Modeling and Simulating the AC Electric Arc using PSCAD EMTDC

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Abstract: -The functional analysis of electric scheme including an AC electric arc involves the use of techniques of modeling the electric arc that should reflect as closely as possible the behavior of the real electric arc. This can be done by means of general programs for non-linear circuits, or programs that are specific for a more restricted domain. In this paper, the modeling of the functioning of the electrical installation of the electric arc furnace was done using the PSCAD-EMTDC simulation program.

Key-Words: - AC electric arc, PSCAD-EMTDC simulation program, modelling, nonlinear element

1 Introduction

Electric arc furnace is a massive generator of disturbing in electrical power system. The three types of disturbing the electrical power system are: generation of the three phased harmonic currents, consuming of an important reactive power and unbalanced high power three-phase charge. In the first two directions it can be used harmonic filters and a reactive power compensation installation. The behavior of the electric arc was analyzed using simulation program PSCAD/EMTDC. PSCAD (Power System Computer Aided Design) is a multi-purpose graphical user interface capable of supporting a variety of power system simulation programs [11].

2 Models of the electric arc

The models of electric arc supplied to AC voltage, given in the reference literature, can be grouped in several categories [1]-[8]. These categories of models include:

- Models based on empirical relations between the diameter or length of the arc, the voltage respectively the current through the arc
- Models using the current-voltage characteristic of the electric arc;
- Models using power sources meant to replace the voltage of the electric arc;
- Models using non-linear and time-variable resistances;
- Models using stochastic processes.

The authors have analyzed the main models of electric arc from the reference literature and have come to important conclusions related to the validity of each model, the way of implementing it and the results of computer simulation of the behavior of arc-ovens. In order to be able to obtained comparative conclusions as to the performances of the models under consideration, all the models were implemented on the same electric installation, most often given in the reference literature [4], [5] and which is considered to be the typical one. The typical installation under consideration is fed from the high voltage bars IT through a three-phase transformer 220/21 KV having the power of 95 MVA, and from the medium voltage bars MT through a three-phase transformer 21/0,4-0,9 KV having the power of 60 MVA. The electric resistance on each phase of the short network is 0,3 $m\Omega$, and the electric reactance on each phase of the short network is 3 $m\Omega$. In order to allow a comparison between the models under consideration, in all the simulations the power of the electric arc was chose 25,4 MW, consist in the power transferred to the metal bath and the power loss on the electric arc, proportional to the surface of the hysteresis curve of the current-voltage characteristic. The usual mean value of the amplitude of the electric arc voltage is according to [4] and [5] of 200 V. If the electric arc voltage has a rectangular shape, the effective value will be equal to the amplitude, according to relation:

$$U_{Aef} = U_A = 200\ \text{V} \tag{1}$$

The mean value of the electric arc resistance along one phase is

$$R_A = R_m = \frac{3U_A^2}{P} = 4{,}72\ \text{m}\Omega\,. \tag{2}$$

One important problem that has to be solved by a model is the possibility of controlling the power of the electric arc. A generally valid solution, irrespective of the model used for the electric arc, may be the modification of the effective value of the voltage supplied by the secondary of the medium voltage transformer. Relation (2) points out two possibilities of controlling the electric arc power, the modification of the amplitude of the electric arc voltage and the modification of the mean value of the equivalent resistance of the electric arc. The scheme of the electrical installation is presented in figure 1. In this way, the authors managed to perform a first checking of the implementation of the models, comparing the results they obtained, with those given in reference literature.

All simulations were carried out using the simulation program PSCAD-EMTDC.

2.1 The model based on the variation of the electric arc resistance

As it is known, the basic operations in the electric arc furnace can be described by the three basic status that can arise during its functioning: the interrupted arc, in which the current is null, the short circuit status, due to the contact of the electrode with the metal bath, in which the value of the current is maximal and the normal status, in which the arc is formed between the arc and the metal bath. During the normal functioning, the resistance of the arc changes, producing voltage fluctuations at the point of common coupling (PCC). The model is based on the hypothesis that this variation can be considered as having a Gauss-type distribution, the values of the resistance for the electric arc being centered on a mean value [5]. The basic idea of this model consists in the fact that for each passage through zero of the current of a phase, a new value of the electric arc resistance for that particular phase is being generated. In order to generate Gauss-distributed values for the electric arc resistance was given in [5] and uses *the Box Mueller* transform. According to it, relation (3) gives the resistance of the electric arc:

$$R_A = R_m + \sigma_R \cdot \sqrt{-\ln(rand1)} \left(\cos(2\pi \cdot rand2) + \sin(2\pi \cdot rand2)\right), \quad (3)$$

where *rand1* and *rand2* are two numbers with uniformly distributed along interval [0,1], automatically generated at each zero crossing of the arc current, R_m are the mean value of the electric arc resistance, and σ_R the dispersion of its values. The simulations we carried out using this model and the values given before for the parameters of the electric installation allowed us to obtain the waveforms of the electric arc current and voltage for one phase, as well as the resistance of the electric arc. The simulations we carried out are given in figure 2. As a result of the simulations we carried out we realized that this model is advantageous as it can be easily implemented, but has as disadvantages the fact that the characteristic current-voltage we obtained does not reflect the real characteristic as well as the fact that in the spectrum of the current and voltage the fundamental harmonic is predominant.

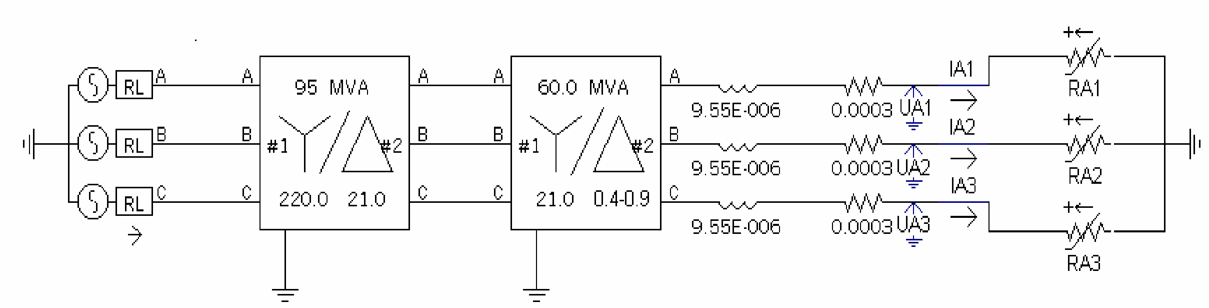

Fig. 1. Diagram of the electric installation of the arc furnace

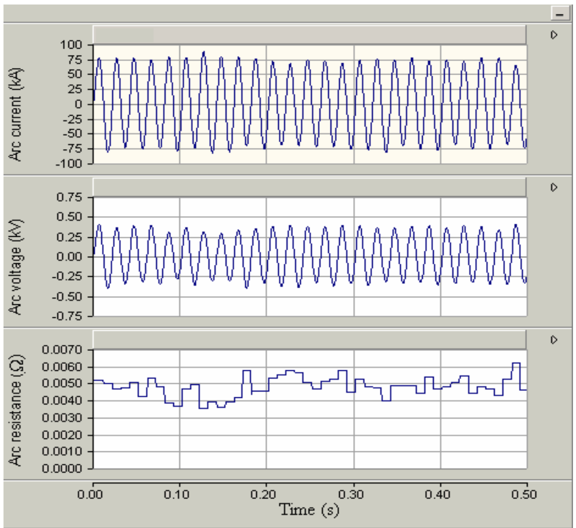

Fig. 2. The variation of the arc current, voltage and resistance according to relation (3).

As a conclusion, one can say that the use of this model confers a resistive character to the electric arc and modifying the mean value of the electric arc resistance can do the regulation of its power

2.2. The model based on the use of the electric arc current-voltage characteristic

This model of the AC electric arc, given in [1], is based on linear approximation of the real characteristic current-voltage, typical for the electric arc. Also, this simulation technique consists in the fact that the parameters of the model depend on the power of the charge and therefore the model parameters depend on the work conditions. As the model uses the power absorbed by the electric arc furnace as an input, it results that the model allows the modification of the characteristic current-voltage, so that the power absorbed can be the one we want to be used by the charge circuit. The principle according to which the model under consideration takes into account the active power absorbed by the circuit is based on the fact that the area of the current-voltage characteristic represents the active power absorbed. The figure 3 presented the typical dynamic characteristic and the linear approximation of the current-voltage characteristic of the AC electric arc. The leveled approximation of the current-voltage characteristic can be defined in the first quadrant by the equation:

$$u = \begin{cases} i \cdot R_1 & 0 \le i \le i_1 \\ i \cdot R_2 + U_{ig} \cdot \left(1 - \frac{R_2}{R_1}\right) & i_1 < i \le i_2 \end{cases} \quad (4)$$

where $i_1 = \frac{U_{ig}}{R_1}$, (5)

$$i_2 = \frac{U_{ig}}{R_2} - U_d \cdot \left(\frac{1}{R_2} - \frac{1}{R_1}\right) \quad (6)$$

Values i_1 respectively i_2 correspond to the ignition voltage, U_{ig}, respectively the drop voltage, U_d, of the electric arc and R_1 and R_2 represent the slopes of segments OA respectively AB. In view of using the equation (4) for the negative half period of the feeding voltage too, it can be rewritten taking into consideration the fact that the values of currents $\boldsymbol{i_1}$ respectively $\boldsymbol{i_2}$ are negative.

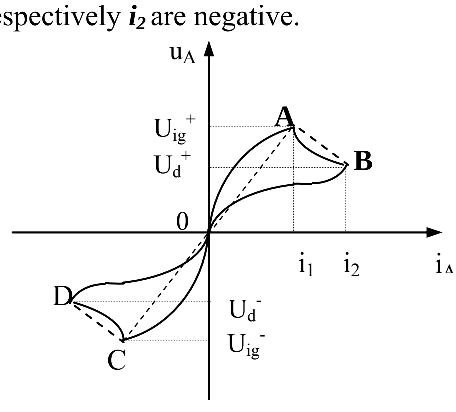

Fig. 3. The real and line characteristic of the electric arc.

As the power absorbed by the electric arc is equal to the area included under the current-voltage characteristic, the resistance of the arc along the segment OA can be calculated according to the relation

$$R_1 = \frac{U_{ig}^2}{\left(P + \frac{U_{ig}^2}{R_2} - \frac{U_d^2}{R_2}\right)} \quad (7)$$

where ***P*** represents the power dissipated within the electric arc. The simulation of the rectifying character of the electric arc using this model can be done by choosing different values for the ignition, respectively drop voltage, along the two half-periods. Under these circumstances, in order that the power dissipated on the electric arc be the same for the two half-periods, it is important that parameter $\boldsymbol{R_1}$ be calculated for each half-period.

In the simulations carried out by means of this model we used for the ignition, respectively cut-off voltage values that were equal for both half-periods, $U_{ig}^+ = \left|U_{ig}^-\right| = 240\ \mathrm{V}$ and $U_d^+ = \left|U_d^-\right| = 200\ \mathrm{V}$. The value of parameter $\boldsymbol{R_2}$ was chosen according to the data given in reference literature $R_2 = -0{,}0007272$; it is negative as segment ***AB*** has a negative gradient [1]. The value of parameter $\boldsymbol{R_1}$ is to be calculated according to relation (7), the power dissipated by the electric arc being $P = 25{,}4\ MW$.

After having carried out the simulations given in figure 4 the authors came to the conclusion that this arc model, is characterized by obtained current-voltage characteristic is a replica of the shape given in figure 3; the characteristic of the electric arc, through parameters R_1 and R_2 depends on the power dissipated in the electric arc. It results that this model allows the simulation of the functioning of the furnace electric installation within a wide range of dissipated powers, the control of the electric arc power being done according to relation (7); within the current range, one can notice the presence of harmonics of 5^{th},7^{th},11^{th} and 13^{th} order, which corresponds to reality. The voltage curve is most distorted on the low voltage line and least distorted on the high voltage line; the current distortion is lower than that of the voltage on the low voltage feed, both from the standpoint of the total harmonic distortion and from the pondered one. From the standpoint of the powers and power factors under non-sinusoidal work conditions, on each of the three feeding lines obtained by means of this model of the electric arc the authors noticed that the active power obtained on the three feeding lines has approximate the same values, the highest value being touched on the high voltage line and the lowest on the low voltage line.

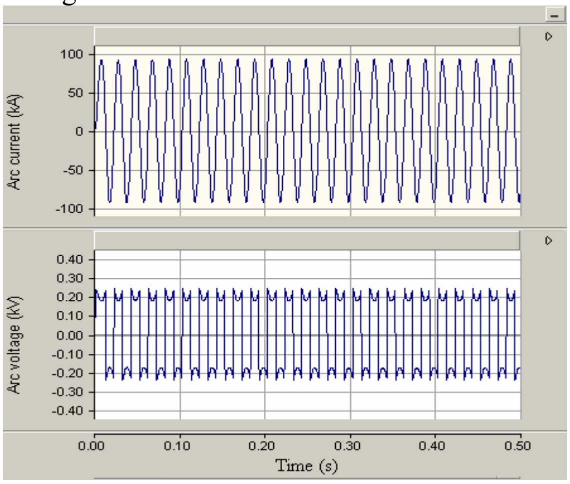

Fig. 4. The variation of arc current and voltage according to relations (29) and (30).

The low value of reactive power on the electric arc, as compared to the one obtained on the low voltage line suggests the fact that this model allows the simulation of a highly resistive character of the electric arc. This difference can be explained by the fact that the reactance value on each phase of the low voltage line (3 mΩ) is comparable to the value of the total resistance on each phase (5,02 mΩ). On the medium and high voltage lines we can obtain higher values of the reactive value, because of the furnace transformer, which shows the necessity of using a compensation system for the reactive power. The deforming effect is most significant on the low voltage line, which can be proved by the much higher value of the deforming factor.

2.3. The model based on the relations between the length of the arc, the voltage and current in the arc

This model, given in [2] and in [7], considers the characteristic current-voltage described by relation

$$U_A = U_A(I_A), \tag{8}$$

relation that can also be written as

$$U_A = U_d + \frac{C}{D + I_A}. \tag{9}$$

In relation (8), $\boldsymbol{U_A}$ and $\boldsymbol{I_A}$ are the voltage and current of the electric arc, $\boldsymbol{U_d}$ is the drop voltage towards which the voltage tends as the current increases. Constants ***C*** and ***D*** determine the difference between the sectors of the characteristic where the current increases or decreases ($\boldsymbol{C_a}$ and $\boldsymbol{D_a}$, respectively $\boldsymbol{C_b}$ and $\boldsymbol{D_b}$). The value of the ignition voltage is obtained for $\boldsymbol{I_A=0}$ and is given by relation

$$U_{ig} = U_d + \frac{C}{D}. \tag{10}$$

The typical values given in [2] and [7]: U_d = 200 V, C_a = 190000 W, C_b = 39000 W, D_a = D_b = 5000 A. As the equivalent impedance of the short network is constant, it is obvious that using during simulations a fix value of the drop voltage, $\boldsymbol{U_d}$, for a certain value of the voltage in the secondary of the furnace transformer, the active power of the electric arc will be constant, its value depending on the constants in the relation (8). According to the above, the use of this model does not allow the control of the active power of the electric arc, but the authors will demonstrate that the control of the electric arc power can be done within loose limits using this model by modifying the drop voltage, which corresponds in practice to the modification of the distance between the electrodes and the metal bath. The analysis of the results we obtained by using this electric arc model will be done by determination of the model performances considering the drop voltage a constant, U_d = *200 V*. If the arc length does not change with time (l = l_0), the dynamic characteristic current-voltage is constant with respect to time. Based on the values of the current and voltage of the electric arc, we compute its power and noticed that for a feeding voltage of

$$U_l = 520\,V \tag{11}$$

we obtained the proposed value, $P = 25{,}4\ MW$.

The voltage in the secondary of the furnace transformer influences the shape and amplitude of the electric arc current, as resulting from figure 5. Thus, one can notice that for a value of the secondary voltage lower than the one given by relation (1) we obtain the status of uninterrupted feeding power, (figure 5.a), for the value given by relation (1) we obtain the meeting to the limit of the condition of uninterrupted work condition, (figure 5.b), while for higher values, the arc current is uninterrupted, (figures 5.c, d). For a value of the line voltage for which we have a power of the electric arc of 25,4 MW**,** given by relation (11), the simulations we carried out allowed us to obtain the wave shapes of the current and voltage of the electric arc of phase 1, given in fig. 6. The shape we obtained for the electric arc voltage closely reflects the results given in the reference literature, both for the real wave, and for the one obtained by simulation [1]. As a result of the simulation, we obtained the current-voltage characteristic presented in figure 7. One can notice that this characteristic shows a (low) hysteresis phenomenon, unlike the theoretical characteristic, which corresponds to the real process [1]. Because the surface of the hysteresis curve represents a measure of the power loss, it results that the

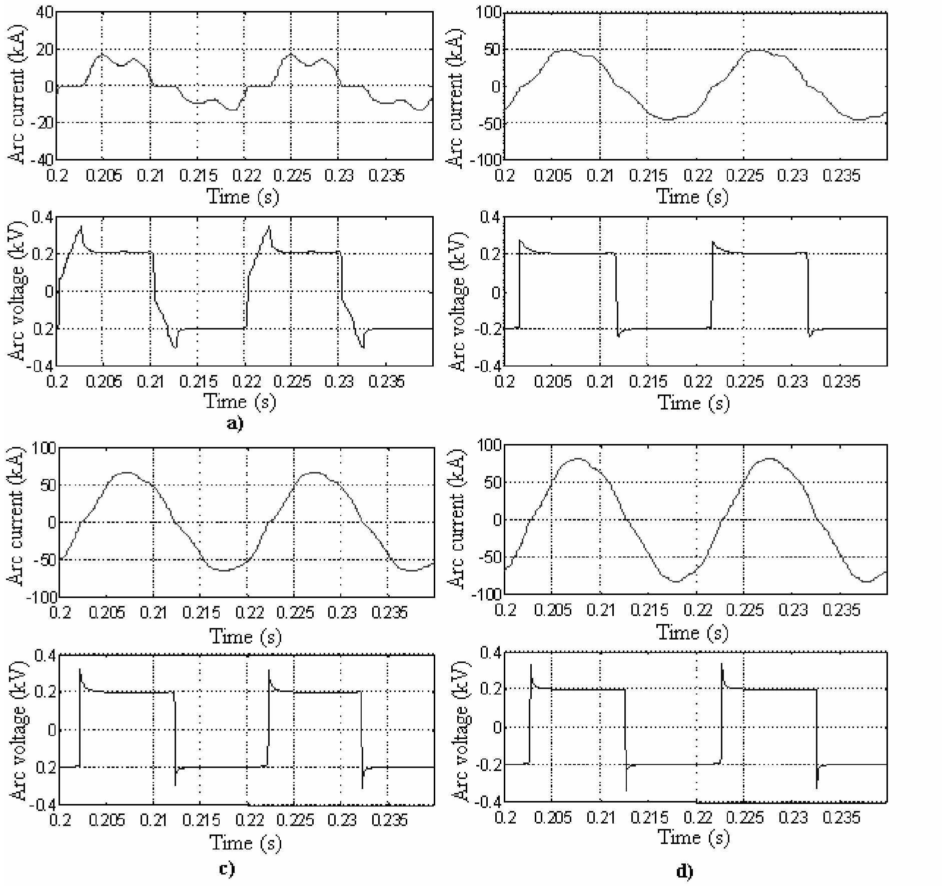

Fig. 5. The variation of the arc current and voltage for various values of the voltage given by the secondary of the furnace transformer a) 380V; b) 450 V; c) 520 V; d) 600V.

simulations may lead to conclusions related to the power loss on the electric arc.

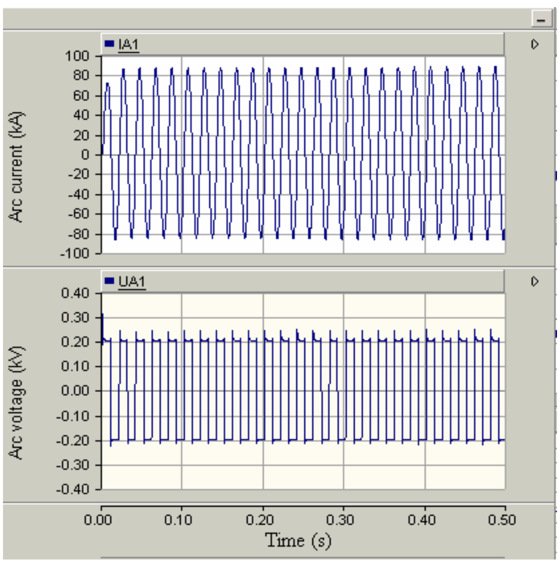

Fig. 6. The variation of the arc current, voltage and resistance, for $U_l = 520\,V$.

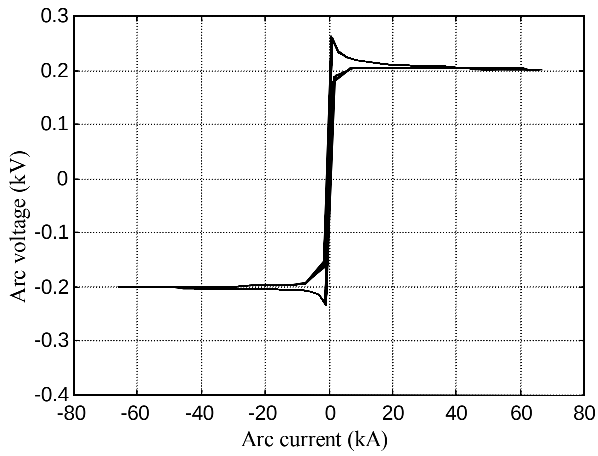

Fig. 7. The characteristic current-voltage of the electric arc for phase 1, obtained by simulation.

One can also notice that there is an asymmetry of the characteristic caused by the different values chosen for constants C_a and C_b from relation (9). Because D_a has been chosen to be equal to D_b the gradients in the growing or decreasing zones are equal too. It results that this model offers the advantage of allowing the simulation of the rectifying character of the electric arc. Using a program implemented on

Matlab we obtained the spectral analysis of the arc current and voltage, using the Fourier transform, the frequency spectrum under consideration ranging within 0 – 1000 Hz, the sampling frequency being 5 KHz. In figure 8 is present the spectral characteristic and the amplitudes of the harmonics of the arc current and voltage, obtained by simulation. One can notice that both in the spectrum of the current and in that of the electric arc voltage, the odd harmonics prevail. This is due to the fact that during the simulations we chose equal values for both half-periods of the drop voltage, $U_d^+ = U_d^- = 200V$.

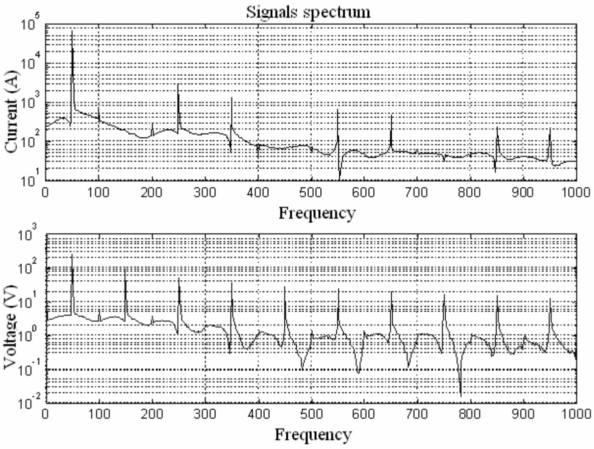

Fig. 8. The spectral characteristic of the electric arc current and voltage

Because the values of the ignition voltages on both half-periods are different, both in the voltage and current spectrum, one can notice the presence of even order harmonics (particularly the second and the fourth, but having much lower amplitudes). In the current spectrum one can notice that, the fundamental let aside, higher amplitude characterizes harmonics 5 and 7 while harmonics 11 and 13 have lower amplitude. Also, with respect to the amplitude of the fundamental, the electric arc voltage harmonics have a much higher amplitude than the current, which also results from the wave forms given in figure 6.

3 Conclusion

In this paper, the authors studied the behavior of the electric arc using three models of electric arc. The study focused on the analysis of the current and voltage shapes, the frequency characteristics, obtained by simulations that used program PSCAD-EMTDC. The best model of the electric arc are, consider by authors the model based on the relations among the arc length, voltage and the current through the arc because their advantages: the possibility of obtaining the shapes of the real electric arc voltage and current curves and the characteristic current – voltage of the real electric arc; while the current frequency characteristic does not include harmonics of an multiple of 3 order, the voltage wave contains these harmonics on the low voltage line, as well as on the medium voltage one (but dimmed), like in real processes.

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