Isolated LLC Resonant DC-DC converter used for MVDC Grids

Mr. M V Kesava Kumar[1], Prof. N. Visali[2]

*Research Scholar, Department of EEE, JNTUA College of Engineering Kalikiri-517234

*Department of EEE, Jawaharlal Nehru Technological University Anantapur-515002

***Abstract*— An Isolated DC-DC converters have many applications in aerospace, telecommunication and in Electrical vehicle applications. This converter used to obtain increase voltage levels by using stored energies of capacitors and inductors. Higher frequencies can reduce the cost and size of the converter. For these concerns BJT's are replaced by MOSFET's and IGBT's which have lower on states resistances and high voltage withstand capabilities. An Isolated DC-DC boost converters are common step-up circuits having many applications in both low and high-power applications. Inductors are used to increase the voltage gain, efficiency and reduces ripple content of currents by using continuous current modes. Capacitors reduce excessive burden on sources. PWM DC-DC converters have a disadvantage of hard switching. This can be over through by using active and passive snubber circuits. The passive snubber circuit consist of resistance and diode in parallel with the switch which are not efficient as much as active snubber circuit The active snubber circuit consists of a resonant circuit near to the transformer which can achieve ZVS or ZCS type switching. Here we use LLC Resonant circuit for better achievement of both ZVS and ZCS. Voltage-multiplier is rarely adopted in isolated DC/DC converter. If transformer output is of current type, rectifier is of capacitive type. Capacitive type rectifier is used to construct voltage- multipliers, which can provide high output voltage. It is illustrated that ZVS of switches on the primary side can achieved and ZCS of diodes on the secondary side can achieved as well. Simulation at frequency of 5KHz for LLC type resonant converter using MATLAB / SIMULINK is conducted and the results can be verified.**

***Index Terms*—LLC resonant converter, high voltage high frequency Transformer, voltage doubler, resonant tank,**

I. INTRODUCTION

High voltage DC-DC converters are more predominant in many industrial applications, like high power soldering equipment, X-ray imaging.

Voltage boost capability is the first and foremost requirement of power converters with lower input voltages, higher efficiencies and higher power densities. But, the ratio of voltage boost is limited by the turn's ratio of transformer. To achieve higher voltages with high gain with both high efficiency and power density diode-capacitor voltage boost cell is most suitable one. When switching frequency is not high, charging and discharging of capacitors produces large inrush currents and will increase switching losses. But there is a constrain that as switching frequency increases there will be more switching losses due to more frequent switching. The more the switching frequency the less will be the size magnetizing components like transformer. Always try to maintain switching frequency constant because variable frequency control can produce problems of EMI makes the design of filters and control circuit difficult.

Hard and Soft Switching:

Hard-switching converters will have more switching power loss. Hard-switching suffers from high EMI's which always results high di/dt and dv/dt when switch is turn ON and turn OFF. As switching frequency increases switching losses may increase. Low switching frequencies may have low power densities which increases the size of the storage elements. To overcome above problems, we will go for soft-switching converters which utilizes capacitance and stray inductance for resonance circuit to get Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS).

Perfect operation of these converters depends on resonant frequency, so they cannot be suitable for fully range of operating conditions. To achieve best resonant operation a small capacitor in series with coupled inductor and also transformer inductance (leakage inductance) is implemented.

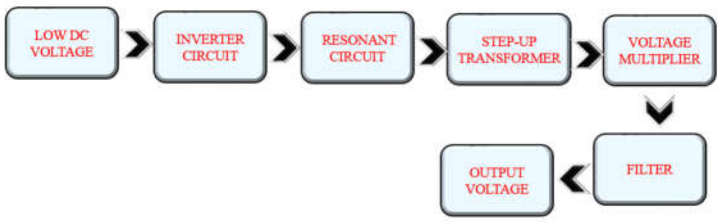

Fig.1. Block diagram of a FB-LLC resonant high voltage DC-DCconverter

Voltage-Fed/Current-Fed:

Transformer Higher Frequency operations with isolated soft-switching methods is of three types (a) Voltage fed resonant converters. (b) current fed resonant converters and (c) fixed-frequency Zero-Voltage Switching (ZVS) PWM bridge converter with resonant transition [13-18].

Voltage-fed Full-Bridge DC-DC converter suitable for high-power applications. It consists of a capacitor at input and a low frequency passage filter at its output. This Voltage Fed isolated converter used for high power applications whereas non isolated type converters used for low power applications which has fast dynamic response. Voltage fed resonant converters operate in variable frequency mode or fixed frequency mode. But as discussed earlier the operation in variable frequency mode suffers from several disadvantages.

Current-Fed DC–DC Converters consist of input inductor used to convert the low voltage of input to high voltage. The current fed converters having the secondary output capacitor are more preferable to get high voltage. This input inductor reduces the ripples at input and provides continuous input current so used for low power applications like Photo Voltaic (PVs) and Fuel Cells (FCs).

These converters may achieve best soft switching and provides higher efficiencies for different power ratings.

The Full-Bridge DC–DC converter used in high-power industrial applications. This type of converter has a DC–AC stage High-Frequency with Isolation Transformer, and a rectification circuit AC-DC and Voltage multiplier circuit to get high voltage.

Unidirectional and Bidirectional:

Most of the converters for dc–dc operation is unidirectional power flow the input source only supplies to the load. In this low number are switches are used so that the efficiency of the converter will be high compared to Bidirectional converters.

Isolation transformers can have boosting ability and also isolation between input to output. Fig. 2 shows a unidirectional isolated dc–dc converter.

ZCS converters are rarely used for low voltage applications because they use MOSFETS but not IGBTs.

The Pulse Width Modulated (PWM) DC-DC converters used for controlling and regulating the output power can suffer switching losses due to hard switching. As switching losses increase with high switching frequency resulting in lower efficiencies and regulation of output voltage is more difficult in the series resonant converters (SRCs) at no load and low conditions. Hence, to overcome these problems, resonant converters are modified as series (LCL) resonant. The LLC resonant tank has a property which can inherently adjust circulating currents while maintaining ZVS. Therefore, the converters have small leakage inductance, large parasitic capacitances [5]. Additionally, a secondary rectifier circuit in series can be used to feed high voltage load to ensure a safe operation within the components.

SRC is the easiest and most convenient to set up data, and it also performs well from load to full load. However, one of the weaknesses of SRCs is their flexibility to control light loads [6-7]; Also, the converter must have a high-voltage capacitor to act as an output filter. For current applications [8] Therefore, SRC is recommended for high frequency and low voltage applications [9]. However, SRCs are also suitable for high-power applications such as power conversion in X-ray generators. On the one hand, the PRC behaves like a constant current at its resonant frequency.

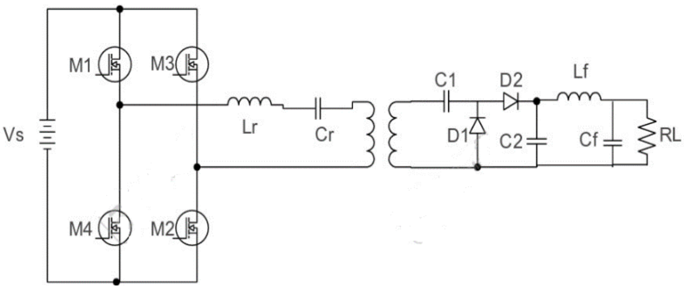

Fig.2. Circuit diagram of a FB-LLC resonant high voltage DC-DCconverter

Fig.1 shows a block diagram of the full- bridge resonant DC-DC converter to get high-voltage. It also consists of an inverter, resonant tank, a transformer operates for high frequencies, and voltage multiplier circuit. In Section II shows the Simulink model of the converter and gives the circuit descriptions. Section III explains mode of operations of the proposed resonant converter which explained in detail. Then, the simulation results of LLC resonant DC-DC high voltage converter are described in Section IV. Conclusion of this research works is in Section V.

II. CIRCUIT DESCRIPTION

Figure 2 shows the circuit diagram of the DC-DC converter concept. The proposed converter consists of four main components: Full Bridge inverter, LLC resonant tank, high voltage transformer and Voltage Multiplier circuit with a well-designed filter circuit. The Full Bridge inverter has four power MOSFETs (M1, M2, M3, and M4). Output capacitances of M1-M4 power switches are shown as C1-C2, respectively.

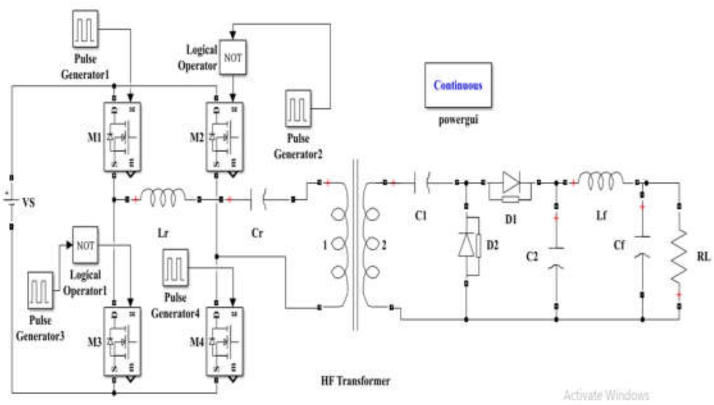

Fig. 3. Circuit Simulink model

The power MOSFETs of the inverter operate in complementary modes with a duty cycle of 50%. To prevent short-circuit phenomenon a dead time is included by using duty cycle. The resonant circuit consists of series capacitance, Cr and series inductance Lr. Series resonance inductor and shunt inductor can be obtained from the transformer itself using magnetic field. The power speed of the converter is greatly increased due to the properties of the magnetic field. In addition, the number of products has been reduced. The high voltage/frequency transformer step up's the secondary voltage to get fixed output voltage level and also obtains the electrical isolation between primary and secondary circuits. To get high voltage system a Voltage Multiplier circuit is used, which consists of two diodes (*D_1*, *D_2*) and two capacitors (*C_1*, *C_2*) operates at high voltages. The bridge rectifier converts AC output on secondary transformer to its DC whereas the filter circuit removes ripples from DC output voltages.

III. MODES OF OPERATION

LLC resonant converters typically operate below the resonant frequency. Therefore, Figure 2 actually represents the operation of the converter when the switching frequency is below the resonant frequency (fs < fr).

It can be seen that the converter has eight operations in one conversion cycle in this four where explained. Equivalent circuits for these operating modes are shown from Figure 4. The switching cycle of the converter starts at time t_0 with angular frequency w_0. Before time t_0 the resonant current $I_{Lr}(t)$ is negative and anti-parallel diodes of power switches *S_1*, *S_4*. Therefore, power switch S1, S4 opens in the ZVS state. On the secondary side, diodes D1 and D2 form the secondary current to form ZCS operation.

Mode 1: Resonant Charging (M1, M4 ON – ZCS Turn-On)

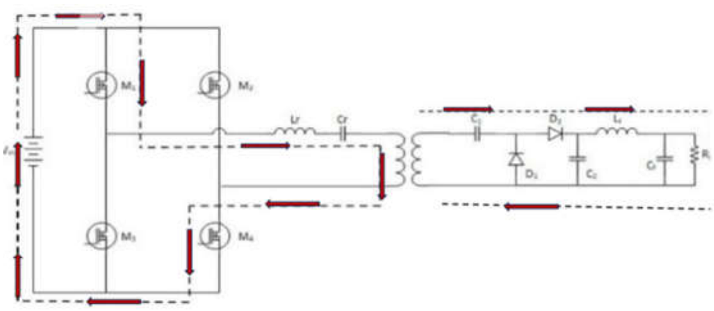

Fig.4. Resonant Charging mode

Operation: M1 and M4 are turned on at zero current (ZCS). The resonant tank Lr and Cr starts charging, and current builds up sinusoidally.

Now the $i_{Lr}(t)$ will be

$$i_{Lr}(t) = I_{Lr,peak}\, cos(w_0 t) - \frac{V_{out}}{nZ_0} sin(w_0 t)$$

Where n is the turns ratio.

At secondary side Diode D1 Conducts, the conduction path during the positive half-cycle, the transformer secondary voltage is positive. Diode D1 conducts, allowing current to flow through the output filter and load. Transformer secondary winding is forward biased. Diode D1 conducts, allowing current to flow through L → RL load → C1. C1 stores energy and also smooths the rectified output by reducing the voltage ripple. C2 is reverse biased via D2, hence it is inactive in this mode. Therefore resonant current equation i_{Lr} is shown below

$$i_{Lr}(t) = I_{Lr,0}\, cos(w_0 t) + \frac{V_{in} - V_{Cr,0}}{Z_0} sin(w_0 t)$$

Where:

$w_0 = 2\pi f_r$

$Z_0 = \sqrt{L_r/C_r}$

$V_{Cr,0}$ is the initial voltage across C_r

Excitation Current: $i_m(t) = i(0)_0 + \frac{V_{pri}}{L_m} t$

Where, V_{pri} is the voltage across the primary.

Output current equation $i_{out}\,(t) = \frac{V_{sec} - V_{out}}{R_{load}}$

The output voltage is filtered by C_f and L_f, resulting in a nearly DC output.

Mode 2: Dead Time Interval (Transition – ZVS Setup)

All switches OFF, body diodes/parasitic capacitors active. **Parasitic capacitances Cds** of MOSFETs discharge/charge via **inductor current**. **Energy in leakage inductance** drives Vds of the next switches to zero. **ZVS achieved** for next commutation switches. Both primary switches turn OFF; transformer voltage is zero or transitioning. No current flows in the secondary → Both diodes are reverse biased. C1 and C2 act as voltage sources during this interval, supplying energy to the load RL. This helps maintain continuous output voltage even during switching transitions.

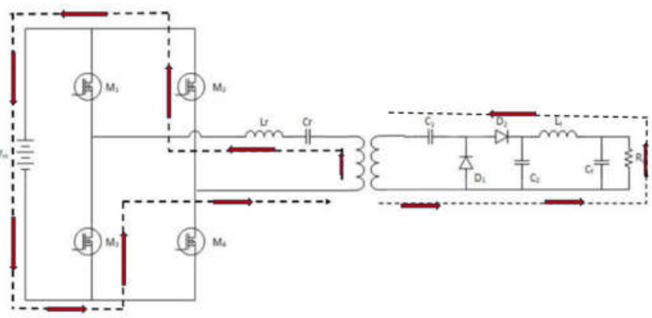

Fig.5. Resonant Discharging

Operation: M1 and M4 turn off at zero voltage (ZVS), and M2, M3 are turned on. The current reverses direction, transformer secondary voltage reverses. Diode D2 conducts, providing current to the load. Similar to Mode 1, but with reversed current direction. discharging the resonant capacitor. Diode D2 Conducts and conduction Path using the negative half-cycle.

Mode 3: During Mode 3 (Q2 & Q3 ON → Negative Vpri)

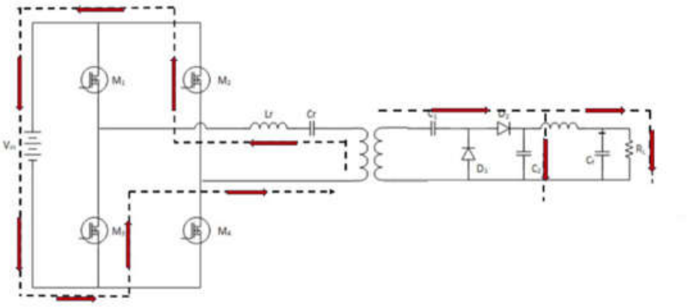

Fig.6. Reverse Power Transfer Mode

Operation: Switches ON: Q2 (bottom-left), Q3 (top-right)
Transformer sees negative voltage (due to reversed current), reversing current through output. Output Diode D2 conducts. Current direction: Negative in primary, but still positive in load after rectification. ZVS: Same as before – Vds reaches 0 before turn-on. Transformer polarity reverses → D2 conducts, D1 is OFF. Current path: Transformer → D2 → L → RL → charges C2. Now, C2 stores energy, filtering the negative half of the rectified waveform. C1 is reverse biased, not conducting.

Mode 4: During Mode 4 (Dead Time Again):
All switches OFF again. Leakage inductance continues current, discharging Vds of Q1/Q4. Sets up next ZVS cycle for Q1/Q4.Similar to Mode 2 → No active switching. Load is powered by C2, which discharges slowly into RL.
Both capacitors play a crucial role in holding voltage level steady between active conduction periods.

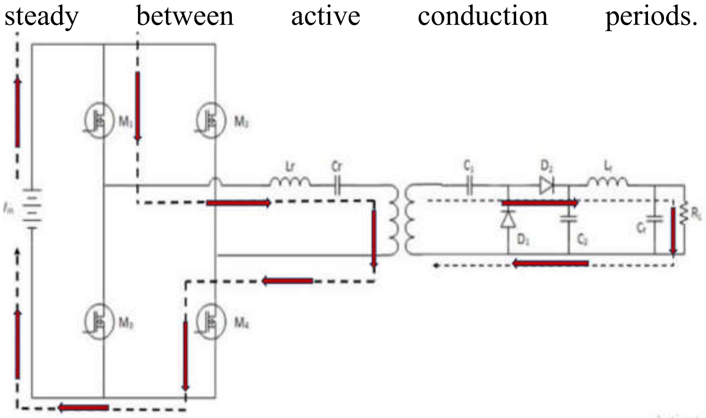

Fig.7. Alternate Resonant Charging

- **Operation:** Similar to Mode 1, but with M2, M3 conducting. The process repeats in the opposite direction.

Mode	Switches ON	Current Flow	Output Diode	Purpose	ZVS Condition
1	Q1 & Q4	Forward	D1	Power to load	✓ Achieved
2	None (dead time)	Freewheeling	Body diodes	ZVS setup for Q2/Q3	✓ Achieved
3	Q2 & Q3	Reverse	D2	Continued load supply	✓ Achieved
4	None (dead time)	Freewheeling	Body diodes	ZVS setup for Q1/Q4	✓ Achieved

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Soft-Switching Conditions

- **ZVS (Zero Voltage Switching):** Achieved when the tank circuit is inductive at turn-on, so the switch voltage is zero when the MOSFET is triggered.
- **ZCS (Zero Current Switching):** Achieved when the tank circuit is capacitive at turn-off, so the switch current is zero at the instant of switching.

Key Equations for Analysis

Resonant Frequency : $f_r = \frac{1}{2\pi\sqrt{L_r C_r}} = 5\text{kHz}$

Tank Current (General):

$$\boldsymbol{i_{Lr}(t) = I_{Lr,0}\, cos(w_0 t) + \frac{V_{in} - V_{Cr,0}}{Z_0} sin(w_0 t)}$$

Output Voltage: Vin x Turns Ratio*Voltage Multiplier (here..2)

1. Voltage Gain Equation

For a typical LLC or series resonant converter, the **voltage gain** (M) is defined as:

$$M = \frac{V_{out}}{n\,.V_{in}} = \frac{833}{2 * 100} = 4.165$$

where

- V_{out}= Output voltage
- V_{in} = Input voltage
- n = Transformer turns ratio (primary: secondary Generalized Gain Equation

IV SIMULATION RESULTS

The proposed LLC resonant high voltage DC-DC converter is simulated using MATLAB Simulink.. The design specifications of the simulated model and the prototype are as follows: V_{in}=100V, C_r=470μF, L_r=2μH, n=2,f_r=5kHz and R_o=1000Ω.

Fig.10 depicts the simulation waveforms of the gate signals across M_1, M_4 and M_2, M_3, and I_{Lr}. In the duty cycl is maintained 50% given by pulse generator. Fig.11 consists of MOSFET voltage (Vds) and MOSFET current (Ids). From this we can conclude that ZVS is achieved.

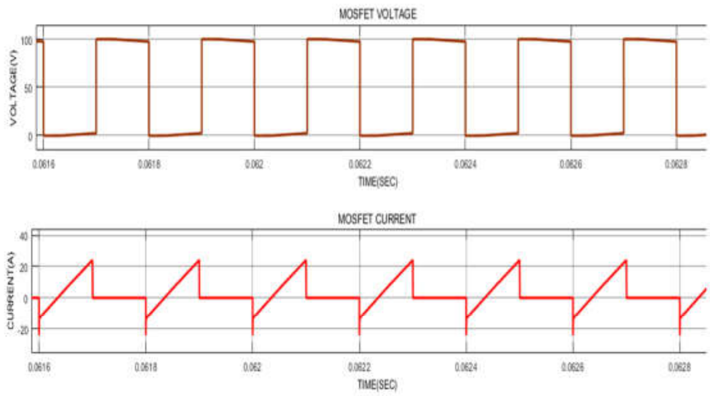

Fig. 8. Input current of MOSFET

In the Fig. 8 one period of the waveform appears to be approximately Ts≈0.01617s−0.01618 the current is zero when the gate is triggered.

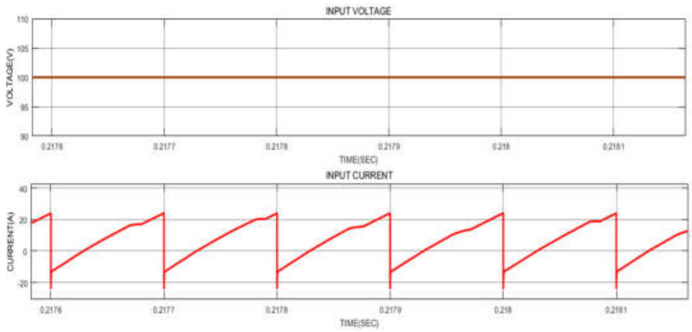

Fig.9. Input Voltage

From Fig. 9, the input voltage Vin(t) is observed to be constant over the given time interval.

Mathematically, we can describe this as:

Vin(t)=VDC =100V

where VDC is a constant DC voltage.

From the graph 2 in above Figure Ipeak+≈20 A Ipeak−≈−20 A

The current also has significant ripple. The peak-to-peak ripple current, ΔIpp, can be estimated as: ΔIpp=Ipeak+−Ipeak−≈20 A−(−20 A) ≈40 A is shown in Fig. 10

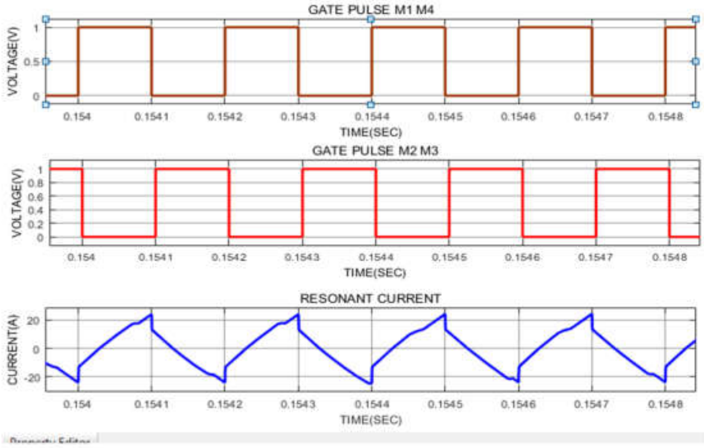

Fig.10. Switching of MOSFET and resonant current

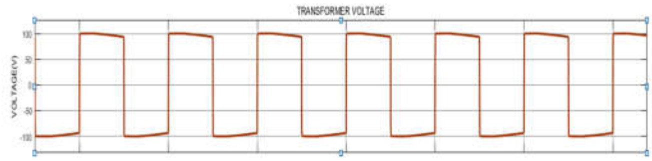

Fig. 11. Voltage across Transformer

These plot Fig. 11 shows the rapidly switching **AC voltages inside the transformer** of the DC-DC converter.

- It is a **square-like wave**, alternating between positive and negative voltages (e.g., +100V to -100V This AC voltage is needed to transfer power across the transformer.

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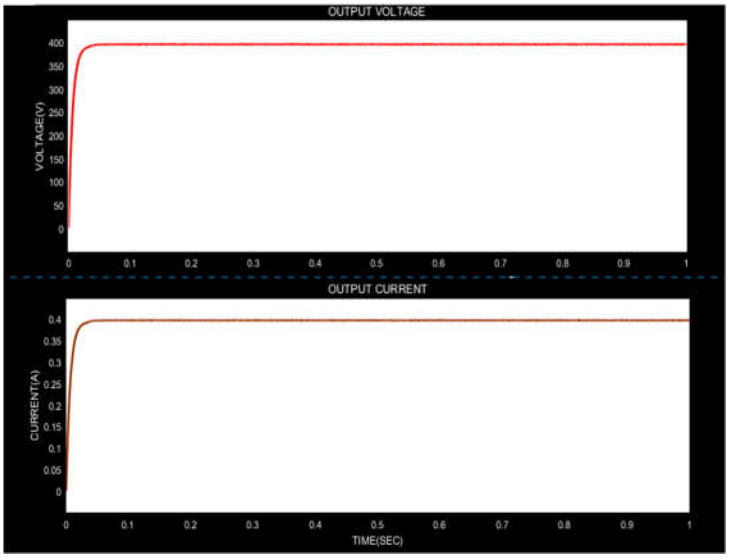

Fig.12. Output Voltage

Fig. 12 depicts the **Output Voltage** of the power converter.

- It starts with a brief jump (overshoot), then quickly settles down to a **stable, constant DC voltage of about 393 Volts**.
- This converter successfully **boosts** the input

voltage (which was 100V) to 393V.

- The flat line indicates a **clean, well-regulated DC power output** with very little ripple, essential for reliable power systems.

V. CONCLUSION

A high voltage LLC resonant DC-DC converter with a multiplier circuit is proposed. The proposed converter consists of a full-bridge inverter, a resonant tank circuit (LLC), a high frequency transformer, and a voltage multiplier (VM) and filter circuit. A high-frequency transformer with a higher turns ratio can be used to increase the input voltage from 100V to 5kV or more. The gain of circuit is reduced stable operating conditions. For perfect operation the switching frequency is to be made equal to the resonant frequency to achieve ZVS at primary and ZCS at secondary diodes. The circuit is simulated and results were plotted.

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