International Journal of Power Control and Computation(IJPCSC)
Vol 7. No.2 – 2015 Pp.113-122

available at : www.ijcns.com
ISSN: 0976-268X

DC-TO-DC ENERGY CONVERSION USING NOVEL LOADED RESONANT CONVERTER

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Abstract

Among the many advantages that resonant power conversion has over conventionally adopted pulse-width modulation include a low electromagnetic interference, low switching losses, small volume, and light weight of components due to a high switching frequency, high efficiency, and low reverse-recovery losses in diodes owing to a low di/dt at switching instant. This work presents a novel loaded-resonant converter for direct current (dc)-to-dc energy conversion applications. The proposed topology comprises a half-bridge inductor-capacitor-inductor (L-C-L) resonant inverter and a bridge rectifier. Output stage of the proposed loaded-resonant converter is filtered by a low-pass filter. A prototype dc-to-dc energy converter circuit with the novel loaded-resonant converter designed for a load is developed and tested to verify its analytical predictions. The measured energy conversion efficiency of the proposed novel loaded-resonant topology reaches up to 88.3%. Moreover, test results demonstrate a satisfactory performance of the proposed topology. Furthermore, the proposed topology is highly promising for applications of power electronic productions such as switching power supplies, battery chargers, uninterruptible power systems, renewable energy generation systems and telecom power supplies.

***IndexTerms*—**Loaded-resonant converter, resonant converter, soft-switching converter.

I. INTRODUCTION

Use of semiconductor power switches in power electronic technology has led to rapid development of this technology in recent years. The switching power converter plays a significant role in the power energy conversion applications. In particular, direct current (dc)-to-dc converters are extensively adopted in industrial, commercial, and residential equipment [1]–[6]. These converters are power electronics circuits that convert a dc voltage into a different level, often providing a regulated output. Power semiconductor switches are the major component of power energy conversion systems. Pulse-width modulation (PWM) is the simplest way to control power semi-conductor switches [7], [8]. The PWM approach controls power flow by interrupting current or voltage through means of switch action with control of duty cycles. In practice, a situation in which the voltage across or current through the semiconductor switch is abruptly interrupted is referred to as a hard-switched PWM. Because of its simplicity and ease in control, hard-switched PWM schemes have been largely adopted in modern power energy conversion applications. Therefore, a large switch voltage and a large switch current occurring simultaneously require that the switch withstands high switching stresses, with a safe operating area, as shown by the dashed lines in Fig.1. Fortunately, connecting simple dissipative snubber circuits in series and parallel with switches in hard-switched PWM converters can reduce switch stresses. However, these dissipative snubber circuits transfer the switching power loss from the switch to the snubber circuit, making it impossible to reduce the overall switching power loss.

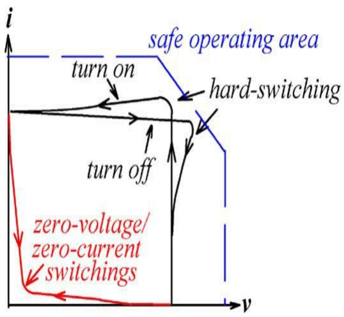

Fig.1. Typical switching trajectories of power switches.

Modern dc-to-dc power converters must be small sized and light weight, as well as have a high energy conversion efficiency. A higher switching frequency implies smaller and lighter inductors, capacitors, as well as filter components of these converters. However, electromagnetic interference (EMI) and switching losses increase with an increasing switching frequency, ultimately decreasing the efficiency and performance of dc-to-dc power converters. To solve this problem, some soft switching approaches must operate under a high switching frequency. Zero voltage switched and zero current switched schemes are two commonly used soft switching methods, in which either the voltage or current is zero during switching transitions, which largely reduce the switching losses, EMI and increase the reliability of the power converters.

While attempting to devise dc-to-dc converters capable of operating at low switching losses, power electronics engineers started developing converter topologies that shape either a sinusoidal current or a sinusoidal voltage waveform, significantly reducing switching losses. Such converters are called soft switching dc-to-dc converters. A soft switching dc-to-dc converter is constructed by cascading a resonant dc-to-ac inverter and a rectifier [9]–[12]. Dc input power is first converted into ac power by the resonant inverter; the ac power is then converted back into dc power by the rectifier. Among the existing soft switching converters, loaded-resonant converters are the most popular type owing to its simplicity of circuit configuration, easy realization of control scheme, low switching losses, and high flexibility for energy conversion applications.

Depending on how energy is extracted from a resonant tank, loaded-resonant converters can be classified into series resonant, parallel resonant and series-parallel resonant converters [13]–[22]. The series-resonant charger is normally formed by an inductor, capacitor, and bridge rectifier. The ac through the resonant tank is rectified at the output terminals, making it possible to obtain the output dc. In contrast to the series resonant converter, the parallel-loaded-resonant converter can control the output voltage at no load by running at a frequency above resonance. The parallel-loaded-resonant converter contains an inductive output filter, explaining why the output current through the capacitor is low and reducing the conduction losses and the ripple voltage of the converter. Furthermore, the parallel-loaded-resonant converter is inherently short circuit protected. Hence, the parallel-loaded-resonant converter is highly promising for dc-to-dc energy con-version applications. Notably, the output voltage at resonance is a function of load and can rise to very high values at no load if the operating frequency is not raised by the regulator. However, the series-parallel converter integrates the best characteristics of series resonant and parallel resonant converters. The resonant tank of this converter is equivalent to that of the parallel-loaded-resonant inverter, except for an additional capacitor in series with the resonant inductor. The series-parallel converter output can run over a wider input voltage and load ranges from no load to full load. For the series-parallel converter with a capacitive output filter, analyzing converter operations and designing circuit parameters are complex tasks because the capacitive output stage is decoupled from the resonant stage for a significant period during the switching cycle. Additionally, the series-parallel converter cannot operate safely with a short circuit at a switching frequency close to the resonant frequency.

Therefore, the energy conversion stage of the series-parallel converter has not been minimized and simplified, resulting in a bulky size and high cost in the applications of dc-to-dc energy conversion. Comparing the above three different loaded-resonant converter topologies reveals that the parallel-loaded-resonant converter is the optimum topology for dc-to-dc energy conversion applications because of its many merits including low switching losses, low stresses, and low noise characteristics. Moreover, for dc-to-dc energy conversion applications, the parallel-loaded-resonant converter is generally recommended as the energy conversion stage due to its simple circuitry and typical input characteristics. However, a large filter inductor to the output side of the bridge rectifier in a traditional parallel-loaded-resonant converter might add significant weight, volume and cost. Based on the parallel-loaded-resonant converter, this work presents a novel loaded-resonant converter. The proposed novel loaded-resonant converter is superior to the conventional parallel resonant converter in terms of miniaturize size, light weight, simple topology and easy control.

The rest of this paper is organized as follows: Section II describes the proposed novel loaded-resonant converter and highlights the operation of the proposed converter. Section III then describes in detail the operating characteristics of the proposed

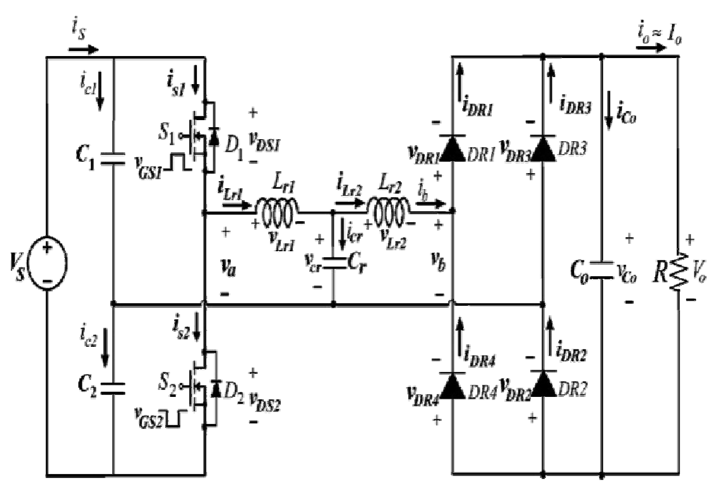

Fig. 2. Proposed loaded-resonant converter for a dc-to-dc energy conversion system.

converter. Next, Section IV summarizes the simulation and experimental results to demonstrate the effectiveness of the proposed converter. Conclusions are finally drawn in Section V along with recommendations for future research.

II. CIRCUIT DESCRIPTION AND OPERATING PRINCIPLES

A. Circuit Description

Energy shortages and increasing oil prices have created the demand for a high energy conversion efficiency and performance. The growing electronic product market has increased the demand for high energy conversion efficiency and high power density of dc-to-dc energy power converters. The soft-switching scheme is the most attractive dc-to-dc energy conversion topology in recent years. The soft-switching method can reduce switching losses and EMI of the switch-mode converter. Fig. 2 shows the proposed loaded-resonant converter for application of the dc-to-dc energy conversion system. The two capacitors, C_1 and C_2, on the input are large and split the voltage of the input dc source. The elements L_{r1}, L_{r2}, and C_r form the resonant tank. The load resistance R is connected across a bridge rectifier via a low-pass filter capacitor C_o. For analysis, the power switching devices are assumed here to be represented by a pair of bidirectional switches operating at a 50% duty ratio over a switching period T. For the half-bridge topology, each bidirectional power switch has an active power switch and an antiparallel diode. The active power switches are driven by nonoverlapping rectangular-wave trigger signals and v_{GS2} with dead time. Thus, we may represent the effect of the power switches by means of an equivalent square-wave voltage source with an amplitude equal to $\pm V_s/2$. Resonant inductor current i_{Lr2} is rectified to obtain a dc bus. The dc bus voltage can be varied and closely regulated by controlling the switching frequency. Because of that, the ac-to-dc power conversion, in this case, is achieved by rectifying the current through resonant inductor L_{r2}, a large filtering capacitance C_o is needed not only to minimize the loading effect of the output circuit, but also to ensure that the voltage across it is mostly constant. Consequently, the voltage across the bridge rectifier has constant amplitudes $+V_o$ and $-V_o$, depending on whether the current i_{Lr2} (t) is positive or negative, respectively. The frequency of this voltage waveform is the same as that of the switching frequency. Based on the above observations, the novel loaded-resonant converter can be modeled as a series $L_{r1} - C_r - L_{r2}$ circuit and a square-wave voltage source $\pm V_o$ in series with the resonant inductor L_{r2}. Fig. 3 shows the simplified equivalent circuit for the proposed loaded-resonant converter.

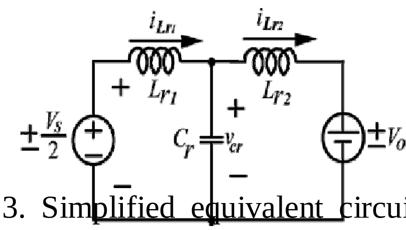

Fig.3. Simplified equivalent circuit for the proposed loaded-resonant converter.

B. Circuit Operating Principles

The following analysis assumes that the converter operates in the continuous conduction mode, in which the semiconductors have ideal characteristics. Fig. 4 displays the idealized steady-state voltage and current waveforms in the proposed novel loaded-resonant converter for a switching frequency f_s that exceeds resonant frequency f_o. Operating above resonance is preferred because the power switches turn on at zero current and zero

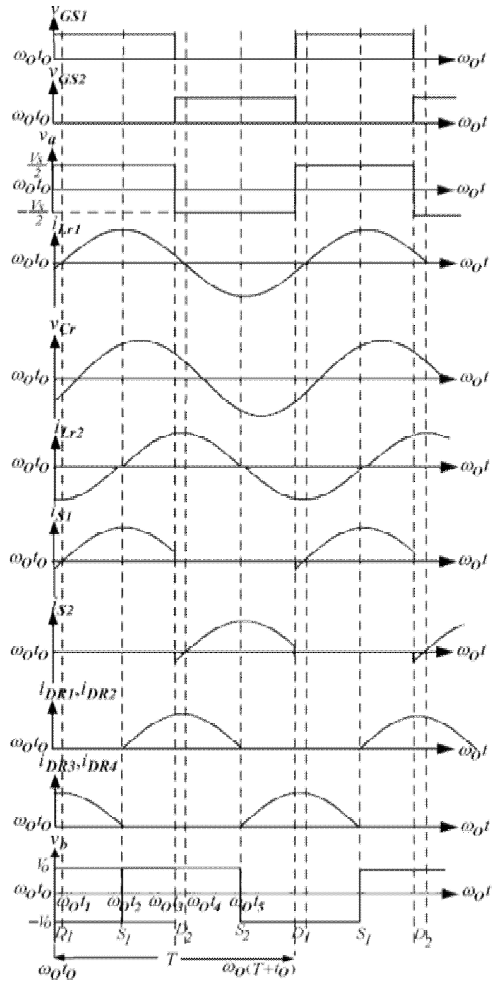

Fig.4. Idealized voltage and current waveforms

Voltage. Thus, the freewheeling diodes do not need to have very fast reverse-recovery characteristics. During the positive half-cycle of the current through the resonant inductor L_{r2}, the power is supplied to the load resistor R through diodes D_{R1} and D_{R2}. During the negative half-cycle of the current through the resonant inductor L_{r2}, the power is fed to the load resistor R through diodes D_{R3} and D_{R4}.

The novel loaded-resonant converter for the application of dc-to-dc energy conversion is analyzed based on the following assumptions.

1) Switching elements of the converter are ideal, such that the decline in forward voltage in the on-state resistance of the power switch is negligible.

2) Equivalent series resistance of the capacitance and stray capacitances is negligible.

3) Characteristics of passive components are assumed to be linear, time invariant, and frequency independent.

4) Filter capacitor C_o at the output terminal of the full-bridge rectifier is usually very large; the output voltage across capacitor C_o can thus be treated as an ideal dc voltage in each switching cycle.

5) Active power switches S_1 and S_2 are turned on and off alternately, by applying a square-wave voltage across the novel loaded-resonant circuit. A situation in which the load quality factor of the novel loaded-resonant converter is sufficiently high suggests that resonant currents, i_{Lr1} and i_{Lr2}, are sinusoidal.

Steady-state operations of the novel loaded-resonant converter in a switching period can be divided into four modes.

Mode I—(Between $\omega_o t_0$ and $\omega_o t_1$):

Periodic switching of the resonant energy tank voltage between $+V_s/2$ and $-V_s/2$ generates a square-wave voltage across the input terminal. Since the output voltage is assumed to be a constant voltage V_o, the

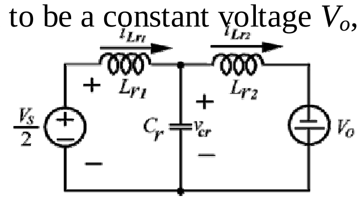

Fig.5. Equivalent circuit of Mode I.

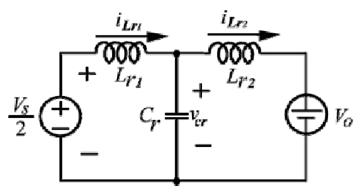

Fig.6. Equivalent circuit of Mode II.

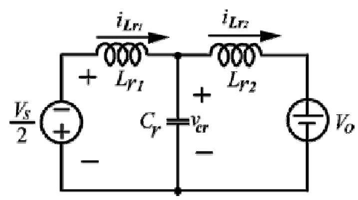

Fig.7. Equivalent circuit of Mode III.

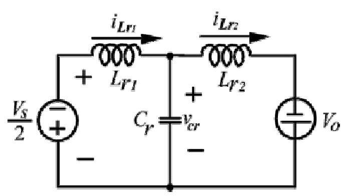

Fig.8. Equivalent circuit of Mode IV.

input voltage to the full-bridge rectifier is V_o when i_{Lr2} (t) is positive and is $-V_o$ when i_{Lr2} (t) is negative. Hence, Fig. 5 displays the equivalent circuit of the proposed novel loaded-resonant converter for the application of dc-to-dc energy conversion in Fig. 2. This time interval ends when i_{Lr2} (t) reaches zero at $\omega_o t_1$.

Before $\omega_o t_0$, active power switch S_2 is excited and conducts a current that equals resonant tank current i_{Lr1}. The active power switch S_1 is turned on at $\omega_o t_0$. However, resonant tank current i_{Lr1} is negative and flows through freewheeling diode D_1. At instant $\omega_o t_1$, resonant tank current i_{Lr1} reverses and naturally commutates from freewheeling diode D_1 to power switch S_1. In this mode, the power switches are turned on naturally at zero voltage and at zero current. Therefore, the current through the active power switch is negative after turning on and positive before turning off.

Although the current in the switches is turned on at zero volt-age and zero current to eliminate turn-on losses, the switches are forced to turn off a finite current, thus allowing turn-off losses exit. Fortunately, small capacitors can be placed across the switches to function as snubbers in order to eliminate turn-off losses.

Mode II—(Between $\omega_o t_1$ and $\omega_o t_2$):

The cycle starts at $\omega_o t_1$ when the current i_{Lr1} resonant tank resonates from negative values to zero. At $\omega_o t_2$, before the half-cycle of resonant current i_{Lr1} oscillation ends, switch S_1 is forced to turn off, forcing the positive current to flow through bottom freewheeling diode D_2. Fig. 6 shows the equivalent circuit.

The positive dc input voltage applied across the resonant tank causes the resonant current that flows through the power switch to go quickly to zero.

Mode III—(Between $\omega_o t_3$ and $\omega_o t_4$):

A turn-off trigger signal is applied to the gate of the active power switch S_1. The inductor current then naturally commutates from active power switch S_1 to freewheeling diode D_2. Mode III begins at $\omega_o t_3$, when diode D_2 is turned on, subsequently producing a resonant stage between inductors L_{r1}, L_{r2} and capacitor C_r. Inductors L_{r1}, L_{r2}, and capacitor C_r resonate. Before $\omega_o t_4$, trigger signal v_{gs2} excites active power switch S_2. This time interval ends when i_{Lr1} (t) reaches zero at $\omega_o t_4$. Fig. 7 shows the equivalent circuit.

Mode IV—(Between $\omega_o t_4$ and $\omega_o t_5$):

When capacitor volt-age i_{Lr2} is positive, rectifier diodes D_{R1} and D_{R2} are turned on with zero-voltage condition at instant $\omega_o t_4$. Fig. 8 shows the equivalent circuit. When inductor current i_{Lr2} changes direction, rectifier diodes D_{R1} and D_{R2} are turned off at instant $\omega_o t_5$, and Mode IV ends.

When driving signal V_{gs1} again excites active power switch S_1, this mode ends and the operation returns to mode I in the subsequent cycle.

During the positive half-cycle of the inductor current i_{Lr2}, the power is supplied to the load through bridge rectifier diodes D_{R1} and D_{R2}. During the negative half-cycle of the inductor current, the power is supplied to the load through bridge rectifier diodes D_{R3} and D_{R4}.

IV. EXPERIMENTAL RESULTS

A prototype was constructed to demonstrate the effectiveness of the proposed loaded-resonant converter. The developed topology was connected to a 24V dc source which is converted into 12V dc using novel loaded resonant converter. Circuit simulations are performed using MATLAB Software. Additionally, the proposed loaded-resonant converter was implemented in practice. Finally, the simulation and practical results were compared with each other.

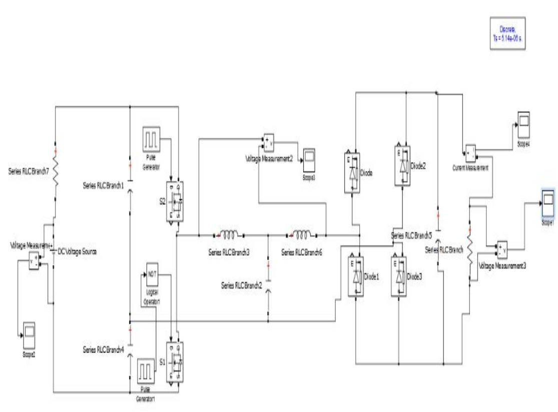

Fig.9. Simulation Circuit of Proposed System.

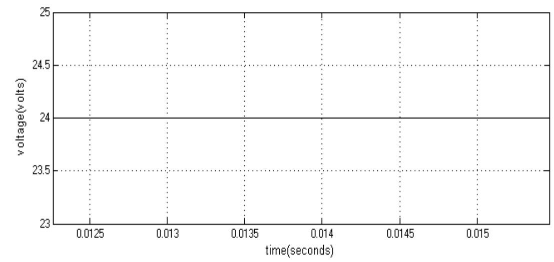

Fig.10.Simulated waveform of Input Voltage.

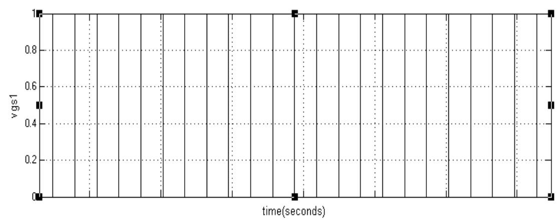

Fig.11. Simulated waveform of Triggered signals on the power switches.

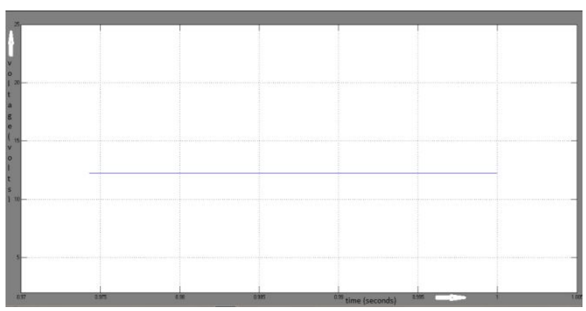

Fig.12. Simulated Waveform Output Voltage of Proposed System.

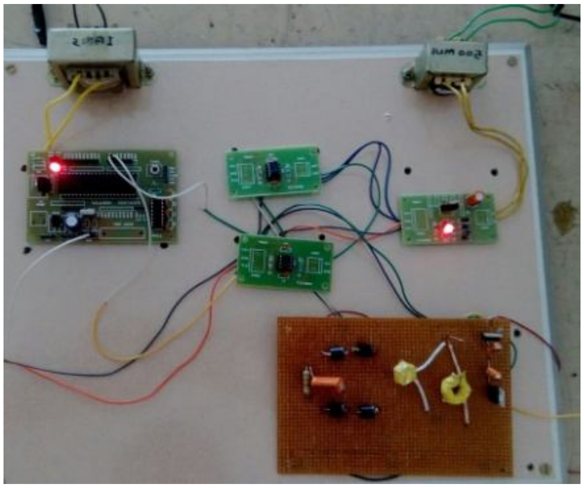

Fig.13. Experimental setup of proposed topology.

Fig.10. shows the simulated input voltage (24V), Fig.11.shows the simulated gate Triggering pulses, Fig.12 shows the simulated output voltage (12V) and Fig.13. shows the experimental setup of proposed topology.

According to the above figures, waveforms of the simulations are consistent with results of the experimental circuit results. Also, power switch can be turned on without retaining voltage, thus achieving ZVS condition with low switching losses. Hence, the energy conversion efficiency of the proposed novel loaded-resonant converter reaches 88.3%.

V. CONCLUSION

This work developed a novel loaded-resonant converter with a bridge rectifier for the application of dc-to-dc energy conversion. The circuit structure is simpler and less expensive than other control mechanisms, which require many components. The developed topology is characterized by zero-voltage switching, reduced switching losses, and increased energy conversion efficiency. The output voltage/current can be determined from the characteristic impedance of the resonant tank by the adjustable switching frequency of the converter, whereas the proposed loaded-resonant converter is applied to a load in order to yield the required output conditions. Experimental results demonstrate the effectiveness of the proposed converter. The energy conversion efficiency is 88.3%, which is quite satisfactory when the proposed loaded-resonant circuit operating above resonance is applied to a dc-to-dc converter. In contrast with the conventional parallel-loaded-resonant converter, energy conversion efficiency can be improved using the novel loaded-resonant converter with a full-bridge rectifier topology. An excellent performance is achieved at a lower cost and with fewer circuit components than with the conventional converter.

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