A Single-Switch AC-AC Converter with High Power Factor and Soft Commutation for Induction Heating Applications

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ABSTRACT

A new single-switch parallel resonant converter for induction heating is introduced. The circuit consists of the input LC-filter, bridge rectifier and one controlled power switch. The switch operates in a soft commutation mode and serves as a high frequency generator. Output power is controlled via switching frequency. The steady state analysis of the converter operation is presented. The theoretical analysis, computer simulation and experimental results are in good agreement.

INTRODUCTION

The ordinary circuit of an AC-AC converter for induction heating typically includes a controlled rectifier and a frequency current or voltage inverter. It is well known that the input control rectifier does not ensure a sine wave input current and is characterized by a low power factor [1-3] Recently many researches of high power factor rectifiers with a single switch have been reported [4,5]. These schemes are also characterized by a close to sine wave input current. Alongside, in [6] the scheme of the AC-AC converter for induction heating is described. The input circuit of this converter is constructed similarly to the input circuit in [4,5], that also ensures a high power factor. However, the invertering circuit is constructed by a traditional mode with four controlled switches.

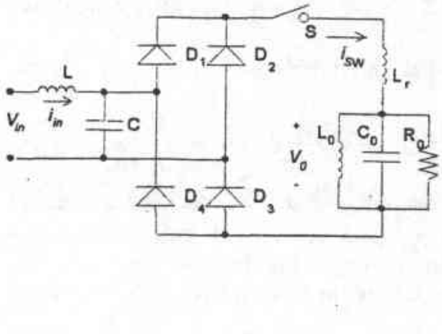

Fig. 1. Circuit diagram.

In the proposed scheme (Fig. 1) of the AC-AC converter the advantages of the above schemes are combined, i. e., on the one hand it is characterized by a high power factor and sine wave input current, and on the other hand the inverter circuit is constructed on a single controlled switch, which serves as a high frequency generator for induction heating.

PRINCIPLES OF OPERATION.

The operating principles of the proposed circuit can be illustrated by theoretical waveforms, as shown in Fig.2. We suppose that the switching frequency is much higher than the input line frequency and in the analysis we chose arbitrary the time interval where $v_{in} > 0$.

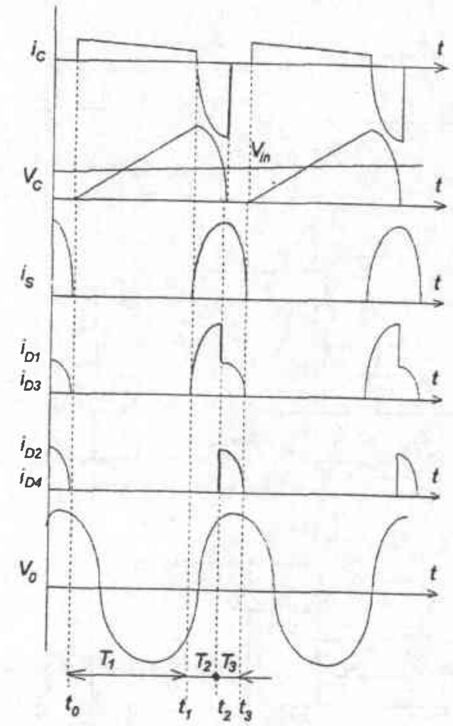

Fig. 2. Ideal switching waveforms.

1). Interval 1: $t_0 < t < t_1$ (equivalent circuit is shown in Fig. 3a). Four diodes $D_1 - D_4$ and the switch S are OFF. In this interval capacitor C charges up practically linearly at a rate and a polarity correspondent to the instantaneous input voltage v.

2). Interval 2: $t_1 < t < t_2$ (equivalent circuit is shown in Fig. 3b). Two diodes D_1, D_3 and the switch S are ON. In this interval capacitor C is discharging via circuit : $C - D - S - L_r - load - D_3$. This interval ends when the capacitor voltage reduces to zero.

3). Interval 3 : $t_2 < t < t_3$ (equivalent circuit is shown in Fig. 3c). All diodes and the switch are ON. In this interval the switch current, i.e. the current through switch S flows via two parallel bridge branches. This interval ends when this switch current decreases to zero. At this moment the switch turns off and the process starts from the beginning.

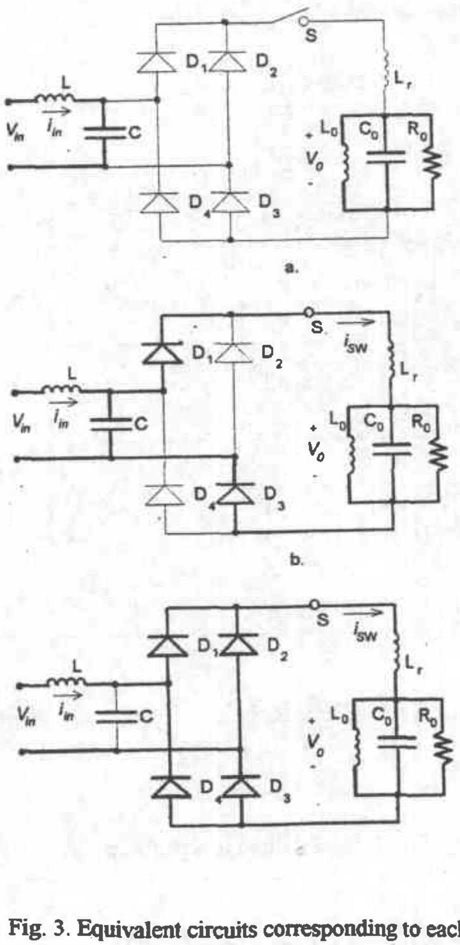

Fig. 3. Equivalent circuits corresponding to each time interval.

OPERATION ANALYSIS

The analysis of the circuit operation is based on the commonly accepted assumption that all circuit components are ideal. The approximate analytical calculations are based on two additional assumptions: a) the switch current can be approximated by a semi-sinusoid; b) the load power is determined by the first harmonic of the load voltage.

The equations are normalized using the following base quantities:

-base voltage $V_B = V_{in}$;

-base impedance $R_B = \sqrt{L_o / C_o}$;

-base current $I_B = V_B / R_B$;

-base power $P_B = V_B I_B$;

-base frequency $\omega_B = 1 / \sqrt{L_o C_o}$;

-base time $T_B = 2\pi / \omega_B$.

Furthermore, the proposed converter has been simulated on the PSPICE-program. As a result, the optimal range of the normalized parameters was chosen. The criteria of this choice were the reasonable levels of the following normalized parameters: maximal value of the switch current ($i^*_{sw.max} = I_{sw.max} / I_B = 6 - 10$) and maximum value of the switch voltage ($v^*_{sw.max} = V_{sw.max} / V_B = 4 - 5$). Fig. 4 shows the plots of these normalized parameters versus a normalized inductance $L^*_r = L_r / L_o$,

normalized frequency $\omega^*_r = \dfrac{1 / \sqrt{L_r C_{in.eq}}}{\omega_B}$ and

normalized switching frequency $\omega^*_s = \dfrac{\omega_s}{\omega_B}$. The ranges of these normalized parameters were chosen as follow: $L^*_r = 0.1 - 0.2$; $\omega^*_r = 3 - 5$; $\omega^*_s = 1 - 2$. In addition, the

normalized values of duty cycle $D_2 = T_2 \dfrac{\omega_s}{2\pi}$ and

$D_{2,3} = (T_2 + T_3)\dfrac{\omega_s}{2\pi}$ versus L^*_r, ω^*_r and ω^*_s were founded (T_2 and T_3 are time periods of circuit operation, see Fig. 2). The corresponding plots are shown in Fig. 4.

Evaluation of the relationship between input and output voltages $M_g = \dfrac{V_o}{V_{in}}$ is based on the follow statements:

a). The relationship between the average input current $I_{in.av}$ and the maximal switch current $I_{in.av} = \frac{2}{\pi} I_{sw.max}$. We take into account that the average current of the input capacitor during full period is zero. In addition, we assume that the input current during the switch period is constant. Thus,

$$\frac{1}{T_s}\int_0^{(1-D_{2,3})T_s} I_{in.av} dt = \frac{1}{T_s}\int_{(1-D_{2,3})T_s}^{(1-D_{2,3}+D_2)T_s} (i_{sw} - I_{in.av}) dt \quad (1)$$

Furthermore, we receive the following relationship:

$$I_{in.av} = \frac{D_{2,3}(1-cos\frac{\pi D_2}{D_{2,3}})}{\pi(1-D_{2,3}+D_2)} I_{sw.max} \quad (2)$$

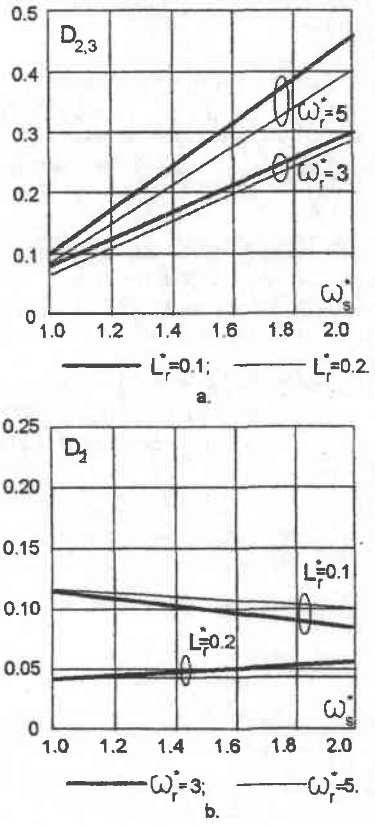

Fig. 4 The duty cycles $D_{2,3}$ and D_2 versus parameters L_r^*, ω_r^* and ω_s^*.

b). The relationship between the peak switch current and its first harmonic is a very complex expression, but with sufficient accuracy this relationship may be taken as follow:

$$I_{sw.1.max} \cong 1.1 D_{2,3} I_{sw.max} \quad (3)$$

c). The relationship between the first harmonic of the switch current and the first harmonic of the load resistive current is

$$I_{R.1.max} = I_{sw..1.max}\frac{1}{\sqrt{1+R_0^{*2}(\omega_s^* - \frac{1}{\omega_s^*})^2}} \quad (4)$$

By equating the input and the output powers, we obtain:

$$M_g = \frac{V_o}{V_{in}} \cong \frac{\sqrt{2}}{(1-D_{2,3}+D_2)} \times \\ \times \frac{\sqrt{1+R_o^{*2}(\omega_s^* - \frac{1}{\omega_s^*})^2}\left(1-cos\frac{\pi D_2}{D_{2,3}}\right)}{1.1\pi(1-D_{2,3}+D_2)} \quad (5)$$

This relationship is also true for the effective values of the line and output voltages, for both of which are sine waves. The values of duty cycles $D_{2,3}$ and D_2 may be calculate from the plot in Fig. 5. These parameters may also be found from the approximate polynomial expressions:

$$D_{2,3} \cong (10 - 985L_r^* - 10\omega_r^* + \\ +100\omega_s^* + 112L_r^*\omega_s^*)10^{-3}; \quad (6)$$

$$D_2 \cong (257 - 97L_r^* - 337.1\omega_r^* - 64.4\omega_s^* - \\ -10L_r^*\omega_r^* + 100L_r^*\omega_s^* + 11.2\omega_r^*\omega_s^*)10^{-3} \quad (7)$$

These expressions have been received for the above mentioned range of parameters with an application of an experimental design theory (the small coefficient members were neglected). The accuracy of the approximate expressions (6) and (7) as been estimated by comparison with the results of the computer simulation and the experiments, which show that the error in every case was less then 10 – 15%.

Experimental verification.

The proposed single-switch AC-AC converter was built and tested. Its input voltage was $V_{r.m.s.} = 50V$. The experimental converter had the following parameters: $L_o = 146\mu H;\ C_o = 2.2\mu F;\ L_r = 20\mu H;$ $L_i = 2.0mH;\ C = 1.0\mu F.$

The switching frequency was $\omega_s = (55-110)\cdot 10^3 s^{-1}$ and output power $P_o = 0.15\text{–}0.6kW$. Fig. 5 shows the experimental waveforms of the load voltage and the switch current.

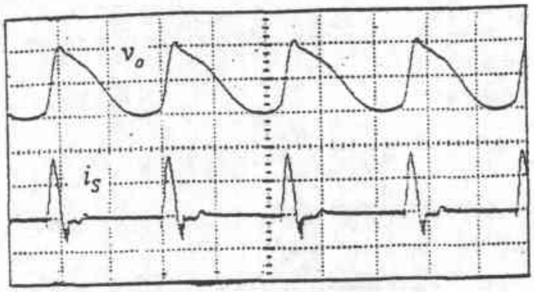

Fig. 5. Experimental waveforms of the load voltage (vertical scale is 100V/div) and switch current (vertical scale is 2A/div); horizontal scale is 50μs / div .

Conclusion

A new circuit of an AC-AC converter for induction heating has been presented and analyzed. The basic features of the proposed circuit are as follow. The converter input current is practically sinusoidal and its power factor is close-to unity. The circuit topology is very simple and includes only one power switch. This switch operates in a soft commutation regime. The converter provides wide range power control (0.25 - 1). Simulation and experimental results demonstrate the actual converter capability.

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