BEHAVIOUR OF ARC WELDER WITH HIGH FREQUENCY LCC RESONANT CONVERTER

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Abstract. The paper presents the theoretical and practical aspects of the design and constructions of a high-frequency full-bridge series-parallel load resonant converter for arc welding. The converter with maximum output current of 150A and an output no-load voltage of 70V operating at frequency from 65kHz to 100kHz is designed. Soft switching for all power switches is achieved by using the non-dissipative snubbers. This converter minimises the size and weight of the magnetic components in the converter, reduces output current ripple and switching losses in semiconductor devices.

Keywords: Resonant converter, Arc welding, High frequency power converters, ZVS converter, Soft switching, DC/DC converter.

1. INTRODUCTION

In the recent years the power converters are often used in many arc welding applications. The size of magnetic components and capacitors depends on the operation frequency [1]. The high frequency operation of the converter minimises the size and weight of the converter and reduces output current ripples. In this paper a welding supply with high frequency inverter is described. The IGBTs are often utilised to achieve high frequency at high power applications. However, the high switching frequency results in increased switching losses in power semiconductor devices at turn-on and turn-off.

The full bridge series-parallel (LCC) resonant converter with capacitive snubbers working above resonance frequency is used in the arc welding supply. The soft switching techniques is used in this converter. Zero-voltage switching for all power switches is ensured to reduce switching losses and achieve high efficiency in full load range and wide range of the output voltage. The optimal design of the resonant components L_S, C_S, C_P is very important for correct operation of the welding supply. The major advantages of the mentioned converter are low switching losses, good adaptation to various operating conditions, fast response, high efficiency, and improved power factor [10].

2. POWER AND CONTROL CIRCUITS

The simplified scheme of the LCC resonant converter as a power supply for arc welding is shown in Fig. 1. The converter consist of the input full bridge uncontrolled rectifier, input capacitive filter, full bridge IGBT inverter, series-parallel resonant components, high frequency high power coaxial transformer, center tapped high frequency rectifier with fast recovery diodes and output inductive filter. The resonant tank comprises three elements: series inductor L_S, series capacitor C_S and parallel capacitor C_P. The capacitor C_S with the inductance L_S present a series resonant circuit. The capacitor C_P is connected in parallel with the transformer primary winding and they represent parallel resonant circuit. The IGBT's of the converter operate with variable switching frequency above resonance frequency in full operating range, hence the power switches are turned-on under zero voltage (ZVS).

In order to reduce turn-off losses of the switches to acceptable level the external capacitors C_1...C_4 (acting as a non-dissipative snubbers) are required. The converter transistors are operated with reduced switching losses, hence the switching frequency can be higher as in conventional hard-switching converters.

For welding process, the maximum arc voltage is about 35V and the voltage needed to a good arc ignition, at no-load, must be around 70V [4]. These conditions can be achieved using correct design of power circuits and suitable control.

The short circuit current and the maximum load voltage must be limited and controlled.

In Shielded Metal Arc Welding (SMAW), which is the most popular welding process, the dc current must be controlled, The control scheme for the resonant converter is shown in Fig. 2. A microcomputer control or an integrated control circuit (e.g. UC 1861) can be utilised for the control of the converter. These circuits includes several functions needed to ensure correct welder behaviour in all operating conditions.

The microcomputer control system consist of the microprocessor, timer, multiplexer, analog-digital converter, output logic circuit, dead time generator and comparators. This control circuit is more difficult as integrated control circuit but its facilities are larger.

The resonant-mode power supply controller UC 1861 offers many features such as error amplifier, voltage controlled oscillator, one shot timing generator with zero crossing detection comparator, steering logic to two output drivers, a 5V bias generator, and undervoltage lockout. A latched fault management scheme provides soft start, restart delay, and a precision reference.

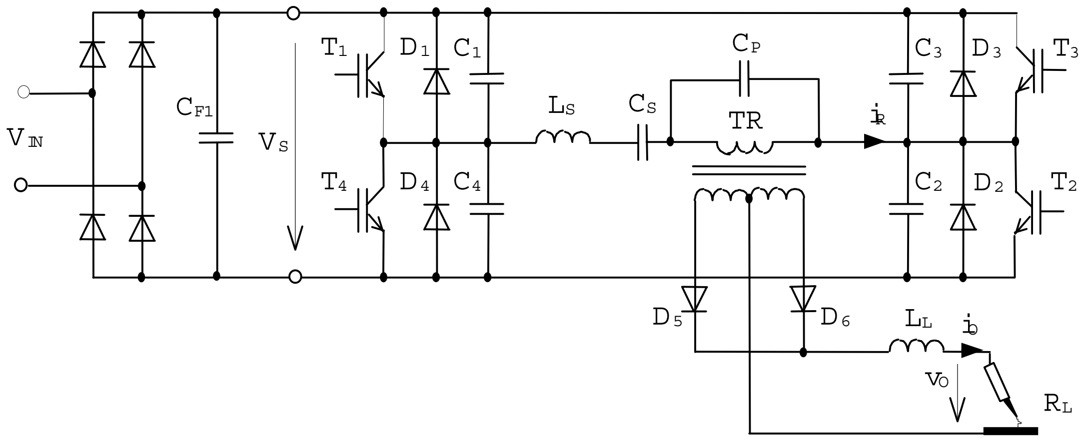


Fig. 1. Full-bridge series-parallel resonant converter for arc welding

The both resonant-mode control circuits are completely galvanically separated from the power circuits.

The resonant inverter working above the resonance frequency requires controlled switch-off times to ensure zero-voltage switching. The zero switch voltage needs to be sensed for both switches T_1, T_4 in the arm and translate through sensing transformers to the zero input of the control circuit VS_1, VS_2.

The output current is sensed by a special current transformer. The rectified voltage from the current transformer CS_1 is fed into the non inverting input of the error amplifier as a feedback.

The output voltage is sensed by a voltage transformer and the rectified voltage VS_5 from transformer is fed into the comparator with hysteresis. If the output voltage v_O is greater than the maximum value V_{Omax} the switching frequency is adjusted on the maximum value, thus the minimum value of the output voltage is achieved. The control circuits ensure that the welding process starts with maximum frequency.

Regulation is achieved by comparing actual voltage, which is proportional to the output current against reference voltage. Any changes of the output current due to load variations cause the pulse frequency change according to load and line conditions, stabilising the output current. The current transformer CS_2 is used by sensing the current in the resonant tank for overcurrent protection of the transistors.

The high voltage MOS and IGBT gate drivers SKHI 20 are used to drive IGBTs.

3. DESIGN OF THE CONVERTER

The simplified model of the LCC-type series-parallel resonant converter used for analysis is shown in Fig. 3.

For simplicity assume that a filter inductor L_L (see Fig. 1.) ensures that output current I_O is fully smoothed. It is also assumed that all components and devices of the converter are ideal. The load is presented by an equivalent resistance R_l [3].

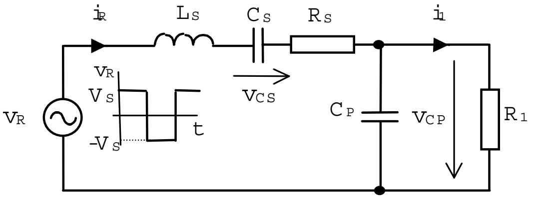


Fig. 3. The equivalent circuit

According to Fig. 3. the state-space model describing the dynamic behaviours of this converter is:

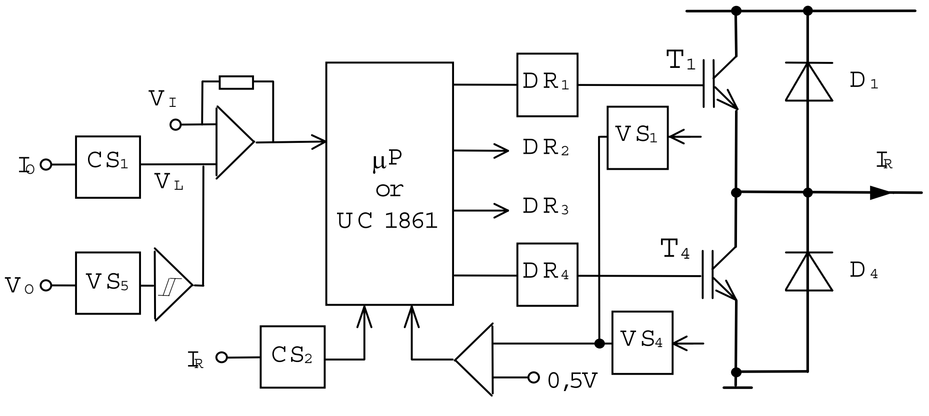


Fig. 2. Control circuit

$$\frac{d}{dt}\begin{bmatrix} v_{CP} \\ v_{CS} \\ i_R \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1/C_P \\ 0 & 0 & 1/C_S \\ -1/L_S & -1/L_S & 0 \end{bmatrix} \cdot \begin{bmatrix} v_{CP} \\ v_{CS} \\ i_R \end{bmatrix} + \tag{1}$$

$$+\begin{bmatrix} 0 \\ 0 \\ 1/L_S \end{bmatrix} .(\pm V_S) + \begin{bmatrix} -1/C_P \\ 0 \\ 0 \end{bmatrix} .i_1 = A.x + b.v + e.z$$

The input voltage is a square wave whose rms value is:

$$V_R = \frac{4.V_S}{\pi.\sqrt{2}} \tag{2}$$

and the resonant components L_S and C_S can be calculates as follows:

$$L_S = \frac{Z_R}{2.\pi.f_{RS}} \tag{3}$$

$$C_S = \frac{1}{L_S.(2.\pi.f_{RS})^2} \tag{4}$$

where the Z_{RS} is a characteristic impedance:

$$Z_{RS} = \sqrt{\frac{L_S}{C_S}} \tag{5}$$

whose value is found from[5]:

$$Z_{RS} = \frac{V_S.f_{RS}}{2.I_{RS}.(f_S - f_{RS})} \tag{6}$$

where the I_{RS} is the resonant current at the short circuit :

$$I_{R_{RMS}} = \frac{2.\sqrt{2}.I_O}{\pi.n} \tag{7}$$

The switching frequency f_S at no-load and short circuit has to be higher than resonant frequency f_R:

$$f_S > f_{RO} = \frac{1}{2.\pi.\sqrt{L_S.\frac{C_S.C_P}{C_S + C_P}}} > f_{RS} = \frac{1}{2.\pi.\sqrt{L_S.C_S}} \tag{8}$$

The f_{RS} is the resonant frequency in the short circuit and the f_{RO} is the resonance frequency at no-load.

The magnitude of the voltage across the resonant capacitor C_P is:

$$V_{CpMAX} = \frac{\sqrt{2}.V_R}{\sqrt{\left(1+\frac{C_P}{C_S}\right)^2.\left[1-\left(\frac{f_S}{f_R}\right)^2\right]^2 + \left[Q_R.\left(\frac{f_S}{f_R} - \frac{f_R}{f_S}.\frac{C_P}{C_P + C_S}\right)\right]^2}} \tag{9}$$

where Q_R is the quality factor and it is defined as:

$$Q_R = \frac{Z_R}{R_1} \tag{10}$$

At no-load when the output voltage is maximum (in this application about 70V) the quality factor Q_R can be neglected.

The normalised peak voltage across parallel capacitor C_P and parallel output resistor R_1 according equation (9) is illustrated in Fig. 4. for the capacitance ratio $C_P/C_S=1$ and 0,5. It is plotted as a function of the ratio f_S/f_{RO} at selected value of Q_R. From Fig. 4. we can find the value of parallel resonant capacitor C_P. The Fig. 5. shows normalised peak voltage across series capacitor C_S as function of f_S/f_{RO} at selected value of Q_R and C_P/C_S.

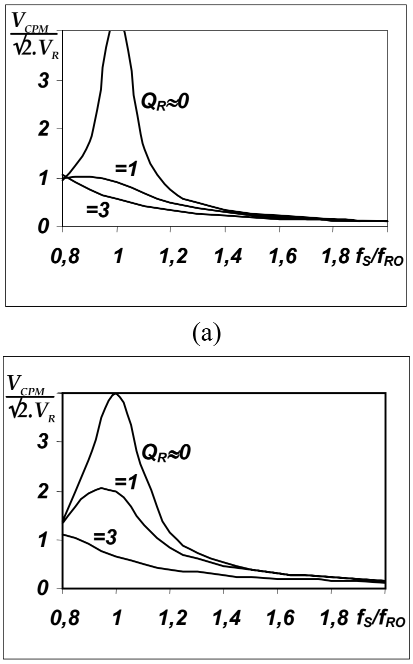
Fig. 5. shows normalised resonant current $I_{RM}.Z_O/V_R.\sqrt{2}$ versus f_S/f_{RS}. It can be seen that high values of the I_{RM} occur at the resonant frequency of the short circuit f_{RS}. The resonant current increases with increasing output resistance R_1 or decreasing Q_R.

The choice of the parallel capacitor C_P has to be a compromise between the significant various of the inverter frequency, the output voltage and high resonant current flowing at no load.

The following parameters of resonant components were obtained: L_S=42μH, C_S=380nF, C_P=380nF for short circuit resonance frequency 42kHz, minimum switching frequency 65kHz and maximum switching frequency 100kHz.

The operating conditions similar to those in the conventional electric arc welders are ensured by the proper design of the control circuits. By using a small value of the parallel capacitance C_P the inverter resonant current increased to higher values than at the short circuits. This nuisance we can removed. The control algorithm recognises two states of the system according to the load current.

The working state is recognised at $i_O > I_{Omin}$ where I_{Omin} is the minimum load current suitable for arc welding. No-load is recognised at $i_O < I_{Omin}$. At the working state the control algorithm adjusts the frequency according to difference between output current and reference signal. If the no-load is recognised the maximum frequency is set.



(a)

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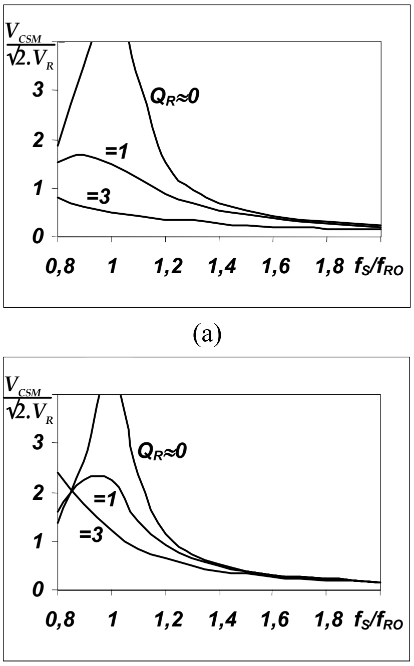
Fig. 4. Normalized maximum voltage across the parallel capacitor versus f_S/f_{RO} for different values of Q_R and C_P/C_S



(a)

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Fig. 5. Normalized maximum voltage acrooss the series capacitor versus f_S/f_{RO} for different values of Q_R and C_P/C_S

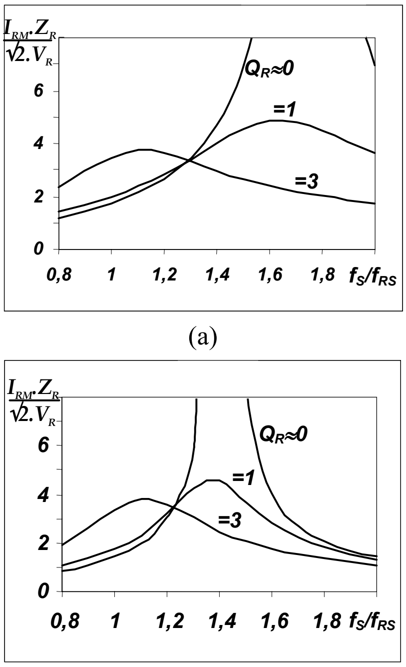

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Fig. 6. Normalized maximum current through the resonant tank versus f_S/f_{RS} for different values of Q_R and C_P/C_S

4. EXPERIMENTAL RESULTS

The measurement was made at voltage V = 300V across the input filter C_{F1}. The rated output current of 150A was reached at arc voltage. The output voltage at no-load circuit is from 40V to 70V. The value of the welding current is set by reference voltage fluently from 40A up to 150A. Waveforms of the voltage across resonant tank v_R and resonant current i_R are displayed in Fig. 7. Fig. 8. shows the switch voltage v_{CE} and switch current i_C. The converter operates above resonance frequency, hence the power switches are turned-on and turned-off under zero voltage switching (ZVS). We can see waveforms of the output current i_O and voltage v_O during full arc welding process in Fig. 9. At no-load the converter is driven to frequency 100kHz and the voltage across the load is about 70V. At short circuit the minimum output current is about 80A at 100kHz. The current of the arc is about 50A.

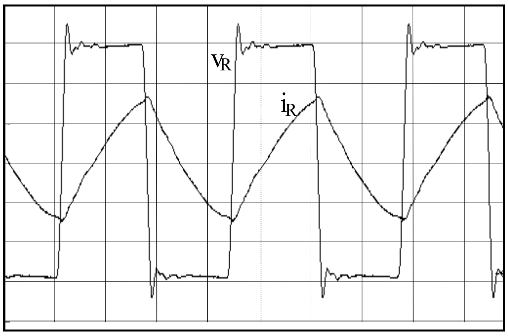

Fig. 7. Resonant voltage across resonant tank v_R and resonant current i_R. t: 5μs/div, v_R: 100V/div, i_R: 20A/div

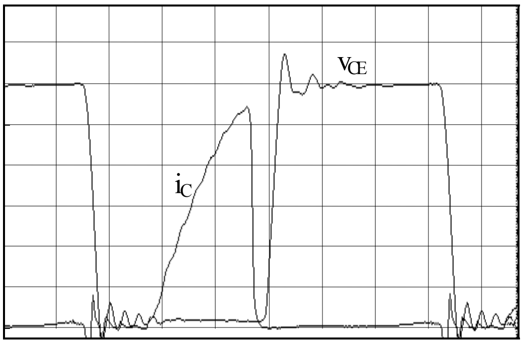

Fig. 8. Switch voltage v_{CE} and switch current i_C. t: 2.5μs/div, v_{CE}: 50V/div, i_C: 5A/div

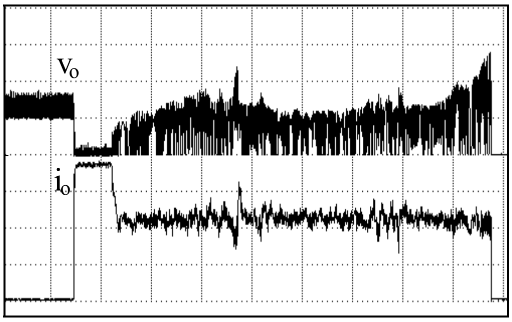

Fig. 9. Output voltage v_o and output current i_o during welding. t: 100ms/div, v_o: 50V/div, i_o: 20A/div

5. CONCLUSION

The dc-dc converter with series-parallel load resonant inverter is used as the arc welding supply. The LCC-type load resonant tank was chosen due to its ability to operate at high frequency and together with control circuits limit voltage and current under open and short circuit conditions, respectively. A full design procedure for arc welding application has been developed and two control circuits for this converter are presented. The theoretical characteristics of the peak stresses are plotted in the normalised output plane.

The dynamical and steady-state properties of the dc-dc converter working at switching frequency from 65kHz to 100kHz with output current from 50A to 150A, output voltage at no-load voltage of 70V was presented.

The presented dc-dc converter is suitable for arc welding source for its small weight and size, good efficiency and fast response.

6. ACKNOWLEDGEMENT

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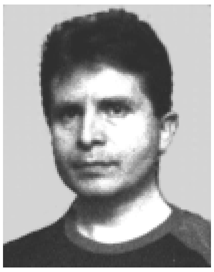

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