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# Damping factor function in AC electric arc models. Part 3: Static and dynamic properties of the arc with intense cooling in plasma torches

**Abstract:** The importance of models of arcs with intense cooling has been shown in AC plasma torch design and usage. The influence of gas mass stream that washes plasma column on the shape of static and dynamic arc characteristics has been considered. The selected effects of using a high frequency auxiliary generator, leading mainly to stabilization of the arc and linearization of its characteristics have been analyzed.

**Keywords**: Electric arc, Damping factor, Time constant, Static characteristic, AC plasma torch

## Introduction

Today's relatively wide interest in theoretical research and experimentation related to a moderately cooled electric arc results from the following factors:

1. significant popularity of welding devices with a free arc, burning in air, in shielding gases, joining "cold" metal elements;
2. significant energy-related and technological importance of electrothermal devices (furnaces) using a free arc, burning in air or in shielding gases, melting the "cold" metal charge (scrap) for a predominant time interval of a whole metallurgical process;
3. relatively high difference in temperature between an arc and the surroundings and resultant high intensity of active gasodynamic disturbance, thus leading to relatively low electric arc burning stability;
4. strong non-linearity of static and dynamic characteristics of such an arc, causing the generation of a wide spectrum of harmonics with relatively high amplitudes, entering various disturbances in the network; generating needs for using harmonic filters, wattless power compensators; stabilising reactors, control transductors etc.;
5. relatively high complexity and increased production costs of stabilised power sources characterised by appropriately steep external characteristic and powering a moderately cooled free arc.

The mathematical modelling of such an arc was discussed in the second part of this series of publications [1]. At the same time it is possible to observe a constantly rising interest in theoretical research and experimentation related to an intensively cooled electric arc [2, 3]. Such a growth in interest can be attributed to the following:

1. increasing popularity of welding and electrothermal devices with a geometrically stabilised arc (stream plasma torches with an internal arc), burning in air, shielding gases, joining or overlaying "cold" metal elements, heating gas charges, producing streams of sprayed liquids, powders etc.;

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2. great technological importance of welding devices with a geometrically stabilised arc (plasma torches with internal and external cascade arc), burning in air or shielding gases, cutting "cold" metal elements;
3. significant energy-related and technological importance of electrothermal (metallurgical and casting) devices with a geometrically stabilised arc (furnace plasma torches with an internal arc), burning in air or in shielding gases, melting the "cold" metal charge (scrap) for a predominant time interval of a whole metallurgical process;
4. very high difference in temperature between an arc and the surroundings, very high rates of gases turbulently washing the column and a resultant very high degree of compression of a column, whose plasma reaches a very high temperature;
5. depending on the mutual position of a column and a gas flow it is possible to improve or worsen arc burning stability;
6. strong non-linearity of static and dynamic characteristics of such an arc, causing the generation of a wide spectrum of harmonics with relatively high amplitudes, entering various disturbances in the network; generating needs for using harmonic filters, wattless power compensators; reactors, transductors etc.;
7. relatively high complexity and increased production costs of stabilised power sources characterised by appropriately steep external characteristics and powering an intensively cooled arc.

Extreme cooling of an electric arc column is obtained by using intense hypersonic (sometimes supersonic) gas washes around the column. In such a situation the excess development of turbulence or the generation of discontinuities of a gas centre may favour the loss of discharge stability and cause arc termination.

Very high intensity of arc cooling is obtained by means of gas-steam, steam, liquid-steam and liquid flows, or even by non-homogenous mixing with powder materials [4, 5]. Intense cooling also takes place during joining or hyperbaric cutting with an electric arc under water. Increased arc heat transfer can be caused by diaphragms and cooled metal ducts of reducing pipes. Arc cooling is also favoured by stretching the arc, particularly if the characteristics of a supply source are close to the characteristics of a voltage source.

Due to the very high temperature of plasma, an effective way of dissipating heat from a long arc is by radiation. However, in stream plasma torches with an internal arc such a component of energy generates losses carried away by water cooling a reducing pipe. A similar phenomenon can be observed on plasma torches for cutting and in plasma furnaces with a lining in the form of metal panels cooled with water, in which the fraction of energy losses through radiation is also high. Replacing panels with a ceramic lining, or more favourably, hiding an arc under a thick layer of slag or flux makes it possible to decrease losses caused by thermal radiation.

Convective heat removal from a column is characterised by limited possibilities due to the double-layered structure of an arc [3, 6]. The efficiency of such dissipation is significantly higher in the case of a short AC arc. Radiation and convection play an indirect role in heating a charge by arc spots, which, as it turns out [7], are of great importance not only in welding engineering but also in electrometallurgy.

AC plasma torches generating heated gas streams (sometimes also powder ones) make use of cavity, ring or bar electrodes. Cavity electrodes or bar electrodes, treated as "non-consumable" electrodes, are usually made of copper (sometimes of graphite) and as a result are cheaper in operation and can be used even with chemically active gases. Bar electrodes can be non-consumable or consumable. In the first case, they are made of tungsten and are used for heating inert gases, nitrogen or hydrogen. In the other case, electrodes are fed to a plasma torch chamber in the form of wires and next are sputtered. In this manner such electrodes can be used for spheroidising or spraying. Similar solutions are used in the case of furnace plasma torches with an external arc. In high power furnaces, where several such plasma torches are used, it is possible to obtain minimum effects of mutual detrimental influence between arcs. Owing to constant emission of electrons from electrodes (self-emission) it is possible to avoid the danger of changing the thermal and emissive state of the cathode, which enables the use of wide adjustment ranges of work current. Such plasma torches can operate both with alternating and direct current and are usually manufactured as one-phase or three-phase devices [2, 3]. The fraction of convective dissipation of energy from a short AC arc is significantly greater than in the case of a long DC arc, which, in turn, is characterised by a high fraction of power dissipated by thermal radiation. For this reason the efficiency of gas-heating AC stream plasma torches is relatively high, and that of furnace plasma torches heating slang and metal bath is relatively low.

The basic disadvantages of an AC arc are the high value of voltage gradient, a small height of a plasma column and no possibility of directing a dominant heat stream into the anode located on the charge. In comparison with a DC arc, an AC arc is accompanied by fluctuations of pressure and gas temperature, higher noise intensity, higher level of electromagnetic interference generated to the network and higher concentration of electrode material vapours in plasma. In addition, an AC arc is significantly less stable and more difficult to control. In order to ensure continuous industrial frequency arc burning it is often necessary to apply an additional high-frequency generator (e.g. 1 MHz) or to use a DC pilot arc.

## Electric arc with intensive cooling in AC plasma torches

An arc column in a DC plasma torch is compressed and stabilised along the axis of an electrode, reducing pipe and nozzle with an intense gas flow. In AC plasma torches the change of electrode polarity disturbs that stabilisation and that is why such an arc is significantly more difficult to compress and stabilise. Additionally, the periodical phenomena of gas deionisation and interelectrode gap breakdowns may take place at moments close to the transition of current through the zero value. For this reason the voltage of the no-load state of the source supplying such a plasma torch is over two times higher than the work voltage of an arc. In the case of supplying a DC plasma torch these voltages are comparable. As a result, the installed power of an AC source is significantly higher. In addition, while supplying a one-phase plasma torch such a source does not always guarantee the symmetry of network load. In such moments it becomes necessary to use additional balancing systems.

If the value of inductance connected in series with an arc is insufficient, the circuit supplying a strongly non-linear resistor (i.e. the arc) may be affected by periodical current flow stoppages resulting in significant deformations of voltage waveforms and the generation of higher harmonics of current. Measures preventing such a phenomenon include the following:

1. properly high increase in serial inductance;
2. connecting high-frequency current generator in parallel to an arc;
3. thermal and ionising support of the main

discharge by a DC pilot arc burning in the common reducing pipe or the nozzle. Due to the previously enumerated advantages of DC plasma torches, they are used in most technological processes. AC plasma torches are used in special cases specified by the technological requirements of processes. Plasma joining of aluminium alloys should be carried out using alternating current. In the intervals of reverse polarity there is a cathode sputtering effect destroying the film of high-melting aluminium oxide, which would prevent a normal metal melting process. A similar situation can be observed while cutting elements made of aluminium or its alloys. Another example can be the operation of several plasma torches located near one another and working at the same time. The minimisation of magnetic interaction of arcs, causing their deflection, can be obtained by using AC plasma torches. Due to the symmetry of three-phase network load, the number of plasma torches should be in a multiple of 3. In addition, supply sources of AC plasma torches are characterised by a simpler design, higher efficiency and greater reliability. For this reason such plasma torches are preferred for the production of high power technological units of relatively low investment and running costs.

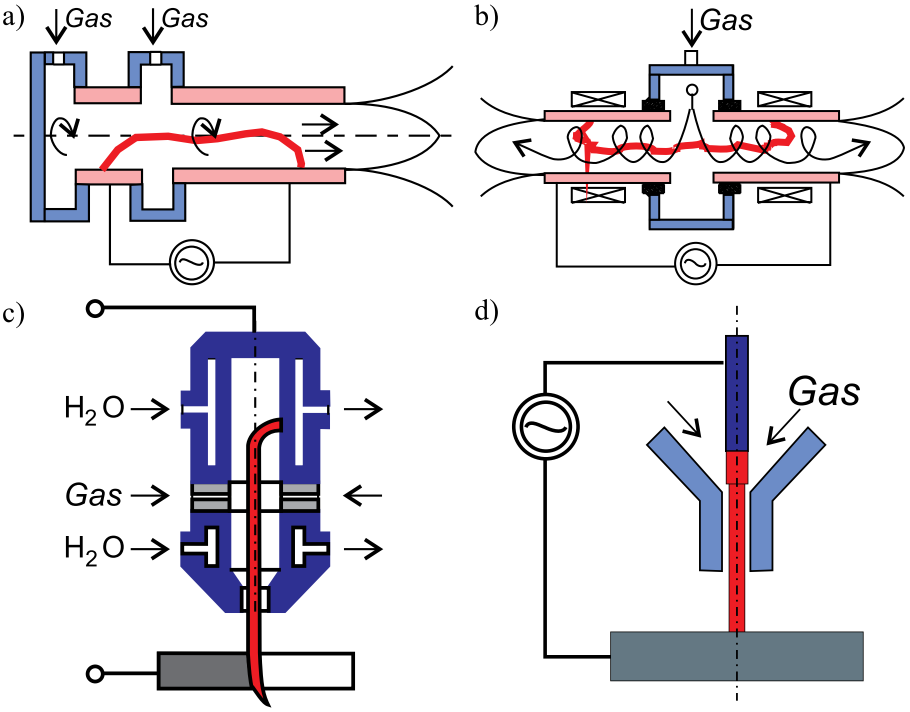

Fig. 1. Schematic diagrams of one-phase plasma torches: a), b) with internal arc; c), d) with cascade internal and external arc

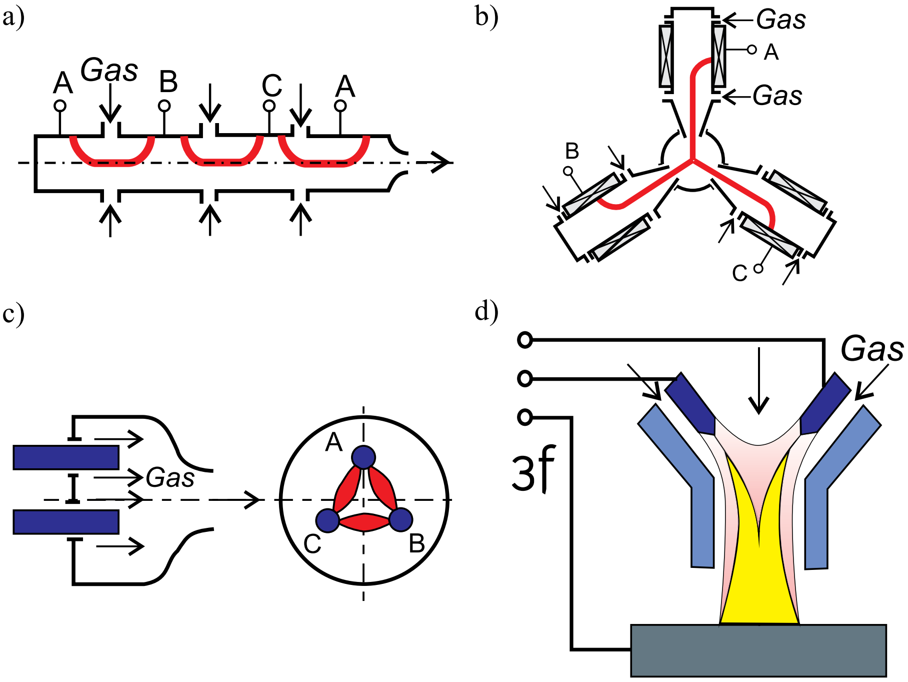

Fig. 2. Schematic diagrams of three-phase plasma torches: a), b), c) with internal arc; d) with cascade internal and external arc

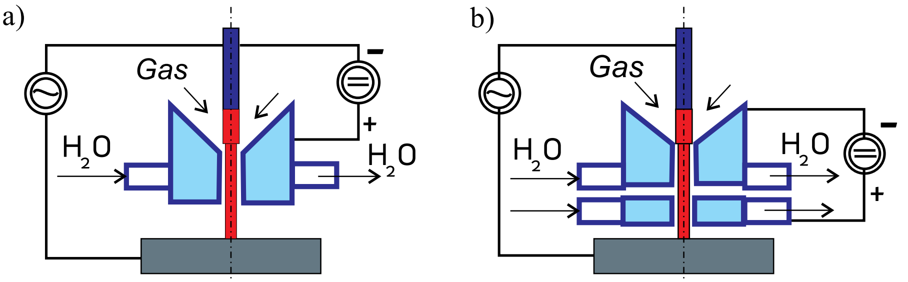

Fig. 3. Schematic diagrams of one-phase plasma torches with DC pilot arc: a) with arc between electrode and nozzle; b) with arc between two nozzles

Figures 1-3 show selected schematic diagrams of AC plasma torches. The plasma torches presented in Figure 1 can be supplied from a one-phase transformer with intensified dissipation. AC plasma torches operate with a moving spot inside a cylindrical copper electrode, owing to which they can work with air. In turn, a DC plasma torch with a motionless spot on a bar tungsten electrode can work with neutral gases. It is similar in the case of three-phase plasma torches, presented in Figure 2. Such solutions ensure better stability of arcs burning at the same time. However, three-phase plasma torches are of a more complex design than one-phase torches as they are built as single or multi-chamber devices. Multi-chamber plasma torches are a combination of three one-phase plasma torches. They are connected to a power network according to delta or star schemes. A disadvantage of such plasma torches is an increased power of heat losses due to a great total area of the whole system. One-phase plasma torches are provided with electrodes in the form of rings, toroids or bars placed in a single chamber.

The improvement of AC arc burning stability can be achieved by energising a plasma torch in a combined manner, i.e. from alternating and direct current sources. An additional DC pilot arc is characterised by a low power. This arc burns either between an electrode and a nozzle (Fig. 3a) or between two nozzles (Fig. 3b). In the latter case a nozzle with a smaller duct diameter plays the role of a cathode, and the one with a greater duct diameter plays the role of an anode. In this way its thermal load changes [8]. The use of additional DC sources and constant maintenance of an electric discharge by such sources may deform arc characteristics. In addition to electrode asymmetry, the columnar asymmetry of dynamic characteristics may also come into being [9].

In order to stabilise a high-power arc discharge of network frequency it is a common practice to impose additional low-current high-frequency excitation on the discharge. Already in the case of DC arc it is possible to observe closed loops containing a section of static characteristic (Fig. 4). When frequency increases the axis of the loop turns, the loop flattens and aims to adopt the form of a section on the straight line OA, passing through the zero point of a coordinate system. In turn, if the frequency of excitation decreases, the loop turns into a section of static characteristic BC.

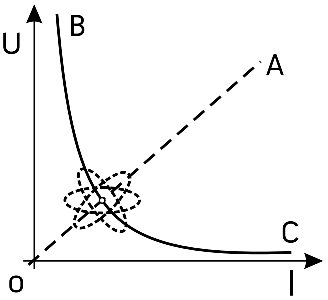

Fig. 4. Effect of additional periodical excitation on arc static characteristic

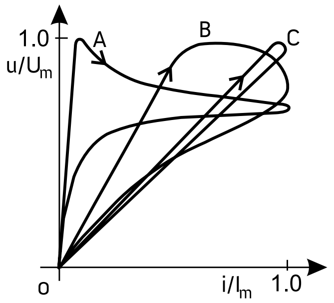

Fig. 5. Dynamic characteristics of arc in cases: A: $\omega\theta = 0,1$; B: $\omega\theta = 1$; C: $\omega\theta = 10$ [10]

Arc discharge dynamic characteristics depend on the relation of time constant $\theta$ of thermal processes in a column and the duration of the period $T$ of exciting current

$$\frac{\theta}{T} = \frac{\omega\theta}{2\pi} \tag{1}$$

The extreme cases of the product of an arc time constant and excitation pulsation are $\omega\theta >> 1$ and $\omega\theta << 1$. Figure 5 presents the evolution of a hysteresis loop expressed in relative units. The evolution may be caused either by the influence of excitation frequency changes or be triggered by changes of arc burning conditions such as the chemical composition of a plasma-creating gas and external effects which intensify cooling a column.

Depending on the amplitude and frequency of additional arc stabilising excitation the thermodynamic properties of plasma may undergo various changes. A visible effect of such changes is the deformation of a hysteresis loop. If the high frequency of a current component is the multiplicity of the basic source current frequency, additional minor oval loops may appear on the border of arc dynamic characteristic [10]. The angle of these loops depends on a frequency. Due to a frequent lack of the synchronisation of sources and a very big difference in their frequencies, it is often possible to observe the thickening of the main hysteresis loop, additionally masked by a relatively high level of arc gasodynamic disturbances.

The impact of a high-frequency auxiliary generator on an arc decreases if

1. inductance of a serial reactor is sufficiently high;
2. root-mean-square discharge current is sufficiently high;
3. thermal insulation of a discharge area is sufficiently effective.

The elimination of the use of high-frequency generators in energising plasma torches is not always fully justified. The reasons are as follows:

1. they are usually the most popular auxiliary systems used for starting plasma torches;
2. they can be used for smooth and wide-range control of plasma torch power by means of a relatively small change of auxiliary discharge current intensity;
3. they enable the reduction or even the elimination of inductive reactance in a circuit, which improves a network load power factor cos$\varphi$ and reduces the inertness of the basic element in a control system;
4. although generators (mainly the simplest, i.e. spark gap ones) are often the source of a high level of harmful harmonics in the network, they make it possible to obtain almost sinusoidal current and voltage wavelengths, even without the presence of a serial inductive element.

## Static and dynamic characteristics of electric arc with intensive cooling

In a vast majority of cases described in scientific reference publications, tests involve welding and electrothermal devices with moderately cooled free arcs. In such solutions the high value of a damping factor function, particularly in the areas where current passes through the zero, eliminates the necessity of the precise representation of arc voltage-current characteristic especially in the low current range. Quite often simple approximations with a hyperbolic function (as in the Mayr model) or with a power function (as models utilising a static characteristic) are sufficient. Although high overshootings caused by repeated interelectrode gaps breakdowns and repeated discharge ignitions are very troublesome in arc modelling, thanks to the representation of naturally increased damping it is possible to overcome numerical integration instabilities during the PC-aided simulation of processes in electric circuits of devices.

In arcs cooled very intensively with a high-rate gas flow, e.g. in stream plasma torches ducts it is possible to observe the effect of a significant time constant reduction. This can be caused by a significant decrease in an arc column diameter reduction and thus an increase in temperature of easier conductive plasma, decrease in the volume of decreasingly viscous core plasma and a decrease in the volume of viscous plasma in the surface layer. Such intensive cooling also causes an increase in gaseous breakdown voltage. The occurrence of these two phenomena at the same time favours the instability and termination of an arc. The static characteristics of a very intensively cooled arc become even more non-linear, just as narrow dynamic AC arc hysteresis loops surrounding these characteristics. The more compressed an arc is, the lower the current to which a transition into a steeply rising part of characteristic corresponds (Fig. 6).

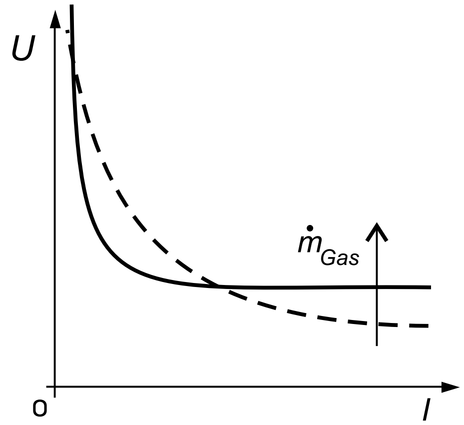

Fig. 6. Static voltage-current characteristics of free DC arc (dashed line) and of gas flow stabilised arc (full line)

In the case of intensively cooled arcs a lowered damping factor function value includes almost the whole current range of characteristics. As a result, it is necessary to provide a precise mathematical representation of arc voltage-current characteristics in the whole range of work current of a device. As AC plasma torches can operate also with direct current, it is necessary to prefer data obtained from tests of such devices. It is even more necessary due to the existence of significant differences in the design and operation of DC and AC plasma torches. For instance, AC plasma torches are not provided with a special cathode node. The practical determination of DC arc static characteristics in intense gas flow conditions and with low discharge current can be easier than in the case of a free arc (Fig. 6). However, the usability of DC arc static characteristics for the creation of an AC arc mathematical model is limited due to the following reasons [11]:

- arc static characteristics in DC plasma torches can be determined only within a narrow range of current changes due to the necessity of maintaining an appropriate thermal state of a cathode guaranteeing an appropriate level of electron thermionic emission;
- reversing the polarity of DC plasma torch electrodes may reveal the asymmetry of voltage-current characteristics;
- intensity of AC arc current field is always higher than in the case of a DC arc of the same power, which results from the periodical partial deionisation of plasma;
- efficiencies of magnetic influence on the DC and AC near-electrode area of can differ.

The higher the rate of a gas washing a column, the shorter the time constant (Fig. 7). The arc time constant in plasma torches is by 2÷3 order shorter ($10^{-6}$÷$10^{-7}$ s) in comparison with ordinary free arcs. In the case of high gas flow rates the time constant of an arc does not depend on the chemical composition of a gas or the type of electrodes [12]. A low time constant reduces the divergence between the shapes of static and dynamic characteristics of an AC arc (Fig. 8). This can constitute the basis for using the extreme points of dynamic characteristic to create a section of “commutative curve”, similarly as in the case of the dynamic approximation of the hysteresis loop of magnetic materials [13].

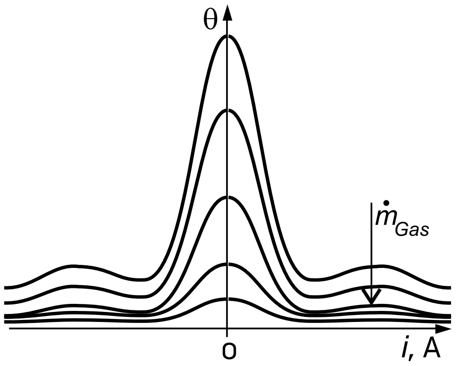

Fig. 7. Diagram of arc damping factor evolution caused by change of gas mass stream in plasma torch

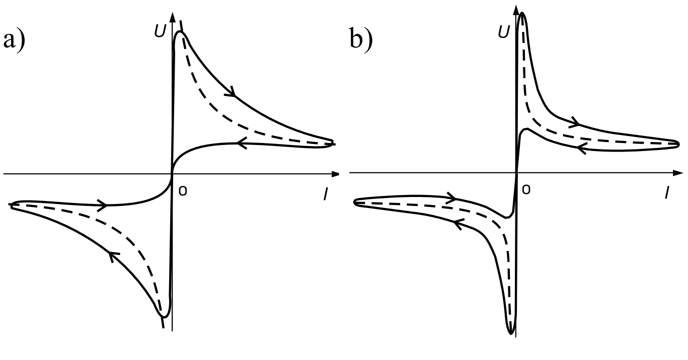

Fig. 8. Dynamic voltage-current characteristics of: a) free arc; b) gas flow stabilised arc

Scientific and technical reference publications provide information about AC arc characteristics in the form of dependences between root-means-square values of current and voltage. The methods of dimensional analysis and similitude theory enable the approximation of data and the creation of formulas binding electric, geometrical and gasodynamic quantities of specific types of plasma torches. Due to the strong deformation of (particularly voltage) wavelength such characteristics can be used for assessing the energy properties of a device. As early as at such a stage of measurements, it is possible to observe the divergence of characteristics obtained with auxiliary high-frequency arc assistance and without such support [2]. This indicates a significant influence of the steep part of "commutative" characteristics on dynamic characteristics. An increased gas flow decreases the temperature of the environment, which results in the evolution of static characteristics. This is due to the fact that the electric strength of a gas is inversely proportional to its temperature [14]

$$E_1 \vartheta_1 = E_2 \vartheta_2 \tag{2}$$

This fact imposes appropriate changes of arc ignition voltage UZ at temperature T

$$U_z(\vartheta) = \frac{U_z(\vartheta_0) \cdot \vartheta_0}{\vartheta} \tag{3}$$

In turn, the dependence of the average gas temperature is almost inversely proportional to its stream [3]

$$h(\vartheta_1) \cdot \dot{m}_1 = h(\vartheta_2) \cdot \dot{m}_2 = P_{Gaz} \Rightarrow$$
$$\Rightarrow \vartheta_2 = h^{-1}\left(\frac{h(\vartheta_1) \cdot \dot{m}_1}{\dot{m}_2}\right) \tag{4}$$

where $h$ – gas specific enthalpy being a monotonically rising function of temperature $\vartheta$; $\dot{m}_1$, $\dot{m}_2$ – gas mass streams; $P_{Gaz}$ – gas stream thermal power.

Due to required high operation parameters such as long active life and the operational stability of AC plasma torches, a unitary gas mass stream should be within specific limits

$$q_{\min} < q = \frac{\dot{m}_{Gaz}}{P_{el}} < q_{\max} \tag{5}$$

where $P_{el}$ – electric power supplied to a plasma torch. If $q < q_{min}$, the attenuation of electrode spot rotating efficiency may cause dangerous local overheating of electrodes and housing which can result in damage to a plasma torch. In turn, if $q > q_{max}$, the excessive development of turbulence may cause the instable operation of a plasma torch leading to the plasma filament breakup and the termination of an arc. In the practice of high-power plasma torch operation [15] the range of indication changes (5) is not significant as it amounts to $q_{max}/q_{min} = 6.5 \div 10$. This affects plasma torch adjustment possibilities by changing current intensity. Due to a very low arc time constant, a simple phase adjustment of current by means of thyristors is not capable of ensuring the stability of discharge in a circuit with the standard reactor inductance. For this reason it is recommended that such an adjustment should involve the use of controlled inductive reactors or constantly active electronic systems, i.e. transistor ones. While designing them it is necessary to take into consideration significant differences between the inertness of processes in electric circuits and gas networks so that the condition of the equation (5) could be fulfilled in steady and transition states.

## Conclusions:

1. An increase in plasma column cooling intensity significantly reduces the value of the damping factor function $\theta(i)$ which, in comparison with a free arc, requires a more precise representation of voltage-current static characteristics, also in the areas where current passes through the zero value.

2. Very low values of the damping factor function $\theta(i)$ may lead to physical instability and numerical integration during the simulation of processes in the circuit of a plasma torch with an electric arc. A proper solution to such a problem may lie in the use of sole static characteristics (more strictly containing commutative characteristics) and treating an arc as an ordinary non-linear resistance ($\theta(i) \approx 0$ s). In turn, in the case of a strong non-linearity $U(i)$, ensuring the burning stability of such an arc requires increasing the time constant of a circuit ($\tau = L/R$) by the serial connection of additional inductance, which also should be represented in a model used for simulations.

3. Due to a very low arc time constant, AC plasma torches with an intense gas flow should be preferably energised from current sources of specific properties, i.e. with significant inductance in the main circuit, with an arc assisted by means of a DC auxiliary discharge or by energising an arc with a current wavelength close to a rectangular one, which implies an appropriate manner of modelling and simulation testing of welding and electrothermal devices.

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