DOI: http://dx.doi.org/10.15407/tpwj2019.07.01

STUDY OF PULSED ARC PROCESSES AT PERIODIC SWITCHING OF VOLT-AMPERE CHARACTERISTICS OF ARC POWER SOURCE

G.A. TSYBULKIN
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The article discusses the pulsed arc processes carried out by periodic switching of the volt-ampere characteristics of the arc power source having different slope. At the same time, the commutation of the mentioned characteristics itself is realized not forcedly, but automatically based on the information about the current state of the system «power source–arc». The main aim is to find out how effective is this method of gas-shielded pulsed arc welding with consumable electrode. The article presents the results of theoretical investigations and computer modelling of self-oscillating processes, occurring in the system under consideration. A formula was derived for a preliminary evaluation of the pulse repetition rate of the welding current. By varying the value of a certain parameter appearing in this formula, it is possible to set the desired repetition rate of the indicated pulses. 9 Ref., 7 Figures.

Keywords: *pulsed arc welding, consumable electrode, switching of volt-ampere characteristics, computer modelling, pulse repetition rate of welding current*

Pulse process of gas-shielded consumable electrode welding can be realized in different ways [1–7]. Today, it is believed that two methods are the most efficient:

- by means of supply on the arc of additional voltage from special pulse generator, connected in parallel to main arc power source;
- periodic switching of volt-ampere characteristics of arc power source having different slope.

The second method is particularly attractive from point of view that it contains potential possibilities to realize a pulsed welding mode not only due to forced switching of volt-ampere characteristics of arc power source as it is realized in work [5]. For example, it is possible to bring into the «power source–arc» system a feed back providing switching of indicated characteristics automatically based on information on current state of this system.

It is assumed that such a solution will allow getting the new useful properties not typical for the pulsed arc welding system with forced switching of volt-ampere characteristics.

It should be noted that the systems, work of which is based on a principle of change of its parameters depending on current state of the system, in a control theory are referred to a system class with variable structure [8].

This paper will consider the pulsed arc processes formed in a system with automatic switching of volt-ampere characteristics. The aim is to determine how effective the indicated method of pulsed arc welding is.

Figure 1 schematically shows the «power source–arc» system including arc power source (*SP*) with two volt-ampere characteristics, slope of which S_1 and S_2 is different, and welding circuit (*WC*) with consumable electrode. Besides, a logical switching device (*LSD*) was added, which, depending on current state of the system, characterized with output voltage of power source $u_s = u_s(t)$, is connected to a welding circuit or electric circuit with parameter S_1 or with parameter S_2, i.e. changes the structure of the system itself on certain law.

Mathematical description of the system. Based on a scheme, presented in Figure 1, and known properties of arc self-regulation [9] let's make the equations describing the dynamic processes, taking place in the considered system:

$$\left.\begin{aligned} u_x &= u_s + Si, \\ u_s &= u_a + (LD + R)i, \\ u_a &= u_0 + El + S_a i, \\ l &= H - h_0 - \frac{1}{D}(v_e - v_m), \\ v_m &= Mi \end{aligned}\right\}, \qquad (1)$$

where u_x = const is the open circuit voltage; $i = i(t)$ is the welding current; $S = |\partial u_s/di|$ is the absolute value of slope of output volt-ampere characteristic, being equal S_1 or S_2 depending on switch K position;

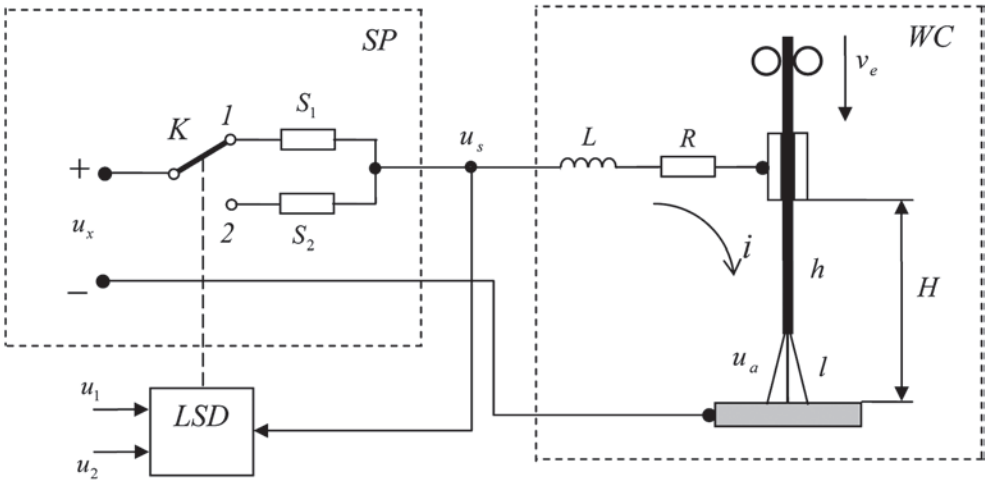

Figure 1. Scheme of «power source–arc» system (see designations in the text)

$u_a = u_a(t)$ is the arc voltage; L is the welding circuit inductance; R is the sum resistance of supply leads, electrode extension and slider contact in a torch nozzle; u_0 is the sum of near-electrode voltage drops; $S_a = |\partial u_a/di|$ is the absolute value of slope of volt-ampere characteristic of arc; E is the electric field intensity in the arc column; $l = l(t)$ is the arc length; H = const is the distance between the edge of current-supplying nozzle and free surface of welding pool; h_0, $h = h(t)$ is the initial and current values of electrode extension; u_e = const, $v_m = v_m(t)$ is the rate of feed and melting of electrode, respectively; $M = dv_m/di$ is the slope of current characteristic of electrode melting; $D = d/dt$ is the operator of differentiation; t is the current time.

Some idealization in relation to the real volt-ampere characteristics of welding current source, namely their approximation to linear functions, was used for compiling equations (1). Figure 2 shows the graphic interpretation of the system of equations (1) in form of a structural scheme. The welding circuit *WC*, included in this system, from point of view of theory of automatic regulation presents itself a closed systems with a natural negative feedback on electrode melting rate v_m, which provides self-stabilization (self-regulation) of arc length $l(t)$ at set rate v_e and set distance H, and relay voltage feedback $u_s(t)$ provides automatic switch of a system structure.

Let's write a law of switching as:

$$S = \begin{cases} S_1, & (u_s \le u_1,\ Du_s < 0), \\ S_2, & (u_s \ge u_2,\ Du_s > 0), \end{cases} \quad S_1 < S_2, \tag{2}$$

where u_1 and u_2 are the threshold values of $u_s(t)$.

We reduce the system of equations (1) taking into account expression (2) to one differential equation

$$(T_L^2 D + TD + 1)u_s(t) = g, \tag{3}$$

in which T_L, T are the coefficients determined by the relationships

$$T_L^2 = \frac{L}{EM}, \quad T = \begin{cases} T_1, & (S = S_1), \\ T_2, & (S = S_2), \end{cases} \tag{4}$$

where

$$T_1 = \frac{S_1 + S_a + R}{EM}, \quad T_2 = \frac{S_2 + S_a + R}{EM},$$

and the right part has a form

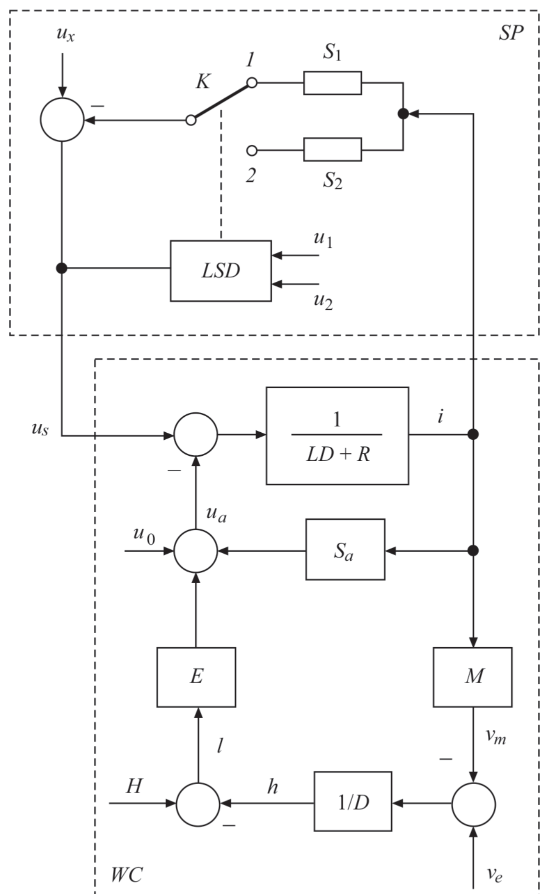

Figure 2. Structural scheme of «power source–arc» system with variable structure (see description in the text)

$$g = \begin{cases} g_1, & (S = S_1), \\ g_2, & (S = S_2), \end{cases} \qquad (5)$$

where

$$g_1 = u_x - S_1 \frac{v_e}{M}, \quad g_2 = u_x - S_2 \frac{v_e}{M}.$$

From expressions (4), (5) it can be seen that coefficient T, present in equation (3), and the right part of this equation g has a stepwise change during system switching from one characteristic to another, i.e. in switching of the connections between the system elements. As for value T_L^2 then it, according to (4), is constant and in the majority of practical cases is significantly lower than T since $L << (S + S_a + R)^2/EM$. This allows instead of equation (3) further on using reduced equation

$$(TD + 1)u_s(t) = g. \qquad (6)$$

The threshold values u_1 and u_2, included in expression (2), are selected based on the following conditions:

$$u_1 = g_2 + \xi, \quad u_2 = g_1 + \xi, \qquad (7)$$

where $\xi > 0$ is the some value selected by technological reasons.

In order to trace the dynamic process, described in equation (6), let's consider sequentially two processes obeying two different differential equations $(T_1D + 1)u_s(t) = g_1$ and $(T_2D + 1)u_s(t) = g_2$.

Let's start from the moment, when switching element K is set in position *1*, as shown in Figure 1. At this stage the welding process takes place according to differential equation $(T_1D + 1)u_s(t) = g_1$. Considering the initial condition $u_s(0) = u_{s0}$ the solution of this equation will have the following form:

$$u_s(t) = (u_{s0} - g_1)\exp\left(-\frac{t}{T_1}\right) + g_1 \qquad (8)$$

(point P corresponds to the initial condition $u_s(0) = u_{s0}$ in Figure 3).

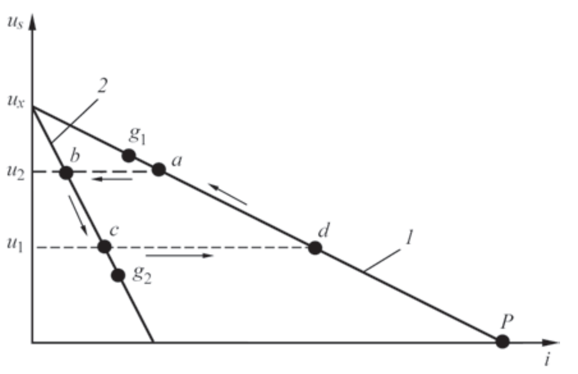

Figure 3. Cyclogram of set self-oscillating mode: *1* — $u_s = u_x - S_1i$; *2* — $u_s = u_x - S_2i$ (see designations in the text)

According to (8) $u_s(t)$ voltage with rise of t increases and tends to its set value $g_1 = u_x - S_1v_eM^{-1}$. However, in moment of time t, when $u_s(t)$ becomes equal to the threshold value $u_2 = g_1 - \xi$, there is switching of the system from characteristic 1 to characteristic *2* according to law (2) (switch K in Figure 1 is set in position *2* at that). A working point of the considered dynamic process (see Figure 3) «stepwise» transfers from point a in point b. At that voltage u_s, being equal to u_2, remains unchangeable, but there is a stepwise decrease of welding current $i = i(t)$. This is the end of the first stage.

The dynamic process on the second stage is regulated by differential equation

$$(T_2D + 1)u_s(t) = g_2.$$

Solution of this equation considering initial condition $u_s(t_1) = u_2$ takes the form

$$u_s(t) = (u_2 - g_2)\exp\left(-\frac{t - t_1}{T_2}\right) + g_2. \qquad (9)$$

Based on (9) voltage $u_s(t)$ starting from moment of time t_1 will decrease tending to set value $g_2 = u_x - S_2v_eM^{-1}$. As soon as $u_s(t)$ becomes equal to $u_1 = g_2 + \xi$ in accordance with (2) there is switching of the system from characteristic *2* to characteristic *1*. At that the working point «stepwise» transfers from point c into point d. Respectively, there is «stepwise» rise of welding current $i = i(t)$.

Now voltage $u_s(t)$ again starts rising in accordance to equation

$$u_s(t) = (u_1 - g_1)\exp\left(-\frac{t - t_2}{T_2}\right) + g_1, \qquad (10)$$

where t_2 is the moment of time, when $u_s(t) = u_1$. Rise of $u_s(t)$ will continue until reaching threshold u_2 in point a. Further the processes in the system will be precisely repeated.

Thus, «slow» movements of the working point on sections *da* and *bc* periodically alternate with «quick» (stepwise) movements on sections *ab* and *cd* provoking oscillations $u_s(t)$ of relaxation type. Therefore, movement trajectory $a \to b \to c \to d \to a$ is a stable cycle indicating steady state self-oscillating mode in the considered system. Periodic change of $u_s(t)$ takes place from u_1 to u_2, i.e. in the limits of earlier set zone (and it, if necessary, can be pretty narrow).

Figure 4 shows that «relaxation» oscillations of voltage $u_s(t)$ have a saw-tooth nature. Period of self-oscillations T_k is determined by sum of two time intervals Δt_1 and Δt_2. Interval Δt_1 during which voltage $u_s(t)$ rises from u_1 to u_2 is determined according to equation (10) by relationship

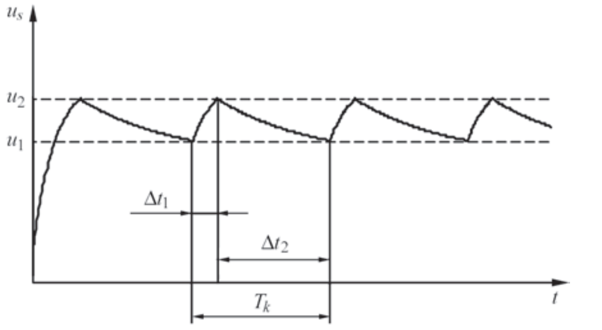

Figure 4. Diagram of change of $u_s(t)$ voltage at set threshold values u_1 and u_2 (see description in the text)

$$\Delta t_1 = T_1 \ln\left(\frac{u_1 - g_1}{u_2 - g_1}\right). \quad (11)$$

Similarly, a time interval Δt_2 during which voltage $u_s(t)$ reduces from u_2 to u_1, is determined in accordance with (9) by expression

$$\Delta t_2 = T_2 \ln\left(\frac{u_2 - g_2}{u_1 - g_2}\right). \quad (12)$$

Formulae (11) and (12) taking into account relationship (7) acquire the next form:

$$\Delta t_1 = T_1 \ln\left(\frac{\Delta g}{\xi} - 1\right), \quad \Delta t_2 = T_2 \ln\left(\frac{\Delta g}{\xi} - 1\right),$$

where $\Delta g = g_2 - g_1 = (S_2 - S_1)v_e M^{-1}$.

Respectively,

$$T_k = (T_1 + T_2)\ln\left(\frac{\Delta g}{\xi} - 1\right). \quad (13)$$

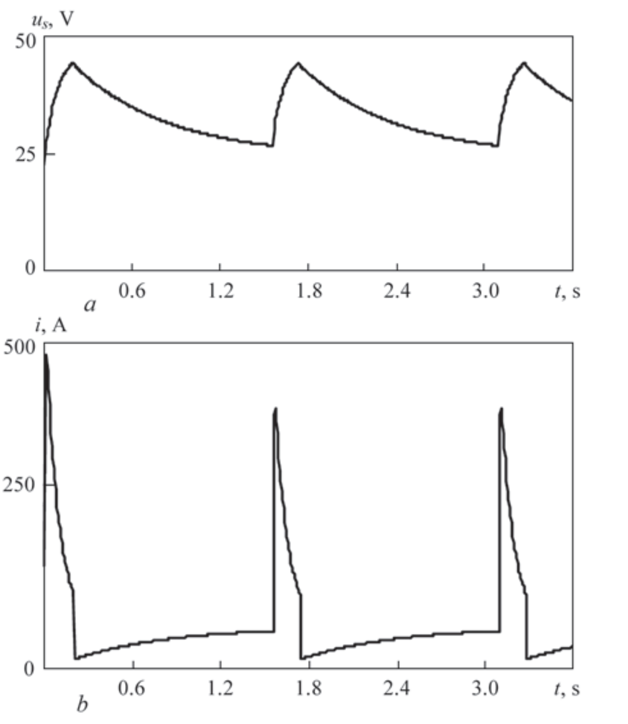

Figure 5. Diagrams at $\xi = 2.5$ V: a — $u_s(t)$; b — $i(t)$

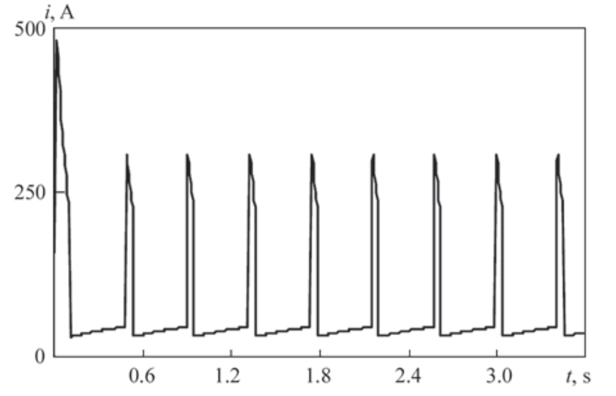

Figure 6. Diagram $i(t)$ at $\xi = 8$ V

A period of relaxation T_k (at earlier selected values of S_1 and S_2) depends only on value of parameter ξ, varying which it is possible to set desired frequency $f = 1/T_k$ of self-oscillating process of the considered system.

The results of computer modelling. Figures 5–7 present the results of modelling of the self-oscillating processes setting in the considered system at the next values of parameters of robotic arc welding: $u_x = 50$ V; $u_0 = 18$ V; $S_1 = 0.05$ V/A; $S_2 = 0.4$ V/A; $S_a = 0.02$ V/A; $R = 0.01$ Ohm; $L = 5{\cdot}10^{-4}$ H; $E = 2$ V/mm; $v_e = 20$ mm/s; $M = 0.31$ mm/(A·s); $H = 17$ mm.

Figure 5, in particular, shows that the output voltage of arc power source $u_s(t)$, as it should be expected, has a saw-tooth shape and welding current $i(t)$ has a pulsed nature. The current pulses appear in the moments of «spontaneous» transfer of current state of the considered system from point c to point d (Figure 3).

Diagram $i(t)$, presented in Figure 6, was obtained at $\xi = 8$ V. Comparing the diagrams, presented in Figures 5 and 6, it is possible to see that increase of ξ provokes rise of pulse repetition rate $f = 1/T_k$.

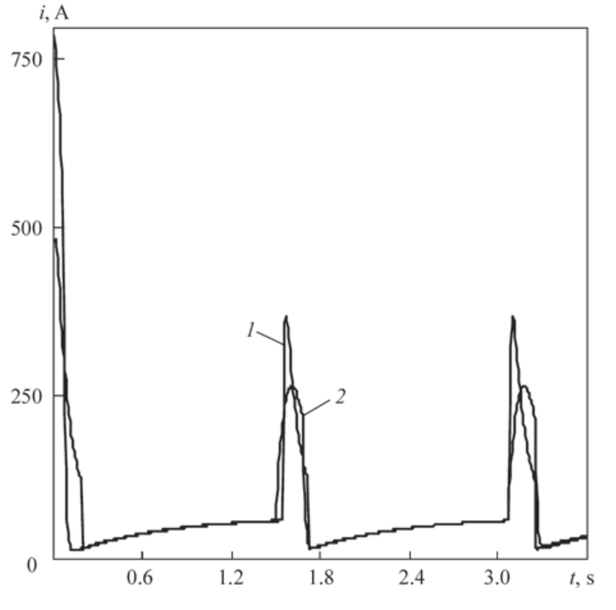

Figure 7. Diagrams $i(t)$ at $\xi = 2.5$ V: *1* — $L = 5{\cdot}10^{-4}$ H; *2* — $L = 5{\cdot}10^{-3}$

Let's come back to the issue of how significant is the effect on the self-oscillating process of a small parameter T_L not considered by us and depending according to (4) on system inductance L. To solve this problem, instead of simplified equation (6), initial equation (3) was used in computer modelling.

Figure 7 presents the results of modelling obtained at two different values of inductance: $L = 5\cdot10^{-4}$ H (curve *1*) and $L = 5\cdot10^{-3}$ H (curve *2*). Let's firstly compare current pulses $i = i(t)$ in Figure 7 (curve *1*) with current pulses in Figure 5, obtained at $L = 0$. They virtually do not differ from each other neither by shape no on height. Respectively, small inductances (i.e. when $L < 5\cdot10^{-4}$ H) do not have significant effect on dynamics of relaxation process $i = i(t)$.

Let's now compare curves *1* and *2* in Figure 7. Height of the pulses reduced only 1.5 times at significant (10 times) increase of inductance L. At that, shape of pulses is somewhat changed (pulse «tip» was smoothed), but nature of relaxation oscillations virtually remains without noticeable changes.

Conclusions

1. The results of theoretical consideration and computer modelling allow making a conclusion about the fact that a satisfactory mode of pulsed arc consumable electrode welding can be realized using the ideas of the system with variable structure.

2. Peculiarities of realizing the considered method of pulsed arc welding lie in the fact that switching of the volt-ampere characteristics is provided not forcedly, but automatically based on information about present state of arc welding process.

3. The main advantage of considered method is a simplicity, reliability and low cost of its realizing.

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Received 02.04.2019