# A High Frequency $EF_2$ Resonant Converter For Constant Voltage Charging Of Electric Vehicle

*Akhila.P.M*
*PG student, Dept. of Electrical and Electronics*
*NSS College of Engineering, Palakkad*
*Email:akhila14894@gmail.com*

*Dr.Devi.V*
*Professor, Dept. of Electrical and Electronics*
*NSS College of Engineering, Palakkad*
*Email:devinsspkd@gmail.com*

**Abstract: The increased use of high frequency resonant converters in fast charging applications and in Switched Mode Power Supplies (SMPS) is found due to their high power density. Among them the single switch resonant converters are mostly preferred because of their lesser complexity. Hybrid Electric Vehicle's (HEV) are rapidly advancing as alternative power trains for green transportation. The vehicles electrification not only involves the traction parts, but also generates new applications for electric power conversion. One of the key blocks inside HEV's is the DC-DC converter. The use of conventional DC-DC converters, at high frequency and resonance will increase the control complexity and losses. With suitable filters, power problems can be managed but will result in huge cost and complexity. To avoid such difficulties, a Class EF2 converter is considered and its performance is observed through MATLAB Simulink software.**

**Keywords: Hybrid Electric Vehicles (HEV), Improved Power Quality Converter (IPQC), Switched Mode Power Supplies (SMPS), Wireless Power Transfer (WPT).**

## I. INTRODUCTION

Achieving sustainable transportation to address future energy requirements is a vital mission of many countries. India is looking forward to improve the Electric Vehicle sector by introducing new National Electric Mobility Plan (NEMP). However, the penetration of EV's demands increased electricity for charging batteries from the utility grids. The other major problems are lack of charging stations, limited range of operation and cost of batteries [1].The commercial success of EV's relies heavily on the presence of high efficiency charging stations to increase the mileage and short charging time. The use of high frequency will improve the overall output power density and thereby reduces the charging time of batteries. The general battery charging method used for EV's is shown in Fig.1. [2].

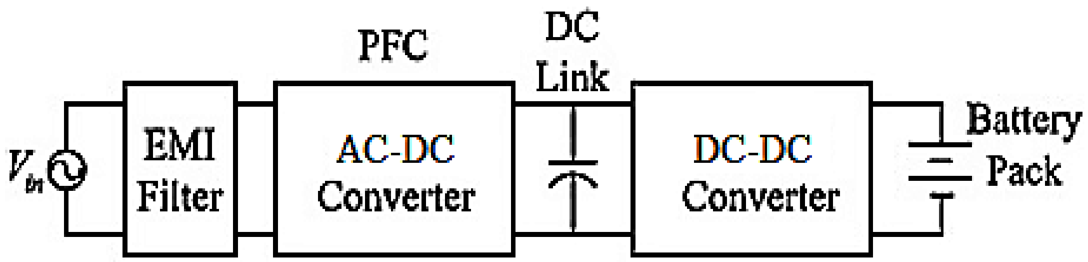


Fig.1. General Battery Charging Method for EV's

### *A. Use of High Frequency DC-DC Converters*

Single switch inverters and rectifiers are the most common choice for Very High Frequency (VHF) or even High Frequency (HF) converters. The Class E inverter and rectifier is the fundamental ZVS single switch topology and the most commonly used arrangement in SMPS and Wireless Power Transfer (WPT) applications. Such inverter configurations are efficient to operate in sensitive loads like biomedical equipment, induction heating devices and HVDC transmission lines as high frequency is obtained. But separate circuit and control strategies are necessary to operate inductive loads as the LC components which are tuned for a specified frequency. Thus an inverter-rectifier arrangement will be suited for fast charging and SMPS applications.

The common single switch resonant converters suitable for high frequency operations are Class E, Class F and the combination of Class E and Class F known as Class EF. The Class E converters will have a single series LC resonance near load and they are mostly used in low power applications. The efficiency of Class E can be improved by adding a resonant network in parallel or in series to load. Resonant network to the load is mainly considered for Class F converters. When this is combined to Class E it will result in a hybrid topology. Hybrid combination of E and F is considered as Class EF while that of E and inverse F is known as Class E/F. In these converters the output power is found to be higher than that of Class E. Here in this paper a high frequency resonant $EF_2$ DC-DC converter is considered for EV battery charging as it exhibits low semiconductor voltage stress, small passive energy storage requirements, fast dynamic response, and good design flexibility compared to common isolated and Improved Power Quality Converter's (IPQC) [3], [4].

### *B. Selectivity of Resonant Converters*

Resonant circuits should respond selectively to signals of a given frequency while discriminating against signals of different frequencies. The Quality Factor (Q) is a measure of selectivity and when Q is high, it is more narrowly selective and when Q is low it is less narrowly selective. Thus at higher values of Q, average power of resonant circuit is higher and when Q is low, average power will be lesser [5].

### *C. Charging System Requirements for Resonant Converters*

There are significant challenges associated with the design of the EV battery chargers, such as high power density, high efficiency, low cost, isolation and voltage adaption while complying with harsh environment automotive. Although the cost of passive elements can usually be decreased by simply increasing the switching frequency, the frequency is mostly limited by the switching losses and the turn ON / turn OFF time. Therefore, soft switching methods and resonant circuits are widely used to increase the switching frequency. Operating from a high input voltage requires a soft transition topology to minimize the switching losses and reduce the high frequency EM1 caused by a high dv/dt. Another challenge of such design is associated with the reverse recovery losses and the noise caused by the high di/dt and dv/dt in the output rectifiers. It is necessary to choose a topology capable of controlling high output current. In addition, galvanic isolation is required to disconnect grid from vehicle electrically. Galvanic isolation can be achieved by means of using a High Frequency (HF) transformer integrated into DC-DC converter [6].

In EV applications, the propulsion battery is required to undergo a continuous sequence of deep discharges followed by recharge to maximum capacity. The prime requirement is therefore a system that provides a rapid and efficient charging, using as simple equipment without damage to the battery. The entire charging process should be arranged in two phases. The first charging phase is at constant current where the battery voltage progressively rises. As soon as the battery voltage reaches the trickle level, the constant voltage charging method should be applied, with the charging current progressively falling down to the maintenance level. The constant voltage charge phase requires a decoupled and very accurate (i.e., close to 1/1000) measure of the battery array voltage, involving an expensive control system [7].

## II. SINGLE SWITCH RESONANT CONVERTERS

*A. Class E Converter:* The Class E inverter shown in Fig.2 gives short circuit self-protection of the switch and good cross regulation which reduces the complexity of controller circuits. For high power applications, this topology can control the output power via duty cycle control or varying the switching frequency by sacrificing efficiency. However, disadvantage is its high peak voltage across the switch, which is 3.5 times the DC voltage at a duty cycle of 0.5, results in less power compared to other inverters with the same voltage and current stresses.

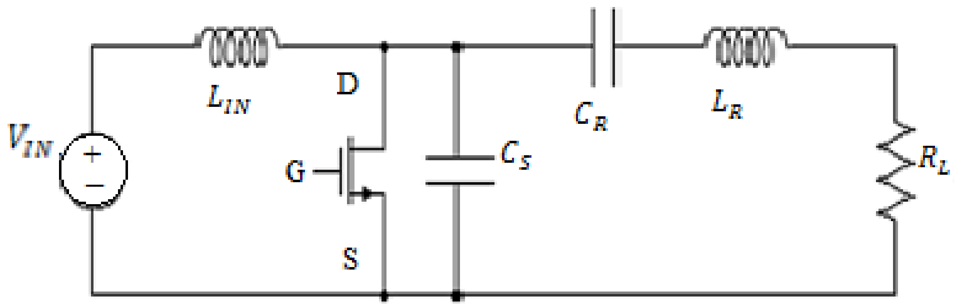


Fig.2. Class E Inverter

A class E inverter with push pull combination is used in induction heating applications. Here the output will be distorted, load is inductive and hence keeping resonance under wide load range is difficult. For low output requirement of a converter, a Class E rectifier is found to be the best choice. The losses of rectifier can be reduced by using asynchronous rectifier eliminating the forward voltage loss. This will however require an additional MOSFET, for the gate drive and control. The Fig.3 shows Class E rectifier [8].

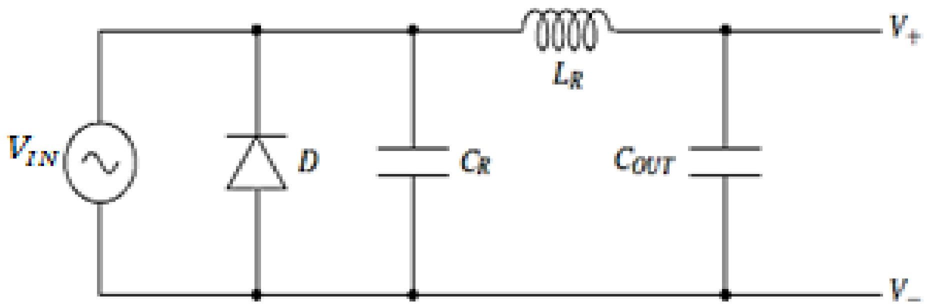


Fig.3. Class E Rectifier

*B. Class F Converter:* The efficiency of Class E can be improved by adding a resonant network in parallel or in series to load. Resonant network to the load is mainly considered for Class F converters. These converters are mainly used in Power Amplifier's (PA's) and Wireless Power Transfer (WPT) systems. Class F boosts both efficiency and output by using harmonic resonators in the output network to shape the switching waveforms. The voltage waveform includes one or more odd harmonics and approximates a square wave, while the current includes even harmonics and approximates a half sine wave. In "inverse class F" the voltage can approximate a half sine wave and the current a full square wave. As the number of harmonic resonators increases, the efficiency of an ideal Power Amplifier (PA) increases from fifty percentage towards unity (e.g., 0.707, 0.8165, 0.8656, and 0.9045 for two, three, four and five harmonics, respectively). The required harmonics arise naturally from non linearities and saturation in the switch. But class F requires a more complex output filter than other PA's [9], [10], [11].

*C. Class $EF_n$ Converter:* In order to inherit the advantages of the Class E inverter and to reduce the number of switches, an inverter topology called the Class $EF_n$ (generally represented as $EF_n$ or $E/F_n$) was considered. The efficiency of Class E can be improved by adding a resonant network in parallel or in series to load. Resonant network to the load is mainly considered for Class F converters. When this is combined to Class E it will result in a hybrid topology. Hybrid combination of E and F is considered as Class EF while that of E and inverse F is known as Class E/F. In these converters the output power is found to be higher than that of Class E. Class $EF_2$ is the hybrid configuration of Class E and $F_2$. In $F_n$ the subscript 'n' can be an even and an odd. In $EF_n$ converters 'n' refers to the ratio of resonant frequency of resonant network to the switching frequency. $EF_n$ is used when 'n' is even. Otherwise if 'n' is odd it is represented as $E/F_n$. In Class $EF_2$ topology an extra resonant circuit is introduced between the drain and source of switch with a zero voltage at second harmonic of switching frequency [12]. The major advantages are reduced peak voltage around three times that of Class E converter, high power output capability compared to other converters and operation with less values of 'Q' with fewer losses and lower power dissipation in switches.

A practical application of Q is that voltage across L or C in a series resonant circuit is Q time's total applied voltage. In a parallel resonant circuit, current through L or C is Q times the total applied current. Formally, Q is the ratio of power stored to power dissipated in the circuit reactance and resistance. A low Q due to a high resistance in series with the inductor produces a low peak on a broad response curve for a parallel resonant circuit. Conversely, a high Q is due to a low resistance in series with the inductor. This produces a higher peak in the narrower response curve. The high Q is achieved by winding the inductor with larger diameter, lower resistance wire [13].

## III. CLASS $EF_2$ RESONANT DC-DC CONVERTER

The common arrangement of a Class $EF_2$ inverter is shown in Fig.4. Here two resonant LC's are provided. There is an input inductor $L_{IN}$ known as input choke to store the energy. $L_{MR}$, $C_{MR}$, $L_R$, $C_R$ are the LC resonant circuits which are used for waveform shaping. The capacitor $C_S$ is acting as a filter across the switch. $V_{IN}$ is the input DC voltage provided to the configuration. The resonant across the switch is to reduce the switching stresses such that a zero voltage can be obtained at second harmonics of switching frequency. The ZVS condition helps to turn the switch ON and OFF as per the resonant condition. Thus low impedance is created at second harmonics. When the switch is OFF the second resonant LC will give a proper wave shaping as per the desired frequency. The major idea is to provide tuned components such that a required voltage level can be obtained. As the circuit is completely tuned, small load variations will affect the output. Thus wide load management is required in these arrangements. Mostly frequency modulation methods are required to control the single switch which is somewhat complicated as the components are in a tuned nature [14]. Thus researches are still going on to overcome these difficulties.

The arrangement of Class $EF_2$ rectifier is shown in Fig.5. Here the LC resonant near to the input inductor should be tuned to the frequency of that of the LC resonant across the switch in inverter configuration, to have proper operation of the converter. $L_2$, $C_2$ are LC resonant elements at Class $EF_2$ rectifier and $C_1$, $C_3$ (reduces the stresses and act as filters) and diode D is used at load side in rectifier. $L_1$ will act as a choke in rectifier arrangement. Thus to reduce the complexity due to overall resonance and commonly used controlled rectifiers are suitable for these converters. Here a full bridge controlled rectifier is used instead of a resonant rectifier. The two different modes of operation of $EF_2$ converter is given in III (A) and III (B) [15].

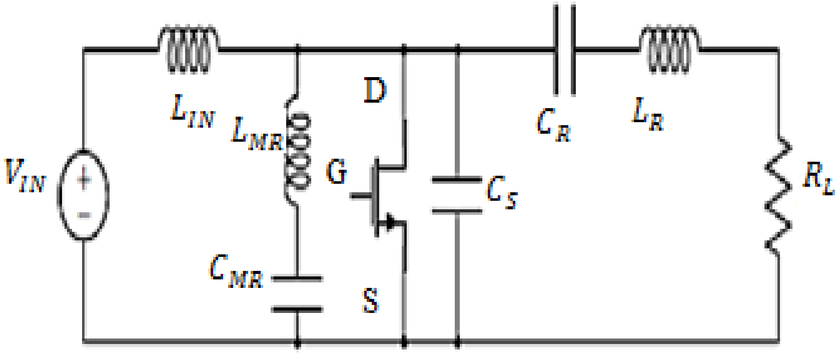


Fig.4. Class $EF_2$ Inverter

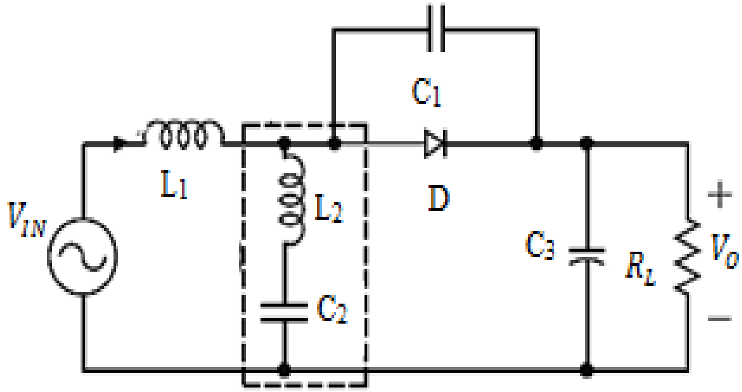


Fig.5. Class $EF_2$ Rectifier

## *A.Mode 1 Operation*

During this mode the switch is turned ON. The switch current consists of source current and load current. To obtain an almost sinusoidal output current, the values of L and C are chosen to have a high quality factor, Q greater than 7. The switch is turned OFF at zero voltage. When the switch is turned OFF, its current is immediately diverted through capacitor $C_S$.

### *B.Mode 2 Operation*

During this mode the switch is turned OFF. The capacitor current becomes the sum of source current and load current. The switch voltage rises from zero to a maximum value and falls to zero again. When the switch voltage falls to zero capacitor current is normally negative. Thus the switch voltage would tend to be negative [15], [16].

## IV. DESIGN CONSIDERATIONS

The design of Class E and Class $EF_2$ is almost similar. An extra resonant $L_{MR}$ and $C_{MR}$ are introduced in Class $EF_2$ when compared to Class E. The design equations are as follows.

The load resistance, $R_L$ can be calculated by,

$$R_L = \frac{8}{\pi^2+4} \times \frac{V_{IN}{}^2}{P_{OUT}} \quad \ldots (1)$$

Here $P_{OUT}$ is the output power of converter, $V_{IN}$ is the DC input voltage given to the converter. The DC resistance $R_{DC}$ is calculated by,

$$R_{DC} = (\pi^2 + 4) \times \frac{R_L}{8} \quad \ldots (2)$$

The DC input current $I_i$ is determined by,

$$I_i = \frac{8}{\pi^2+4} \times \frac{V_{IN}}{R_L} \quad \ldots (3)$$

The maximum switch current $I_{SM}$ is,

$$I_{SM} = \left(\frac{\sqrt{\pi^2+4}}{2} + 1\right) \times I_i \quad \ldots (4)$$

Value of Quality Factor Q is selected based on the Reference [16]. The value of resonant inductor $L_R$ and $C_R$ is determined by,

$$L_R = \frac{Q_L \times R_L}{\omega} \quad \ldots (5)$$

$$C_R = \frac{1}{\omega \times R_L \times (Q_L - \frac{\pi^3 - 4\pi}{16})} \quad \ldots (6)$$

The capacitor across switch $C_S$ is determined by,

$$C_S = \frac{8}{\omega \times R_L \times (\pi^3 - 4\pi)} \quad \ldots (7)$$

The value of input inductor $L_{IN}$ is determined by,

$$L_{IN} = \frac{2\pi^2+8}{4} \times \frac{R_L}{f_s} \quad \ldots. (8)$$

Here $f_s$ is the switching frequency. The value of resonant inductor $L_{MR}$ and $C_{MR}$ is determined by,

$$L_{MR} = \frac{1}{15\pi^2 f_S{}^2 C_S} \quad \ldots (9)$$

$$C_{MR} = \frac{15}{16} \times C_S \quad \ldots (10)$$

Here,

$$\omega = 2\pi f_s \qquad \dots (11)$$

## V. SIMULATION AND RESULTS

A 700W prototype with 1MHz switching frequency is considered for simulation. The simulation is done using the MATLAB Simulink software (version R2016a). A DC voltage of 50V is used as input. Through a coupled inductor the inverted DC is rectified by means of a controlled full bridge rectifier. A small phase shift is provided to the switches in rectifier side to set a high frequency output at the secondary of coupled inductor. The two switches from different legs will operate at a time such that the other two will remain OFF at that condition as inverted pulses are given to those inactive switches. Here the inverter switch is operated with a duty ratio of 0.8 to attain maximum boosted output at high frequency. The $EF_2$ inverter has two resonant LC circuits. A capacitor is provided at the output of the inverter to have a filtering action. Inverter provides an output which is square of the input DC voltage. An output DC voltage around 300V is obtained in simulation without ripples and an output of 700W which clearly shows that the circuit is efficient to deliver high power densities. The simulation parameters are shown in Table.1.

Table.1. Simulation Parameters

| PARAMETER | SPECIFICATION |
|---|---|
| Power Output, $P_{OUT}$ | 700W |
| Switching Frequency, $f_s$ | 1MHz |
| Input Voltage, $V_{IN}$ | 50V |
| Resonant Capacitors, $C_R$, $_{CMR}$ | 493nF, 1µF |
| Duty Ratio, D | 0.8 |
| Resonant Inductors, $L_{MR}$, $L_R$ | 53µH, 53µH |
| Input Inductor, $L_{IN}$ | 53µH |
| Load Resistance, $R_L$ | 100Ω |
| Filter Capacitor, $C_S$, $C_0$ | 5nF, 0.001µF |

The Fig.6 shows the simulation diagram of $EF_2$ converter without filter. The output and input voltage waveforms are shown in Fig.7. The primary and secondary voltage waveforms of the coupled inductor are shown in Fig.8. The simulation is performed for 0.01 seconds as the switching frequency is very high. But it is exhibiting fast steady state during this time. A small clamping is present in these waveforms due to the phase shift provided in rectifier switches and that can be managed with suitable value of capacitor filter. The gate pulses are shown in Fig.9.

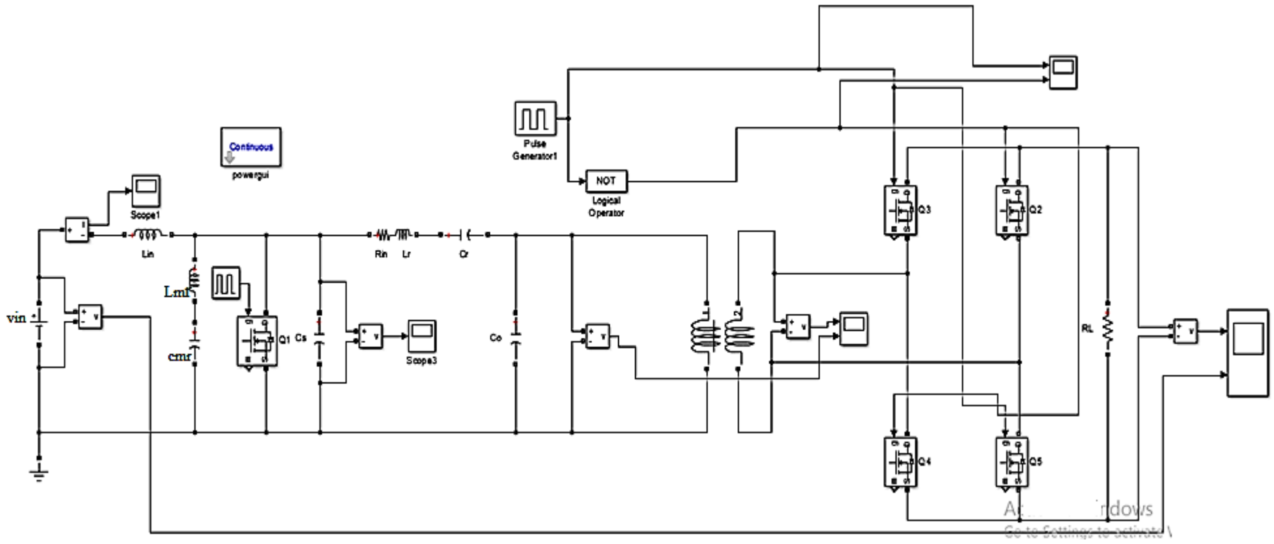

Fig.6.Simulation Diagram of $EF_2$ Converter without Filter

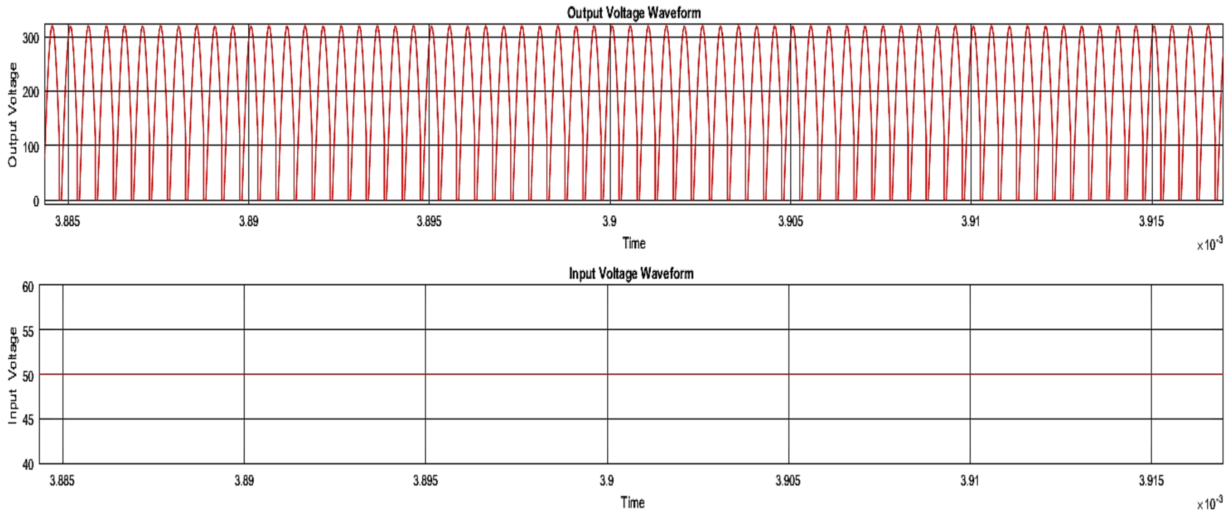


Fig.7.Ouput and Input Voltage Waveforms

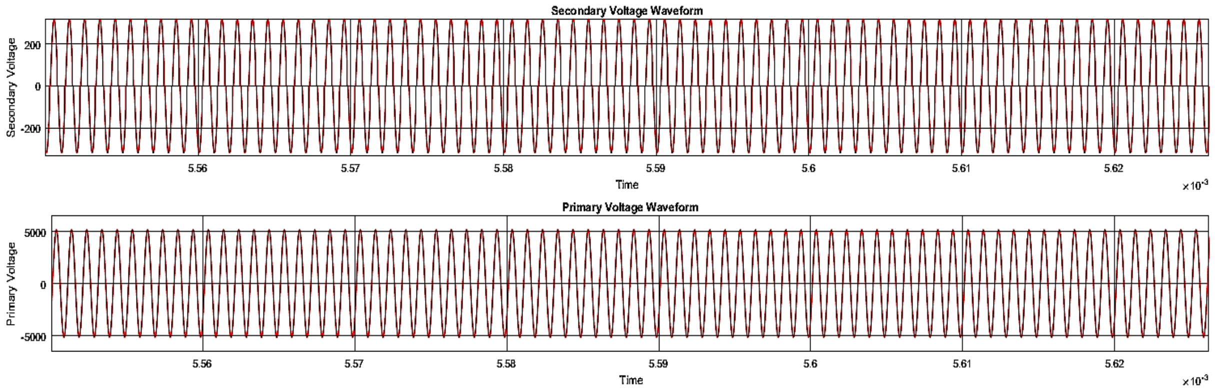


Fig.8. Primary and Secondary Voltage Waveforms

The Fig.10 shows the simulation diagram of $EF_2$ converter with filter and battery. The State of Charging (SOC) of battery is selected as 80 percentage. The battery voltage is normally selected as low when compared to the input given to battery and here it is selected as 100V. Whenever the input voltage to the battery decreases from the desired value, the battery will show discharge mode of operation. Here charging mode of the circuit is considered and the voltage based battery charging waveform is shown in Fig.11.

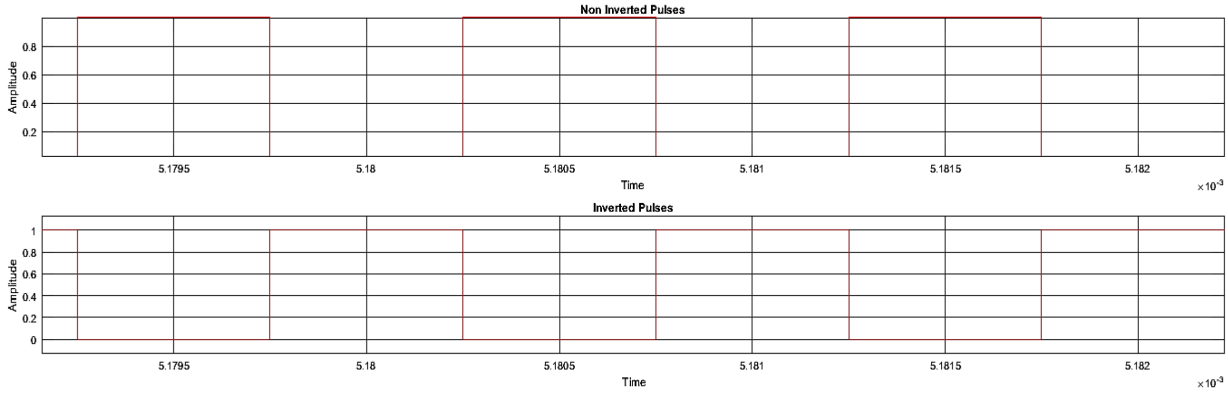


Fig.9.Gate Pulses

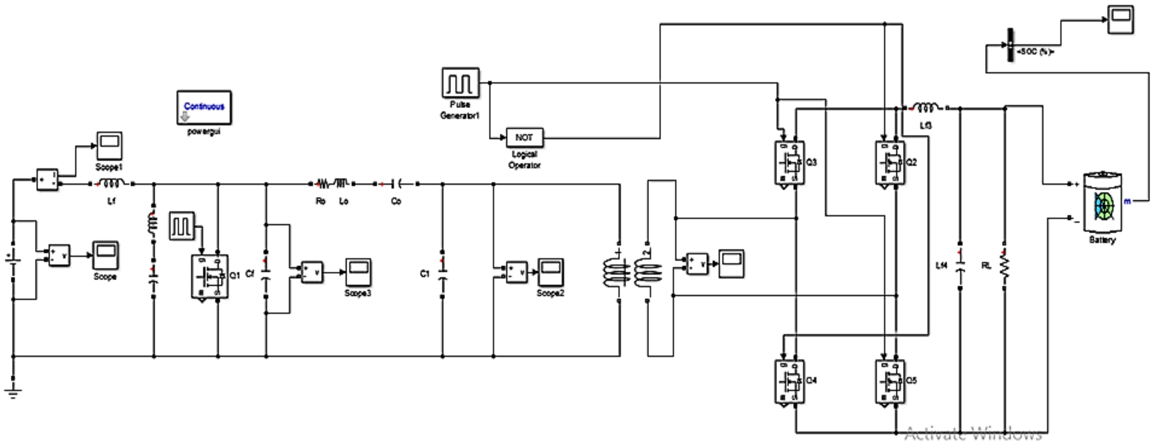


Fig.10. Simulation Diagram of $EF_2$ Converter with Filter and Battery

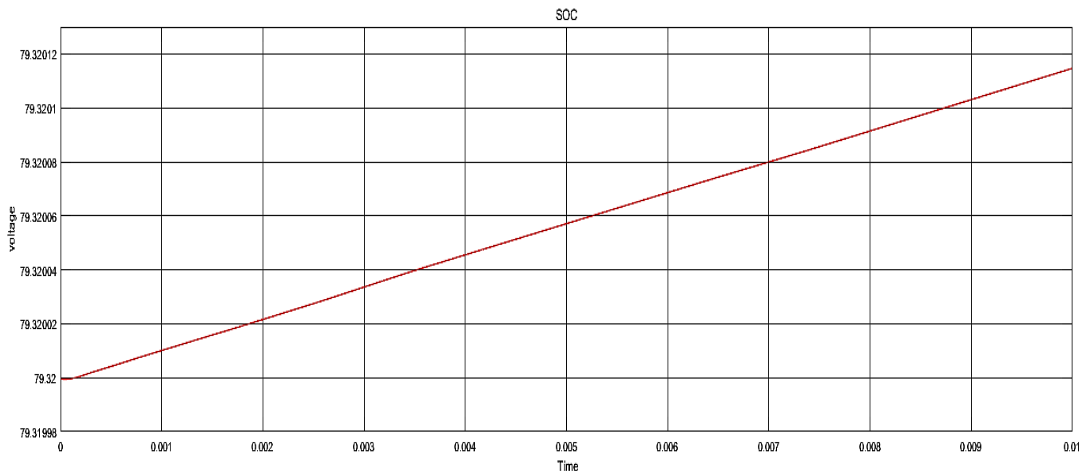


Fig.11. Voltage Based Battery Charging Waveform

A closed loop control of rectifier is shown in Fig.12 and the voltage based battery charging waveform and the gate pulses are shown in Fig.13 and Fig.14. Here the output voltage of rectifier is compared with a constant DC voltage value of 230V to form an error signal. This error signal is modified by a Proportional Integral (PI) controller and the output is given to a relational operator to compare with a triangular carrier. This gives suitable pulses to the rectifier switches to get a regulated output. The inversion of pulses are done through a logical NOT operator.

When the filter is introduced with the rectifier arrangement a constant DC is obtained as in Fig.15 which shows that circuit much capable of avoiding large filters to get steady DC. Also the power output waveform in Fig.16 is achieving steady state much faster showing the better dynamic response of the circuit.

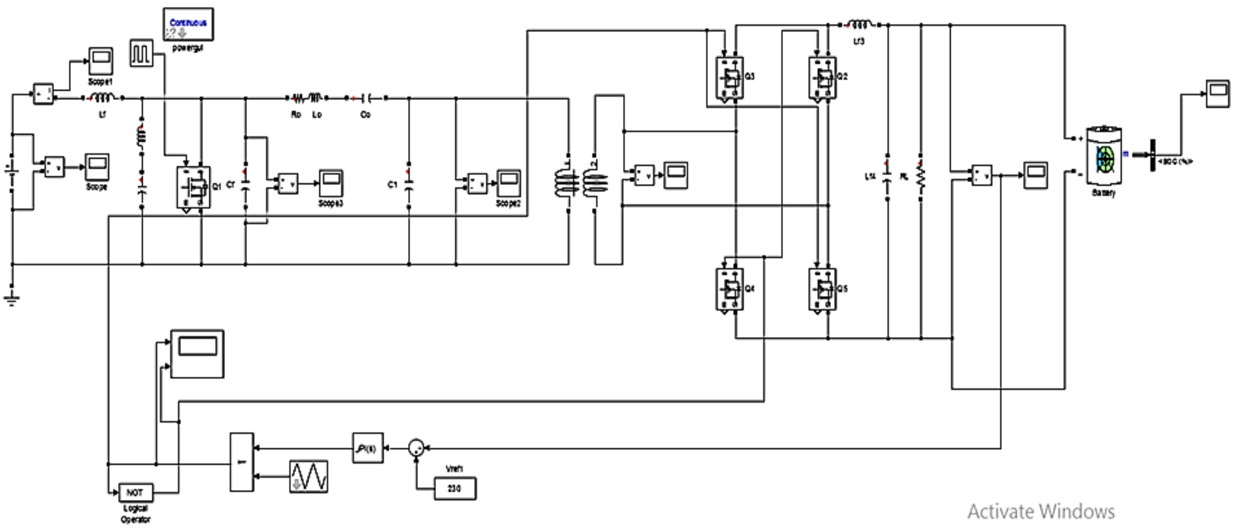


Fig.12.Closed Loop Simulation Diagram

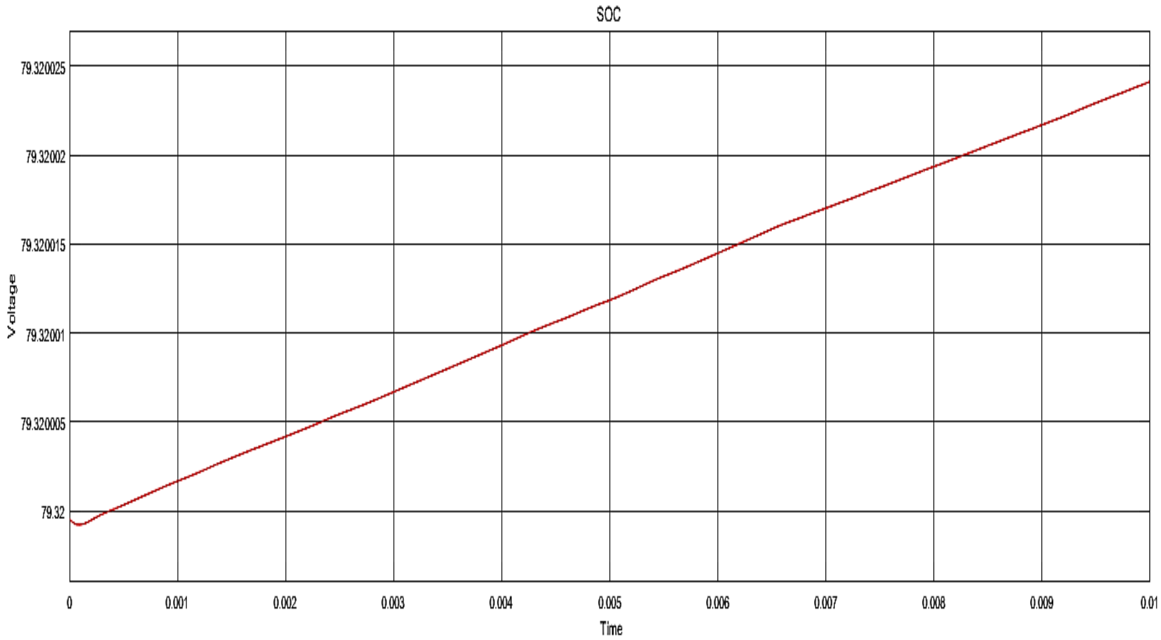


Fig.13. Voltage Based Battery Charging Waveform

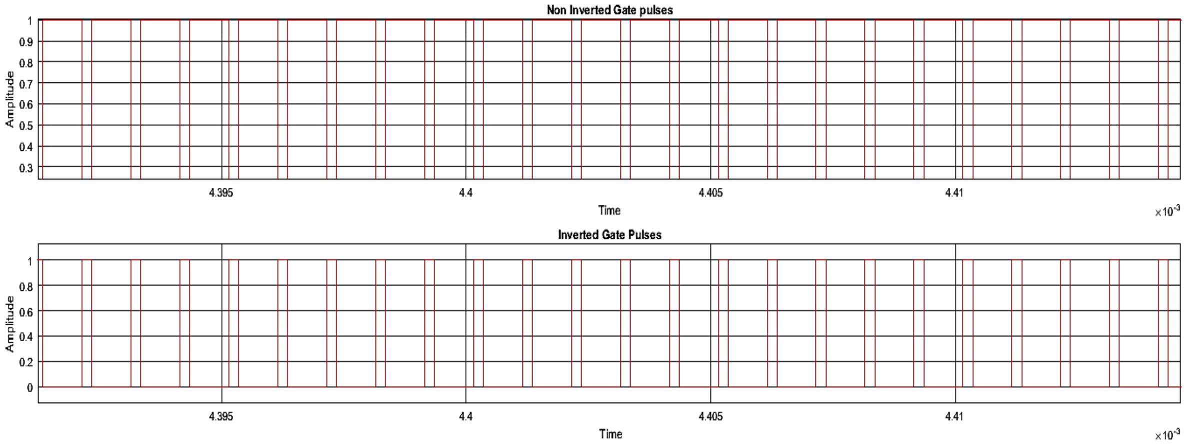


Fig.14.Gate Pulses

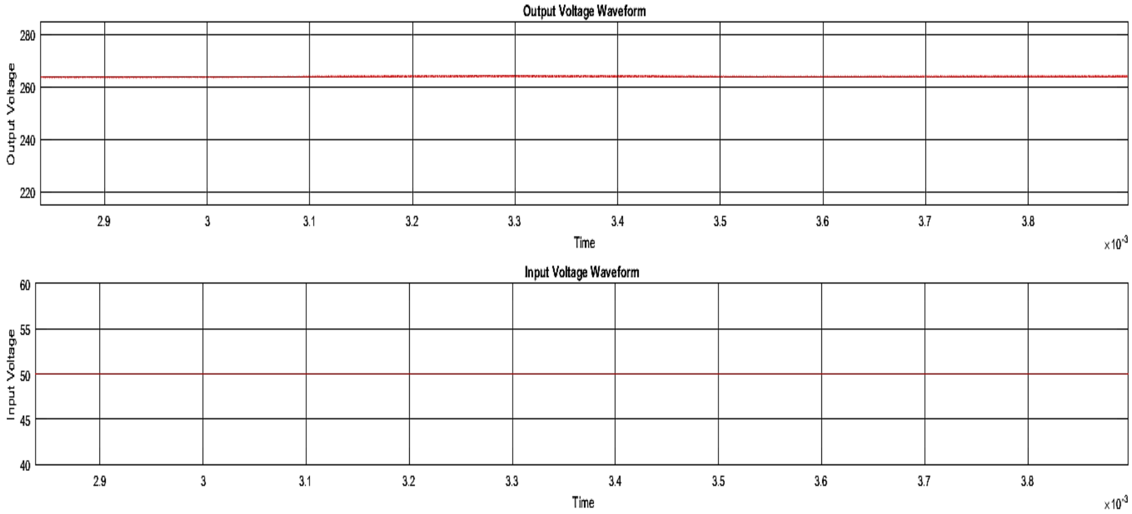


Fig.15.Ouput and Input Voltage waveforms

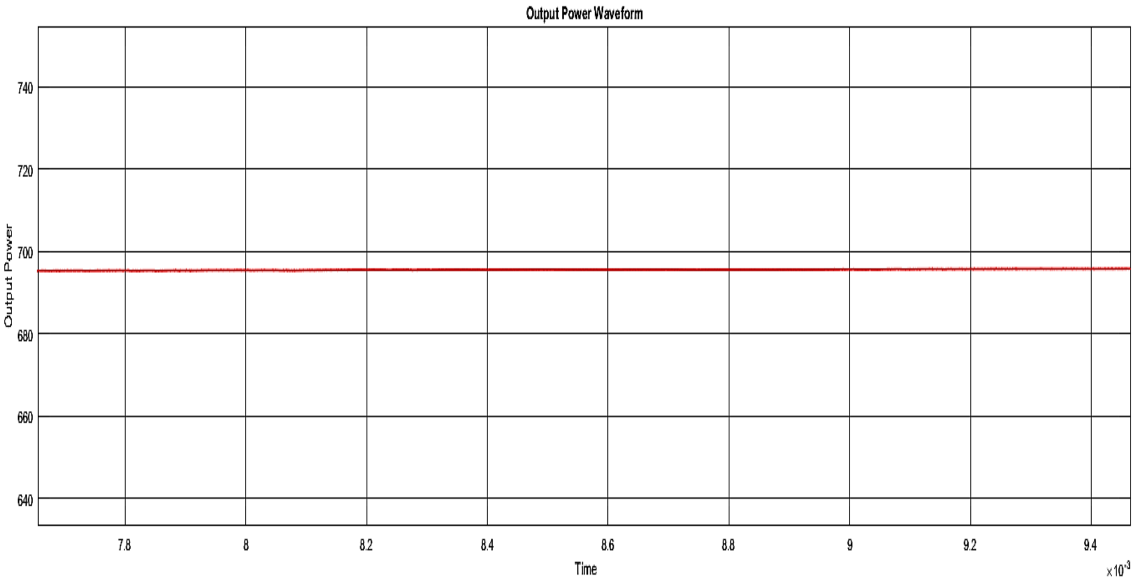


Fig.16.Output Power Waveform

## VI. HARDWARE IMPLEMENTATION

The complete Hardware Arrangement is shown in Figure.17. A 230/12V step-down transformer is considered for supplying power to the driver circuits and to the microcontroller ATmega328. Microcontroller requires 5V which is obtained by diode bridge rectifier followed by the voltage regulator LM7805. A 16MHz crystal oscillator will gives the required clock for the microcontroller. As high frequency operation is considered ATmega328 is preferred. The other major advantage is the 32KB flash memory so that large amount of data can be transferred. It also provides 2KB SRAM and 1KB EEPROM for better data storage and retrieval. The supply for driver TLP250 is obtained by step-down transformer followed by a diode bridge rectifier and a filter capacitor. The supply for the driver is in the range of 10 to 35 volts. It can be operated up to 100 KHz. The microcontroller gives the required pulses to the five switches present in the converter arrangement. The pulses obtained in this manner are boosted by means of the driver TLP250. In this way the switches are turned ON and OFF. The converter can be supplied by means of a common DC source or by means of an adapter of 230 to 12 volts as it is designed for a supply voltage of 12 volts. The IGBT switches are used for the converter as high frequency operation is considered. Here KGT250N120NDH IGBT is used for operation. The switch is capable to withstand a current of 25A across it. The switch is capable to withstand the frequency up to 250 KHz. The inductors are designed and winded on O cores as the values are in low range.

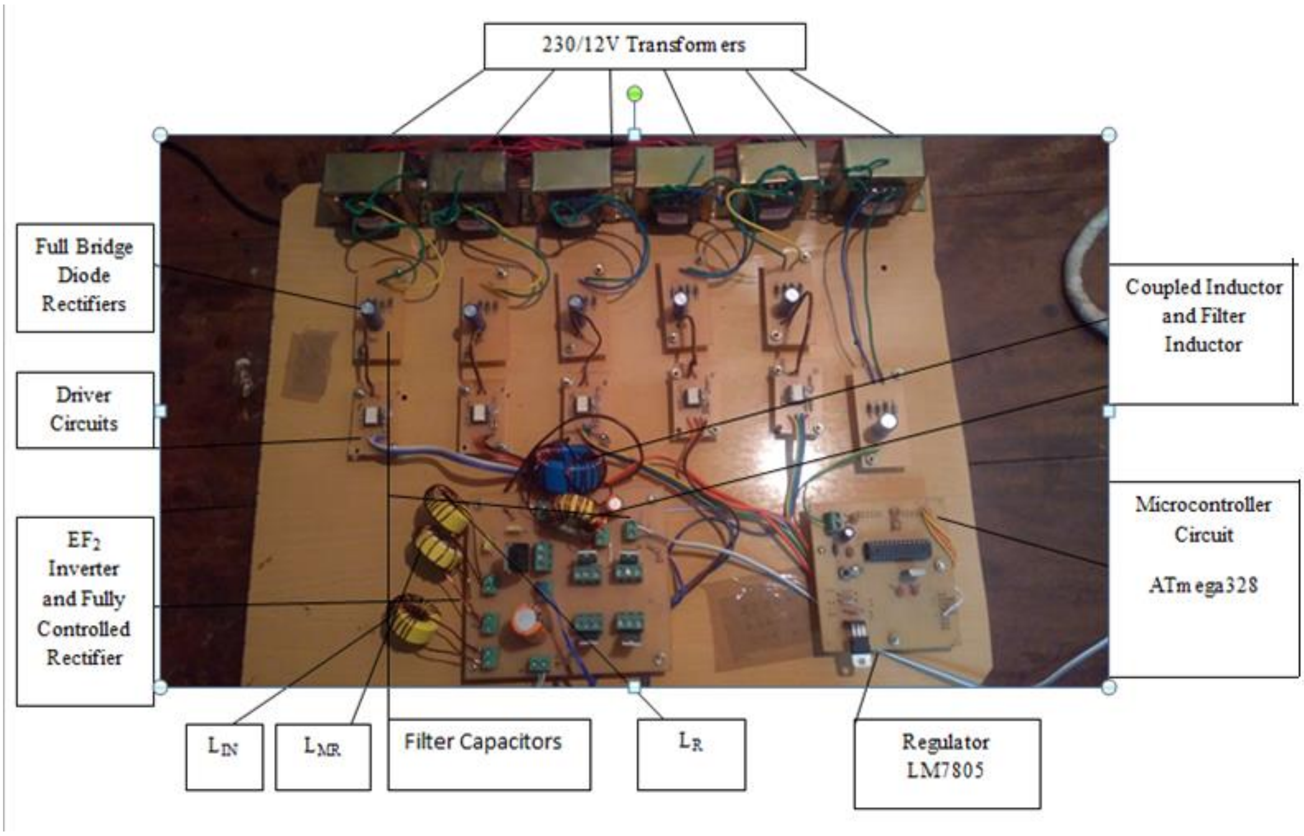


Fig.17. Hardware Setup

The design considerations are discussed in section IV. In hardware the Quality Factor(Q) is assumed as 10. Thus the expected output voltage from inverting section is around 120V. The DC input to the converter is given by means of a 12V battery. The circuit is designed for the power output of 20W. The gate pulses for single switch is shown in Fig.18 and for fully controlled rectifier is shown in Fig.19 and in Fig.20.

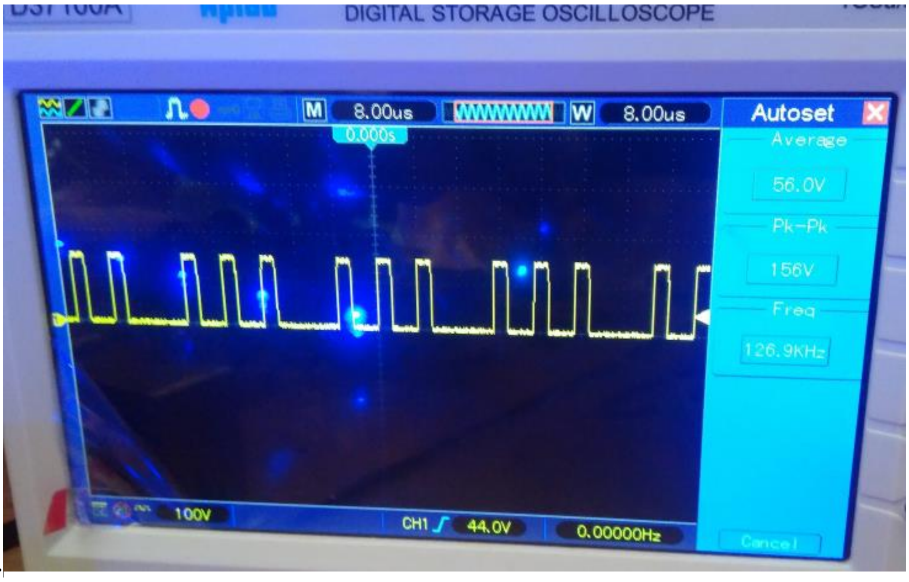


Fig.18. Gate pulses for Single Switch


Fig.19. Gate Pulses Using SPWM

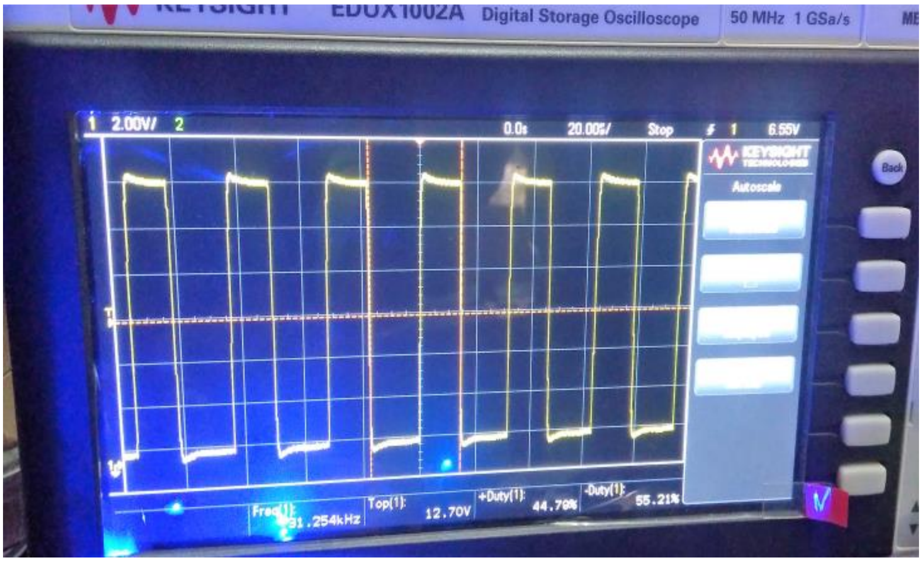


Fig.20. Inverted Gate Pulses Using SPWM

The inverted output from $EF_2$ from the primary side and secondary is shown in Fig.21 and Fig.22. The inverted output is around 80V.

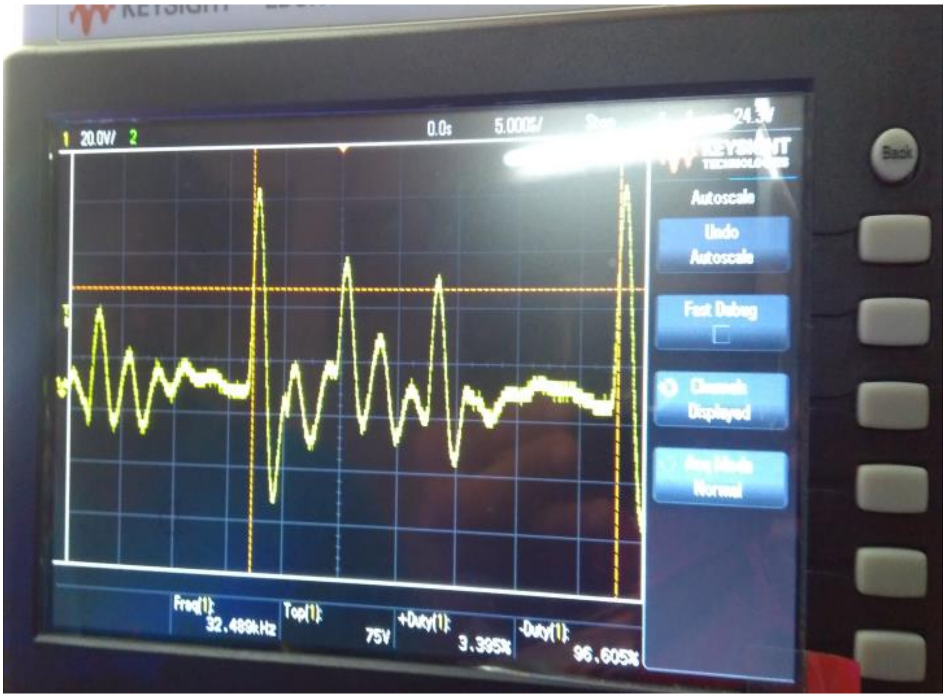


Fig.21. Inverted Output From Primary Side


Fig.22. Inverted Output From Secondary Side

The DC output waveform is shown in Fig.23 and value is shown in Fig.24. From the hardware outputs it is possible to charge a 12V 1.3Ah battery. The current obtained from output is around 0.5A. Thus the time required for charging can be reduced for the battery being considered. When compared with simulation the hardware is providing an output two times that of input voltage. From the simulation considerations it is clear that the circuit is much suitable for very high frequencies upto 30MHz. In such cases the circuit is expected to deliver much voltage and power which shows high possibilities for EV charging.

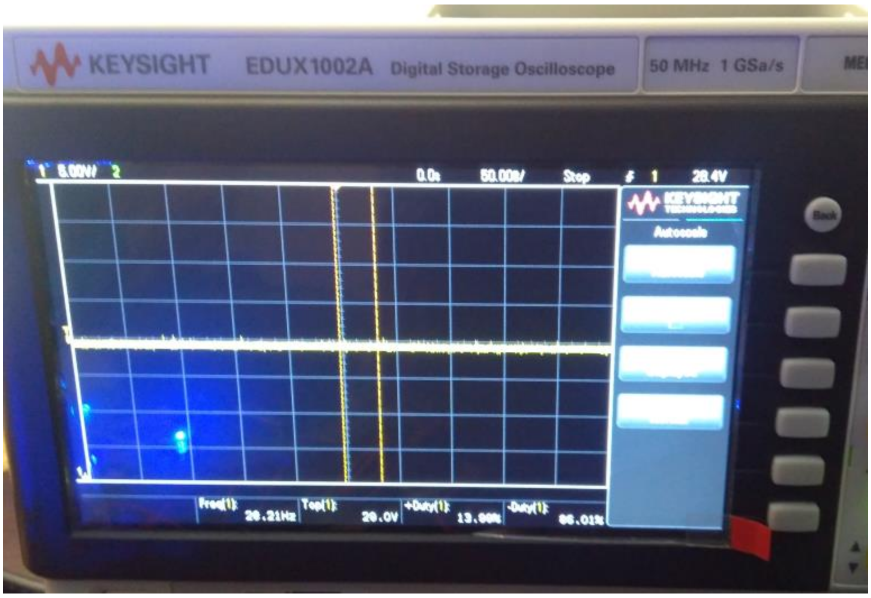


Fig.23. DC Output Waveform


Fig.24. DC Output Measured Through Multimeter

## VII. CONCLUSION

A resonant $EF_2$ converter is proposed for battery charging requirements of EV's as the conventional DC-DC converter configurations are bulky in nature with high soft switching losses. Thus the proposed resonant converter can do a great job compared to existing configurations. Due to the boosting nature large DC voltages and high power densities can be obtained without much distortion. The only difficult part is the maintenance of resonance for which researches are still going on. A 700W prototype with 1MHz switching frequency is considered for simulation. A common DC voltage source of 50V is used as input. An output DC voltage of 300V is obtained in simulation without ripples and also the circuit delivers an output power of 700W which clearly gives an idea that circuit is efficient to deliver high power densities. By increasing the power output capability of the circuit through a suitable design it is very much possible for fast charging of EV. By the usage of HF the primary side is delivering boosted output and thus by using Very High Frequencies (VHF) the rectified output can be improved further. Thus there are wide possibilities in fast charging through this arrangement.

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