ABOUT THE INFLUENCE OF THE SOURCE FEEDER ON THE PLASMA SPRAY COATING PROCESS

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During plasma spray coating process, the generated electric arc in the plasma chamber is a nonlinear load for the power source. The rotation of the arc in the plasma chamber has an impact on its physical dimensions, such as length and cross-section. This influence is directly related to the voltage drop between the anode and cathode in the plasmatron. This process is stochastic and forms voltage, which timing diagram shows pseudo-periodicity. If consider the electric arc with a power line of the plasmatron as a total load of the power source, the whole energy output of the source can be decomposed as energy delivered on the plasmatron and energy stored in the power line. This study examines the impact of the power line on the electrical parameters of the process plasma-spray coating process.

Keywords: plasma spray coating, data acqusition system, signal processing

1. Introduction

In the constructions of indirect plasmatron with vortex stabilization of the arc depending on the pressure of the plasma gases and the structure of the distribution sleeve of the plasmatron is formed a turbulent outflow of plasma gases, which act on the generated electric arc in the plasma chamber [1, 2, 3].

Changes in the physical size of the arc, as the length and cross-section and following rotation in the chamber, affect the voltage drop between the anode and cathode (u_{AK}). This is a stochastic process, which forms a voltage whose timing diagram is observed to be pseudo-periodic [3, 4, 5]. In the literature, energy of the plasma spray coating process often is regarded to be transmitted from the power source to the construction of the plasmatron without taking into account the parameters of the feeder [1, 2, 6]. At the same time the parameters of the source line - cross-section and length, have a strong influence on the distribution of the energy in the output stage of the source. If the electric arc with a power line plasmatron is considered as a total load of the power source, the whole energy output of the source can be decomposed as energy delivered to the plasmatron and energy stored in the power line. This distribution is highly dependent on the electrical parameters of the power line. Given that the electric arc is a nonlinear element with random variation of its resistance, as well as the rapid change of the current in the circuit, the power line must be considered as an impedance of inductive type with electrical resistance R and self-inductance L. These determine

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the rate of the self-inducted voltage and heat losses due to the dissipated active power. The major factors influencing the value of these electrical quantities are physical parameters of the power line: length cross-section, specific electrical resistance, type of the cable. On the other hand, the dynamics in the chamber of the plasmatron, suggest rapid change of the current and voltage in the line, as well as regions with big slope in their timing diagram, which would cause enlarging of the bandwidth of these values, and therefore appearance of "skin" effect.

2. Characteristics of the power line and an overview of the main influencing factors

For the experiments is used an indirect plasmatron, in which anode and cathode are incorporated into the body of the plasmatorn. The plasmatorn is powered by a source, which is realized as a three-phase controllable symmetric thyristor bridge [5]. The main technical parameters of the plasmatron equipment (plasma chamber, power source and plasma gases flow rate unit) are given in chapter 5. On the poles of the plasmatron (anode and cathode) is applied the voltage from the power source (u_T). This voltage is applied by means of two separate cables type H07V-R each of which is constructed by a copper stranded wire with a length of 8.5 m. and cross-section $S = 150\cdot10^{-6}$ m^2. The circuit of the power line is shown in Fig. 1.

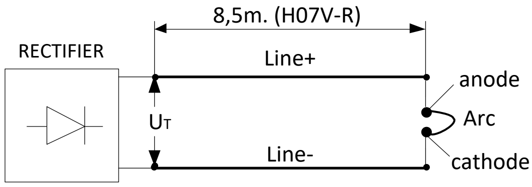

Fig. 1. Simplified diagram of the plasmatron power supply.

For calculation of the electrical parameters of the power cable some basic approaches are well known. Electrical parameters of the cable depend on its physical sizes, as well as the frequency band of the signal [7, 8]. The resistance according to cable catalogue data [9] on each of the power lines is R = 951 μΩ. For the self-inductance is obtained L = 11.4 μH, which for the used wire is calculated according to the expression [7]:

$$L = 2l\cdot\left[\left(\ln\left(\frac{2l}{d}\right)\cdot\left(1+\sqrt{1+\left(\frac{d}{2l}\right)^2}\right)\right)-\sqrt{1+\left(\frac{d}{2l}\right)^2}+\frac{\mu}{4}+\left(\frac{d}{2l}\right)\right], \qquad (1)$$

where l is length, d is diameter of the cable, μ is permeability ($4\pi\cdot10^{-7}$ H/m).

Then the impedance of each power line is function of the angular frequency ω and for the parameters found above (R and L) can be expressed as:

$$Z(\omega) = R + jX = R + j\omega \cdot L = 951 \cdot 10^{-6} + j\omega \cdot 11.4 \cdot 10^{-6}. \qquad (2)$$

Due to the vortex stabilization of the arc in the plasma chamber, dynamic equilibrium is established. Small tolerances are observed, which periodically expand and contract plasma arc and change its geometrical dimensions and respectively the resistance of the arc (R_{darc}). Therefore, equivalent diagram of the electric arc as a nonlinear element in the circuit, can be represented by serial connection of a passive linear element, which shows the static component of u_{AK} ($i\cdot R_{darc}$) and a source of pseudo-periodic signal (u_{arc}), expressing the fluctuations in this voltage. The impact of the power line can be determined by measuring the instantaneous value of the voltage at its both ends: the output of rectifier (u_T) and on the terminals of the plasmatron (u_{AK}) [5, 10]. To implement the experiment are used data acquisition system (DAQ) type NI USB-6211 and its adjacent LabVIEW software, as well as the proper voltage and current transducers [10, 11, 12]. According to these assumptions, the equivalent circuit of the plasmatron power line is shown on Fig. 2.

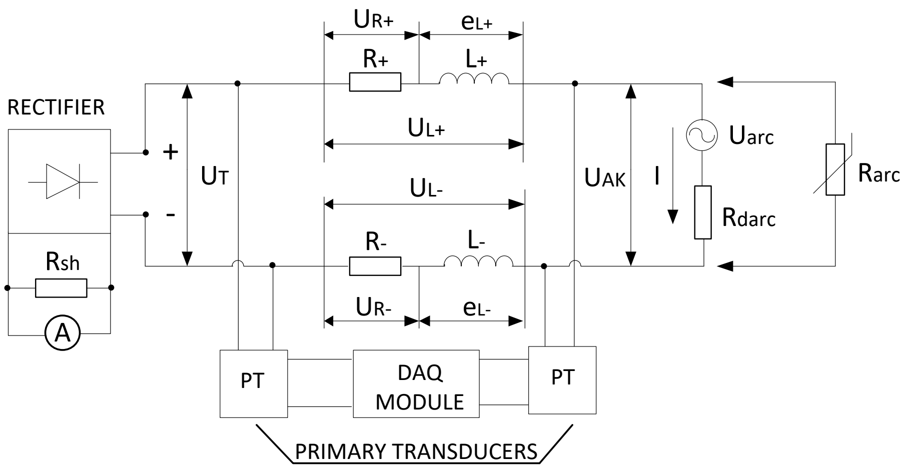

Fig. 1. Connection of the DAQ module to the plasmatron system and equivalent circuit of the power line.

Since the two power wires have identical physical parameters, then:

$$u_{R+} = u_{R-} = u_R,\ e_{L+} = e_{L-} = e_L,\ u_{L+} = \mathrm{u}_{L-} = \mathrm{u}_L\,.$$

Considering the above equations, can be written the Kirchhoff's voltage law for the power circuit of the plasmatron:

$$u_T = 2 \cdot u_L + u_{AK} = 2 \cdot u_R - 2 \cdot L \cdot \frac{di}{dt} + i \cdot R_{darc} + u_{arc} . \quad (3)$$

The impact of the power line is expressed by the value of voltages u_R and e_L. The value of u_R depends on the physical parameters of the conductors, and on the spectrum of the current in the circuit (due to the "skin" effect). The self-inducted voltage in the wires (e_L) is a function of the self-inductance of the line and the alternating component of the current in the circuit. The latter is determined by the pulsations of u_T and u_{arc}. Their spectrum has relation with the effective cross-section of the line (due to the “skin” effect) and thus would affect on the conductivity of the power lines [13]. Depth of the "skin" layer is defined by the expression [14]:

$$\delta = \sqrt{\frac{2 \cdot \rho}{\omega \cdot \mu_0 \cdot \mu_r}} \cdot \sqrt{\sqrt{1 + (\rho \cdot \omega \cdot \varepsilon_0 \cdot \varepsilon_r)^2} + \rho \cdot \omega \cdot \varepsilon_0 \cdot \varepsilon_r} , \quad (4)$$

where ρ is the resistivity of the line, ω - angular frequency, μ_r - relative permeability of the conductor, μ_0 - permeability of the free space, ε_r - relative permittivity of the conductor, ε_0 - vacuum permittivity. Practically, when $\omega \ll 1/\rho \cdot \varepsilon_0 \cdot \varepsilon_r$, the second radical tends to unity and the depth of the "skin" layer can be expressed as [14]:

$$\delta = \sqrt{\frac{2 \cdot \rho}{\omega \cdot \mu_0 \cdot \mu_r}} . \quad (5)$$

Since the current in the output circuit actually can be expressed by a random function, which displays certain periodicity and then to assess the impact of "skin" effect it is necessary to obtain the spectrum of the signal in the power line. The high-frequency components of the spectrum would show the impact of the rapid changes in the output values on the effective cross-section of the cables.

3. Measurement results and calculations

The main parameters by setting test conditions of the experiment is the electrical current of the power line, mixture of the metal powder for coating as well as the flow rate of the plasma gases [15]. As the result, instantaneous value of the voltages u_T, u_{AK} are observed. The experiments are carried out for three different values of the current within the nominal operating range of the plasmatron. These values are chosen to be in the middle and at the limits of this current span: 300 A, 400 A and 500 A. As plasma gases are used argon and nitrogen. Coating powder is nickel-based mixture with a small percentage ingredients of iron, boron, chrome, silicon and carbon dust [15].

The dynamic span of the received signals reaches more than 250 ÷ 300 V. During the experiments, in order to adjust the level of the measured signals to correspond to the scope of the NI - 6211, primary transducers (Fig. 2 - PT) are used. Thus, in the measurement electrical circuit, for the voltages u_{AK}, u_T as primary transducers are included voltage dividers with koefficient of reducing:

$$K_R = \frac{U_i}{U_o} = 100\,, \tag{6}$$

where U_i is input voltage, U_o is output voltage of the devider.

For the curent measurement as a transducer is used shunt (Fig. 2 - R_{sh}) with the following parameters: maximum working current - I_M = 600 A, maximum drop of the voltage U_M = 100 mV (by I_M = 600 A).

In Table 1 are given the experimental conditions: operating current, the flow rate of plasma gases (argon - Q_{Ar}, nitrogen - Q_N), the flow rate of the coating powder - Q_{Ni}, and average value of the rectified voltage - u_T.

Table 1

The experiments initial conditions

Q_{Ar} = 20 L/min; Q_N = 2 L/min; Q_{Ni} = 500 g/h	
I	***u_T (av)***
A	**V**
300	50
400	51
500	52

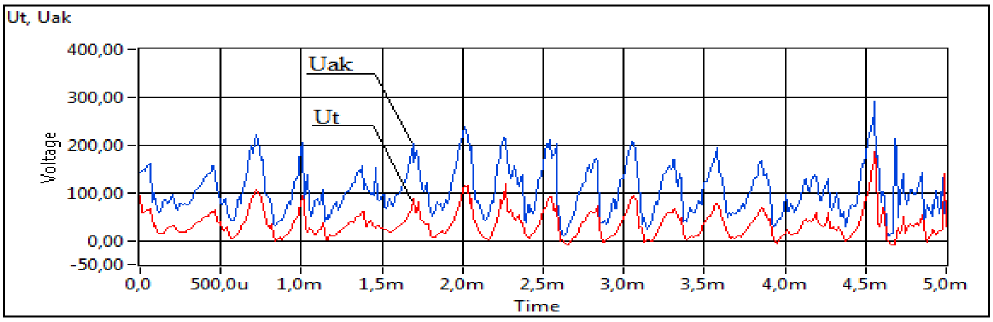

Fig. 2. Instantaneous values of the u_{AK} and u_T at operating current 400 A.

The timing diagram of the measured voltages at current of 400 A are presented in Fig. 3. Fig. 4 shows the alternating components of the same voltages. It can be seen that timing diagram are similar, but with significant offset of the u_{AK} against u_T. This actually shows influence of the feeder on the plasma spray coating process.

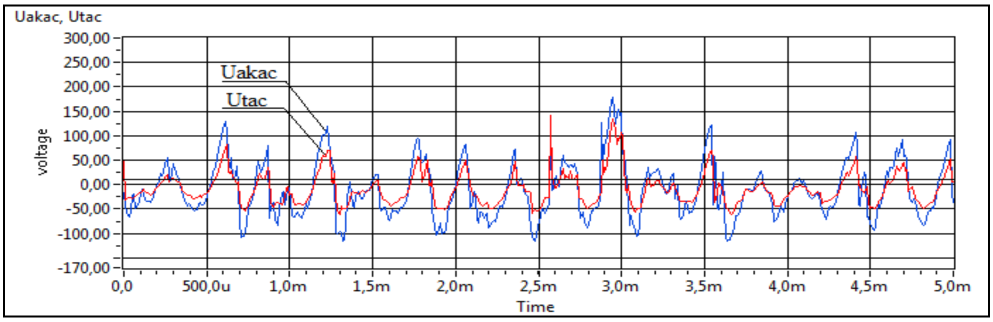

Fig. 3. Alternating components of the voltages u_{AK} and u_T by operating current 400 A.

The results of the harmonic analysis at the operating currents are shown in Fig. 5 (a, b, c). The harmonic analysis shows, that at low frequencies the first three harmonics in the spectrum are due to the pulsations from the rectifier (300 Hz, 600 Hz and 900 Hz). Pulsations in the voltage u_{AK} caused by the pressure of the plasma gases and angular velocity of the arc are manifested as harmonic components in 2 kHz - 4 kHz bandwidth.

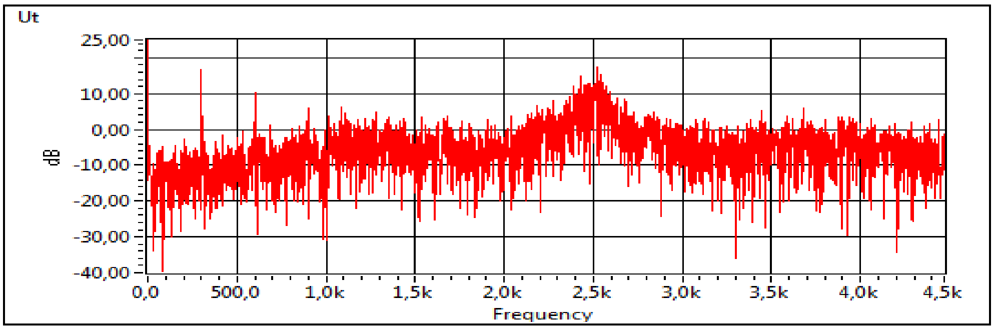

Fig. 4 a. Spectrum of the voltage u_T at operating current 300 A.

For modes 300 A and 400 A in 2.2 – 2.7 kHz bandwidth, harmonic components with peaks respectively on 2.5 kHz and 2.45 kHz are observed. For mode 500 A, the spectrum of the high frequency components is splited into two bands with peaks on 1.2 kHz and 3.7 kHz (Fig. 5 a, b, c). The level of these harmonics is commensurable with the components in the spectrum, caused by u_T.

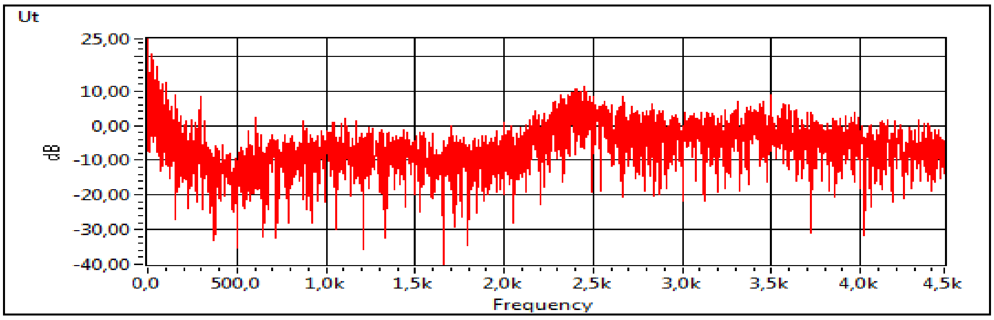

Fig. 5 b. Spectrum of the voltage u_T at operating current 400 A.

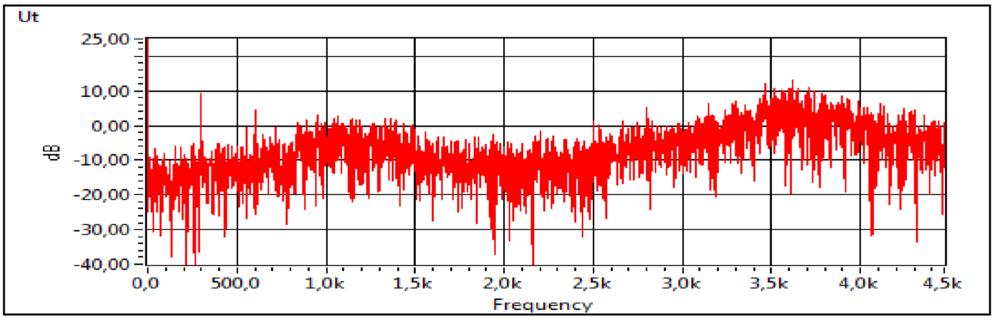

Fig. 5 c. Spectrum of the voltage u_T at operating current 500 A.

According to (5) and substituting ρ = 1.678 nΩ·m, $\mu \approx \mu_r$ = 1.257 µH/m and at the indicated upper frequencies, for the “skin” depth are received the following data, presented in Table 2.

Table 2

„Skin“ depth at found frequencies for operating currents

I	**A**	300	400	500
f	**kHz**	2.5	2.45	3.7
δ	**mm**	1.3	1.32	1.07
δS	**%**	62.4	61.8	68.4
I	**A**	300	400	500
f	**kHz**	2.5	2.45	3.7

The cable of the power line is H07V-R type and its catalogue data [9] show a diameter of $18.8 \cdot 10^{-3}$ m. The skin depth for the obtained peaks of the bandwidths is substantially smaller than the diameter of the conductor. This leads to a significant reduction in the effective cross-section for the frequency components in the band 2 kHz - 4 kHz. In Table 2 the parameter δS shows relative reduction of the cross-section of the cable.

For the operating current 500 A and the resistance of the conductor R = 951 µΩ (for static component of the current), the voltage drop on the power lines is obtained to be U_R = 0.95 V, which is negligible compared to the self-inducted voltage e_L. Then, according to (3), the main effect of the line is expressed by e_L, and the difference between u_{AK} and u_R can be written as:

$$u_L = u_T - u_{AK} = 2 \cdot \left(L \cdot \frac{di}{dt} \right) = 2 \cdot e_L . \tag{7}$$

Fig. 6 shows the timing diagram of u_L, which represents the difference between both measured voltages (u_T and u_{AK}). It is obviously that u_L has the same periodicity, as the studied voltages u_{AK} and u_T. Table 3 presents the numerical results for the impact of the power line of the plasmatron.

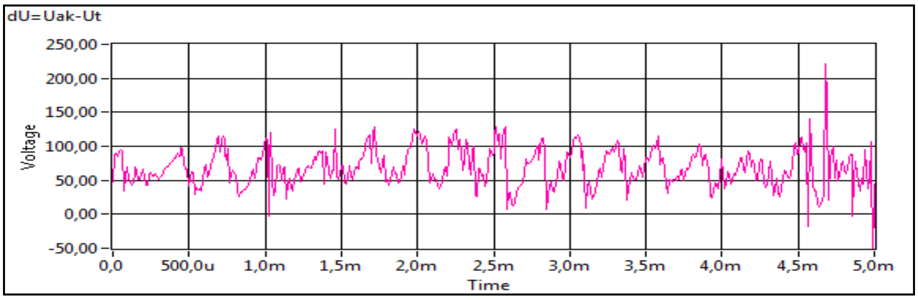

Fig. 5. Instantaneous values of the u_L at operating current 400A.

The average value of the self-inducted voltage on the both cables of the power line is within the interval from 69.27 V to 102.26 V. For comparison, Table 3 presents the average (U_{AKDC}, U_{TDC}) and RMS (U_{AK}, U_T) values of the measured voltages (u_{AK} and u_T), as well as the RMS values of their alternating components (U_{AKAC}, U_{TAC}). Regardless of the negligible small voltage U_R, the dissipated active power for the static component of u_{AK} in the supply line is between 171.2 W and 475.4 W.

Table 3

Influence of the power line. Main parameters

I	U_{AKDC}	U_{TDC}	U_{AKAC}	U_{TAC}
A	**V(av)**	**V(av)**	**V(rms)**	**V(rms)**
300	119.53	50.26	71.58	53.78
400	130.03	50.93	75.79	54.80
500	154.23	51.97	77.12	46.40
I	U_L	P_{DC}	U_{AK}	U_T
A	**V(av)**	**W**	**V(rms)**	**V(rms)**
300	69.27	171.2	139.33	73.61
400	78.92	304.2	150.51	74.54
500	102.26	475.4	172.44	69.67

4. Conclusions

The results of the experiments clearly show that the power line affects the plasma spray coating process by two main ways:

- by the dissipated active power in the line due to the electrical resistance of copper conductors, which is expressed as heat losses;
- by the appearance of self-inducted voltage, due to the self-inductance of the wire, resulting in a magnetic field around the line.

The results obtained for these main influencing factors lead to the conclusion, that dynamic processes in the plasmatron, respectively the rapid change of the dynamic resistance of the arc, have the supreme effect on the plasmatron‘s voltages of which depends the influence degree of the power line on the electrical parameters of the plasma spray coating process.

This study proves the crucial meaning of the relationship between the frequency spectrum of the electrical parameters of the plasmatron and the effective cross-section of the power line, which is a direct result of the "skin" effect in the cables.

The observed effect could be examined in details via accurate measurements with the help of the DAQ system. The analysis of the process must be performed with the instantaneous values measurements (for the voltage and current), conducted in parallel with the harmonic analysis and taking into account the fast fluctuations of the voltages. Thus the uncertainty, caused from the cable’s parameters will be eliminated.

5. Appendix

The plasmatron’s main opperating parameters are given below:

- Nominal coating productivity:
  - for metal powder 12 kg/h;
  - for non-metal powder 6 kg/h;
- Accuracy of the metal powder flow rate 1.5 %;
- Nominal electric power 10 ÷ 50 kW;
- Maximum real power 50 kW;
- Maximum gas flow rate 3 m^3/h;
- Coating distance 80 ÷ 200 mm.

Data Acquisition system type NI – 6211 contains 8 differential or 16 single ended analog inputs (AI), 2 analog outputs (AO), 4 digital inputs/outputs. The main parameters of NI - 6211 are [15]:

- Sample rate (f_s) 250 kS/s;
- Resolution 16 bits;
- Maximum working voltage for analog inputs (V_i) ±10 V;

- Input impedance (AI to ground) >10 GΩ;
- Data transfer USB Signal Stream, programmed I/O

Acknowledgements

The author expresses gratitude to the staff of the company SIFCO and its head Prof. H. Skulev for providing the equipment and technical resourses for the experiments.

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