

# Study for the electric arc of alternative current at the single phase welding machine using the Matlab/Simulink environment

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**Abstract.** In this paper is presented a mathematical model of the electric arc for an alternative current welding machine of low power. The electric arc model is based on dividing the voltage-current characteristic of the electric arc in many functioning zones. For the model of the entire welding machine are used real parameters as the ones of the proper welding machine. The voltage and current harmonics spectrum that is obtained during the welding process is presented. Also, the waveforms for the current and voltage of the electric arc plotted against time and the voltage-current characteristic of the electric arc are illustrated. The electric arc is considered as being supplied by alternative voltage from the electrical power network using a single phase transformer which has the output voltage of 80 volts. The model of the welding machine is developed in Simulink and the variations of some parameters of the electric arc are obtained by modifying of them in a Matlab function. Also, in this paper is presented the total harmonic distortion for the voltage and current of the electric arc obtained during simulation of the welding machine.

## 1. Introduction

Welding is the technological process of making permanent joints of metal or nonmetallic components through the interaction of adjacent atoms. The welding process [1] is the introduction in a zone, by concentrating in time and space, of an amount of electrical energy in the welding area to bring out the atoms from their stable equilibrium state and approaching the adjacent atoms at equal or lower distances than the crystalline network parameter so they can recrystallize in a common network corresponding to a new stable state [2]. This energetic mechanism is illustrated in Figure 1.

Taking into consideration the energy sources which is performing local heating the welding processes are classified in welding with electrothermic, electrochemical and corpuscular energies [3].

In the case of welding with electrothermic energy the source of energy is the electric arc or the Joule effect. Welding with electric arc can be carried out by the following methods: with coated electrode, with shielding gas, under a stream or by other methods [4].

In this paper is studied the behavior of the electric arc in the welding process with coated electrode for a single phase welding machine of the alternative current. This study is performed by simulation in the Matlab/Simulink programming environment, by modifying the welding parameters. It is modified



the supply voltage, the operating frequency of the power supply or the electric arc characteristics. The electric arc was modeled taking into consideration the voltage-current characteristic of the electric arc.

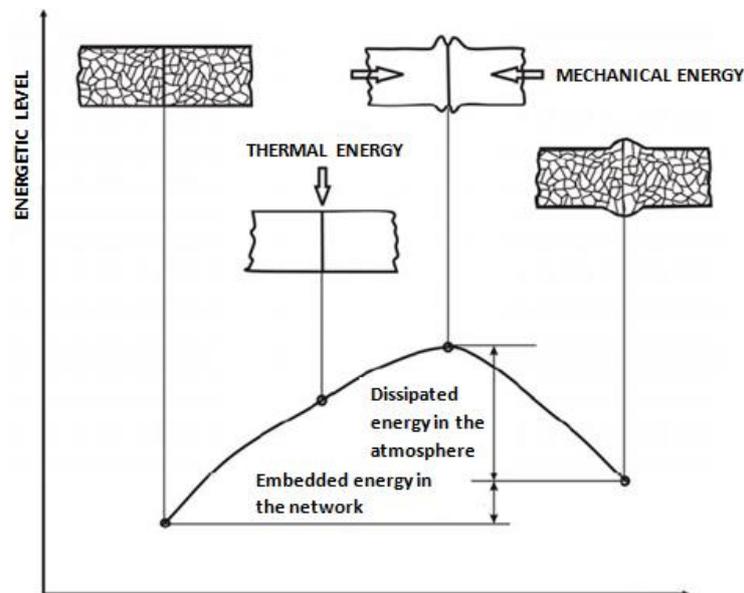


Figure 1. Welding phases

## 2. Presentation of the paper

### 2.1. Electric Arc of Alternative Current

Electric arc welding is a method of permanent joining of metal parts from an assembly, using the heat from the electric arc developed between the welding electrode and the material to be welded.

It is estimated that currently over 35% of steel production is assembled by electric arc welding processes and therefore can be considered that electric arc welding is one of the largest consumers of electricity.

Also, one can take into account that the welding machines are receivers which are causing important disturbances in the power network.

Opened electric arc is ignited when the electrode which is connected to one of the terminals of the welding machine's power source is brought into contact with the piece which is connected to the other terminal of the source. The supply source current (short circuit current) produces a strong heating of the irregularities on the contact surfaces, melting them.

By slow removal of the electrode, the molten weld metal stretches and shrinks its section. Current density increases and when is reached the temperature of boiling metal, the bridge breaks and appears the electric arc in metallic vapors slightly ionizable [2].

Electric arc extinction is achieved by removing the electrode from the piece (arc stretching), which results in an intense deionization of the discharged space.

The welding electric current that is developed between the electrode and the work piece, periodically changes its polarity, the role of cathode and anode alternating from the electrode to the work piece and backwards with a frequency  $f$  of the supply voltage. As a result, the current passes twice zero during a period of the supply voltage. Because of the deionization the electric arc is extinguish for a short time, when current passes by zero.

A particularity of the electric arc is the rectifying effect of the current, due to the different thermophysical properties between the electrode and the work piece. For this reason, the electric arc ignition conditions are different and the electric arc burns more in the half period in which the electrode is cathode. The presence of the continuous component reduces the welding quality because it

decreases the depth of the welding penetration, so the magnetic circuit is saturated and appears the deforming power consumption.

## 2.2. Modeling of the electric arc characteristics

Considered as a circuit element, the electric arc has the properties of being a nonlinear resistor, characterized by a nonlinear dependence between the voltage and current intensity of the electric arc.

Voltage-current characteristics of the electric arc can be static or dynamic, as the intensity of the electric arc current varies and which can be very low (in particular null) or on the contrary can be very high.

Unlike the electric arc of continuous current, the electric arc of alternative current is only a quasi-stationary process which, at the length unit of the column [2], it is characterized by the powers equation presented in (1):

$$E_a i = p + \frac{dQ}{dt} \quad (1)$$

where  $Q$  is the energy of the arc column volume,  $E_a$  is the electric potential gradient,  $i$  is the current intensity, and  $p$  is the power transferred to the environment in the form of heat per unit of time. According to the Mayr advanced hypothesis, dependence of the conductance  $G$  for the arc column in relation to the content of energy  $Q$  can be expressed by the equation (2).

$$G = K e^{\frac{Q}{Q_0}} \quad (2)$$

where  $K$  and  $Q_0$  are constants. As for the column unit length, it can be written (3).

$$G = \frac{i}{E_a} \quad (3)$$

After applying logarithms and derivative in time and taking into account (1) and (2) is obtained equation (4).

$$\frac{1}{G} \frac{dG}{dt} = \frac{1}{T_a} \left( \frac{v_a i}{p \ell} - 1 \right) \quad (4)$$

In (4)  $v_a$  is the voltage of the electric arc column of length  $l$ . Assuming a constant values,  $P_0$ , for the power dissipated per unit length of the column and adopting the notation:

$$T_a = \frac{Q_0}{P_0} \quad (5)$$

where  $T_a$  is the time constant of the electric arc, differential equation (4) becomes:

$$\frac{1}{i} \frac{di}{dt} - \frac{1}{v_a} \frac{dv_a}{dt} = \frac{v_a i - P_0 \ell}{P_0 \ell T_a} \quad (6)$$

Relation (6) is also known as equation of electric arc in dynamic regime [2]. Considering that the current intensity through the electric arc is sinusoidal, like:

$$i(t) = \sqrt{2} I \sin \omega t \quad (7)$$

for the solution of differential equation (6) one can obtained the expression:

$$v_a(t) = \frac{\sqrt{2}P_0 \ell \omega t}{I \left[ 1 - \frac{\sin(2\omega t + \varphi)}{\sqrt{1 + (2\omega T_a)^2}} \right]} \quad (8)$$

where:

$$\varphi = \text{arctg} \left( \frac{I}{2\omega T_a} \right) \quad (9)$$

### 2.3. Characteristics of the electric arc supplied with alternative voltage

It can be considered that during the burning of the electric arc supplied with alternative voltage, the equivalent electric circuit of electric arc can be represented as illustrated in Figure 2.

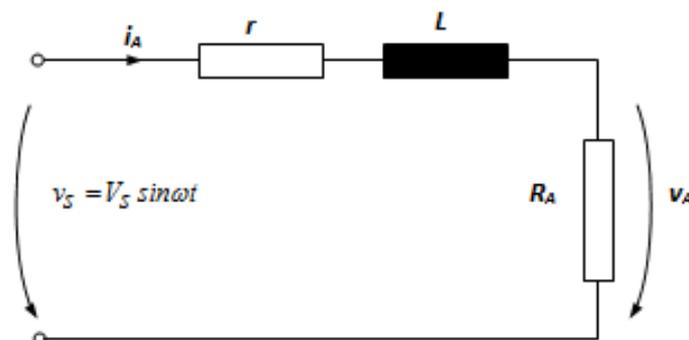
In this figure parameters  $r$  and  $L$  represents the resistivity, respectively the inductivity of the equivalent electric circuit and  $R_A$  and  $v_A$  is the resistivity of the electric arc, respectively the voltage of the electric arc [5], [6].

Waveforms for the electrical parameters from the equivalent circuit are presented in Figure 3. One can obtain the following conclusions:

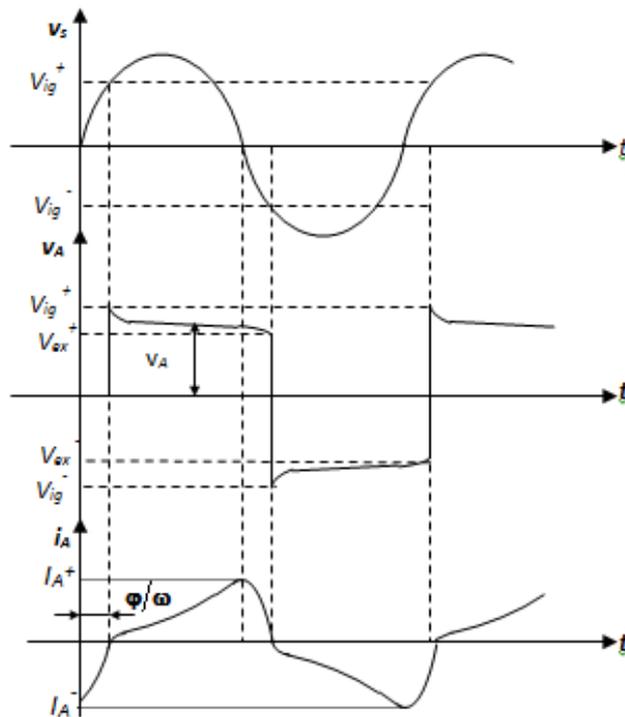
- The electric arc is a nonlinear receiver because during the burning of the electric arc the voltage of the electric arc is approximately the same and the current is varying;
- Electric arc has a resistive character because the electric arc voltage and electric arc current are in the same phase;
- The electric arc current passes two times zero for each period of the source voltage, so, the electric arc is extinguished and ignited with a double frequency as compared to the one of the applied voltage;
- The ignition voltage of the electric arc is greater as compared to the electric arc voltage;
- The electric arc current is periodical, but nonsinusoidal;
- The electric arc supplied with alternative voltage has a rectifying character [7].

In Figure 4 is presented the dynamic voltage-current characteristic of the electric arc supplied with alternative voltage which is illustrated in the reference literature [8], [9]. This characteristic is obtained taking into account the variation of the voltage and current of the electric arc presented in Figure 3.

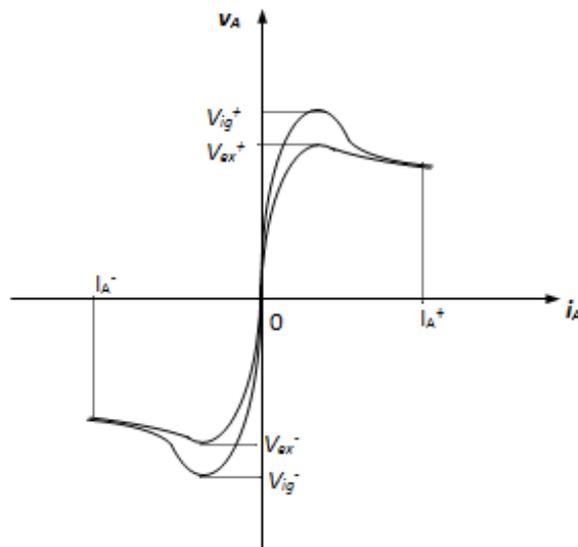
Electric arc current can be in one of the two regimes: interrupted or uninterrupted current. If the electric arc burning is in the interrupted current regime the functioning of it is unstable and the electric arc current waveform is strongly distorted. So, it is necessary that the electric arc burning to be without breaks.



**Figure 2.** The equivalent electric circuit of electric arc supplied with alternative current



**Figure 3.** Waveforms for the electrical parameters in the electric arc circuit



**Figure 4.** Voltage-current-characteristic of the electric supplied with alternative voltage

In order to burn the electric arc without breaks, in the assumption that  $V_{ig}^+ \cong |V_{ig}^-| \cong V_{ex}^+ \cong |V_{ex}^-| \cong V_A$  and the supply voltage has a sinusoidal shape  $v_s(t) = V_s \cdot \sin \omega t$  should be fulfilled the condition (10).

$$V_s \cdot \sin \geq V_A \tag{10}$$

which leads to relation (11).

$$\frac{V_A}{V_s} \leq \sqrt{\frac{I}{I + \frac{\pi^2}{4}}} = 0,54, \quad (11)$$

Resulting that in order to have an uninterrupted current it is necessary that the welding machine has to operate having a power factor as illustrated in (12).

$$\cos \varphi \leq 0,85 \quad (12)$$

### 3. The implementation of the welding process in Matlab/Simulink

In Figure 5 is presented the Matlab/Simulink block diagram which corresponds for the equivalent electric circuit of the electric arc supplied with alternative current as illustrated in Figure 2. This block diagram was developed by using equation (13) which was obtained by applying second Kirchhoff's law for the electric circuit presented in Figure 2.

$$v_s = i(t) \cdot R + L \cdot \frac{di}{dt} + v_{arc} \quad (13)$$

In order to obtain the current of the electric circuit from equation (13) it is used relation (14).

$$i(t) = \frac{1}{L} \int v_L dt \quad (14)$$

Based on equations (13) and (14) is implemented the simulation of the welding process in Matlab/Simulink. In this simulation the electric arc is simulated using the relation (15), but implemented even for negative values of the parameters [10].

$$v_a = \begin{cases} i \cdot R_1 & 0 \leq i \leq i_1 \\ i \cdot R_2 + V_{ig} \cdot \left(1 - \frac{R_2}{R_1}\right) & i_1 < i \leq i_2 \\ i_2 \cdot R_2 + V_{ig} \cdot \left(1 - \frac{R_2}{R_1}\right), & i > i_2 \end{cases} \quad (15)$$

Where

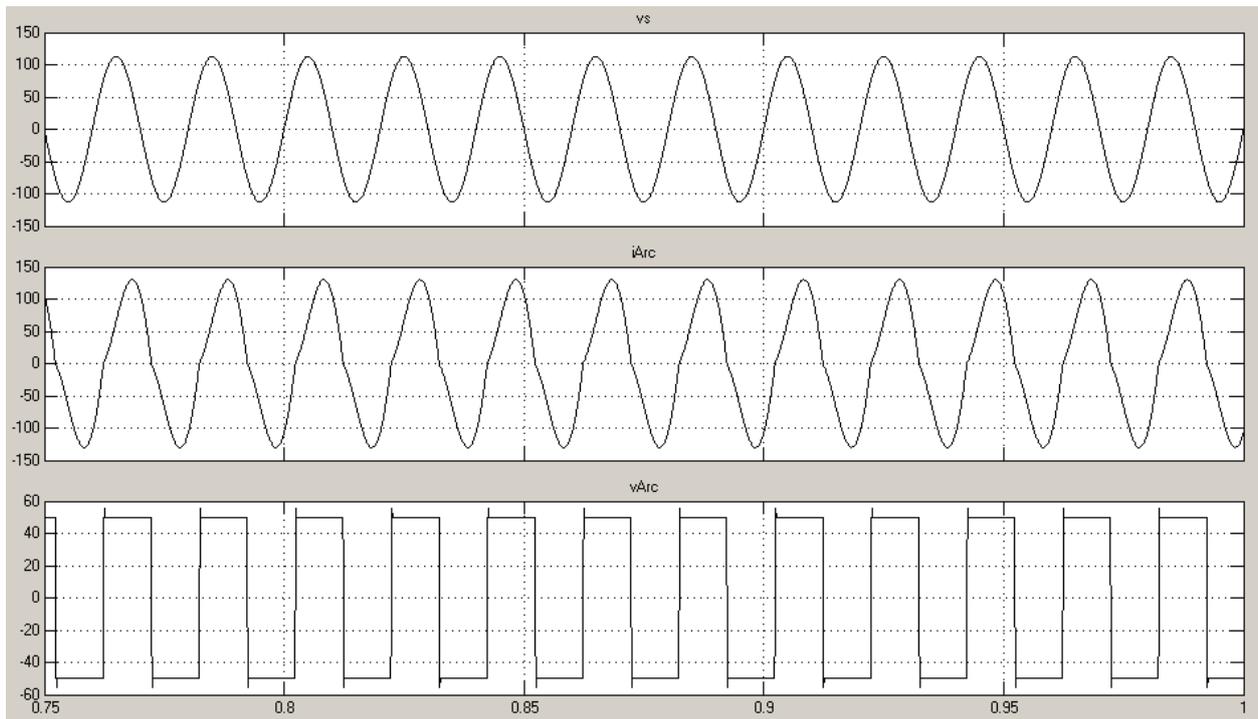
$$i_1 = \frac{V_{ig}}{R_1}, \quad (16a)$$

$$i_2 = \frac{V_{ex}}{R_2} - V_{ig} \cdot \left(\frac{1}{R_2} - \frac{1}{R_1}\right) \quad (16b)$$

For the block diagram illustrated in Figure 5 are used real values for the parameters of the welding machine like the ones of the equipment taken into consideration to study.

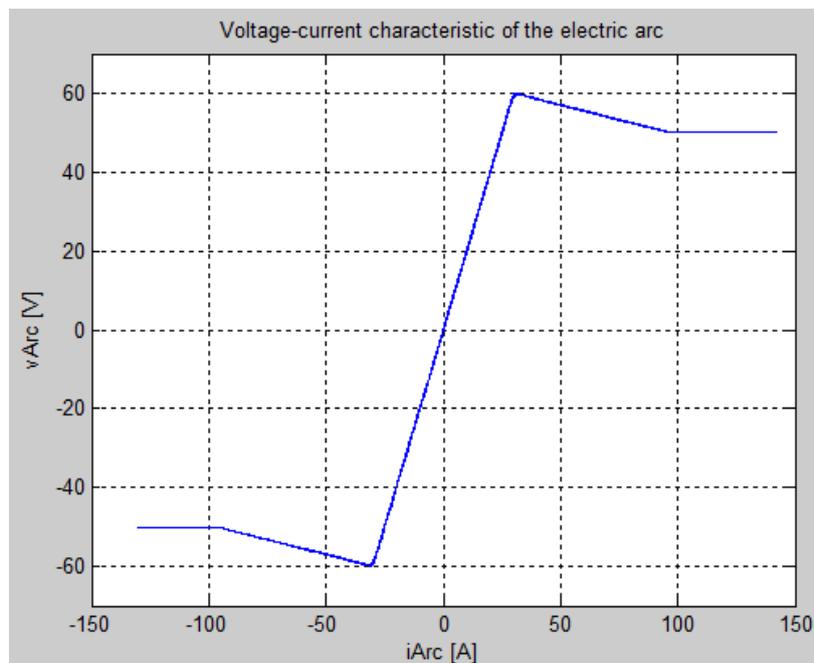
Also, the model parameters were chosen as the electric arc current shouldn't be in the interrupted regime and the voltage should follow the real waveforms of this parameter.





**Figure 6.** Waveforms for the electrical parameters

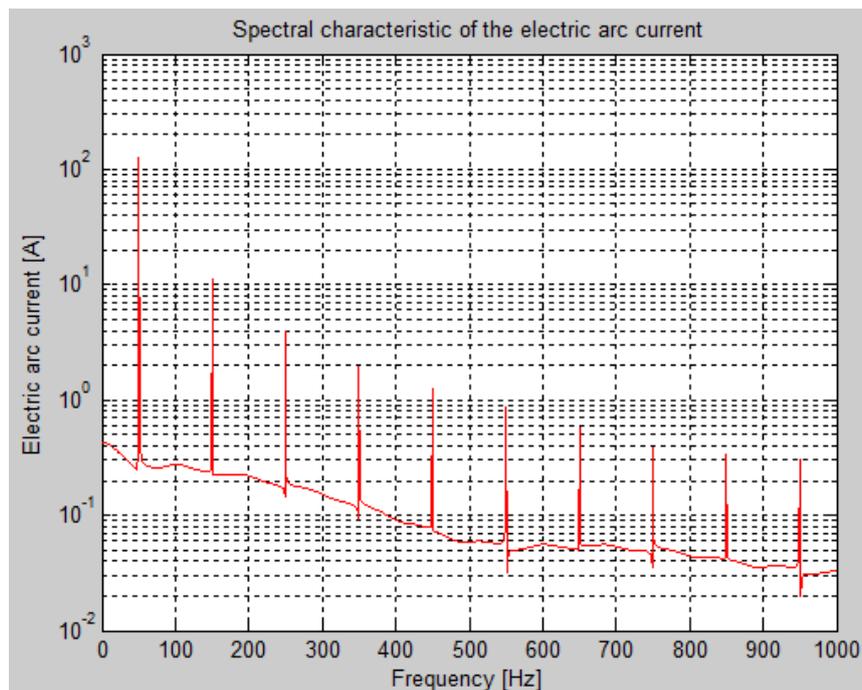
In Figure 7 is illustrated the voltage-current characteristic of the electric arc obtained for the values before presented. By analyzing of it one can conclude that the welding machine is a nonlinear circuit element, this could be linearized just on some operating zones as is evidenced by the voltage-current characteristic of the electric arc.



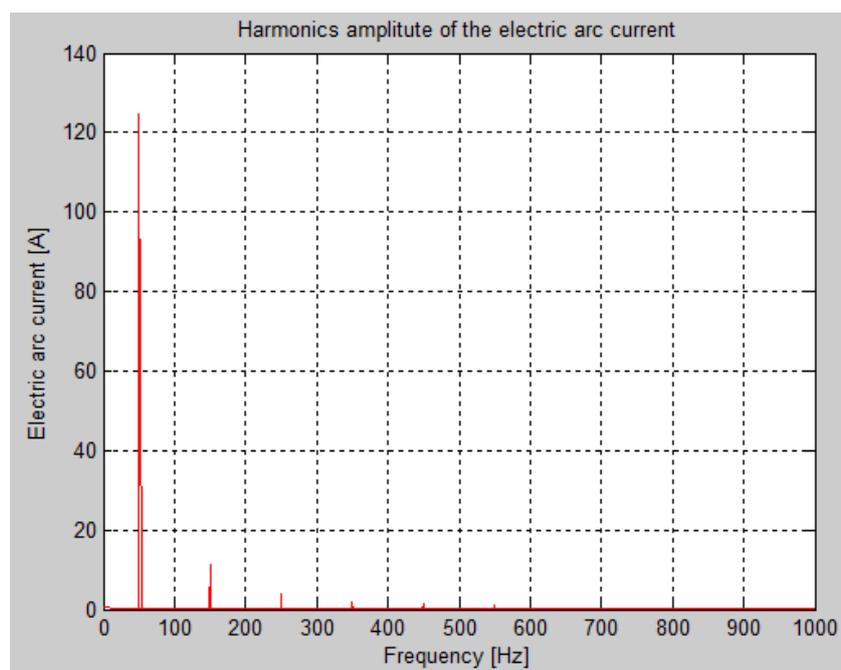
**Figure 7.** Voltage-current characteristic of the electric arc

In Figure 8 is illustrated the spectral characteristic of the electric arc current for the variations of the electric parameters illustrated in Figure 6. Current harmonics are presented on a semilogarithmic scale taking into consideration a range of frequency until  $1000\text{ Hz}$ .

In Figure 9 is presented the harmonics amplitude for the electric arc current using a different representation. One can notice that are presented only odd harmonics of current, the fundamental one having amplitude of approximately  $110\text{ A}$ .



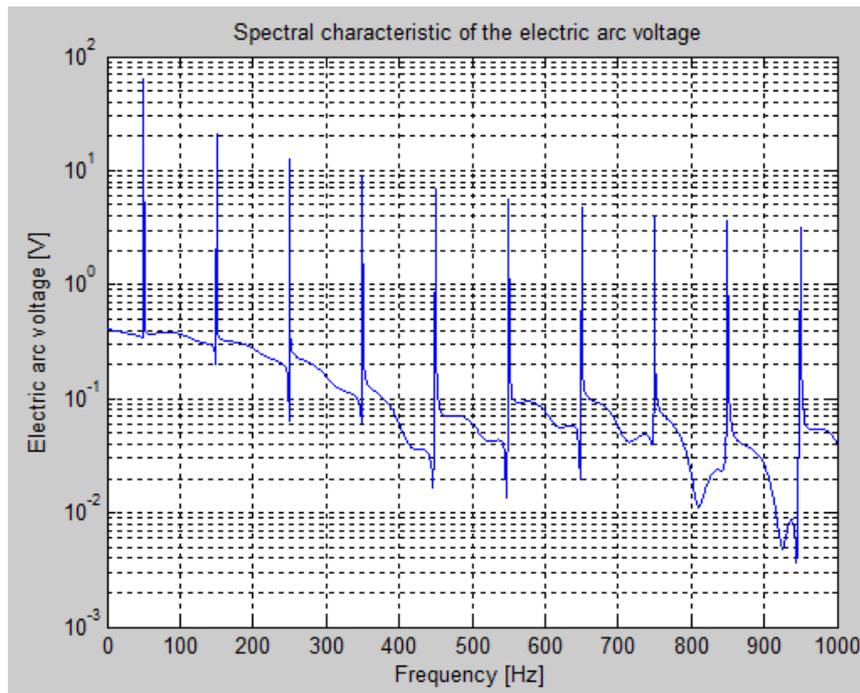
**Figure 8.** Spectral characteristic of the electric arc current



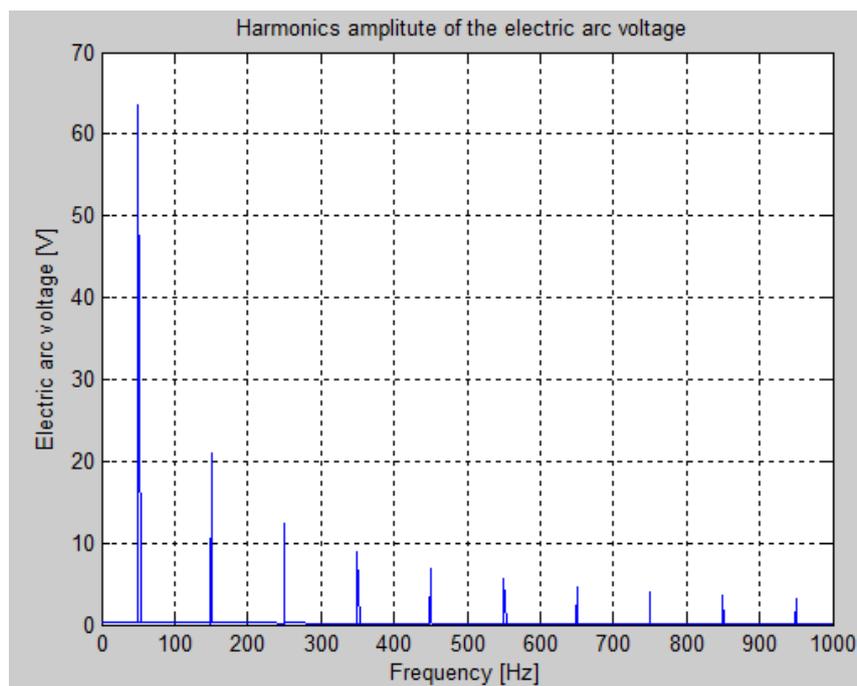
**Figure 9.** Harmonics amplitude of the electric arc current

In Figure 10 is illustrated the spectral characteristic of the electric arc voltage for the variations of the electric parameters illustrated in Figure 6. Current harmonics are presented on a semilogarithmic scale taking into consideration a range of frequency until  $1000\text{ Hz}$ .

In Figure 11 is presented the harmonics amplitude for the electric arc voltage using a different representation. One can notice that are presented only odd harmonics of voltage, the fundamental one having amplitude of approximately  $64\text{ V}$ .



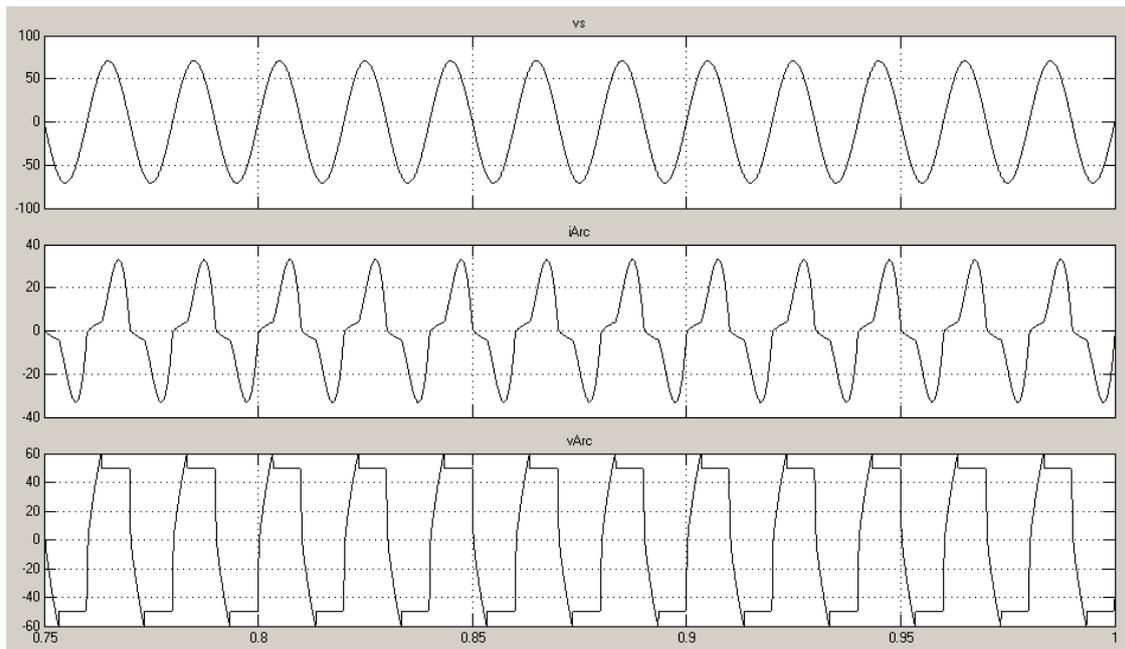
**Figure 10.** Spectral characteristic of the electric arc voltage



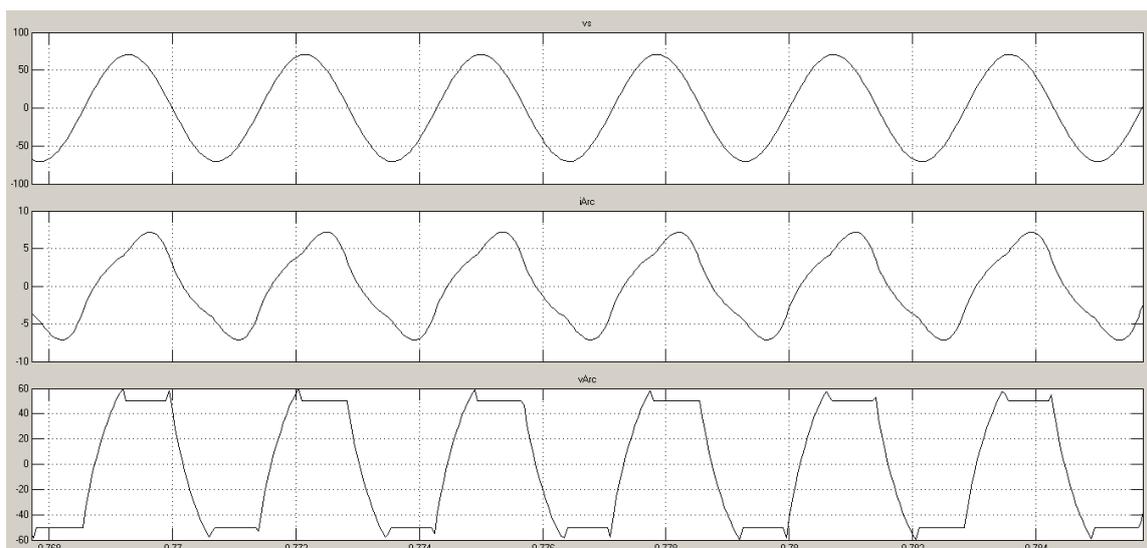
**Figure 11.** Harmonics amplitude of the electric arc voltage

Analyzing the Figures 8, 9, 10 and 11 one can conclude that are presented only the odd harmonics and the amplitude of them are decreasing while its order increase.

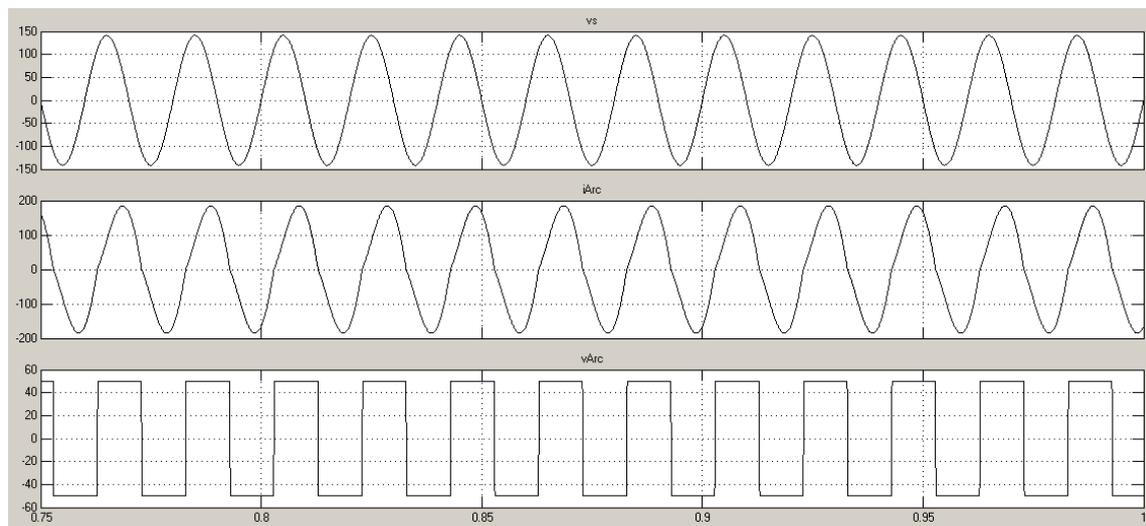
In order to obtain the influence of the supply voltage and of the power supply source operating frequency simulation were made. In Figure 12 is presented the case when the supply voltage was set to  $50\text{ V}$ , so the amplitude is approximately  $70\text{ V}$  and the operating frequency is  $50\text{ Hz}$ . In Figure 13 is presented the case when the operating frequency is set to  $350\text{ Hz}$  and the supply voltage is  $50\text{ V}$ . In Figure 14 is presented the case when the operating frequency is set to  $50\text{ Hz}$  and the supply voltage is  $100\text{ V}$ .



**Figure 12.** Waveforms for the electrical parameters for supply voltage of  $50\text{ V}$  and the operating frequency is  $50\text{ Hz}$



**Figure 13.** Waveforms for the electrical parameters for supply voltage of  $50\text{ V}$  and the operating frequency is  $350\text{ Hz}$



**Figure 14.** Waveforms for the electrical parameters for supply voltage of 100 V and the operating frequency is 50 Hz

Following the results obtained during simulation for different values of the power supply source one can conclude that appear a worsening of the electric arc characteristics while reducing the supply voltage value. In this situation it can be observed that the current of the electric arc is in the interrupted regime.

Also, if the operating frequency of the power supply source is above 350 Hz it can be observed that the electric arc is in the stable area.

If the supply voltage is 100 V and the operating frequency of the power supply source is 50 Hz it can be noticed that the electric arc current waveform is approximately a sinusoidal one and the electric arc voltage waveform has a rectangular shape, so the arc is stable.

#### 4. Conclusions

Following the experimental model simulation of the electric arc one can noticed the electric arc behavior for a welding machine of low power, this behavior illustrating the nonlinearity of the electric arc as presented in the voltage-current characteristic of the electric arc. By setting of both installation and model parameters with values as corresponding for the real welding machine is obtained an electric arc current having waveforms approximate to a sinusoidal and the electric arc voltage is strongly distorted. The THD factors for the voltage and current of the electric arc have considerable values so are necessary some actions in order to reduce them. So, the cost of such welding machine can be high and have to be taken into consideration the advantages for such of the investment.

One can conclude that are presented only the odd harmonics and its values are decreasing when the order of the harmonic increase.

The harmonics of the current and voltage of the electric arc were obtained by writing a Matlab program that was developed by the author of this paper. The values of the harmonics are obtained as concordant to the previsioned ones.

Following the simulations performed for different supply voltage values or different power supply operating frequency one can notice that in order to improve the characteristics of the electric arc it is necessary to increase the supply voltage or to increase the operating frequency of the power supply source. First solution is less advantageous remaining the solution with increasing the operating frequency. This aspect is fulfilled by developing of the frequency convertor welding machines.

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