

A High Voltage Gain Step-up Resonant DC-DC Converter Topology with Reduced Switch Count

A Sowmya¹ | Dr. D Murali²

¹PG Scholar, Department of EEE, Government College of Engineering, Salem, Tamil Nadu, India.

²Associate Professor, Department of EEE, Government College of Engineering, Salem, Tamil Nadu, India.

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ABSTRACT

The resonant converters have attracted a lot of attention because of their high efficiency and low switching losses. This paper presents the analysis of a high voltage gain non-isolated step-up DC-DC converter topology using resonant technology. The proposed converter configuration has reduced number of power semiconductor switches compared to the existing isolated converter topology having four semiconductor switches. The proposed topology employs capacitor-inductor-capacitor (C-L-C) resonant circuit configuration. The size of the proposed converter and the losses in the converter are greatly reduced. Both the converters with resonant components are simulated in Matlab/Simulink platform to validate their performance. The time-domain simulation results demonstrate that the proposed non-isolated converter gives improved voltage gain compared to the existing two-stage isolated resonant DC-DC converter.

KEYWORDS: C-L-C configuration, DC-DC converter, Matlab/Simulink, Resonant technology, Time-domain simulation results, Voltage gain.

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I. INTRODUCTION

There are certain applications, such as renewable energy, photovoltaic arrays and fuel cell stacks, automobile electrical systems, and uninterruptible power systems, which require high voltage gain and efficiency based power converters [1]. Two step-up converters can be cascaded to realize a high voltage gain [2]. In cascaded scheme, the final output voltage is only regulated by the duty-ratio of the boost pre-regulated converter. Due to the hard-switching operation in the pre-regulated stage, the efficiency is limited and it is hard to be highly promoted.

The input-parallel-output-series (IPOS) architectures for the combined converters to

achieve high voltage gain are proposed by some authors in [3]. These architectures are responsible for the increase of cost and circuit size with the reduction of reliability. The concept of high-step-up coupled-inductor boost converters is given by some authors to achieve high voltage gain [4]-[6]. The coupled-inductor approach makes the design process of the magnetic component complex, especially under high turns-ratio situations. The energy stored in the leakage inductor would also result in high spikes. An interleaved boost converter with a Bifold Dickson voltage multiplier suitable for interfacing low-voltage renewable energy sources to high-voltage distribution buses and other applications that require a high voltage gain conversion ratio is presented in [7]. However,

high-order voltage- multiplier circuits result in increase of cost, circuit size and power loss [8].

In recent years, resonant converters have become more popular and are also widely applied to achieve a high voltage gain. One key attractive characteristic is that a resonant converter can easily achieve high efficiency and allow high frequency operation with their intrinsic wide soft-switching ranges. Hence, Zero Current Switching (ZCS) or Zero Voltage Switching (ZVS) can be easily realized during switching transitions. The ZVS reduces converter-generated Electro-Magnetic Interference (EMI) and ZCS is used to commutate the semiconductor switches. The LC Series Resonant Converter (SRC) has a variety of Continuous Conduction Modes (CCMs) and Discontinuous Conduction Modes (DCMs) [9]. In addition, the SRC is hard to regulate the output voltage under light load conditions while the LC Parallel Resonant Converter (PRC) is hard to regulate the output voltage under heavy load conditions. The LLC resonant converter is attractive and shows a lot of unique improvements [10]. However, the design process of an LLC transformer needs a lot of attention to obtain a satisfactory compromise between the leakage and magnetizing inductances [11]. The power loss caused by the circulating current associated with magnetizing inductance is large when the switching frequency is far from the resonant frequency. Moreover, in SRC, LCC and LLC converters, the low input voltage situations may lead to the use of more bulky resonant capacitors in parallel to improve the efficiency.

A DC/DC converter topology for charging high voltage bulk capacitors for pulsed load applications is presented in [12]. This converter is capable of efficiently transferring power from 30 V input to a capacitor charging from 0 V to 6 kV. An isolated high step-up converter with secondary-side resonant loops is proposed and analyzed in [13]. By placing the resonant loops on the secondary side, the current stress for the resonant capacitors is greatly reduced. The power loss caused by the equivalent series resistance of the resonant capacitor is also decreased. Clamp diodes in parallel with the resonant capacitors ensure a unique DCM in the converter. The reverse-recovery problems of diodes are also alleviated by the leakage inductor. This high step-up converter is able to produce only a 400 V DC output with a 35 V – 42 V input DC voltage. A resonant converter topology, comprising of a half-bridge inductor-capacitor-inductor (L-C-L) resonant

inverter and a bridge rectifier, is proposed in [14]. This converter is able to produce only 12 V DC with a input voltage of 24 V. A new arrangement of loaded resonant converter for DC-DC energy conversion applications is analyzed in [15]. This circuit consists of a capacitor-inductor-capacitor (C-L-C) resonant inverter and a half-bridge diode rectifier. This configuration is able to produce only 21 V output DC voltage with 24 V input DC voltage. For the purpose of finding a high efficiency step-up converter suitable for the low input voltage field, an improved configuration of step-up converter comprising of C-L-C resonant inverter and a bridge rectifier with clamp diodes is proposed in this paper. The C-L-C resonant converter is more preferable than the L-C-L configuration because it improves the energy conversion efficiency and also reduces the equipment cost. The proposed configuration has the elimination of two semiconductor switches and a transformer.

The structure of the research work presented in this paper is organized in the following sequence: The various modes of operation of the existing LC series resonant converter are briefly explained in section 2. The proposed improved converter configuration is presented in section 3. The simulation results and discussions are given in section 4. This is followed by the conclusion in the concluding section 5.

II. EXISTING RESONANT CONVERTER CONFIGURATION

A schematic of the existing converter with clamp diodes on the secondary side is shown in Fig. 1 [13]. The various modes of operation are illustrated in Fig. 2, Fig. 3, Fig. 4, Fig. 5, and Fig. 6 respectively. For the sake of simplicity, the converter is called “LC-DS”, which means “LC resonant converter with clamp Diodes on the Secondary side”. Therefore, the LC-DS is symmetrical to the LC-DP. The input structure consists of four active switches (S_1 - S_4), which forms a full-bridge configuration to fully utilize the input voltage. On the secondary side of the transformer, two rectifier diodes (D_1 and D_2) and two clamp diodes (D_3 and D_4) with paralleled resonant capacitors (C_1 and C_2) form the rectifier stage. The leakage inductor L is inserted on the secondary side. The resistance of the load resistor is denoted by R_L . A capacitor C_0 is placed at the output. As a result, the output voltage contains negligible harmonics of the switching frequency. The resonant process can be determined by the leakage inductor and the two resonant capacitors. ‘ N ’ denotes the transformer turns-ratio. The

following assumptions are made for the configuration:

- (i). All of the component models are ideal and the parasitic parameters are not considered here.
- (ii). The switching dead-time is neglected.
- (iii). The magnetizing inductor L_m is large enough and the magnetizing current is neglected.

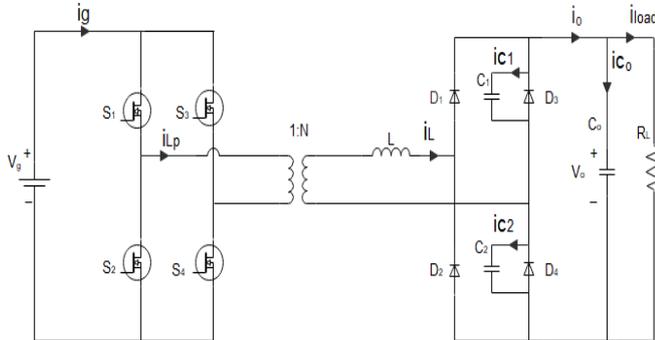


Fig. 1 Existing converter configuration

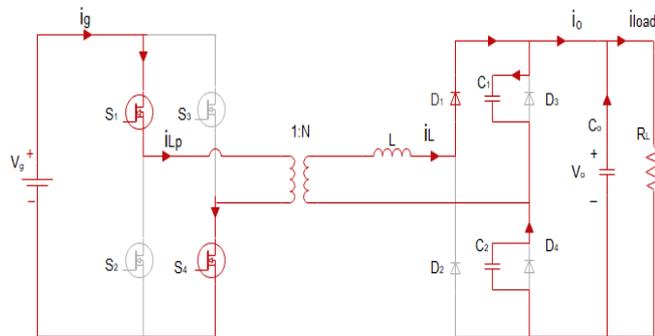


Fig. 2 Conduction path during Mode I ($t_0 < t < t_1$)

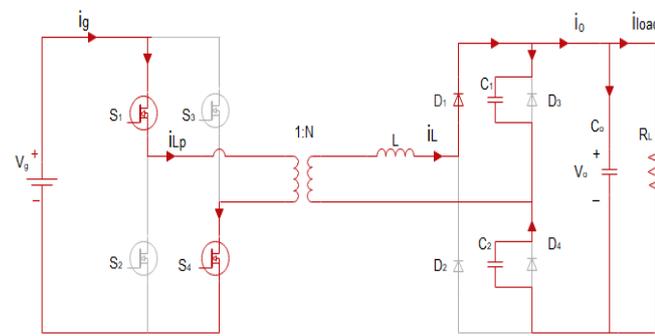


Fig. 3 Conduction path during Mode II ($t_1 < t < t_2$)

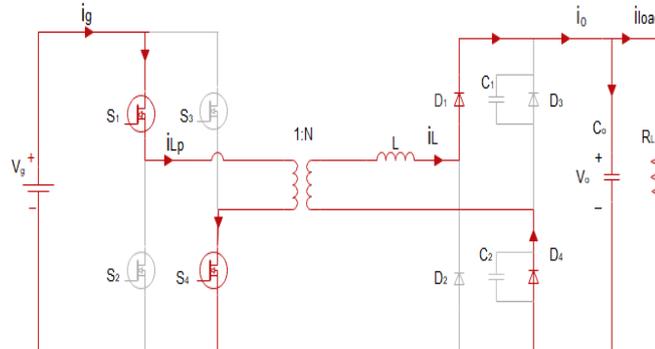


Fig. 4 Conduction path during Mode III ($t_2 < t < t_3$)

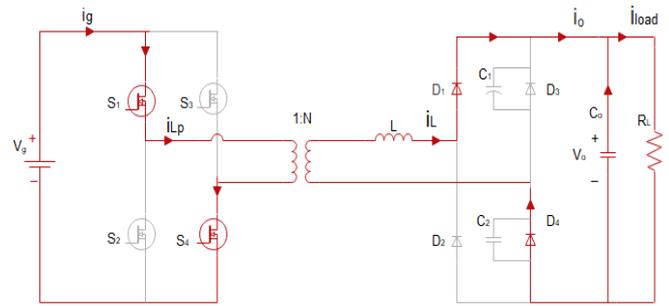


Fig. 5 Conduction path during Mode IV ($t_3 < t < t_4$)

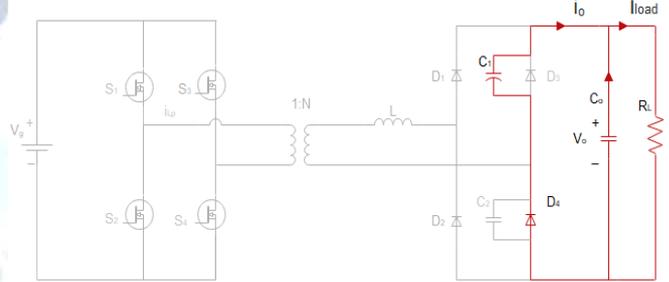


Fig. 6 Conduction path during Mode V ($t_4 < t < t_5$)

III. PROPOSED RESONANT CONVERTER TOPOLOGY

The proposed converter topology is shown in Fig. 7. In the proposed converter configuration, the step-up transformer is replaced by resonant tank circuit and the two switches are replaced by the inductors. Hence, the size of the converter is reduced and the cost is low compared to the existing converter. By having the inductors along with the switches, the voltage gets boosted up in the circuit.

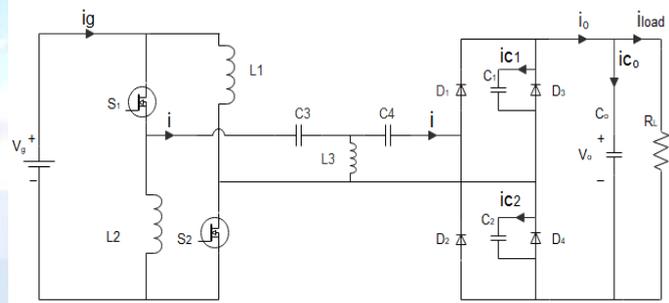


Fig. 7 Proposed converter topology

MODE 1:

The Fig. 8 shows the conduction path of the converter through the resonant components during Mode 1. The switch S_2 is excited before the period $\omega_0 t_0$. The switch S_1 will be turned on at $\omega_0 t_0$. The current from resonant circuit is negative and it will flow through the freewheeling diode D_1 to switch on S_1 . Hence, the switches are turned on naturally at zero voltage and zero current instants. Therefore, the current through the switch which is in conduction mode will be negative before turn on and positive before turn off.

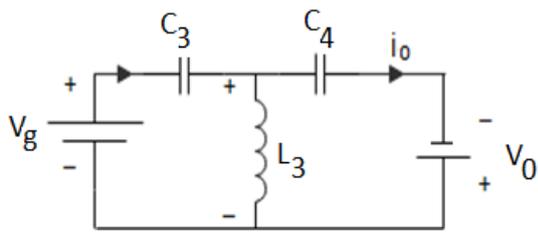


Fig. 8 Conduction path through the resonant circuit during Mode 1

MODE 2:

During this mode, the current through resonant tank circuit is transforming from negative to zero at $\omega_0 t_1$. The switch S_1 is commutated to turn off, forcing the current to flow through the freewheeling path D_2 . The Fig. 9 shows the conduction path of the converter through the resonant components during Mode 2. The positive DC input voltage applied across the tank circuit causes the resonant current that flows through the switches to go to zero.

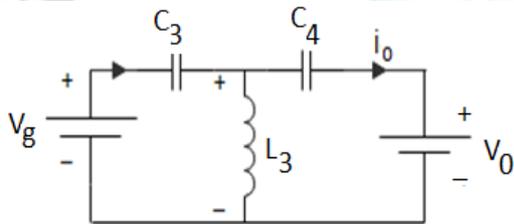


Fig. 9 Conduction path through the resonant circuit during Mode 2

MODE 3:

Now a turn-off trigger signal is given to the gate of S_1 which is in conduction mode. The inductor current then spontaneously turns off S_1 from active mode to flow through freewheeling path D_2 . This mode starts when diode D_2 starts conducting. The equivalent arrangement for this mode is shown in Fig. 10.

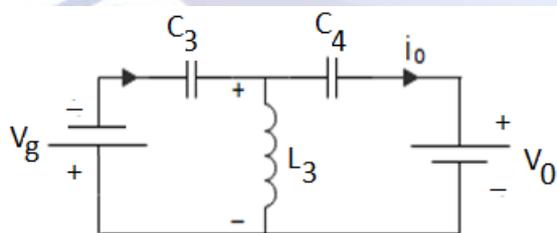


Fig. 10 Conduction path through the resonant circuit during Mode 3

MODE 4:

When voltage across the resonant tank circuit is positive, the rectifier diodes come to conduction mode and the input voltage is applied to the load through these diodes. Similarly, when the direction of current flow is changed in resonant tank circuit, these diodes are turned off because of the reverse voltage. When the trigger signal V_g is applied, the

excitation starts and the process is repeated from Mode 1. The Fig. 11 shows the conduction path of the converter through the resonant components during Mode 4.

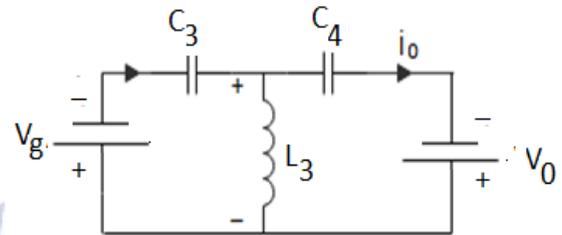


Fig. 11 Conduction path through the resonant circuit during Mode 4

IV. SIMULATION RESULTS AND DISCUSSION

The existing isolated resonant converter topology is simulated in Matlab / Simulink environment as shown in Fig. 12. There are two stages in the existing scheme; the first stage is DC-AC conversion, the second stage is AC-DC conversion. The transformer with turns-ratio of 1:6 and magnetizing inductance of 73 μH isolates the two stages. The value of inductance of the series inductor is 30 μH . The resonant capacitors C_1 and C_2 each have 30 nF capacitance. The output capacitor C_0 has 73 μF capacitance. The load resistance R_L is 2 k Ω . The switching frequency is 30 kHz. The existing topology gives a DC output voltage of 400V with an input DC voltage of 40V with transformer ratio of 1:6. The duty cycle ratio of the switches is taken as 50% ($d=0.5$). When the duty cycle is in the range between 0.5 and 0.8, the output voltage level may get boosted up to 10 times the input voltage. The output current is of the order of 0.2 A. The waveforms of output voltage and output current are shown in Fig. 13 and Fig. 14.

The simulation of the proposed non-isolated resonant converter configuration is carried out in Matlab / Simulink platform as shown in Fig. 15. This configuration also has two stages; the first stage is DC-AC conversion, the second stage is AC-DC conversion. A resonant circuit is employed between the two stages. The inductors on the input side have inductance of 180 μH each. The resonant components have values of $C_3 = C_4 = 10 \mu\text{F}$ and $L_3 = 410 \mu\text{H}$. The capacitors C_1 and C_2 across the diodes have capacitance of 30 nF each. The output capacitor C_0 has 80 μF capacitance. The load resistance R_L is 2 k Ω . The switching frequency is 30 kHz. The resonant frequency (f_r) of the C-L-C circuit is calculated as 22 kHz.

$$f_r = \sqrt{\frac{1}{L_3 \left(\frac{1}{C_3} + \frac{1}{C_4} \right)}} = 22 \text{ kHz}$$

An input DC voltage of 40 V is given to the circuit, with the duty cycle ratio of the switches as 80% (d=0.8). A DC output voltage of around 1000 V is obtained when the duty cycle is varied between 0.5 and 0.8. The voltage gain of the proposed converter is almost 25 times the input voltage. Moreover, in the proposed converter system, the switches are reduced to two thereby reducing the losses and the size of the converter. The gate pulse given to the switches of the converter is as shown in Fig. 16. The waveforms of output voltage and output current for the proposed converter are shown in Fig. 17 and Fig. 18. The output current is of the order of 0.5 A.

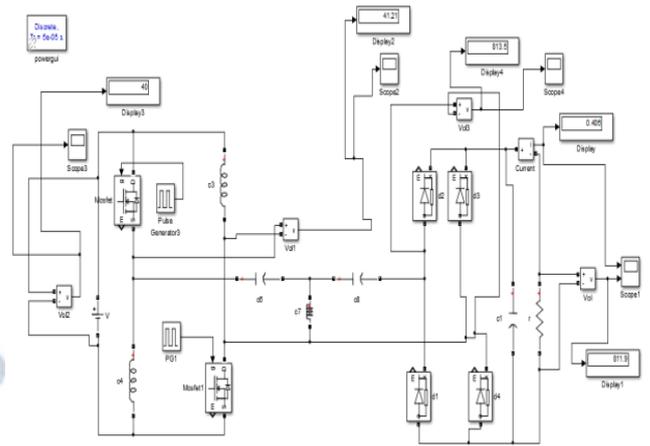


Fig. 15 Simulation diagram of the proposed resonant converter configuration

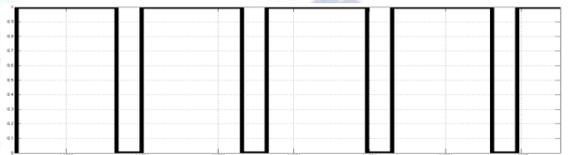


Fig. 16 Gate pulse to the switches of the proposed converter

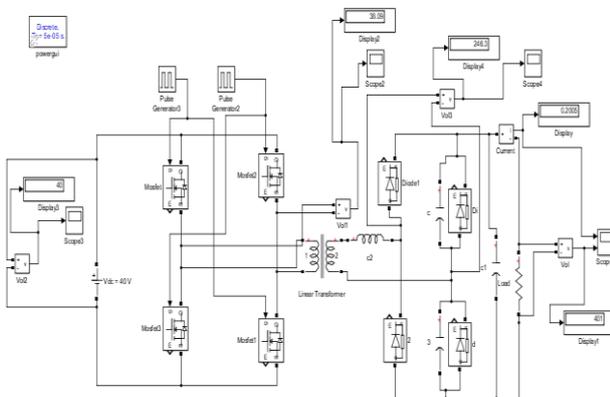


Fig. 12 Simulation diagram of the existing resonant converter topology

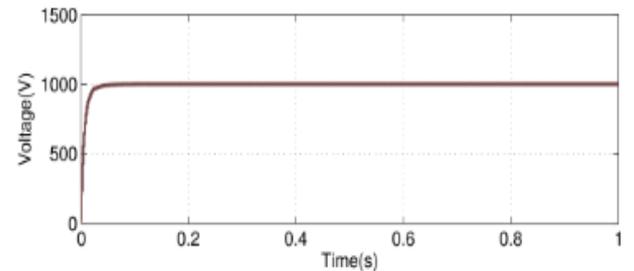


Fig. 17 Output voltage waveform of the proposed converter topology

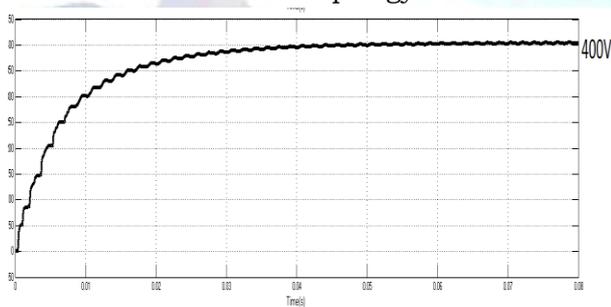


Fig. 13 Output voltage waveform of the existing converter topology

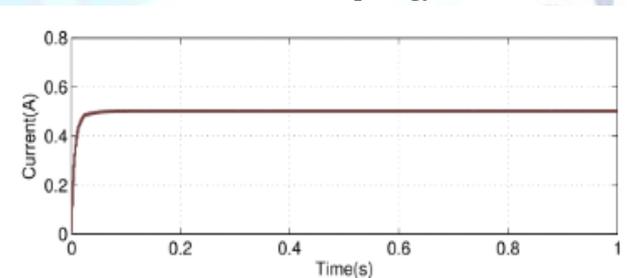


Fig. 18 Output current waveform of the proposed converter topology

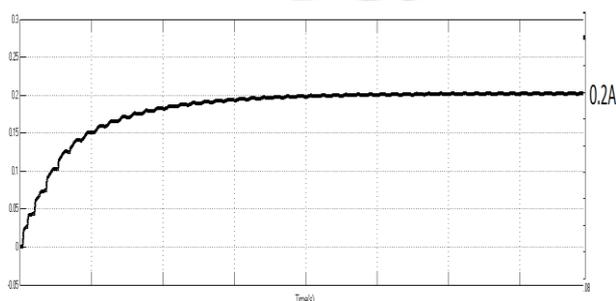


Fig. 14 Output current waveform of the existing converter topology

The current and voltage waveforms of the resonant capacitor C_3 and C_4 for the proposed converter configuration are shown in Fig. 19, Fig. 20, Fig. 21, and Fig. 22 respectively.

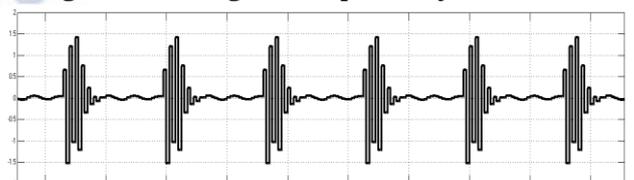


Fig. 19 Waveform of current through the resonant capacitor C_3

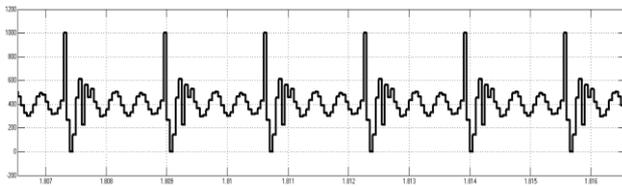


Fig. 20 Waveform of voltage across the resonant capacitor C_3

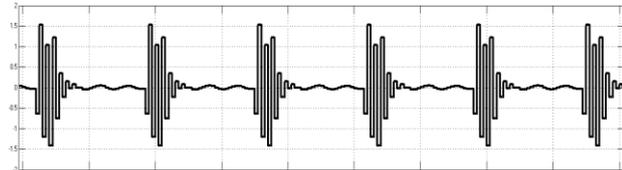


Fig. 21 Waveform of current through the resonant capacitor C_4

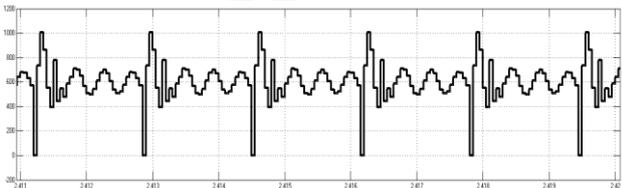


Fig. 22 Waveform of voltage across the resonant capacitor C_4

V. CONCLUSION

In this paper, the performance analysis of a DC-DC resonant converter with clamp diodes on the secondary side is proposed. The proposed converter configuration is compared with that of the existing topology. The digital simulations are carried out in Matlab/Simulink environment to validate the performance of the proposed converter. The results demonstrate that the proposed converter configuration has the capability to produce an output voltage which is almost 25 times the input voltage, whereas the existing converter topology could produce the output voltage which is only 10 times the input voltage. Hence, the proposed converter configuration can improve the voltage gain of the system. Moreover, in the proposed non-isolated converter topology, the number of power semiconductor switches is reduced thereby the switching losses, the voltage stresses and the current stress of the resonant capacitors are significantly reduced. In both the existing and proposed converter configurations, the switches are turned on and off by the conventional PWM technique. Therefore, the non-isolated configuration is suitable to realize high DC voltage gain and slightly improved efficiency.

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