

GUI for studying the parameters influence of the electric arc model for a three-phase electric arc furnace

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Abstract. This paper presents an analysis regarding the modeling of the behavior for a three-phase electric arc furnace installation. Therefore, a block diagram is implemented in Simulink that represents the modeling of the entire electric arc furnace installation. This block diagram contains also the modeling of the electric arc which is the element that makes the electric arc furnace behaving as a nonlinear load. The values for the model parameters of the electric arc furnace installation are like the ones from the real installation taken into consideration. Other model parameters are the electric arc model ones. In order to study the influence of the parameters of the electric arc models, it is developed a Matlab program that contains the graphical user interfaces. These interfaces make connection with the models of the electric arc implemented in Simulink. The interfaces allow the user to modify parameters for each of the electric arc model. Current and voltage of the electric arc are the variables taken into account to study the influence of the parameters on the electric arc models. Waveforms for voltage and current of the electric arc are illustrated when a parameter of the model is modified in order to analyze the importance of this parameter on the electric arc model. Also, for each of the models is presented the voltage-current characteristic of the electric arc because this characteristic gives information about the behavior of the electric arc furnace installation.

1. Introduction

In our days the steel is used in many fields of industry, such as alimentary, constructions, automobile, chemically and marine. The liquid steel is obtained by the electric arc furnaces (EAFs) which can be of two categories: alternative current (AC) and continuous current (DC) furnaces [1]. In this paper is studied the behavior of a three-phase EAF [2] with direct action. In order to perform the control of this kind of plant it is necessary to study the electric arc and this is the purpose of this paper. In order to understand the model of the electric arc all the model parameters should be analyzed to notice the importance of each of them on the model. After knowing the model of the process can be developed control strategies. The models presented in this paper are developed by the authors of this paper in other researches [3-5].

2. Electric Arc Furnace Plant

In Figure 1 are illustrated the main constructive elements of a three-phase EAF [4] with direct action. This kind of EAF has three graphite electrodes which are supplied by a three-phase power transformer [6]. These three electrodes are used to melt the metals loaded in the furnace tank. When the current



passes through the electrodes and there is a significant amount of electrical charges to the electrodes appears the phenomena of the electric arc discharging [7] formed between the electrodes and the metals. In order to study the behavior of the EAF it is necessary to study the electric arc because this is the nonlinear element of the circuit [8]. The EAF is supplied by a three-phase power transformer placed in a special chamber and flexible cables makes connection between this transformer and the electrodes of the EAF. Electrode arms support the three electrodes of the EAF and a hydraulic system is used to obtain different arc lengths by moving up or down the electrode arms.

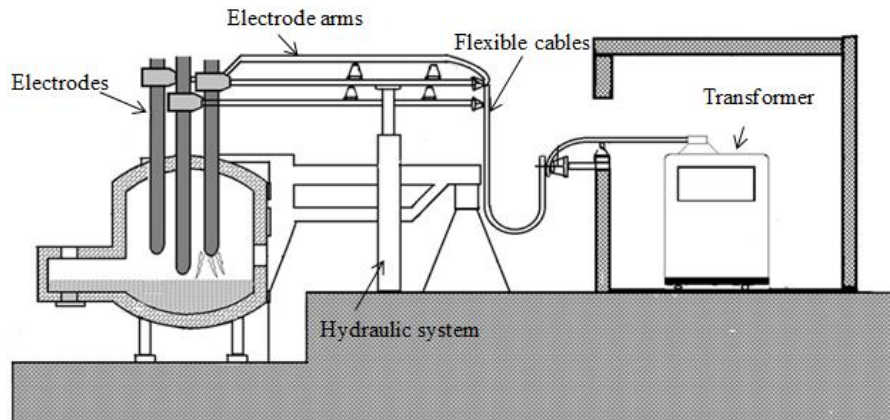


Figure 1. Main constructive elements of a three-phase EAF with direct action

3. Modeling of the Electric Arc

In Figure 2 is illustrated the power supply electric circuit of an EAF for a single phase. The EAF has a resistive character [9] this is why it can be considered as a variable resistance. In Figure 2 the electrical parameters are as follows: v is the alternative voltage from the secondary side of the furnace transformer for a single phase, I is the electric current for a single phase in the secondary side of the furnace transformer, r is the total electrical resistance for a single phase of the secondary side of the furnace transformer, L is the total electrical inductivity for a single phase of the secondary side of the furnace transformer, R_{arc} is the resistance of the electric arc, being reported at the voltage from the primary side of the furnace transformer. In Figure 3 are illustrated the waveforms for the supply voltage, v_s , the electric arc voltage, v_{arc} and the electric arc current, i_{arc} , as presented in the reference literature [10].

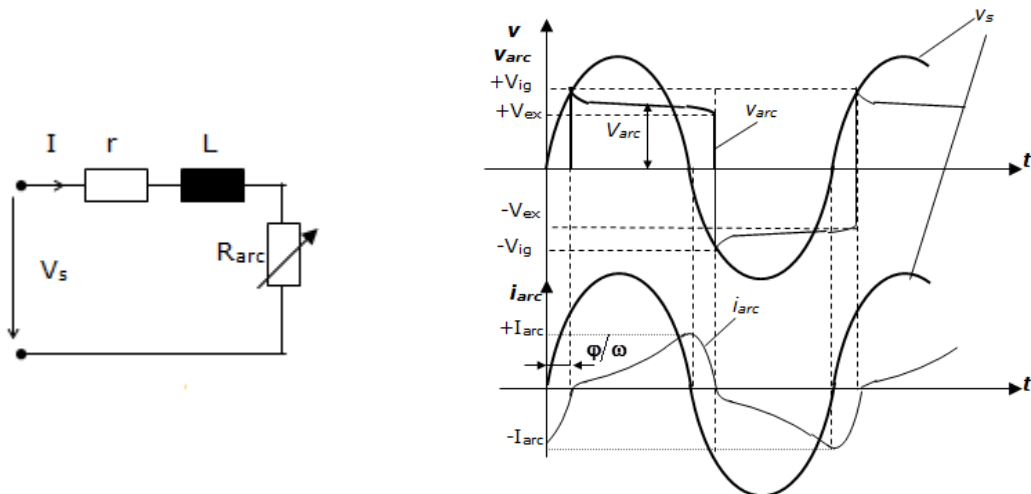


Figure 2. The power supply electric circuit of an EAF for a single phase

Figure 3. The waveforms for the supply voltage of the EAF, electric arc voltage and electric arc current

In this study were chosen the following values of the parameters: total resistance $r=0.47 \text{ m}\Omega$ and total reactance $X=5.5 \text{ m}\Omega$. Voltage from the secondary side of the furnace transformer was set as considered that the transformer has plot set on step 16 which correspond to the 894 V. These values are taken from a real industrial plant.

2.1. Exponential Model of the Electric Arc

In (1) is presented the mathematical model of the electric arc and in (2-6) are illustrated the computation of some model parameters. In (1) v is the voltage of the electric arc, i is the current of the electric arc, v_{ex} is the extinction of the electric arc, v_{ig} is the ignition voltage of the electric arc, v_m is the average between the ignition and extinction voltage and R_1, R_2, R_3 are lines slopes of the voltage-current characteristic presented in Figure 4, this being the desired characteristic to be obtained with the model presented in (1).

$$v = \begin{cases} -v_{ex} + (i_3 - i_4) \cdot R_3, & i < -i_4 \text{ and } di/dt \geq 0 \\ & \text{or } i < -i_4 \text{ and } di/dt < 0 \\ -v_{ex} + (i + i_3) \cdot R_3, & i \in [-i_4, -i_3) \text{ and } di/dt \geq 0 \\ R_1 \cdot i, & i \in [-i_3, i_1) \text{ and } di/dt \geq 0 \\ & \text{or } i \in [-i_1, i_3) \text{ and } di/dt < 0 \\ v_{ex} + (v_{ig} - v_{ex}) \cdot e^{(i_1 - i)/i_2} & i \in [i_1, i_2) \text{ and } di/dt \geq 0 \\ v_m + (i - i_2) \cdot R_2 & i \in [i_2, i_4] \text{ and } di/dt \geq 0 \\ v_{ex} + (i_4 - i_3) \cdot R_3 & i > i_4 \text{ and } di/dt \geq 0 \\ & \text{or } i > i_4 \text{ and } di/dt < 0 \\ v_{ex} + (i - i_3) \cdot R_3 & i \in [i_3, i_4] \text{ and } di/dt < 0 \\ -v_{ex} + (v_{ex} - v_{ig}) \cdot e^{(i_1 + i)/i_2} & i \in [-i_2, -i_1] \text{ and } di/dt < 0 \\ -v_m + (i + i_2) \cdot R_2 & i \in [-i_4, -i_2] \text{ and } di/dt < 0 \end{cases} \quad (1)$$

$$i_1 = v_{ig} / R_1 \quad (2)$$

$$i_2 = 2 \cdot i_1 \quad (3)$$

$$i_3 = v_{ex} / R_1 \quad (4)$$

$$i_4 = (v_m - v_{ex} + i_3 \cdot R_3 - i_2 \cdot R_2) / (R_3 - R_2) \quad (5)$$

$$v_m = (v_{ig} + v_{ex}) / 2 \quad (6)$$

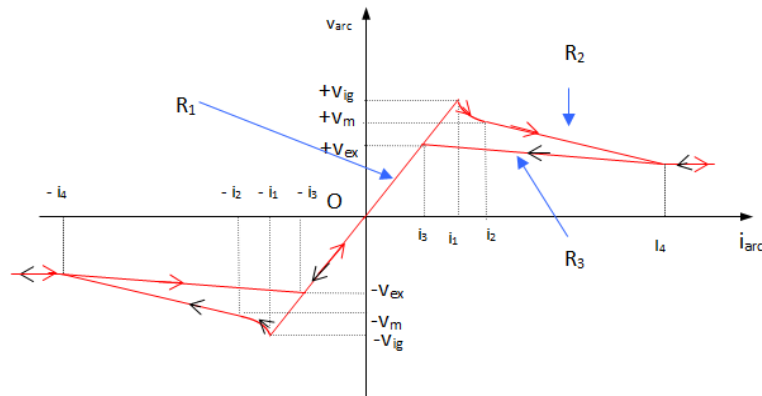


Figure 4. Desired voltage-current characteristic

In Figure 5 is presented the block diagram developed by the authors of this paper in Simulink and which was implemented by applying second Kirchhoff's theory in the electric circuit from Figure 2. *ARC* block contains the mathematical model presented in (1), *Source* block is the voltage from the secondary side of the furnace transformer, *R* is the total resistance of the circuit and *L* is the total inductivity of the circuit. All the model parameters values are modified from the graphical user interface (GUI) presented in Figure 6.

In Figure 6 is illustrated the GUI for the exponential model which allows user to modify the model parameters in order to notice their importance on the voltage and current of the electric arc. For each of the model parameter was chosen a range in which it can be varied. In order to study the influence of each of the model parameters on the voltage and current of the electric arc, each parameter was modified in two cases. First of all was set an initial value and then were chosen two different values as compared to the initial one, first after taking *800 samples* and the second after *1500 samples*. In one second was set to take *10000 samples*. When a parameter is modified the other parameters are set to the initial values.

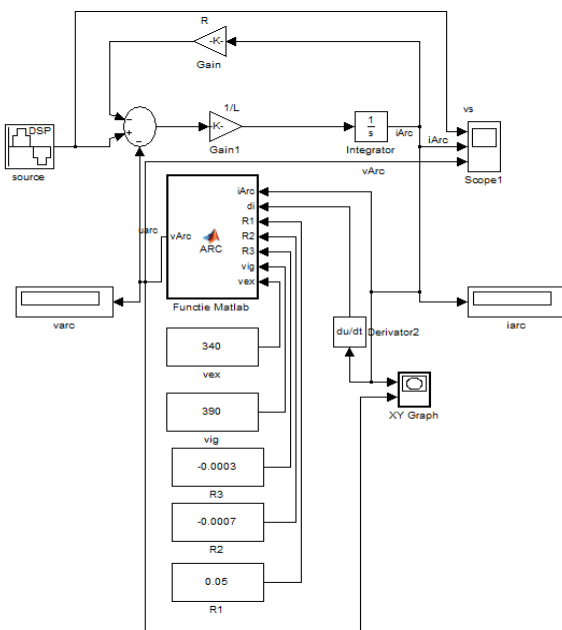


Figure 5. The block diagram for the exponential model of the electric arc

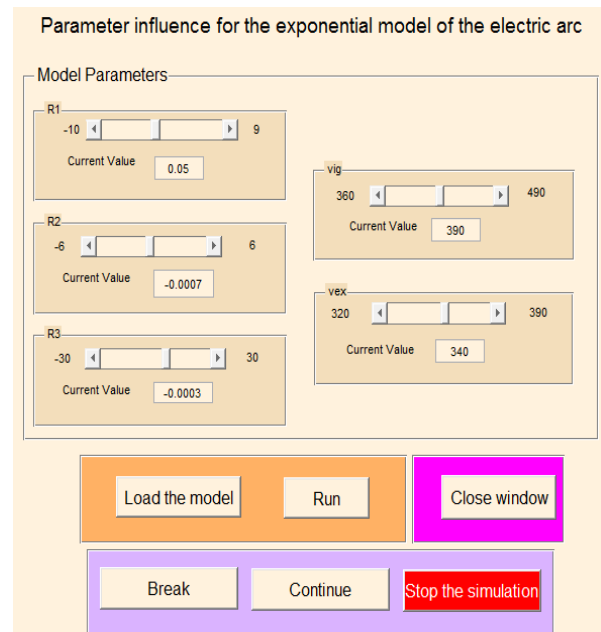


Figure 6. GUI for the exponential model of the electric arc

In Figure 7 is presented the voltage-current characteristic of the electric arc when the ignition voltage of the electric arc is modified and in Figure 8 is presented the voltage-current characteristic of the electric arc when the extinction voltage of the electric arc is modified. These two characteristics were obtained by plotting electric arc voltage against electric arc current. Because for the real plant cannot be measured the electric arc voltage, the voltage-current characteristic was represented also by plotting the voltage measured before the EAF against the current of the EAF.

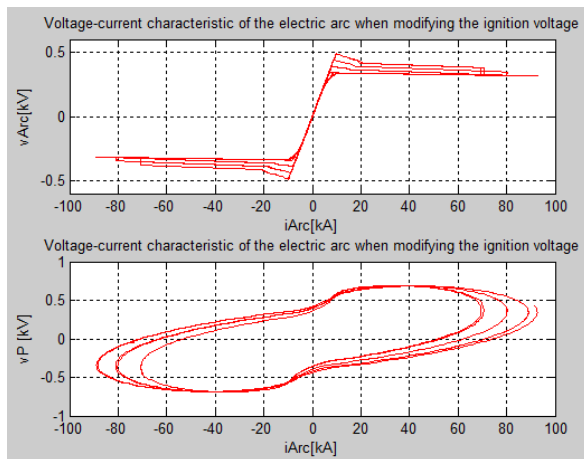


Figure 7. Voltage-current characteristic of the electric arc when modifying the ignition voltage

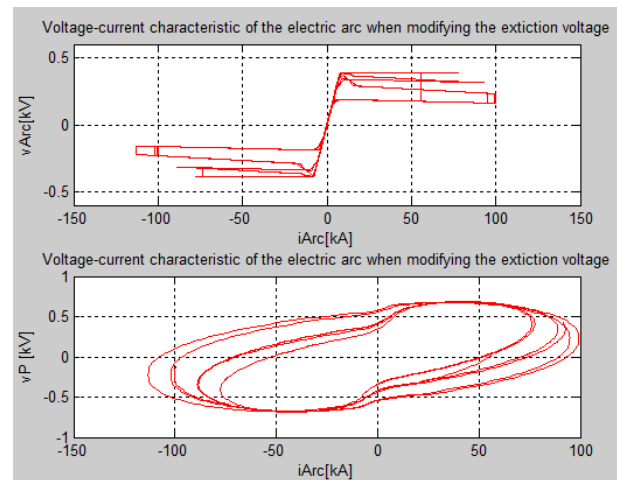


Figure 8. Voltage-current characteristic of the electric arc when modifying the extinction voltage

In Figure 9 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying the ignition voltage. Initial value for the ignition voltage is 390 V, after taking 800 samples was modified to 490 V and after 1500 samples was set to 440 V.

One can notice from Figure 9 that when the ignition voltage is increasing the electric arc current is decreasing and when the ignition voltage is decreasing the electric arc current is increasing. In both cases the electric arc voltage is distorted.

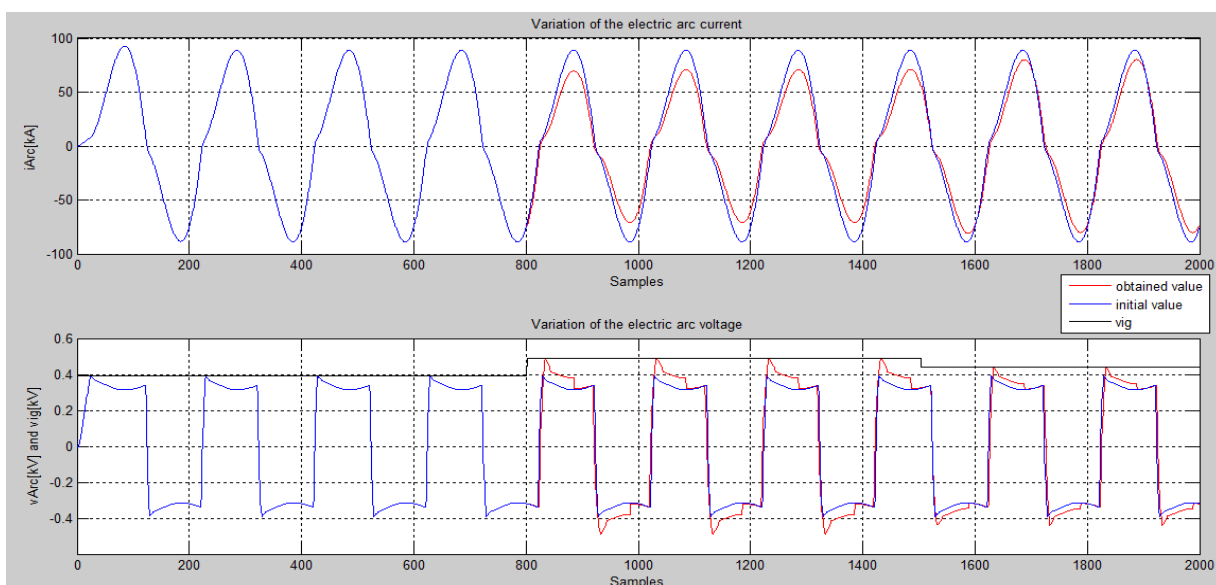


Figure 9. Variation of the electric arc current and voltage when is modified the ignition voltage

In Figure 10 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying the extinction voltage. Initial value for the extinction voltage is 340 V , after taking 800 samples was modified to 390 V and after 1500 samples was set to 190 V . One can notice that when the extinction voltage is increasing the electric arc current is decreasing and when the extinction voltage is decreasing the electric arc current is increasing. Regarding the electric arc voltage one can notice that if the ignition and the extinction voltages have the same value the electric arc voltage has a rectangular shape and when is a difference too large between the ignition and the extinction voltages the electric arc voltage is strongly distorted.

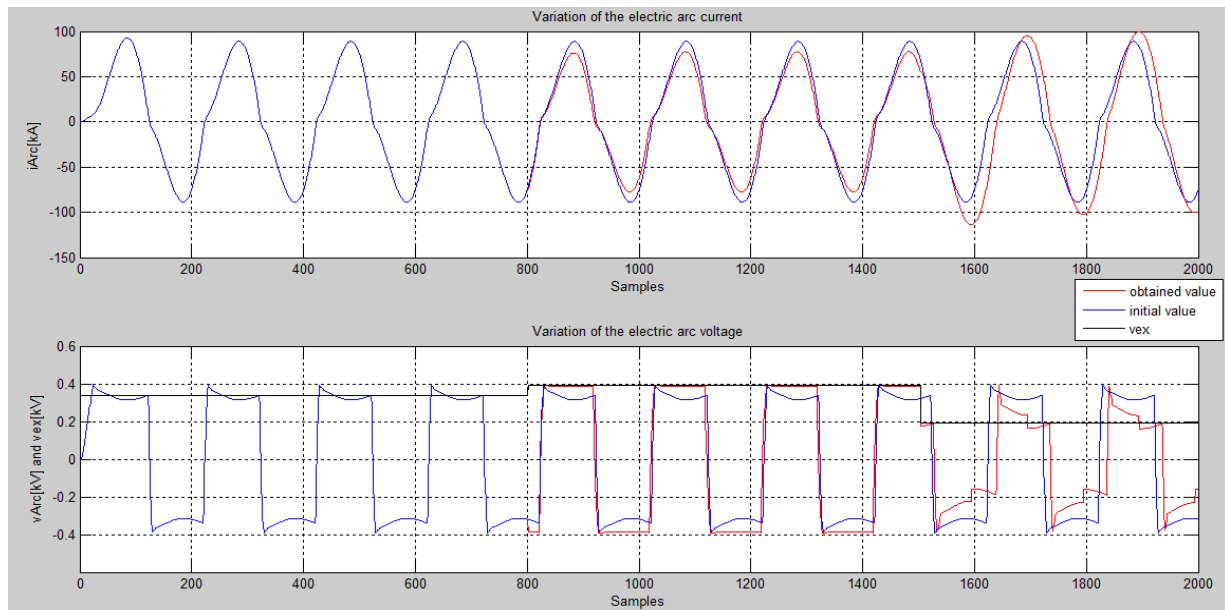


Figure 10. Variation of the electric arc current and voltage when is modified the extinction voltage

In Figure 11 is presented the voltage-current characteristic of the electric arc when the line slope R_1 is modified and in Figure 12 is presented the voltage-current characteristic of the electric arc when the line slope R_2 is modified. For both characteristics were used two representations as mentioned before.

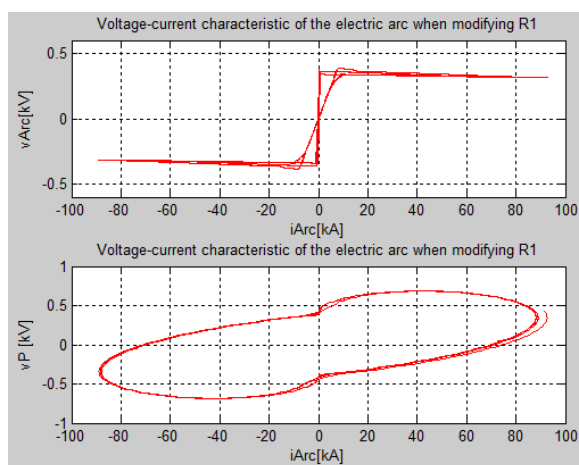


Figure 11. Voltage-current characteristic of the electric arc when modifying the line slope R_1

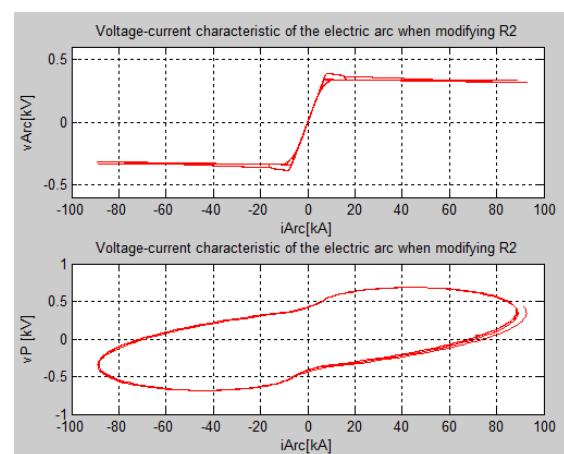


Figure 12. Voltage-current characteristic of the electric arc when modifying the line slope R_2

In Figure 13 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying line slope R_l . Initial value for R_l is 0.05, after taking 800 samples was increased with 2 and after 1500 samples was decreased with 10. One can notice that the amplitude of both voltage and current of the electric arc is the same, concluding that this parameter do not has a large influence on the amplitude on the electric arc voltage and current.

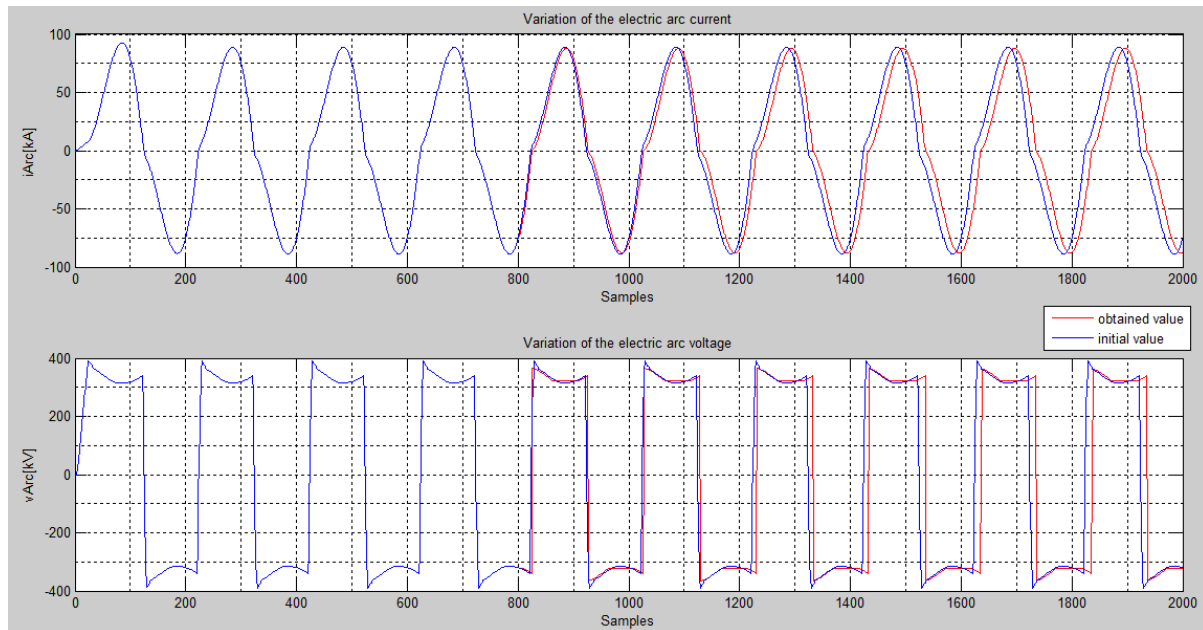


Figure 13. Variation of the electric arc current and voltage when is modified the line slope R_l

In Figure 14 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying line slope R_2 . Initial value for R_2 is -0.007, after taking 800 samples it was increases with 5 and after 1500 samples was decreased with 10.

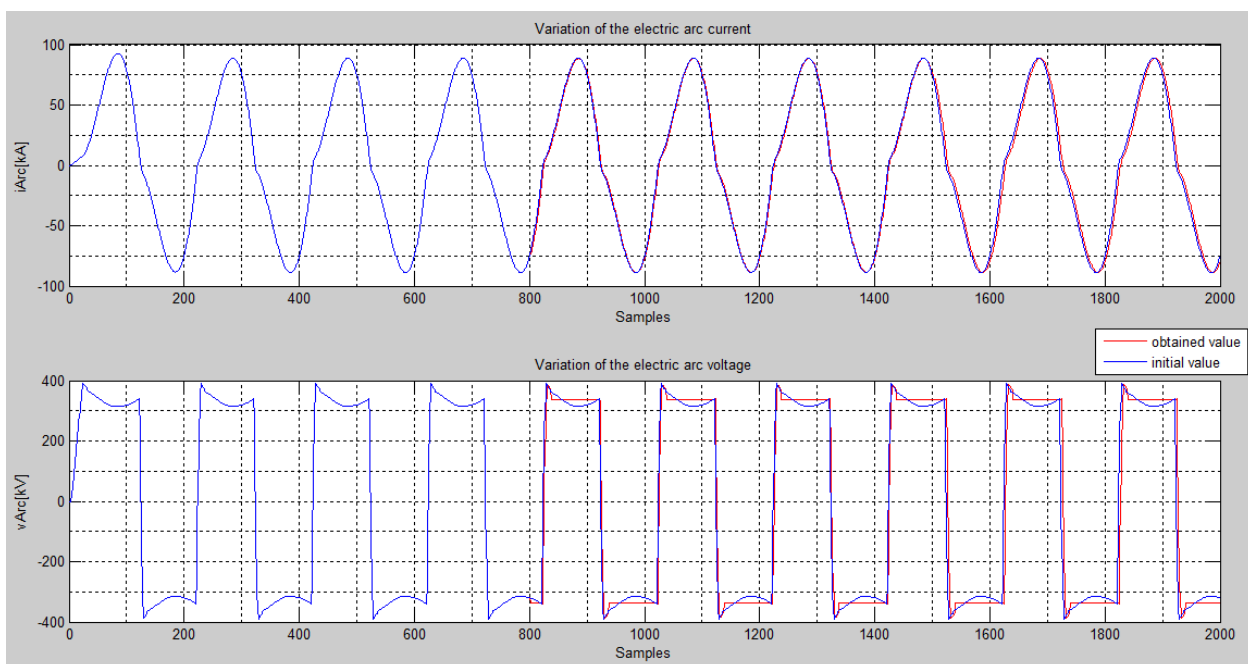


Figure 14. Variation of the electric arc current and voltage when is modified the line slope R_2

One can notice from Figure 14 that the amplitude of both voltage and current of the electric arc is the same, concluding that this parameter do not has a large influence on the amplitude on the electric arc voltage and current.

In Figure 15 is presented the voltage-current characteristic of the electric arc when the line slope R_3 is modified and in Figure 16 is presented the variation of this model parameter. For both characteristics were used two representations as mentioned before.

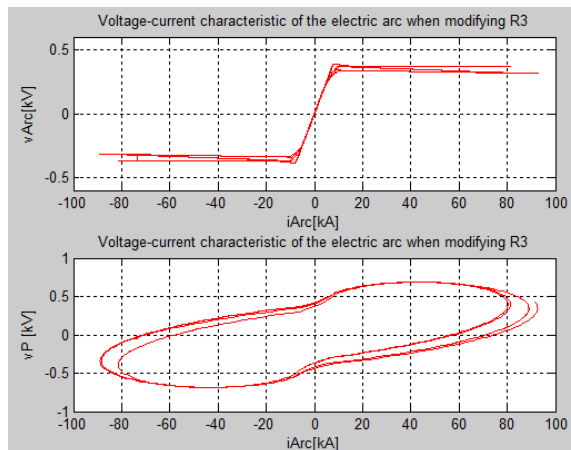


Figure 15. Voltage-current characteristic of the electric arc when modifying the line slope R_3

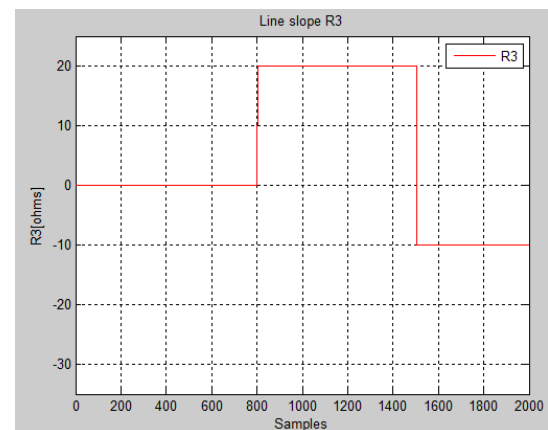


Figure 16. Variation of the line slope R_3

In Figure 17 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying line slope R_3 . Initial value for R_3 is -0.003 , after taking *800 samples* it was increases with 20 and after *1500 samples* was decreased with 30.

One can notice that the amplitude of the electric arc current is influenced in a small measure, but the electric arc voltage is more close to a rectangular shape.

In conclusion for the exponential model of the electric arc the ignition and the extinction voltage of the electric arc can influence in a large percentage the voltage and current of the electric arc.

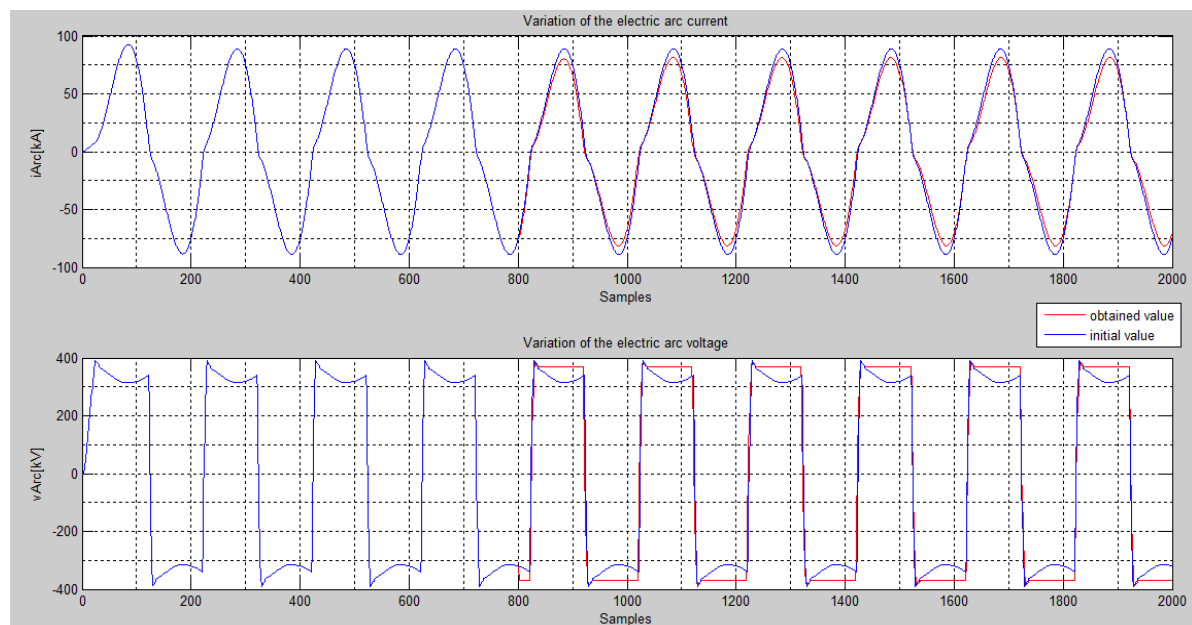


Figure 17. Variation of the electric arc current and voltage when is modified the line slope R_3

2.2. Hyperbolic Model of the Electric Arc

In (7) is presented the hyperbolic mathematical model of the electric arc. In this model v is the voltage of the electric arc, i is the current of the electric arc, v_{ex} is the extinction of the electric arc, C is a constant having value 190000, D is a constant having value 5000 and R_l is the line slope for the range $[-i_l, i_l]$ of the voltage-current characteristic presented in Figure 18, this being the desired characteristic to be obtained with the model presented in (7).

$$v = \begin{cases} i \cdot R_l, & i < i_l \text{ and } di \geq 0 \text{ or } i > -i_l \text{ and } di < 0 \\ -v_{ex} + \frac{C}{D + |i|}, & i < -i_l \text{ and } di < 0 \text{ or } di \geq 0 \\ v_{ex} + \frac{C}{D + |i|}, & i > i_l \text{ and } di < 0 \text{ or } di \geq 0 \end{cases} \quad (7)$$

$$v_{ig} = v_{ex} + C / D \quad (8)$$

In Figure 19 is presented the block diagram developed by the author of this paper in Simulink and which was implemented by applying second Kirchhoff's theory in the electric circuit from Figure 2. *ARC* block contains the mathematical model presented in (1), *Source* block is voltage from the secondary side of the furnace transformer, R is the total resistance of the circuit and L is the total inductivity of the circuit. All the model parameters are modified from the graphical user interface (GUI) presented in Figure 20.

In Figure 20 is illustrated the GUI for the hyperbolic model which allows user to modify the model parameters in order to notice their importance on the electric arc voltage and current. For each of the model parameter was chosen a range in which it can be varied. In order to study the influence of each of the model parameters on the electric arc voltage and current, each parameter was modified in two cases. First of all was set an initial value and then were chosen two different values as compared to the initial one, first after taking 800 samples and the second after 1500 samples. In one second was set to take 10000 samples similarly to the previous model. When a parameter is modified the other parameters are set to the initial values.

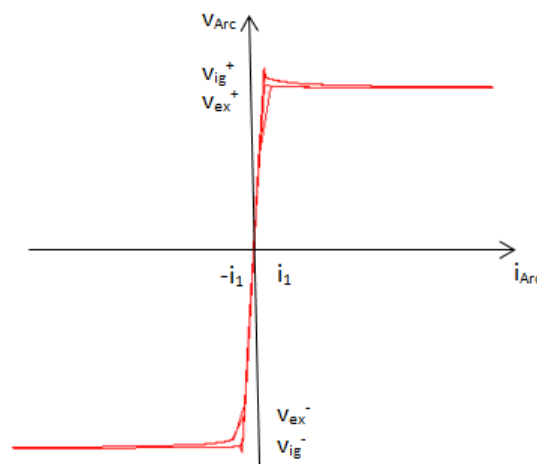


Figure 18. Desired voltage-current characteristic

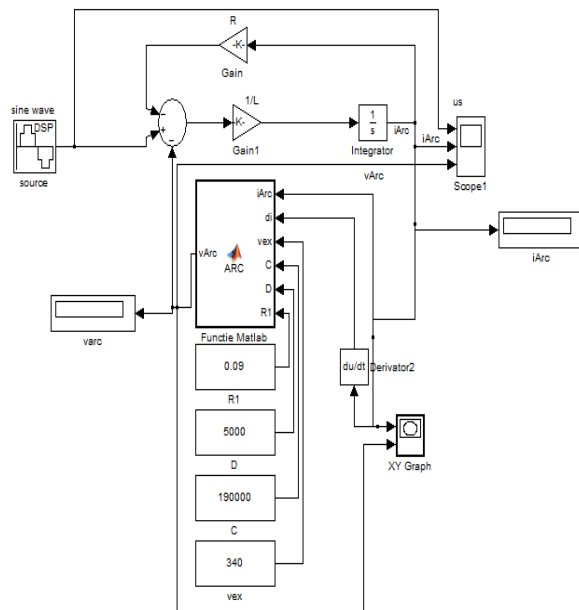


Figure 19. The block diagram for the hyperbolic model of the electric arc

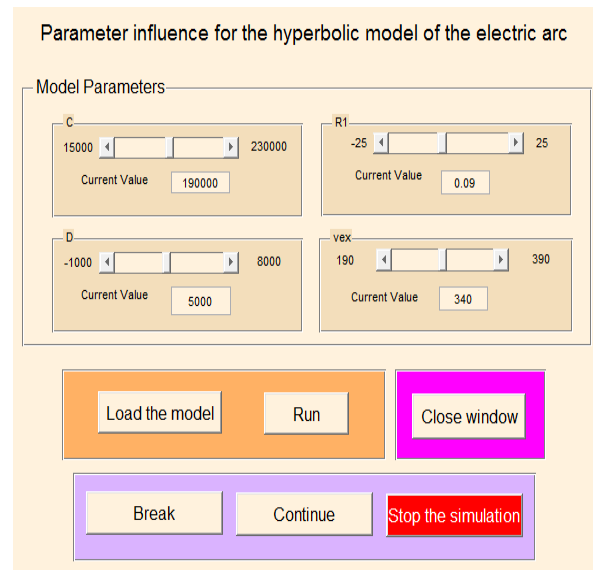


Figure 20. GUI for the hyperbolic model of the electric arc

In Figure 21 is presented the voltage-current characteristic of the electric arc when the extinction voltage of the electric arc is modified and in Figure 22 is presented the voltage-current characteristic of the electric arc when the line slope R_l is modified. These two characteristics were obtained by plotting electric arc voltage against electric arc current. Because for real plant cannot be measured the voltage of the electric arc was represented also the voltage-current characteristic obtained by plotting the voltage measured before the EAF against the current of the EAF.

In Figure 23 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying the extinction voltage. Initial value for the extinction voltage is 340 V , after taking 800 samples was modified to 390 V and after 1500 samples was set to 190 V . One can notice that when the extinction voltage is increasing the electric arc current is decreasing and when the extinction voltage is decreasing the electric arc current is increasing.

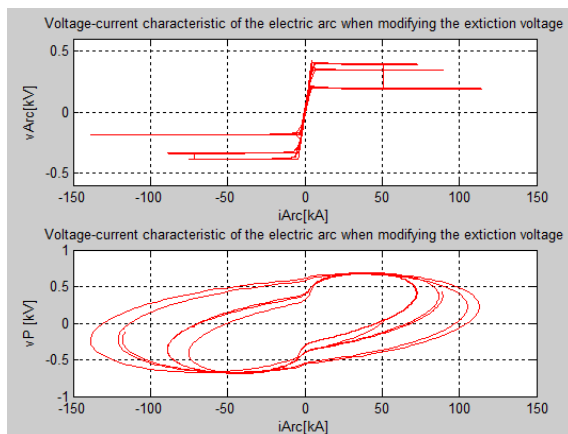


Figure 21. Voltage-current characteristic of the electric arc when modifying the ignition voltage

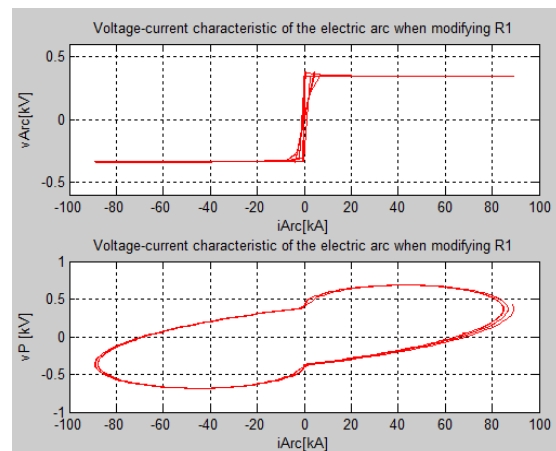


Figure 22. Voltage-current characteristic of the electric arc when modifying the line slope R_l

Regarding the electric arc voltage one can notice that if the extinction voltage is modified than the waveform of the electric arc voltage is maintaining the shape because the ignition voltage of the electric arc is computed taking into consideration the extinction voltage of the electric arc.

In Figure 24 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying line slope R_l . Initial value for R_l is 0.09, after taking 800 samples was increased with 20 and after 1500 samples was decreased with 40. One can notice that the amplitude of both voltage and current of the electric arc is the same, concluding that this parameter do not has a large influence on the amplitude of the voltage and current of the electric arc.

In Figure 25 is presented the voltage-current characteristic of the electric arc when the constant C is modified and in Figure 26 is presented the voltage-current characteristic of the electric arc when the constant D is modified. For both characteristics were used two representations as mentioned before.

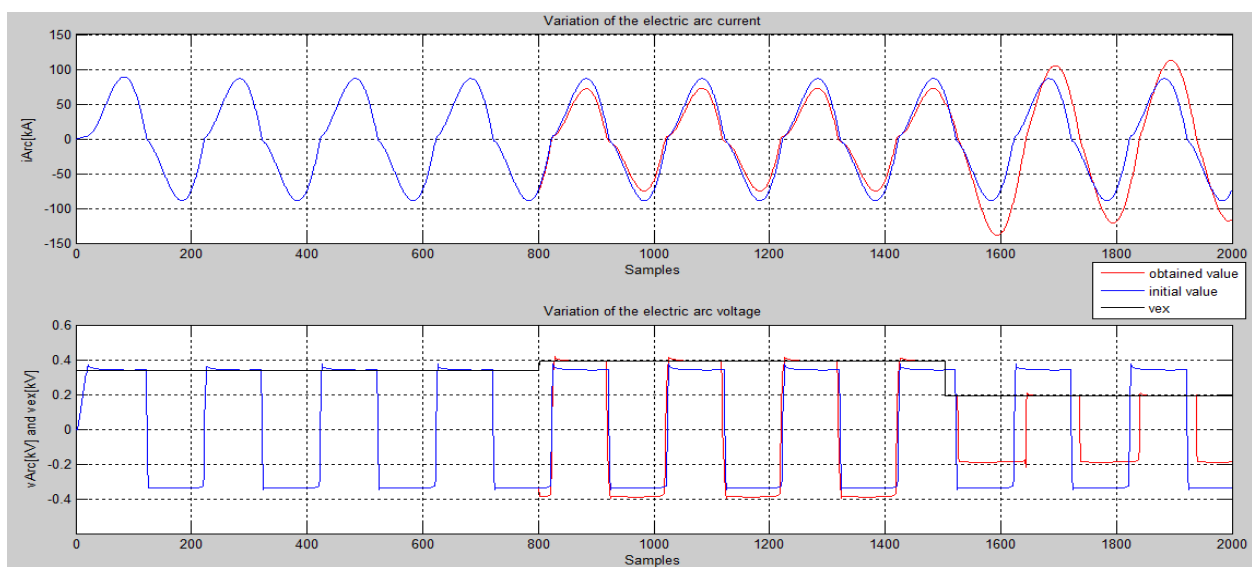


Figure 23. Variation of the electric arc current and voltage when is modified the extinction voltage

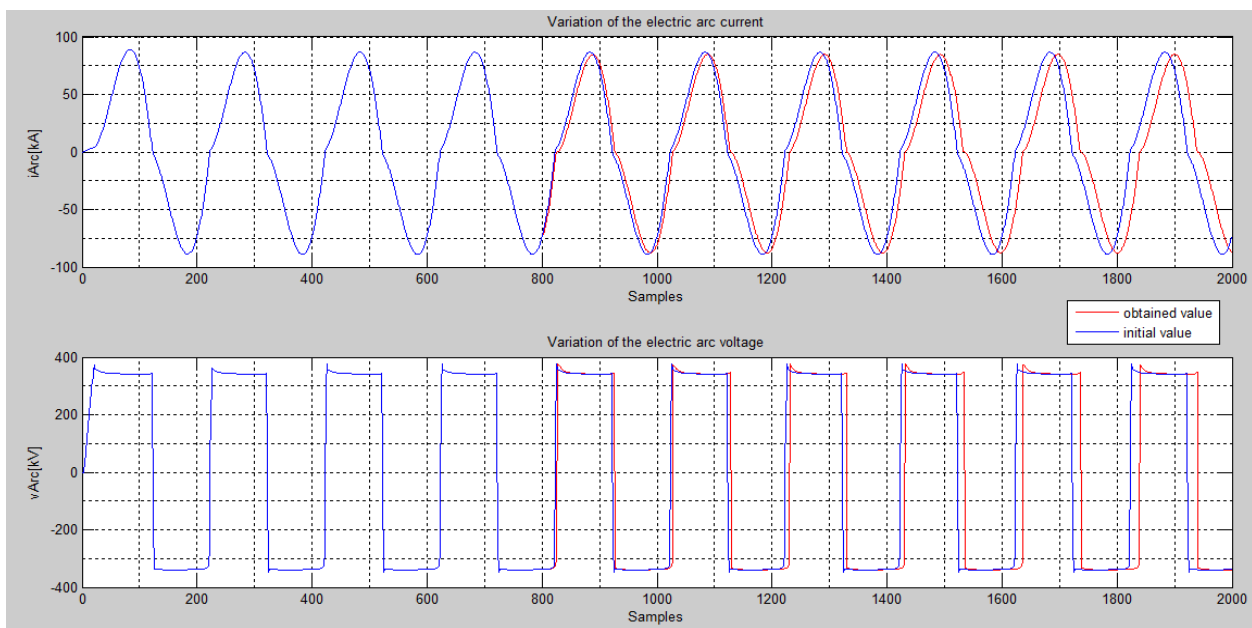


Figure 24. Variation of the electric arc current and voltage when is modified the line slope R_l

In Figure 27 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying constant C . Initial value for C is 190000 when the derivative of the current is positive and 39000 when the derivative of the current is negative, after taking 800 samples was set C to 230000 and after 1500 samples was set to 40000 for the positive derivative of the current. One can notice that the amplitude of both voltage and current of the electric arc is the same, concluding that this parameter do not has a large influence on the amplitude of the voltage and current of the electric arc.

In Figure 28 are illustrated the waveforms for the electric arc current and for the electric arc voltage when modifying constant D . Initial value for D is 5000, after taking 800 samples was set D to 15000 and after 1500 samples was set to -1000. One can notice that the amplitude of both voltage and current of the electric arc is the same, but when D has negative value the ignition voltage of the electric arc has a peak to large.

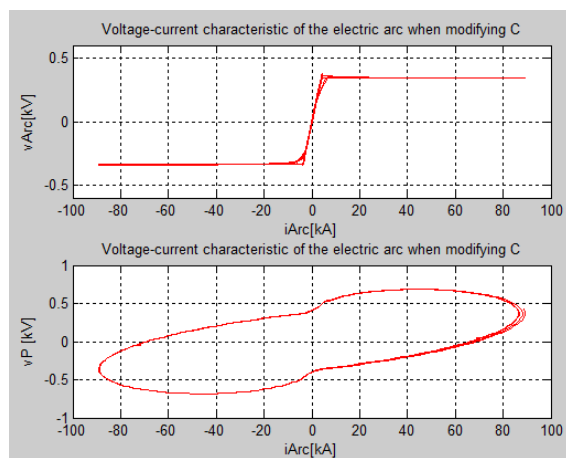


Figure 25. Voltage-current characteristic of the electric arc when modifying C

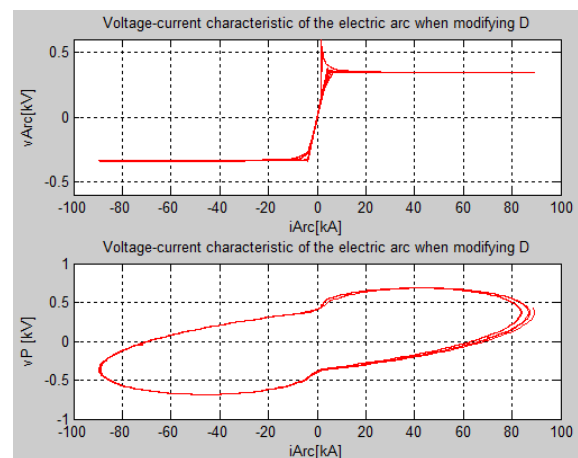


Figure 26. Voltage-current characteristic of the electric arc when modifying D

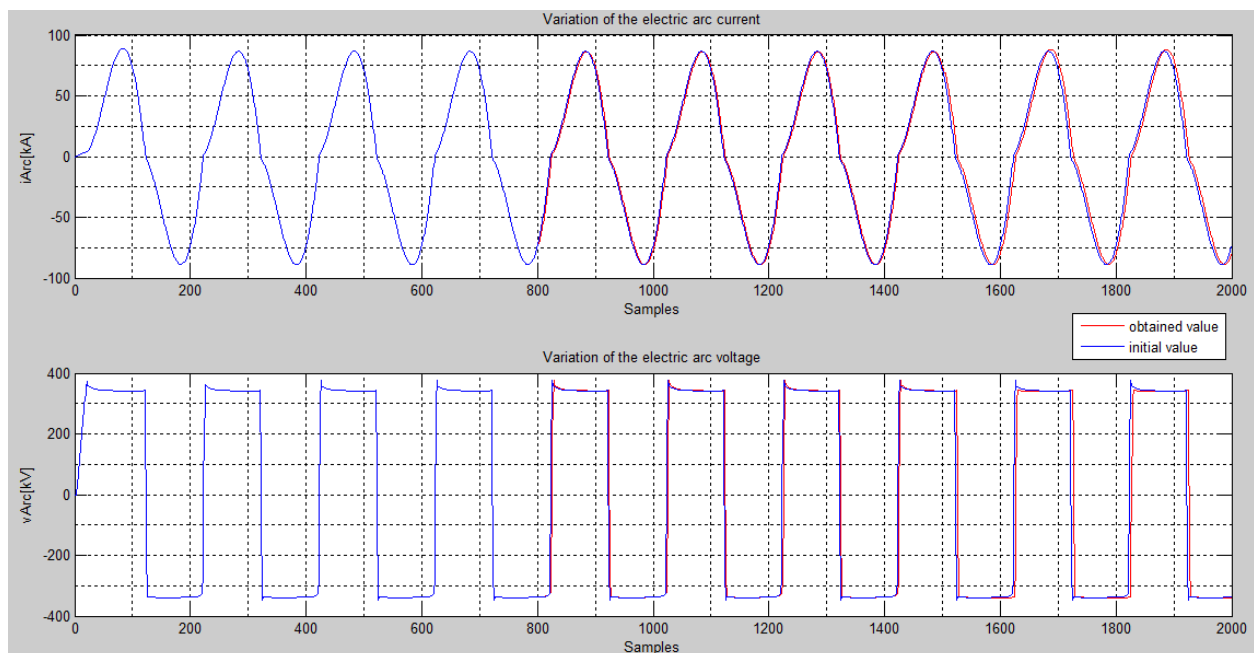


Figure 27. Variation of the electric arc current and voltage when is modified C

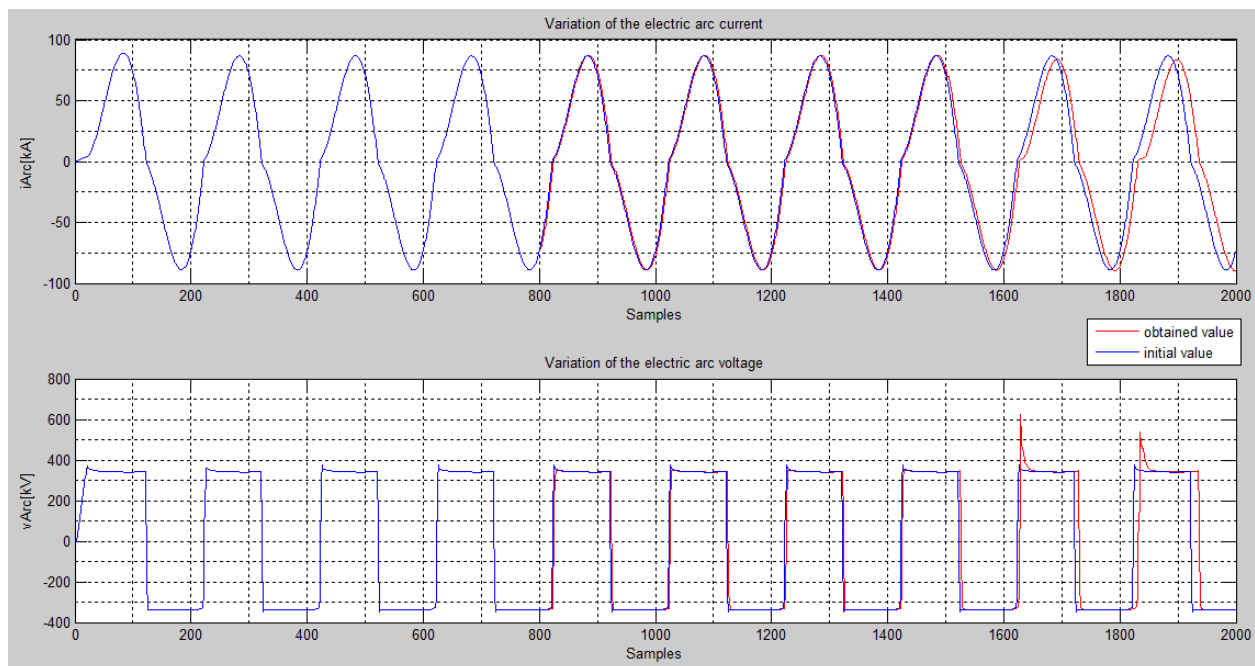


Figure 28. Variation of the electric arc current and voltage when is modified D

4. Conclusions

In this paper two models of the electric arc were developed in Matlab/Simulink in order to simulate the electric arc furnace behavior. For each of the model were implemented GUIs which allow modifying the parameters of each of the two models of the electric arc in order to study the importance of them on the voltage and current of the electric arc. Parameters of the electric arc furnace were set like the ones of the real installation taken into consideration.

By analyzing the results obtained from simulation one can conclude that in each model the significant parameters that influence the voltage and current of the electric arc are the ignition and the extinction voltage of the electric arc. Starting from the presented models can be developed other models of the electric arc.

Parameters influence in the electric arc modeling is important because it is required to know very well the model of the process in order to design control strategies for the entire installation, because for an EAF can be controlled the position of the electrodes in this way obtaining the desired arc power, increasing the productivity of liquid steel and reducing the damages caused by the breakage of the electrodes.

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