# Comparative Analysis of Resonant Converters

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This paper presents the comparison among the different resonant converters especially in the Analysis of Total Harmonic Distortion (THD). The THD of output current from the inverter circuit (or) resonant current of different resonant converters such as series LC, LLC and LCC is determined. The resonant converters are to be operated above the resonant frequency to obtain the Zero Voltage Switching (ZVS) to achieve the lesser switching losses. The simulation of various resonant converters is performed in the MATLAB/Simulink software.

**Keywords**: Resonant Converter, Resonant Frequency, Total Harmonic Distortion (THD), Resonant Current.

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# 1 Introduction

In recent years, resonant converters are becoming more popular and widely used in aerospace and industrial applications because of numerous advantages [4]. The main advantage of resonant converters is achieving low switching losses by using the soft switching techniques compare to PWM hard switching techniques. Furthermore, the low switching losses ensures the converters which will enable the resonant the switches to operate (or) work at high switching frequency.

The soft switching techniques like Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) which are used to shape the voltage and current waveforms respectively. By enhancing the soft switching technique which can achieve high power density, low electromagnetic interference (EMI), high reliability, less harmonic distortion, and high efficiency of the converter. For high frequency applications, ZVS is usually more preferrable choice over ZCS and due to the discharging of its inherent junction capacitance, it can also eliminate the major switching losses in the converters [6].

For the analysis of harmonic content in the AC voltage (or) current, the Fast Fourier Transform (FFT) is the standard method to measure the quality of the waveform Total Hamonic Distortion (THD). The full bridge inverter output current waveform THD is calculated by using Eq. (1) [3].

$$THD = \sqrt{\sum_{2}^{n=\infty} \frac{{I_n}^2}{{I_1}^2}} \tag{1}$$

where, $I_n$ is the amplitude of nth harmonic order of current waveform; $I_1$ is the amplitude of the fundamental harmonic order of current waveform.

This paper presents about the THD of the inverter output current among the series LC, LLC, and LCC resonant converters is determined by using the MATLAB/Simulink software.

# 2 Resonant Converters Description and Configuration

Generally, the resonant converters consist of DC input voltage source, high frequency isolation transformer, switch network, diode rectifier network, resonant tank network, filter network and DC load. Figure1 shows the block diagram of conventional resonant converters, and which mainly consist of 3 parts (or) sections namely resonant tank network, switching network, and rectifier network with low pass filter andeach part having specific operations.

Firstly, DC input supply is fed to the switching network which is likely called the inverter circuit and it can be having any type of switch networks such as Full Bridge, Half Bridge, and Push Pull which converts DC input to AC square wave voltage, at which the switches are controlled by rapid on and off switching which depends upon the switching frequency. Afterwards, the AC supply is fed to the resonant tank network [7]. This network is also known as frequency selective network, the reason behind is under the condition of resonant, the inductive reactance is equal to the capacitive reactance, and which generates (or) produces the resonant frequency. By the utilization of resonant tank, the harmonic distortion, and the electromagnetic interference (EMI) is reduced and generates (or) produces the sinusoidal current and voltage and further having an isolation transformer in the circuit for the purpose of electrical isolation between input network and output network. Finally, the resonant tank output is rectified by using the diode rectifier network and further filtered by the Low Pass Filter (LPF) to generate (or) produce the required output voltage.

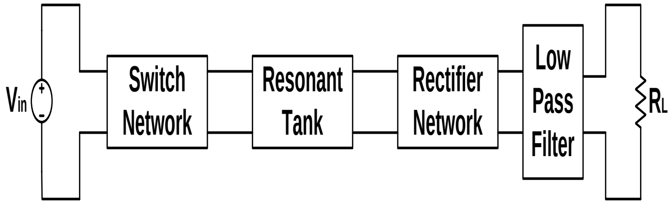


**Figure 1.** Block diagram of Conventional Resonant Converter.

Generally, the resonant converters are classified into three types of namely Series, Parallel and Series-Parallel. In this paper, the discussion is mainly done among the three resonant converters such as series LC, LLC, and LCC converters which mainly differentiated by its resonant tank. Accordingly, the effective load resistance of the resonant converter to the resonant tank ($R_e$) value can be estimated by using Eq. (2),

$$R_e = \frac{8}{\pi^2} R_L \tag{2}$$

## 2.1 Series LC Resonant Converter

Figure 2.1 shows the circuit diagram of series LC resonant converter which consists of two components namely series inductance and capacitance. The series LC resonant converter having the resonant frequency ($f_r$) as shown in Eq. (3) and,

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{3}$$

The Voltage Gain ($M_v$) is the ratio of output and input voltage of the converter (or) any system which is evaluated by the Eq. (4).

$$M_V = \frac{V_o}{V_i} = \frac{1}{2\pi\sqrt{1 + \left(\frac{X_L - X_C}{R_e}\right)^2}} \tag{4}$$

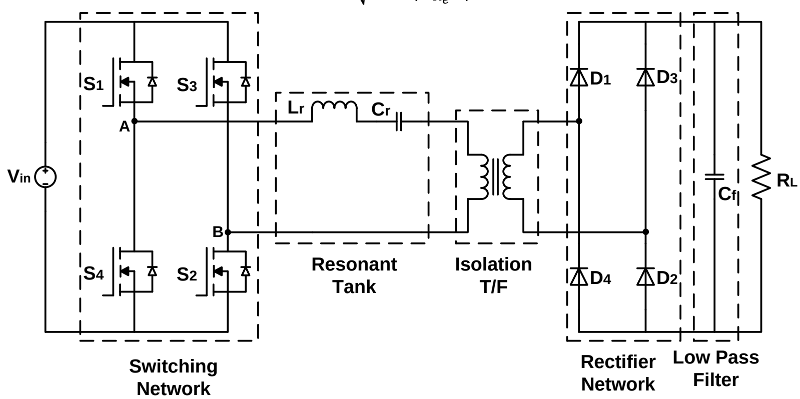


**Figure 2.1.** Circuit diagram of Series LC Resonant Converter

### 2.2 LLC Resonant Converter

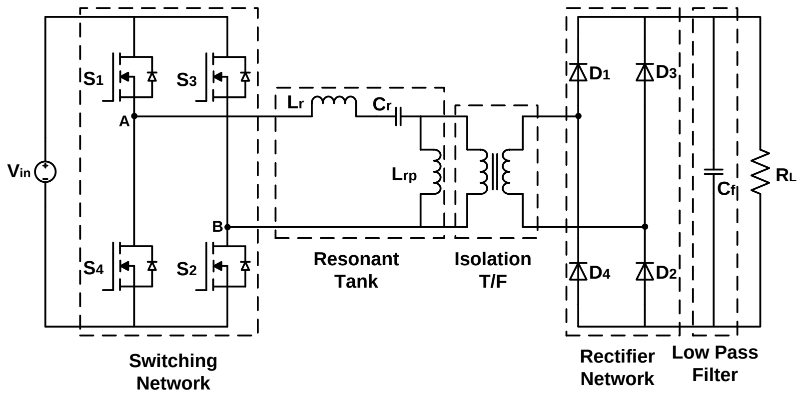


**Figure 2.2.** Circuit diagram ofLLC Resonant Converter

Figure 2.2 shows the circuit diagram of series LLC resonant converter which consists of three components namely series inductance and capacitance along with parallel inductance is also connected which is also known as magnetizing inductance. The LLC resonant converter topology generates (or) produces the two resonant frequencies $f_{r1}$ and $f_{r2}$ respectively. On the one hand, the series resonant frequency ($f_{r1}$) which depends upon the series elements ($L_r$, $C_r$) of the resonant tank. On the other hand, the parallel resonant frequency ($f_{r2}$) which depends upon the whole three tank elements ($L_{rp}$, $C_r$, and $L_r$) as shown in Eq. (5) and (6)[2].

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{5}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_{rp})C_r}} \tag{6}$$

The Voltage Gain ($M_v$) is evaluated depending on the inductance ratio ($L_{rp}/L_r$) which is unity and resonant frequency ($\omega_r$) and switching frequency ($\omega_s$) [5] is shown in Eq. (7)

$$M_V = \frac{8}{\pi^2\sqrt{4\left[1-\left(\frac{\omega_r}{\omega_s}\right)^2\right]^2 + \left[\frac{\omega_r L_r}{R_e}\left(\frac{\omega_s}{2\omega_r} - \frac{\omega_r}{\omega_s}\right)\right]^2}} \tag{7}$$

### 2.3 LCC Resonant Converter

Figure2.3 shows the circuit diagram of LCC resonant converter which consists of three components namely series inductance and capacitance along with parallel capacitance is also connected. The LCC resonant converter topology generates (or) produces the two resonant frequencies $f_{r1}$ and $f_{r2}$ respectively. On the one hand, the series resonant frequency ($f_{r1}$) which depends upon the series elements ($L_r$, $C_r$) of the resonant tank. On the other hand, the parallel resonant frequency ($f_{r2}$) which depends upon the whole three tank elements ($L_r$, $C_r$, and $C_{rp}$) as shown in Eq. (8) and (9) [8].

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{8}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{L_r\left(\frac{C_r C_{rp}}{C_r + C_{rp}}\right)}} \tag{9}$$

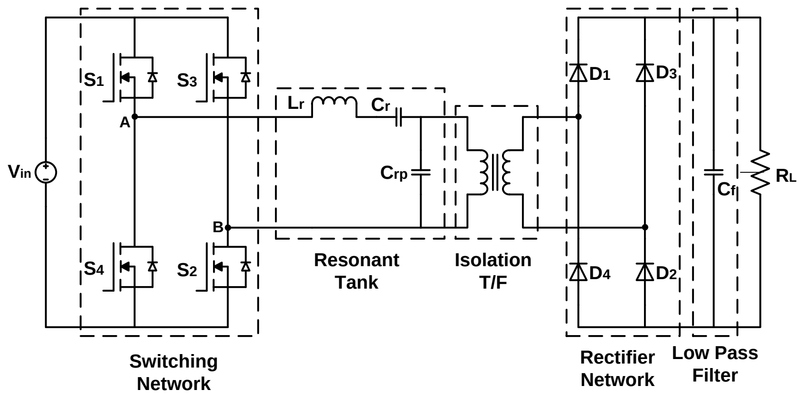


**Figure 2.3.** Circuit diagram of LCC Resonant Converter

The Voltage Gain (Mv) is evaluated depending on the capacitance ratio (Crp/Cr) which is unity and resonant frequency (ωr) and switching frequency (ωs) [5] is shown in Eq. (10).

$$M_V = \frac{8}{\pi^2\sqrt{4\left[1-\left(\frac{\omega_s}{\omega_r}\right)^2\right]^2 + \left[\frac{1}{\omega_r C_r R_e}\left(\frac{\omega_s}{\omega_r} - \frac{\omega_r}{2\omega_s}\right)\right]^2}} \tag{10}$$

# 3 Simulation

The three different resonant converters such as series LC, LLC, and LCC converters are simulated by using MATLAB/Simulink software under the condition of Zero Voltage Switching (ZVS) which is obtained by making the switching frequency ($f_s$) is above the resonant frequency ($f_r$). The following simulation sections are used to find out the THD of the different resonant converters such as series LC, LLC, and LCC resonant converter.

## 3.1 Simulation Parameters

Dc input supply ($V_{in}$) = 40 v; Switching frequency ($f_s$) = 95 khz; Resonant inductance ($L_r$) = 100 μH ( $L_r = L_{rp}$); Resonant capacitance ($C_r$) = 35 nF ( $C_r = C_{rp}$); Resistance ($R_L$) = 23 Ω; Transformer ratio = 1:1; Resonant frequency ($f_r$) = 85.1 Khz.

## 3.2 Simulation Models

The series LC, LLC, and LCC resonant converters MATLAB Simulink model diagrams are shown in **Figure 3** for the determination of THD of the resonant converters.

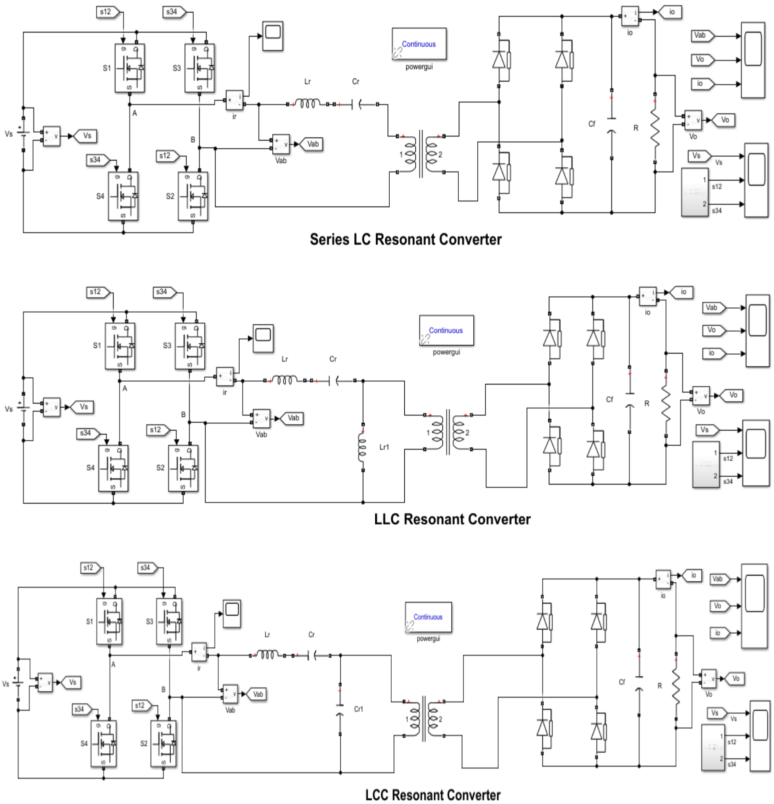


**Figure 3**. MATLAB Simulink model diagram of 1) series LC 2) LLC 3) LCC resonant converters.

## 3.3 Simulation Results

The resonant converter circuits such as series LC, LLC, LCC converters are performed and simulated in MATLAB Simulink software. The input voltage ($V_{in}$) is 40v which is given to switching network as shown in Figure 4.

The full bridge inverter having the four switches which are working alternately. Although, the switches $S_1$ and $S_2$ are triggered by 50% of duty cycle for the first half cycle from t=0 to t/2 simultaneously and the other two switches $S_3$, $S_4$ are also triggered by 50% of duty cycle for the second half cycle from t= t/2 to t simultaneously to produce a square wave of the voltage which is furtherly used to feed the resonant tank network [1].

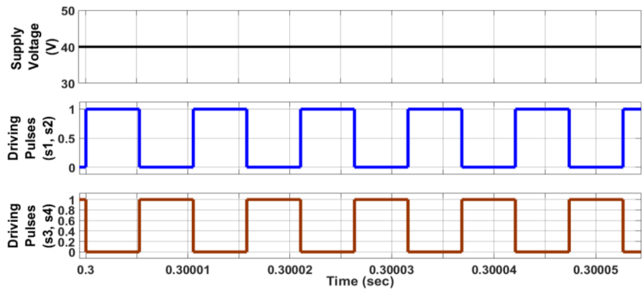


**Figure 4**. Supply voltage and driving pulses for S1&S2, and S2&S4.

The operation of the resonant converters is done under the condition of Zero Voltage Switching (ZVS) i.e., (switching frequency is above the resonant frequency) in CCM1 conduction mode [1].

The inverter output current is generated as sinusoidal waveforms which is also called as resonant current, because this current is flowing through the resonant tank. The resonant currents of series LC, LLC and LCC resonant converters are shown in the Figure 6 in which the amplitude of the resonant current waveforms of series LC and LLC resonant converters having less compared to the amplitude of the resonant current waveform of LCC resonant converter.

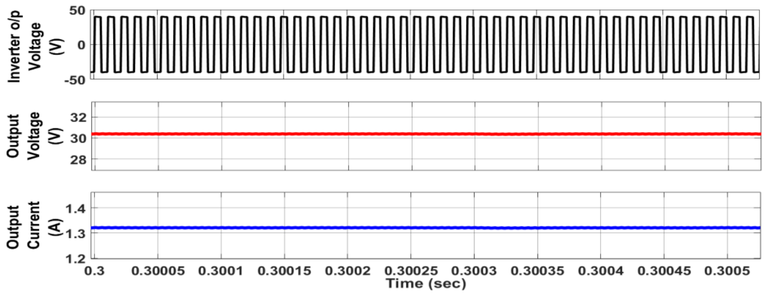


Figure 5.1.

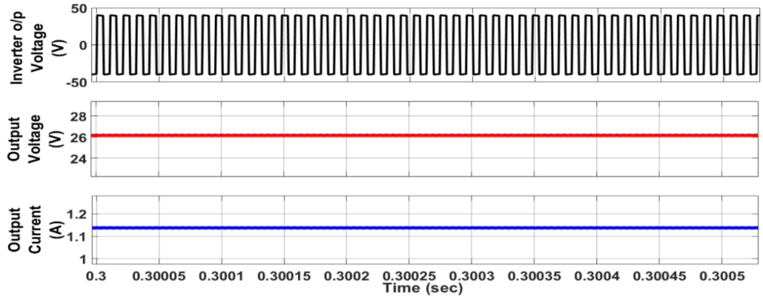


Figure 5.2.

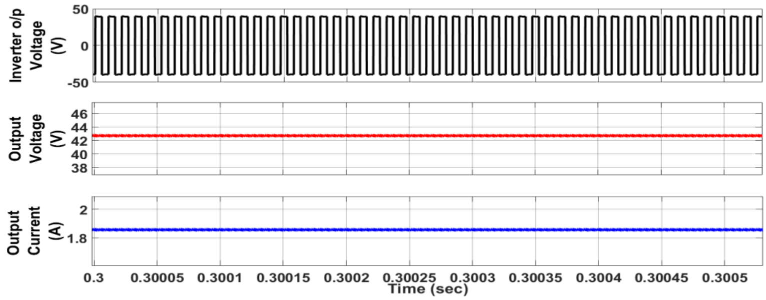


Figure 5.3.

**Figure 5.** Inverter output voltage, output voltage and output current of 1) series LC 2) LLC 3) LCC resonant converters.

The output voltage of the inverter circuit is square waveform which having the amplitude of 40v because of low switching losses there is no variation in the waveforms of the three resonant converters. The output dc voltage and current waveforms of the three different resonant converters after the rectification and filtering by rectifier and LPF network respectively as shown in the Figure 5 along with the inverter output voltage waveforms. By the Figure 5 we can conclude that the LCC resonant converter operates in the boost mode whereas as series LC and LLC resonant converters are operates in the Buck mode.

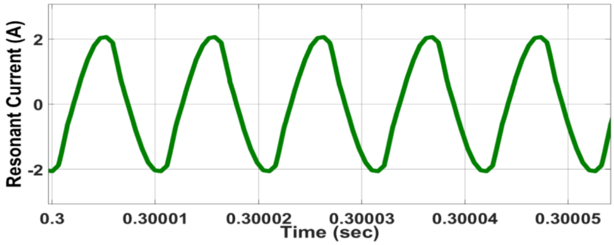


Figure 6.1.

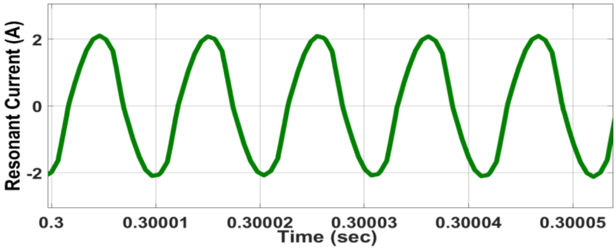


Figure 6.2.

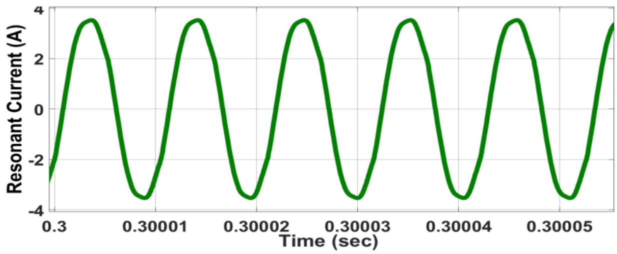


Figure 6.3.

**Figure 6.** Resonant current ($i_r$) waveforms of 1) series LC 2) LLC 3) LCC resonant converters.

The Harmonic analysis of the different resonant converters such as series LC, LLC, and LCC converters are simulated under ZVS condition by using MATLAB_SIMULINK software. The Total Harmonic Distortion (THD) of the series LC, LLC, and LCC resonant converters are shown in Figure 7. By this, it can be noted that the THD of LLC resonant converter is lesser when compared with the series LC resonant converter and higher when compared with the LCC resonant converter. Finally, the LCC resonant converter is having an advantage of low THD when compared with the series LC and LLC resonant converter to prove the better resonant converter to select in the different applications.

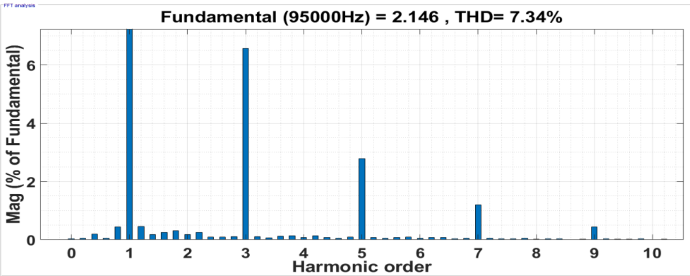


Figure 7.1.

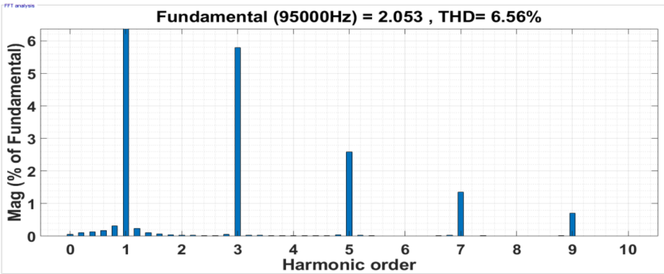


Figure 7.2.

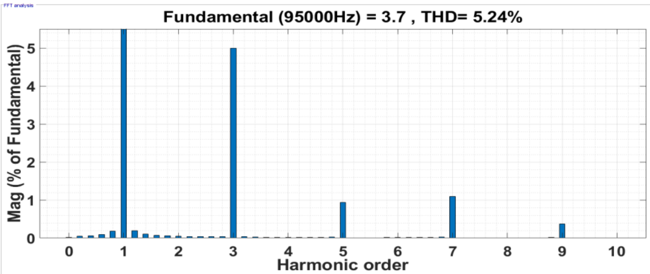


Figure 7.3.

**Figure 7.** Harmonic spectrum of resonant current ($i_r$) of 1) series LC 2) LLC 3) LCC resonant converters.

# 4 Conclusion

In this paper, the THD of the three different resonant converters are determined. Comparatively, the LCC resonant converter having THD of 5.24% which is less compare with the Series LC and LLC resonant converters. Finally, we can conclude that the LCC resonant converters having the better overall performance compared with series LC, and LLC resonant converters.

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