



A High Efficient, Compact 4th Order CLCL Converter Features to Use Constant-Current Power Supply

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ABSTRACT: This paper presents a 4th order CLCL resonant converter which can be used as a constant current power supply (CCPS) with immittance property. This structure is one of the resonance converter topologies that has not been studied. This converter is designed with immittance characteristic with two inductors and two capacitors in the resonant network. A detailed analysis and design process of a 200w converter as a constant current supply have been provided and simulation results are verified with results of a constructed converter. In analyzing this converter, the AC analysis method is used. This converter with its unique structure, a combination of series and parallel resonant converter has the advantages of both. As a constant current supply, CLCL resonant converter has the advantages of rigidity against short circuit, no need to control against load changes, easy operation in parallel mode, low circulating currents and high efficiency about 93%, due to its soft-switching operation. For this converter, leakage and magnetizing inductance of a transformer can be used as a part of the resonance network and it decreases the converter size. As a result, the cost of constructing the converter is reduced. Also, series capacitor eliminates the DC component and prevents the transformer saturation in unbalanced conditions. With fixed-frequency performance, filter design will also be easier. Other structures have only some of these benefits, but this structure has all these. Considering these advantages, the proposed topology can be used in a variety of applications such as magnetic power supplies, capacitor charging power supplies and driver for laser diodes.

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1- Introduction

Resonant converters (RC) have special features such as zero-voltage switching (ZVS)[1], zero current switching (ZCS)[2], high-frequency performance [3], high efficiency [4], small size and low electromagnetic interference (EMI)[5]. These converters are used as DC power supplies for industrial, commercial, and domestic applications, and AC power supplies for induction heating [6], power factor correction [7] and ballast lamp discharging [8].

Series [9] and parallel [10] resonant converters (SRC and PRC) are the basis of the performance of the topologies of the other RCs which have two reactive elements. Each of these converters as the basis for resonant converters has advantages and disadvantages, and to remove limitations in SRC and PRC [11], resonant converters with three and four reactive elements are applied [12]. Despite the simplicity in design of third-order resonant converters, in terms of design flexibility and attraction of parasitic circuit elements, these converters have more restrictions than 4th order converters in the absorption of the circuit's parasitic elements and design flexibility [13]; therefore, 4th order converters are more suitable to investigate.

By utilizing these basic structures, in this paper, we have achieved a 4th order topology that has a significant improvement in no-load regulation characteristic compared to the two previously mentioned topologies. This converter with its unique structure, a combination of series and parallel resonant converter, has the advantages of both. As a constant current supply, CLCL resonant converter has the advantages of rigidity against short circuit, no need to control against

load changes, easy operation in parallel mode, low circulating currents and high efficiency. When this 4th order converter, called the resonant CLCL converter, operates at a switching frequency equal to the resonance frequency, it will provide a load-dependent output voltage. Thus, the output voltage can be set against wide changes in load. Magnetic components of this converter could be integrated with the transformer and hence it can be a great candidate as a power supply with regulated output voltage. Circuit diagram of this topology is shown in Fig. 1. CLCL resonant network consists of inductors L_1 and L_2 , and capacitors C_1 and C_2 which is excited by a half-bridge square wave inverter. The model shows that the resonant CLCL converter provides an output voltage which depends on the load and no-load regulation. When the circuit works at the resonant frequency, the resonant CLCL converter acts as a current source. Under these conditions, the output current is kept constant regardless of load changes. Moreover, performing at resonant mode, the output current of the inverter which is the inductor (L_2) current, is in-phase with the voltage, that reduces changes in part-load conditions. The maximum efficiency of this converter in the part-load condition is less than full load condition, due to conduction losses. The resonant CLCL converters can be used to achieve a high power factor in rectifiers.

The feature that changes this resonant converter from a high-frequency constant voltage-source converter to a high frequency constant current-source converter is the utilization of immittance characteristic within this converter [14]. A constant current source is used in many commercial, industrial, and research applications such as electromagnetic [15], capacitor charging [16], battery charging [17], arc welding, etc. [18]. Resonant CLCL converters with the

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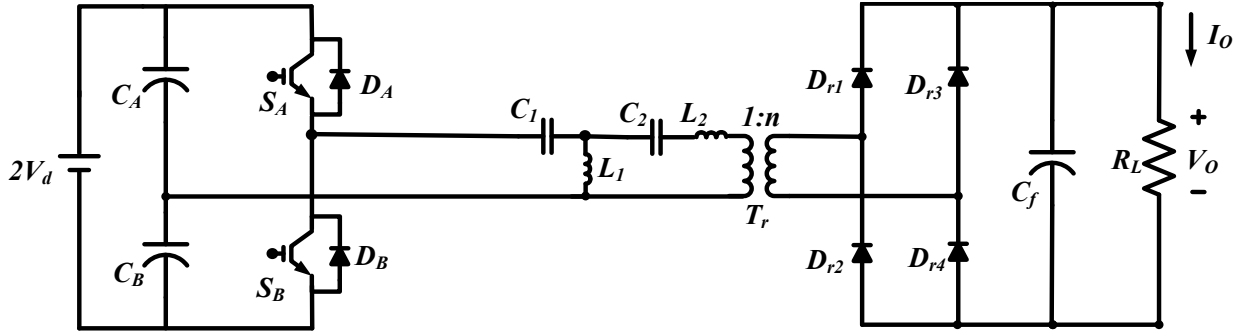


Fig. 1. Circuit diagram of the CLCL topology

advantages of a current-source can be a potential candidate for these applications.

The main use of the converter as a CCPS is for driving high power laser diode which these laser diodes are driven with the current basically. Laser diodes are one of the various types of lasers that are used widely in the lighting industry, medical industry, printing industry as well as higher-power applications such as welding, cutting, burning and sintering, brazing, lithography, marking plastic, metal, and silicon. The main characteristics of these laser diodes are noted as follows: Low resistance and High input current.

Although the laser diode behaves like a normal diode electrically, this laser diode turns on when a knee voltage is greater than 1 V. The equivalent circuit of a laser diode is shown in Fig. 2. In this figure, values of L, C, and R are very small and R_d is very large; but the inductor and capacitor in the equivalent circuit can be neglected in low frequencies in about hundreds of kHz. Therefore, the steady-state equivalent circuit of this type of diode similar to the conventional diode dynamic model is modeled as a resistance [19].

The rest of this paper is organized as follows. In section 2, the analysis of this converter is described. Designing of the converter with the required features for the high power laser diode is presented in section 3. The simulation and construction of the presented converter are given in section 4, respectively. At last, the conclusions of this paper are provided in section 5.

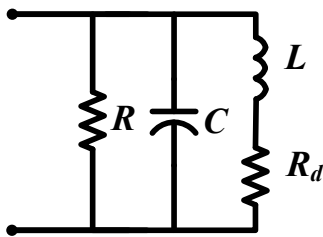


Fig. 2. Circuit diagram of a laser diode

2- Analysis of the converter

Among analysis methods, the AC analysis method is chosen. In the AC analysis [20], the rectifier and filter output have been replaced by an equivalent resistance and the square-wave input voltage-source is replaced with an equivalent sine-wave one. It is assumed that the transmission of power from input to the output is done only by the main component. Also, higher-order harmonics are neglected because of the low-pass property of the resonant network. The simplified equivalent circuit for the analysis is shown in Fig. 3.

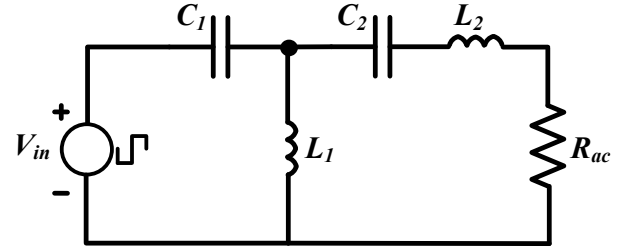


Fig. 3. Simplified equivalent circuit of the converter

The following assumptions have been made, too:

- Equivalent ac resistance (R_e) for the rectifier with a capacitor filter and the RMS value of the main component of the square-wave input voltage are explained in the following terms [21]:

$$V_{in,rms} = \frac{2\sqrt{2}}{\pi} V_d, R_e = \frac{8 R_L}{\pi^2 n^2}. \quad (1)$$

- Resonance frequency (ω_o) and normalized switching frequency (ω_n) are defined by:

$$\omega_o = \frac{1}{\sqrt{L_1 C_1}}, \omega_n = \frac{\omega}{\omega_o}, \quad (2)$$

where ω is the switching frequency.

- Also, the characteristic impedance (Z_n) and F are defined as follows:

$$F = \frac{n^2 \omega_o L_1}{R_e} = \frac{n^2 Z_n}{R_e}, Z_n = \sqrt{\frac{L_1}{C_1}} \quad (3)$$

The ratio of the capacitors and the ratio of inductors are defined as follows:

$$\gamma = \frac{L_2}{L_1}, \psi = \frac{C_2}{C_1}. \quad (4)$$

The voltage gain (V_{no}) and the current gain (I_{no}) of the converter which are in fact normalized output Voltage and current are expressed as follows:

$$I_{no} = \frac{nI_o}{V_d/Z_n}, V_{no} = \frac{V_o/n}{V_d}. \quad (5)$$

Also, voltage gain and current gain of the resonant CLCL converter is shown in detail by expressions, below:

$$V_{no} = \frac{-j\psi\omega_n^3}{F(\gamma\psi\omega_n^4 - (1+\psi+\gamma\psi)\omega_n^2 + 1) + j\psi\omega_n(1-\omega_n^2)}, \quad (6)$$

$$I_{no} = \frac{-j8F\psi\omega_n^3}{\pi^2 F(\gamma\psi\omega_n^4 - (1+\psi+\gamma\psi)\omega_n^2 + 1) + j\psi\omega_n(1-\omega_n^2)}. \quad (7)$$

Eq. (7) shows that if the converter operates at $\omega_n = 1$, the

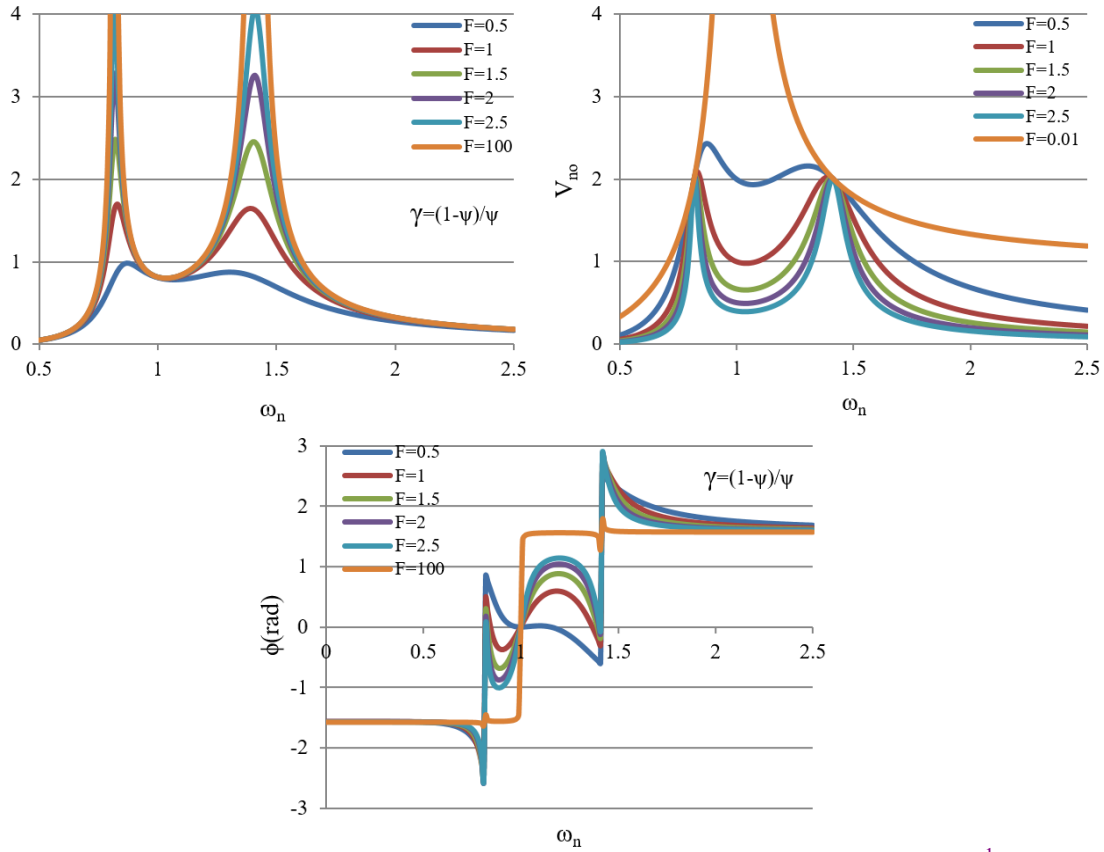


Fig. 4. (a) I_{no} , (b) V_{no} and (c) ϕ in CLCL according to different values of F and CLCL $\gamma = \frac{1-\psi}{\psi}$

output current will be independent of load and under these conditions:

$$I_{no} |_{\omega_n=1} = \frac{8}{\pi^2}. \quad (8)$$

Then, the equation for RMS value of normalized current of capacitor C_1 (I_{C1N}), based on the reference current (V_d / Z_n) has been expressed in (9). It is also possible to achieve stress relationships of voltage and current on each element. The relationships for the value of normalized current inductor L_1 (I_{L1N}), inductor L_2 (I_{L2N}) and capacitors C_2 (I_{C2N}) and also RMS value of the normalized voltage of these elements (V_{L1N} , V_{L2N} , V_{C1N} , and V_{C2N}) based on the reference voltage and current (V_d and V_d / Z_n) achieved. Current of capacitor C_1 (I_{C1N}) is summarized as follows :

$$I_{C1N} = \frac{I_{C1,rms}}{V_d / Z_n} = \frac{2\sqrt{2}}{\pi} \frac{-\psi\omega_n^2 - j\left((1+\gamma)\omega_n^2 - \frac{1}{\psi}\right)F\psi\omega_n}{F(\gamma\psi\omega_n^4 - (1+\psi + \gamma\psi)\omega_n^2 + 1) + j\psi\omega_n(1-\omega_n^2)}. \quad (9)$$

By operating at $\omega_n = 1$, the current of the capacitor C_1 is simplified as follows :

$$I_{C1N} |_{\omega_n=1} = \frac{2\sqrt{2}}{\pi} \frac{-\psi + j\left((1+\gamma) - \frac{1}{\psi}\right)F\psi}{F(\gamma\psi - (1+\psi + \gamma\psi) + 1)}. \quad (10)$$

Therefore, the phase angle between V_{in} and I_{L1} could be obtained by :

$$\phi |_{\omega_n=1} = \tan^{-1} \left(\frac{\left((1+\gamma) - \frac{1}{\psi} \right) Q\psi}{-\psi} \right) \quad (11)$$

If the designed converter operates with $\gamma = \frac{1-\psi}{\psi}$ at $\omega_n = 1$, for all F values, ϕ will be equal to zero. Therefore, the converter provides a constant output current which is in-phase with the

source voltage and current in all loading conditions. These conditions called immittance conditions changes a voltage source to a current source.

The variation of I_{no} for different values of F and $\gamma = \frac{1-\psi}{\psi}$ is shown in Fig. 4 (a). For $F = 100$ which is related to a condition close to the short-circuit load, the characteristic shows the current-source behavior of the converter. Fig. 4(b) shows the variation of V_{no} for different values of F and $\gamma = \frac{1-\psi}{\psi}$. For $F = 0.01$, which is related to a condition close to the open-circuit load, it shows the voltage-source behavior of the converter. As illustrated in Fig. 4(b), the converter has the voltage source property in two operating frequencies with voltage gain 2. Fig. 4.(c) indicates the ϕ changes as a function of ω_n for different values of F and $\gamma = \frac{1-\psi}{\psi}$. It can be seen that for all the values of F , the output current is independent of the load for $\omega_n=1$. In other words, this topology can be used as a voltage source, in addition to the current source applications. Meanwhile, for all values of F , $\phi = 0$ at $\omega_n=1$. For resonant converters, the existence of a lag between inverter's output voltage and current is required to achieve ZVS. Eq. (11) shows that the resonant CLCL converter can operate in a lagging power factor, if $\gamma < \frac{1-\psi}{\psi}$. Therefore, the required phase delay can be achieved by keeping the γ slightly less than the $\frac{1-\psi}{\psi}$.

3- Design of the converter elements

To design converter elements, serious attention is paid to the current ripple; due to this, a laser diode is sensitive to the current ripple and the laser diode will be burnt by changing the current more than the allowed amount. At the next level, the amount and density of the converter power are considered. To design CLCL converter, the values of voltages, currents,

and reactive elements for impedance resonance network has been determined. Conditions $\omega_n=1$ and $\gamma=\frac{1-\psi}{\psi}$ is required for the converter operation as a current source. By defining (kVA / kW) rate which is an indicator of the physical size of the converter and using voltage and current of each element in impedance conditions [22], the following equation would be obtained:

$$\left. \frac{KVA}{KW} \right|_{\omega_n=1, \gamma=\frac{1-\psi}{\psi}} = \frac{V_{C_1N} I_{C_1N} + V_{C_2N} I_{C_2N} + V_{L_2N} I_{L_2N} + V_{L_1N} I_{L_1N}}{H^2/F} \quad (12)$$

By applying Eq. (12) for the CLCL topology and simplifying, the following equation is obtained:

$$\left. \frac{KVA}{KW} \right|_{\omega_n=1, \gamma=\frac{1-\psi}{\psi}} = \frac{\pi^2}{4} \frac{1}{\psi} F + \frac{16}{\pi^2} \frac{1}{F} \quad (13)$$

Fig. 5 shows Eq. (13) as a function of F . Graphs show that for a certain value of F , the ratio (kVA / kW) is minimal. This value is called optimal F value (F_{opt}) and corresponds to the optimal value of (kVA / kW) and is shown as $(kVA / kW)_{opt}$. Equations for F_{opt} and $(kVA / kW)_{opt}$ are as follows:

$$F_{opt} \Big|_{\omega_n=1, \gamma=\frac{1-\psi}{\psi}} = \frac{8}{\pi^2} \sqrt{\psi} \quad (14)$$

$$\left(\frac{KVA}{KW} \right)_{opt} \Big|_{\omega_n=1, \gamma=\frac{1-\psi}{\psi}} = \frac{4}{\sqrt{\psi}} \quad (15)$$

As the characteristics are shown in Fig. 5, the values of F_{opt} and $(kVA / kW)_{opt}$ differ for each ψ value. As the ψ value increases, the $(kVA / kW)_{opt}$ ratio decreases; or in other words, the power density rises. Also, this causes a reduction in the inductance and the circuit total size. From the expression, bigger ψ is sufficient for operation; but on the other hand, increasing ψ reduces γ more and therefore the size of L_1 and L_2 inductances drastically diminishes and variation in output current increases under load changes, thus, the current-source property of the converter declines. Since the circuit current variations should not exceed 2 percents under load changes, even without using a control loop, $\psi=0.25$ is chosen to design the circuit elements.

General design input are the DC input voltage, the output current (I_o), maximum load resistance ($R_{L,max}$) and switching frequency (f_s). With a full load F , equivalent to F_{opt} , equations

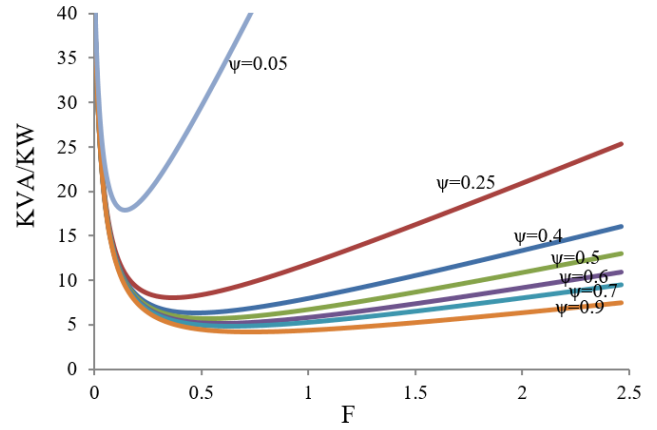


Fig. 5. KVA/kW diagram of CLCL topology as a function of F for different values ψ

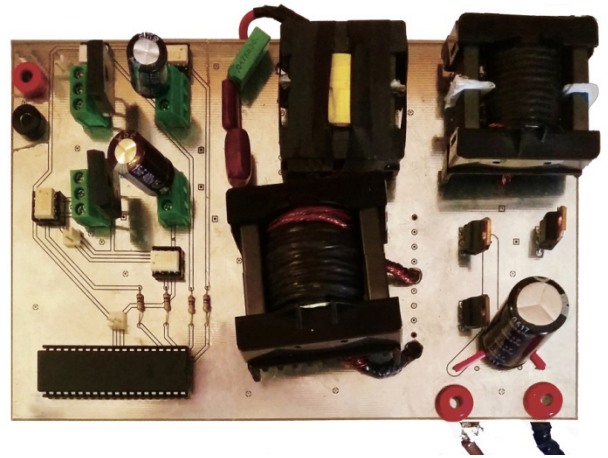


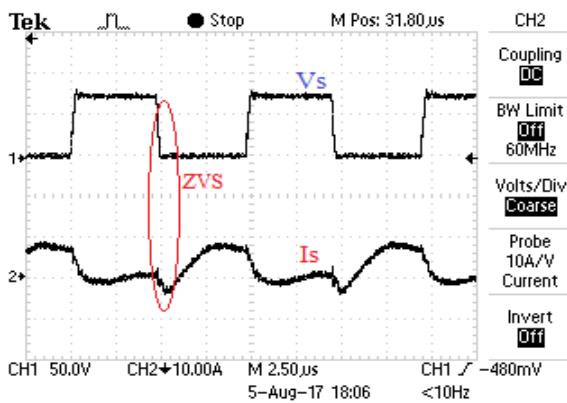
Fig. 6. A view of the built converter

for n , L_1 , L_2 and C_1 according to parameters of the converter terminal are as follows:

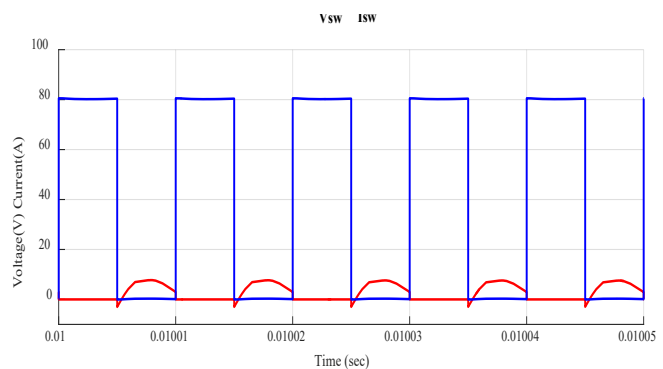
$$n = \frac{I_o R_{L,max}}{V_d} \sqrt{\psi} \quad (16)$$

$$L_1 = \frac{4}{\pi^3} \frac{V_d^2}{I_o^2 R_{L,max} f_s} \frac{1}{\sqrt{\psi}} \quad (17)$$

$$C_1 = \frac{\pi}{16} \frac{I_o^2 R_{L,max}}{V_d^2 f_s} \sqrt{\psi} \quad (18)$$



(a)



(b)

Fig. 7. Voltage and current waveform of the switch: (a) simulation, (b) prototype

Table 1. The converter specification

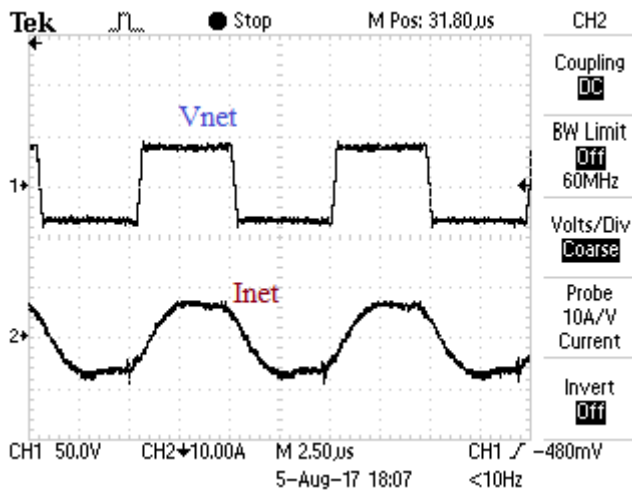
Parameter	Quantity
V_d	80 V
I_o	10 A
n	4
R_L	2 Ω
f_s	100 KHz
L_1	21.6 μ F
C_1	120 nF
γ	3
Ψ	0.25
$C_A C_B$	100 μ F

4- Simulation and Prototyping of the converter

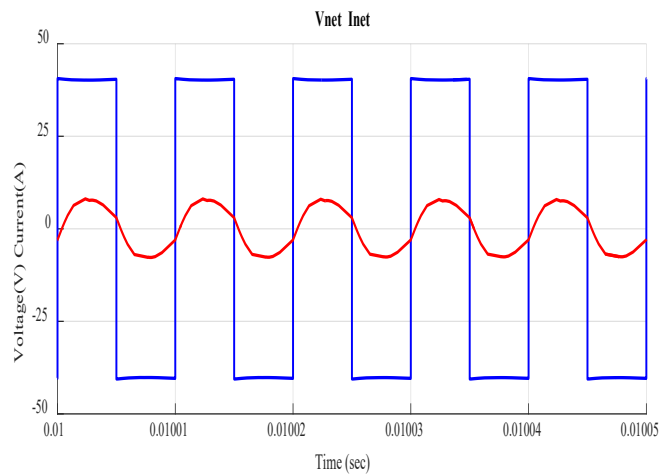
A simulation is done to verify the ability of the resonant CLCL converter as a current source and then to confirm the results, a model of the converter is built by modeling of the laser diode with resistance. So the results can be compared with each other. To construct a model of the converter, the specifications are shown in Table 1.

However, with aforementioned quantities, the circuit operate in in-phase mode and due to tolerances in the magnetic elements, it would be better to work in the lag mode to realize the ZVS in switches [23]. Therefore, the value of C_f would be slightly larger than the value given above to ensure that the switches will have ZVS operation.

To construct the converter, the leakage inductance of the transformer has been integrated as part of the L_2 inductance; in a way that leakage inductance of the transformer is 7 micro Henry and by integrating with L_2 , the inductance size reaches 58 micro Henry. A view of the realized converter is shown in Fig.6. Results of the converter realization are provided in

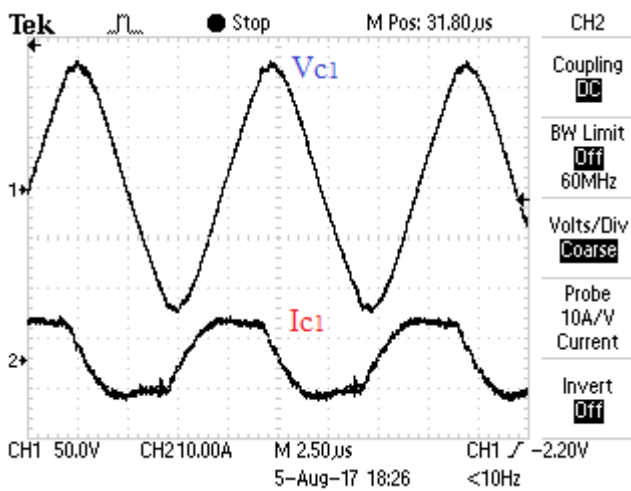


(a)

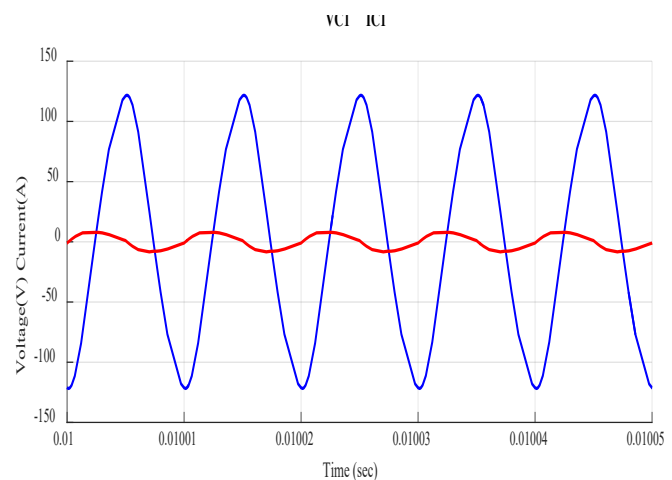


(b)

Fig. 8. Input voltage and current waveforms of the resonant network: (a) simulation, (b) prototype

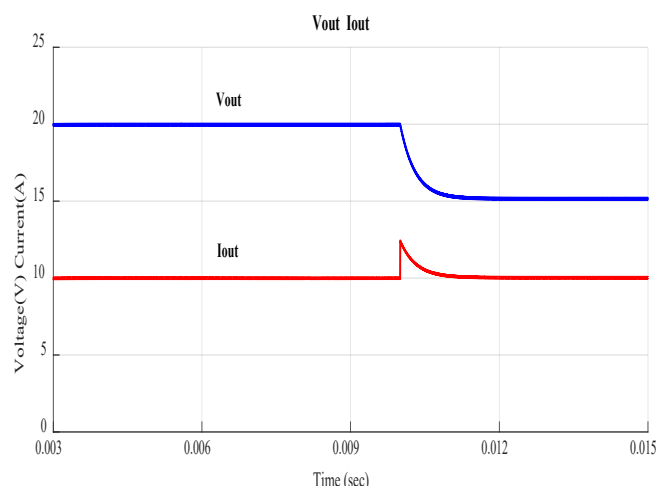
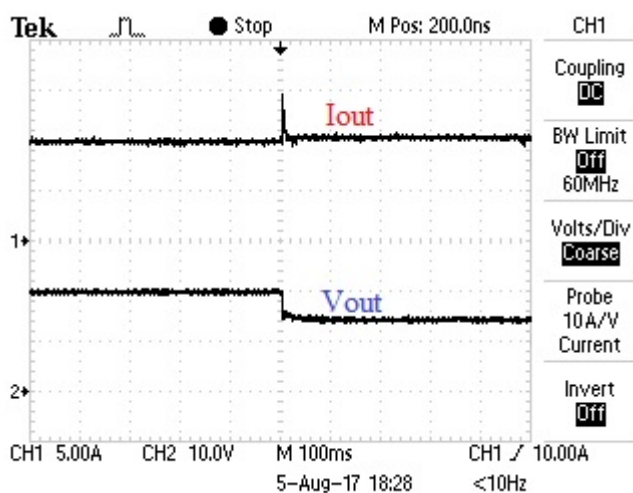


(a)



(b)

Fig. 9. Voltage and current waveforms of the resonant capacitor: (a) simulation, (b) prototype.



(a) (b)
Fig. 10. Voltage and Current waveforms in Changing load: (a) Simulation, (b) Prototype

Figures 7 to 10.

Voltage and current waveform of the switch is shown in Fig. 7. As the figure shows, the switch is turned-on softly and also in practice switches have soft switching (ZVS). From the figure it seems that voltage across the switch is 80 V which is twice the voltage designed; also the peak current is about 8 A. In Fig. 8, the input voltage and current waveforms of the resonant network are shown in which the ZVS is clearly visible. The voltage across the switch is twice the voltage across the network, Therefore the voltage across the network alters between +40V and -40V.

Voltage and current waveforms of the converter’s capacitor C_1 are shown in Fig. 9. Also, in this figure, the sinusoidal shape of the voltage and current of the capacitor due to the resonance with L_1 can be seen. The 90-degree phase difference between voltage and current is also due to resonance.

Fig. 10, shows the changes in output voltage and current when the load decreases from 2 ohms to 1.5 ohms. As the figure reveals, with the load altering from 2 ohms to 1.5 ohms, the current is almost constant and has not changed so much, but the output voltage is reduced. Therefore, it proves that the converter can practically operate as a constant current power supply without a feedback control.

Fig. 11 shows a plot of output current versus load resistance. As Fig. 11 indicates, by reducing the load from the rated value, 2 Ω to a point close to the short circuit in load, output current has not changed so much and its total changes are less than 2 percent of the nominal current that is perfect for applications where accurate constant current source exists. Thus, it shows the independence of the output current of

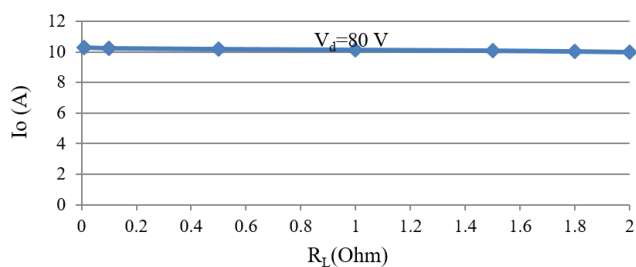


Fig. 11. Diagram output current as a function of load resistance

the converter from its load and the fact which the converter operates as a constant-current power supply, regardless of the load. This feature is very convenient for a driver of a laser diode.

Fig. 12 shows a graph of the converter efficiency according to the output power. In the blue graph, the load resistance is kept at its nominal value of 2 Ω and the input voltage is decreased from its rated value. According to the plot, for output power near 20 W, the efficiency of the converter is above 80 percents which indicates that this topology in amounts far away from its nominal value, offers a good efficiency. Meanwhile, in the red graph, the input voltage is kept at its nominal value of 80 V and the load resistance is decreased from its rated value to a point close to the short circuit in load. According to the plot, for output power near 40 W, the efficiency of the converter is above 80 percent.

Employing a resonant converter as a constant current power supply is used in several articles with different topologies. [21-23]. The proposed converter in this paper is more efficient than other converters. Also, one of the main advantages of this converter is the inherent dc blocking of the isolation transformer due to the series capacitor in the resonant network. This converter has more output current capability, in other words, the range of the current of converter is 0 to 10 A, which is much larger than many converters. Also, with the

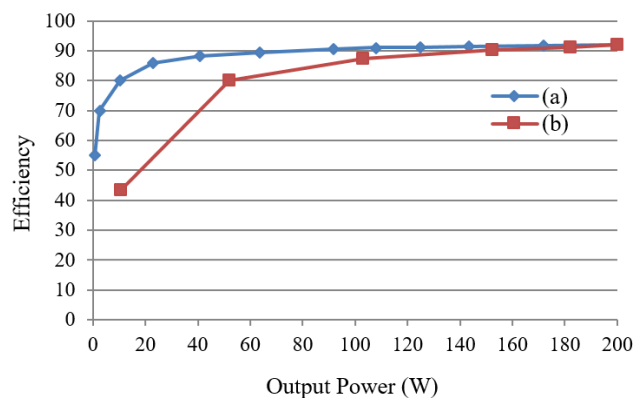


Fig. 12. Diagram efficiency as a function of power output. Plot (a) : $R_L=2 \Omega$ and V_d is varied from 10 to 80 V. Plot (b) : $V_d=80$ V and R_L is varied from 2 to 0.1 Ω

optimal design of inductors and capacitors, it is possible to use isolation transformer magnetization inductance in addition to the leakage inductance, which reduces the dimensions of the converter and reduces the cost. Therefore, this converter is an important candidate for use as a power supply.

5- Conclusion

This paper presents a detailed analysis of a resonant CLCL converter as a constant current source for laser diode driver and closed-form expressions of the converter gain and the stresses on the components. The converter shows a voltage gain that depends on the load and current gain that is independent of the load at a given operating frequency, which is suitable for a constant current power supply.

Conditions for the optimal design of the converter, for the minimum size of the resonant network, are revealed. In general, the leakage and magnetizing inductance of the transformer can be useful in resonant CLCL network. It is shown that using a series capacitor prevents the DC component in the isolation transformer. Efficiency at full-load is more than 92 percent, with an output current of 10 A, due to negligible eddy current and soft-switching operation. The advantages of the presented topology, especially with features constant current source and high efficiency can lead this converter to a vast variety of applications, especially for the constant current ones, for example, laser diode driver.

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