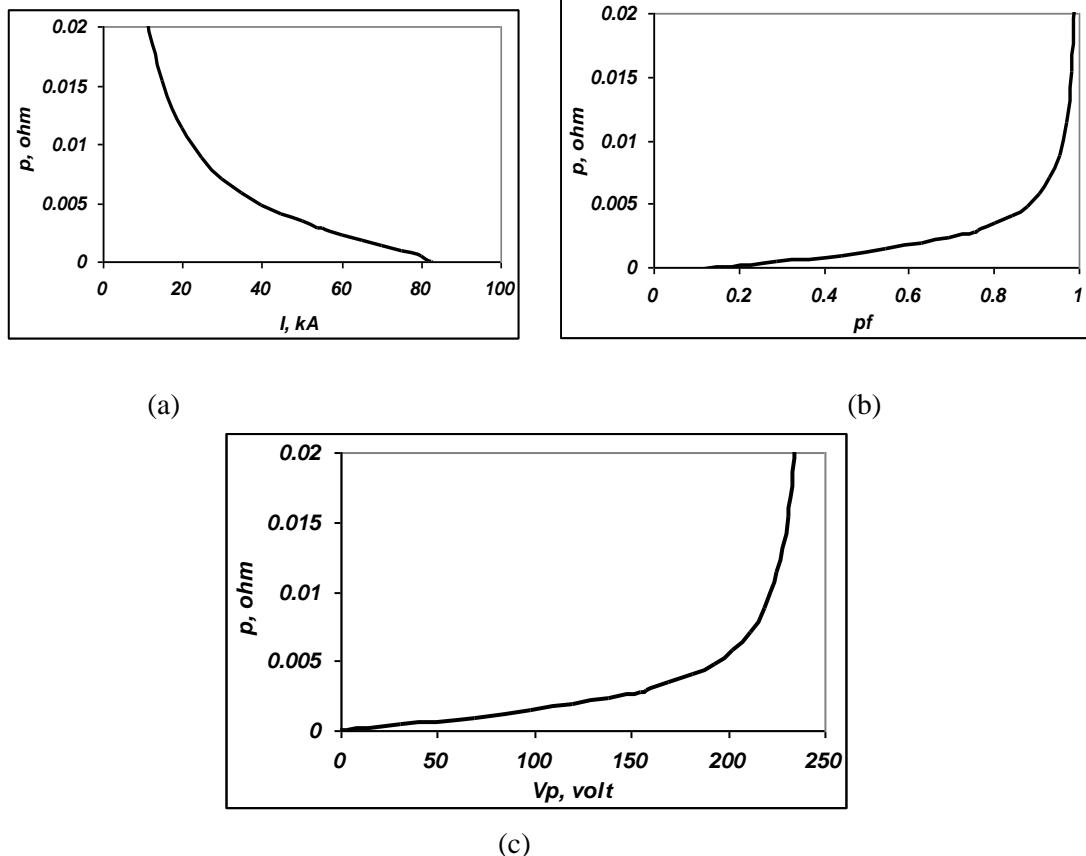


Fig. (5) Arc resistance characteristics

(a) Arc current, kA (b) Arc power factor, pf (c) Arc voltage V_p

3. CRITERIA FOR DETECTION OF STEADY STATE VOLTAGE INSTABILITY

Detection of steady-state voltage instabilities is performed through load flow techniques or through certain mathematical criteria. Among those qualitative criteria: dE_s/dV_p criterion, L -indicator criterion, and Z_{Th}/Z_{Load} criterion. The results of these criteria will be checked by using the critical voltage criteria. Those criteria are given in detail in ref. [3], which is a qualitative exact criterion.

3.1 The Z_{Th}/Z_{Load} Criterion [3]:

A simplified theory of voltage stability [3, 9] may be immediately derived from the optimal impedance solution of a two nodes system. When the load increases, Z_{Load}

decreases the current I circulating in the system increases, leading to a voltage drop which is proportional to the current; the voltage V_{load} at the load terminal decreases. According to above equation, the collapse of the system at load bus occurs when the impedance of the load is equal to the equivalent impedance looking into the port between load bus and the ground, $Z_{Load}=Z_{Th}$. For a secure system at load bus, we must have $Z_{Th}/Z_{load} \leq 1$, therefore, Z_{Th}/Z_{Load} can be taken as a measure of voltage stability at load bus $Z_{Th}/Z_{Load} = 1$ is the critical value. If this value violate unity system voltage becomes unstable.

3.2 L-Indicator or On-Line Global Criterion [3, 10]:

An indicator L is recently defined [3, 6]. Its value varies in the range between zero and one for stable conditions. ($L=1$) indicates critical stable condition. Its violation of one indicates unstable condition. Such an indicator allows predicting steady-state voltage instability or the proximity of a collapse, using information of a normal load flow and some simple numerical calculations. It can be used for on-line testing of steady-state voltage stability during power system operation. For steady-state voltage of the whole system to be guaranteed, the voltage stability criterion can be written as: ($L < 1$). For two nodes system this criterion tends to be:

$$L = \left| 1 - \frac{V_s}{V_p} \right| = \frac{|Z_s||S|}{V_p} \tag{17}$$

Therefore: $L = 0$, when $V_p = V_s$, and $L = 1$, when $V_p = 0.5V_s$, and $L > 1$, when $V_s > V_p$.

3.3 dE_s/dV_p Criterion [3]:

The first criterion relating to voltage instability, as proposed by Weedy [4], in 1968, is the dE_s/dV_p criterion. This criterion was firstly, suggested by Venikov, for simple two nodes links. It relates the sending and receiving-end voltages (E_s, V_p) of that simple link feeding a load of powers (P, Q). The receiving-end voltage V_p is stable when $(dE_s/dV_p) > 0$, for a given link having impedance Z . In evaluation of the dE_s/dV_p for the basic two nodes system. It is shown that voltage stability holds when a factor $k'_c > 0$ where k'_c is obtained from dE_s/dV_p and is defined as:

$$k'_c = \cos(\delta_{12} + \alpha) \left[\frac{\partial Q_r}{\partial V_r} + \frac{2V_r}{Z_l} \cos \alpha \right] + \sin(\delta_{12} + \alpha) \left[\frac{\partial P_r}{\partial V_r} + \frac{2V_r}{Z_l} \sin \alpha \right] - \frac{E_s}{Z_l} > 0 \tag{18}$$

Critical steady-state node voltage stability arises when $k'_c = 0$ and instability appears when $k'_c < 0$. The criterion depends mainly on the partial differentiation of both load power and reactive power with respect to its terminal voltage magnitude.

3.4 Critical Voltage Criterion [3, 10]:

The results of the above three criteria are qualitative ones. Before their application to load nodes, a Thevenen’s equivalent is obtained for each load node under study.

Critical voltage of these nodes and its corresponding maximum power can be used as a checking index for the numerical qualitative results of the above criteria [3, 9].

$$V_{cr} = -\sqrt{\left(\frac{-1}{2A^2}\right)(K - E_s^2)} \quad (19)$$

Where:

$$K = 2AB(P_r \cos(\beta - \alpha) + Q_r \sin(\beta - \alpha))$$

A load having voltage less than the node critical voltage or having a power more than the node maximum power corresponding to its critical voltage announces a state of voltage instability.

4. RESULTS AND DISCUSSIONS

4.1 Arc Stability Dependence on both Arc Furnace Load Power Factor and Arc Currents:

Stability of the arc is dependent on both the current and the power factor of the furnace circuit. The arc stability is dependent on the current as shown in Table (1). At higher currents, the arc is fatter and the region between the electrode and the charge is more ionized. The arc therefore ignites earlier and more reliably at high currents and low power factor. In order to examine the arc furnace load voltage stability, the arc current is changed from 5kA up to 60kA, the above three criteria are examined. At arc current of 53.87kA, the arc resistance as the furnace load presents case of voltage instability.

Table (1) The arc stability dependent on the arc current in kA with three criteria methods ($V_{cr}=158.52$ volts)

Arc Current kA	Arc Resistance m.ohm	Arc Power MW	Arc Voltage Volt	Power Factor pf	dZ_{TH}/dZ_{Load} Criterion	L-Inductor Criterion	dE_s/dV_p Criterion
5.0	47.9	3.59	239.55	0.998	0.061	0.124	89.0
10.0	23.6	7.07	235.75	0.993	0.125	0.132	52.0
15.0	15.4	10.40	231.05	0.984	0.191	0.181	49.2
20.0	11.3	13.53	225.45	0.971	0.261	0.213	45.5
25.0	8.8	16.42	218.90	0.954	0.336	0.286	40.7
30.0	7.0	19.02	211.34	0.933	0.418	0.337	35.9
35.0	5.8	21.28	202.72	0.908	0.508	0.458	29.5
40.0	4.8	23.15	192.94	0.878	0.610	0.527	23.4
45.0	4.0	24.55	181.87	0.843	0.728	0.681	15.6
50.0	3.4	25.40	169.36	0.8015	0.869	0.830	7.4
53.87	2.9	25.62	158.52	0.765	1.000	1.005	-0.24
55.0	2.8	25.60	155.15	0.753	1.043	1.143	-6.5
60.0	2.3	25.00	138.89	0.696	1.271	1.370	-13.3
At maximum power: $\zeta=85.5\%$, $P_{Loss}=4.353MW$, $S=81.45MW$, $Q=75.74MVAR$, $P=29.97MW$							

The arc is extinguished at each current zero, and the voltage between electrode and charge immediately after the arc extinction is higher at a low power factor than at a high one when the apparent power as shown in Table (2).

Table (2) The arc stability dependent on the arc load power factor with three criteria methods ($V_{crit}=159.1$ volts)

Power Factor pf	Arc Resistance m.ohm	Arc Power MW	Arc Voltage Volt	Arc Current kA	dZ_{Th}/dZ_{Load} Criterion	L-Inductor Criterion	dE_s/dV_p Criterion
0.1	2.42	25.17	142.41	58.98	1.226	1.949	-66.9
0.2	2.46	25.27	143.94	58.52	1.196	1.918	-56.6
0.3	2.45	25.38	146.60	57.72	1.158	1.865	-45.5
0.4	2.66	25.51	150.52	56.50	1.104	1.790	-33.7
0.5	2.85	25.61	155.93	54.74	1.033	1.690	-21.0
0.547	2.96	25.62	159.10	53.67	1.000	1.004	-0.3
0.6	3.13	25.58	163.20	52.23	0.942	0.973	2.2
0.7	3.56	25.23	173.03	48.59	0.610	0.927	5.5
0.8	4.33	24.06	186.42	43.02	0.679	0.853	6.3
0.9	6.15	20.60	205.58	33.41	0.478	0.743	13.0
1.0	∞	0.00	242.48	0.00	0.000	0.532	22.4
At maximum power: $\zeta=85.56\%$, $P_{Loss}=4.32MW$, $S=39.05MW$, $Q=25.06MVAR$, $P=29.94MW$							

In order to examine the arc furnace load voltage stability, the arc power factor is changed from 0.1 up to unity, the above three criteria are examined. At arc power factor 0.547, the arc resistance as the furnace load presents case of voltage instability. The three criteria proved this phenomenon. Noting that this value corresponds the maximum current at maximum furnace input power.

4.2 Effects of Arc Furnace Transformer Voltage Variations on Arc Furnace Parameters ($V_s=210, 420, \text{ and } 840$) volts:

The arc voltage is lower for a higher current i.e, shorter arc. With the same arc power to the left and to the right of the maximum point, the wear on the walls and roof will be less, if we choose to operate to the right of the maximum point. Transformer secondary voltage V_s is varied from (120 to 800) Volts, depending on the size of the furnace and the operation being performed. Voltage change is accomplished with a load tap changing transformer or a regulator in the primary circuit or with on load taps in the furnace transformer for ($V_s=210, 420, \text{ and } 840$) volts as show in fig. (6), variations on arc furnace parameters with arc furnace current and arc furnace power factor. Arc furnace resistance p , ohm, arc furnace current I , in (kA), and arc furnace voltage V_p , in (volts) in fig. (4, a, b, c). With power factor plots arc furnace voltage V_p , arc furnace power P_p , in (MW), and arc furnace power, in (MW) are plotted in fig. (4, d, e, f).

4.3 Effects of Circuits and Leads Reactance on Arc Furnace Performance ($X=1.45, 2.9, \text{ and } 5.8$) m.ohm:

For a certain applied apparent power and a certain power factor a lower arc voltage and a higher electrode current will be obtained if the reactance (X) of the furnace circuit is reduced. This is illustrated in fig. (7), for three values of reactance ($X=1.45, 2.9, \text{ and } 5.8$) m.ohm balanced furnaces, where the arc power and the electrode voltage versus the electrode current have been plotted. Figure (7) shows the three curves characteristics. To minimize the refractory wear, efforts are made in modern furnaces to reduce the phase reactance of the conductors by using flexible cables as short as possible and arranged with as small a phase clearance as possible with respect to movements of the furnace. Recently, static VAR compensators [5] have been proposed for the same purpose.

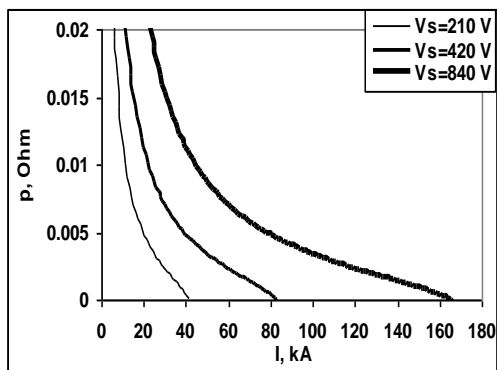
4.4 Effects of Circuits and Leads Resistance on Arc Furnace Performance ($r=0.25, 0.5, \text{ and } 1.0$) m.ohm:

For a certain applied apparent power and a certain power factor a lower arc voltage and a higher electrode current will be obtained if the resistance (r) of the furnace circuit is reduced. This is illustrated in fig. (8), for three values of resistances ($r=0.25, 0.5, \text{ and } 1.0$) m.ohm, for balanced furnaces, where the arc power and the electrode voltage versus the electrode current have been plotted. Figure (8) shows the three furnaces characteristics plots. To minimize the refractory wear, efforts are made in modern furnaces to reduce the phase resistances of the conductors by using certain cables with high conductivity.

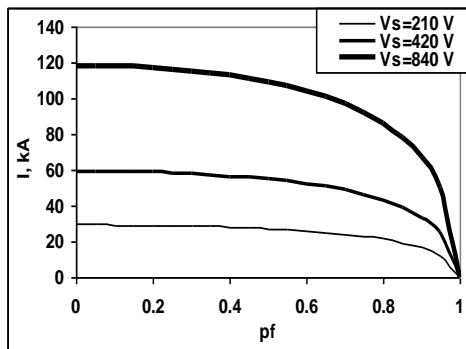
4.5 Furnace Operating Point and Furnaces Power Factors:

In some methods of operation, the furnace transformer secondary voltage is at a high level during the initial part of the meltdown for maximum power output. Constant current cannot be maintained until a significant quantity of the charge has been melted, because of the changing shape of the mass of scrap as it liquefies. The arc is quite irregular and the load fluctuates. Widely from short-circuit when the electrodes contact the metal to no-load when the arc is extinguished. Since scrap is usually bulky, the furnace must be recharged one or more times during meltdown. Arc resistances are usually unequal. Reducing of the power merely by decreasing the current leads to a higher electrical efficiency but also more substantial wear of the refractory.

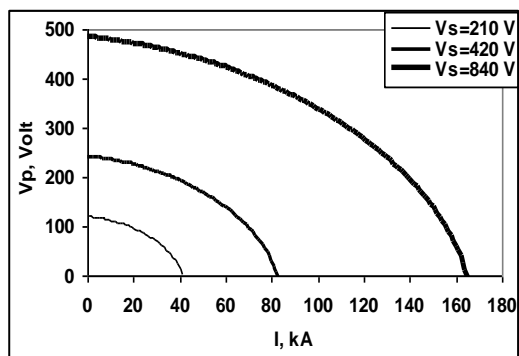
Since rather a large percentage of the arc power is lost through heat radiation to the roof instead of heating the melt, it is in fact doubtful whether the total efficiency will be better. Furthermore, the arc becomes less stable. Reducing of the power through merely decreasing the voltage results in a poorer electrical efficiency and shorter arcs. The lower efficiency, however, will not only be to the worse as mentioned above. It can be said that with normally designed furnace conductors, one generally keeps slightly to the left of the maximum point of the arc power. An operating point is often selected where the power factor is (0.7 to 0.8).



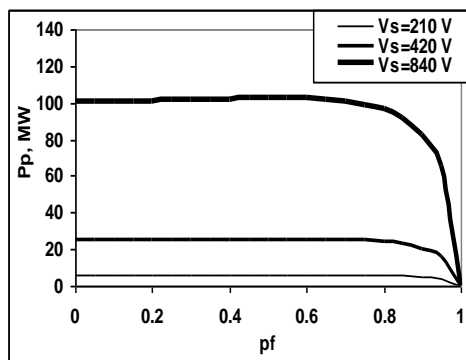
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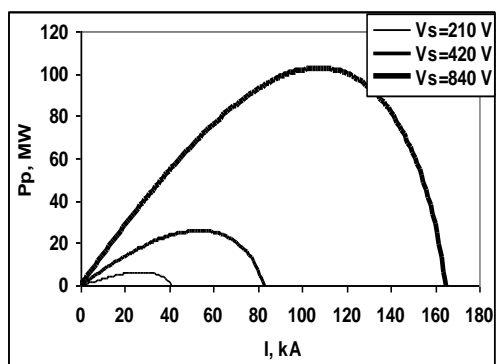
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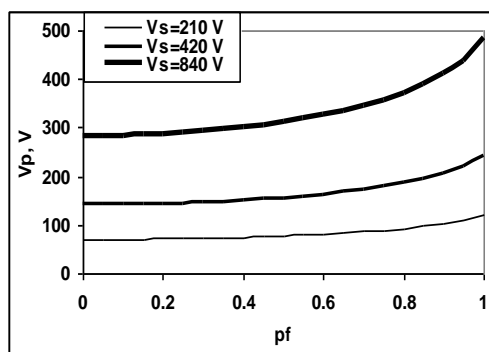
(b)



(e)



(c)



(f)

Fig. (6) Effects of furnace transformer voltage (V_s) variations on arc furnace parameters with arc furnace current and arc furnace power factor

(a) Arc resistance p , ohm

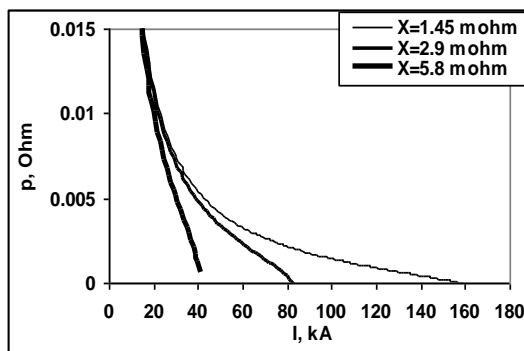
(b) Arc voltage V_p , Volt

(c) Arc power P_p , MW

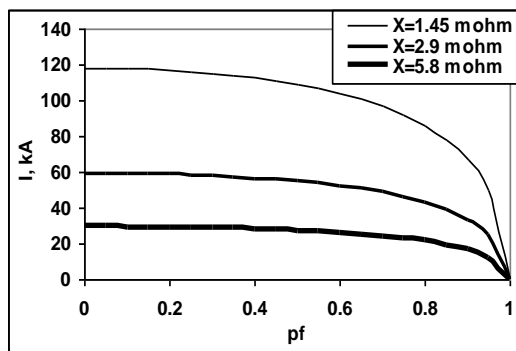
(d) Arc current I , kA

(e) Arc voltage V_p , Volt

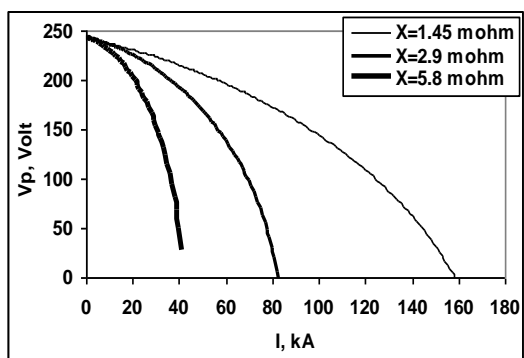
(f) Arc power P_p , MW



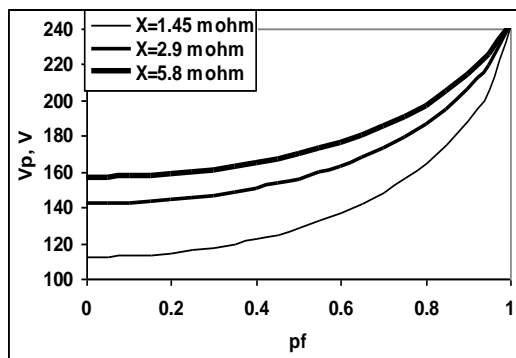
(a)



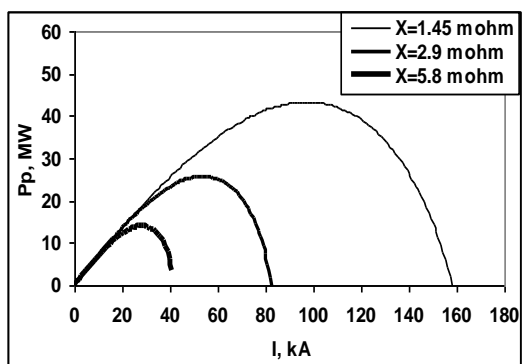
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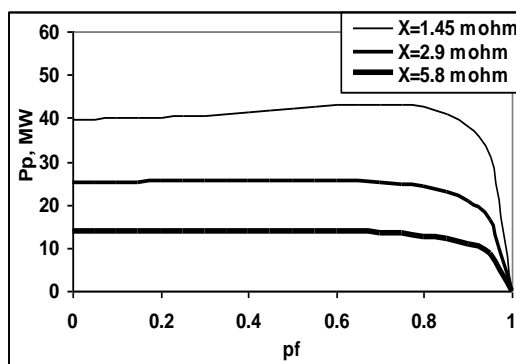
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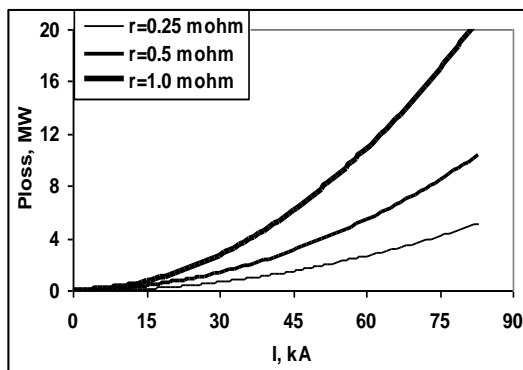


(f)

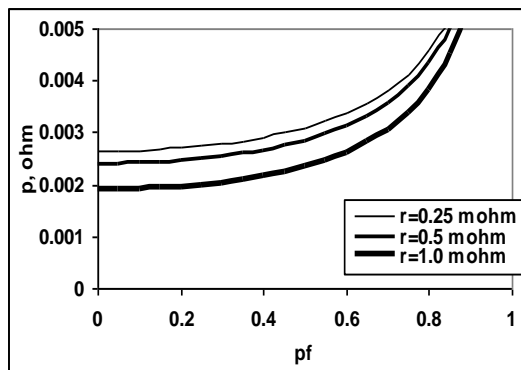
Fig. (7) Effects circuits and leads reactance (X) variations on furnace performance with arc furnace current and arc furnace power factor

- (a) Arc resistance p , ohm
- (b) Arc voltage V_p , Volt
- (c) Arc power P_p , MW

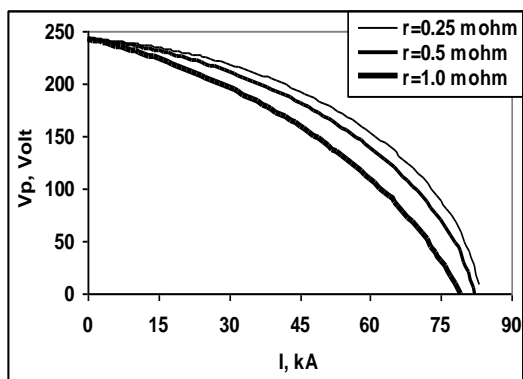
- (d) Arc current I , kA
- (e) Arc voltage V_p , Volt
- (f) Arc power P_p , MW



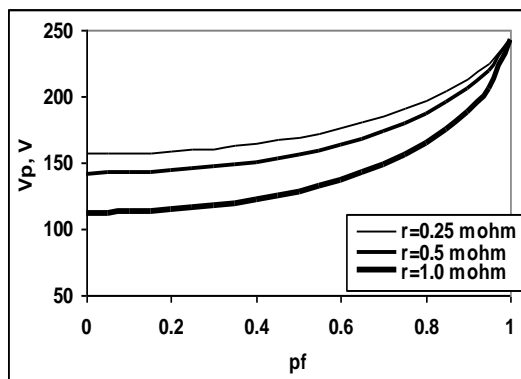
(a)



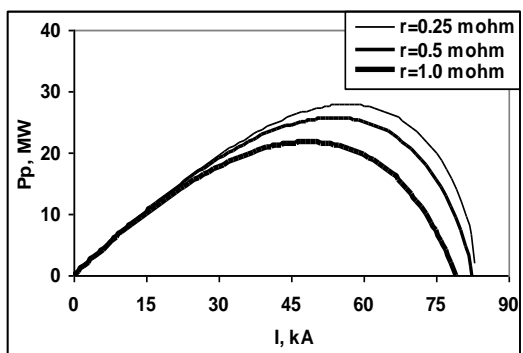
(d)



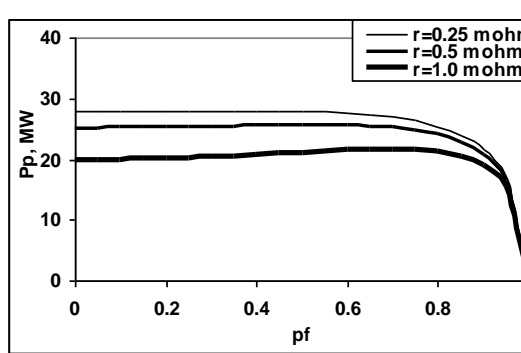
(b)



(e)



(c)



(f)

Fig. (8) Effects circuits and leads resistance (r) variations on furnace performance with arc furnace current and arc furnace power factor

(a) Arc resistance p , ohm

(b) Arc voltage V_p , Volt

(c) Arc power P_p , MW

(d) Arc current I , kA

(e) Arc voltage V_p , Volt

(f) Arc power P_p , MW

5. CONCLUSIONS

- (a) Arc furnace load voltage stability is examined through three different criteria. They are checked by critical voltage criterion which represents a quantities experimental criterion.
- (b) Arc furnace load characteristic with depends arc current and power factors is examined with different assumed circuit parameters.

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اتزان الجهد لأحمال أفران القوس الكهربى

يتناول البحث دراسة لاتزان الجهد لاحمال الافران ذات القوس الكهربى للحصول على مرحلة الاستقرار. ويدرس هذا البحث مدى تأثير الممانعات المختلفة فضلا عن مقاومة القوس الكهربى مع كل فولتية الجهد. وفى نفس الوقت معامل القدرة يكون ما بين 0.7 الى 0.8 هذا يعنى زيادة الفواقد وقلة الانتاج ومشاكل فى الجهود فى الشبكة المغذية للافران. كما يوضح البحث دراسة ثلاث طرق للتأكد من اتزان الجهد لاحمال افران القوس الكهربى مع تغير التيار و معامل قدرة الحمل واستحدثت صيغة للوصول لاقصى تيار ممكن بعده يتم عدم اتزان الجهد وهو المقابل لاقصى قدرة تسحبها الفرن سبب ارباع معينة.