Loaded Resonant Converter for the DC to DC Energy Conversion Applications

U.Vinod kumar*, P.Sai Sampath Kumar**, (PG student, RGM CET)*, (Asst. Professor, RGM CET)**, Vinodkumar251@gmail.com*, sammitsme@gmail.com**.

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 $dV/dt$ 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.

Index Terms: Loaded resonant converter, resonant converter, and Soft switching converter.

I. INTRODUCTION

Use of 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 Figure 1.

![Figure 1: Typical switching trajectories of power switches.](image)

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.

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-alternating current (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]–[23]. 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 conversion 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 proosed 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. Figure 2 shows the proposed loaded-resonant converter for application of the dc-to-dc energy conversion system.

![Figure 2: Proposed loaded-resonant converter for a dc-to-dc energy conversion system.](image)

The two capacitors, C1 and C2, on the input are large and split the voltage of the input dc source. The elements L1, L2, and Cr form the resonant tank. The load resistance R is connected across a bridge rectifier via a low-pass filter capacitor Cr. 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 non-overlapping rectangular-wave trigger signals VGS1 and VGS2 with dead time. Thus, we may represent the effect...
of the power switches by means of an equivalent square-wave voltage source with amplitude equal to ±V/2. Resonant inductor current \( i_{L2} \) 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 \( L_2 \); a large filtering capacitance \( C \) 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 \( +V \) and \( -V \), depending on whether the current \( i_{L2} \) 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 modelled as a series \( L_1 - C - L_2 \) circuit and a square-wave voltage source \( ±V \), in series with the resonant inductor \( L_2 \). Figure 3 shows the 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. Figure 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 \( f_0 \). Operating above resonance is preferred because the power switches turn on at zero current and zero 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 \( L_2 \), 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 \( L_2 \), 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 \( C \) at the output terminal of the full-bridge rectifier is usually very large; the output voltage across capacitor \( C \) can thus be treated as an ideal dc voltage in each switching cycle; and

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, \( i_{L1} \) and \( i_{L2} \), are sinusoidal.

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

**Mode 1** — (Between \( \omega_{o1}t_0 \) and \( \omega_{o1}t_1 \)): Periodic switching of the resonant energy tank voltage between \( +V/2 \) and \( -V/2 \) generates a square-wave voltage across the input terminal. Since the output voltage is assumed to be a constant voltage \( V_o \), the input voltage to the full-bridge rectifier is \( V_o \) when \( i_{L2} \) (t) is positive and is \( -V_o \) when \( i_{L2} \) (t) is negative. Hence, Figure 5 displays the equivalent circuit of the proposed novel loaded-resonant converter for the application of dc-to-dc energy conversion in Figure 2. This time interval ends when \( i_{L2} \) (t) reaches zero at \( \omega_{o1}t_1 \).

![Figure 4: Idealized voltage and current waveforms.](image-url)
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 $\omega t_1$ and $\omega t_2$): The cycle starts at $\omega t_1$ when the current $i_{L1}$ resonant tank resonates from negative values to zero. At $\omega t_2$, before the half-cycle of resonant current $i_{L1}$ oscillation ends, switch $S_1$ is forced to turn off, forcing the positive current to flow through bottom freewheeling diode $D_2$. Figure 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 $\omega t_3$ and $\omega t_4$): 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 $\omega t_3$, then the system is considered as unstable. The L indices are calculated for all the load buses and the maximum of the L indices gives the proximity to the system to voltage collapse. When diode $D_2$ is turned on, subsequently producing a resonant stage between inductors $L_{r1}$, $L_{c2}$ and capacitor $C_r$. Inductors $L_{r1}$, $L_{c2}$, and capacitor $C_r$ resonate. Before $\omega t_4$, trigger signal $V_{sp2}$ excites active power switch $S_2$. This time interval ends when $i_{L1}(t)$ reaches zero at $\omega t_4$. Figure 7 shows the equivalent circuit.

Mode IV— (Between $\omega t_4$ and $\omega t_5$): When capacitor voltage $i_{L2}$ is positive, rectifier diodes $D_{R1}$ and $D_{R2}$ are turned on with zero-voltage condition at instant $\omega t_5$. Figure 8 shows the equivalent circuit. When inductor current $i_{L2}$ changes direction, rectifier diodes $D_{R1}$ and $D_{R2}$ are turned off at instant $\omega t_6$, and Mode IV ends. When driving signal $V_{sp1}$ 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 $i_{L2}$, 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 $D_{R4}$.

III. OPERATING CHARACTERISTICS

Figure 2 shows the novel loaded-resonant converter for the application of dc-to-dc energy conversion system. The switching frequency of the active power switches is assumed to be greater than the resonant frequency so that the resonant current is continuous. With a large capacitive filter at the output terminal of the bridge rectifier, the output voltage may be assumed to be constant.

To facilitate the analysis of the operation of the novel loaded-resonant converter, the circuit in Figure 2 can be simplified to a schematic circuit as shown in Figure 3. Since the output voltage is assumed to be a constant $V_o$ then the input voltage of the bridge rectifier, $V_{in}$, is $V_o$ when $i_{L1}$ is positive and is $-V_o$ when $i_{L2}$ is negative.

The input part of the novel loaded-resonant converter for the application of dc-to-dc energy conversion is composed of a dc input voltage source $V_i$ and a set of power switches. The active power switches are controlled to produce a square-wave voltage $v_o$. Since a resonant circuit forces a sinusoidal current, only the power of the fundamental component is transferred from the input source to the resonant circuit. Hence, it is sufficient to consider only the fundamental component of this converter. The novel loaded-resonant converter with a bridge rectifier stage for dc-to-dc energy conversion system is analyzed by considering the fundamental frequency of the Fourier series for the voltages and currents. The error due to this approximation is rather small when the switching frequency is higher than the resonant frequency. The fundamental mode equivalent circuit is shown in Figure 9.
The proposed novel load-resonant converter can be simplified as shown in Figure. 10. Then, the equivalent resonant capacitor \( C_{eq} \) and equivalent resistor \( R_{eq} \) can be evaluated respectively,

\[
C_{eq} = \frac{(aR_cC_f)^2}{(a^2R_c^2C_f+a^2R_c-a^2R_c-1)^2}
\]

(6)

\[
R_{eq} = \frac{R_c}{(aR_cC_f)^2+(aR_c-a^2R_c-1)^2}
\]

(7)

The loaded quality factor of the novel loaded-resonant circuit is defined as

\[
Q_L = \frac{f_c}{\omega_{eq}}
\]

(8)

Importantly, the proposed novel loaded-resonant converter is characterized by the feature that the reactance of the resonant tank depends on the switching frequency. Therefore, the output voltage can be regulated by adjusting the switching frequency of the proposed novel loaded-resonant converter. Owing to this characteristic, the proposed loaded-resonant converter is the preferred configuration for the applications of dc-to-dc energy conversion.

### IV. EXPERIMENTAL RESULTS

A prototype was constructed to demonstrate the effectiveness of the proposed loaded-resonant converter. The developed topology was connected to a 24-V dc source. Table 1 lists the circuit parameters for the proposed loaded-resonant converter. Circuit simulations are also performed using PSpice software. Additionally, the proposed loaded-
resonant converter was implemented in practice. Finally, the simulation and practical results were compared with each other. Figure 11 (a) and (b) shows the trigger signals on the power switches, where vGS1 denotes the trigger signal on switch S1, and vGS2 represents the trigger signal on switch S2. Figure 12(a) and (b) plots the input voltage and current waveforms of the resonant tank. Figure. 13(a) and (b) shows the waveforms of resonant capacitor voltage Vcr and resonant capacitor current Icr.

Figure 11: Trigger signals on the power switches Simulated waveform

Figure 12: Input voltage and current waveforms of the resonant tank Simulated waveform.

Figure 13: Waveforms of switch signal vds1 and switch current is1 simulated waveform.

Figure 14: Voltage waveforms of rectifier diodes DR1 and DR2.

Figure 15: Input voltage vb and current ilr2 of the bridge rectifier

Figure 16: Resonant capacitor current icr and resonant capacitor voltage vcr

Figure 17: Current wave forms of rectifier diodes iDR1 and iDR2
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.

V. CONCLUSION

This work developed a novel loaded-resonant converter with a bridge rectifier for the application of dc-to-dc energy con-version. 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.

REFERENCES


2006.


P. Sai Sampath Kumar received the B.Tech (Electrical and Electronics Engineering) degree from the Jawaharlal Nehru Technological University, Hyderabad in 2008 and M.Tech (Power Electronics) in 2011 from Jawaharlal Nehru Technological University, Anantapur. He is currently an Asst. Professor of the Dept. Electrical and Electronics Engineering, Rajeev Gandhi Memorial College of Engg. & Tech, Nandyal. His field of interest includes Matrix Converters, Pulse Width Modulation, Power Electrical & Drives and Power Systems (E-mail: sammitsme@gmail.com).

U. Vinod Kumar received the B.Tech (Electrical and Electronics Engineering) degree from the Jawaharlal Nehru Technological University, Anantapur in 2011 and pursuing M.Tech (Power Electronics) in from the Jawaharlal Nehru Technological University, Anantapur. His field of interest includes Resonant Converters, pulse width Modulation, Power Electrical & Drives and Power Systems (E-mail: vinodkumar251@gmail.com).