An Improved Time Domain Arc Furnace Model for Harmonic Analysis

M. Anxo Prieto Alonso, and Manuel Pérez Donsión

***Abstract*--In this paper it is presented an arc model to carry out harmonic analysis of an AC three-phase arc furnace with a single- phase circuit. This model is based on V-I characteristic of the arc and takes into account the effect of the arcs unbalance over the zero sequence harmonics. The model is implanted in EMTDC and tuned with field data. Simulations are performed in continuos work using Montecarlo method to obtain arc length. Simulations results obtained with this model are compared for the main harmonics with actual data and simulation data obtained with other models. The comparison is carried out with the probability density functions of the harmonics.**

***Index Terms*-- Furnaces, power system harmonics, harmonic analysis.**

I. INTRODUCTION

The electric arc furnaces are used for melting and refining metals, mainly iron in the steel production. Nowadays, arc furnaces are designed for very large power input ratings and due to the nature of both, the electrical arc and the melt down process, these devices can cause large power quality problems on the electrical net, mainly harmonics, interharmonics, flicker and voltage imbalances [1]. The Voltage-Current characteristic of the arc is non-linear, what can cause harmonic currents. These currents, when circulating by the electric net can produce harmonic voltages, which can affect to other users. Beginning of the melt down process is the most critical part of the cycle in terms of disturbances [2].

Different studies on arc furnaces harmonics analysis can be found in the bibliography of the topic. Most of these accomplish the time domain simulation of the arc furnace with the single-phase circuit [3]-[4]-[5]-[6]. Another authors accomplish the simulation with a three-phase circuit [2]-[7]-[8].

Time domain analysis of the arc furnace with a three-phase circuits are quite costly concerning computation time, and those which are accomplished on a single phase circuit are not quite exact concerning harmonic content, mainly the magnitude of zero sequence components.

M. A. Prieto and M. P. Donsión are with the Department of Electrical Engineering, Vigo University, Vigo, SPAIN .

The furnace shell is isolated and it represent a star connection of the three arcs, then if a three-phase arc furnace operation were balanced, the zero sequence components of the current wave would be null. Really, unbalanced operation is the normal situation in the meltdown process and this produces zero sequence harmonics in the arc current. However, due to the influence between phases, these harmonic components do not reach the values that we would find in the current wave of a single-phase operation arc.

II. THE ELECTRICAL CIRCUIT OF THE FURNACE

The electric power arrives at the studied steel plant at very high voltage and is converted to low voltage suitable for the arc furnace. Transformers perform this task in two stages. The melting furnace is connected to the electric net by means of a HV/MV (220/30 kV) transformer (T1) and is fed by a MV/LV transformer (T2). The furnace side of this transformer has adjustable voltage from 990 to 660 V in order to vary the furnace power. Also, there is in the steel mill a refine furnace of small power. Fig. 1 shows the electric circuit of the furnaces in the steel mill, where are also represented a filter for the second order harmonic and the static var system (SVS).

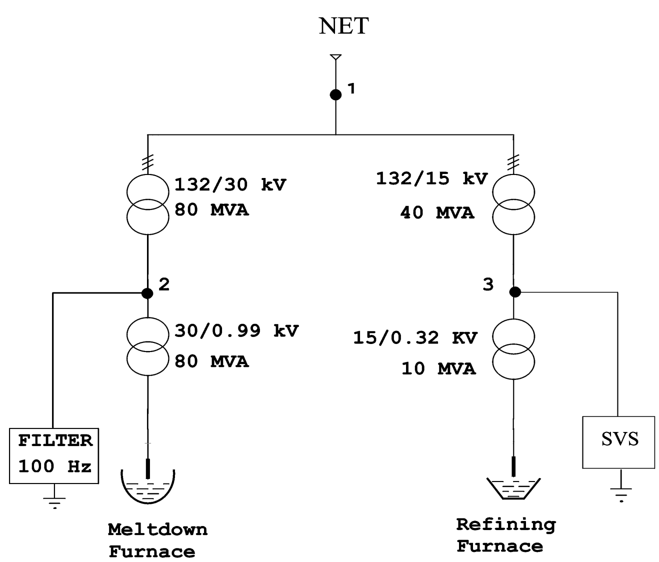

Fig. 1. Electrical circuit of the furnaces.

The electrical diagram circuit of the melting furnace can be represented in a simplified way as shown in Fig. 2. X_L is the short circuit reactance at the PCC (Point of Common Coupling), X_e is a variable reactance used for the arc stabilisation (fliker compensation) and its value can vary from 0.418 to 0.209 p.u. X_H group the lead, electrode and arc reactance, and a variable resistance represents the electrical arc. The other electrical and electronic equipment of the steel mill is fed through another independent line. Per unit values of the circuit reactances are presented in table I.

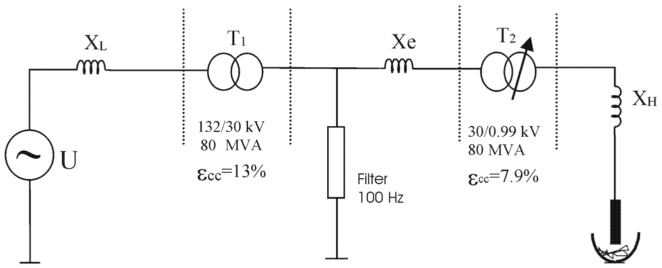

Fig. 2. Electrical circuit of the melt down furnace

TABLE I
PER UNIT VALUES OF THE CIRCUIT ELEMENTS

Element	**X p.u.**
Line	0.315
Transformer 1 (T1)	0.13
Arc stabilisation reactance	0.418 ÷ 0.209
Transformer 2 (T2)	0.10
Furnace reactance	0.003

III. ARC MODEL

A high current electric arc could be well represented with the conductance model proposed by Cassie and expressed in (1).

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\Theta}\left(\frac{v^2}{v_o^2} - 1\right) \tag{1}$$

Where:

g is the dynamic conductance

Θ is the time constant

v is the instantaneous arc voltage

v_o is the voltage considered as constant in the arc

V-I characteristic of an AC electric arc has a shape as represented in Fig. 3. There are many proposed models obtained by simplification of this characteristic. Fig. 4 shows a graphic representation of one of these models.

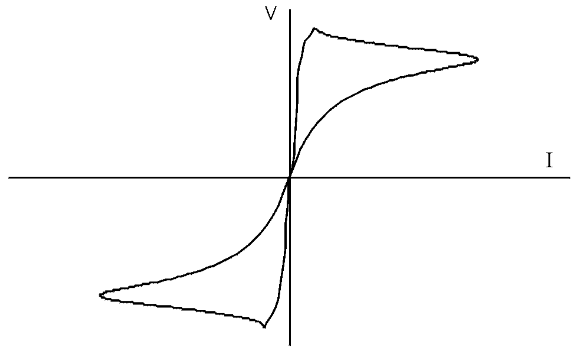

Fig. 3. Voltage-Current characteristic of a single-phase electric arc.

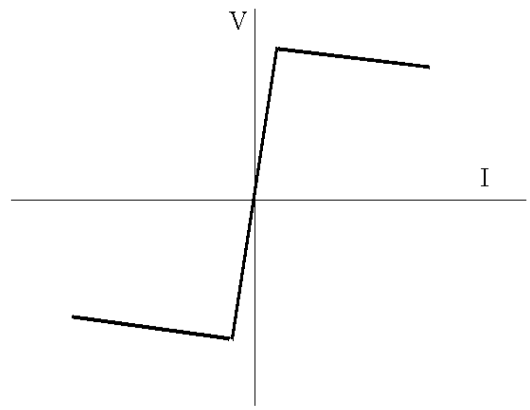

Fig. 4. Simplified V-I model of the arc

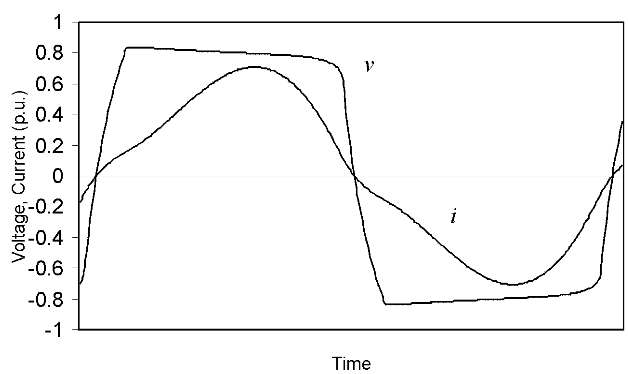

Fig. 5. Voltage and current waves in the arc

Simulations with a single-phase circuit using this arc model lead us to current and voltage waves as represented in Fig. 5. Voltage wave is very close to a square wave and current wave is more similar a sinusoidal wave but with harmonic content, basically 3, 5 and 7 order harmonics. This model can represent with a good approximation the behaviour of an AC single-phase electric arc and they can be used to represent the arcs in a three-phase simulation.

If it is represented with this model the behaviour of an arc in a three-phase arc furnace, making the simulation with a single-phase circuit, the degree of similarity depends on the particular situation that is been simulated. We can say, that the behaviour of the model will be very similar in an instant in which one of the arcs is extinguished and the others two are maintained operating, that is, open circuit in one of the phases as represented by the current waves in Fig. 6. Although this is a real situation in a three-phase furnace operation and it can be produced several times during de meltdown process, regularly the three arcs coexist.

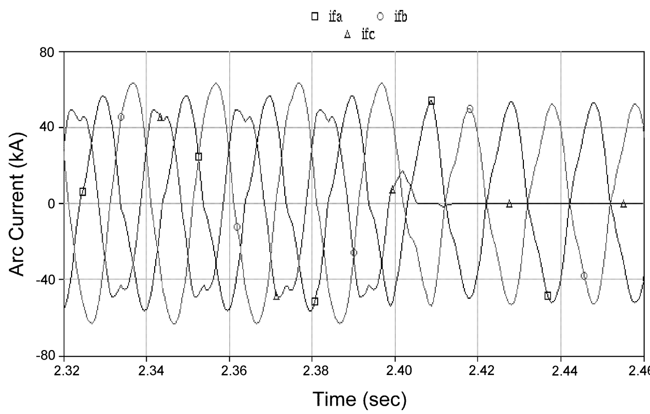

Fig. 6. Arc currents when only two of the arcs coexist.

Three-phase arc furnaces shell used for steel melting has not ground return and represents a star connection for the three arcs. In the hypothetical case of a balanced operation, due to this connection, no zero sequence harmonics would be present in the current wave of the arcs. In that situation, the voltage and current waves in the arc are different to those represented in Fig. 5.

The operation of the furnace is not balanced, furthermore, it is not probable a total balance situation during the melt down process. Even so, the influence of this connection of the arcs causes that the content of third harmonic and its multiple in current wave will be lower than those levels expected in single-phase operation.

Simulating the electrical behaviour of the three-phase arc furnace through EMTDC in stable and balanced operation, that is, constant and equal arc length in the three electrodes, and using for the arc simulation the Cassie model, it is obtained a current waves in the arcs as represented in Fig. 7. In this situation, the voltage wave in the arc is as represented in Fig. 8. It does not present a squared shape and it appears a kind of step due to the fact that the third harmonic level is reduced almost to 50%. In the current wave do not appear zero sequence components due to the star connection of the three arcs.

Simulation of harmonics contents of a three-phase arc furnace through single-phase circuit needs an arc model that represent the characteristics previously emphasised.

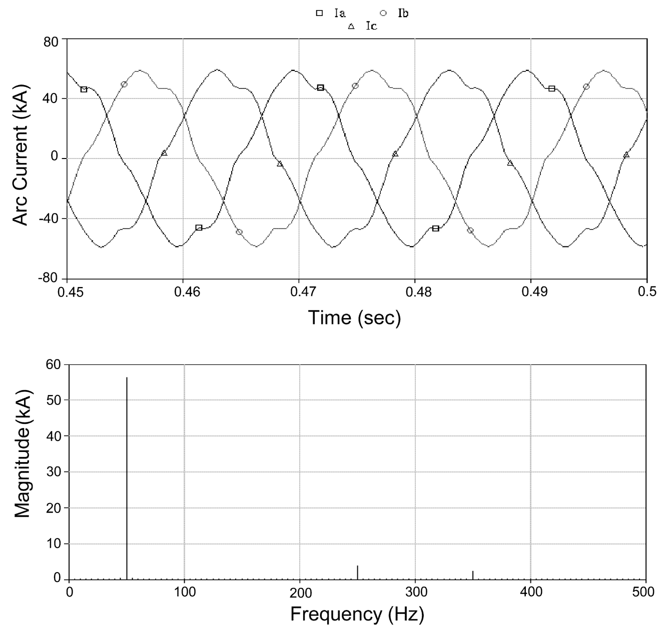

Fig. 7. Current waves in the arcs and their harmonic content.

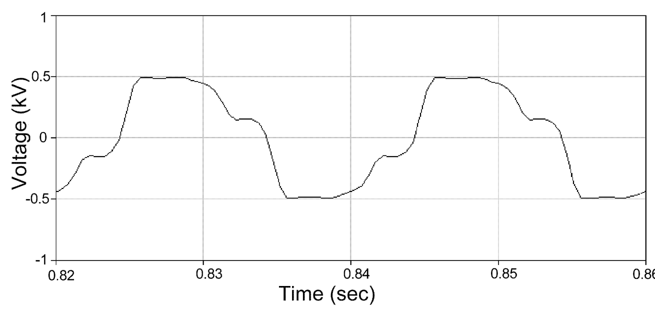

Fig. 8. Arc voltage wave in a three-phase arc furnace balanced operation.

With the voltage and current waves obtained in three-phase balanced operation of the furnace it is built the V-I characteristic presented in Fig. 9. The differences with that represented in Fig. 3 corresponding to a single-phase operation are evident. In any case, both characteristics can represent an arc in a three-phase furnace, although in extreme operation conditions, total imbalance and balance. Fig. 3 would correspond to an arc of a given length in a moment in which the current of one of the others arcs would be zero, that is, the corresponding arc would have been extinguished. Fig. 9 represents an arc in totally balanced operation of the three-phase furnace. These two extreme situations are particular situations of the meltdown process, and what it can be expected are intermediate situations.

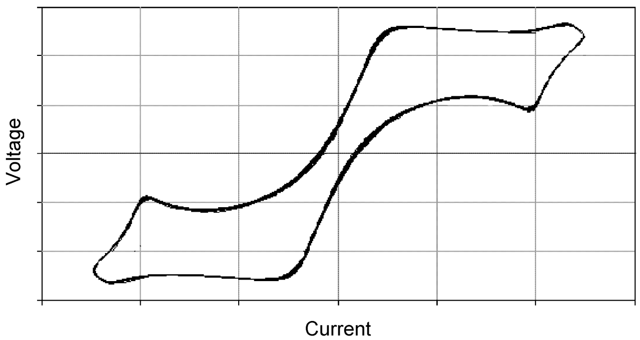

Fig. 9. V-I characteristic of de arc in balanced operation.

From the situation previously pointed it is proposed a V-I arc model to use in time domain simulation of three-phase arc furnace with a single-phase circuit. The model is obtained from the V-I characteristics represented in Fig. 9 and Fig. 3 by linear approximation of the different V-I sections in the way showed in Fig. 10.

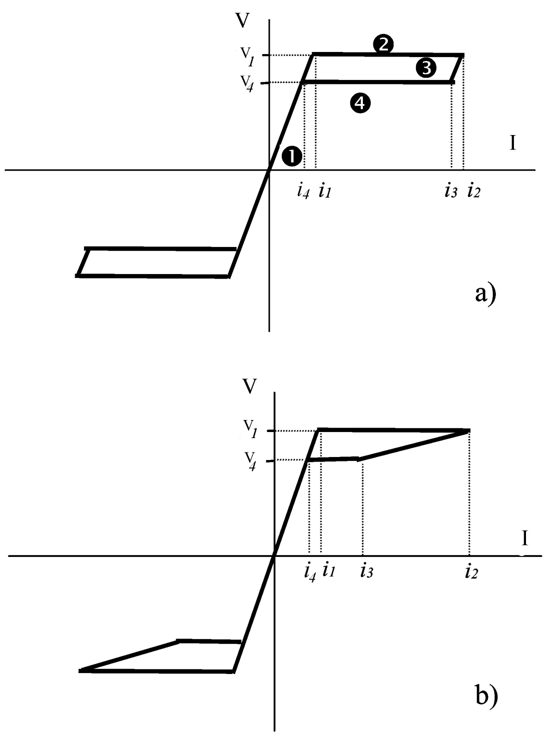

Fig. 10. Linear approximation of the V-I characteristic

The different sections of the V-I characteristic, 1,2,3 and 4, are characterised by its slopes R_1, R_2, R_3, R_4. The physical meaning of these slopes during a positive half cycle is described below:

R_1 corresponds to the first period, when the arc goes from extinction to reignition and the arc acts as a constant resistance. Its value is high and is defined by the necessary voltage for the arc establishment, which depends of the arc length.

R_2, R_3 and R_4 correspond to the period when the arc is established. R_2 represents the voltage variation of the arc when the current is increasing. Its value is close to zero because the arc voltage is practically constant. R_3 represents the arc voltage drop due to the arc reignition that is being produced in one of the other phases and depends on the degree of imbalance. R_4 has the same value than R_2 in the arc model and represent the variation of the voltage before the extinction of the arc. The last period is represented again by R_1 and corresponds to the arc extinction.

The V-I characteristic is expressed by (2):

$$v = \begin{cases} R_1 \times i & i < i_1 \text{ and increasing} \\ & i < i_4 \text{ and decreasing} \\ R_2 \times (i-i_1) + V_1 & i_1 < i < i_2 \text{ and increasing} \\ R_3 \times (i-i_2) + V_2 & i_3 < i < i_2 \text{ and decreasing} \\ R_4 \times (i-i_3) + V_3 & i_4 < i < i_3 \text{ and decreasing} \end{cases} \qquad (2)$$

Where

$i_1 = V_1/R_1$; $i_2 = f(V_1,R_2)$; $i_3 = f(V_2, R_3)$; $i_4 = V_3/R_4$;

The values of V_1 to V_4 are giving as a function of the arc length and represent the voltages of the end of the corresponding section.

Considering variable the value of R_3, then the characteristic represented in Fig. 10.b) can be obtained from Fig. 10.a) changing this value and, in this case, the characteristic would correspond to the situation in which one of the arcs would be extinguished. The difference between both situations is the slope R_3. The variation of harmonic content of the current wave is function of this value and it is represented in Fig. 11 for the most important harmonics. The level of the third harmonic is the most affected and its value is duplicated when R_3 vary from 10 to 0.3. The variation of 5 and 7 order harmonics is produced in opposite sense than the 3rd and it is of smaller quantity.

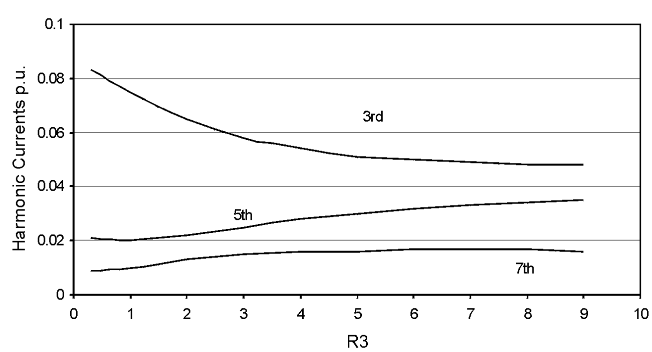

Fig. 11. Variation with R3 of the harmonic content in the arc current.

In the same way, harmonic level also depends of the values of the other parameters as represented in Fig. 12 and Fig. 13.

Fig. 14 shows the voltage and current waves in the electric arc obtained with the proposed model over a single-phase circuit. The voltage wave is similar to that represented in Fig. 8. The comparison between both waves is accomplished through its harmonic components.

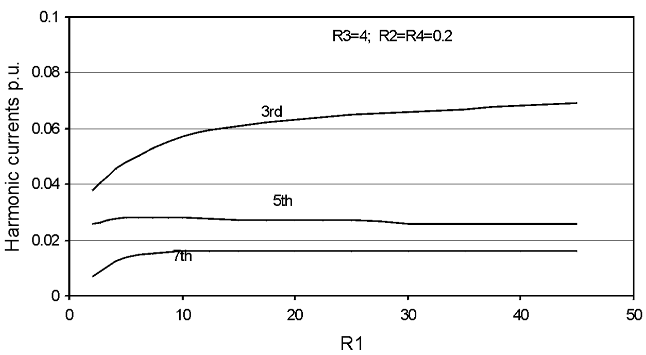

Fig. 12. Variation with R_1 of the harmonic content in the arc current.

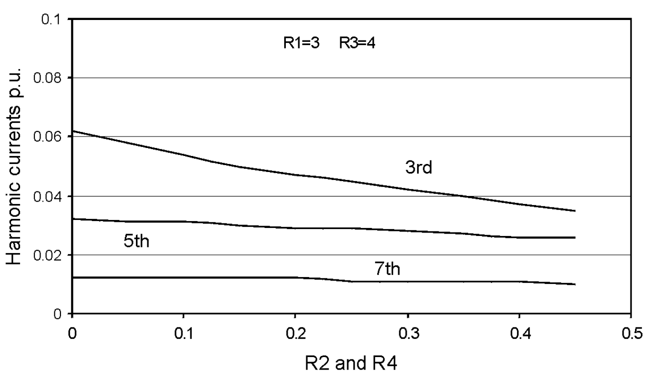

Fig. 13. Variation with R_1 and R_4 of the harmonic content in the arc current.

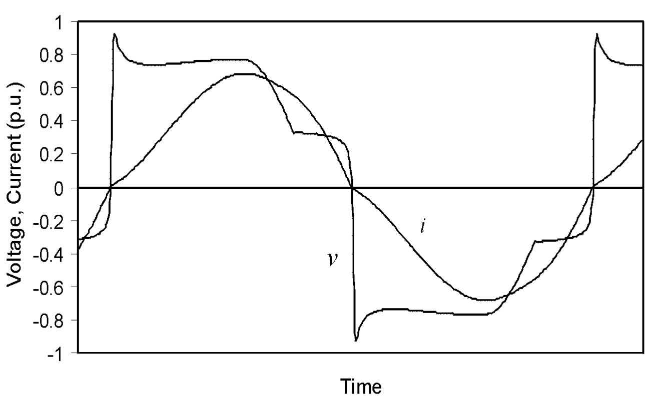

Fig. 14. Voltage and current waves in the arc.

IV. HARMONIC CONTENT

Table II shows the harmonic content of the voltage and current waves in the arc obtained through simulation with the arc model from Fig. 3 (model 1) and with the proposed arc model (model 2). In either case the values correspond to the same value of the fundamental component of the current of 0.707 p.u. In the voltage wave it is appreciated a decrease in the value of the fundamental component and mainly the level of third harmonic.

TABLE II
HARMONIC COMPONENTS IN THE ARC FOR MODELS 1 AND 2

	Harmonics	**Model 1**	**Model 2**
Arc Voltage	Fund.	0.698	0.636
	3rd	0.209	0.072
	5th	0.122	0.122
	7th	0.083	0.058
	9th	0.062	0.043
Arc Current	Fund.	0.705	0.705
	3rd	0.089	0.030
	5th	0.031	0.031
	7th	0.015	0.011
	9th	0.009	0.006

The main difference in the current wave is fundamentally the decrease of the value of the third order harmonic. Its value is reduced to the third part respect to those obtained with the model 1. To obtain this effect is the aim of the proposed model. The reduction can vary when the parameters of the model are modified. Also, there are differences in levels of the others harmonics, but they are smaller.

V. RESULTS

Some of the parameters, which define the model, vary continuously and the others can be considered constant. The arc length changes randomly due to both the movement of the scrap when it is melting and the movement of the electrodes. On the other hand, R_3 depends on the degree of existing imbalance between phases and this imbalance has a random behaviour.

The model validation is accomplished through continued simulation for different values of the arc length, which are generated applying the Montecarlo method to the distribution of Vo obtained from measured values of the arc current as showed in Fig. 15. The change in the value of the arc length is produced randomly between 1 and 12 cycles. Also, the values of R_3 are generated randomly between 0.3 and 25 with a uniform distribution. Fig. 16 shows the variation of the arc voltage, current and resistance along several cycles.

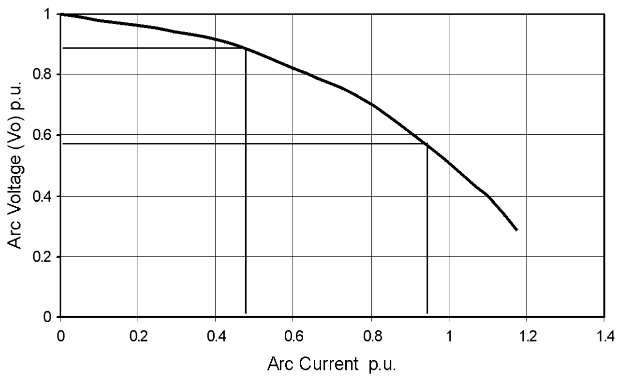

Fig. 15. Arc current versus arc voltage

The employed simulation time corresponds to one real operation minute. During this time continually the Fast Fourier Transform (FFT) is applied with overlapping each 4 cycles and probability distributions are obtained for the most important harmonic with a total amount of 750 values. The harmonic levels compared are the 3rd, 5th and 7th. Second harmonic levels are not compared because the errors could be large in this kind of waves applying the FFT.

The probability distribution functions of the fundamental component of the current obtained applying the two models have a high degree of coincidence with real distribution. Fig. 17 represent distribution functions, which correspond to the measured values and calculated values with the proposed model.

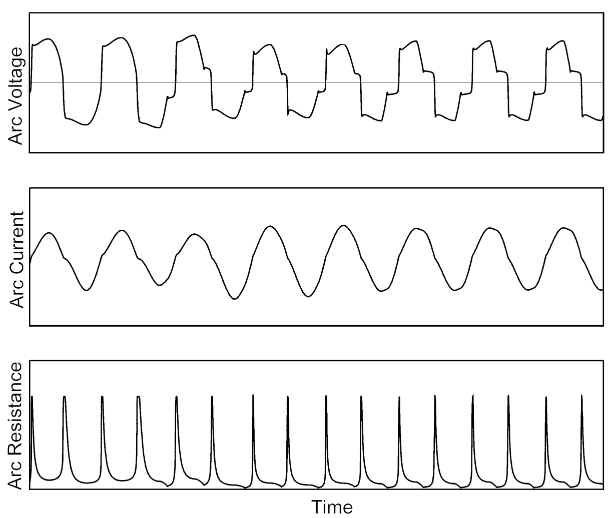

Fig. 16. Voltage, current and resistance of the arc

Fig. 18 shows the probability distribution functions for third harmonic in three cases: for measured values (1), for model 1 calculated values (3) and for proposed model calculated values (2). The differences between measurement values and calculated values with model 1 are very large.

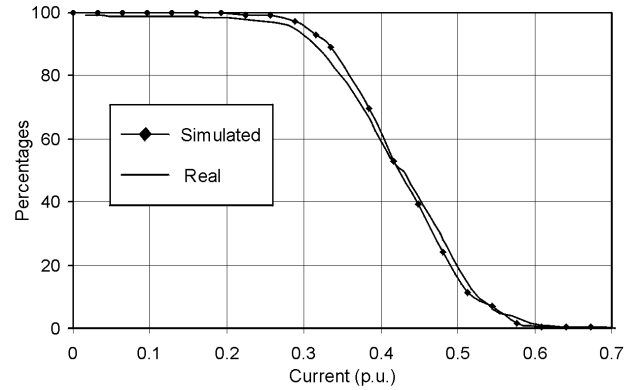

Fig. 17. Distribution function of the fundamental component of the current

With the proposed model it is obtained a good approximation to the measured values for third harmonic. The probability distribution functions of 5 and 7 order harmonic corresponding of the measured values and the simulation values obtained with the proposed model are shown in Fig. 19. Practically there is a total coincidence in the corresponding section to low values. In the highest, the simulated values are a little below than real.

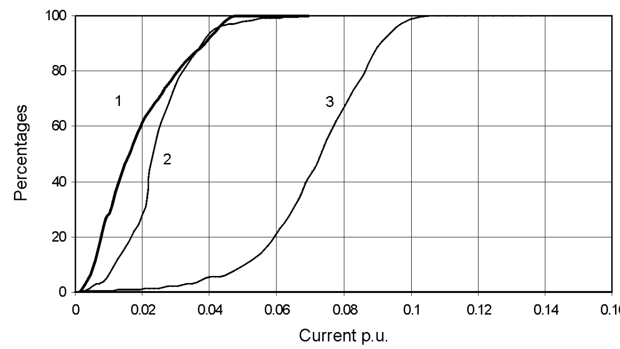

Fig.18. Distribution functions for the third order harmonic.

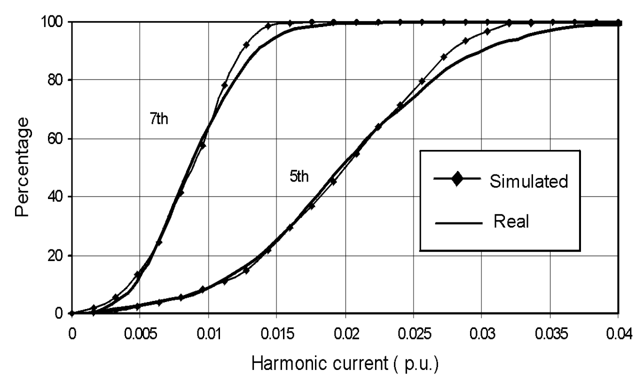

Fig. 19. Probability distribution functions for 5th and 7th harmonic.

VI. CONCLUSIONS

The proposed arc model for three-phase arc furnace simulation with a single-phase circuit from harmonics point of view is well adjusted to the real behaviour. It takes into account the effect of the circuit configuration on the zero sequence components, what causes that the probability distribution function of the third order harmonic is quite approximated to that obtained from the measures. This implies that the random variation of R_3 with uniform distribution between 0.3 and 15 is suitably for this model. Good results are obtained also for the other harmonics considered important by its magnitude.

VII. REFERENCES

[1] Lavers, B. Danai, “Statistical analysis of electric arc furnace parameter variations”, *IEE Proc.*, Vol. 132 Part C, No. 2, pp. 82-93, March 1985.

[2] H. Schau, D. Stade, “Mathematical modelling of three-phase arc furnaces”, *Proc. 1994 IEEE International Conference on Harmonics in Power Systems*, pp.422-428.

[3] J. D. Lavers, Behnam Danai, P.P. Biringer, “A method of examining in detail electric arc furnace performance,” *IEEE Transactions on Industry Applications*, Vol. 21, pp. 137-146, Jan/Febr 1985.

[4] Srinivas Varadan, Elham b. Makram , Aldy Girgis, “A new time domain voltage source model for an arc furnace using EMTP,” *IEEE T-PWRD*, Vol. 11, No. 3, pp. 1685-90, July 1996.

[5] Montanari, M. Loggini, A. Cavallini, L. Pitti, D. Zanielli, “Arc furnace model for the study of flicker compensation in electrical networks,” *IEEE T-PWRD*, Vol. 9, No. 4, October 1994.

[6] Tongxin Zheng, Elham B. Makram, “An adaptive arc furnace model,” *IEEE T-PWRD*, Vol. 15, No. 3, pp. 931-939, July 2000.

[7] Brociek Wieslaw, “Circuital representation of cooperatin of a three-phase uhp arc arrangement with an electric power system,” *Rozprawy Elektrotechniczne*, v 33, n 3-4 , pp. 857-871, 1987.

[8] A. M. Dan, A. Mohacsi, D. Stade, H Schau, S. Kramer, “Comparison of Different Ways to Simulate Arc Furnace Power Quality Impacts,” *Proc. 1994 IEEE International Conference on Harmonics in Power Systems*, pp. 422-428.

VIII. BIOGRAPHIES

M. Anxo Prieto Alonso was born in Ourense, Spain, in 1962. He received the Ph.D in Electrical Engineering from de University of Vigo in 2000. He is presently a teacher in the Department of Electrical Engineering of Vigo University. His present research interest includes power quality and analysis of disturbance effects on induction motors behaviour.

Manuel Pérez-Donsión received his MSc in industrial engineering from Universidad Politécnica de Cataluña in 1980 and his PhD from Universidad de Vigo in 1986. In 1987 he became a Full Professor. He was head of the Escuela Técnica Superior de Ingenieros Industriales y Minas from 1995 to 2001. From 2001 to now he is the head of Electrical Engineering Department. He is member of the International Steering Committee of ICEM and Spanish chairman of the Jornadas Hispano Lusas de Ingeniería Eléctrica. His main research interests are linked to the Electrical Machines Modelling, Diagnostics and Control, Power Quality and Renewable Energy with special emphasis in Small Hydropower and Wind Energy. He was the author of over sixty research papers of which some were presented at national and international conferences, and others were published in relevant reviews and journals. He has also been involved with several research projects.