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ABSTRACT

In this paper, a comparative study of interleaved boost integrated LC, LCC and LLC resonant converters with fixed frequency PWM control is proposed and investigated. Two phase Interleaved boost converter is used which shares the full bridge circuit with the resonant converter, to reduce the current ripple and to increase efficiency. Zero voltage switching (ZVS) and Zero current switching (ZCS) techniques are used to reduce switching losses in the circuit. To reduce the voltage stress in the circuit, turn off switching voltages are clamped to bus voltage. Performance parameters such as Gain, Quality factor and Efficiency of different resonant converter are compared and analysed. The interleaved boost integrated resonant converters are implemented in MATLAB (R2010a) and the simulation results are presented.

Index Terms— Fixed frequency pulse width modulation, LC, LLC, LCC, Zero voltage switching, Zero current switching.

I. INTRODUCTION

A boost converter (step-up converter) is a DC-to-DC power converter with an output voltage greater than its input voltage. Filters made of capacitor are normally added to the output of the converter to reduce output voltage ripple. Power for the boost converter can come from any suitable DC sources, such as batteries, solar panels, rectifiers and DC generators. Since power ($P=VI$) must be conserved, the output current is lower than the source current[1]. The concept of interleaving is that of increasing the effective pulse frequency of any periodic power source by synchronizing several smaller sources and operating them with relative phase shifts[1]-[2]. In high power applications, the voltage and current stress can easily go beyond the range that one power device can handle. Multiple power devices connected in parallel and series could be one solution. Instead of paralleling power devices, paralleling power converters is another solution which could be more beneficial. Furthermore, with the power converter paralleling architecture, interleaving technique comes naturally[2]. Benefits like harmonic cancellation, better efficiency, better thermal performance, and high power density can be obtained. On the ac side, the total harmonic distortion (THD) in voltages and currents of the regulatory standards must be respected[3]. A further constraint comes from the switching loss that is proportional to the valve switching frequency. The input and output filter capacitance is usually determined by the required number of capacitors sufficient to handle the dissipation losses due to the ripple current[4]. Interleaving multiple converters can significantly reduce the switching pulsed current go through the filter capacitor. By properly choosing the channel number and considering the duty cycle(D), the ripple current may be reduced to zero[5]. Further interleaving increases the ripple

frequency to be n (n is the total channel number) times the individual switching frequency [6]. Interleaving technique can effectively reduce the filter capacitor size and weight.

II. INTERLEAVED BOOST INTEGRATED RESONANT CONVERTER

DC supply is used as the power for the boost converter, where the boost converter converts low voltage to high voltage the interleaved boost converter used in the block reduces the ripple current and regulates the output voltage. The output from the boost converter is connected to the full bridge converter where the interleaved boost converter shares the switches with the full bridge converter, the ZVS and ZCS techniques are used. Full bridge converter which is followed by resonant tank circuit can be of LC,LCC and LLC which is a combination of inductor and capacitor. The harmonics induced from the tank can be filtered and the regulated output is obtained at the load. Fig. 1.1 presents the block diagram of the interleaved boost integrated resonant converter. Resonant converter topologies are being widely used in power processing systems because of their soft-switching characteristics at high frequencies[7].

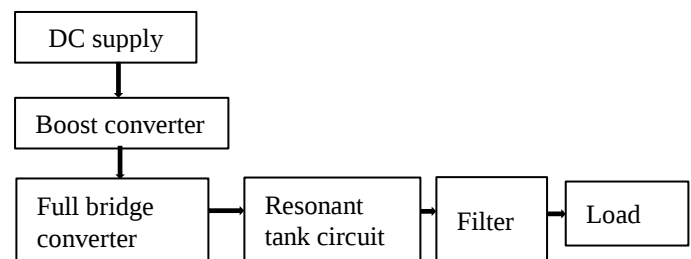


Fig. 1.1 Block diagram of the system

The advantages of this topology is high-frequency operation include smaller size and lighter weight for the passive components. The chief advantage of resonant converters are reduced switching loss, Zero-current switching, Zero-voltage

switching, Turn-on or turn-off transitions of semiconductor devices can occur at zero crossings of tank voltage or current waveforms, thereby reducing or eliminating some of the switching loss mechanisms. Hence resonant converters can operate at higher switching frequencies than comparable PWM converters. Zero-voltage switching also reduces converter-generated electromagnetic interference, Zero-current switching can be used to commute SCRs[7]-[10]. In this paper three forms of resonant converters LC, LCC and LLC resonant converters are being compared based on the performance parameters like gain, quality factor and efficiency with the application of PI and PID controllers.

A. Resonant tank converters

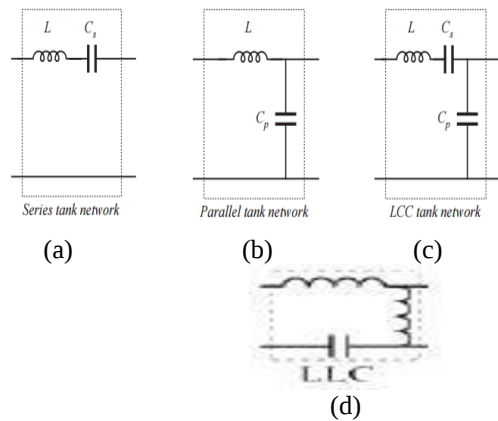


Fig. 2. The a) LC series b) LC parallel c) LCC d) LLC

Resonant converters are used to reduce or to eliminate the switching losses. These resonant converters have various combination of series and parallel LC circuits to reduce ripple and to increase efficiency .

B. Interleaved boost integrated LLC,LCC and LC resonant converter

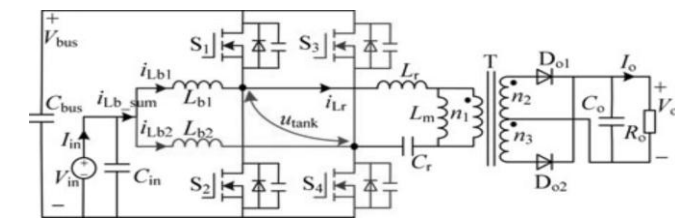


Fig. 3. Circuit of LLC resonant converter

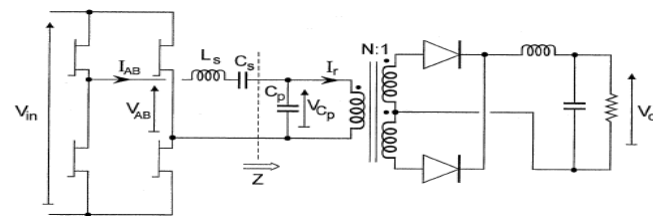


Fig. 4. circuit of LCC resonant circuit

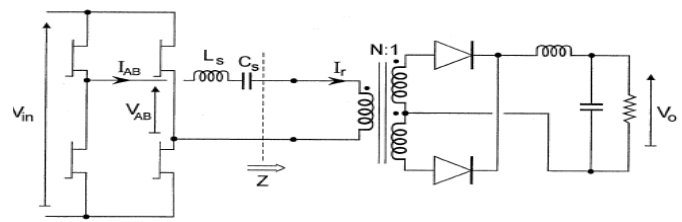


Fig. 5. circuit of LC resonant circuit

Fig. 3,4,5 represents the circuit diagram of LLC,LCC and LC circuit. Source voltage is given to the boost inductors, these boost inductors are divided into two paths so that the current through the inductors are paralleled and the losses can be minimized. Switches are shared by the full bridge converter and the boost converter. The turn off voltage of the switches are clamped to the bus voltage. Diodes are connected to the secondary side of the transformer where the ZCS conditions are achieved. Different types of resonant tank are compared to obtain a efficiency in the circuit.

III .DESIGN PROCEDURE

Voltage Gain of Boost Converter is given by the relation as

$$(V_{in} - V_{bus}) + 0 + (V_{in}t_1 + V_{in}t_2 + V_{in}t_3 + V_{in}t_4) = 0$$

$$V_{in}(T) - V_{bus}t_o - V_o t_1 = 0$$

$$V_{in}(T) = V_{bus}t_o$$

$$\frac{V_{bus}}{V_{in}} = \frac{T}{T_o} = \frac{1}{D} = 1.25 \quad (3)$$

Gain of LC converter is given by

$$G_{max} = \frac{V}{nv_{gmax}} = 0.5 \quad (4)$$

Gain of LCC Converter is given by the relation

$$R_{eq} = \frac{\pi^2}{8} R_L = 1.18 \quad (5)$$

$$G = \frac{I_o R_{eq}}{V_d} = 0.67 \quad (6)$$

Gain of LLC converter is given by the relation

$$G_{min} = \frac{1}{D_{max}} = \frac{1}{0.8} = 1.25$$

$$n = \frac{G_{min} V_{inmax}}{V_o} = 7.1$$

$$G_{max} = \frac{V_{inmax} * G_{min}}{V_{inmin}} = 2.5,$$

$$\frac{nV_o}{V_{in}} = 1.25 \quad (7)$$

Resonant Inductance is given by

$$L_r = \left(\frac{nV_o}{2\pi f_r} \right) \left(\frac{V_o}{P_{max}} \right) = 50.7 \mu H \quad (8)$$

Resonant Capacitance is given by the formulae

$$C_r = \frac{1}{(2\pi f_r)^2 L_r} = 45 nF \quad (9)$$

Quality factor is given by

Output Voltage of the interleaved boost integrated resonant converter is given by

$$V = I_0 R_0 \quad (11)$$

IV .Comparative study of resonant converters

A. Gain vs quality factor characteristics of resonant converter

From the characteristics[fig. 6.(a),(b),(c)] it is evident that the quality factor increases, as gain decreases, so that the gain is affected by quality factor and inductor ratio, Minimum quality factor means minimum characteristic impedance. So to minimize circulating current and conduction losses magnetizing inductor and parallel capacitor values should increase. The gain characteristics indicates that the gain value of LLC is higher than LCC and LC converters. Wide gain range is obtained in LLC converter while LCC and LC converters are affected by high quality factor.

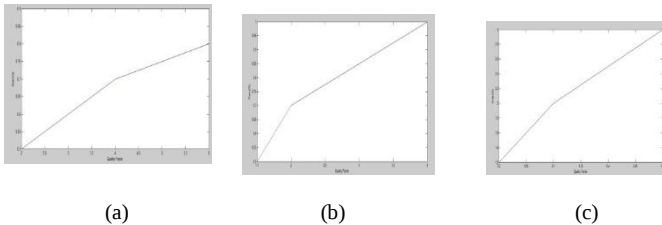


Fig. 6.Gain versus Quality Factor characteristics of (a)LC, (b)LCC and (c)LLC converters

Tab. 1. Simulation results of Quality factor and Gain values for resonant converters under study

Parameters	LC		LCC		LLC	
Gain	0.7	0.8	0.7	1	3.2	2.2
Quality factor	4	6	2	4	0.3	0.5

B. Efficiency vs output power of resonant converter

The efficiency vs output power characteristic of LC, LCC, LLC converters[fig.7.(a),(b),(c)] shown. The efficiency of LLC converter is 95% which is high compared to other two converters. In LCC and LC converter the parallel capacitors uses are of higher value hence the size is large also high transformer ratio is implemented which reduces the efficiency. The ripple current is quite high in LC and LCC converter which affects the voltage regulation.

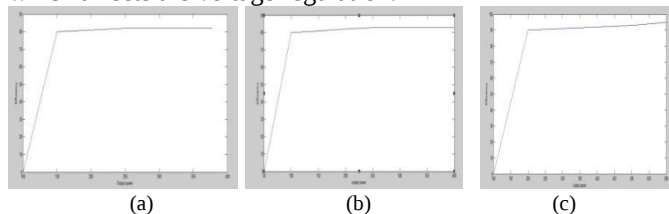


Fig. 7.Efficiency Vs Output Power characteristics of (a)LC, (b)LCC, (c)LLC resonant converters.

The graph represented in Fig. 7.(a),(b),(c) shows the comparative analysis and study of LLC, LCC and LC resonant DC-DC converter. The parallel resonant inductor is determined for load matching to ensure optimal efficiency. Additionally, the inductance ratio of the series and parallel

$$Q = \frac{\sqrt{L}}{n^2 * R_0} = \frac{22.5}{(4)^2 * 1.12} = 1.25 \quad (10)$$

resonant inductors is specified in terms of the voltage gain and input power factor for the LLC resonant tank. Considering the turns ratio, quality factor and frequency limitation, the converter covers wide input and load variation whereas the output voltage and current have more ripples in LCC and LC converter. Based on the obtained results, the LLC converter is a suitable topology for high efficient power adapters, providing a high and nearly constant efficiency throughout the complete load and input voltage range. Since the parallel inductance and the series inductance can be integrated within one single transformer, only an additional series capacitor for the resonant tank is necessary, reducing the component count. Nevertheless, the integration of two magnetic inductance within the transformer complicates its design dramatically, due to the difficult prediction of the magnetizing and leakage inductance. Moreover, even small variations of the inductance ratio result in a rather large drop of the efficiency of this converter. By contrast, the design of the resonant tank of the LCC converter is much easier, since only the series inductance has to be integrated as the leakage inductance. While at the LLC converter a certain inductor ratio must be set, a certain capacitor ratio is necessary at the LCC converter simplifying the design process. Hence, the resonant LCC tank is the preferred solution for electronic ballast for compact fluorescent lamps, where in addition the parallel capacitor provides a current path for filament heating and a sufficient starting voltage for ignition. Since there is a transformer with a high turn's ratio necessary, the parasitic capacitances on the secondary side are sufficient for acting as the parallel capacitor in the resonant tank. Based on the obtained results and comparison analysis LLC resonant converter is more efficient converter compared to LCC and LC resonant converters.

V. Simulation

The simulation of resonant converters using the MATLAB (R2010a) is done and the results are given in subsequent topics.

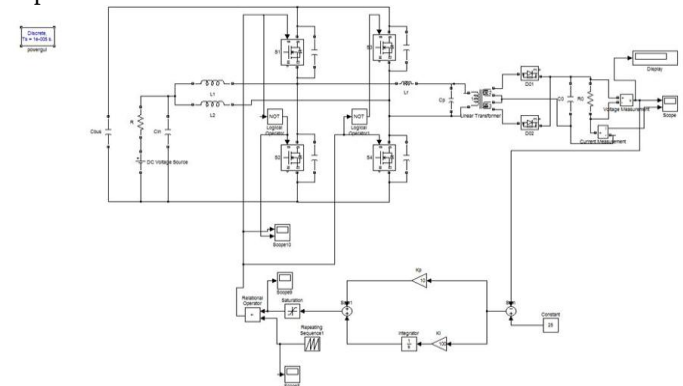


Fig. 8.Simulation circuit diagram of LC resonant converter with PI controller. The circuit in Fig. 8. shows the closed loop simulation circuit of LC resonant converter with PI controller. This simulation has a run time of 10seconds, with K_p and K_i values as 10 and

100. The interleaved boost inductors each with 300mH is linked to the resonant tank of LC converter.

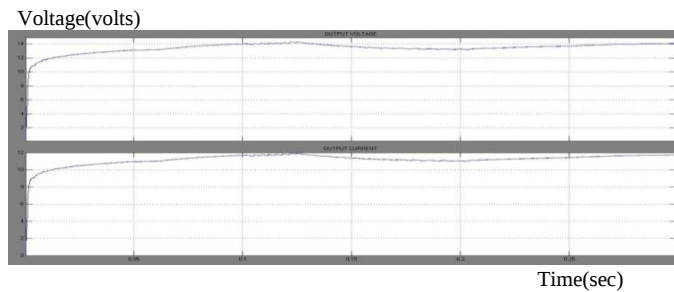


Fig. 9. Simulation result of LC resonant converter with PI controller

This output waveform in Fig. 9. shows the current and voltage waveform of 240V input. It can be seen from the waveform that there are slight fluctuations in voltage and current due to resonant conditions. The result shows that ripple in the output is high and efficiency is reduced compared to other resonant converter. So PID controller is used to reduce the distortions.

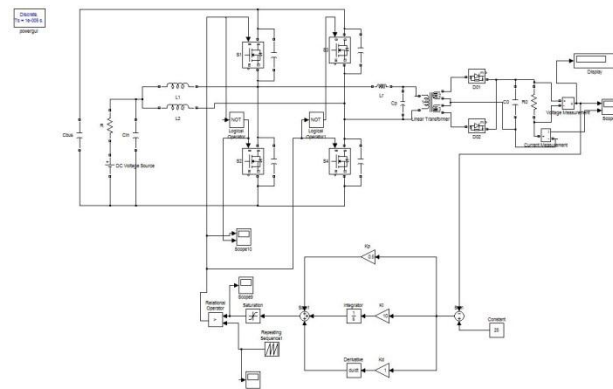


Fig. 10. Simulation circuit diagram of LC resonant converter with PID controller

The simulation circuit in Fig. 10. shows the resonant converter with PID controller as this controller predicts the error and also fast response are added advantage. Here PID controller K_P, K_I, K_D is given values as 10,100,1.

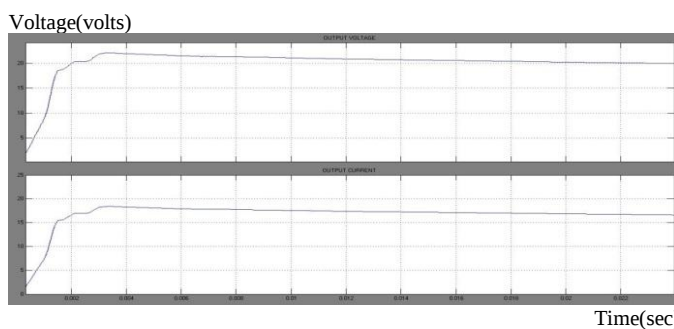


Fig. 11. Simulation result of LC resonant converter with PID controller

The simulation result in Fig. 11. shows the waveform of output voltage and current .In this waveform the output waveform doesn't have any fluctuations as in PI controller, derivative mode is included to reduce the error in the circuit and to obtain a ripple free output.

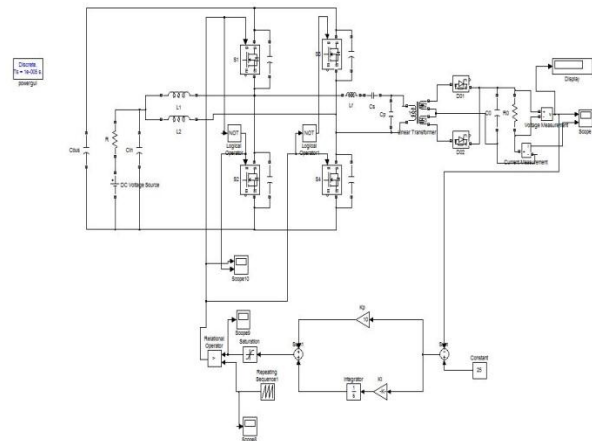


Fig. 12. Simulation circuit diagram of LCC resonant converter with PI controller

The simulation circuit in Fig. 12. shows the LCC resonant converter with PI controller with boost inductors coupled to the LCC resonant tank, the run time of the circuit is 10 seconds, K_P, K_I values as 10 and 100.

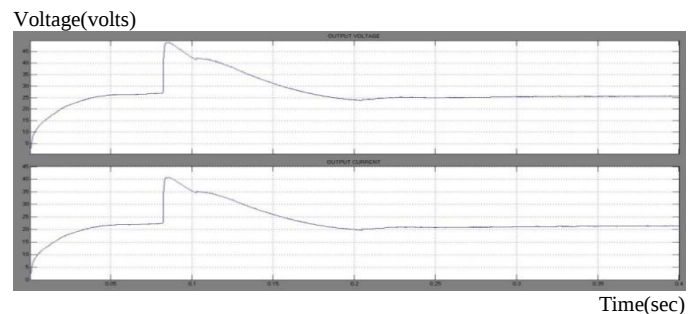


Fig. 13. Simulation result of LCC resonant converter with PI controller

The simulation output waveform shown in Fig. 13. is the LCC resonant converter with PI controller. The output waveform is found to have ripple in its waveform due to the large size capacitor and also due to the resonance in the circuit. To overcome this the PID controller is implemented with adjusted values of capacitor.

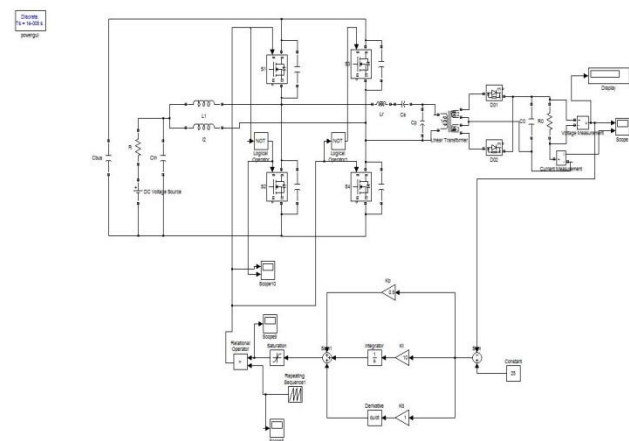


Fig. 14. Simulation circuit diagram of LCC resonant converter with PID controller

The simulation circuit in Fig. 14. shows the LCC resonant converter with PID controller. The run time for the circuit is 10 seconds. The values for the PID controller has K_P, K_I, K_D as

0.5,1,10. To eliminate the error as in the PI controller PID controller is implemented.

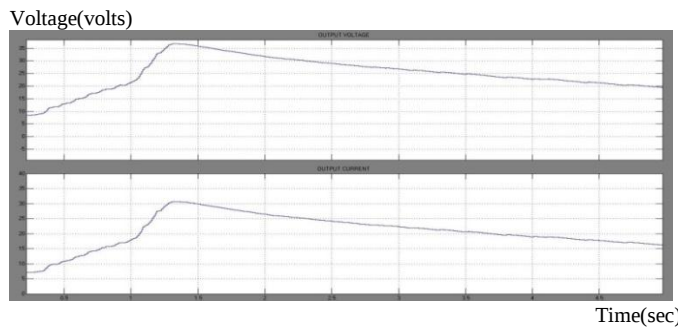


Fig. 15. Simulation result of LLC resonant converter with PID controller
 The simulation output waveform in Fig. 15. shows the result of LLC resonant converter with PID controller. The result shows that there is reduced ripple with improved characteristics. Due to the large size capacitance in parallel the circuit gets more ripple.

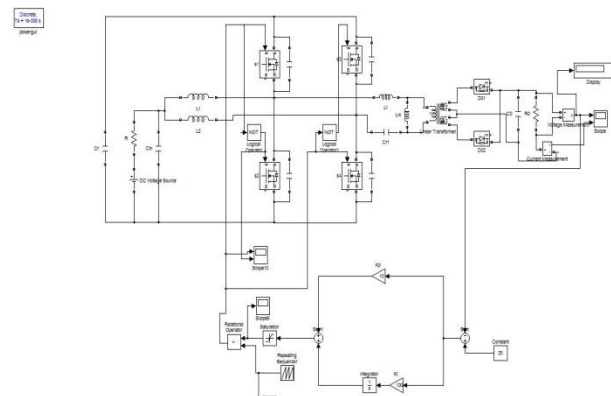


Fig. 16. Simulation circuit diagram of LLC resonant converter with PI controller

The simulation circuit in Fig. 16.shows the LLC resonant converter with PI controller with integral and derivative values as 10 and 100. The run time of the circuit is 10 second.

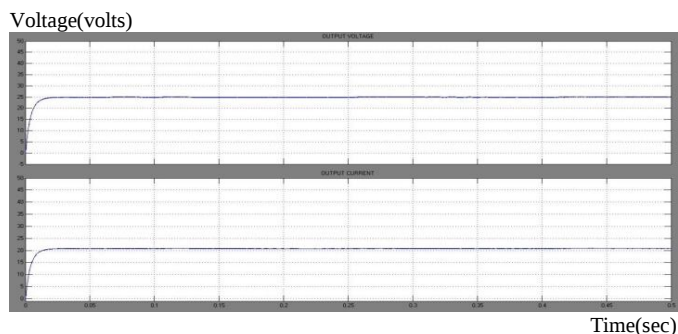


Fig. 17. Simulation result of LLC resonant converter with PI controller
 The output waveform in Fig. 17. shows the LLC resonant converter with PI controller, this circuit has a reduced ripple and also waveform is found to be better for a 240V than LC and LCC converter. To further reduce the ripple content in the waveform we go for PID controller.

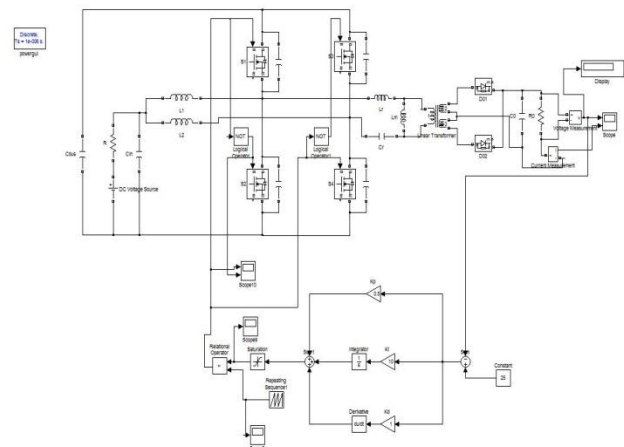


Fig. 18. Simulation circuit diagram of LLC resonant converter with PID controller

The simulation circuit in Fig. 18. shows the LLC resonant converter with PID controller. The PID values are 0.5,10 and 1. The run time of the simulation is 10 seconds
 Voltage(volts)

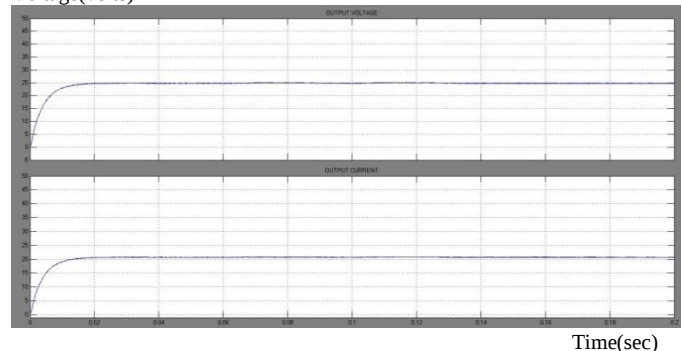


Fig. 19. Simulation result of LLC resonant converter with PID controller
 The output voltage and current waveform of LLC resonant converter in Fig. 19. shows the reduced ripple and also efficient output. The ripple is reduced in the waveform. The parameters used in the circuit are tabulated below.

Parameters used in simulation

Tab 2. Parameters values used in simulation circuit

Parameters	Symbols	Value
Input voltage	V_{in}	240volts
Duty ratio	D	0.5
Resonant inductance	L_r	50.7 μ H
Resonant capacitance	C_r	50Nf
Parallel resonant capacitor	C_p	50nF
Series inductance	L_s	50.7 μ H
Bus capacitance	C_{bus}	47 μ H
Boost inductance	L_{b1}, L_{b2}	300 μ H

PI controller

Tab 3. Simulation results of various resonant converters under study using PI controller

S.No.	Input Voltage	LC Resonant Converter		LCC Resonant Converter		LLC Resonant Converter	
		V_o	I_o	V_o	I_o	V_o	I_o
1.	200	20.6	19	23	19	21	17
2.	240	23.3	21	24	21	24.9	21

PID controller

Tab 4. Simulation results of various resonant converters under study using PID controller

S.No	Input Voltage	LC Resonant Converter		LCC Resonant Converter		LLC Resonant Converter	
		V_o	I_o	V_o	I_o	V_o	I_o
1.	200	18	15	21.7	16	21	17
2.	240	21	18	22.1	19	25	22

Compared to the results obtained from PI and PID controllers, which is presented in table 3 and 4 it is evident that the LLC resonant converter with 240v input yields 25v output and 22amps output current which is more compared to LC and LCC converter with PI and PID controller.

V . CONCLUSION

In this paper a comparative study of interleaved boost integrated LC, LCC, LLC resonant converters with fixed frequency PWM control is analyzed and implemented with PI and PID controller. As seen from the results obtained, the input current ripple is reduced using interleaved boost converter. ZVS (Zero voltage switching) and ZCS (Zero current switching) techniques reduce the conduction losses. The current and voltage ripple in LC and LCC converters are more compared to LLC converter. Quality factor and Gain has main impact on the efficiency. Efficiency is high in LLC converter with 95% compared to LC (82%) and LCC(83%). From the simulation results, the inference is that LLC converter is suitable for high power applications and is highly efficient than LC and LCC converters.

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