

Fig.1 – Boost-MG SwRC

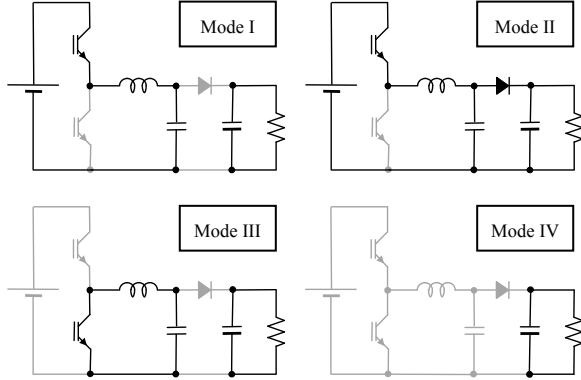


Fig.2 – Equivalent circuit of each operating mode

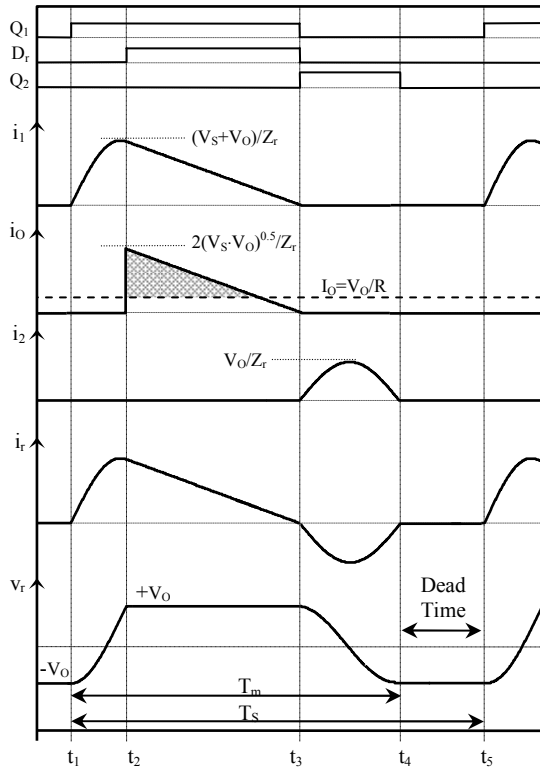


Fig.3 – Typical steady-state waveforms

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

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

$$t_3 - t_2 = \frac{1}{\omega_r} \frac{2\sqrt{A}}{A-1} \quad (11)$$

*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.

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

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

$$t_4 - t_3 = \frac{\pi}{\omega_r} \quad (14)$$

*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.

$$\int_{T_S} V_S i_1 dt = \int_{T_S} \frac{V_o^2}{R} dt \quad (15)$$

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.

$$A = 1 + 2RC_r f_s = 1 + \frac{r}{\pi} \times \frac{f_S}{f_r} \quad (16)$$

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.

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

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.  $r/\pi$  is plotted in Fig. 4. Since  $A_m$  cannot be less than unity, for proper operation  $r$  should be greater than unity.

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

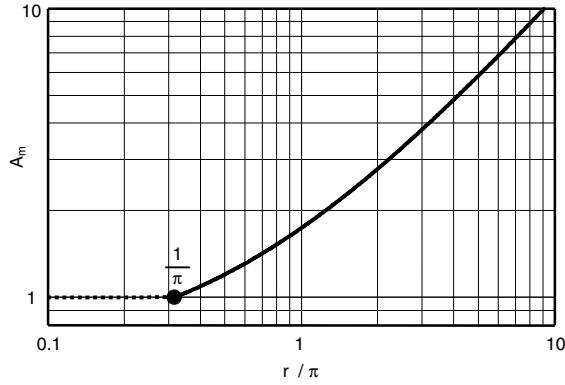


Fig.4 –  $A_m$  versus  $r/\pi$

#### IV. PERFORMANCE

The peak to peak output voltage ripple  $\Delta V_O$  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).

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

The circuit efficiency  $\eta$  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  $L_r$ ,  $\eta$  is obtained as (21). Equation (22) is result of curve fitting and has very good accuracy.

$$\eta = \frac{P_{out}}{P_{loss} + P_{out}} \quad (20)$$

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

$$\rho \cong 1.558A - 0.192 \quad (22)$$

#### V. DESIGN PROCEDURE

Consider a 100W prototype step-up converter for  $V_S=156V \pm 10\%$ ,  $V_O=312V$ , 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 211 $\Omega$ . With 20% overdesign,  $Z_r$  is set to 176 $\Omega$ .

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

*Step 3) Determining  $\omega$ :* 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  $T_r/2 = 5\mu s$ , the circuit element values are obtained as  $L_r=280\mu H$ ,  $C_r=9nF$ , 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.

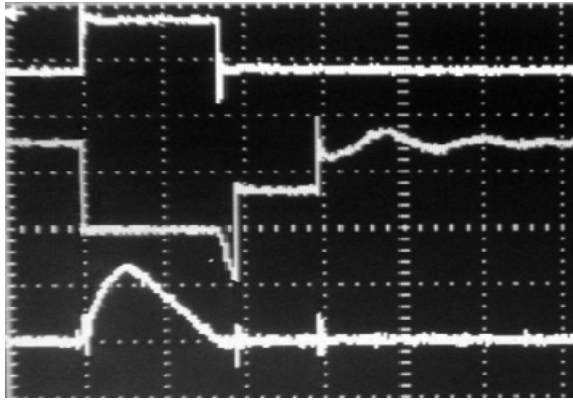


Fig.5 – Soft-switching operation of  $Q_1$  ( $5\mu\text{s}/\text{div}$ ),  $V_{GE}$ :  $20\text{V}/\text{div}$  (top),  $V_{CE}$ :  $200\text{V}/\text{div}$  (middle), and  $I_C$ :  $2\text{A}/\text{div}$  (bottom)

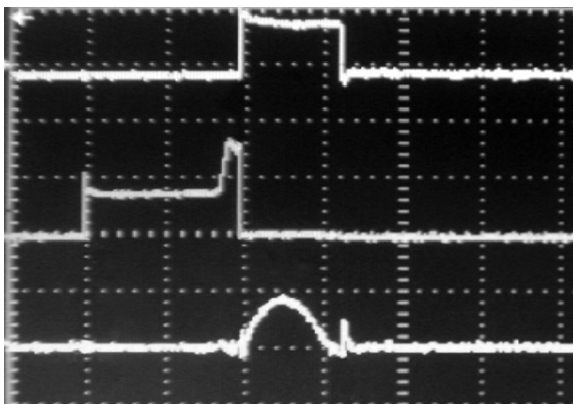


Fig.6 – Soft-switching operation of  $Q_2$  ( $5\mu\text{s}/\text{div}$ ),  $V_{GE}$ :  $20\text{V}/\text{div}$  (top),  $V_{CE}$ :  $200\text{V}/\text{div}$  (middle), and  $I_C$ :  $2\text{A}/\text{div}$  (bottom)

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