EE-560
Power Electronic Converters

Half-Bridge CLLC Resonant Converter

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Chapter 1

Introduction

Numerous devices, including cars, chargers, renewable energy systems, and uninterrupted power supply (UPS), use DC-DC converters. DC that is galvanically insulated .Energy storage systems typically choose DC converters. Usually, the converters act as an interface between a high voltage battery pack and a DC link. Resonant CLLC DC-DC converters are excellent options for bidirectional Energy storage systems because of their high efficiency, bidirectional power flow, and galvanic isolation. A bidirectional half-bridge CLLC converter is designed and assessed in this work. In the design, an ideal soft-switching function is used. The design process a few factors are needed. Soft-switching, which drastically reduces switching losses, is possible with the correct inductor and capacitor combination. In addition to operating the circuit in resonance, we also run it at 50 percentage duty cycle. The fundamental harmonic approximation technique makes it simple to describe the output side of this circuit as an equivalent resistor. Because of this, it is easy to model the circuit into its equivalent. In order to create symmetrical and asymmetrical Half bridge CLLC converters .

Bidirectional dc–dc converters are necessary for ENERGY storage systems (ESSs), microgrids, automotive, and other applications. These converters serve as an interface between a low-voltage bus, which typically implements an energy storage device like a battery or a supercapacitor, and a high-voltage bus, which installs an energy generation device. However, depending on the state-of-charge (SOC), the battery or supercapacitor's voltage typically fluctuates over a large range, and as voltage rises, so does the cost . As a result, a high voltage ratio between input and output must be provided when integrating with an ESS.Bidirectional dc-dc is crucial for preserving the dc bus voltage and system power balance.

The design of a CLLC bidirectional resonant converter can benefit from the research on conventional LLC resonance. Low electromagnetic interference (EMI) and soft switching from zero to full loads are possible with an LLC resonant converter, which is commonly utilized for single direction applications. In order to get high voltage gain and high efficiency, a few isolated full-bridge bidirectional dc/dc converter topologies and control schemes have been proposed recently. A schematic of a half-bridge CLLC converter with magnetic integration design is shown in Fig. 1.1 Comparing with full- bridge CLLC topology, the half-bridge one has benefits in terms of reduced weight, size and cost, since the number of corresponding driving circuits and cooling systems can be reduced, and consequently, the overall efficiency of the half-bridge structure would be higher than that of the full-bridge CLLC topology. The bridge capacitors $C_{11}, C_{12}, C_{21}, C_{22}$ the half-bridge CLLC circuit can also function as resonant capacitors. Furthermore, with a proper transformer design, the CLLC circuit uses the leakage inductance of the transformer

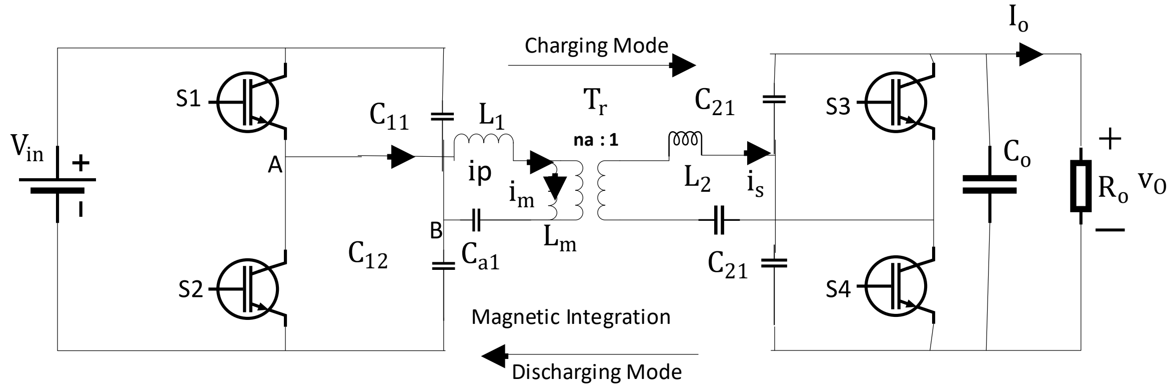

Figure 1.1: SCHEMATIC HALF-BRIDGE CLLC CONVERTER

instead of two individual inductors, L_1, L_2 which slightly increases the power loss of the transformer, but eliminates the power losses of the two inductors and reduces the overall size of the converter.The converter simultaneously uses zero- voltage switching (ZVS)-on for the inverting stage choppers and zero-current switching (ZCS)- OFF for the rectifier switches. However, under the high dc voltage gain state, the primary side of the resonant network has a large current stress that increases the losses of the transformer and the resonant network.

Chapter 2

WORKING

To create the intended sinusoidal current waveform through the circuit, the resonant capacitor and inductor must resonate at a specific frequency. Zero-voltage or zero-current switching (ZVS or ZCS) is achieved by the circuit because the resonance frequency and the switching frequency are tightly tuned. In order to provide efficient energy transfer and a reduction in switching loss, the capacitive component will shape the voltage waveform and the inductive component will help shape the current waveform. The resonant component values are often set to produce a resonant frequency, mainly for stabilization and to guarantee soft switching during load transitions. In CLLC, the transformer and the magnetizing inductor are frequently connected. This allows power to flow both ways and stores energy.Additional soft-switching support is provided by magnetizing inductance, which modulates the major side current of the converter under light-load or high-load circumstances. Additionally, it restricts the circulating current, which lessens power loss from the low load.

Fig. 2.1 illustrates typical waveforms of a bidirectional half- bridge CLLC circuit operating at a switching frequency lower than its resonant frequency. All the switches are off during dead band time between t_a and t_b to prevent the bridges from short- circuit. There are no power transferring from the primary side to the secondary side in this interval, therefore the secondary side resonant inductor currenti_s is zero. The gate voltage,$v_{s1}$is applied at timet_b , when the primary side resonant inductor current, i_p is negative, which means the switch current of S_1 freewheels through the body diode. Therefore, att_1,S_1 will turn on with ZVS. Beyond t_b ,i_s is positive and power are delivered from the primary side to the secondary side through the transformer . Betweent_b andt_c, since L_m is much larger than L_1,$i_p$resonates whereas the magnetizing inductance current, i_m, keeps increasing almost linearly. Wheni_p meets i_m att_c,i_p andi_m resonate together and no power transfer to the secondary side, thereforei_s becomes zero and the body diode of S_3 turns off with ZCS automatically. Similar operating waveform can be found for the other half cycle but with opposite current direction.

2.1 TOPOLGY

The bidirectional half-bridge CLLC converter has a symmetrical structure consisting of a primary inverting stage and a secondary rectifying stage. In comparison to a full-bridge CLLC converter, the half-bridge topology uses primary side inverting stage capacitors C_{11}, C_{12} and secondary side rectifying stage capacitors C_{21}, C_{22} as resonant capacitors. L_1 and L_2 are resonant inductors, and with a proper transformer design, the resonant inductances can be integrated into the transformer's primary and secondary windings. n and L_m are the turns ratio and magnetizing inductance of the transformer, respectively. The bidirectional CLLC converter has two power flow modes: charging mode (power flows

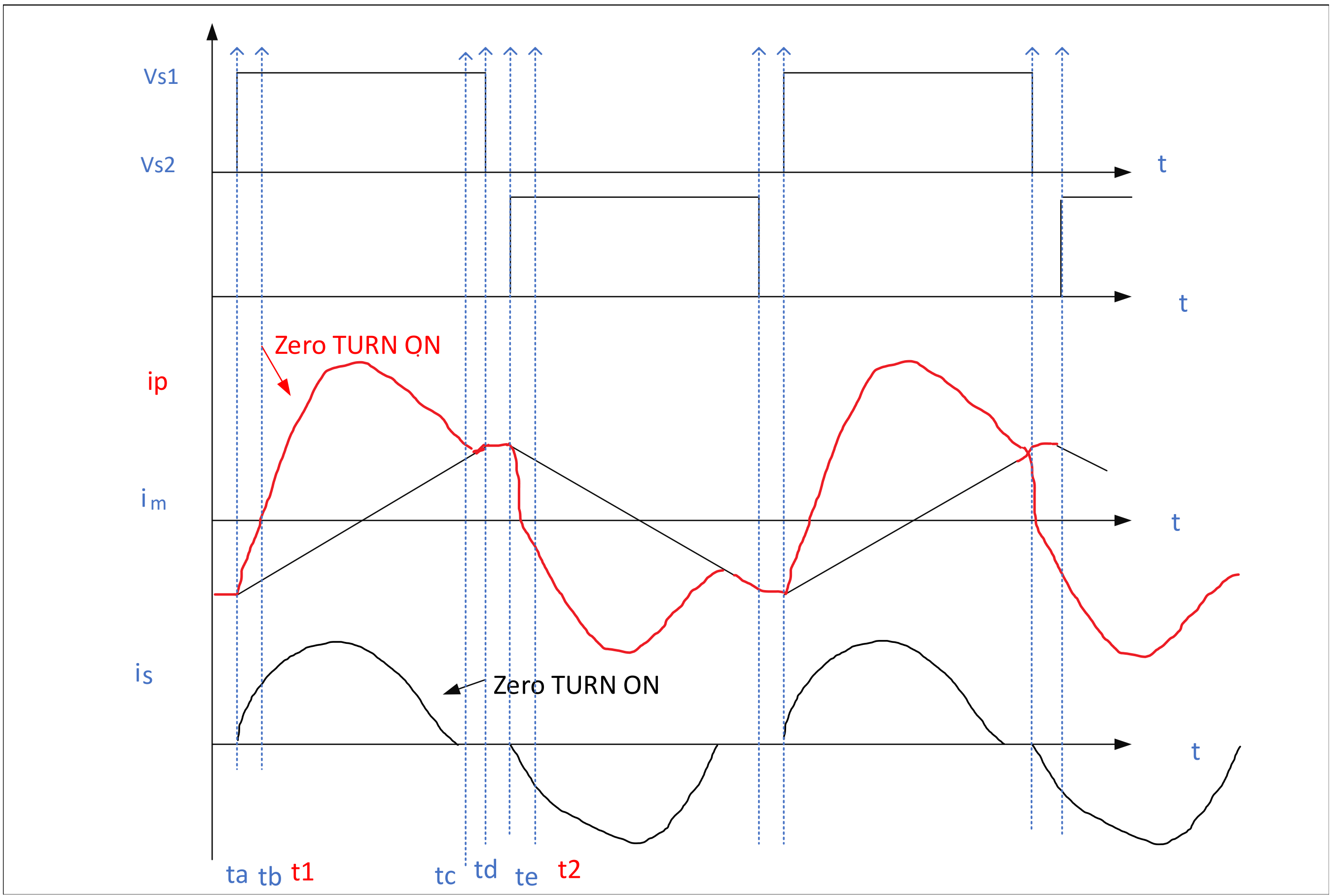

Figure 2.1: Typical waveforms of a bidirectional half-bridge CLLC converter.

from the DC link to the battery) and discharging mode where power flows from the battery to the DC link.

2.2 CHARGING MODE

The equivalent circuit of the half-bridge CLLC converter in charging mode is shown in Fig. 2.2 R_e,L'_2,C'_{21}, and C'_{22} are the equivalent R_O,L_2,C_{21}, and C_{22} of the converters, respectively. In charging mode, the transfer function H(s) can be derived as follows:

$$H(s) = \frac{1}{n} \cdot \frac{R_e}{R_{e,FB} + Z'_{L2} + Z'_{C2}} \cdot \frac{(R_e + Z'_{L2} + Z'_{C2}) \| Z_{Lm}}{Z_{L1} + Z_{C1} + (R_e + Z'_{L2} + Z'_{C2}) \| Z_{Lm}}$$

The gain of the half-bridge CLLC converter can be derived as:

$$G_{charging} = |H(s)| = |\frac{V_{out}}{V_{in}}| = \frac{1}{n} \cdot \frac{1}{\sqrt{a^2 + b^2}}$$

where,

$$a = \frac{1}{h} + 1 - \frac{1}{h.\omega^2}$$
$$b = \left(\frac{k}{h} + 1 + \frac{1}{g \cdot h} + \frac{1}{g}\right)\frac{Q}{\omega} - (\frac{k}{h} + 1 + k)Q \cdot \omega - \frac{Q}{g \cdot h \cdot \omega^3}$$
$$\begin{cases} h = \frac{L_m}{L_1}, k = \frac{L_2'}{L_1}, g = \frac{c_2'}{c_1}, \omega = \frac{\omega_s}{\omega_r} \\ \omega_r = \frac{1}{\sqrt{L_1 C_1}}, \ Q = \frac{\sqrt{L_1/C_1}}{R_e} \end{cases}$$

Q is quality factor,W_r and W_s are the resonant frequency and the operating frequency, respectively, and is the normalized frequency. A detailed derivation of Re for a Half-bridge CLLC converter is done by using the First Harmonic Approximation (FHA). Similarly, for the half-bridge CLLC converter, the parameters can be expressed as:

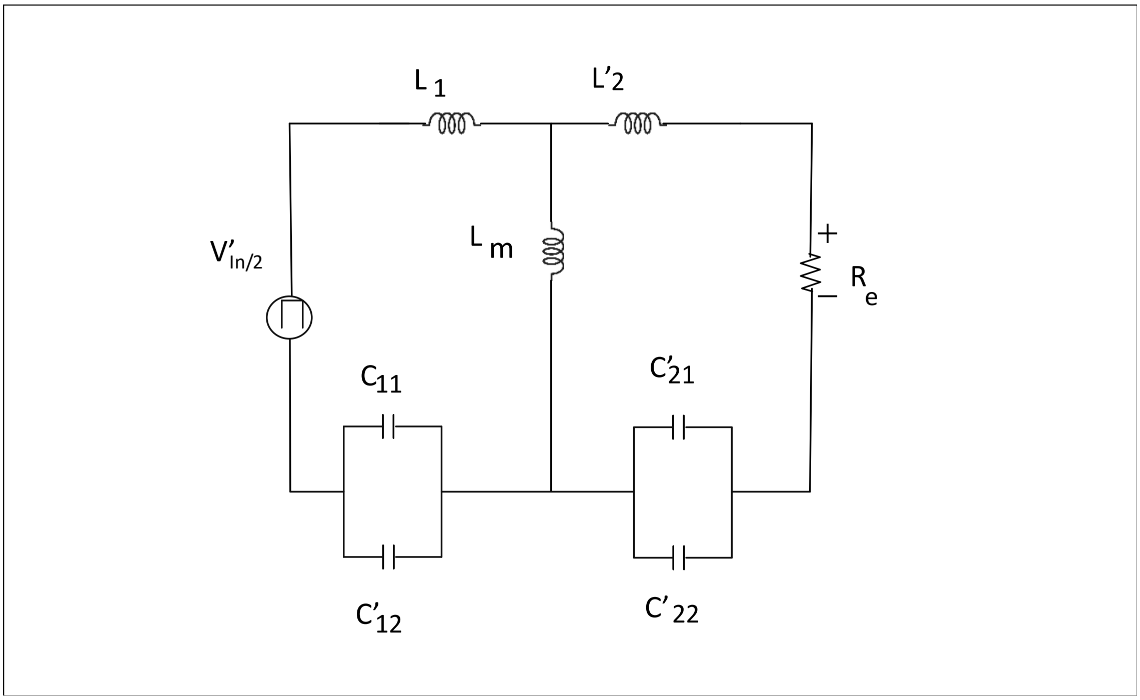

Figure 2.2: Equivalent circuits of the half-bridge CLLC converters in charging mode.

$$R_e = (2n^2/n^2)R_o \quad L_2' = n^2 L_2 \quad C_1 = C_{11} + C_{12}$$
$$C_2' = C_{21}' + C_{22}' \quad C_{21}' = C_{21}/n^2 \quad C_{22}' = C_{22}/n^2$$

Fig. 3.1 illustrates different gain curves at various load conditions versus normalized frequency. With a lower Q, the maximum gain increases, but the slope of the curve when W1 decreases. In this case, k and g are set to be 1 to simplify the design, which meansL_1=L_2' andC_2=C_2'.h is set to be 4.

2.3 DISCHARGING MODE

The equivalent circuits of the half-bridge CLLC converter in discharging mode is shown in Fig. 2.3. The gain of the converter is derived as follows:

$$G_{dischargig} = n \cdot \frac{1}{\sqrt{c^2 + d^2}}$$

where,

$$c = \frac{1}{h} + 1 - \frac{1}{h'\omega'^2}$$

$$d = \left(\frac{k'}{h} + 1 + \frac{1}{g'.h'} + \frac{1}{g'}\right)\frac{Q'}{\omega'} - (\frac{k'}{h'} + 1 + k')Q' \cdot \omega' - \frac{Q'}{g'.h'.\omega'^3}$$

$$\begin{cases} h' = \frac{L'_m}{L_2}, k' = \frac{L'_1}{L_2}, g' = \frac{c'_1}{c_2}, \omega' = \frac{\omega_s}{\omega'_r} \\ \omega'_r = \frac{1}{\sqrt{L_2 C_2}}, Q' = \frac{\sqrt{L_2/C_2}}{R'_e} \end{cases}$$

The parameters can be calculated as:

$$\begin{array}{lll} R'_e = (2/n^2\pi^2)R'_o & L'_1 = L_1/n^2 & C'_1 = C'_{11} + C'_{12} \\ C_2 = C_{21} + C_{22} & C'_{11} = n^2 C_{21} & C'_{12} = n^2 C_{22} \\ L'_m = L_m/n^2 & & \end{array}$$

With the same L and C values, the discharging mode will have the same resonant frequency as the charging mode has, which meansW'_r=W_r.k,g, and h will keep the same values as the k, g, and h in charging mode, respectively. However, since the equivalent load changes, Q will be changed as:

$$Q' = n^2 R_o / R'_o Q$$

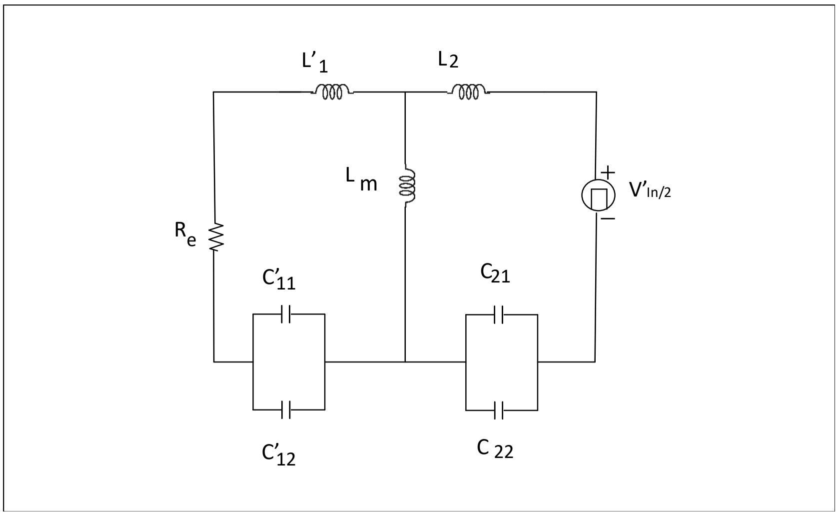

Figure 2.3: Equivalent circuits of the half-bridge CLLC converters in discharging mode.

Chapter 3

SOFT SWITCHING REGION

The resonant tank of the half-bridge CLLC circuit can present inductive or capacitive depending on operating frequency. As shown in Fig. 3.1, the resonant network is inductive when the slope of the gain is negative, and ZVS can be realized in this region. Furthermore, in order to ensure ZVS turning on, the magnetizing inductor current should be large enough to fully discharge and charge the output capacitors of the MOSFETs during the dead band time. Therefore, the magnetizing inductance should be small enough. The maximum value of $L_m$for a Half-bridge CLLC converter is calculated as

$$L_m \leq \frac{t_{db}}{8C_{oss}f_{s,max}},$$

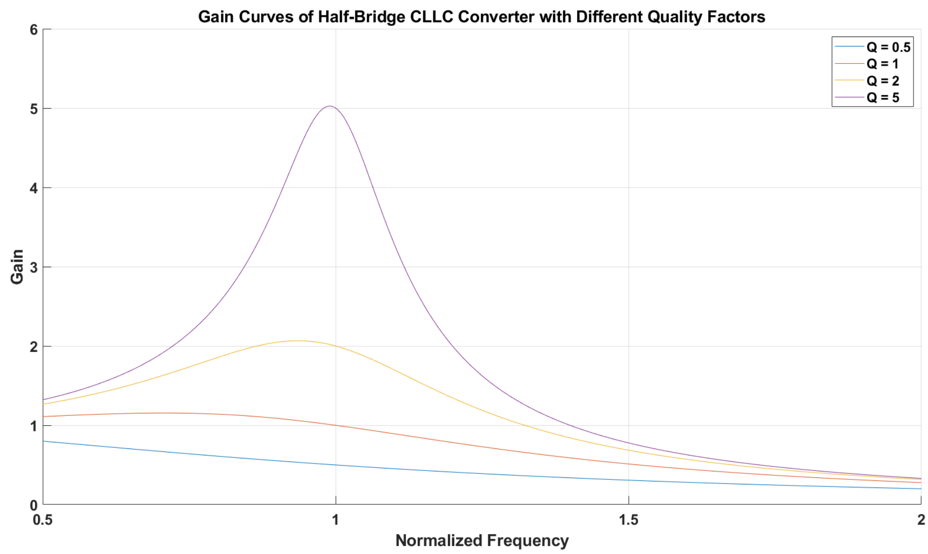

Figure 3.1: Gain curves versus normalized frequency at different loads.

where, t_{db} is the dead band time, C_{oss} is the output capacitance of MOSFET, and $f_{s,max}$ is the maximum switching frequency.

Chapter 4

CALCULATION OF PARAMETERS

Given,

$$V_{in} = (100V) \quad V_o = 400V \quad C_1 = C_{11} = C_{12}$$
$$C_2 = C_{21} = C_{22} \quad f_{sw} = 25kHz \quad P_O = 1KW$$

Resonant frequency $f_r = f_{sw} = 25kHz$ and quality factor we are assuming Q = 0.45

$$G_{charging} = |H(s)| = |\frac{V_{out}}{V_{in}}| = \frac{1}{n} \cdot \frac{1}{\sqrt{a^2 + b^2}}$$

$$G_{charging} = |H(s)| = |\frac{V_{out}}{V_{in}}| = \frac{1}{4} \cdot \frac{1}{\sqrt{a^2 + b^2}}$$

and considering g = 1;and k = 1; h = 4 where L_m = 4 times of L_1 for better output and stepping up the voltage

$$a = \frac{1}{h} + 1 - \frac{1}{h.\omega^2}$$
$$b = \left(\frac{k}{h} + 1 + \frac{1}{g \cdot h} + \frac{1}{g}\right)\frac{Q}{\omega} - (\frac{k}{h} + 1 + k)Q \cdot \omega - \frac{Q}{g \cdot h \cdot \omega^3}$$
$$\begin{cases} h = \frac{L_m}{L_1}, k = \frac{L_2'}{L_1}, g = \frac{c_2'}{c_1}, \omega = \frac{\omega_s}{\omega_r} \\ \omega_r = \frac{1}{\sqrt{L_1 C_1}},\ Q = \frac{\sqrt{L_1/C_1}}{R_e} \end{cases}$$

After calculation we will get
a = 1.25, b = -158962.5 $L_1 = L_2 = 0.7uH$ and $C_{11} = C_{12} = C_{21} = C_{22} = 3.5uF$
Transformers ratio n = 400/100 = 4
from the output power which is given that$P_O = 1KW$ we can calculate the load resistance as
$P_O = \frac{V^2}{R} = \frac{1000}{400^2} =$ 160ohm $L_m = 2.8uH$
And the same similar values for the both charging and discharging mode.

Chapter 5

DESIGN AND SIMULATION

5.1 SIMULINK MODEL

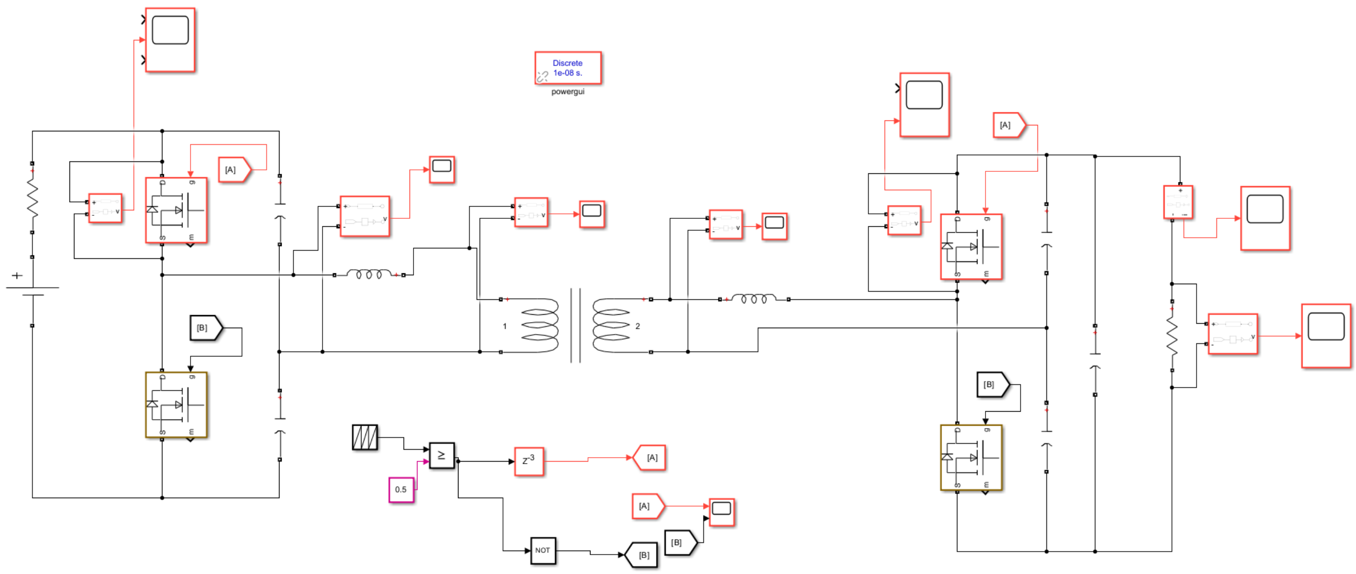

Figure 5.1: SIMULATION OF HALF-BRIDGE CLLC CONVERTER

This is the simulation and after substituting the desired and calculated values that we got above.

$$\begin{cases} L_1 = 0.7\mu H,\ L_2 = 0.7\mu H \\ C_{11} = C_{12} = 3.5\mu F,\ C_{21} = C_{22} = 3.5\mu F \end{cases}$$

5.2 SIMULATION RESULTS

5.2.1 GATE PULSE

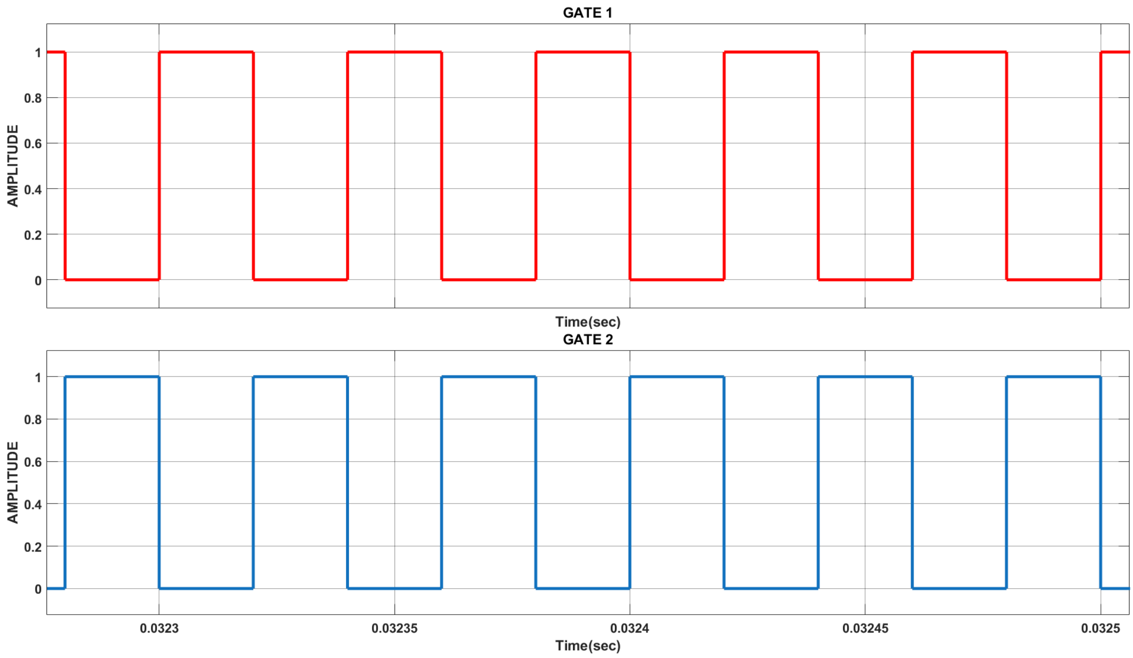

Figure 5.2: GATE SIGNAL PULSE

5.2.2 VOLTAGE AND CURRENT WAVEFORMS

We will get the output voltage as 383.5V as it is a open loop simulink model there will be some deviation from the desired output.And Current as$I_0 = 2.5A$

[4] [3] [1] [2]

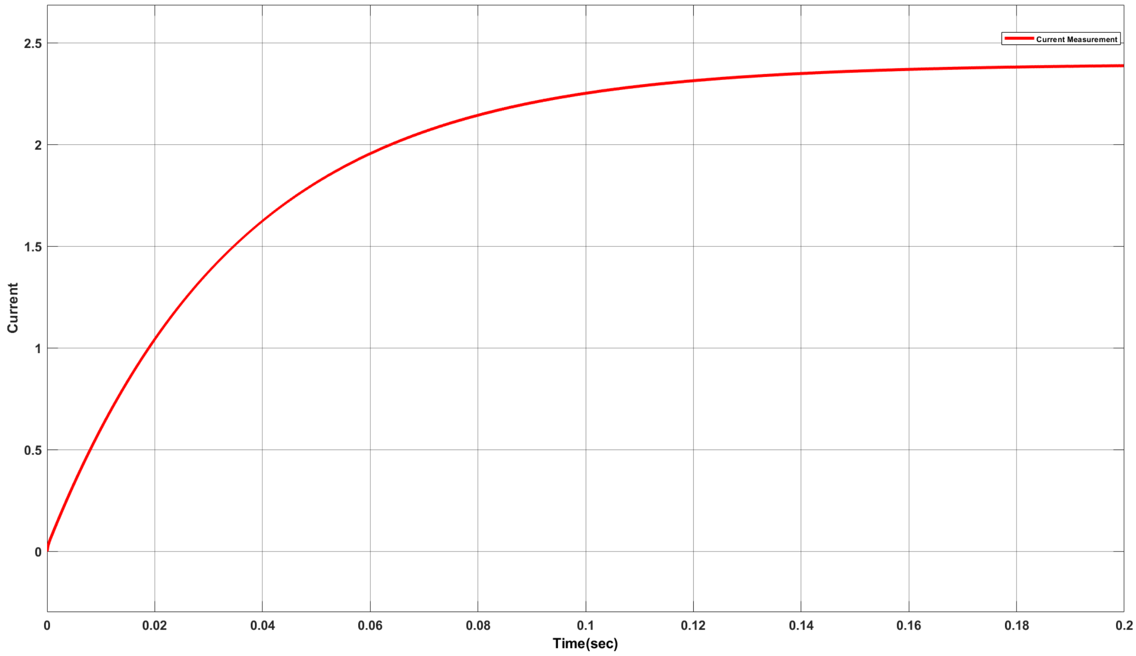

Figure 5.3: OUTPUT CURRENT WAVEFORM

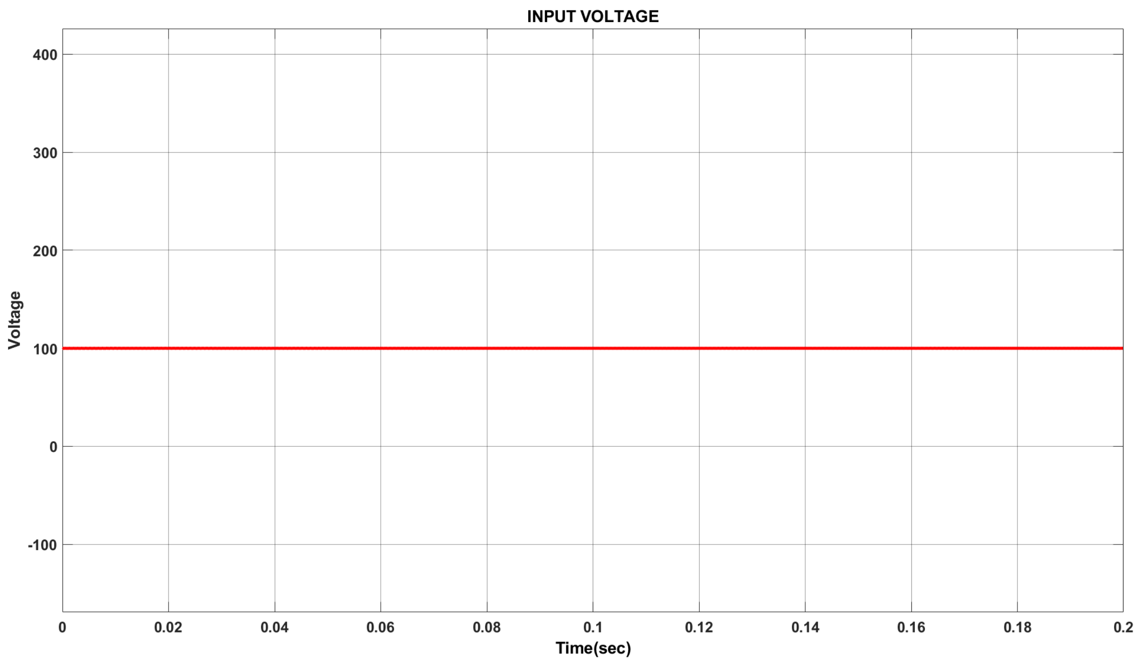

Figure 5.4: INPUT VOLTAGE WAVEFORM

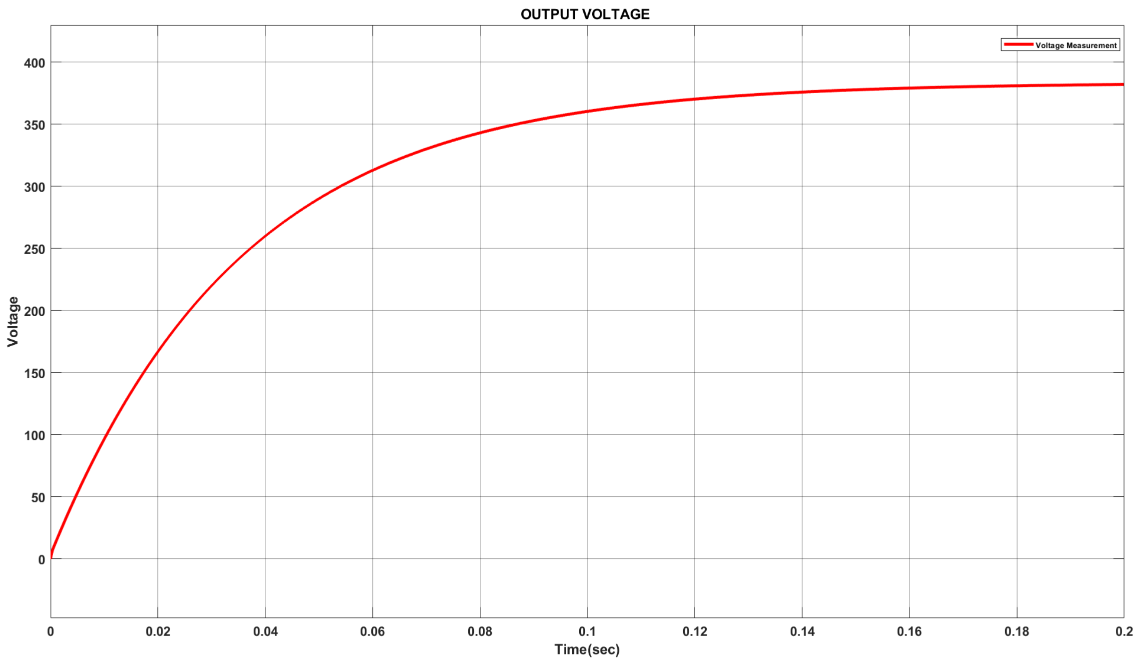

Figure 5.5: OUTPUT VOLTAGE WAVEFORM

Bibliography

[1] Ruijia Cai, Yundong Ma, Ruiran Dai, Zhiqiang Zhao, Peng Wang, and Pengfei Wang. An any-cell-to-any-cell equalization based on half-bridge cllc converters for lithium-ion battery strings. In *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 01–06, 2022.

[2] Kuo-Yuan Lo, Shin-Yue Chen, and You-Xuan Guo. Design of an interleaved half-bridge cllc resonant ac-ac converter. In *2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia)*, pages 1494–1498, 2022.

[3] Hsuan-Yu Yueh, Jing-Yuan Lin, Haung-Jen Chiu, Chen-Yen Chu, Yu-Chen Chang, and Sih-Yi Lee. Three-level bi-directional half-bridge cllc resonant converter for dc micro-grid. In *2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019 - ECCE Asia)*, pages 1904–1909, 2019.

[4] Chunjiang Zhang, Pengcheng Li, Zhizhong Kan, Xiuhui Chai, and Xiaoqiang Guo. Integrated half-bridge cllc bidirectional converter for energy storage systems. *IEEE Transactions on Industrial Electronics*, 65(5):3879–3889, 2018.

CONCLUSION

Hence,I successfully generated the simulations of Half-Bridge cllc bidirectional converter desired output.And also I Plotted the Gain Curves Graphs to observe the how gain changes with respect to frequency and quality factor