A New Resonant Step-Up Converter Based on Unidirectional Switches

Masoud Jabbari*, *Student Member, IEEE*, Hosein Farzanehfard*, *Member, IEEE,*

and Shahrohk Farhangi**, *Member, IEEE*

* Department of Electrical and Computer Engineering, Isfahan University of Technology (IUT), Isfahan, Iran, 84154

** Power Electronics Lab, School of Electrical and Computer Engineering, University of Tehran, Iran

Abstract: **In this paper, a new resonant step-up converter is presented where all active elements operate under soft-switching condition. Unidirectional switches such as reverse-blocking IGBTs are employed and to be more compatible with IGBT characteristics, ZCS condition is provided. A complete analysis of the proposed converter and experimental results from a 100W prototype converter are presented.**

***Index Terms*: DC-DC Converter, Soft Switching, Resonant Converter, Step-up, RB-IGBT.**

I. INTRODUCTION

Soft-switching techniques are developed to reduce switching losses and electromagnetic interference (EMI). At soft-switching condition, switching frequency can be increased to reduce the converter size and weight. This condition is commonly attained by zero voltage switching (ZVS) and/or zero current switching (ZCS). Soft-switching converters are generally derived by modifying hard-switching converters [1]-[6].

Resonant converters are a family of soft-switching converters in which energy is transferred through a resonance tank and switching is performed at zero-crossing instants of current and/or voltage. However, in this technique, a part of energy stored in the resonance tank is returned to the source via the switches anti-parallel diodes. This increases the circulating energy and consequently the conductive losses and switch current stresses. Moreover, the core of a basic resonant converter is the inverter and thus source and load do not have a common ground [1]. This issue greatly restricts the application of non-isolated resonant converters. In high power applications IGBT switch is preferred. To be more compatible with IGBT characteristics, and specifically covering the tailing-current problem, ZCS condition is more proper [7]-[9]. Reverse-blocking IGBTs (RB-IGBT) are also developed and yield considerable advantages in some converters [10]-[15].

Recently a new family of resonant converters namely Switched Resonator Converters (SwRC) is developed where fifteen soft-switching converters are synthesized by employing unidirectional switches [15]. In this paper, a boost-type switched resonator converter is presented which provides ZCS commutation at turn on/turn off switching instants. The important aspects, essential equations, and experimental results of this converter are presented.

II. PROPOSED CONVERTER ANALYSIS

Topology of Boost-MG SwRC, where 'MG' represents the topology formation [15], is shown in Fig. 1 where both switches are unidirectional (RB-IGBT). Equivalent circuit of each operating mode and steady-state key waveforms are shown in Fig. 2 and Fig. 3 respectively. Following relations are defined.

$$\omega_r = \frac{1}{\sqrt{L_r \cdot C_r}} \qquad f_r = \frac{1}{T_r} = \frac{\omega_r}{2\pi} \tag{1}$$

$$Z_r = \sqrt{L_r / C_r} \tag{2}$$

$$r = R / Z_r \tag{3}$$

$$A = V_O / V_S \tag{4}$$

Assume that prior to Mode I, the output voltage V_O is greater than source voltage V_S, the resonance voltage v_r is $-V_O$, resonance current i_r is zero, and Q_1 and Q_2 are off. To simplify the analysis, all the circuit elements are assumed ideal, and the capacitor C is considered large enough so that the output voltage is constant during one switching cycle. The circuit operates in four modes as following.

Mode I ($t_1 - t_2$): At t_1, Q_1 is turned on at ZCS and C_r charges through a resonance with L_r. At t_2, v_r reaches V_O and D_r becomes forward biased.

$$\frac{v_r(t)}{V_S} = 1 - (1+A)\cos\left(\omega_r \cdot (t - t_1)\right) \tag{5}$$

$$\frac{i_r(t)}{V_S / Z_r} = (1+A)\sin\left(\omega_r \cdot (t - t_1)\right) \tag{6}$$

$$t_2 - t_1 = \frac{1}{\omega_r}\left[\pi - \cos^{-1}\frac{A-1}{A+1}\right] \tag{7}$$

Mode II ($t_2 - t_3$): At t_2, D_r turns on at ZVS and the resonance current flows through it. Since C is much larger than C_r, voltage of node J is almost constant and equal to V_O during this mode. Thus magnitude of i_r decreases linearly until at t_3, it reaches zero and both Q_1 and D_r are turned off at ZCS.

$$\frac{i_r(t_2)}{V_S / Z_r} = \frac{i_{D_r,\max}}{V_S / Z_r} = 2\sqrt{A} \tag{8}$$

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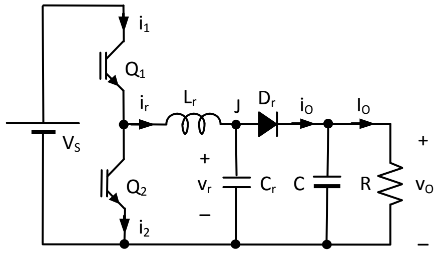

Fig.1 – Boost-MG SwRC

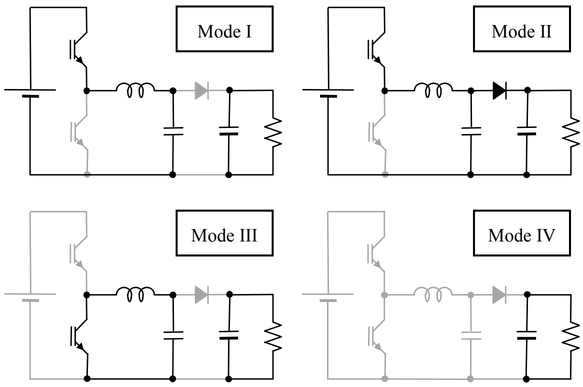

Fig.2 – Equivalent circuit of each operating mode

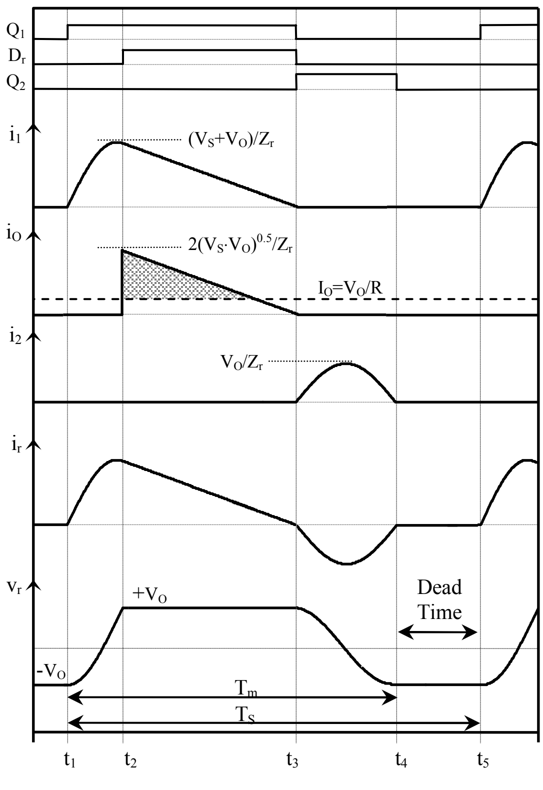

Fig.3 – Typical steady-state waveforms

$$\frac{i_r(t)}{V_S/Z_r} = 2\sqrt{A} - (A-1)\,\omega_r\,(t - t_2) \tag{9}$$

$$\frac{v_r(t)}{V_S} = A \tag{10}$$

$$t_3 - t_2 = \frac{1}{\omega_r}\frac{2\sqrt{A}}{A-1} \tag{11}$$

Mode III (t_3 – t_4): At t_3, Q_2 is turned on at ZCS and voltage polarity of C_r is reversed via a resonance with L_r. At t_4 the resonance current reaches zero and thereby Q_2 is turned off at ZCS.

$$\frac{v_r(t)}{V_S} = A\cos\left(\omega_r \cdot (t - t_3)\right) \tag{12}$$

$$\frac{i_r(t)}{V_S/Z_r} = -A\sin\left(\omega_r \cdot (t - t_3)\right) \tag{13}$$

$$t_4 - t_3 = \frac{\pi}{\omega_r} \tag{14}$$

Mode IV (t_4 – t_5): In this mode, Q_1 and Q_2 are both off and the load is supplied by the output capacitor. Duration of this interval is determined by the controller so that proper voltage regulation is attained (dead-time control).

According to the equivalent circuits of each operating mode, all stray inductors and the switches parasitic inductor are absorbed by L_r and the parasitic capacitor of D_r is absorbed by C_r.

III. VOLTAGE GAIN

If the output voltage is less than the source voltage, by turning Q_1 on the diode D_r conducts immediately. Consequently, the output voltage increases to greater than the source voltage. Therefore the proposed converter is step-up.

At steady-state, the converter voltage gain A can be calculated by holding the energy conservation principle in one switching cycle.

$$\int_{T_S} V_S\, i_1\, dt = \int_{T_S} \frac{V_O^2}{R} dt \tag{15}$$

Where $f_S = T_S^{-1}$ is switching frequency. By substituting (6) and (9) in (15), voltage gain is obtained as (16). As a result, output voltage gain is proportional to the switching frequency.

$$A = 1 + 2RC_r f_S = 1 + \frac{r}{\pi} \times \frac{f_S}{f_r} \tag{16}$$

In absence of dead-time, the converter operates at its maximum power handling capability where the switching frequency is also at maximum. This situation is named maximum power delivery condition. The interval from t_1 to t_4 is defined as T_m. By using (7), (11) and (14), (17) is obtained.

$$\frac{T_m}{T_r} = 1 + \frac{1}{\pi}\left[\frac{\sqrt{A}}{A-1} - \frac{1}{2}\cos^{-1}\frac{A-1}{A+1}\right] \tag{17}$$

By substituting (17) in (16) and after a few calculations, (18) is obtained. This equation gives maximum achievable voltage gain, A_m, versus r. A_m vs. r/π is plotted in Fig. 4. Since A_m cannot be less than unity, for proper operation r should be greater than unity.

$$r = (A_m - 1)\cdot\left[\pi + \frac{\sqrt{A_m}}{A_m - 1} - \frac{1}{2}\cos^{-1}\frac{A_m - 1}{A_m + 1}\right] \tag{18}$$

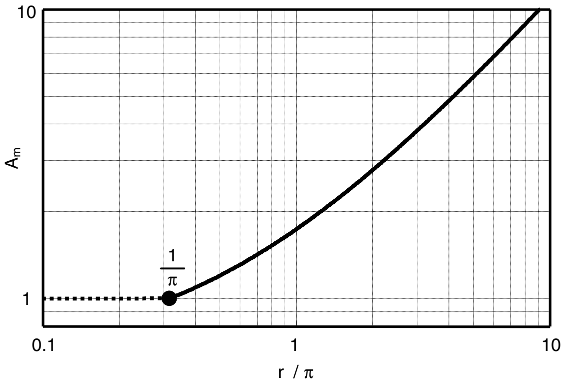

Fig.4 – A_m versus r/π

IV. PERFORMANCE

The peak to peak output voltage ripple ΔV_O can be calculated approximately assuming that the ripple component is entirely absorbed by the output capacitor and its DC part flows through the load [1]. The shaded area in Fig. 3 represents an additional charge which produces the ripple component. After a few calculations output voltage ripple is obtained as (19).

$$\frac{\Delta V_O}{V_O} = \frac{C_r}{C} \times \frac{\left(2r - \sqrt{A}\right)^2}{2r^2 (A-1)} \tag{19}$$

The circuit efficiency η is calculated as (20) where P_{out} and P_{loss} represent output power and dissipation power respectively. By defining V_D as the diode forward voltage, $V_{CE,SAT}$ as the IGBT saturation voltage, and R_r as the parasitic resistance of L_r, η is obtained as (21). Equation (22) is result of curve fitting and has very good accuracy.

$$\eta = \frac{P_{out}}{P_{loss} + P_{out}} \tag{20}$$

$$\eta = 1 - \frac{V_D}{V_O} - \frac{V_{CE,SAT}}{V_O} \times (2A - 1) - \frac{R_r}{Z_r} \times \rho \tag{21}$$

$$\rho \cong 1.558A - 0.192 \tag{22}$$

V. DESIGN PROCEDURE

Consider a 100W prototype step-up converter for V_S=156V±10%, V_O=312V, and $\Delta V_{O,max}$=5%.

Step 1) Determining Z_r: According to the maximum power delivery condition A_{max} (=2.22) should be greater than A_m. By applying A_m=2.22 in (18), r is obtained 4.61. By substituting this value in (3) and applying R=312^2/100, Z_r is attained 211Ω. With 20% overdesign, Z_r is set to 176Ω.

Step 2) Determining C/C_r: According to (19), it can be proven that ΔV_O is maximum for A_{min} (=1.82) and r_{max} (=∞ for no-load). By using (19), C/C_r is obtained 48.8 for 5% ripple at the worst condition.

Step 3) Determining ω_r: According to (7), (11) and (14), it can be shown that on time duration of Q_2 is always less than on time duration of Q_1. Equation (14) denotes that Q_2 on time duration is T_r/2, thus the resonance frequency should be determined by considering the employed speed of switches. With T_r/2 = 5μs, the circuit element values are obtained as L_r=280μH, C_r=9nF, and C=441nF. With these values, maximum switching frequency at steady-state is determined about 70KHz.

VI. EXPERIMENTAL RESULTS

Employed switches are IXDH20N120, and D_r is BYT52M. For V_S=156V and V_O=312V, soft-switching performance of Q_1 and Q_2 are shown in Fig. 5 and Fig. 6 respectively. These waveforms are independent from the converter output power. In both figures, waveforms of gate-emitter voltage, collector-emitter voltage, and collector current of the switches are shown respectively from top. The converter efficiency for V_S=156V is measured 96% over the range of load variations.

VII. CONCLUSIONS

A new soft-switching resonant step-up converter is presented in this paper where ZCS condition is provided by utilizing a series resonance tank. Unidirectional switches are employed and thereby energy circulation is prevented. Resulting in, switches current stresses are reduced and the converter efficiency is increased. ZCS condition is also compatible with the characteristics of reverse-blocking IGBTs. A further important advantage is that no-load condition is easily handled. Moreover, low number of elements is employed, and the source and load have common ground despite of the conventional resonant converters. Experimental results confirm the integrity of the proposed converter and its theoretical analysis.

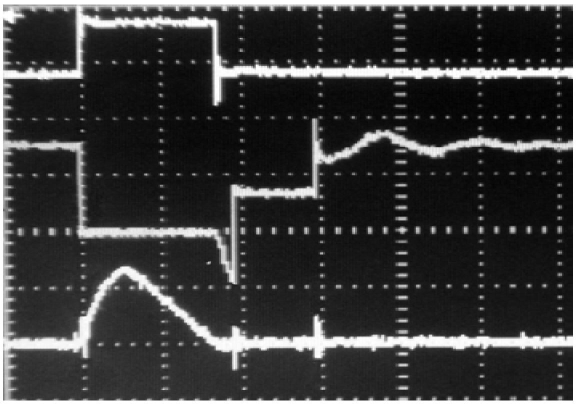

Fig.5 – Soft-switching operation of Q_1 (5µs/div), V_{GE}: 20V/div (top), V_{CE}: 200V/div (middle), and I_C: 2A/div (bottom)

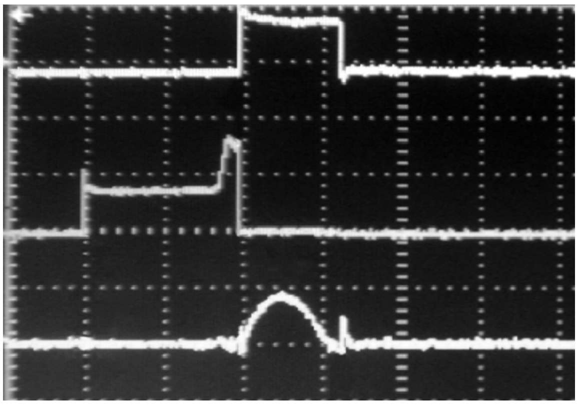

Fig.6 – Soft-switching operation of Q_2 (5µs/div), V_{GE}: 20V/div (top), V_{CE}: 200V/div (middle), and I_C: 2A/div (bottom)

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Masoud Jabbari: He is currently electrical Ph.D. student in Isfahan University of Technology (IUT), Iran. His research interests include soft-switching techniques in high-frequency high-power dc-dc and dc-ac converters, power factor corrections, and active power filters.

Hosein Farzanehfard: Since 1993, he has been a faculty member with the Department of Electrical and Computer Engineering, Isfahan University of Technology (IUT), Iran. He is currently an Associate Professor and the President of the Information and Communication Technology Institute. His research interests include high-frequency soft switching converters, pulse power applications, power factor corrections, and active power filters.

Shahrokh Farhangi: received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from The University of Tehran, Tehran, Iran. He is an Associate Professor in the Department of Electrical and Computer Engineering, University of Tehran. His research interests include the design and modeling of power-electronic converters, drives, and renewable energy systems.