DESIGN AND PERFORMANCE ANALYSIS OF LLC RESONANT CONVERTER

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OF

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SUBMITTED BY:
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CANDIDATE'S DECLARATION

I, SUNIL KUMAR, Roll No. 2K20/PES/21 student of M.Tech (POWER ELECTRONICS SYSTEM), hereby declare that the project Dissertation titled "**DESIGN AND PERFORMANCE ANALYSIS OF LLC RESONANT CONVERTER**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition."

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CERTIFICATE

This is to certify that the Project Dissertation titled "DESIGN AND PERFORMANCE ANALYSIS OF LLC RESONANT CONVERTER" which is submitted by SUNIL KUMAR, whose Roll No. is 2K20/PES/21, Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi	**DR. VANJARI VENKATA RAMANA**	**MR. KULDEEP SINGH**
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ABSTRACT

High-performance, high-step-up DC-DC converters are required for many battery-powered applications. For example, in order to power a high intensity discharge (HID) lamp ballast used in vehicle headlamps, the dc–dc converter must boost the battery voltage from 12 V to 100 V during steady-state operation. The computer and telecommunications industries have evolved, a well-defined 48 V battery plant is an ideal solution for supplying hours of reserve time during ac mains outages. The dc-input converter must raise the dc bus voltage from 48 V to around 380–400 V.

High voltage-gain DC–DC converters are typically used to step-up from low voltage (24–48 V) to high voltage (380–400 V). The challenge for high voltage-gain converters is to create a large voltage gain while maintaining high efficiency over a wide input and load range. Soft-switching approaches reduce switching loss and allow for large increases in converter switching frequency.

Early work in this dissertation is based on comparative study of DC-DC step up converters consisting Boost, Cuk, Flyback and LLC Resonant Converter for a input voltage of 48 volts and output voltage at 380 volts working on switching frequency of 100 kHz. At next stage closed loop control of converters is compared for output voltage regulation at 400 volts while a varying input voltage from 18 to 30 volts.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

V_{in}	Input Voltage
V_o	Output Voltage
L_m	Magnetizing inductor
L_r	Resonant inductor
C_r	Resonant Capacitor
C_o	Output Capacitor
R_o	Load resistance
P_o	Output power
A	Ampere
V	Volts
H	Henry
F	Farad
Ω	ohm
µ	micro
F_r	Resonant Frequency
F_s	Switching Frequency
F_n	Nominal Frequency

Abbreviations

PSC	Partial shading condition
RC	Resonant Converter
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
MOSFET	Metal-oxide-semiconductor field-effect transistor
IGBT	Insulated Gate bipolar transistor
SCR	Silicon-controlled rectifier
MPPT	Maximum Power Point Tracking
GMPP	Global maximum power point

LMPP	Local maximum power point
SM	Switched mode
RC	Resonant Converter
RT	Resonant Tank
RSC	Resonant Switch Converters
RR	Reverse Recovery

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION AND BACKGROUND

To meet the rapid growth of consumer electronics and to reduce power wastage in high Power applications such as telecommunications and switch mode (SM) power supplies, among others. The converter is now designed to work at high frequencies, although high frequencies result in greater switch loss. In a resonant converter, the soft – switching mode lowers switching loss. A few topologies of converters and approaches have already been presented forward. In high-power applications, resonant converters (RC) are employed instead of PWM converters. Resonant converters have one major disadvantage: its non-linear nature, which results in dynamic response for varying output conditions and switching frequencies. As we all know, losses in power switching devices such as MOSFETs, IGBTs, and SCRs limit the greatest working frequency of converters. The term "resonant converter" refers to a type of conversion device that uses a resonant circuit which consists an inductor and a capacitor. An RC is a type of converter that has minimum one LC tank circuit. A Resonant Tank (RT) is a circuit that contains minimum one L (inductor) and one C (Capacitor). In steady state operation, these converters feature at least one mode that includes an LC tank.

The size and weight of the converter will be lowered due to the employment of components which work on high-frequency. The frequency of switching is increased.

Resonant Link Converters:

Resonant link converters are divided into two categories:

- Voltage Source RC:

  (a) Series loaded RC (SLR).

  (b) Parallel loaded RC (PLR).

  (c) Hybrid RC.

- Current Source Parallel RC.
- Class E RC.

Resonant Switch Converters (RSC):

These provide soft switching by use of RT which helps to make voltage across switch to zero before we turn it on.

Resonant DC-Link Converters:

RT apart from helping in soft switching provide a buffer between two different natured source and load such as DC as a source and Load as AC. This DC link is provided by resonant inductor. Zero switching loss topologies are also included in these converters.

Resonant AC-Link Converters:

Here resonant inductor acts as a buffer link between the AC supply and the load which is DC.

Benefits of a RC

1. As switching frequency is increased and switching losses are reduced so device heating is less.
2. As heating is less that’s why cooling demand is lowered.
3. Size and weight are lowered.
4. Because power devices work at soft switching, the efficiency of the converter is improved by an extent.
5. There is less noise.
6. Electro Magnetic Induction levels are lowered. Also, Radio Frequency Interference is less in these circuits.

Resonant Converter Disadvantages

1. The peak current values of the power devices will be higher.
2. A control circuit is required in addition to the resonant converter circuit. As a result, the complexity rises.

The LLC type of RC is chosen as the best and effective topology for this project. In a variety of industrial applications, LLC combines the advantages of both series RC and parallel RC. As no load regulation is not possible in series RC that is a disadvantage which we have to overcome before choosing a converter topology. Also circulating current which doesn't depend on load is a great disadvantage for parallel RC. ZVS and ZCS switching are used on the inversion side and rectification sides of the LLC resonant converter. RC may operate over a wide frequency range and offer higher efficiency as reduction in switching losses which is beneficial as compared to PWM and other hard switching converters. For these resonant converters, some literature uses the intellectual PI and Fuzzy controllers. This new DC has been tinkered with. In this dissertation, boost converter is used for closed loop of this RC. This topology gives high efficiency and reliable voltage regulation.

1.2 DC-DC CONVERTERS:

Buck converter, Boost converter, Buck-Boost Converter, Cuk Converter, and SEPIC Converter are non-isolated DC-DC converters.

1.2.1 BOOST CONVERTER:

A boost converter is one of the most basic types of switch-mode converters (also known as a step-up converter). As the name says, the converter takes an input voltage and boosts it. In other words, it functions similarly to a step-up transformer in that it raises DC voltage from low to high while lowering current from high to low while retaining the same power output [1].

The only components are an inductor, a semiconductor switch, a diode, and a capacitor. Boost converters are quite basic and require few components because they were invented and built in the 1960s to power electronics on aircraft.

The output voltage relationship is as follows:

$$V_o = \frac{V_{in}}{(1 - D)}$$

1.2.2 CUK CONVERTER:

The Cuk converter is a DC-DC power electronic converter named after its inventor, Slobodan Ćuk. When compared to buck, boost, and buck-boost converters, the Cuk converter has a higher component count. Two inductors, two capacitors, one diode, and one switch make up the Cuk converter [2], [3], [4]. Cuk converter is a hybrid of buck and boost converters, with the input side looking like a boost converter and the output side looking like a buck converter, coupled by a single capacitor.

The main applications for this DC-DC Converter are regulated dc power supply with a negative polarity output in reference to the input voltage's common terminals and an average output that is either higher or lower than the dc input voltage.

The capacitor C1 is used to store and transport electricity from the input to the output. vc1 is always higher than either the input or output voltage. The average output to input relationships are comparable to a buck-boost converter circuit [5]. The switch-duty cycle is used to control the output voltage.

The output voltage relationship is as follows:

$$\frac{\mathrm{V_o}}{\mathrm{V_i}} = -\frac{D}{(1-\mathrm{D})}$$

1.2.3 FLYBACK DC-DC CONVERTER:

Flyback converter is an isolated DC-DC converter which can do both step-up and step-down. A high frequency transformer is present here for isolation and voltage ratio purpose. The basic circuit diagram of Flyback DC-DC converter is as shown Fig.2.3. This converter consists of two passive elements and one high frequency transformer [6]. Overall circuit of flyback consists DC Supply, one switching device as MOSFET, one diode, one inductor, one high frequency transformer, one capacitor and load. It also can step-up and down with duty ratio around 0.5.

It can be used to obtain more than one output by using output winding of transformer. Flyback converter can be operated on a wide range of input voltage variations. Fly-back is less efficient than many converters but it is simple to design as discussed for various applications and ratings in [7]–[9]. It is approved in limited output power ranges due to its low rate.

The output voltage relationship is as follows:

$$V_o = \frac{V_{in} * D}{(1-D)} * (\frac{N_2}{N_1})$$

1.2.4 LLC RC (RESONANT CONVERTER):

The LLC RC is best known for operation at higher switching frequencies. LLC converter improves efficiency because it has low switching losses. Power switches of RC works on zero voltage switching this reduces power wastages during switching. FM, phase shift and variable resonant frequency can be used for regulation purpose of LLC converter. When operating at F_n=1 i.e., F_s=F_r at a gain of 1 this RC will provide best efficiency. Two inductors (L_r, L_m) and one capacitor (C_r) form a tank which is called LLC tank. In LLC converter, two resonant frequencies w_{r1} and w_{r2} are observed. One is given by set of resonant inductor and capacitor. Another one is the resonant frequency which is given by summation of L_m and L_r with resonant capacitor (C_r) [11] .

This Series–Parallel RC can regulate the output voltage over a wide range of load variation. As discussed earlier this topology achieves soft switching of power switches over a wide range of variation in load.

The output voltage relationship is as follows:

$$K(Q,m,Fn) = \frac{V_{oac}}{V_{in\_ac}} = \frac{Fn^2(m-1)}{\sqrt{(m \cdot Fn^2 - 1)^2 + Fn^2 \cdot (Fn^2-1)^2 \cdot (m-1)^2 \cdot Q^2}}$$

1.2.5 Burst Mode Control of LLC Resonant Converter:

LLC resonant converters are now used to achieve improved efficiency. However, with rising demand, its light-load efficiency is still insufficient. The LLC resonant converter's light-load efficiency is improved by using burst-mode control[12]. Burst mode operation can be employed for exhausted batteries that require the LLC converter to operate. This approach is only used to resurrect neglected batteries. Instead of a train of pulses, a continuous pulse pattern will be provided within a particular switching frequency in this manner of control. Depending on the duty ratio, the switching device will be turned off for the remainder of the time period. This reduces the load on the gadget, which reduces the ripple. As a result, overall efficiency improves. To boost efficiency even further, the Synchronous Rectification method is created, in which switching devices replace the typical diodes of output rectifiers in LLC resonant converters and for filter design requirement in various applications this [13] literature presents a brief study.

1.3 MOTIVATION:

High-performance, high-step-up dc–dc converters are required for many battery-powered applications. For vehicle headlamps DC-DC converter must provide a gain from 12 volts of battery to a required voltage of 100 volts.

48 V battery plants are coming as a solution when there is electricity outage, mainly for application in industrial sector of computer and IT [14]. The dc-input converter must raise the dc bus voltages at tenfold from 48 V. In these applications of high gain converters must have high effectiveness.

In this dissertation famous DC-DC step up converter's performance is compared for a DC input voltage of 48V and Output voltage as 400V for 1000-watt application.

1.4 SPECIFIC OBJECTIVES:

The hard-switching is more lossy as compared to soft switching. Also, power density is limited by the reactive element size and high frequency transformer size. When switching frequency is increased switching losses increases. By increasing switching frequency size of reactive components reduces. That's why high switching frequencies are essential for achieving high-power density, reducing size of converter and good transient response.

Low R_{DS-on} device when operated at low voltage waste low power in conduction. Soft-switching approaches reduce switching loss, if that can be achieved in a converter it will benefit in increasing its efficiency.

This dissertation introduces comparative study of DC-DC step up converters consisting Boost, Cuk, Flyback and LLC Resonant Converter for an input voltage considering a battery source application of 48 volts and output voltage at 380 volts working on switching frequency of 100 kHz. At Next Stage Closed Loop control of converters is compared for output voltage regulation at 400 volts while a varying input voltage from 18 to 30 volt. Future work is based on the Closed Loop control of LLC Resonant with Magnetic Control [15]. LLC Resonant converter provides following merits over other topologies [16]

1. Better EMI performance.
2. High efficiency and high energy density
3. Electrical isolation and low harmonic pollution

4. Wide output ranges
5. Low voltage stress, low switching losses, high operation frequency, high gain

1.5 ORGANISATION OF THESIS:

This thesis is divided into four chapters.

- In chapter 1, the brief introduction of DC-DC step-up converters used and their basic theory, output voltage relation and advantages has been described. This part also provides the motivation and research purpose.
- In chapter 2, a literature review on the DC-DC step-up converters used and control techniques of these converters has been mentioned.
- In chapter 3, Design of respective converters, their component table, modelling analysis and simulation is presented.
- In chapter 4, Conclusion based on various comparison parameters is presented. Also, Future work on LLC RC is discussed in brief in this section

CHAPTER 2 LITERAUTRE REVIEW

We are to adopt renewable energy due to high pollution and depletion of natural resources. As we have a lot of solar irradiance available so we can use solar energy more conveniently and as a greener energy. For these applications, high voltage-gain efficient DC–DC converters must be designed to use to step-up from low voltage in range of 24 to 48 V to a output of high voltage (380–400 V)[17], [18], [19], [20]. The challenge for power electronics engineers is to design a reliable, efficient and high gain converters which can operate at a wide input and load range.

As previously stated, various MPPT approaches are available such as

- Perturb & Observe (P&O)
- Incremental Conductance (IC)
- Open Circuit Voltage method
- Short Circuit Current method

For closed-loop applications, some topologies in isolated converters like half-bridge, full bridge, flyback, forward and push-pull converter is discussed in [9], [21], [22]. Isolation in converters can be used for a variety of purposes.

Because of high output voltage Reverse Recovery (RR) has to be strong. The simplest non-isolation topologies are conventional converters. Regrettably, the switch on high output voltage side has a high $R_{DS\text{-}on}$[18]. As duty ratio is high so high amplitude current of a short duration passes through rectifier which causes RR to be difficult. High $R_{DS\text{-}on}$ and weak RR are limiter for output power rating of converters. Isolated converters provide tenfold gain even at low duty ratio. When the duty is equal to 0.5, the voltage gain of the flyback converter is equal to voltage ratio of transformer.

2.1 TOPOLOGIES:

2.1.1 CIRCUIT DIAGRAMS:

BOOST CONVERTER:

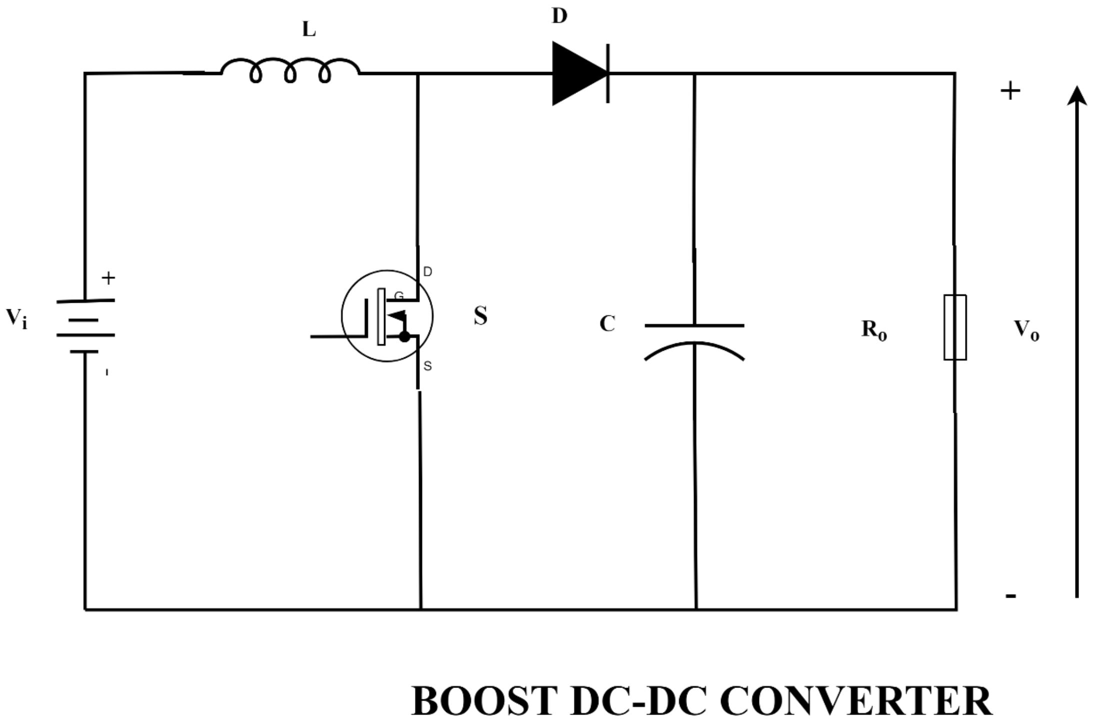


Fig 2.1 Boost converter circuit diagram

CUK CONVERTER:

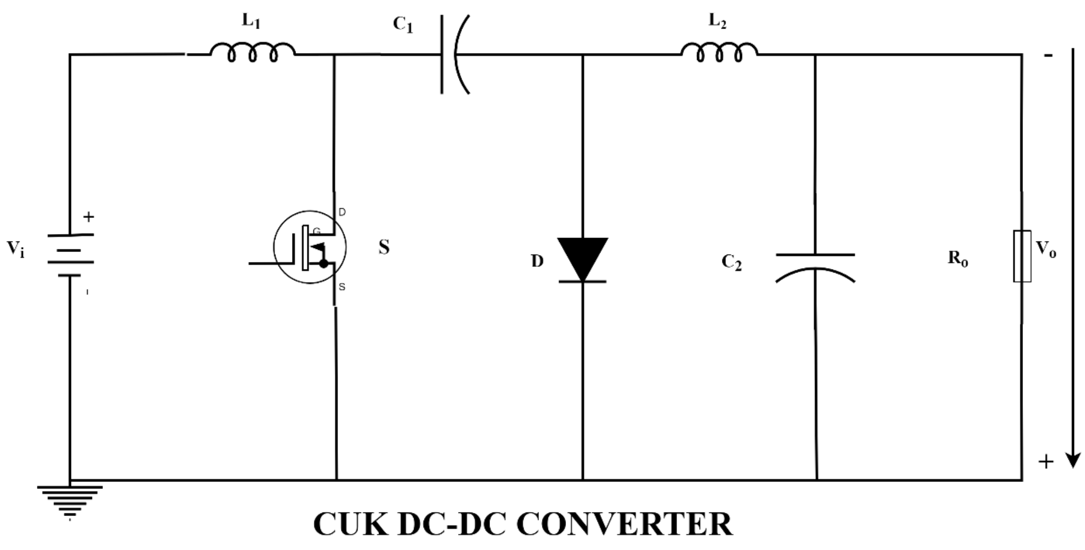


Fig 2.2 Cuk converter circuit diagram

FLYBACK CONVERTER:

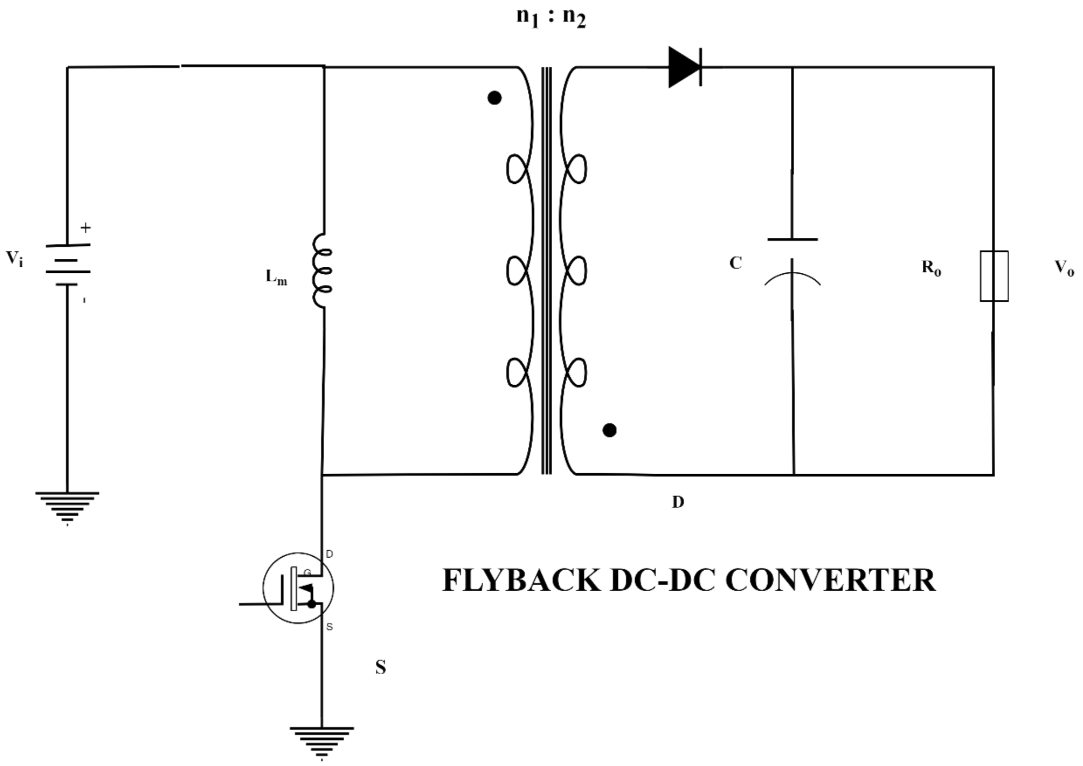


Fig 2.3 Flyback converter circuit diagram

LLC RESONANT CONVERTER:

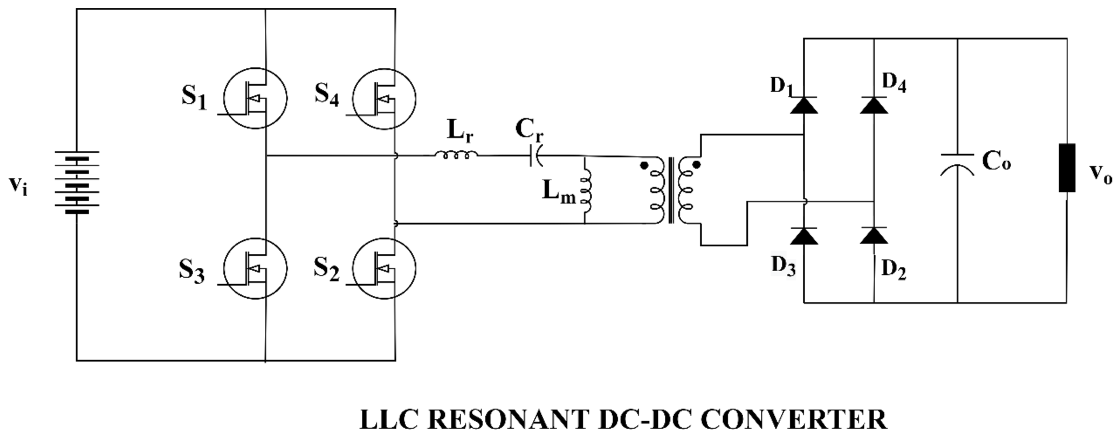


Fig 2.4 LLC Resonant DC-DC converter circuit diagram

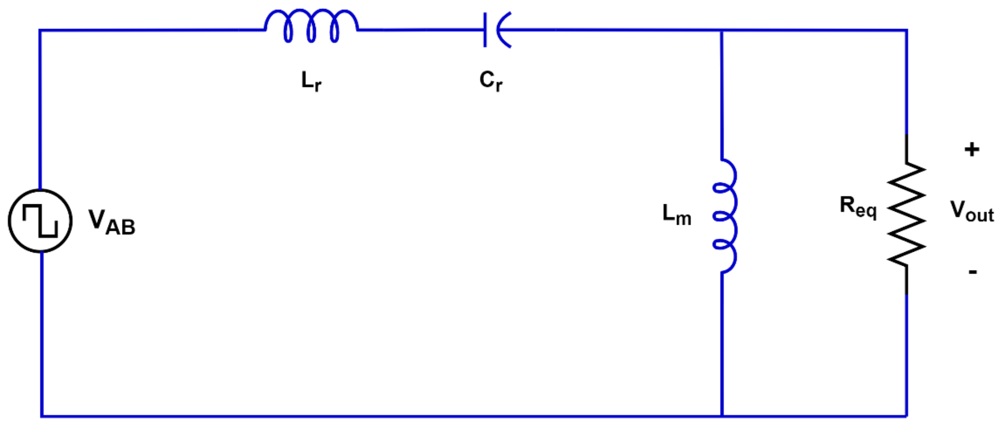
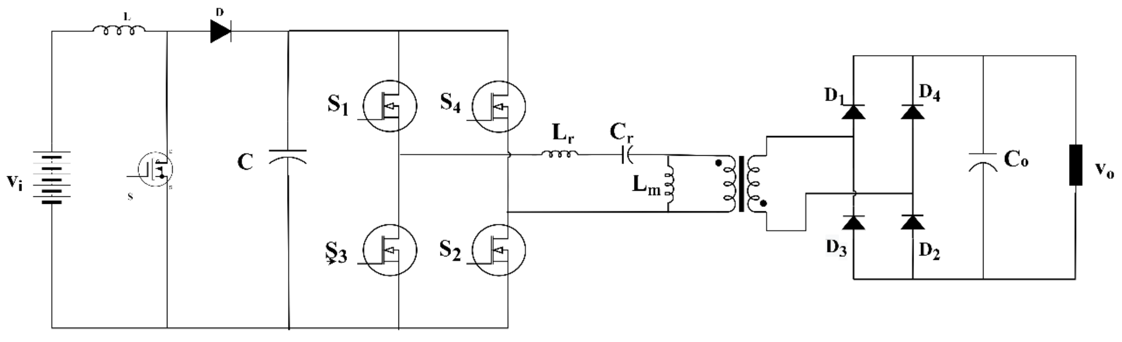


Fig 2.5 Equivalent circuit of LLC Resonant circuit

CLOSED LOOP LLC RESONANT CONVERTER USING BOOST CONVERTER:



LLC RESONANT DC-DC CONVERTER WITH BOOST CONVERTER

Fig 2.6 Closed loop LLC resonant converter using boost converter

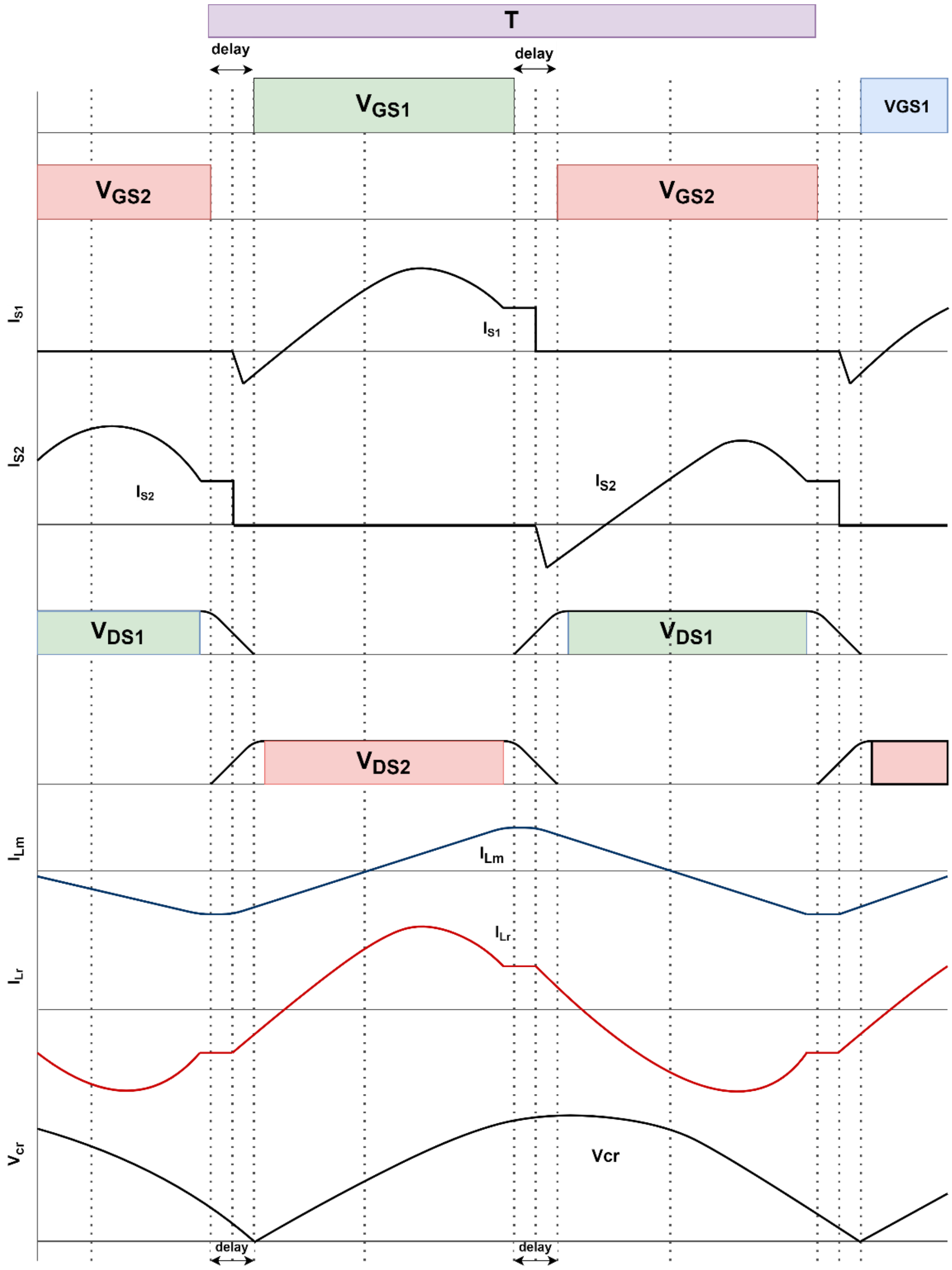


Fig 2.7 Theoretical waveforms across components of LLC Converter

2.2 LLC RESONANT CONVERTER:

Gain of LLC converter depends on switching frequency, resonant frequency and quality factor. So variable switching frequency, variable resonant frequency and resonant capacitor voltage can be used to control the output of this converter. Also secondary side phase shift control is employed in some applications [23].

Many literatures introduce various controlling techniques for controlling of LLC Resonant converter for various applications [24]–[27][28]. For Electric vehicle charging applications various high efficiency AC-DC and DC-DC converters are studied in [29].

The most common charger architecture, as shown in Fig. 2.8, has a DC-DC conversion at stage 2 and a boost type rectification stage for active power factor adjustment.

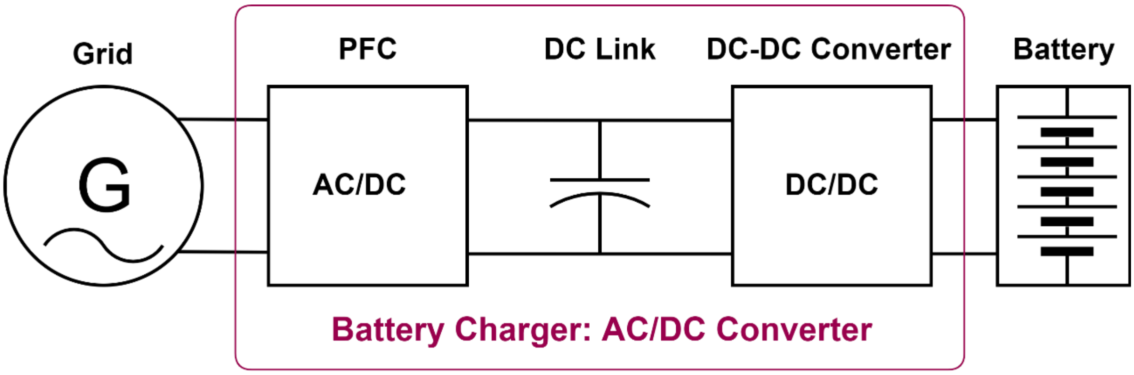


Fig 2.8 Typical power architecture of a battery charger

2.2.1 Compression Network (CN):

The transformer's secondary output side has an uncontrolled rectifier stage. A network consisting inductor and capacitor in series is connected before rectification stage to further reduce ripples and smoothen the output waveforms of converter. Load is resistive. It includes L_R and C_R, as well as filtering the input of rectifier stage. In this particular network C_{DC} capacitor is used to stop dc current.

2.3 Fast-Charging System:

Constant current constant voltage charging is known as a fast charging method. At earlier when State of Charge of a battery is below 70% then it charged at a constant current which is equal to 0.1C where C is the capacity of battery. After this stage battery is charged with constant voltage to avoid overcharging and to improve battery life. Super Capacitor has different charging characteristics compared to Li-ion battery. Li-ion battery is charged with constant current constant voltage method.

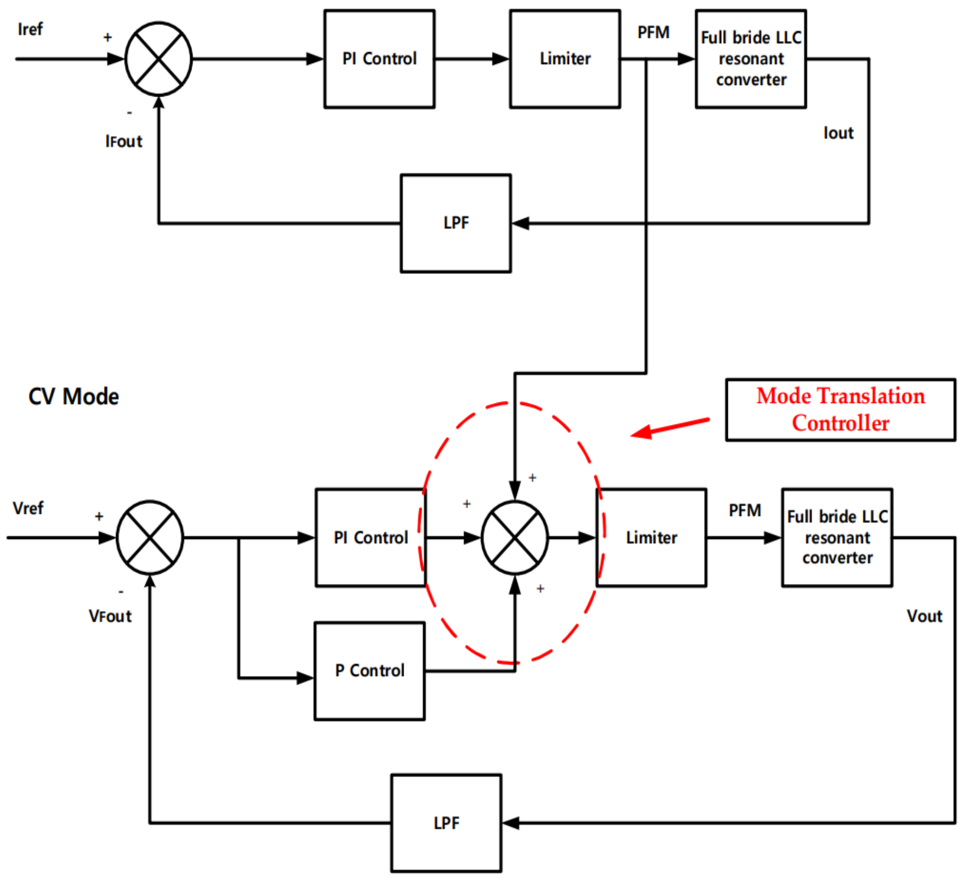


Fig 2.9 CC-CV Charging Algorithm of LIB

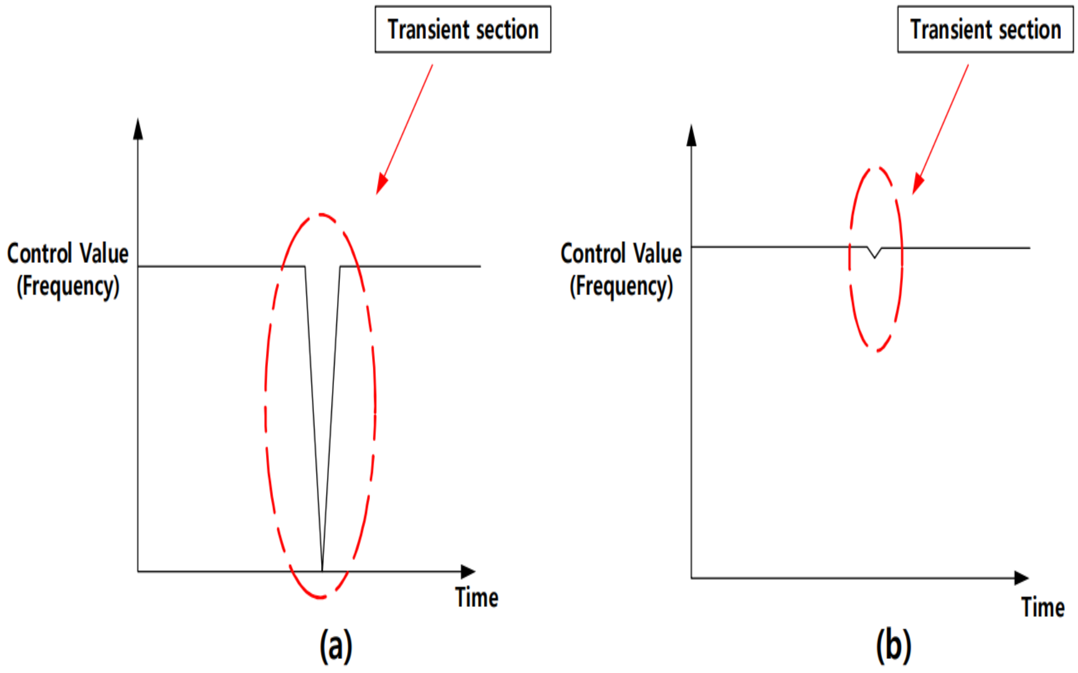


Fig 2.10 Transition before a) and after b) of Algorithm

CC-CV charging block diagram is given in Fig 2.11. Whereas Transition state is given by Fig 2.12. Low pass filter improves quality of digital controller and minimizes noise. For a battery of capacity 40 Ah and open circuit voltage of 48 V we can charge it with constant current charge stage at a maximum current of 4 amperes and after that, in Constant voltage charging state it is charged with a constant voltage around 48 V.

2.4 PV CHARACTERSTICS OF NON-IDENTICAL CELLS:

When non-identical cells are connected in series then at a particular stage of operation some cells act as a sink in same circuit and it makes it less efficient.

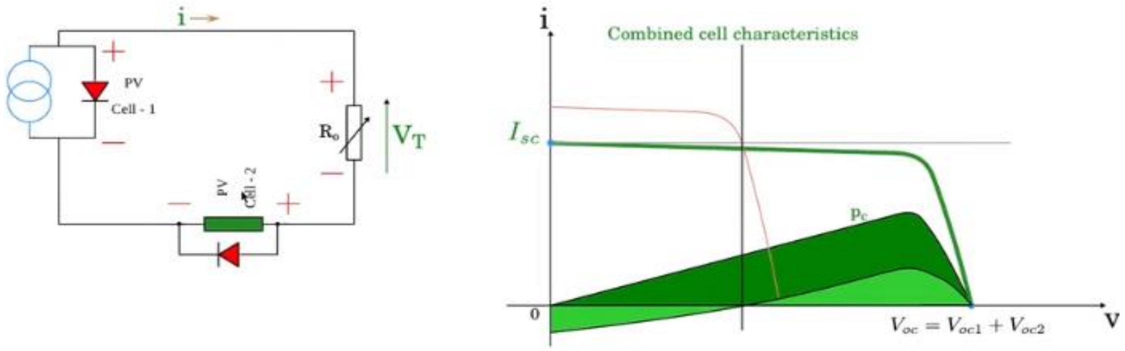


Fig 2.11 Combined cell characteristics of non-identical cells without bypass diode

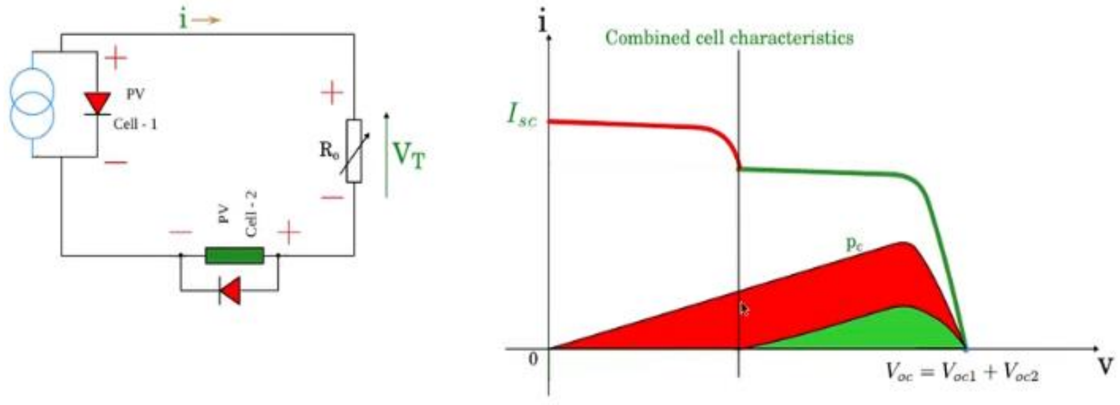


Fig 2.12 Combined cell characteristics of non-identical cells with bypass diode

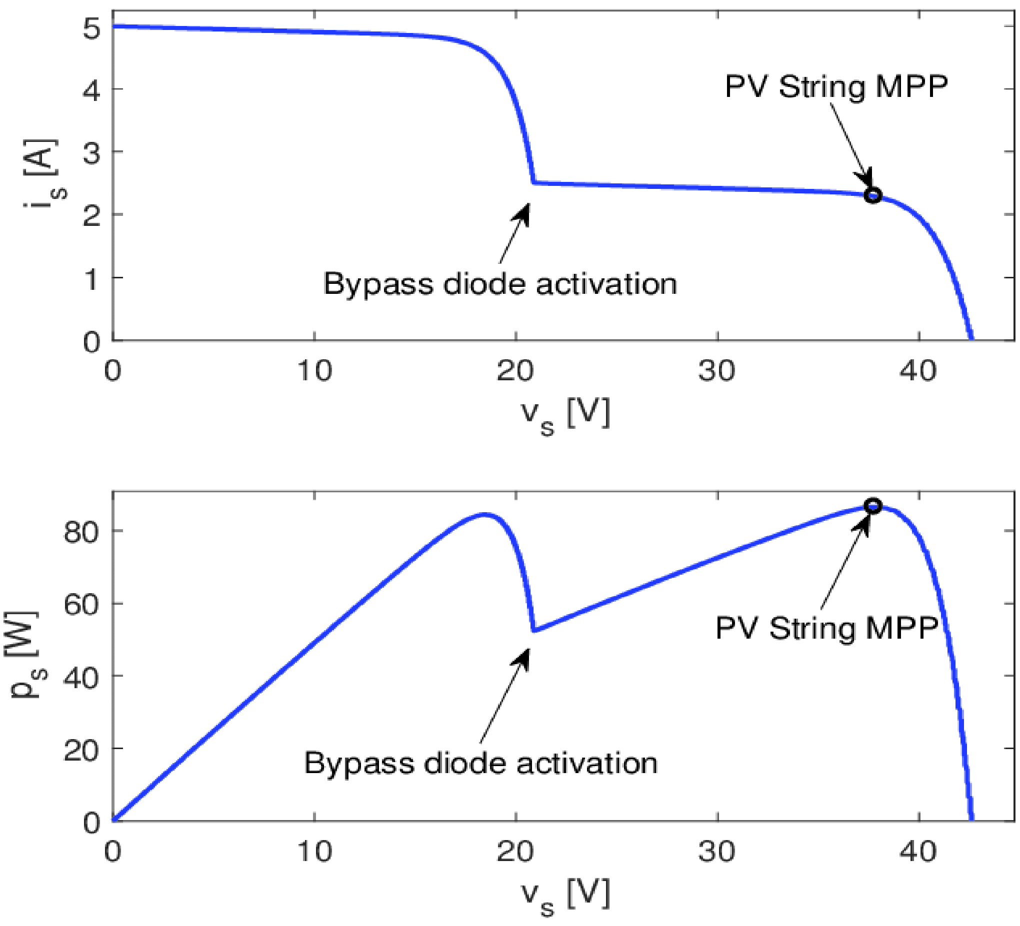


Fig 2.13 I-V and P-V characterstics of non-identical cells connected in series

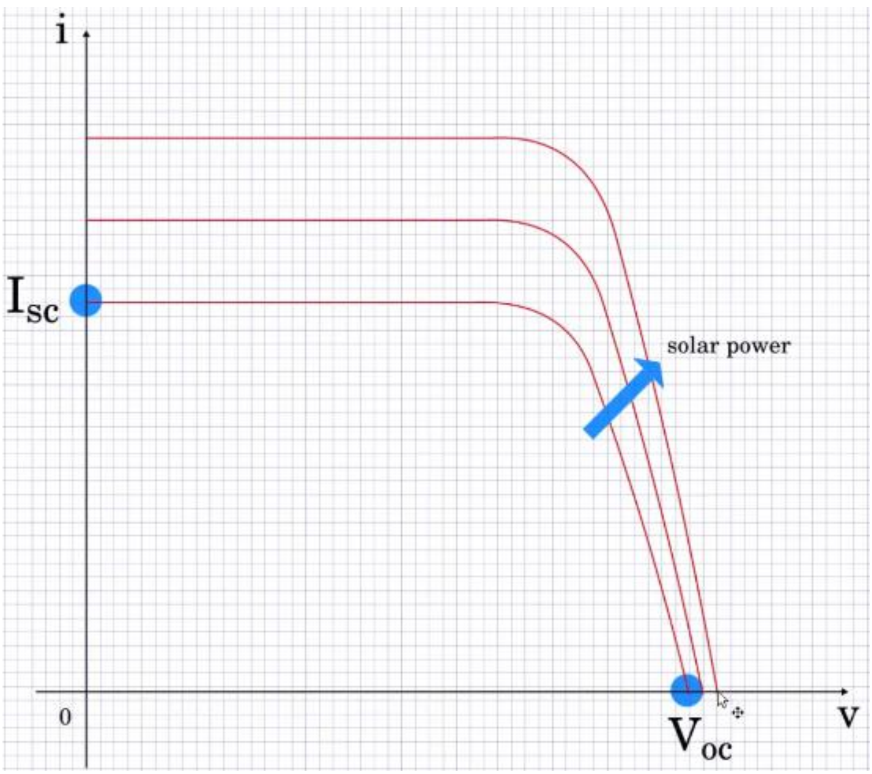


Fig 2.14 Comparison of I-V characteristics of non-identical cells

CHAPTER 3 DESIGN AND SIMULATION

3.1 DESIGN OF CONVERTERS

3.1.1 DESIGN OF BOOST CONVERTER:

Solving for $\mathrm{V_o = 380\ V}$ $\mathrm{V_i = 48\ V}$ $\mathrm{P_o = 1\ kW}$ $\mathrm{f = 100\ kHz}$ $\Delta\mathrm{V} = 5\%$ and $\Delta\mathrm{I} = 2\%$

We get $R = 144.4\ \Omega$ and $\mathrm{I_o} = \frac{380}{144.4} = 2.63\ \mathrm{A}$

Basic formula

$$\frac{\mathrm{V_o}}{\mathrm{V_i}} = \frac{1}{(1-\mathrm{D})}$$

We get $\mathrm{D} = 87.37\%$

for L and C:

Ripple Current $= \frac{(\mathrm{D}*\mathrm{V_i})}{\mathrm{f}*\mathrm{L}}$ And the Ripple Voltage is $= \frac{(\mathrm{D}*\mathrm{I_o})}{\mathrm{f}*\mathrm{C}} = \frac{(\mathrm{D}*\mathrm{V_o})}{\mathrm{R}*\mathrm{f}*\mathrm{C}}$

$$L_m = \frac{V_{in}D}{\Delta i_{L_m} f} = 167.75\ \mathrm{mH} \qquad \mathrm{C} = \frac{D}{R(\frac{\Delta V_o}{V_o})f} = 5.75\ \mu\mathrm{F} \qquad I_L = \frac{I_o}{(1-D)} = 20.84\ A$$

3.1.2 DESIGN OF CUK CONVERTER:

Basic formula

$$\frac{\mathrm{V_o}}{\mathrm{V_i}} = -\frac{\mathrm{D}}{(1-\mathrm{D})}$$

We get $\mathrm{D} = 88.79\%$

for L and C:

$$\Delta\mathrm{I_{L1}} = \frac{(\mathrm{D}*\mathrm{V_i})}{\mathrm{f}*\mathrm{L_1}} \qquad \Delta\mathrm{I_{L2}} = \frac{(\mathrm{D}*\mathrm{V_i})}{\mathrm{f}*\mathrm{L_2}}$$

$$\Delta V_{C1} = \frac{(D * I_o)}{f * C_1} = \frac{(D * V_o)}{R * f * C_1} \qquad \Delta V_{C2} = \frac{(1 - D) * V_o}{8 * L_2 * C_2 * f^2}$$

$$L_1 = \frac{V_i D}{\Delta i_{L_1} f} = 1.025 \text{ mH} \qquad L_2 = \frac{V_i D}{\Delta i_{L_2} f} = 8.2 \text{ mH}$$

$$C_1 = \frac{D}{R(\frac{\Delta V_o}{V_o})f} = 1.09\ \mu F \qquad C_2 = \frac{1-D}{8{**}L_2 * (\frac{\Delta V_o}{V_o}) * f^2} = 3.42\ nF$$

$$I_L = \frac{I_o}{(1 - D)} = 20.84\ A$$

3.1.3 DESIGN OF FLYBACK CONVERTER:

$$V_o = \frac{V_{in} * D}{(1 - D)} * (\frac{N_2}{N_1})$$

We get $D = 49.74\%$ $\frac{N_2}{N_1} = 8$

for L and C:

$$I_{L_m} = \frac{I_{in}}{(D)} = 41.885\ A \qquad \Delta i_{L_m} = I_{L_m} * \frac{I_{ripple}}{100} = 0.838\ A$$

$$L_m = \frac{V_{in} * D}{\Delta i_{L_m} * f} = 0.000285 = 285\ \mu H \qquad C = \frac{D}{R(\frac{\Delta V_o}{V_o})f} = 688.92\ nF$$

$$L_{min} = \frac{(1 - D)^2 R}{2f} * (\frac{N1}{N2})^2 \qquad [For\ continuous\ current]$$

$$L_{min} = 2.84 \mu H$$

$L_m \geq L_{min}$

3.1.4 DESIGN OF LLC RESONANT CONVERTER:

$$G = \frac{V_o}{V_{in}} = \frac{1}{2} \cdot K(Q, m, Fn) \cdot \frac{N_s}{N_p} K(Q, m, F\mathrm{n})$$

$$= \frac{V_{oac}}{V_{in\_ac}} = \frac{Fn^2(m-1)}{\sqrt{(m \cdot Fn^2 - 1)^2 + Fn^2 \cdot (Fn^2 - 1)^2 \cdot (m-1)^2 \cdot Q^2}}$$

$$F\mathrm{n} = \frac{f_s}{f_r} \qquad f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad Q = \frac{[\sqrt{\frac{L_r}{C_r}}]}{R_{ac}}$$

$$R_{ac} = \frac{8}{\pi^2} \cdot \frac{N_p^2}{N_s^2} \cdot R_o \qquad m = \frac{L_r + L_m}{L_r}$$

3.2 COMPONENTS:

3.2.1 COMPONENT RELATIONSHIP OF CONVERTERS:

Table 3-1 COMPONENT RELATIONSHIP OF CONVERTERS

Components	BOOST CONVERTER	CUK CONVERTER	FLYBACK CONVERTER
L_1	$\frac{V_{in}D}{\Delta i_{L_m} f}$	$\frac{V_i D}{\Delta i_{L_1} f}$	$\frac{V_{in} * D}{\Delta i_{L_m} * f}$
C_1	$\frac{D}{R(\frac{\Delta V_o}{V_o})f}$	$\frac{D}{R(\frac{\Delta V_o}{V_o})f}$	$\frac{D}{R(\frac{\Delta V_o}{V_o})f}$
L_2	NA	$\frac{V_i D}{\Delta i_{L_2} f}$	NA
C_2	NA	$\frac{1 - \mathrm{D}}{8 ** \mathrm{L}_2 * (\frac{\Delta V_o}{V_o}) * f^2}$	NA

3.2.2 COMPONENT VALUES OF BOOST CONVERTER:

Table 3-2 COMPONENT VALUES OF BOOST CONVERTER

D	88.37%
L	167.75 mH
C	5.75 µF
R_o	144.4 Ω

3.2.3 COMPONENT VALUES OF CUK CONVERTER:

Table 3-3 COMPONENT VALUES OF CUK CONVERTER

D	88.79%
L_1	1.025 mH
C_1	1.09 µF
L_2	8.2 mH
C_2	3.42 nF
R_o	144.4 Ω

3.2.4 COMPONENT VALUES OF FLYBACK CONVERTER:

Table 3-4 COMPONENT VALUES OF FLYBACK CONVERTER

D	47.94%
L	285 µH
C	0.6889 µF
N_2/N_1	8
R_o	144.4 Ω
L_{min}	2.84 µH

3.2.5 COMPONENT VALUES OF LLC CONVERTER:

Table 3-5 COMPONENT VALUES OF LLC CONVERTER

Components	Values
V_i	48 V
V_o	380 V
P_o	1000 W
Q	0.4
m	6.5
L_r	1.165 µH
L_m	6.41 µH
C_r	2.1765 µF
C_o	200 µF
R_o	144.4 Ω
F_s for LLC	100 kHz
F_r	100 kHz

3.3 MODELING ANALYSIS:

State-space modeling is used to complete the modeling. Modeling is used to collect data for the system model and to forecast system behavior based on various input scenarios. Although there are other ways for modeling converters, state-space modeling is the most advantageous. [51], [52] presents ZVS modelling and synchronous reference frame. Assuming zero initial conditions, transfer function modeling can be applied to linear, time invariant systems. Using equivalent circuit as given in Fig 2.5 and modes of operation of LLC converter State Space model is prepared.

A. Analysis of State-Space: Before achieving state space model some assumptions were made so first discuss these assumptions. The following are the assumptions that were assumed:

a) All the components of boost DC-DC converter are considered as ideal.

b) The F_n is less than 1.

c) The output filter is large enough so that output voltage V_o is fixed.

d) The losses are negligible

B. Stability analysis:

One key benefit State-space modeling offers is:

It can be used to realize the system's internal state. By plotting and studying the bode plot of whole operation of the RC, the system's stability can be determined using the state–space model. Figure 5 in chapter 2 depicts the LLC's equivalent circuit.

The state-space input matrix for LLC RC by using equivalent circuit is given as:

$$\begin{bmatrix} i_1' \\ i_2' \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ [-\frac{L_m C_0 + L_m C_1}{L_r L_m C_0}] & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ L_r L_m C_0 \end{bmatrix} [V_{\mathrm{dc}}]$$

And the output equation is,

$$[\mathrm{y}] = [0 \quad \mathrm{L_1 C_1 C_0}] \begin{bmatrix} \mathrm{i_1} \\ \mathrm{i_2} \end{bmatrix}$$

The stability analysis of the system is used to design the closed loop system. The bode shows the magnitude and phase plot for the LLC RC, from the phase plot it can be depicted whether closed loop system is stable or not.

3.4 STATE SPACE MODEL OF LLC RC:

$$A = \begin{bmatrix} -\frac{H_{ip}+r_s}{L_s} & -\frac{[\Omega_s L_s + H_{ic}]}{L_s} & -\frac{1}{L_s} & 0 & \frac{H_{ip}}{L_s} & \frac{H_{ic}}{L_s} & -\frac{H_{vcf}}{L_s} \\ \frac{\Omega_s L_s - G_{ip}}{L_s} & -\frac{[G_{ic}+r_s]}{L_s} & 0 & -\frac{1}{L_s} & \frac{G_{ip}}{L_s} & \frac{G_{ic}}{L_s} & -\frac{G_{vcf}}{L_s} \\ \frac{1}{C_s} & 0 & -\frac{C_s\Omega_s}{C_s} & 0 & 0 & & 0 \\ 0 & \frac{1}{C_s} & \frac{C_s\Omega_s}{C_s} & 0 & 0 & 0 & 0 \\ \frac{H_{ip}}{L_m} & \frac{H_{ic}}{L_m} & 0 & 0 & -\frac{H_{ip}}{L_m} & -\frac{H_{ic}+L_m\Omega_s}{L_m} & \frac{H_{vcf}}{L_m} \\ \frac{G_{ip}}{L_m} & \frac{G_{ic}}{L_m} & 0 & 0 & -\frac{G_{ip}-L_m\Omega_s}{L_m} & -\frac{G_{ic}}{L_m} & \frac{G_{vcf}}{L_m} \\ \frac{K_{is}r_c'}{C_f r_c} & \frac{K_{ic}r_c'}{C_f r_c} & 0 & 0 & -\frac{K_{is}r_c'}{C_f r_c} & -\frac{K_{ic}r_c'}{C_f r_c} & -\frac{r_c'}{RC_f r_c} \end{bmatrix}$$

$$B = \left[-\frac{[L_s w_0 I_c]}{L_s} \quad \frac{[L_s w_0 I_s]}{L_s} \quad -\frac{[C_s w_0 V_c]}{C_s} \quad \frac{[C_s w_0 V_s]}{C_s} \quad -\frac{[L_m w_0 I_{mc}]}{L_m} \quad \frac{[L_m w_0 I_{ms}]}{L_m} \quad 0\right]$$

$$C = \left[K_{is} * r_c' \quad K_{ic} * r_c' \quad 0 \quad 0 \quad -K_{is} * r_c' \quad -K_{ic} * r_c' \quad \frac{r_c'}{r_c}\right]$$

$$D = 0$$

$$\frac{d\hat{x}}{dt} = A\hat{x} + B\hat{u}$$

$$\hat{y} = C\hat{x} + D\hat{u}$$

$$\frac{\hat{v}_o}{\hat{w}_{sn}} = C(SI - A)^1 B + D$$

Where A, B, C and D are the state-space system matrices,

$\hat{x} = (\hat{\imath}_s, \hat{\imath}_c, \hat{v}_s, \hat{v}_c, \hat{\imath}_{ms}, \hat{\imath}_{mc}, \hat{v}_{cf})$ is a state vector of the state-space model,

$\hat{u} = (\hat{w}_{sn})$ is the control input vector, and $\hat{y} = (\hat{v}_o)$ is the output vector

3.5 CLOSED LOOP LLC RESONANT CONVERTER USING BOOST CONVERTER:

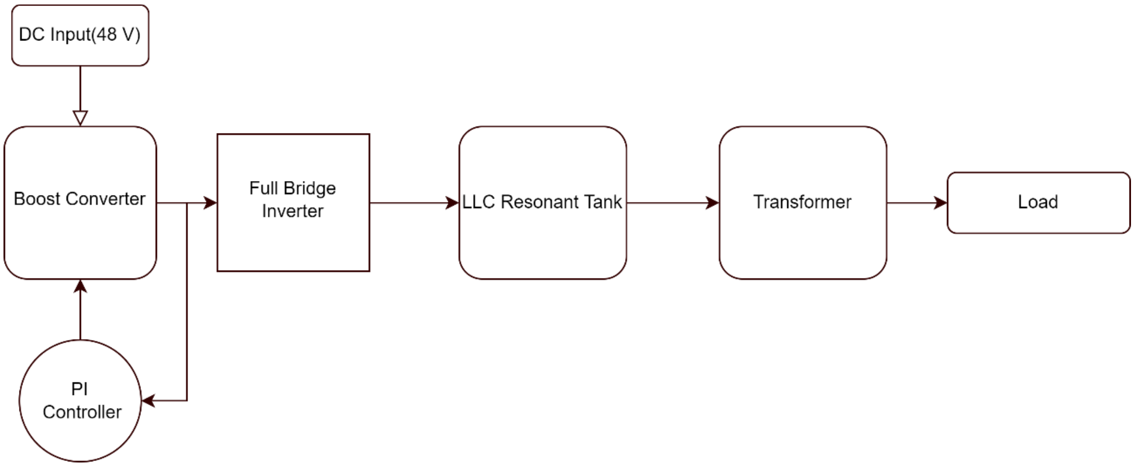


Fig 3.1 Block diagram of closed loop LLC resonant converter with boost converter and PI controller

3.6 GAIN CURVE:

3.6.1 MATLAB CODE to plot Gain curve:

```
clc;
m = [2 3 4.5 5 6 6.5 7 15];             %//=(Lm+Lr)/Lr//
 Fn = logspace(-1, 1, 1000);

 colors = ['m' 'b' 'k' 'c' 'r' 'g' 'r' 'bl' 'm'];
 QF = [6 5 3 1 0.7 0.5 0.4 0.3 0.2];
 for p = 1:9
     figure
     for i = 1:8
         LLC_Gain = (((8/(3.16^2))*(Fn.^2)*(m(p)-1))./(((m(p)*(Fn.^2)-1).^2+((Fn.^2).*((Fn.^2)-1).^2).*((m(p)-1).^2)*(QF(i)^2)).^0.5));
         semilogx(Fn,LLC_Gain,'color',colors(i),'LineWidth',3)
         hold on
     end
    legend('QF = 6','QF = 5','QF = 3','QF = 1','QF = 0.7','QF= 0.5','QF = 0.4','QF = 0.3','QF = 0.2')
    title(['|G|(\omega)vs \omega with m ', num2str(m(p))],'FontSize', 24)
xlabel('\omega_x','FontSize',24)
ylabel('|G|(\omega_x)','FontSize',24)
grid on
 end
```

Fig 3.2 MATLAB code for plotting gain curves of LLC Converter

3.6.2 GAIN CURVE USED FOR DESIGN OF LLC RESONANT CONVERTER:

Gain curve with different m

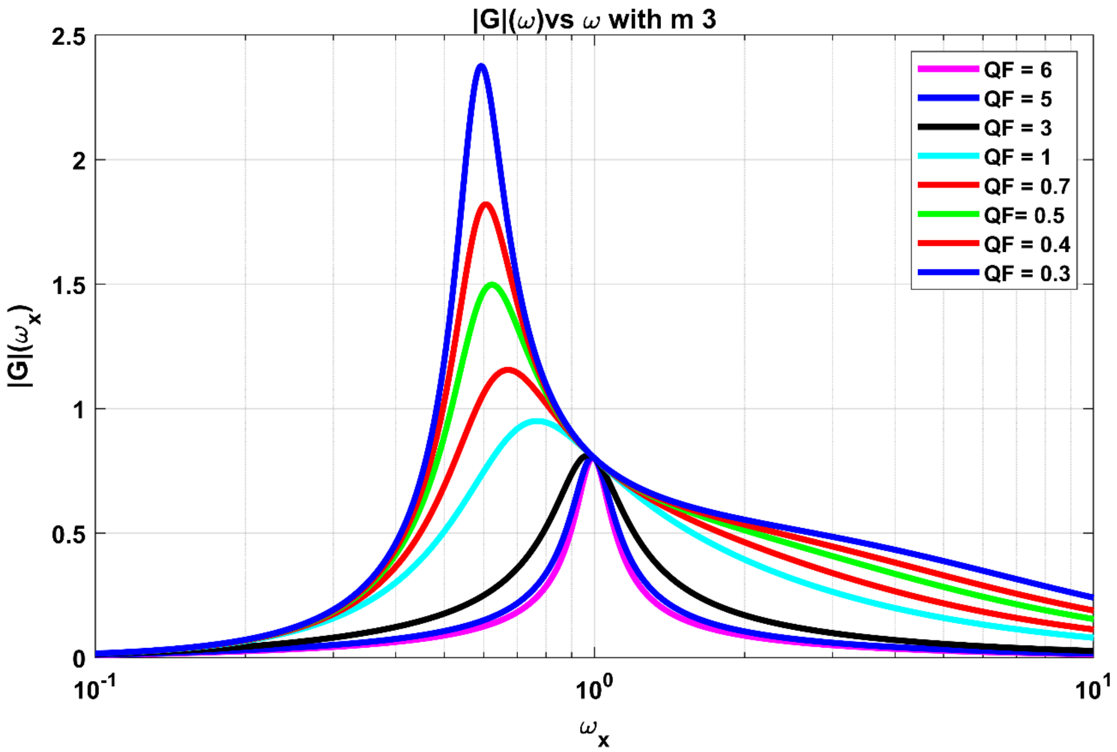


Fig 3.3 Gain Curves of LLC with m=3

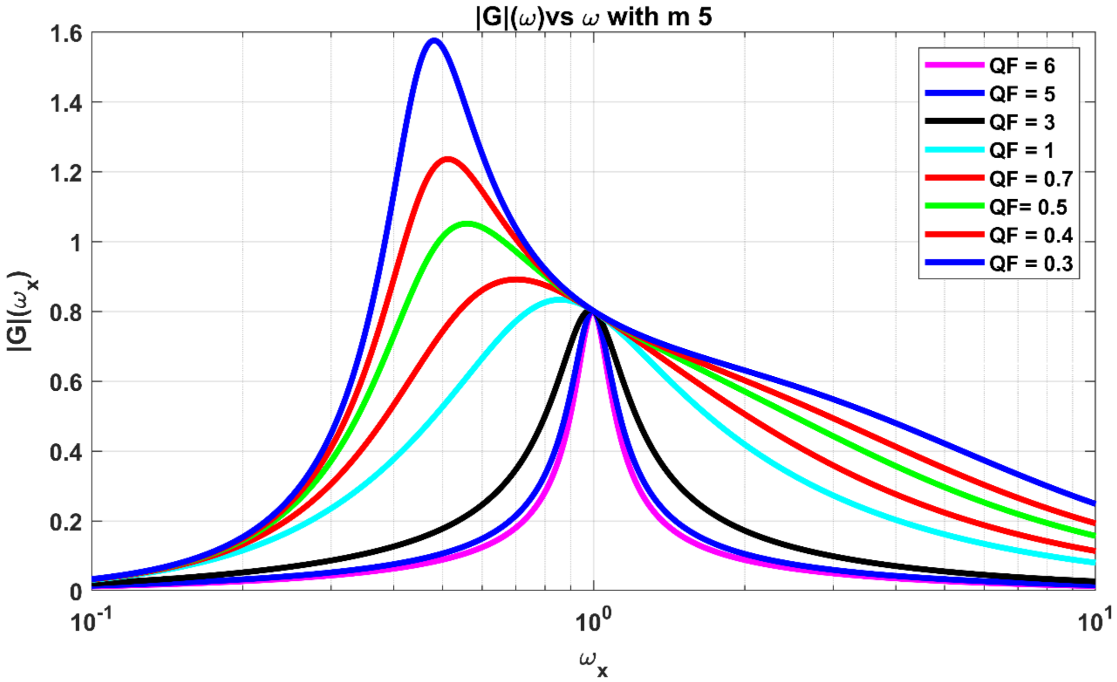


Fig 3.4 Gain Curves of LLC with m=5

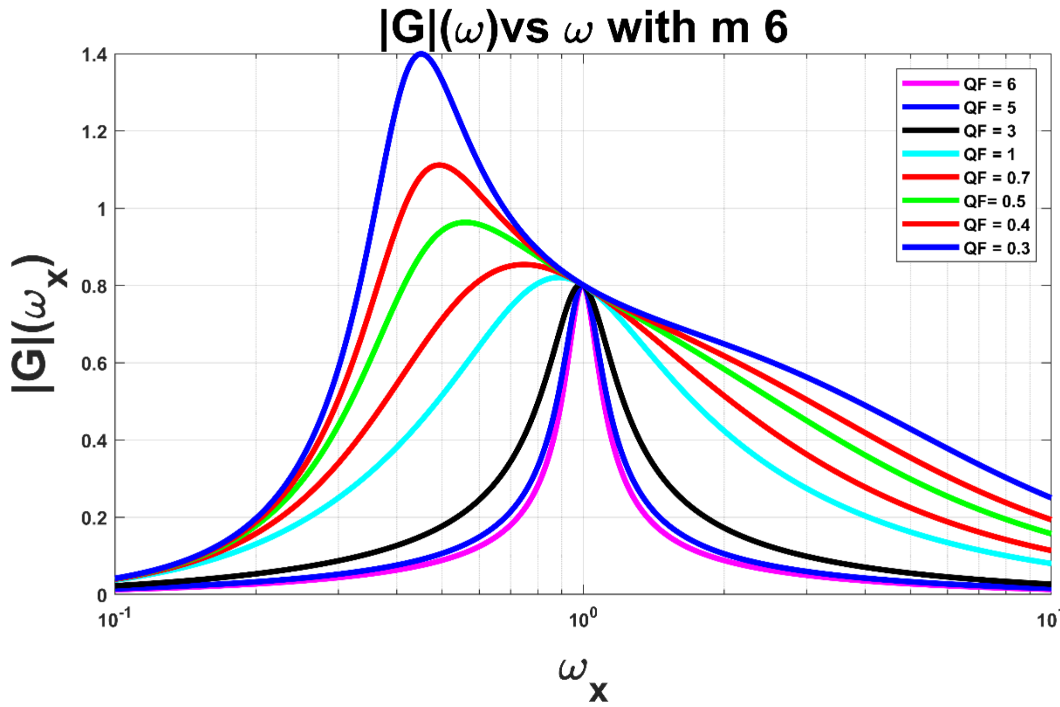


Fig 3.5 Gain Curves of LLC with m=6

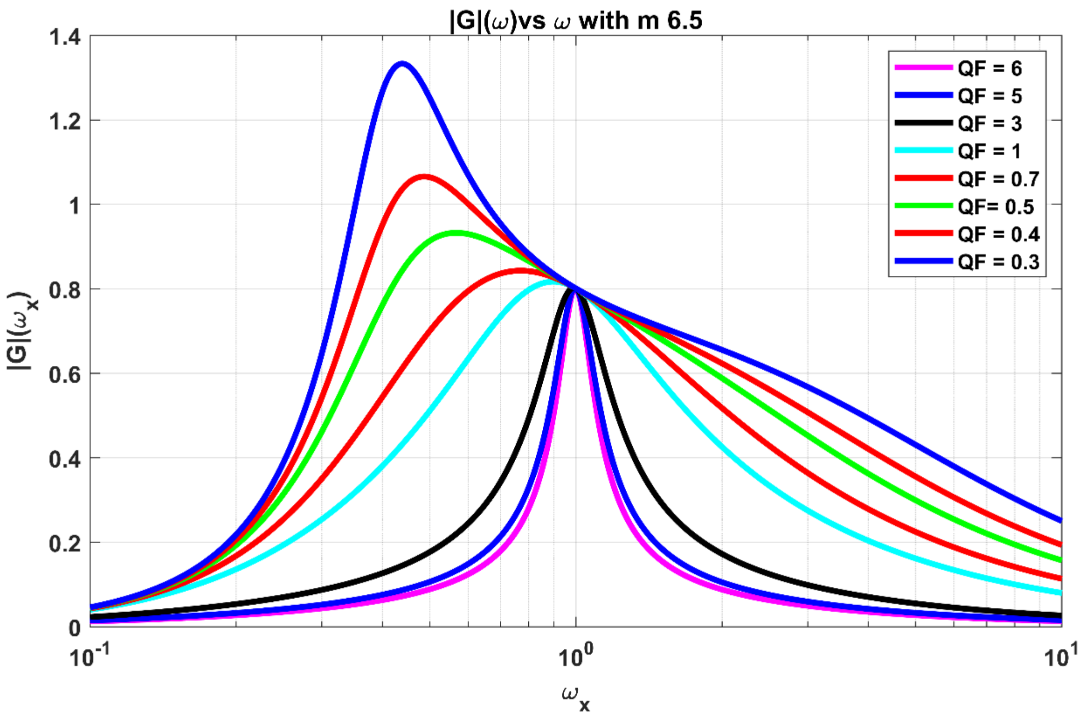


Fig 3.6 Gain Curve used for designing LLC Tank with m=6.5 and Q=0.4

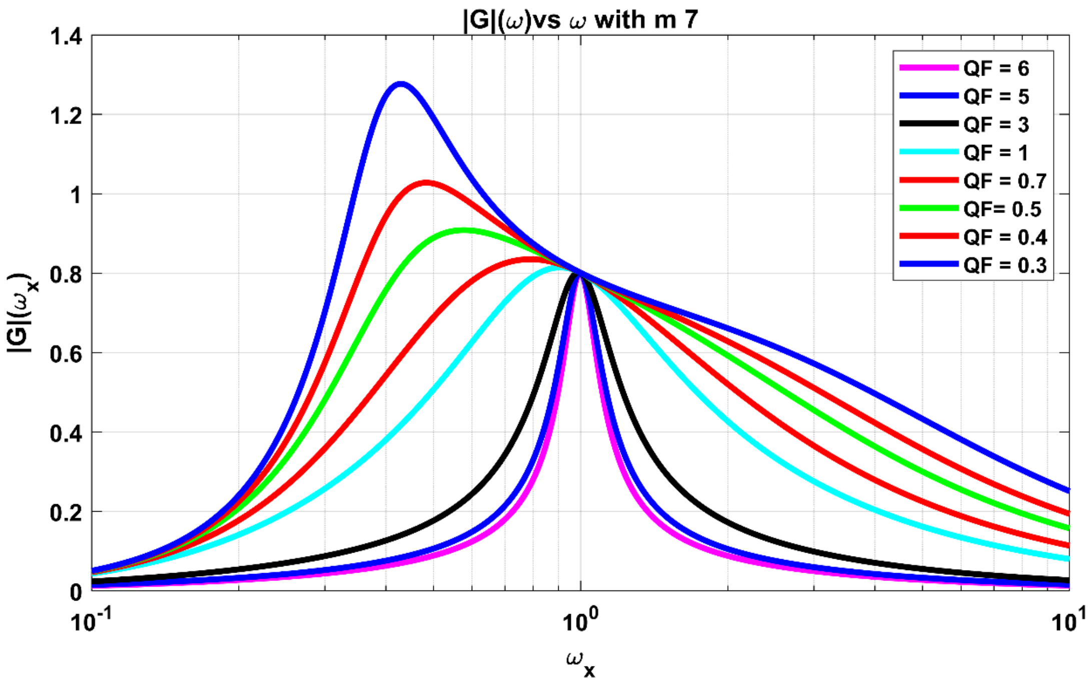


Fig 3.7 Gain Curves of LLC with m=7

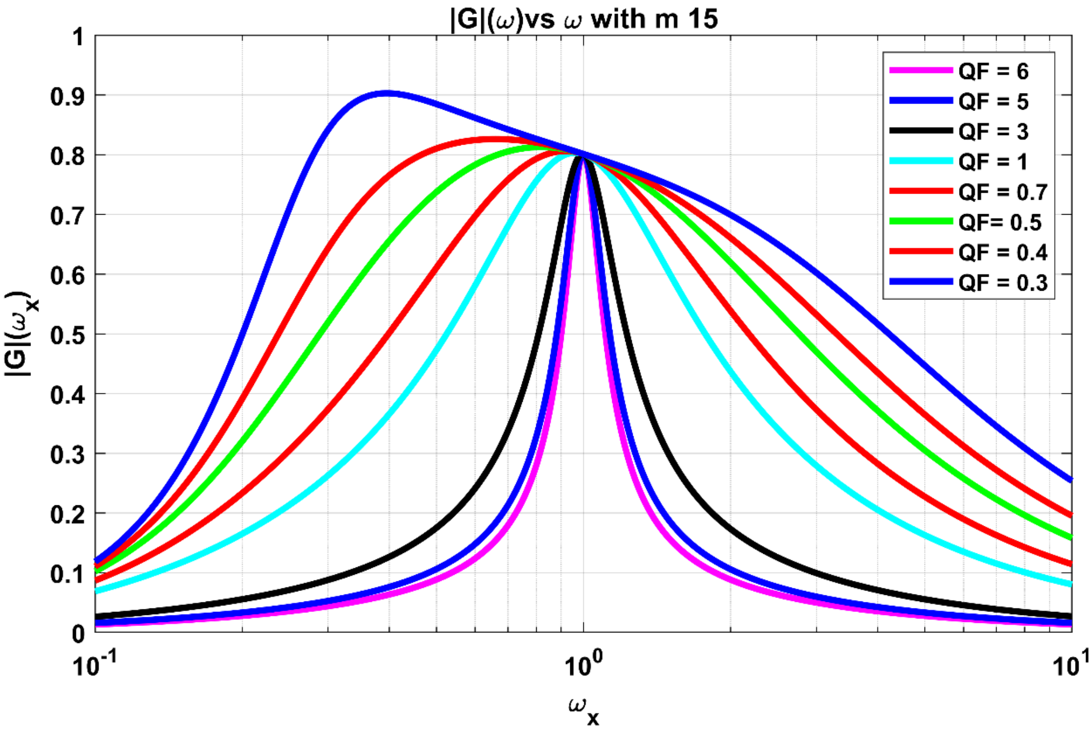


Fig 3.8 Gain Curves of LLC with m=15

3.7 MATLAB SIMULATION

3.7.1 BOOST DC-DC CONVERTER

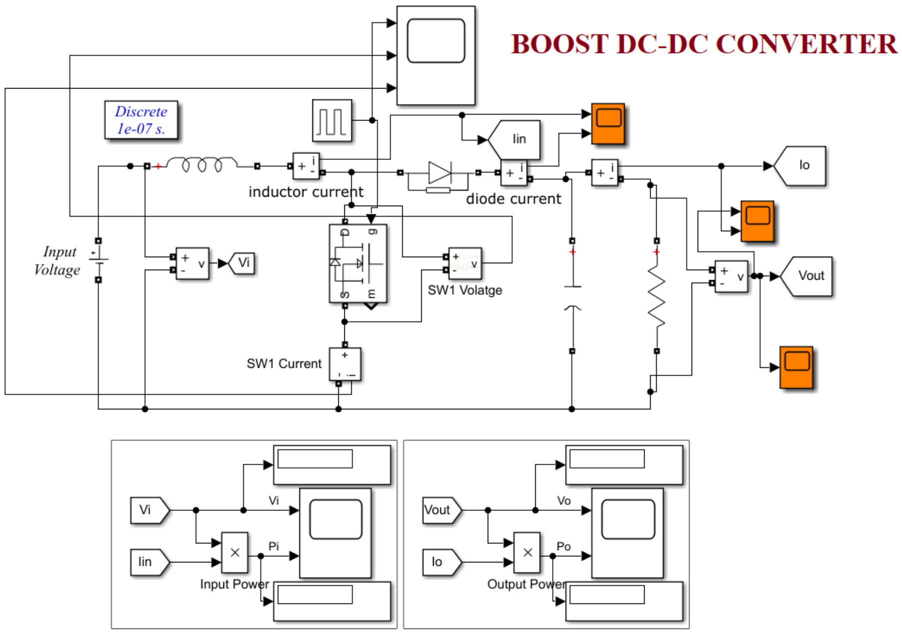


Fig 3.9 MATLAB Simulation of Boost DC-DC converter

3.7.2 CUK CONVERTER

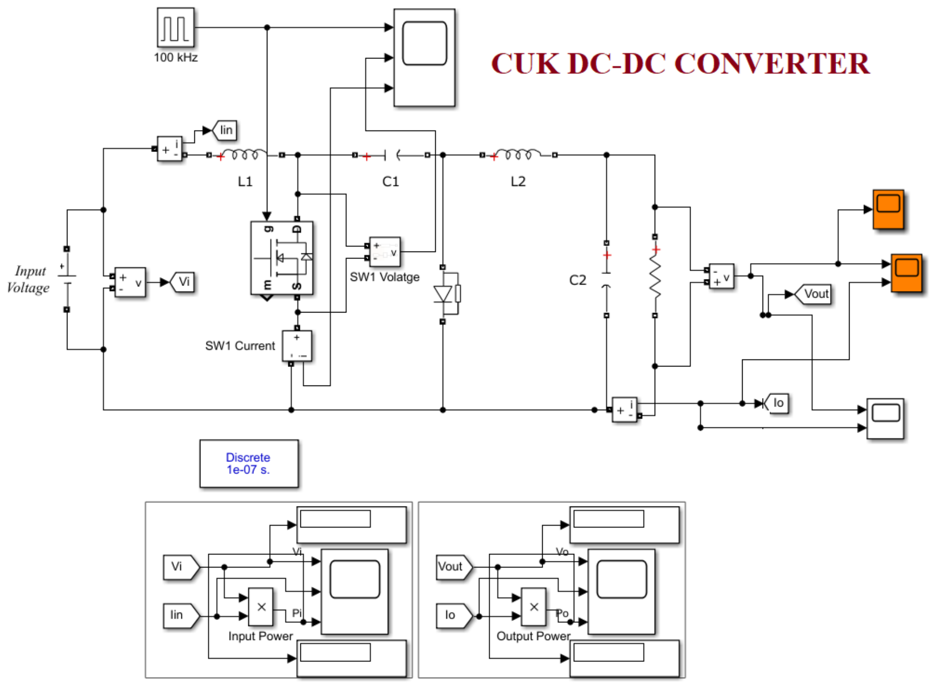


Fig 3.10 MATLAB Simulation of CUK converter

3.7.3 FLYBACK CONVERTER

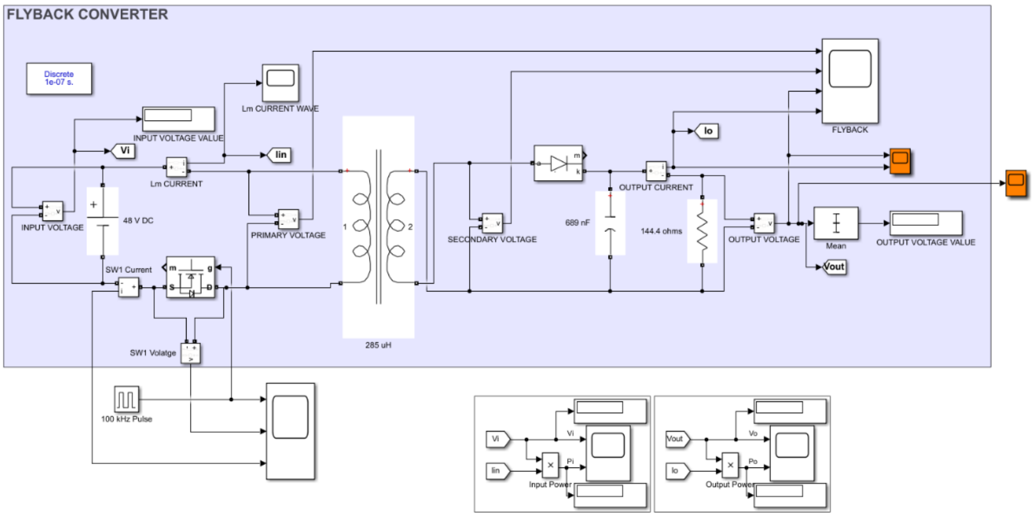


Fig 3.11 MATLAB Simulation of Flyback DC-DC Converter

3.7.4 LLC RESONANT DC-DC CONVERTER

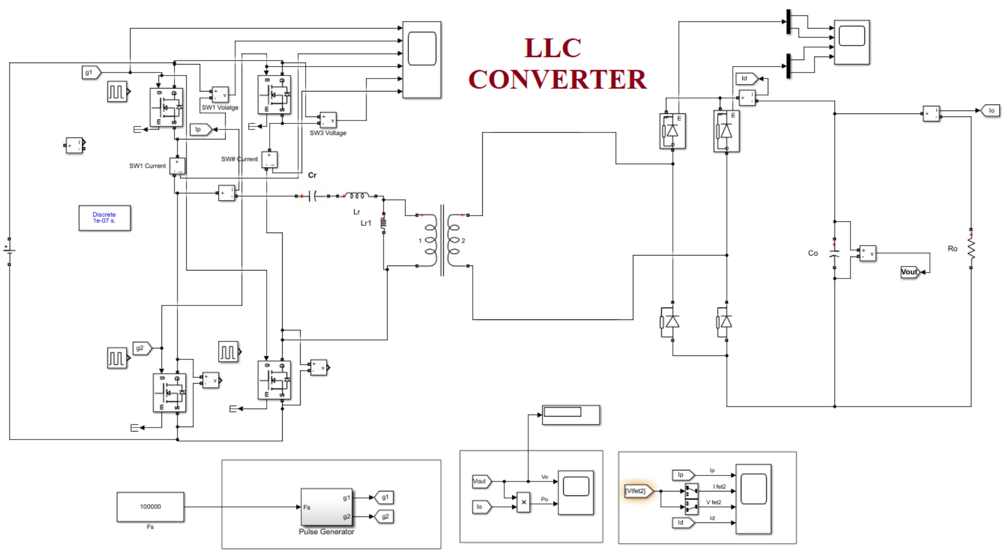


Fig 3.12 MATLAB Simulation of LLC Resonant DC-DC Converter

3.7.5 CLOSED LOOP LLC RESONANT CONVERTER USING BOOST

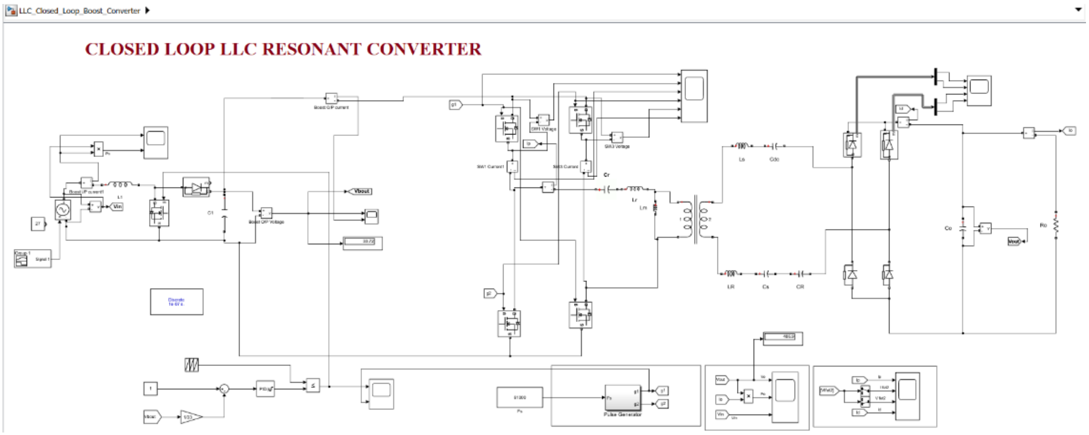


Fig 3.13 MATLAB Simulation of Closed Loop LLC Resonant converter using Boost Converter at input side

3.8 RESULTS OF MATLAB SIMULATION:

3.7.1 OUTPUT VOLTAGE AND CURRENT COMPARISON:

Comparison between the outputs of topologies used for an input voltage of 48 volts and output voltage expected at 380 volts when all converters are working on switching frequency of 100 kHz is presented in this section. Ripple percentage at output was taken as 2 percentage.

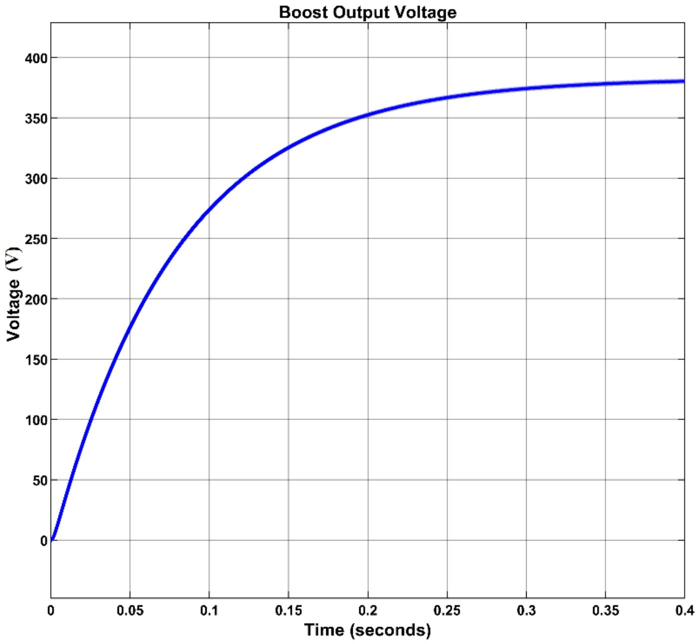


Fig 3.14 Output voltage waveform of Boost converter

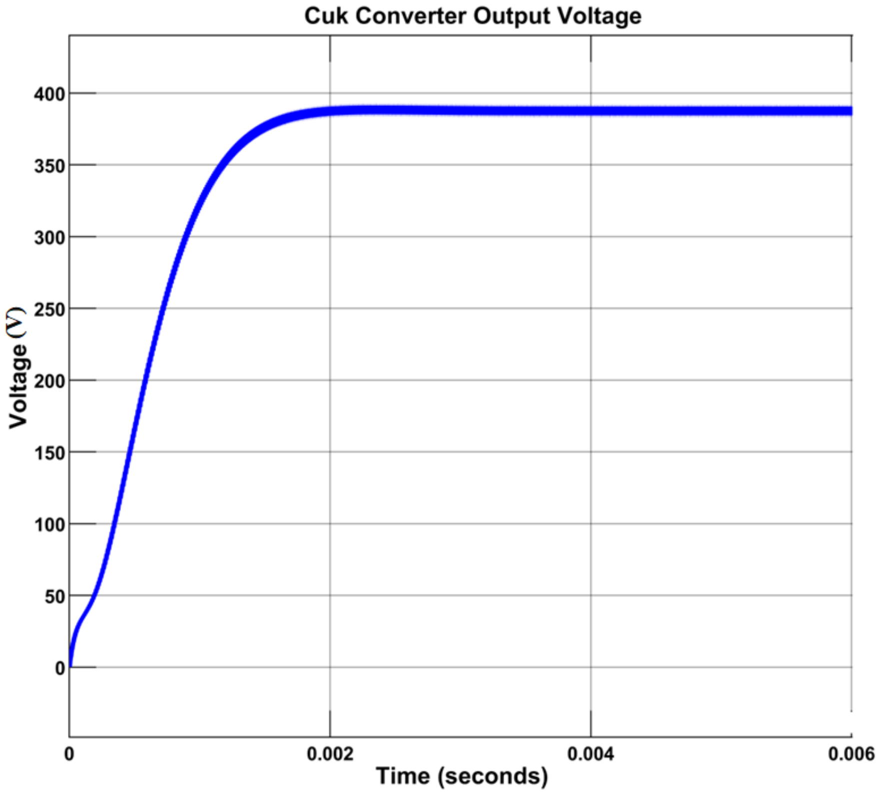


Fig 3.15 Output voltage waveform of Cuk DC-DC converter

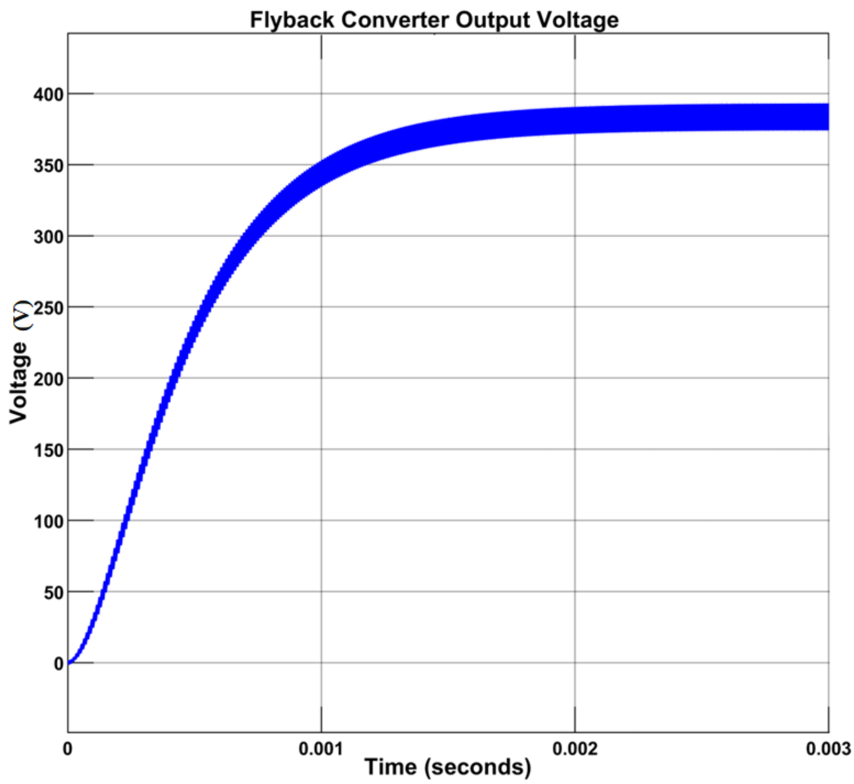


Fig 3.16 Output voltage waveform of Flyback converter

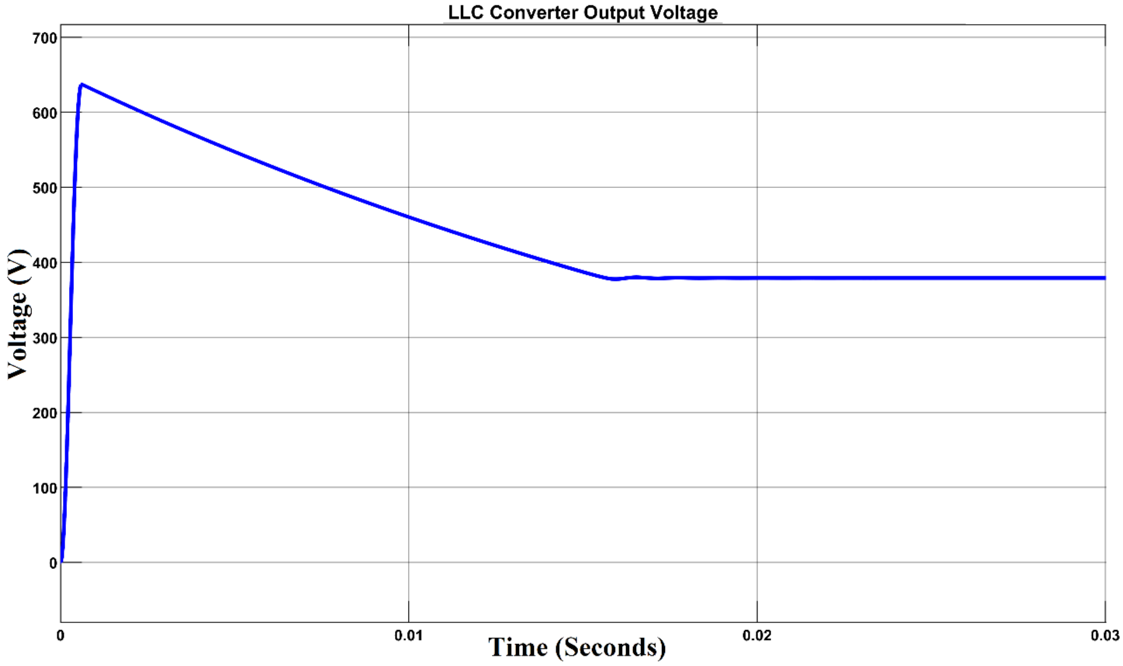


Fig 3.17 Output Voltage waveform of LLC Resonant converter

3.7.2 OUTPUT VOLTAGE RIPPLE AND CURRENT RIPPLE COMPARISON:

As comparison of output voltage is presented in previous section. For Ripple percentage taken as 2 percentage. Below given waveforms presents the ripple in output voltages of respective converters.

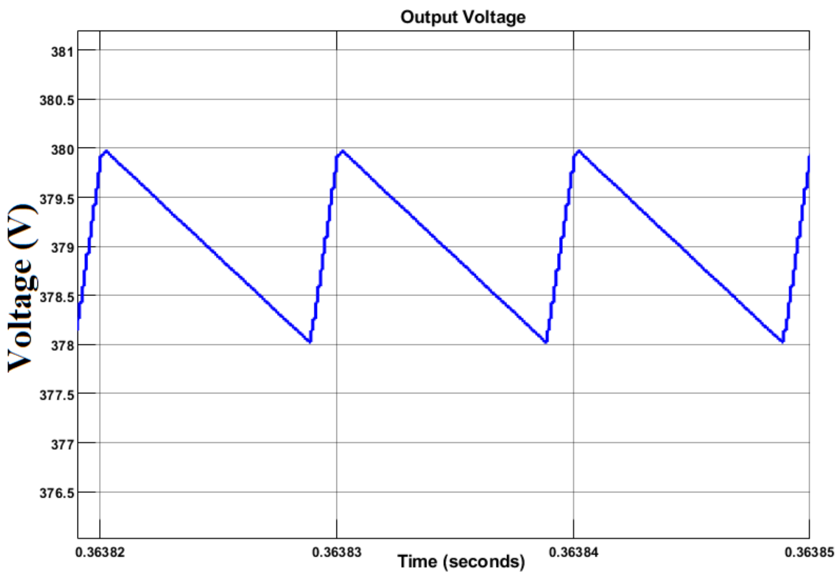


Fig 3.18 Output Voltage Ripple of Boost converter

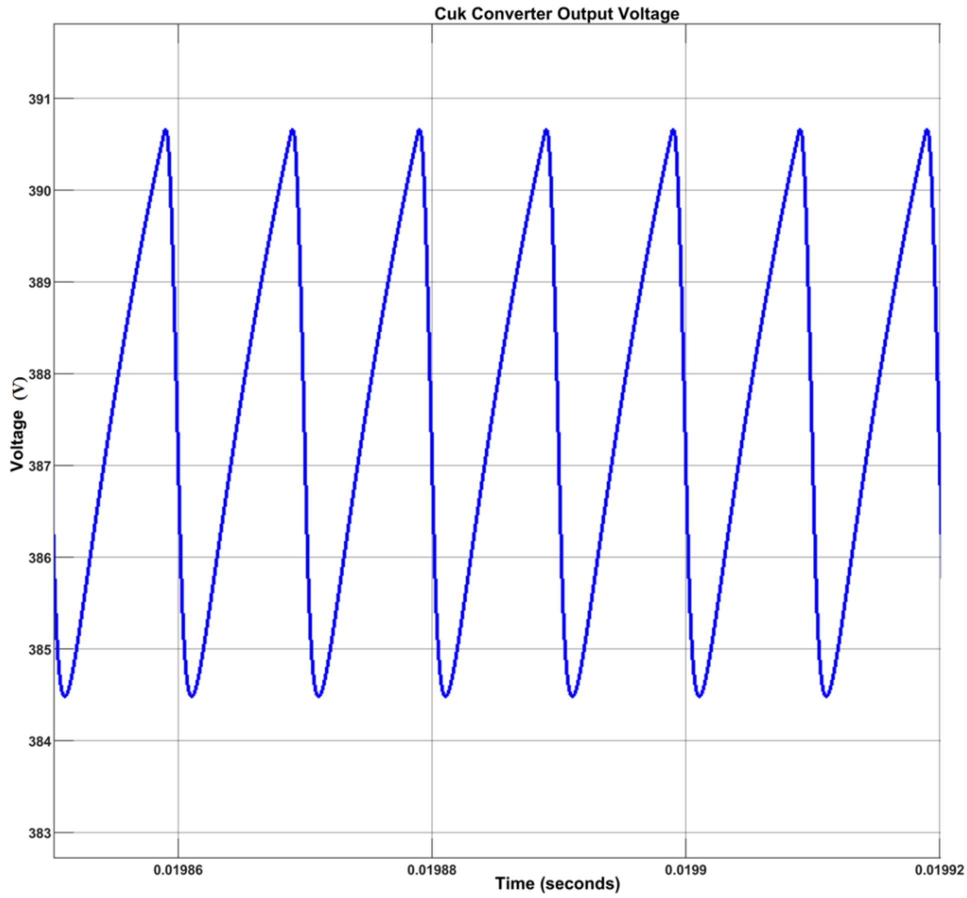


Fig 3.19 Output Voltage ripple of Cuk converter

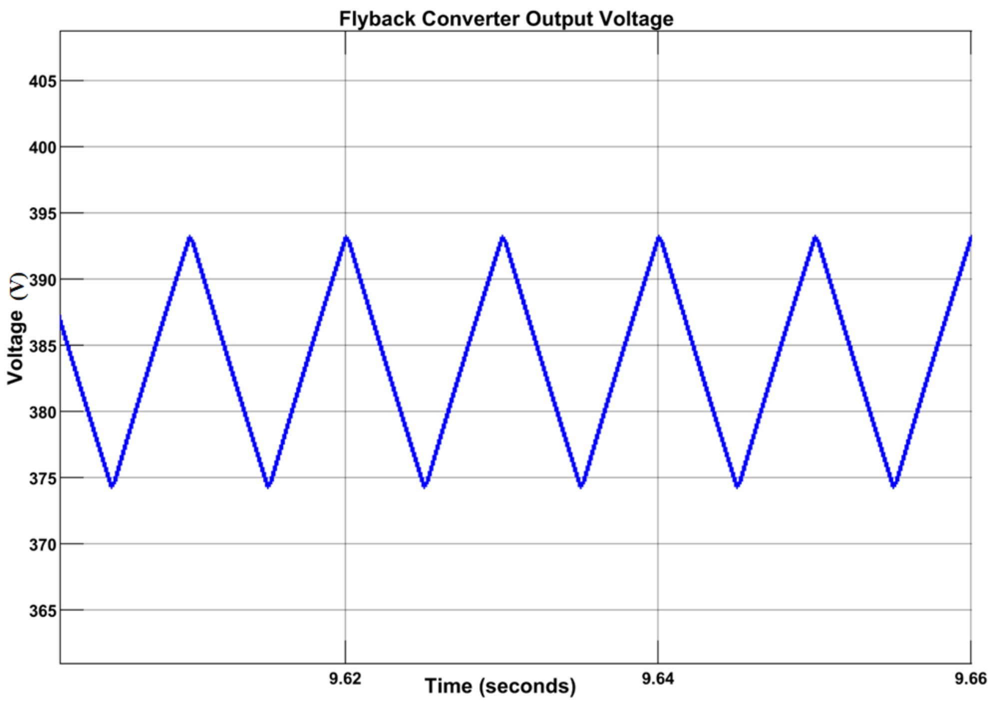


Fig 3.20 Output Voltage ripple of Flyback converter

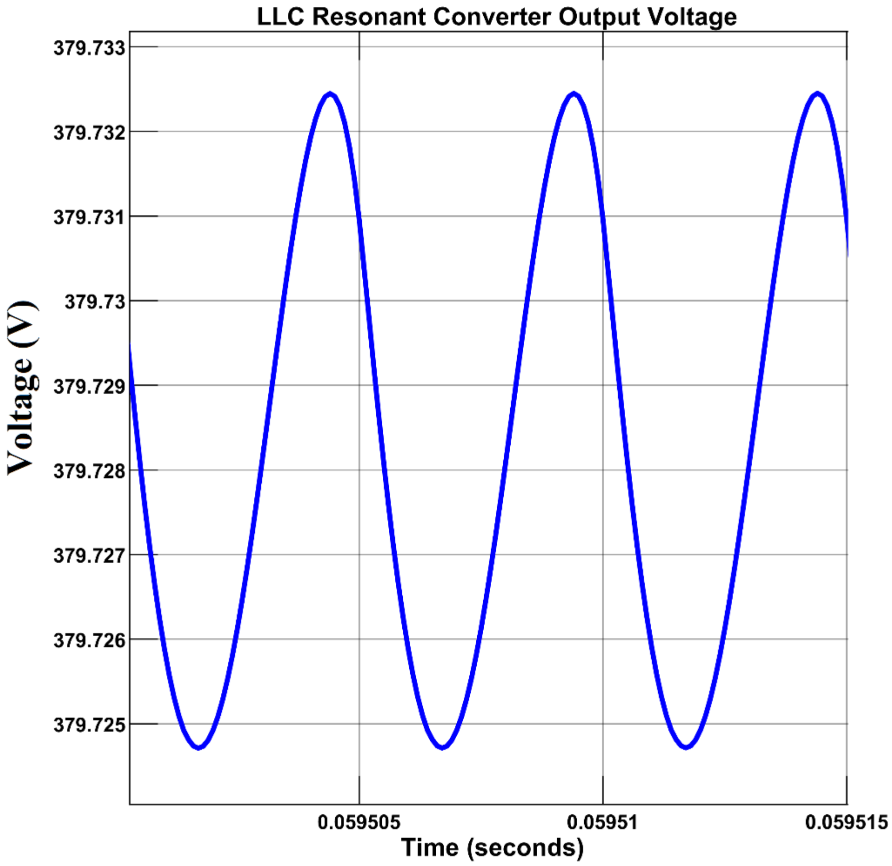


Fig 3.21 Output Voltage ripple of LLC Converter

3.7.3 SWITCH WAVEFORMS COMPARISON:

As we know the very reason to limit the maximum switching frequency of a converter is switching losses across its power switching devices such as MOSFETs, IGBT, SCR, diodes etc. To fully utilize magnetic components in a circuit and reduce its bulkiness it is a necessary step to switch to high switching frequency converters which has low switching losses because of their soft switching capability of power switching devices. One of these types of converters is LLC Resonant converter which uses it's LC tank for ZVS of its primary switches i.e., on inverting side and ZCS of its secondary switches i.e., on rectification side.

This section compares the switching waveforms of respective converters to highlight the difference between their switching mechanism i.e., Hard Switching or Soft Switching. Also, we can realize the voltage stress across switching devices in this section.

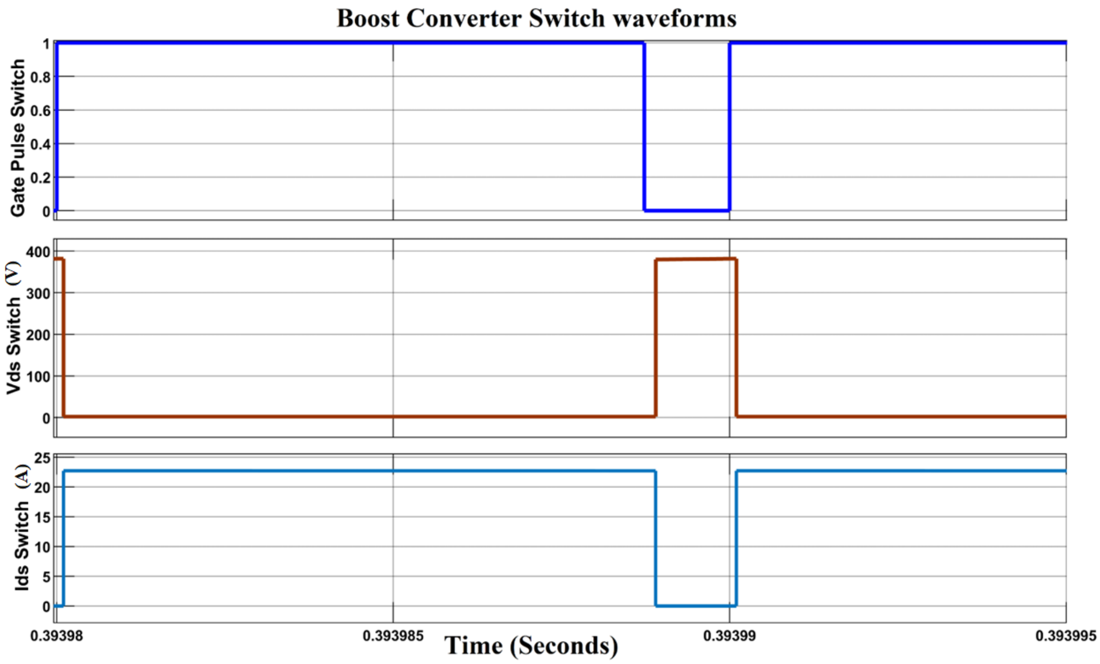


Fig 3.22 Waveforms across switch of Boost Converter

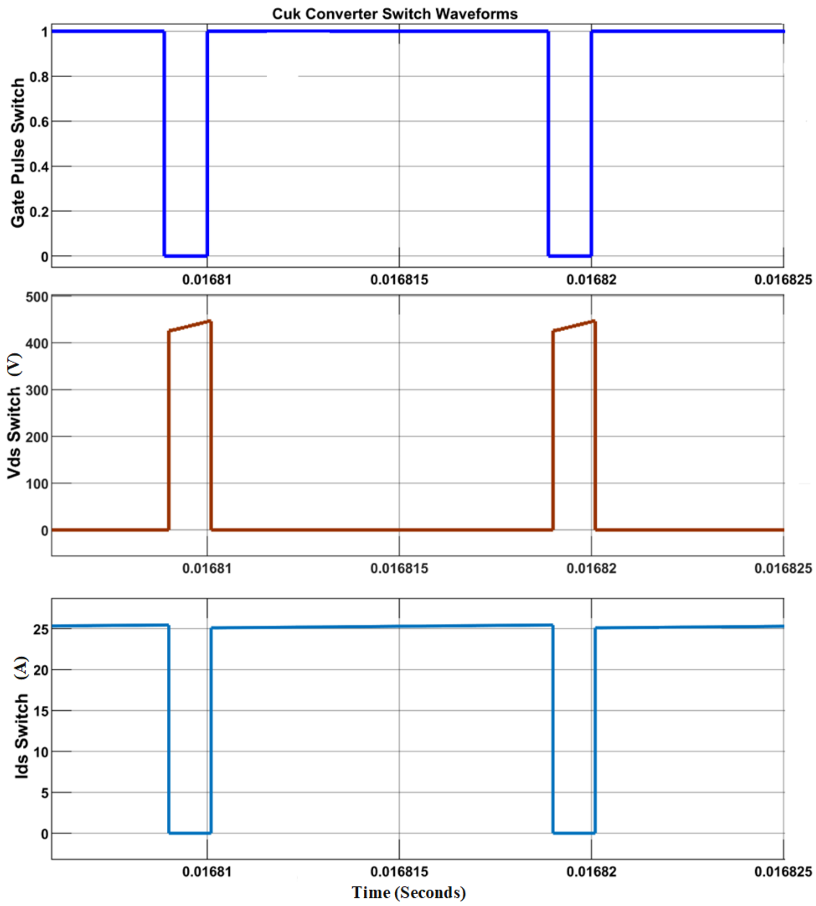


Fig 3.23 Waveforms across switch of Cuk Converter

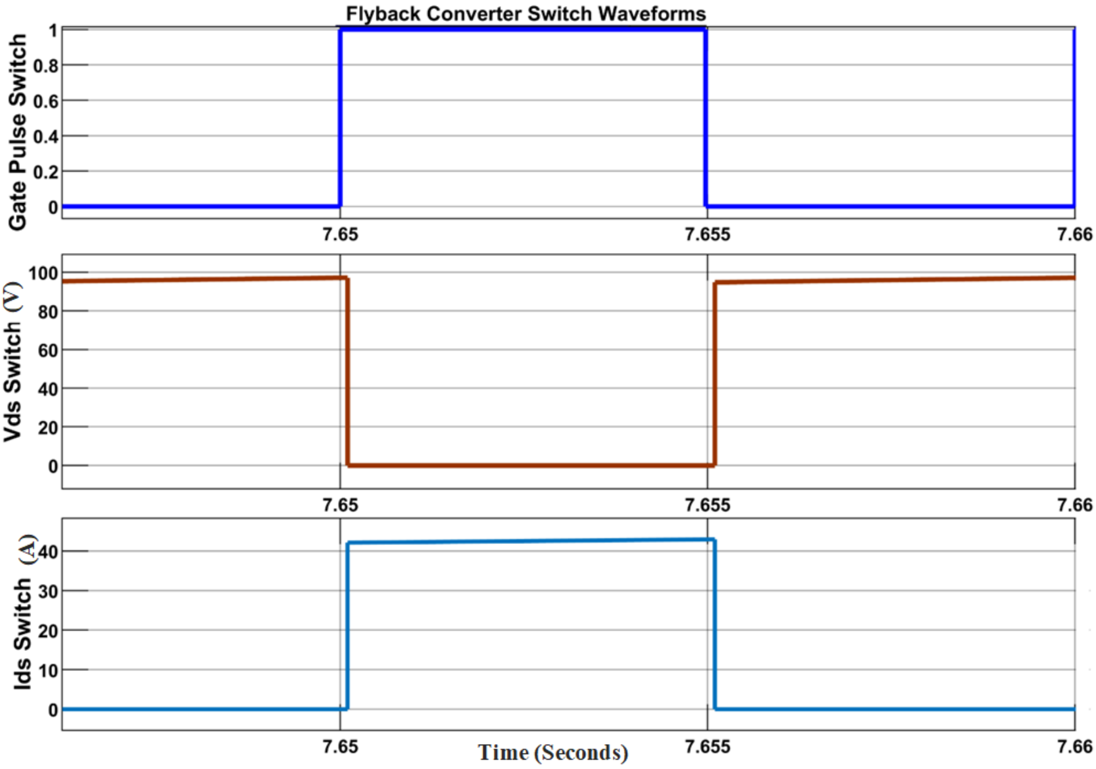


Fig 3.24 Waveforms across switch of Flyback DC-DC Converter

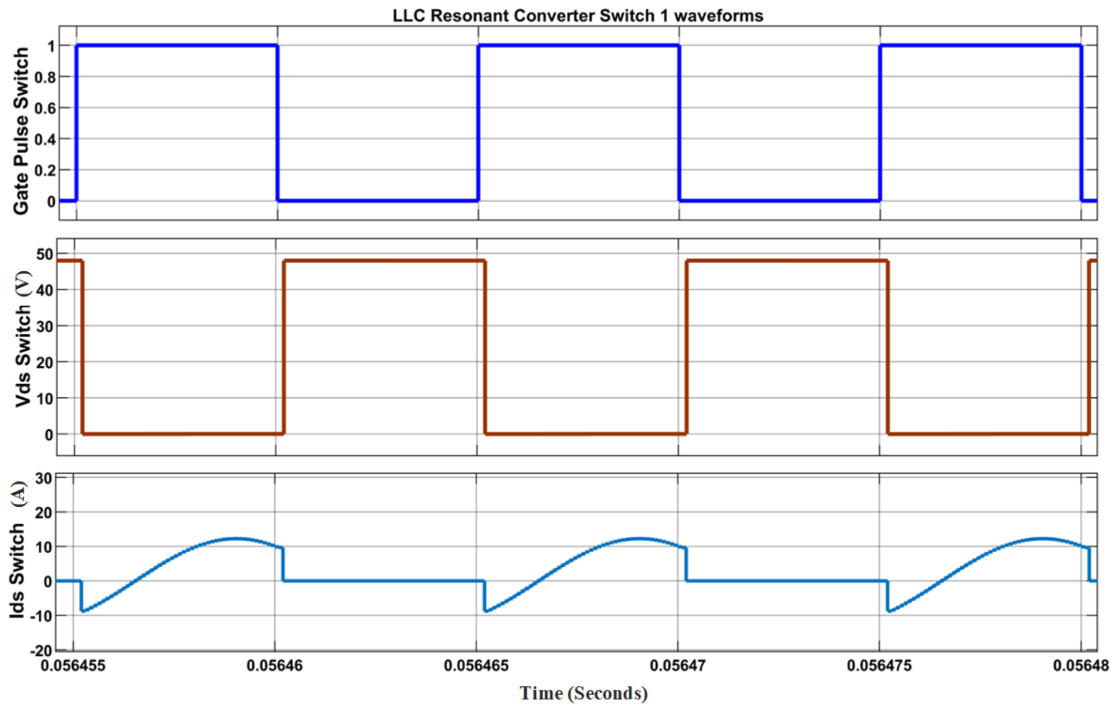


Fig 3.25 Waveforms across switch of LLC Resonant Converter

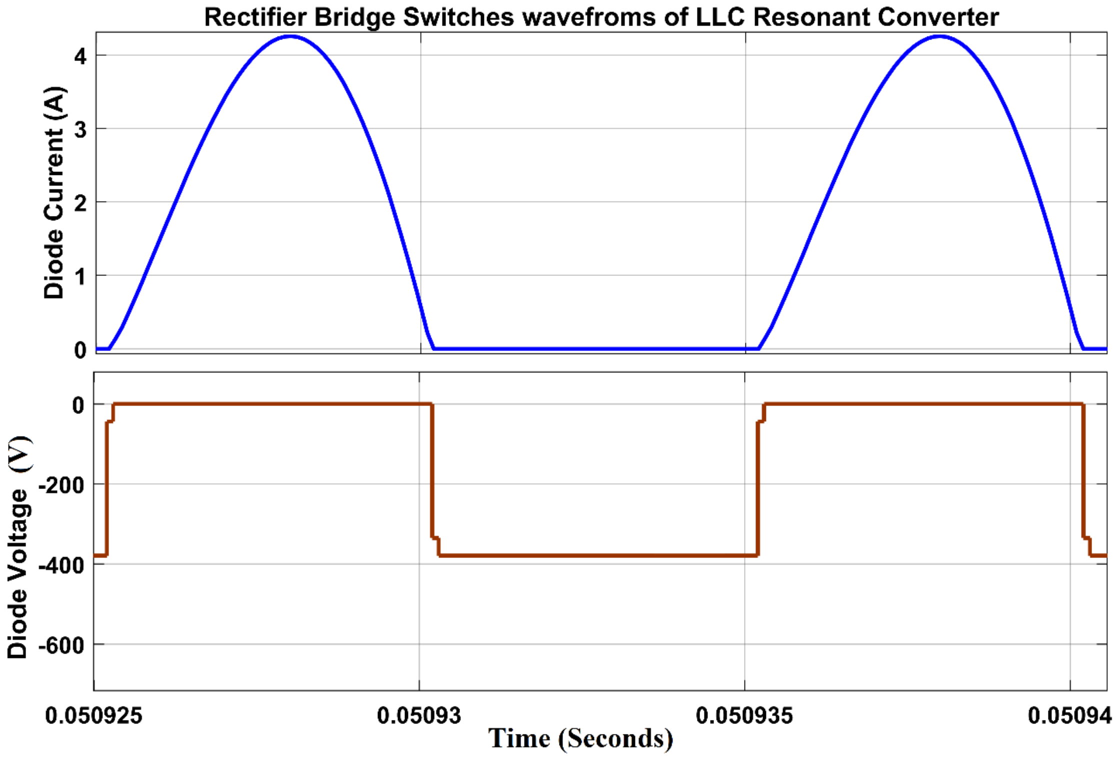


Fig 3.26 Waveforms across secondary side switches in LLC converter

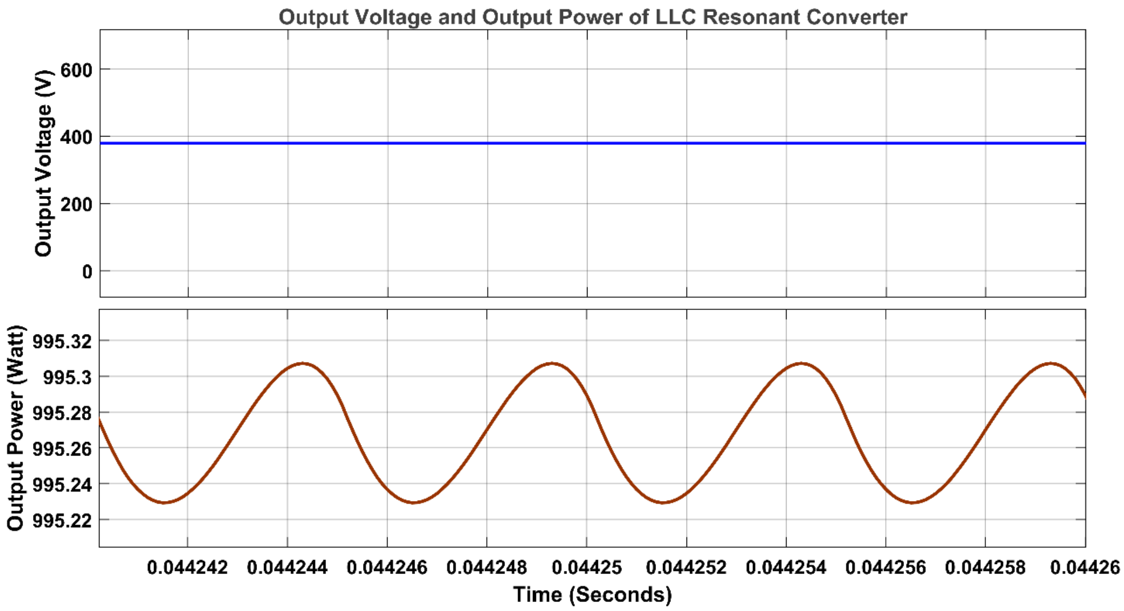


Fig 3.27 Output Power of LLC Resonant converter

3.7.4 COMPONENT VALUES OF CLOSED LOOP LLC CONVERTER:

Table 3-6 COMPONENT VALUES OF CLOSED LOOP LLC RC USING BOOST CONVERTER

Components	Values
V_i	18-30 V
V_o	400 V
P_o	250 W
Q	0.4
m	6.5
L_r	2.3 µH
L_m	12.65 µH
C_r	1.1 µF
C_o	200 µF
R_o	640 Ω
F_s for LLC	100 kHz
F_r	100 kHz
L_1	2.42 mH
C_1	60 µH

3.7.5 SIMULATION RESULT OF CLOSED LOOP LLC RESONANT CONVERTER

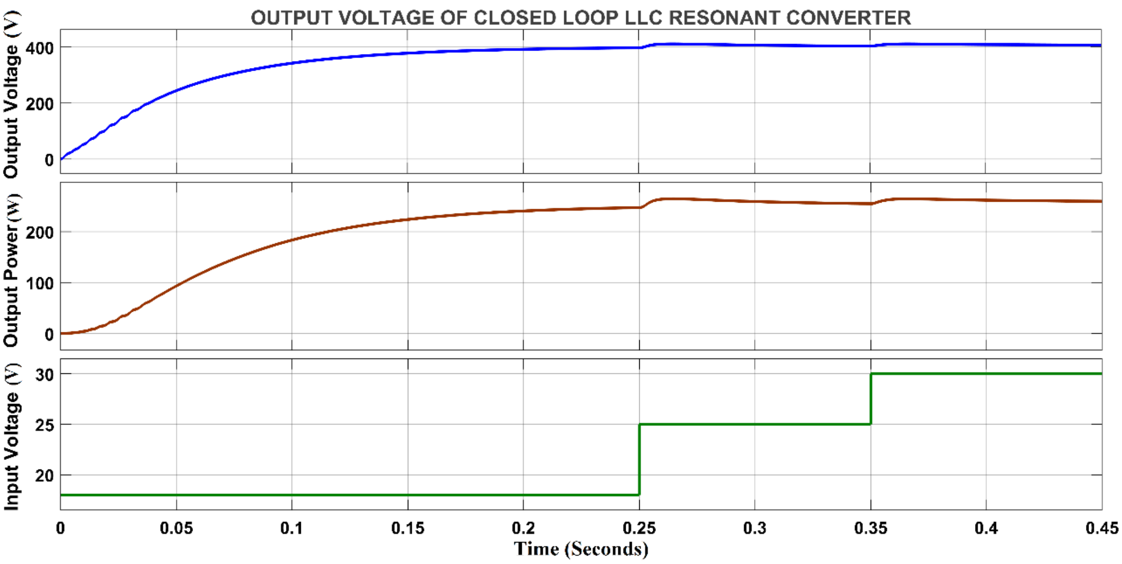


Fig 3.28 Waveforms of LLC Closed Loop converter a) Output Voltage b) Output Power c) Variable Input Voltage

CHAPTER 4 CONCLUSION

Table 4-1 COMPARISON OF DISCUSSED CONVERTER ON PARAMETERS LIKE VOLTAGE, RIPPLE AND EFFICIENCY

CONVERTER\PARAMETER	**V_{oavg}** (At steady state)	**V_{ripple}**	**Efficiency**
BOOST CONVERTER	380.4 V	2 V	999*100/1086=91.99
CUK CONVERTER	387.6 V	7 V	1040*100/1080=96.3
FLYBACK CONVERTER	384 V	17 V	1020*100/1065=95.77
LLC RESONANT CONVERTER	379.1 V	0.014 V	995.27*100/1021=97.48

After going through the comparison table, we can conclude that LLC Resonant converter is best suitable DC-DC converter for the application of stepping-up a battery pack's voltage of 48 V to a tenfold gain output voltage of 380. It was observed from the voltage waveform comparison that output voltage ripple of LLC Resonant converter is least and negligible as compared to other discussed topologies. Also output voltage of LLC Converter and boost converter are close to desired output voltage than rest topologies.

By comparing settling time of discussed topologies, we can observe that for boost converter Ts is about 400 ms, for cuk converter it is 2-3 ms, Flyback has a settling time of 3-4 ms and LLC has output waveform settling at time between 15-20 ms. Cuk and flyback converter has fast response but are less accurate and more ripple prone. On other side boost converter has a reliable average output voltage and a ripple of 2 volts but its settling time is very high. LLC converter has a moderate settling time, reliable output voltage and minimal ripple at output side.

Hence LLC converter emerges as best DC-DC converter out of all discussed converters for this particular application.

In closed loop LLC Converter, a variable input voltage from 18 to 30 volts was given and a regulated voltage of 400 volts was observed at output side of this topology.

4.1 FUTURE WORK:

Gain of LLC converter depends on switching frequency, resonant frequency and quality factor. So variable switching frequency, variable resonant frequency and resonant capacitor voltage can be used to control the output of this converter.

As we have discussed, conventionally LLC converter is controlled by using variable frequency or phase shift control is adopted. These methods are complex in designing control circuit and magnetic components are not fully utilized in this approach. Also varying frequency over a large range is difficult and Soft Switching of devices is achieved within a range of operation on gain curve of converter.

Future work includes the closed loop control of LLC resonant converter using magnetic control [53]. The magnetic control is done by varying resonant inductor value to achieve a variable resonant frequency and hence the output regulation of LLC converter.

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LIST OF COMMUNICATED PAPERS

1. Sunil Kumar, Vanjari Venkata Ramana, Kuldeep Singh, "DESIGN AND PERFORMANCE ANALYSIS OF LLC RESONANT CONVERTER" Asian Conference on Innovation in Technology (ASIANCON), Pune, India.