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Natural Mode Constant Power Source for Manual Arc Welding

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***Abstract*—Energy growing demand and environmental issues put more emphasis on optimal energy use – by equipment and in process. In this paper a novel switch-mode load-resonant welding power source with output characteristic having constant power range is suggested. Due to the constant power operation and parametrical arc stability during manual welding process the better electrical and thermal performance and even weld bead could be obtained. The circuit of the suggested converter and criteria for its resonant components selection are given in order to describe proposed topology in relation to load conditions during welding. Theoretical and practical studies are conducted on experimental setup and first promising results have been obtained for given converter that are briefly presented and discussed.**

***Index Terms*—Load management, energy efficiency, welding, AC-DC power converters.**

I. Introduction

Nowadays, manual arc welding (SMAW or MMA) is widely used welding process characterized by electric arc burning in the air and mainly it is a DC current one. The voltage of stable arc is in average in the range 26÷30 V (for 100÷200 A load current) and this voltage is only slightly dependent on the current. However, electric arc by itself is not a stable load at all.

In view of welding process efficiency it is desirable to provide weld pool with stable thermal power by mean of electric arc [1]. However, voltage fluctuations in electric arc lead to welding current changes and power supplied to the arc is changing chaotically.

To stabilize arc it is commonly used to keep the welding current constant. Thus, power supplies for manual arc welding are typically represented by regulated current sources. These current sources comprise a feedback circuits to compare real welding current and its reference value [2]–[4].

Small mass of welding plasma cloud could cause the oscillation of arc's resistance that reaches some hundreds of kilohertz. Thus, power supply and its feedback circuitry are operating in permanent transient mode. Usually, the current stability in transient mode is not the best one. And in addition to voltage fluctuations, some undefined current fluctuations occur. Consequently, undefined fluctuation in thermal power is growing even more and welding quality will suffer too. Thus providing the constant power to welding bead could improve welding process.

In order to achieve such a constant power operation mode it is suggested to use a power converter having naturally varying resonant tank topology and providing constant power to output. To verify the applicability of proposed topology in relation to welding load the actual research was conducted and its results are discussed further in the paper.

II. Supplying Welding Arc with Constant Power

The thermal power of welding arc could be stabilized much better if it is supplied with constant-power source. The current supplied by constant-power source is defined according to relation

$$i = \frac{P}{u}, \tag{1}$$

where P – given power of welding arc; u – arc voltage (instantaneous value); i – arc current (instantaneous value).

Herein, the load current changes in such a way that arc voltage also changing so that multiplication of voltage and current remains the same. When the current value in (1) exceeds some specified limit, the converter turns into constant current operation mode.

The switch-mode power supply can be transformed into constant power source if we put its control to operate in accordance with (1). However, typical converter will suffer from slow feedback as well. Thus the fast converter without feedback is preferable.

There is known one such uncontrolled AC/DC converter with parallel and series resonance alternation (PSA) having a constant-power operation zone in its output characteristics [5]. This converter operates at mains frequency (50 or 60 Hz) and includes capacitor and inductor in resonant tank circuit. As the voltage of welding arc is relatively low this yields in a very large resonant capacitor that is the main drawback of given topology.

There is also a switch-mode PSA (SM-PSA) converter [6]; one of its circuit topologies is given in Fig. 1.

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Due to the higher operation frequency the capacitance of resonant capacitor C1 and inductance of inductor L1 are relatively small and given topology can be implemented.

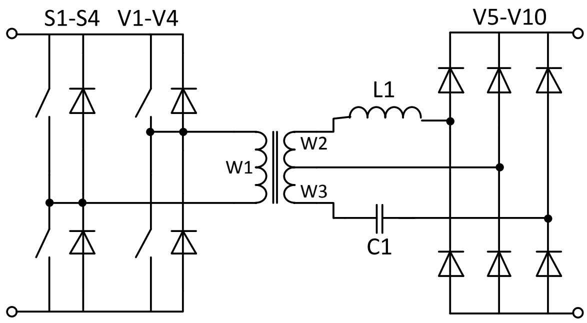

Fig. 1. Switch-mode PSA converter.

The current and power output characteristics represented in Fig. 2 are given for the case when no-load voltage is up to 80 V and duty cycle of inverter transistors is half of switching cycle D = 0.5. These curves are received by computer simulation, wherein load was represented by reverse DC voltage source imitating the electric arc. By changing its voltage from 0 to 80 V the whole operation range from no-load to short-circuit was covered.

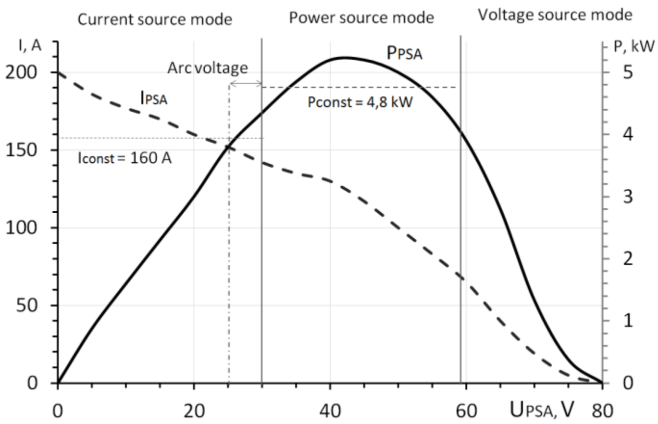

Fig. 2. Simulated output current (I_{PSA}) and power (P_{PSA}) curves of switch-mode PSA converter depending on load voltage.

As it is seen in Fig. 2 this range can be conditionally divided into three regions. At 0÷30 V it behaves almost as a current-source mode, where load current changes from 200 A at short-circuit to 135 A at 30 V. At 30÷58 V it is almost in power-source mode, where power changes only in the range between 4.3 kW÷5.2 kW÷4.1 kW. At 58÷80 V it is similar to some extent to voltage source converter, where current changes from 70 A to zero.

This is a natural output characteristic (without any regulation) of switch-mode PSA converter circuit shown in Fig. 2 and it is in principle suitable for supplying electric arc. It has an inherent short-circuit current limitation and zone of constant power.

The missing feedback reduces current oscillations during transients due to the parametrical variation of resonant tank topology that could take place up to six times of supply frequency [5]. And it corresponds well to good performance arc welding power source that requires the alteration between the modes can be as fast as possible [7].

Nevertheless, there are some specific issues described further.

III. SWITCH-MODE PSA CONVERTER – DEVELOPING OF CIRCUIT TOPOLOGY

First of all it is necessary to change the state in the range of nominal arc voltage 26÷30 V, where converter operates as a current source, but not as a power source that is in contradict with the suggested approach.

Additionally, the arc power needed at rated voltage is about 4.2 kW that is lower than the rated power of converter (5.2 kW). The rated point of arc and rated power of converter could be shifted to one point by decreasing secondary voltage of transformer (1.5 times in given case). But this, in its turn, reduces no-load voltage to 53 V, while for comfort arc ignition and stable operation with different types of electrodes the no-load voltage is preferable to be higher [8].

This issue could be solved by upgrading circuit of power converter. The auxiliary voltage source could be added to the circuitry of PSA converter (additional secondary winding W4) with two rectifying diodes V15, V16 and one current limiting inductor L4. The new modified circuit of SM-PSA is given in Fig. 3.

Another possible drawback is a significant current harmonics in capacitor C1 and in corresponding transformer winding W3 [5]. In the case of rectangular shape voltage the 3rd harmonic component is about 30% that also supports increasing of 3rd current harmonic.

These current harmonics appear mostly in the range close to load short-circuit. The equivalent circuits for short-circuit mode are given in Fig. 4.

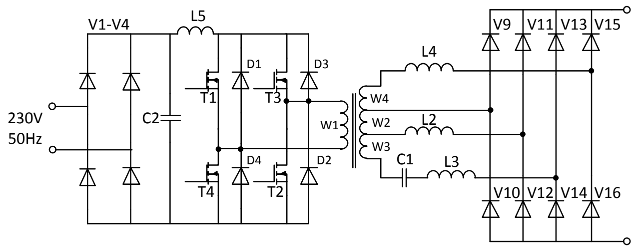

Fig. 3. Modified resonant circuit of SM-PSA converter.

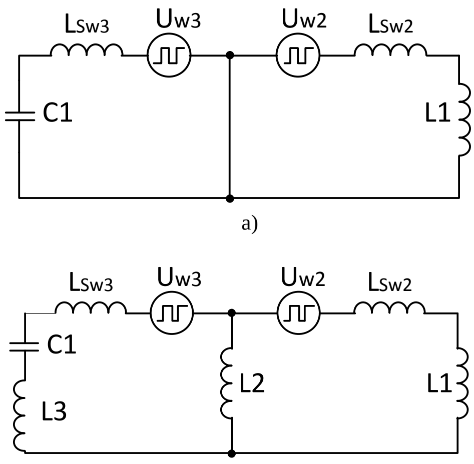

Fig. 4. Equivalent circuits of PSA converter in short-circuit mode: a) without additional inductor; b) with additional inductors L2 and L3.

Circuit in the Fig. 4, b corresponds to converter that has one more inductor L2 (connected to the transformer tap) and inductor L3 connected in series with capacitor C1. The secondary windings are replaced with rectangular voltage sources U_{W3} and U_{W2}, with their respective leakage inductances L_{Sw3} and L_{Sw2} connected in series. The short circuit at rectifier output is just replaced here by short circuit at rectifier input.

In a short-circuit mode, there is a series resonant tank topology forming in C1 branch. Equivalent circuit in Fig. 4, b has leakage inductance L_{Sw3}, rectangular voltage source U_{w3} and L2 and L3. In its turn, to avoid undesirable resonances the self-oscillation frequency f_0 of this circuit must be known beforehand.

The relation of self-oscillation frequency f_0 to supply voltage frequency f_m can be determined as

$$\frac{f_0}{f_m} = \sqrt{\frac{x_C}{x_{SC}}} \quad \text{or} \quad \frac{f_0}{f_m} = \sqrt{\frac{x_C}{x_{SC} + x_{L2} + x_{L3}}}, \tag{2}$$

where x_C, x_{L2}, x_{L3}, and x_{SC} are reactances for fundamental component at supply frequency (i.e. 40 kHz for given switch-mode power supply). If self-oscillation frequency is equal to the frequency of third harmonic component, there is a series resonance condition in C1 branch and current of 3rd harmonic component appears higher than current of main harmonic component f_m that is very undesirable.

The effect of 3rd harmonic changes miserable when $f_0/f_m < 1.5$. Thus, it is a good practice to implement L2 or L3 or both and calculate them so, that

$$\sqrt{\frac{x_C}{x_{SC} + x_{L2} + x_{L3}}} < 1.5 \quad \text{or} \quad x_{SC} + x_{L2} + x_{L3} > 0.44\, x_C \tag{3}$$

The third problem is a current increase during transition to short-circuit mode. The current grows from 145 A to 200 A or about 1.4 times (Fig. 2). Large current at short-circuit causes spatters of welded metal that is not desirable [1]. The load short-circuit current can be limited if use a resonant circuit, which includes inductors L2 and L3 (Fig. 3), but inductor L1 is missed. The corresponding phasor diagram for main harmonic is given in Fig. 5.

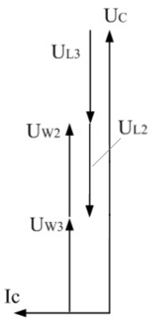

Fig. 5. Phasor diagram for short-circuit mode without L1.

Voltage on additional inductor L2 must be equal to winding W2 voltage. In this case during short-circuit mode the current appears mostly through the secondary winding W3. Current in winding W2 does not flow as inductor L2 voltage (U_{L2} in Fig. 5) is equal to voltage on winding W2 (U_{W2} in Fig. 5). However, the exact equality of voltages is hardly achievable due to the phase shifts and harmonics, but, nevertheless, current in winding W2 remains low.

IV. THE PARAMETERS OF DEVELOPED WELDING POWER SOURCE

The circuit of studied converter is given in Fig. 3. If compare it to original (Fig. 1) there are added mains rectifier V1–V4, smoothing capacitor C2, inductors L2, L3, L4 and output diodes V15, V16. One more secondary winding W4 is added to the transformer. Inductor L1 is missing. Inductor L5 added in DC circuit is to reduce high current rates at turn-on that grounds are described below.

During load short-circuit the current rate in transistors could be very high. It is possible due to the energy saved in resonant tank elements (L1, L2, L3, L4) that each half-period goes partly through transformer and inverter back to DC circuit. Wherein at transistors T1&T2 switching-on the current goes firstly through transistors and then naturally changes its direction and flows in their antiparallel diodes D1&D2. And at the next half-period which starts with transistors T3&T4 switching-on these diodes D1&D2 are still conducting. Because of that, there is a short circuit path in D1–T4 (D2–T3) connections. Its duration depends on the reverse recovery time of these diodes.

Levels of converter's current and power are defined by the values of resonant components selected.

The parameters of reactive elements are the next:

- L2 0.5 μH C1 9 μF;
- L3 0.5 μH C2 2000 μF;
- L4 10 μH L5 4 μH.

The curves of output current and power for studied converter prototype are given in Fig. 6.

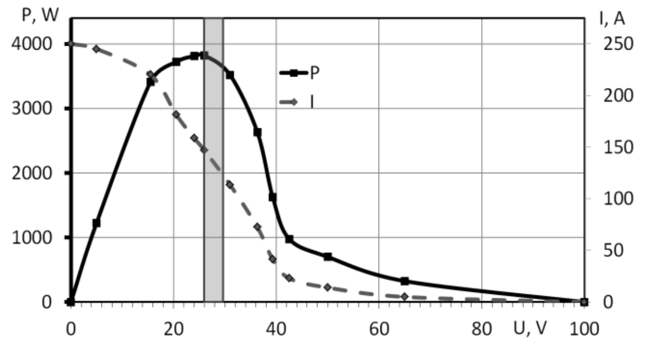

Fig. 6. Relation of output current I_d and output power P_d to load voltage U_{arc}.

This output characteristic in Fig. 6 is obtained by direct measurements on prototype operating with permanent frequency and gating pulse width. Test load was a high power variable resistance. The maximal output power is achieved at output voltage ranging 16÷30 V. These output current and power curves are shaped out in accordance to different current paths that appears through rectifying diodes V9–V16. The parametrical selection of each path is defined by the arc voltage value U_{arc}.

The waveforms of transformer primary current and inverter switch voltage during welding are given in Fig. 7.

These curves are corresponding to the maximal load condition with resistive load tests. The current in primary winding is almost sinusoidal. Waveforms presented in Fig. 8

are for the same converter at load short-circuit mode.

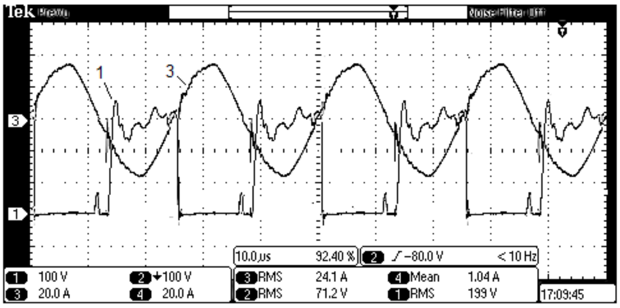

Fig. 7. Voltage over inverter switch (1) and current in transformer primary winding (3).

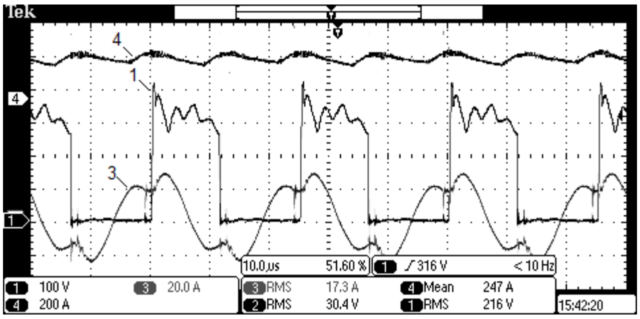

Fig. 8. Voltage over inverter switch (1), current in transformer primary winding (3), and load current at short-circuit (4).

V. CONCLUSIONS

Even supply of thermal power to welding spot is a problem in a case of manual arc welding due to the unpredictable change of arc voltage yielding in changing of power of welding arc. The power of arc could be stabilized if current is changed in that way so the product of voltage and current remains constant. If feedback circuit is used to control arc current it is a difficult to achieve needed speed of reaction because of the fast voltage oscillation in welding arc. Some better results could provide the suggested switch-mode converter with parallel and series resonance alternation that has a natural constant power characteristic in welding range. In this range at voltage drop the current increases parametrically without any control by converter and vice versa. That way we can get a stabilized power at welding bead at arc nominal voltage ranging typically 26÷30 V. “Cooperation” of varying resonant circuit topologies with output rectifier yields here in the required output characteristic.

This characteristic is obtained by utilizing full-bridge rectifier with four-phase input, where one input is connected through capacitor, second and forth through inductor and third input connected directly to transformer secondary. Resonant circuits are selected in a way to have near sinusoidal currents with low harmonic content.

The proposed converter has been developed by using simulation software PSIM and verified by measurements on converter’s prototype test setup. The experimental and simulation results were corresponded well, and the rationality of the studying method was verified. It also provides new ideas on improvement of manual arc welding power sources.

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