LLC Resonant Converter: Operation, Design and Control Method

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Abstract

This article explains how LLC resonant converters work, how to design your own, and methods for controlling them. Our aim is to make it easy to understand these converters, enabling you to design and control them effectively for various applications.

1 Introduction

DC-DC converters are crucial components in modern electronics, serving to efficiently convert one voltage level to another. There are many typologies of DC-DC converters, each with its pros and cons. One of these typologies is the LLC resonant converter, which is used in many fields, including EV. This article explains the operation, design, and control methods of the LLC resonant converter.

2 Overview of LLC Resonant Converter

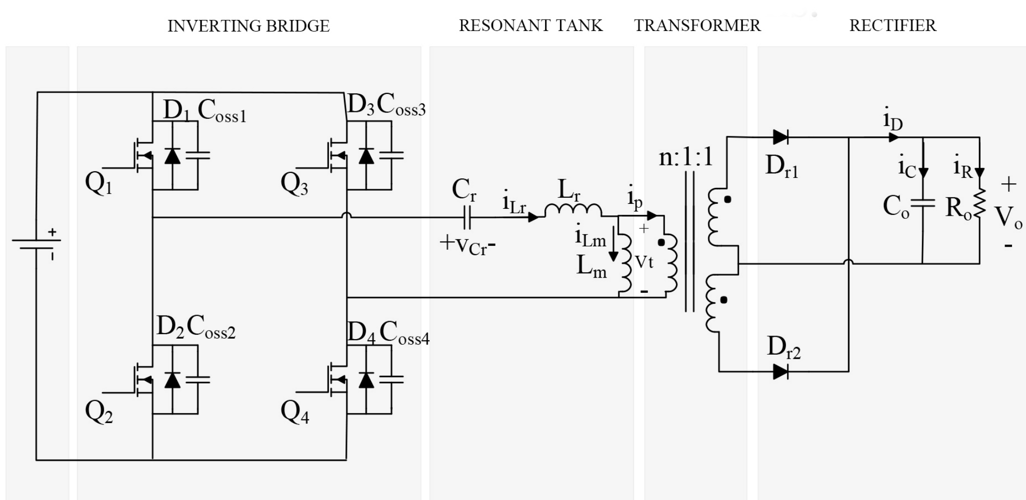


Figure 1: LLC Resonant Converter

LLC resonantconverter mainly consists of 4 main parts: Inverting bridge (full bridge or half bridge), resonant tank, transformer and rectifier bridge as shown Figure 1. The gain of LLC converter can be calculated by the following equation:

$$Gain = bridge\ gain * resonant\ tank\ gain * turns\ ratio\ (Ns/Np) \tag{1}$$

Ns: Secondary side turns ratio
Np: Primary side turns ratio

The bridge can be full bridge or half bridge. Full bridge gain = 1 and half bridge gain = 0.5. Full bridge consists of 4 switches but half bridge consists of only two switches. in our design we will use full bridge inverter as shown in Figure 1 so the bridge gain equals 1.

3 Resonant Tank Gain

The resonant tank is made up of a resonant capacitor (Cr) and two inductors: the resonant inductor (Lr), in series with the capacitor and transformer, and the magnetizing inductor (Lm), in parallel. The tank's role is to filter out the square wave's harmonics, outputting a sine wave of the fundamental switching frequency to the input of the transformer as shown in Figure 2.

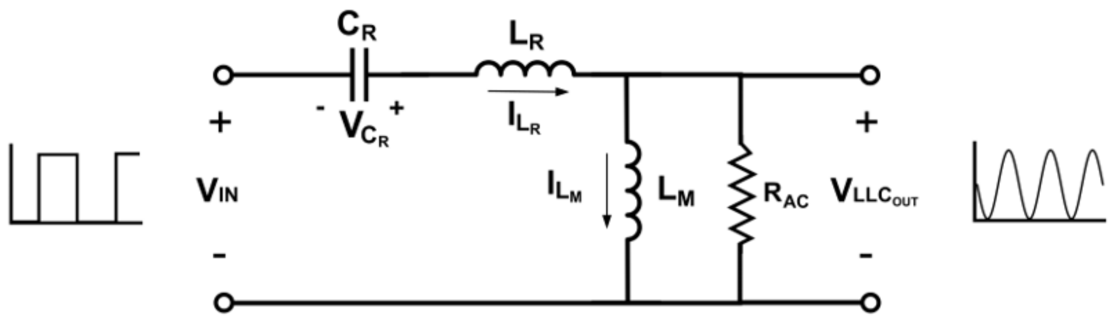


Figure 2: Resonant Tank Circuit

After analysis of the tank circuit, the resonant tank gain equation:

$$K(Q, m, F_x) = \frac{F_x^2(m-1)}{\sqrt{(m \cdot F_x^2 - 1) + F_x^2(F_x^2-1)^2 \cdot (m-1)^2 \cdot Q^2}} \tag{2}$$

where,

$$Q = \frac{\sqrt{L_r/C_r}}{R_{ac}} \qquad \text{(Quality factor)} \tag{3}$$

$$R_{ac} = \frac{8}{\pi^2} \cdot \frac{N_p^2}{N_s^2} \cdot R_\circ \qquad \text{(Reflected load resistance)} \tag{4}$$

$$F_x = \frac{f_s}{f_r} \qquad \text{(Normalized switching frequency)} \tag{5}$$

$$f_r = \frac{1}{2\pi\sqrt{L_r \cdot C_r}} \qquad \text{(Resonant frequency)} \tag{6}$$

$$m = \frac{L_r + L_m}{L_r} \qquad \text{(Ratio of total primary inductance to resonant inductance)} \tag{7}$$

using previous equations we can design our resonant tank by assuming variable with a constant value then start to calculate other parameters.

4 Operation Regions of LLC Resonant Converter

According to the switching frequency, the LLC converter operation can be divided into three regions, as shown in Figure 3.
Either the input or output voltage fluctuation in the LLC converter yields the intense decrease in its efficiency. In order to have a constant DC voltage in the output side,the LLC converter has to work in the ZVS region in which the switching frequency is smaller than the resonant frequency, region 2 in Figure 3. In this region, the primary and secondary side switches work in ZVS and ZCS situations, respectively. In order to ensure ZVS in region 2, the sufficient peak of the magnetizing current and enough dead time to charge or discharge all parasitic capacitors are required. Due to ZVS in the primary side and ZCS in the secondary one, region 2 is commonly used for DC transformer applications.

Also, region 1 in Figure 2 provides ZVS in a larger frequency range. If the LLC resonant converter is used in a wide output voltage range application by switching modulation frequency, region 1 is preferred. Theoretically, region 1 ensures wider switching modulation ranges, while the load varies in a wide range. It should be noted that if the input DC voltage is increased, ZVS can be partially maintained for primary side switches and the remaining hard-switching yields more heat and power loss. Various control methods have been proposed to improve light load efficiency in LLC resonant converters [2].

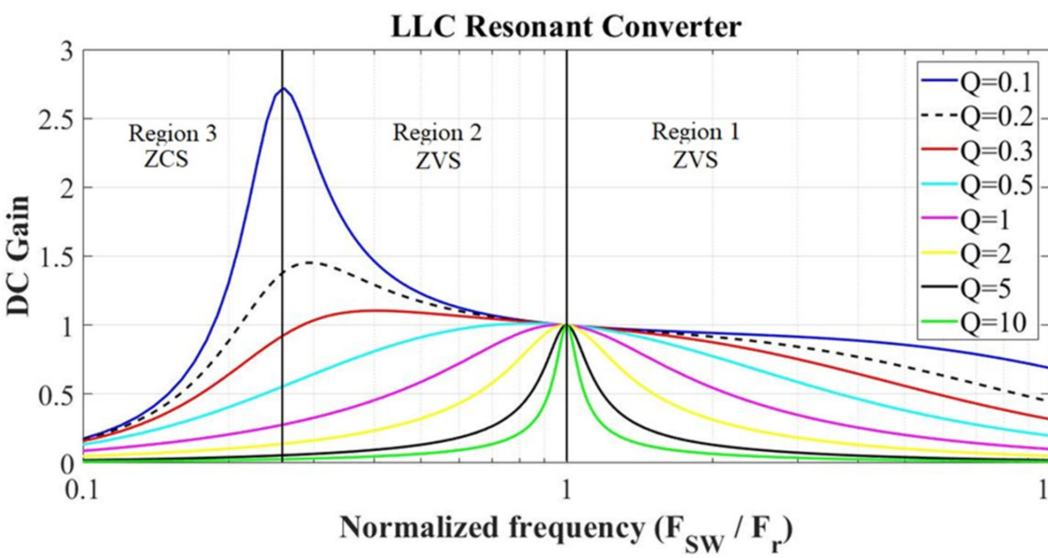


Figure 3: LLC resonant converter operation regions.

there are 3 modes of operation according to switching frequency:

- **At resonant frequency operation**
  Each half of the switching cycle contains a complete power delivery operation, where the resonant half cycle is completed during the switching half cycle.By end of the switching half cycle,the resonant inductor current ILr reaches the magnetizing current ILm, and the rectifier current reaches zero.The resonant tank

has unity gain and best optimized operation and efficiency, therefore, transformer turns ratio is designed such that the converter operates at this point at nominal input and output voltages.

- **Above resonant frequency**
  Each half of the switching cycle contains a partial power delivery operation,similar to the resonant frequency operation, but it differs in that the resonant half cycle is not completed and interrupted by the start of the other half of the switching cycle, hence primary side MOSFETs have increased turn off losses and secondary rectifier diodes have hard commutation.The converter operates in this mode at higher input voltage,where a step down gain or buck operation is required

- **Below resonant frequency**
  Each half of the switching cycle contains a power delivery operation, at the time when resonant half cycle is completed and resonant inductor current ILr reaches the magnetizing current, the freewheeling operation starts and carries on to the end of the switching half cycle, hence primary side have increased conduction losses due to the circulating energy.The converter operates in this mode at lower input voltage,where a step up gain or boost operation is required.

5 LLC resonant Converter Closed Loop Control

In any DC-DC converter, it's important to keep the value of the output voltage constant. The change in load leads to a change in output voltage in the case of open-loop control. Using closed-loop control is necessary, so LLC converter closed-loop control can be achieved by the cascaded control loop, as shown in the Figure 4.

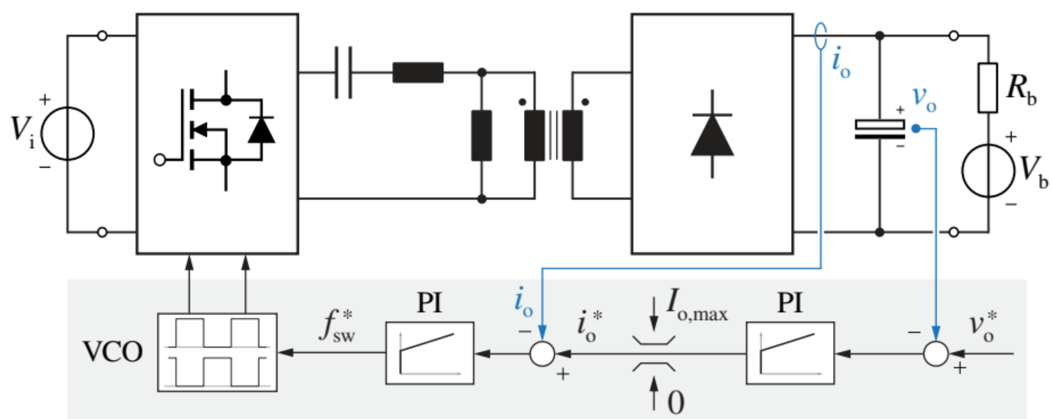


Figure 4: Cascaded Closed Loop Control for LLC Resonant Converter

The cascaded control loop is used to control both the output voltage and the current value. If the control loop consisted of a single PI controller that only controls the output voltage, during the transient of the circuit, the current value may become too high, potentially exceeding the rated switch current [1].

There are two PI controllers used in this setup. The first PI controller's input is the voltage error (the reference value minus the measured value), while the second PI controller's input is the current error (the output of the first PI controller minus the measured current value), as shown in the Figure 4.

6 Calculations of Resonant tank

By using a MATLAB script file, you can determine the values of resonant components used in an LLC resonant converter. The following script file requires inputs such as the range of input and output voltages, switching frequency, and the converter power.

The MATLAB script is available in this link **Download MATLAB Script File**

The code:

```
%--------------- DC Input ------------------
Vin = 700;            % operating input voltage
Vin_rated = 700;      % rated input voltage

Vin_min = 650;        % minimum input voltage
Vin_max = 800;        % maximum input voltage

%--------------- Output Load ------------------
Vo = 450;             % operating output voltage
Vo_rated = 450;       % rated output voltage
Vo_min = 400;         % minimum output voltage
Vo_max = 600;         % maximum output voltage

Po_rated = 7000;      % rated output power

% load percentage with respect to the rated load
K_load = 1;

Q_rated = 0.3;        % Q factor at the rated condition

%--------------- Operating Conditions ------------------
f_res = 70000;        % resonant frequency
K_ind = 6;            % parallel-to-series inductance ratio

% relative frequency factor for open-loop operation
K_rel_freq = 0.75;

%-------------- Parameters from Calculations ---------

fsw = f_res*K_rel_freq;     % switching frequency fsw


%--------------- Transformer and Load -----------------

% Ns/Np ratio
a_sp = (Vo_max+Vo_min)/(2*Vin_rated);
a_sp2 = a_sp*a_sp;

% rated load resistance
Ro_rated = Vo_rated*Vo_rated/Po_rated;

% Ro_rated referred to the primary side
```

```
Ro_rated_pri = Ro_rated/a_sp2;

% load resistance at the operating conditions
Ro = Ro_rated/K_load;

%-------------- Resonant Circuit -----------------
% Minimum gain and maximum gain required

G_dc_min = Vo_min/(a_sp*Vin_max);      % minimum gain
G_dc_max = Vo_max/(a_sp*Vin_min);      % maximum gain

% resonant inductance
Ls = (Q_rated*Ro_rated_pri)/(2*pi*f_res);

% resonant capacitance
Cs = 1/(2*pi*f_res*Q_rated*Ro_rated_pri);

% transformer magnetizing inductance
Lm = K_ind*Ls;

% Q value at the operating conditions
% Q = Zo / R;  Zo = sqrt(Ls/Cs);

Q = sqrt(Ls/Cs)/(Ro/a_sp2);

%------------------------------------------------
```

The results of running these scripts will provide the values of Lr, Lm, and Cr, as well as the turns ratio of the transformer. The code generates values according to equations. These values may not be found in the market, so using the nearest available value in the market is necessary. After selecting these values, the simulation stage is necessary to ensure that the converter operates at the required voltages and can provide the needed power.

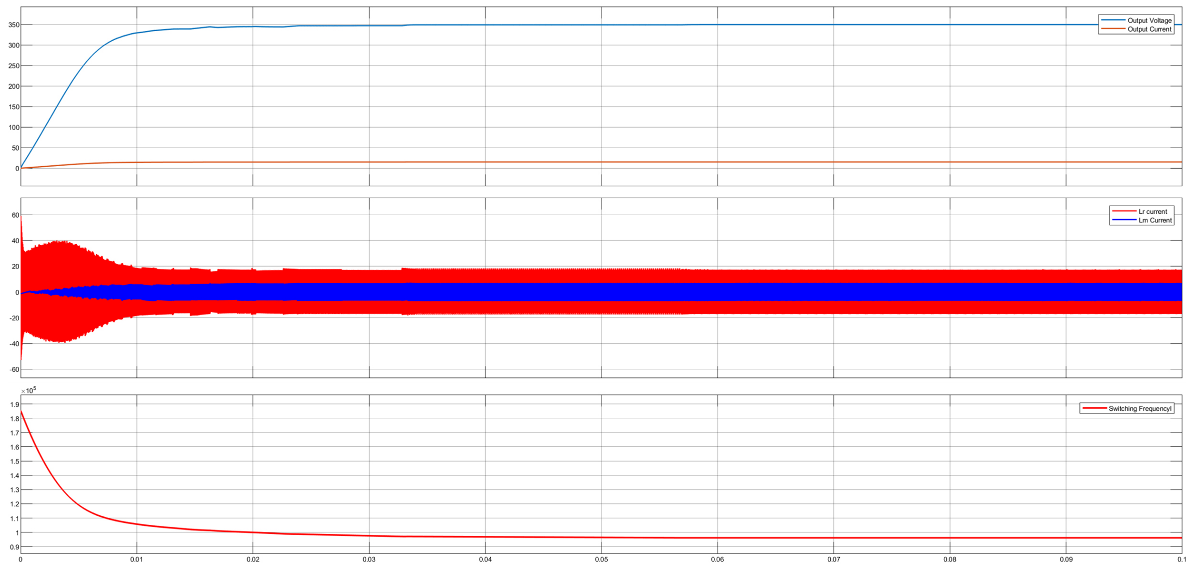
7 LLC resonant Converter Simulation

Using MATLAB Simulink, a model of an LLC resonant converter is built. It consists of the power electronics circuit, a voltage controller ("cascaded PI controller"), a variable frequency pulse generator, and scopes to view the results.

The MATLAB model is available in this link **Download Model**

The simulation ratings:

- Input voltage: 650 - 800 volt rated 700 Volt
- Output voltage: 350 - 500 volt rated 400 Volt
- Frequency 70K Hz
- Rated power: 7000 watt
- Lr: 3.8e-05 H
- Lm: 2.32e-04 H
- Cr: 1.3e-07



At Steady State

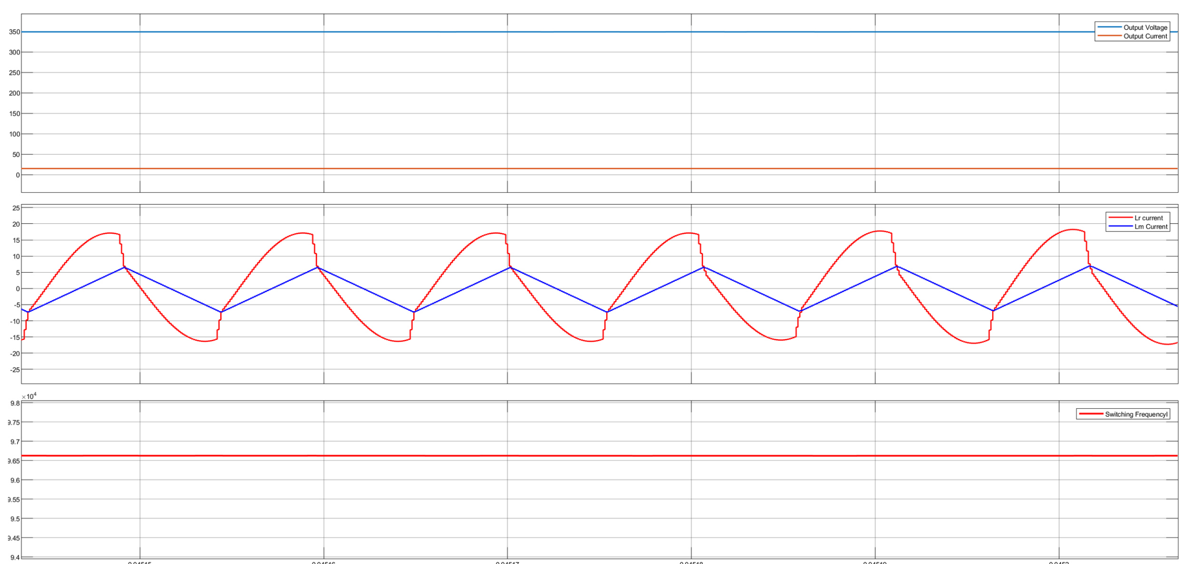
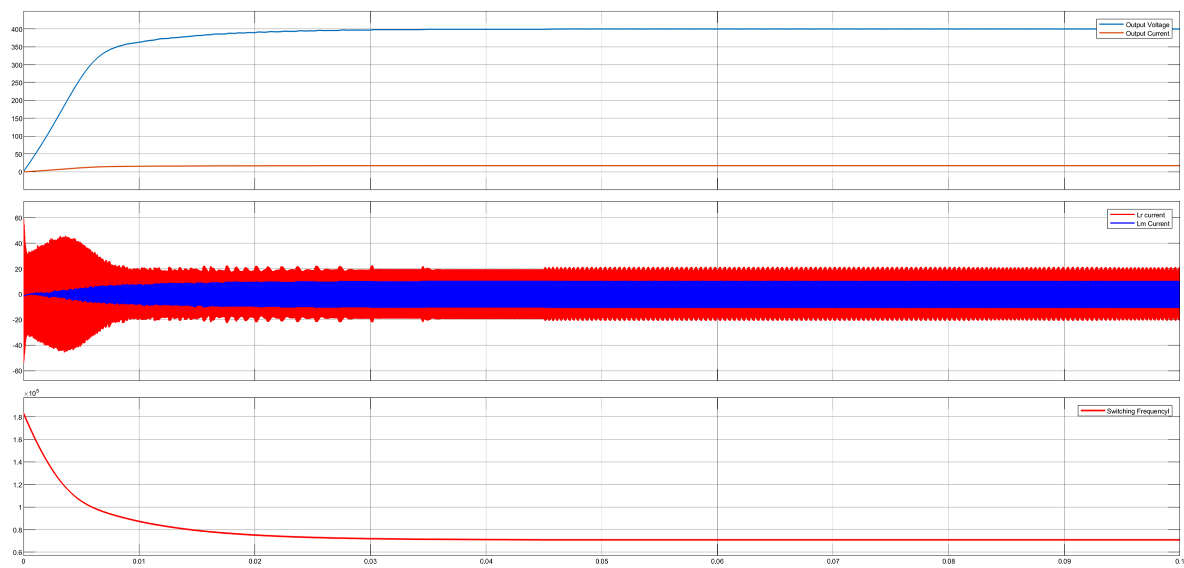


Figure 5: Results in case of Reference voltage equal 350V



At Steady State

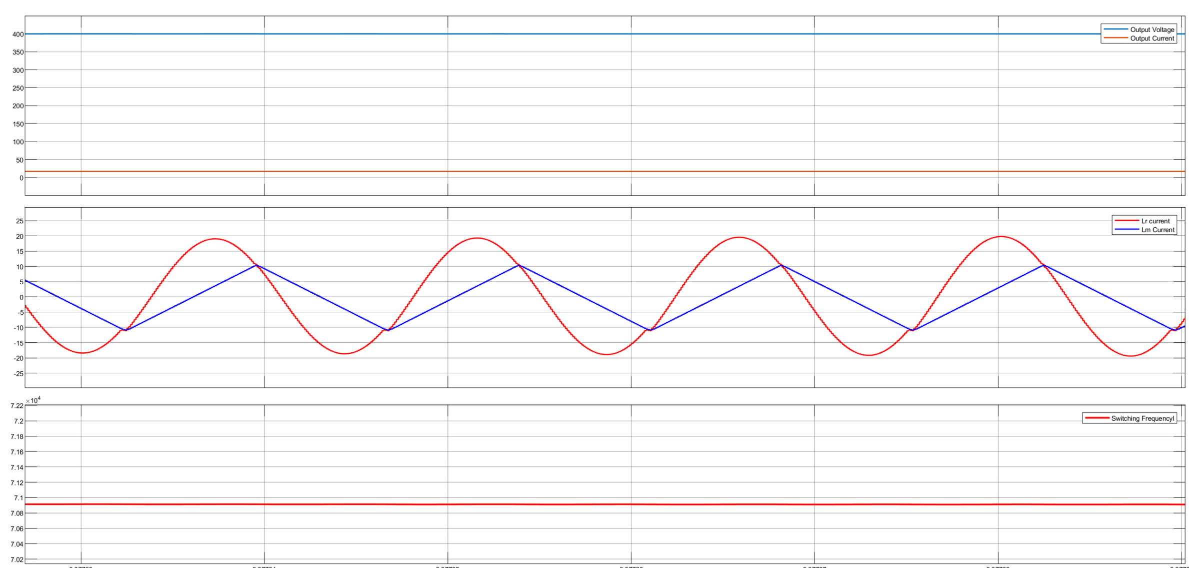
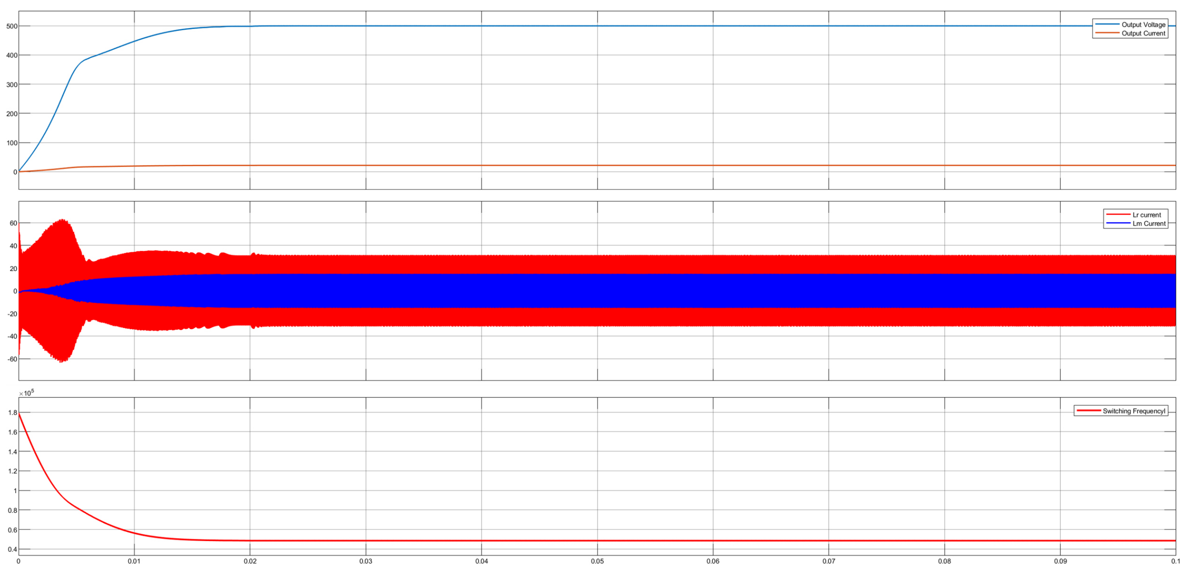


Figure 6: Results in case of Reference voltage equal 400V



At Steady State

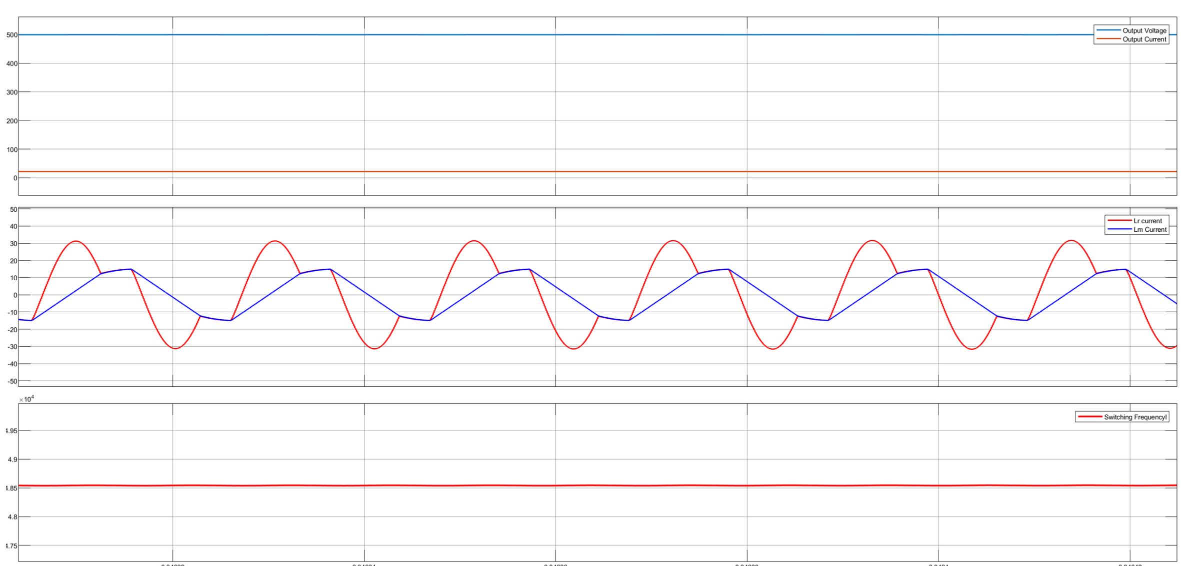


Figure 7: Results in case of Reference voltage equal 500V

8 Conclusion

The LLC resonant converter is an isolated DC-DC converter with high efficiency, around 96%. It can be used for bucking or boosting the input voltage. The LLC resonant converter can be controlled by adjusting the switching frequency of its inverting bridge, allowing it to operate in three modes. It finds application in various fields such as electrical vehicles, solar panels, and more.

References

[1] Davide Cittanti, Matteo Gregorio, Eric Armando, and Radu Bojoi. Digital multi-loop control of an llc resonant converter for electric vehicle dc fast charging. In *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 4423–4430. IEEE, 2020.

[2] Seyed Abolfazl Mortazavizadeh, Simone Palazzo, Arturo Amendola, Enzo De Santis, Dario Di Ruzza, Giuseppe Panariello, Annunziata Sanseverino, Francesco Velardi, and Giovanni Busatto. High frequency, high efficiency, and high power density gan-based llc resonant converter: State-of-the-art and perspectives. *Applied Sciences*, 11(23):11350, 2021.