ANALYTICAL STUDY OF CURRENT CONTROLLER OF POWER SOURCE FOR MICROPLASMA WELDING

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An area of stable converter operation as regards arc voltage was determined. Dependence of the converter coefficient current amplification on its efficiency, voltage of power supply unit and arc voltage drop was established. An analytical dependence of arc current on arc voltage drop, voltage of power supply unit and switching frequency was found. The necessity of application of ferrite core in a choke, inductance of which decreases with current increase, was shown. The need for buffer capacitor was substantiated.

Keywords: *microplasma welding, plasmatron, plasma, plasma plume, arc voltage drop, transistor module, snubber, inductance, choke, buffer capacitor, switching frequency*

Investigations of microplasma welding at the E.O. Paton Electric Welding Institute started in the second half of 1960s. The work was conducted in parallel both on fundamental studies of low-amperage arc, and on applied issues of development of technologies and equipment. Features of each welding process required development of not only advanced technologies and arc powering circuits, but also new specialized power sources, taking these features into account.

Large-scale introduction of microplasma welding in all the industrial sectors took place in 1970–1985s. More than 15,000 units of equipment and automatic machines for welding thin metals, including aluminium and its alloys, were manufactured and provided to industry. Equipment and technology were sold to foreign companies of Sweden, Japan, France and other countries.

At present the demand for microplasma welding is much lower. One of the main causes is old-fashioned equipment. It is large-sized, power- and material-consuming, and difficult-to-repair because of outdated components. It cannot be applied for high-speed processes of welding sheet structures from aluminium and its alloys.

Therefore, development of small-sized highly dynamic equipment based on batch-produced inverter power supply units and converters is an urgent and promising task.

Modern industry produces a great variety and number of small-sized inverter power supply units with a high energy intensity (about 536 W/kg), as well as powerful field and bipolar transistors at affordable prices. All this creates the necessary prerequisites for development of a new generation of equipment for microplasma welding with high dynamic properties with analog or numerical control of welding modes.

The purpose of this work is comprehensive analysis of downconverter operation for the case of development of microplasma welding power source, as well as revealing new capabilities for development of advanced technologies, meeting modern requirements, thus allowing increase of the demand for a simple, reliable and efficient method of welding thin metals.

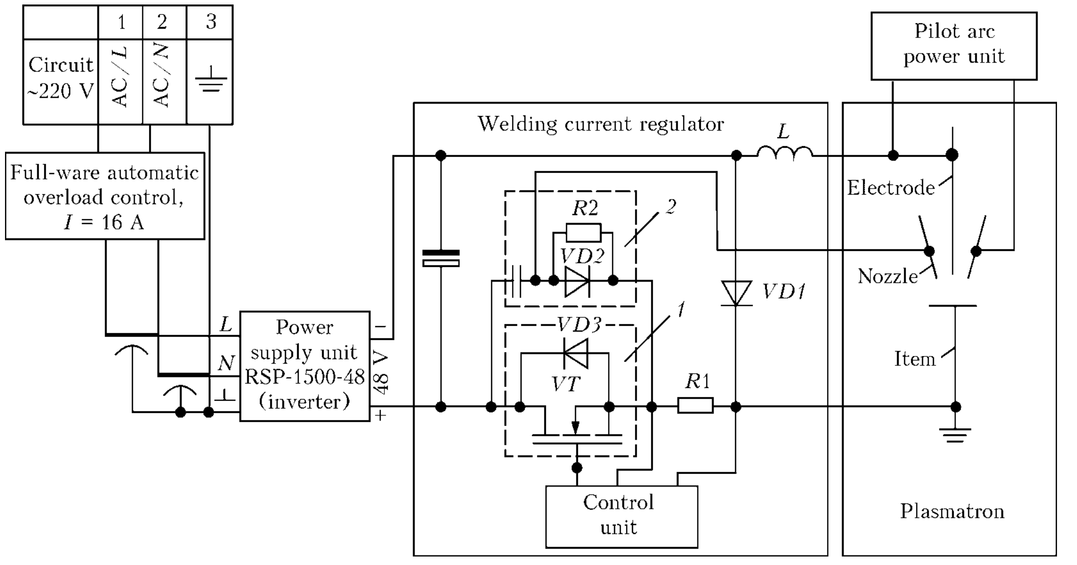
Such a source consists of RSP-1500-48 inverter and chopper. Its diagram is shown in the Figure and is similar to schematics described in works [1, 2], with the difference that the energy accumulated in the snubber capacitor, at transistor unblanking is released not to *R2*, but to the arc through the electrode or plasmatron nozzle.

Study [3] gives analysis of downconverter operating for ohmically capacitive load in linear approximation in the steady-state mode (not at first switching-on) for electronic equipment. A feature of the considered material is the fact that the converter operates for arc load (non-linear element of electric circuit) in a broad range of adjustment of arc current, for instance 5–50 A at different arc voltage drops, dependent on plasmatron nozzle channel, arc length, kind and flow rate of shielding gases, in the range of frequencies safe for hearing.

A detailed and integral description of operation of power source circuit will also be beneficial for welding technologists using microplasma in technological processes of treatment of various materials.

Plasmatron is the microplasma welding tool. Its preparation for operation requires feeding plasma gas (argon), igniting the pilot arc and positioning it so that the plasma plume flowing out of the plasmatron channel, touched the anode — item. Mode of short-circuiting and ignition of the short-circuiting arc is not considered in this work.

At switched on power supply unit and applying control voltage to the gate, transistor is unblanked, power source voltage $U_{\rm p}$ comes to electrode–item discharge gap, leading to ignition of straight polarity arc. Arc current grows gradually due to self-induction. When it has reached value I_m assigned by control unit, transistor is switched off. Voltage drop on inductance changes polarity, *VD1* diode is opened, and inductance starts powering the arc. Energy stored in it during unblanked state of transistor, is released into



Block-diagram of a microplasma power source: *1* — transistor module; *2* — snubber

the arc during time τ_0 of transistor blanked state. If τ_0 is long, energy is completely released from inductance. In this case, converter generates individual current pulses with exponential shape of their descending part. As τ_0 decreases, pulses become closer, and a moment comes when there is no pause between them. Further decrease of τ_0 leads to the subsequent pulse being superposed on the descending part of the previous pulse, thus forming lower current level I_0. Inductance releases only part of its energy. Upper current level I_m is assigned by control unit. The lower τ_0, the higher I_0 level, i.e. $I_0 = f(\tau_0)$. Difference between I_m and I_0 determines the amplitude of arc current ripple. On the one hand, ripple amplitude should be small, as in this case the strength of sound radiation of the arc decreases, and, on the other hand, decrease of ripple amplitude narrows the range of current adjustment and essentially increases converter switching frequency.

At high values of current I_m the probability of double arc formation in the plasmatron becomes higher, and at high arc current ripple the quality of weld metal protection becomes worse. Fluctuations in the arc column develop in synchronism with current ripple. Arc column now expands at current rise, now contracts at its decrease. These fluctuations are transmitted to the shielding gas zone, leading to air inflow. The same phenomenon is also found in pulsed welding with zero current component between the pulses. At limited power of the power supply unit current amplitude $I_m > I_p$ (nominal value of power source current) can be provided by buffer electrolytic capacitor connected at converter input. Its high capacity allows generating current pulses of a high amplitude, greatly exceeding the load current of power supply unit I_p. During time τ_1 of transistor unblanked state, the arc is practically powered by the capacitor. After transistor blanking, power supply unit further charges the capacitor up to voltage U_p and restores capacitor energy losses. Therefore, maximum current amplitude $I_m >> I_p$ is limited not by power supply unit current, but by transistor type. For instance, transistor GA200SA60U passes current of 100 A, while transistor SKM180A allows raising current up to 180 A.

Let us consider the operation of downconverter at direct current with certain assumptions. Arc voltage drop (at $I_a \geq 5$ A) [4] and inductance value are independent on arc current. We will neglect all the electric losses on chopper active and passive elements. These losses require additional consumption of power of the power supply unit. They are described in detail in [2]. Assumptions made do not have any influence on analysis of welding current regulator operation, they just simplify mathematical analysis. During investigations all these losses are allowed for in the form of converter efficiency.

It is known that to generate current I_m power supply unit should spend energy not only for powering the arc, but also for energy accumulation in the inductance. When transistor is blanked, this energy comes back into the circuit and powers the arc with the switched off power supply unit. It gives to the arc as much energy as has accumulated in it.

At transistor switching on the current does not immediately reach its nominal value, as with ballast rheostat, but rises gradually. Self-induction phenomenon consists in inducing additional electromotive force, proportional to the rate of current variation, but with the opposite sign. Therefore, Ohm's law for arc welding can be written as follows:

$$U_p - U_a - LdI/dt = IR \quad \text{or} \quad dI/dt + (R/L)I = (U_p - U_a)/L, \qquad (1)$$

where U_a is the arc voltage drop; L is the choke inductance; R is the ohmic resistance of the power circuit; I is the current; t is the current time.

Let us consider the regularity of current increase at switched on transistor. Under the impact of power supply unit voltage U_p applied to electrode–item discharge gap, main arc is excited and current starts rising.

Separating variables in equations (1) and performing integration, we have

$$-RdI/(U_p - U_a - IR) = (R/L)dt;$$
$$U_p - U_a - IR = A \exp(-Rt/L). \quad (2)$$

Integration constant A is determined from initial conditions: at $t = 0$, $I = I_0 > 0$. It is obvious that $A = U_p - U_a - I_0R$. Omitting intermediate computations, we obtain

$$I = (U_p - U_a)(1 - \exp(-Rt/L))/R + I_0 \exp(-Rt/L). \quad (3)$$

To simplify analysis we will use Taylor expansion and will limit ourselves to linear term of the series. In this case, expression (3) becomes

$$I = I_0 + (U_p - U_a - I_0R)t/L. \quad (4)$$

It is seen that current I rises linearly (similar to [3]). When value I_m has been reached, control unit switches off the transistor. Duration of the time of transistor unblanked state during which current I rises from I_0 up to I_m is calculated by the following formula:

$$\tau_1 = (I_m - I_0)L/(U_p - U_a - I_0R). \quad (5)$$

Note that current I is not only arc current, power supply unit current, but also current of energy accumulation in inductance L. At switched off transistor power supply unit is disconnected ($U_p = 0$) and the arc is powered from inductance L through releasing diode *VD1*, bypassing shunt *R1*. Current I starts decreasing from value I_m to I_0. From equation (2), omitting mathematical computations, we obtain

$$I = I_m - (U_a + I_mR_0)\tau/L. \quad (6)$$

Here $R_0 = R - R_1$.

It is seen that current decreases linearly in time. At $\tau = \tau_0$ equation (6) becomes

$$I_0 = I_m - (U_a + I_mR_0)\tau_0/L. \quad (7)$$

Duration of transistor blanked state is equal to

$$\tau_0 = (I_m - I_0)L/(U_a + I_mR_0) \approx (I_m - I_0)L/U_a. \quad (8)$$

Let us denote ratio τ_1 to τ_0 through β. Taking into account expressions (5) and (7), neglecting terms I_0R and I_mR_0 in view of their smallness compared to U_p and U_a, β becomes

$$\beta \approx U_a/(U_p - U_a). \quad (9)$$

The shape of arc current pulse is close to isosceles triangle, if $2U_a$ is negligibly smaller than U_p. Parameter β is equal to about 0.85 at $U_a = 22$ V and $U_p = 48$ V. If $U_p >> 2U_a$, then τ_1 becomes shorter, β becomes smaller, and switching frequency increases 1.47 times at $U_p = 60$ V compared to $U_p = 48$ V. Period of one cycle also decreases $T = (\tau_1 + \tau_0)$. Replacing τ_1 through β, we have

$$T = \tau_0(1 + \beta). \quad (10)$$

Using equations (4)–(8) it is easy to determine average values of arc current I_a, and power supply unit current I_p within one cycle (period T). Omitting mathematical computations, they become

$$I_a = (I_m + I_0)/2, \quad I_p = (I_m + I_0)U_a/(2U_p). \quad (11)$$

Analyzing expression (11), we come to the conclusion that $I_a > I_p$ and it is the greater, the smaller the arc voltage drop and the higher voltage U_p of power supply unit.

In the actual converter power supply unit spends the energy not only for accumulation and powering the arc, but also for electric losses in the chopper. They are the smaller, the higher the quality and the more rational the wiring.

Ratio of power released in the arc, to power consumed from the power supply unit, is the converter efficiency, i.e.

$$(U_aI_a)/(U_pI_p) = \eta, \quad \text{or } I_a/I_p = \eta U_p/U_a. \quad (12)$$

If we connect the ammeters at converter input and output, they will show different values. Ammeter in the arc circuit will show greater current than ammeter in the power supply unit circuit. Ratio of these currents is the current gain factor. Measured current gain factor was equal to 1.64, and calculated converter efficiency $\eta = 0.75$ (at $U_a = 22$ V and $U_p = 48$ V). In [2] it is equal to 0.75–0.81. This discrepancy is possibly accounted for by the fact that the current ratio was measured on a mock-up, and not on the actual converter.

Let us consider one more important characteristic of the converter — ratio of current I_0 to I_m. They are set and regulated by control unit.

Let us denote this ratio as α. From (8) we have

$$1 - \alpha = (U_a/L)(\tau_0/I_m). \quad (13)$$

It is easy to see that α parameter does not depend on current I_m, if τ_0 parameter is linearly related with current I_m by ratio $\tau_0 = \gamma I_m$ (γ is the coefficient of proportionality, $s \cdot A^{-1}$). Then (13) becomes

$$\alpha = 1 - (\gamma U_a/L) \quad (14)$$

and ratio of I_0 to I_m no longer depends on I_m in the entire range of its adjustment. This means that at adjustment of current I_m it is also necessary to adjust parameter τ_0, connected to it by a linear relationship. Development of such a control unit is the objective of further research.

In analog control circuits not only current I_m is adjusted, but also parameter τ_0 has a fixed value. If the circuit of control by parameter τ_0 is constructed so that at arc current, for instance $I_a = 20$ A, parameter

$\alpha = \alpha_0$, then at adjustment of current $I_a > 20$ A parameter α increases, i.e. $\alpha > \alpha_0$. Difference between currents $I_m - I_0$ decreases $(1 - \alpha) < (1 - \alpha_0)$. This only improves the microplasma welding process and weld quality. At arc currents $I_a < 20$ A, parameter α starts decreasing $(\alpha < \alpha_0)$ and difference $I_m - I_0$ increases. With decrease of current I_a current I_0 quickly tends to zero. This is due to the fact that energy accumulated in the inductance, decreases quadratically with decrease of current I_m. This energy, long before repeated unblanking of the transistor, is completely released into the arc and current $I_0 = 0$. Arc runs in the form of individual current pulses, even with pauses between them. Welding process with interruption of arc current continuity makes weld formation difficult, and sometimes impossible. This exactly is the main disadvantage of the control circuit with fixed τ_0 value. Thus, the need for upgrading the current control circuit of the converter as part of the power source for microplasma welding has been substantiated.

It is interesting that even with such a control circuit there exists α_1 value which is independent on current I_m, i.e. has a constant value in the entire range of arc current adjustment. This is the case when difference of currents $I_m - I_0$ multiplied by certain number δ, is equal to arc current, i.e. when $I_a = \delta(1 - \alpha_1)I_t$. Equating the righthand part of this equation to the righthand part of equation (11) and cancelling I_m, we have

$$(1 + \alpha_1)/2 = \delta(1 - \alpha_1) \quad \text{or} \quad \delta = (1 + \alpha_1)/(2(1 - \alpha_1)). \qquad (15)$$

Using equations (7)–(9) and (15), arc current becomes

$$I_a = \delta U_a(U_p - U_a)/(U_p LF), \qquad (16)$$

where F is the switching frequency.

Differentiating I_a for U_a and equating the derivative to zero, we find that current I_a reaches its maximum value I_{max}:

$$I_{max} = \delta U_p/(4LF) \text{ at } U_a = 0.5U_p. \qquad (17)$$

At the same time I_{max} is determined, proceeding from maximum power transmitted by arc power supply unit, i.e.

$$I_{max} = \eta W_p/U_a = 2\eta W_p/U_p \text{ at } U_a = 0.5U_p, \qquad (18)$$

where W_p is the power of power supply unit.

Equating righthand parts of (17) and (18), we find

$$\delta = 8\eta W_p LF/U_p^2. \qquad (19)$$

Substituting values of parameters η, U_p, W_p into (19) and making the calculations, we find $\delta = 1.171875$ (at $LF = 2\cdot10^{-5}$ H$\cdot1.5\cdot10^4$ Hz = 0.3). Substituting this value of δ into (15), we calculate $\alpha_1 = 0.4$.

From (11) we calculate $I_a = 0.7I_m$. We get the same value of arc current I_a from difference $\delta(I_m - I_0)$, i.e. we have an identity, and expression (16) becomes

$$I_a = 1.167U_a(U_p - U_a)/(U_p LF) \text{ at } \alpha_1 = 0.4. \qquad (20)$$

Stable operation of current regulator with release of choke energy to the arc through diode *VD1* is possible only at $U_a < 0.5U_p$. At U_a approaching $0.5U_p$ emf of self-induction decreases, and when it becomes smaller than U_a, choke stops releasing the energy to the arc. At transistor unblanking emf is summed up with U_p and the rate of current rise increases approximately 2 times. Emf of self-induction increases by as many times. Under certain circumstances, the process becomes uncontrollable, which is dangerous for the transistor. Thus, the arc length can be changed only in the zone of $U_a < 0.5U_p$.

Equation (20) is interesting, as it allows calculation not only of the range of adjustment of current I_a, but also of frequency range safe for hearing. If we assign constant product I_aL, frequency F will no longer depend on current I_a, i.e. converter choke should be made to have a ferrite core, the inductance of which decreases with rise current of I_a.

It is not easy to calculate such a choke not only because magnetic susceptibility of ferrite changes with heating temperature, but also because it has a complex dependence on magnetic field intensity. In such a case it is possible to use an experimental graphic dependence $L = f(I_a)$. This dependence is easily derived, if the choke is loaded by current from a storage battery (for instance, car battery) and current is adjusted by a rheostat, and inductance is measured, for instance, by emittance measuring device E7-15 or UT603 instruments.

Although in mathematical analysis the functions are not graphically assigned, their graphic presentations are often used, as easy visibility and illustrativeness of the graph make it an indispensable auxiliary means of studying the functions. Note that with increase of current I_a inductance of a choke with a ferrite core tends to a constant value in the limit, when ferrite magnetization reaches saturation. If at current $I_a = 50$ A inductance has reached a constant value, for instance $L = 20$ μH, and at current $I_a = 5$ A it is equal to 200 μH ($I_aL = 10^{-3}$), current converter will operate at constant frequency of 13.9 kHz in the entire range of current adjustment $I_a = 5$–50 A (at $U_p = 48$ V, $U_a = 22$ V and $\alpha_1 = 0.4$). Proceeding from the fact that F is a constant value, equation (20) can be presented as

$$I_a LF = 1.167U_a(U_p - U_a)/U_p < 13.9. \qquad (21)$$

Righthand part of this equation for microplasma welding is a constant value at unchanged arc length U_a = const. At microplasma welding $U_a < 22$ V, depending on selection of shielding gas, arc length [4], as well as plasmatron nozzle channel diameter. Therefore, for this welding process RSP-1500-48 power supply unit with 48 V voltage is quite acceptable, the more so since the upper limit of U_a adjustment reaches 56 V.

It is not difficult to make choke on ferrite experimentally. The smaller the inductance, the smaller its weight and overall dimensions, material and labour costs for its manufacture. Even if the inductance differs only slightly from $I_aL = 10^{-3}$, frequency at arc current adjustment is «floating» a little. The main thing is for it not to leave the zone safe for hearing.

Let us consider the operation of buffer capacitor. Let us assume that the capacitor charged up to voltage U_p, is disconnected from the power supply unit, and the arc is loaded through the converter. The arc runs until the capacitor has discharged to voltage $U_c = 2U_a$.

Amount of energy ΔW_c spent by the capacitor for powering the arc, is written as

$$\Delta W_c = \eta C(U_p^2 - 4U_a^2)/2, \quad (22)$$

where C is the capacitor capacity; η is the converter efficiency.

During period T the arc consumes energy I_aU_aT. Dividing ΔW_c by energy consumed by the arc, we will find number of cycles N:

$$N = \eta C(U_p^2 - 4U_a^2)F/(2U_aI_a). \quad (23)$$

Substituting the above values of parameters (U_p, U_a, F, η) and performing calculations for $C = 5.6\cdot10^{-3}$ F, we have N = (8.4, 5.6, 4.2, 2.8) at currents I_a = (50, 75, 100, 150) A, respectively. These calculations show that the electrolytic capacitor as part of downconverter is absolutely necessary in case of low-power inverter power supply units. Arc current can 1.5–2 times exceed the load current of the power supply unit.

One power supply unit RSP-1500-48, even at a lower converter efficiency $\eta = 0.75$, transmits 1125 W of power to the arc. For microplasma welding at U_a = 22 V arc current is equal to 51 A, and at U_a = 18 V current I_a = 62.5 A. Current gain factor is equal to 1.62 and 2, respectively. Here current consumed from power supply unit is equal to 31 A, which is equal to 97 % of maximum load current. At inverter connection by the circuit shown in the Figure, with feed-through capacitors it operated in a stable manner for arc equivalent with ballast rheostat for 45 min even with overload by power by 13 %.

Thus, the power supply unit power is the fist limiter of arc current. Arc current can be increased 2 times, if two such units are connected in parallel. Developer envisages parallel operation of the units for a common load. However, not every transistor can switch high arc currents. Second limiter for arc current, namely maximum collector current I_{coll} comes into force here, i.e.

$$I_{coll} \geq I_m = 1.4286 I_a \text{ or } I_a \leq 0.7 I_{coll}. \quad (24)$$

When GA200SA60 transistor is used in the converter the power source is limited from above by current I_p = 70 A, and for transistor SKM180A — by arc current I_a = 126 A. Therefore, GA200SA60 transistor is recommended for power source with one power supply unit RSP-1500-48, and SKM180A transistor — for operation of two power supply units in parallel.

CONCLUSIONS

1. A region of stable operation of the converter was established, which is determined by arc voltage drop $U_a < 0.5U_p$.

2. It is shown analytically that a converter with inductive accumulator is current amplifier. Gain factor is directly proportional to product of ηU_p and inversely proportional to arc voltage drop.

3. Inductance of a choke with a ferrite core decreases with current rise and tends to a constant value, when core magnetization reaches saturation. Such a choke ensures a smooth adjustment of arc current and maintains the frequency in the selected range, if $LI_a \approx$ const.

4. Dependence of arc current on voltage drop across it, power supply unit voltage, choke inductance and frequency, was determined allowing calculation of the range of arc current adjustment with acceptable ripple amplitude in the frequency range safe for hearing.

5. It is shown that it is possible to develop a modern small-sized power-intensive highly-dynamic power source for microplasma welding for arc voltage drop $U_a < 0.5U_p$ on the basis of batch-produced inverter power supply units and downconverter.

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