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Closely Parametrical Model for an Electrical Arc Furnace

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Abstract**—**To maximise furnace production it's necessary to optimise furnace control, with the objectives of achieving maximum power input into the melting process, minimum network distortion and power-off time, without compromise on quality and safety. This can be achieved with on the one hand by an appropriate electrode control and on the other hand by a minimum of AC transformer switching.

Electrical arc is a stochastic process; witch is the principal cause of power quality problems, including voltages dips, harmonic distortion, unbalance loads and flicker. So it is difficult to make an appropriate model for an Electrical Arc Furnace (EAF). The factors that effect EAF operation are the melting or refining materials, melting stage, electrode position (arc length), electrode arm control and short circuit power of the feeder. So arc voltages, current and power are defined as a nonlinear function of the arc length. In this article we propose our own empirical function of the EAF and model, for the mean stages of the melting process, thanks to the measurements in the steel factory.

Keywords**—**Modelling, electrical arc, melting, power, EAF, steel.

I. Introduction

NONLINEAR loads are the principal cause of power quality problems including voltage dips, harmonic distortion and flicker [2],[11],[12]. Electric arc furnace is the worst nonlinear loads type, and its nonlinearity is due to the chaotic nature of arc impedance [6], where its conductivity is determined from its temperature and pressure [10]

The increasing in iron demand, such as in vehicle industries, encourage the steel-works to invest more and more in the recovery of metals, thanks to electrical or chemical furnaces

The electric arc furnace is used to provide high quality steels from a raw material of steel scrap.

Typical furnace is shown in Fig. 1. It consists of a refractory lined shell and removable roof.

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Three graphite electrodes, held in clamps on the end of a supporting mast arm, pass through holes in the furnace roof.

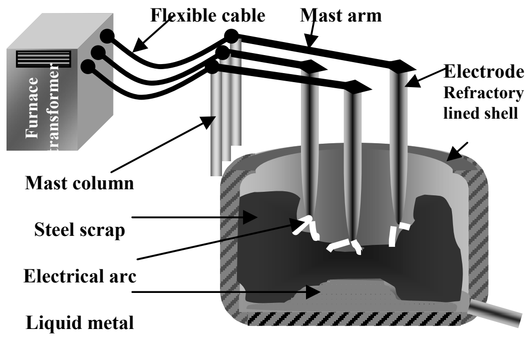

Fig. 1 Typical electrical arc furnace

Electrical power is supplied to the electrodes by an adjustable voltage tap transformer, and the heat generated by electric arcs striking between the electrodes and the scrap melts the steel Fig. 2.

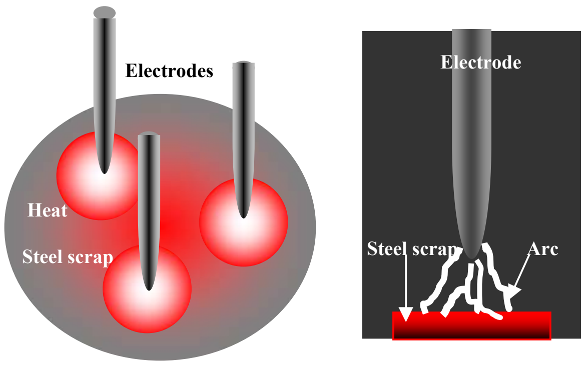

Fig. 2 Heat conversion by electric arc

The maximum electrical power to heat conversion occurs for a particular length of electric arc [7], and any deviation from this optimum length impairs the power utilisation efficiency. The steel scrap surface is irregular by nature of the scrap, and, as parts of the scrap melt, it moves about, changing the contours of the surface. Thus, random disturbances in the arc length occur continuously. It is the function of the position control system to respond to such disturbances by moving the electrode to maintain the arc length at its preset value [8].

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Typical EAF Process

First we charge the furnace with scrap, after that the electrodes could be lowered, each of which has its own regulator and mechanical drive. The electrodes are connected to the furnace transformer's, which may be rated from 90 to 265 volts, thanks to 9 taps.

To achieve meltdown as quickly as possible one must follow the following stages [1],[3]

Stage-1: The current is initiated by lowering the electrodes, above the material.
Stage-2: Electrodes bore through the scrap to form a pool of liquid metal.
Stage-3: Electrical arc will be lengthened by increasing the voltage to maximum power.
Stage-4: Arc length is changed so that the shorter arc will deliver a higher portion of its heat to the metal below the electrode
Stage-5: Chemical treatments to improve steel quality is done under low power to maintain steel liquid
Stage-6: Stop of melting

II. Model Description

Our EAF melt steel, by applying an AC current to a steel scrap charge by means of graphite electrodes. It requires about 520 kwh/ton, and produce 700t/year approximately Fig. 3,a.

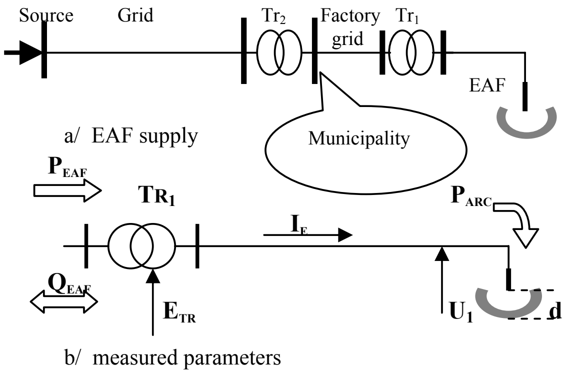


Fig. 3 Studied model

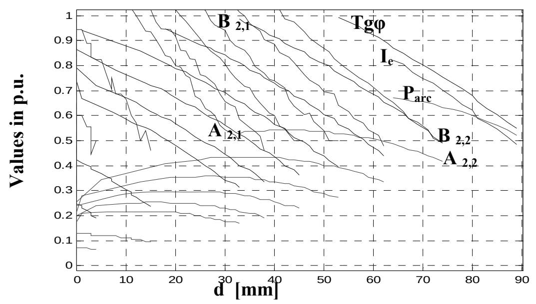


Fig. 4 EAF process

All the processes of electrical arc furnace (Annex) can be summarized in figure 4 [9]**.** we have record 32 measurements of each measured parameter for 9 transformer taps Fig. 3.b normal operation must make the compromise between the limitations according to maximum power and acceptable current respectively $[A_{n,1}\ A_{n,2}]$ and $[B_{n,1}\ B_{n,2}]$, where n is tap index. Then conferring itself to this constraint the adjustment law of electrodes position will be done according to Smax.

III. Treatment of Measured Parameters

The EAF is modelled together with the neighbouring network [4]. The circuit equation of the furnace transformer to the end of electrodes can be writhen as follow:

$$E_{tr} = \sqrt{3} Z_1 I_e + U_1 \ ,$$

Where U_1, Ie & Z_1 are respectively electrode voltage, current and impedance of EAF transformer with flexible cable

$$\text{Then, } Z_1 = \frac{\left[E_{tr} - U_1\right]}{\sqrt{3} I_e} = \frac{\Delta U_1}{\sqrt{3} I_e} \tag{1}$$

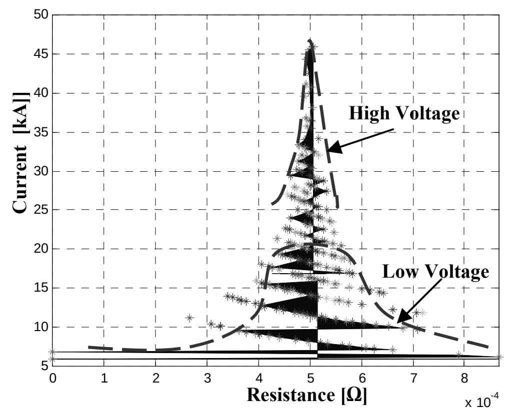
$$Z_1 = \sqrt{R_1^2\left(I_2, T\right) + X_1^2\left(T\right)} \tag{2}$$

$$R_1 = \frac{P_{EAF} - P_{arc}}{3 I_e^2} \tag{3}$$

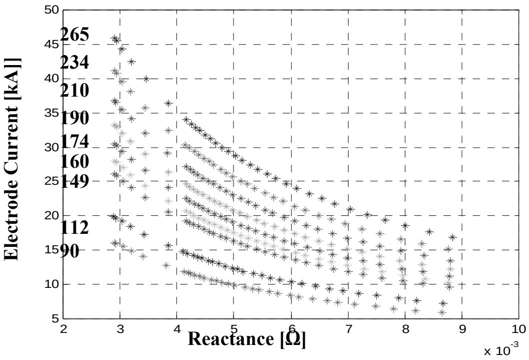
Where P_{EAF} is total active power of EAF. And P_{arc} is the active power of arc.

So, from equations (1,2,3) we can deduct

$$X_1 = \frac{1}{\sqrt{3} I_e} \sqrt{\Delta U_1^2 - \frac{\left[P_{EAF} - P_{arc}\right]^2}{3 I_e^2}}$$



a/ Distribution of R_1



b/ Distribution of X_1

Fig. 5 Calculation of Z_1 form the 9x32 measurements

On Figs. 5 a & b we show the variation of resistance $R_1$and inductance $X_1$of the transformer with the flexible cable which supplies the electrodes.

$$R_1=R_{tr}+R_{\text{flexible cable}}$$

Indeed for the various tests carried out:

- R_1 has a Gaussian distribution; this is due to the combined effect of the current and the time of its application. Dispersion has a more important in low voltage, because metal takes more time to melt; from where it overheating the transformer winding and flexible cable.
- As inductance X_1 is the consequence of electromagnetic fields, which weakened with the increase of temperature, gives it a deadened exponential variation.

In order to reduce this parametric dispersion we propose a reinforcement in cooling by forced ventilation of transformer windings and increase water flow which crosses the flexible cables

$$R_{arc}=\frac{P_{arc}}{3I_e^2}$$

$$Q_{EAF}=Q_{arc}+\Delta Q$$

$$Q_{arc}=Q_{EAF}-3I_e^2X_1$$

Where Q_{EAF} is total reactive power of EAF

And Q_{arc} is the reactive power of arc

$$X_{arc}=\frac{Q_{arc}}{3I_e^2}$$

Following to this treatment an empirical model is proposed

$$R_{arc}=A_R(u)e^{\alpha(u)d} \text{ ; Where}$$

$$A_R=\frac{\left[0,7.(U-210)^2+1,7\right]}{50^2}.10^{-3} \text{ ;}$$

$$\alpha=0,097e^{0,011(90-U)}-\frac{1,7}{(U-112)^2+80}+\frac{100}{(U-360)^2+50}$$

$$X_{arc}=A_X(u)d^2+B_X(u) \text{ ; Where}$$

$$A_X=1,05.10^{-3}e^{0,075(90-U)} \text{ ;}$$

$$B_X=\frac{3,14.U}{153}-3.10^{-3}e^{0,075(90-U)}$$

d - is the distance between electrode and scrap

In the operating zone the arc impedance decreases with the increase of voltage and increases with the distance between electrodes and metal. The analysis shows that for high voltages and short distance of arc, the electrostatic field created between the electrode and metal is more important as the electromagnetic fields, thus gives to the arc a capacitive character defined by the negative values of Xarc. For this purpose we give a model of electric arc shown in Fig. 6.

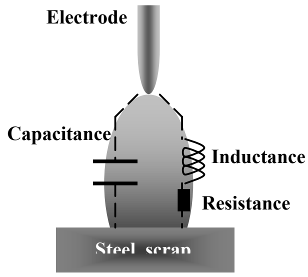


Fig. 6 Electric arc model

$$Q_{arc}=Q_{arc}^L+Q_{arc}^C \tag{4}$$

$$Q_{arc}^L=K_Ld \tag{5}$$

$$Q_{arc}^C=-K_C/d \tag{6}$$

Q_{EAF}^L Is the inductive reactive power of arc

Q_{arc}^C Is the capacitive reactive power of arc

From equations (4,5,6) we can write

$$Q_{arc}=\frac{\left[K_Ld^2-K_C\right]}{d}$$

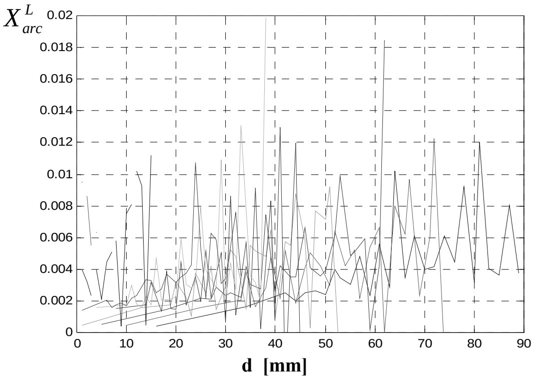
$$K_L(n)=\frac{Q_{arc}(n+1)d(n+1)-Q_{arc}(n)d(n)}{d^2(n+1)-d^2(n)}$$

n is the measurement number

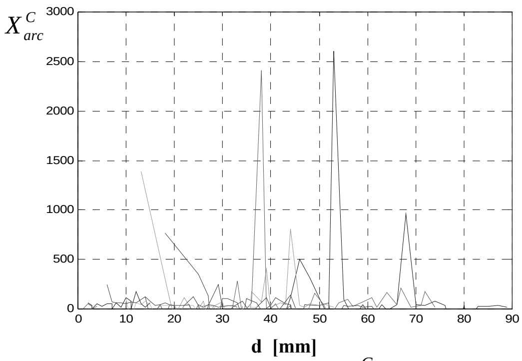
$$K_C(n)=K_L(n)d^2(n+1)-Q_{arc}(n+1)d(n+1)$$

$$Q_{arc}^L=K_Ld=3X_{arc}^LI_e^2 \Rightarrow X_{arc}^L=K_Ld/3I_e^2$$

$$Q_{arc}^C=-K_C/d=-U_1^2/X_{arc}^C \Rightarrow X_{arc}^C=U_1^2d/K_C$$



a/ Dispersion of X^{L}_{arc}



a/ Dispersion of X^{C}_{arc}

Fig. 7 Calculation of Z_{arc} form the 9x32 measurements

After numerical treatment of measured parameters we propose a model for the principal stages of melting process summarised in Fig. 8.

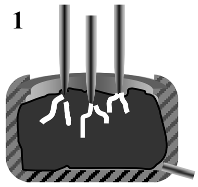
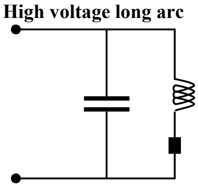
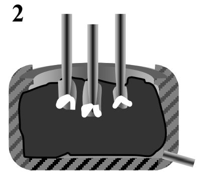
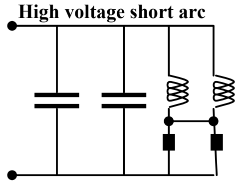
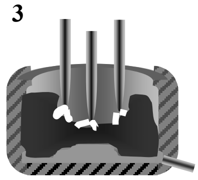
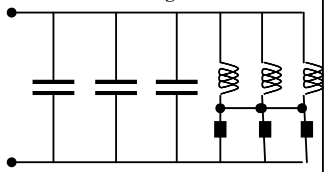
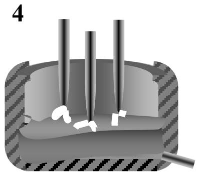
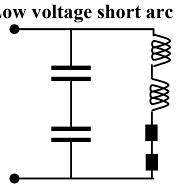
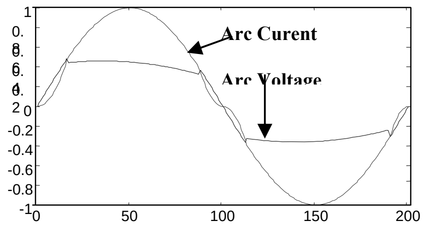
Stage	Model
1 	**High voltage long arc** 
2 	**High voltage short arc** 
3 	**Medium voltage short arc** 
4 	**Low voltage short arc** 

Fig. 8 The proposed model of EAF for each melting stage



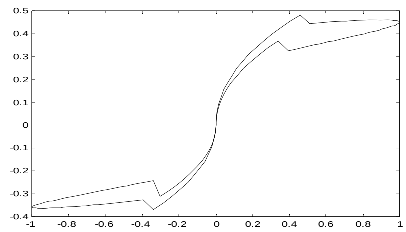


Fig. 9 Temporal and [IV] representation of electric arc current & voltage

The major part of power quality problems occurs in the stage 1 & 2, because of the physical movement and settling of the scrap.

Irregularity in the voltage wave forms is caused by abrupt initiation [5] and interruption of current witch provides a source of harmonic currents. Fig. 9 a &b Thus voltage and current waves deviate considerably from symmetrical sinusoidal form

So we propose to substitute the electrical energy by a chemical one, like natural Gas, and the EAF will be electrically supplied only in stage 3 & 4.

IV. Conclusion

This analysis leads to the conclusion that the arc behaves in such a way that all the arc characteristics are controlled by the expansion of the arc, which is the main feature used to physically describe the arc behaviour. The arc expansion is evident from the arc shape, which is defined as the region where conduction of electricity takes place. The arc shape depends on: current density, magnetic flux density, electric conductivity, electric potential, and temperature fields

The proposed model reveals a new parameter of the electrical arc furnace which is the capacitances.

Because of The continuous adjustment of electrode position, the integration of this model in the regulation loop, reduce the operator action; thus reduction of human errors due to the visual estimate, then this automation enables us to make a better management of energy from where the reduction of the consumption (kWh/tone).

The empirical relations of the condenser and the inductance of the furnace, enable us to avoid some very dangerous oscillations of the current and the voltage which disturb the nearness loads. Our recommendation to steel makers, is to substitute electrical energy for stage 1 & 2 by a chemical one, because of power quality constraint

Annex

EAF Features

EAF type	: 80LHF12,5
Transformer rating	: 12,5 [MVA]
Short circuit reactance	: 2,9 [mΩ]
Maximum electrode current	: 30,84 [kA]
Number of voltage taps	: 9
Voltage range	: [90 V ÷ 265 V]
Primary voltage	: 63 [kV]
Weight capacity	: 80 t
Temperature gradient	: 3 ÷ 4 [°C/mn]
Furnace diameter	: 2,47 [m]
Electrode diameter	: 0,35 [m]
Distance electrode to wall	: 0,71 [m]

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