A Novel Resonant LLC Soft-Switching Buck Converter

[1]Masoud Jabbari
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Masuod.jabbari@gmail.com

[2]Habib Kazemi
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Habib_kazemii@yahoo.com

[3]Nahid hematian
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Mrshematian@yahoo.com

[4]Ghazanfar Shahgholian
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Shahgholian@iaun.ac.ir

***Abstract*—a new LLC resonant DC–DC buck converter is presented. The employed multi-resonant tank provides soft-switching conditions for all semiconductor devices independent from the operating voltages and the load current. The proposed converter enjoys useful advantages such as low element count, unconditional soft switching operation, self short-circuit protection, high efficiency and low EMI. Circuit analysis and important relations are presented in this paper. Experimental results from a 60W laboratory prototype confirm the presented theoretical analysis.**

Keywords —buck converter; soft-switching; DC-DC converter; ZCS; power supply.

I. INTRODUCTION

Soft-switching converters have been widely employed for DC-DC power conversion because at soft-switching conditions, switching losses and electromagnetic interference (EMI) are reduced. Moreover, switching frequency can be increased to enhance the converter power density. This condition is commonly attained by zero-voltage switching (ZVS) or zero current-switching (ZCS) [1]-[15].

Resonant converters are a family of soft-switching converters in which energy is transferred through a high frequency resonant tank, and switching is performed at zero-crossing instants of the switches current or voltage. A series resonant LC tank is the simplest network which is employed in the resonant converters to provide ZCS [1]-[8]. The main advantage of this converter (series resonant converter, SRC) is major size reduction of the passive components. Further resonant networks such as LLC, LCC, etc. are also proposed however the number of elements is increased and the system possesses complicated characteristics [11]-[15]. As a non-isolated converter, a restriction of the conventional resonant converters is the requirement of a full-wave rectifier which detaches the common ground of the load and source. This is in addition to the increased number of elements and conduction losses.

A new family of resonant converters so-called switched-resonator converters is proposed in [8]. Based on the mentioned general scheme in [8], this paper presents a new resonant step-down converter shown in Fig. 1. In this converter, passive components include a high frequency resonant LLC tank and a filtering capacitor at the output. ZCS condition is achieved at both turn-on and turn-off switching instants independent of the load-current and operating voltages. Comparing with the HB-SRC, not only the proposed converter has three power diodes less, which results in lower conduction losses and lower price, but also it is suitable for non-isolated applications. Moreover, the inductor placed in series with Q_1 and Q_2 inhibits creation of spiky current produced in the conventional bridge arms due to the severe reverse recovery problem of the switches anti-parallel diodes. Experimental results from a 60W/150kHz prototype verify the integrity of operation and the presented theoretical analysis.

II. BUCK CONVERTOR ANALYSIS

The proposed buck converter showing in Fig. 1 consists of two switches (Q_1, Q_2), a resonant LLC network (L_{r1}, L_{r2}, and C_r), the rectifying diode (D_r), and the output filtering capacitor (C). The converter has five operating modes as illustrated in Fig. 2. To simplify, it is assumed the converter is in steady state, all switching devices and passive elements are ideal, and the output capacitor C is large enough such that the output voltage is constant during one switching cycle.

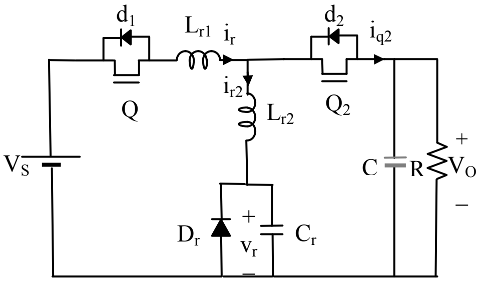

Fig. 1 Proposed buck converter

978-1-4799-2399-1/14/$31.00 ©2014 IEEE

The following quantities are defined.

$$\mathrm{L_r} = \mathrm{L_{r1}} + \mathrm{L_{r2}} \ , \ \alpha = \frac{\mathrm{L_{r2}}}{\mathrm{L_r}} \tag{1}$$

$$\omega_{\mathrm{r}} = \frac{1}{\sqrt{\mathrm{L_r C_r}}} \ , \ \mathrm{f_r} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{2}$$

$$Z_r = \sqrt{\frac{L_r}{C_r}} \ , \ r = \frac{R}{Z_r} \ , \ A = \frac{V_o}{V_s} \tag{3}$$

$$V_r(t) = \frac{v_r(t)}{V_s} \ , \ I_{r2}(t) = \frac{i_{r2}(t)}{V_s / Z_r} \tag{4}$$

Figs.3 shows the steady-state waveforms. The initial currents of all inductors are zero and the initial voltage of the resonant capacitor C_r is $V_r = 2V_o$. The operating modes are as follows.

Mode I (t_0-t_1)

Prior to t_0, the current of L_{r1} is zero, then Q_1 is turned on at t_0 under the ZCS condition and C_r charges through a resonance with L_{r1} and L_{r2} up to $2V_S$-$2V_O$. At the end of this mode, the current of Q_1 reaches zero and therefore this switch is turned off at ZCS.

$$I_r(t) = (1-2A)\sin\left(\omega_r(t-t_0)\right) \tag{5}$$

$$V_r(t) = 1-(1-2A)\cos\left(\omega_r(t-t_0)\right) \tag{6}$$

$$t_1 - t_0 = \sqrt{\alpha}\,\frac{T_r}{2} \tag{7}$$

$$V_r(t_1) = 2(1-A) \tag{8}$$

$$I_{r2}(t_1) = 0 \tag{9}$$

Mode *II (t_1-t_2)*

At t_1, Q_2 is turned on at ZCS and a resonance starts between C_r and L_{r2} which discharges C_r through L_{r2} and delivers power to the output. At t_2 the resonance voltage v_r reaches zero.

$$I_{r2}(t) = \frac{(A-2)}{\sqrt{\alpha}}\sin\left(\frac{\omega_r}{\sqrt{\alpha}}(t-t_1)\right) \tag{10}$$

$$V_r(t) = -A + (2-A)\cos\left(\frac{\omega_r}{\sqrt{\alpha}}(t-t_1)\right) \tag{11}$$

$$t_2 - t_1 = \frac{\sqrt{\alpha}}{\omega_r}\left[\pi - \cos^{-1}\frac{A}{A-2}\right] \tag{12}$$

$$I_{r2}(t_2) = \frac{-2}{\sqrt{\alpha}}\sqrt{1-A} \tag{13}$$

$$V_r(t_2) = 0 \tag{14}$$

Mode III (t_2-t_3)

By reaching v_r to zero at t_2 the diode D_r is forward biased at ZVS and the stored magnetic energy in L_{r2} is delivered to the output during this mode. By reaching i_{r2} to zero at t_3, the switch Q_2 and the diode D_r are both turned off at ZVZCS. During this mode, v_r stays constant at zero.

$$I_{r2}(t) = I_r(t_2) + \frac{A\omega_r}{\alpha}(t_3 - t_2) \tag{15}$$

$$V_r(t_3) = 0 \tag{16}$$

$$t_3 - t_2 = \frac{2\sqrt{\alpha(1-A)}}{A\omega_{\mathrm{r}}} \tag{17}$$

$$I_{r2}(t_3) = 0 \tag{18}$$

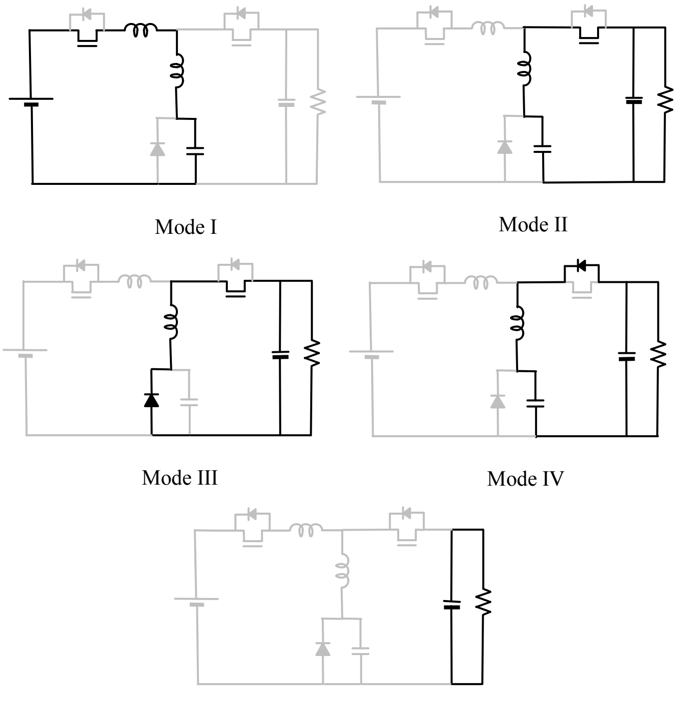
Mode I
Mode II
Mode III
Mode IV
Mode V

Fig. 2 Equivalent circuits of the proposed buck converter

Mode IV (t_3-t_4)

At t_3, the anti-parallel diode of Q_2 (d_2), is forward biased at ZVS and then the voltage polarity of C_r reverses via a resonance with L_{r2}. At t_4, the resonance voltage v_r reaches 2Vo and d_2 is turned off at ZCS.

$$I_{r2}(t)=\frac{A}{\sqrt{\alpha}}\sin\left(\frac{\omega_r}{\sqrt{\alpha}}(t-t_3)\right) \tag{19}$$

$$V_r(t)=A-A\cos\left(\frac{\omega_r}{\sqrt{\alpha}}(t-t_3)\right) \tag{20}$$

$$t_4-t_3=\frac{\sqrt{\alpha}T_r}{2} \tag{21}$$

$$V_r(t_4)=2V_o \tag{22}$$

$$I_{r2}(t_4)=0 \tag{23}$$

Mode V (t_4-t_5)

During this mode, all semiconductor devices are off and the load is supplied by the output capacitor (dead time). By controlling the duration of this mode, the converter voltage gain is determined.

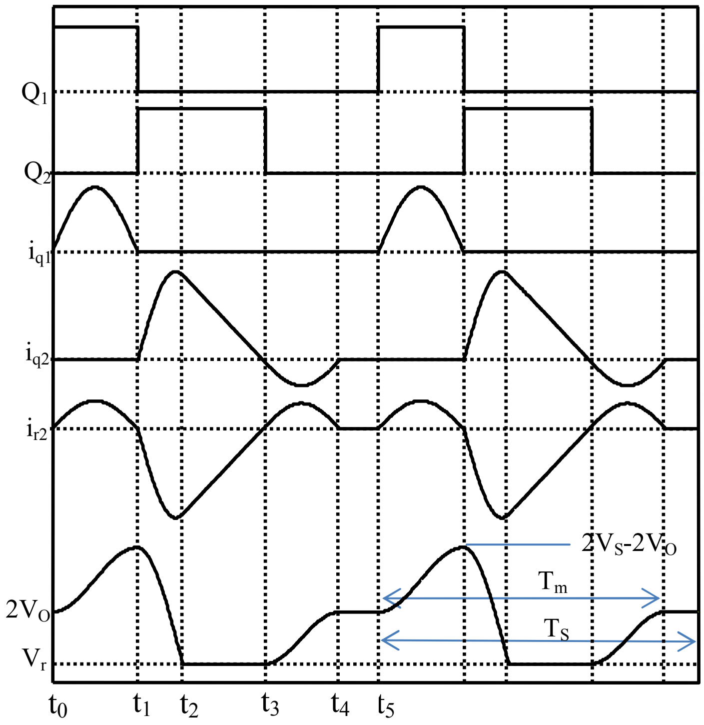

Fig. 3 Steady-state key waveforms

III. VOLTAGE GAIN

At steady state, the converter voltage gain can be calculated by satisfying the energy conservation principle as (24). By substituting (5) in (24) and simplifying, (25) is obtained in which $f_s=1/T_s$ is the switching frequency and f_r is the resonant frequency.

$$\int_{T_s} V_s i_{q1} dt=\frac{V_o^2}{R}T_s \tag{24}$$

$$S=\frac{r}{\pi}.\frac{f_s}{f_r}=\frac{A^2}{1-2A} \tag{25}$$

In absence of dead-time (Mode V), the switching frequency is at maximum and thus maximum voltage gain is also attained which is defined by A_m. The minimum switching period is defined as T_m which is obtained as (26). By substituting $f_s=T_m^{-1}$ in (24), (27) is attained, wherein, in fact, A_m is a function of r. This equation is required for converter design. For α=0 and α=1, A_m against r/π is sketched in Fig. 4.

$$\frac{T_m}{T_r}=\frac{1}{2}+\sqrt{\alpha}+\frac{\sqrt{\alpha}}{\pi}\left[\frac{\sqrt{1-A}}{A}-\frac{1}{2}\cos^{-1}\frac{A}{A-2}\right] \tag{26}$$

$$r=\frac{A_m^2}{1-2A_m}\left[\frac{\pi}{2}+\pi\sqrt{\alpha}+\frac{\sqrt{\alpha(1-A_m)}}{A_m}-\frac{\sqrt{\alpha}}{2}\cos^{-1}\frac{A_m}{A_m-2}\right] \tag{27}$$

At output short circuited, A is zero and thus according to (26) T_m goes infinity. Since T_m is the shortest switching period, power transferring is automatically stopped when the output is short-circuited (self short-circuit protection).

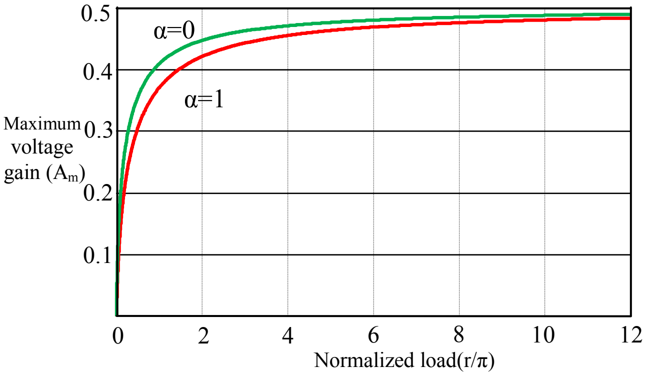

Fig. 4 Maximum attainable voltage gain against r/π

IV. DESIGN PROCEDURE

The parameter α can be used as one degree of freedom for attaining the maximum of efficiency. Consider a 60W prototype converter with the following specifications:

1. Input voltage, V_s=155V ±10%V
2. Output voltage, V_O =48V±1%
3. Resonant frequency, F_r =150kHz
4. And with 20% overdesign

Step 1- Determining α: The curve of efficiency versus α is sketched in Fig.5. This figure is the result of simulation with Pspice software. According to this figure, by choosing α=0.8 the efficiency is set at maximum.

Step 2- Determining Z_r: r is obtained by substituting $A_m=48/(155\times0.9)$ in (27), then according to (3), r =1.52 is obtained where $R=V_o^2/P_{out,max}$ is the load resistance. By applying 20% overdesign Z_r= 23.2Ω is obtained. Then, C_r=46nF, L_{r1}= 4.9µH, L_{r2}= 19.6µH are calculated.

Step 3- The resonant tank characteristics angular frequency ω_r determines switching frequency and should be ascertained by considering the technology of the employed switches.

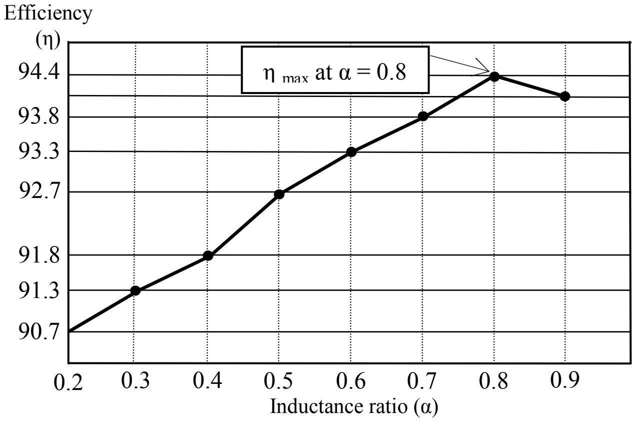

Fig. 5 Maximum attainable efficiency against α

V. EXPERIMENTAL RESULTS

A prototype of the proposed buck converter is implemented, and the waveforms are presented to verify the theoretical analysis. Input and output voltages are 155V and 48V, respectively. The main and auxiliary switches are IRF640 (200V, $R_{DS(ON)}$=0.18Ω), diode is MUR840 (400V) and the output capacitor is 100uF. The passive elements are C_r=46nF, L_{r1}= 4.9µH, L_{r2}=19.6µH. Both inductor cores are ferrite type, and the resonant capacitor is MKP type (metalized polyethylene). The waveforms of Q_1 and Q_2 are presented in Fig. 6. All semiconductor devices operate under soft-switching conditions (TABLE I). A guard-time equal to 400ns exists between Q_1 turn-off and Q_2 turn-on. The converter efficiency is measured greater than 94%

.

TABLE I: Soft-switching operation

Mode	**I**	**II**	**III**	**IV**	**V**
Q_1	Turn on-ZCS	Turn off-ZCS	OFF	OFF	OFF
Q_2	OFF	Turn on -ZCS	ON	Turn off-ZVZCS	OFF
D_r	OFF	OFF	Turn on -ZVS	Turn off-ZVZCS	OFF

VI. CONCLUSIONS

A new LLC resonant buck converter is presented. In the proposed converter, the input and output terminals possess common ground and all semiconductor devices, operate under soft-switching condition which result in increase of efficiency and power density and decrease of EMI. Modal analysis, important equations and design procedure are presented. Experimental results from a 60W laboratory prototype verify the proposed converter operation.

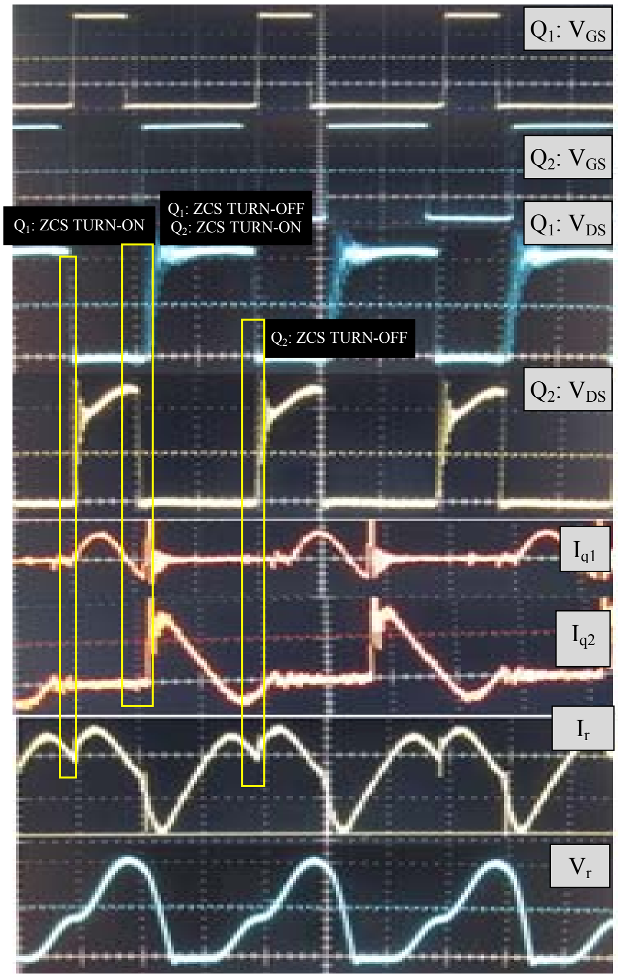

Fig. 6 Practical Results, respectively from the top: V_{GS} of Q_1 (5V/div), V_{GS} of Q_2 (5V/div), V_{DS} of Q_1 (50V/div), V_{DS} of Q_2 (50V/div), I_{q1} (200mA/div), I_{q2} (200mA/div), I_r (200mA/div) and V_r (50V/div). Time scale=5µs/di

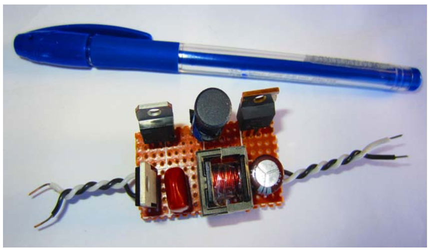

Fig. 7 Implemented converter

REFERENCES

[1] N. Mohan, T.M. Undelan and W.P. Robbins, “Power Electronics Converters,’’ Applications and Design, John Wiley & Sons, 2002, 3rd ed.

[2] M. Jabbari, N.H. Najafabadi, G. Shahgholian and M. Mahdavian, “A novel resonant LLC soft-switching inverting-buck converter,’’ Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2013 10th International Conference, Publication Year: 2013 , Page(s): 1 – 6.

[3] C. Pan, C. Chuang and C. Chu, “A Novel Transformer-less Interleaved High Step-down Conversion Ratio DC-DC Converter with Low Switch Voltage Stress,” Industrial Electronics, IEEE Transactions on ,Publication Year: 2014 , Page(s): 1.

[4] M. Jabbari, S. sharifi, m. delshad, M. Mahdavian, “ LCLL resonant step-down/up converters,’’ ElectricalEngineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2012 9th International Conference on, Publication Year: 2012 , Page(s): 1 – 4.

[5] M. Jabbari and H. farzanehfard, “ Analysis and experimental results of switched-resonator-based buck-boost and inverting-buck converters,’’ Power Electronics for Distributed Generation Systems (PEDG), 2010 2nd IEEE International Symposium, Publication Year: 2010 , Page(s): 412 – 416.

[6] M. Borage, S. Tiwari, and S. Kotaiah, “LCL-T resonant converter with clamp diodes: a novel constant-current power supply with inherent constant-voltage limit,” *IEEE Trans. Ind. Elect.*, vol. 54, no. 2, April 2007, pp. 741-746.

[7] Li.Yajun, Lai. Xinquan, Ye. Qiang and Yuan. Bing, “Novel short-circuit protection technique for DC-DC buck converters,” Circuits, Devices & Systems, IET , Publication Year: 2014 , Page(s): 90 – 99.

[8] M. Jabbari, and H. Farzanehfard, “Family of Soft Switching Resonant DC-DC converters,” *IET Power Electron., 2009*, Vol. 2, Iss. 2, pp. 113–124.

[9] M. Veerachary, V. Jain, “Analysis of zero-voltage transition fourth-order buck converter,” Advances in Energy Conversion Technologies (ICAECT), 2014 International Conference on , Publication Year: 2014 , Page(s): 152 – 157.

[10] Chu. Enhui ,Hou.Xutong ,Zhang. Huaguang ,Wu. Mengyang and Liu .Xiuchong,” Novel Zero-Voltage and Zero-Current Switching (ZVZCS) PWM Three-Level DC/DC Converter Using Output Coupled Inductor, “ Power Electronics, IEEE Transactions on Publication Year: 2014 , Page(s): 1082 – 1093.

[11] T. Zhan, Y. Zhang, J. Nie, Y. Zhang and Z. Zhao, “A Novel Soft-Switching Boost Converter with Magnetically Coupled Resonant Snubber,” Power Electronics, IEEE Transactions on, Publication Year: 2014 , Page(s): 1.

[12] F. Dianbo, F.C. Lee, L. Ya, and X. Ming, “Novel multielement resonant converters for front-end dc/dc converters,” *IEEE PESC’08*, June 2008, pp. 250-256.

[13] B.-R. Lin, C.-C. Chen, “Zero voltage switching DC converter for high-input voltage and high-load current applications,” Power Electronics,IET , Publication Year: 2014 , Page(s): 124 – 131.

[14] X. Xie, J. Zhang, C. Zhao, Z. Zhao and Z. Qian, “Analysis and optimization of LLC resonant converter with a novel over-current protection circuit,” *IEEE Trans. on Power Electron.*, vol. 22, no. 2, 2007,pp.435-443.

[15] J.-W. Yang, H.-L. Do, “Soft-Switching Bidirectional DC-DC Converter Using a Lossless Active Snubber, “Circuits and Systems I: Regular Papers, IEEE Transactions on, Publication Year: 2014 , Page(s): 1 – 9.