

SIMULATION OF POWER ELECTRONIC CONVERTERS FOR EV CHARGING APPLICATIONS

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Abstract

The global depletion of fossil fuels has accelerated the development of renewable energy sources for electricity generation and promoted the adoption of electric vehicles (EVs) over traditional petrol and diesel-based vehicles. One of the main challenges facing EVs is the development of fast and efficient charging systems. This paper proposes an innovative integrated bidirectional converter with a single-stage on-board charger, aimed at reducing the number of switches, as well as minimizing the size and weight of power electronic interfaces. The proposed multifunctional electronic interface ensures reliable and efficient charging for EVs. In most conventional EV architectures, a bidirectional DC/DC converter is placed between the battery and the propulsion motor inverter. This converter boosts the battery voltage and manages power flow efficiently, delivering or absorbing power during vehicle cruising, acceleration, and regenerative braking. However, in traditional designs, the bidirectional DC/DC converter operates solely during propulsion, while a separate AC/DC converter is used for battery charging. The proposed integrated solution addresses these limitations, providing an optimized approach for EV charging and propulsion operations.

Keywords: EV, HEV, Power Charging, electrical vehicle to Grid, etc.

1. INTRODUCTION

Today, the need for new types of energy conversion and storage systems is growing because of the rising human population and the increasing use of energy-powered devices for daily life. As the world's population and economy continue to grow rapidly, fossil fuels are running out quickly, and concerns about environmental damage, like greenhouse gas emissions, are becoming more serious. Also, with modern technology, more electronic devices are replacing manual labor, leading to even

higher energy consumption.

The need for better fuel efficiency and lower greenhouse gas emissions is pushing the automotive industry to make big changes. Car manufacturers are moving towards electrifying vehicles by introducing plug-in hybrid electric vehicles (PHEVs) and fully electric vehicles (EVs), together known as plug-in electric vehicles (PEVs).

In these PEVs, the electrical system usually includes an energy storage unit (like a battery) connected to an electric motor through an inverter. A battery charger is also a necessary part of the system.

In most PEVs, a bidirectional DC/DC converter is used between the battery and the motor inverter. This converter boosts the battery voltage and controls the power flow during cruising, acceleration, and regenerative braking.

However, in the traditional design, the bidirectional converter only works during propulsion, and a separate AC/DC converter is used to charge the battery.

This setup means there are two separate converters for two different operations. A better solution would be to combine the charger with the bidirectional DC/DC converter, making the system smaller, lighter, and cheaper.

The main power electronics that add to the size and weight of electric and plug-in hybrid vehicles are the inverter, the on-board charger, and the bidirectional DC/DC converter.

The goal of this paper is to design and test a smart charging system that can prioritize some EVs to charge faster than others. Businesses could use this system to offer different charging options and pricing, making EVs more affordable and appealing.

The paper considers a situation like an office parking lot where cars are charged using solar photovoltaic (PV) panels for shade. It introduces a time-multiplexing method, which charges vehicles using solar energy based on their priority.

Simulations and experiments show that this method can successfully deliver different amounts of energy to EVs based on their priority levels. Further research can focus on reducing the total charging time and understanding how frequent switching might affect battery life.

2. PROBLEM IDENTIFICATION AND OBJECTIVES

The overall electric powertrain with a single integrated power electronic converter is illustrated in Fig. 1. In this structure, the charger and the bidirectional dc/dc converter share the same power stage as charging and propelling do not happen at the same time. As a result, overall cost, weight, and volume of the power electronic converter can be reduced effectively through reducing the number of switches, sensors, and large volume energy storage elements such as inductors.

In this regard, this paper proposes a new integrated single-stage charger topology for PEVs, which can also be used in retrofit conversion of an HEV to a PHEV. The proposed converter uses minimum circuit components offering a further cost-effective solution in comparison to the other integrated charger topologies presented in the literature review. With the boost charging capability, it enables operating with wide single-phase charging voltage ranges including 120/220/240 VAC, considering the battery voltage is between 300–400 V, which is the case in Chevy Volt. In addition, it is capable of stepping up and stepping down the voltage in both power flow directions during cruising and acceleration, as well as regenerative braking.

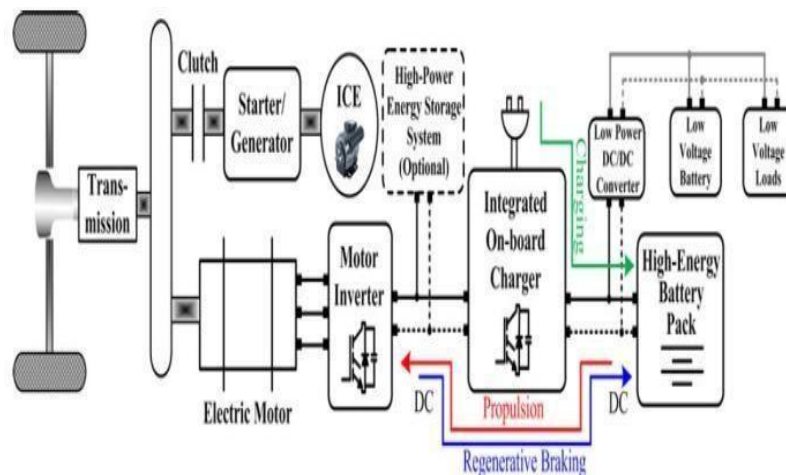


Fig. 1. System level structure of a parallel powertrain PHEV with on-board integrated battery charger

This paper is organized as follows: -

- The advantages and motivation of using an integrated charger and a bidirectional dc/dc converter in the powertrain.

- The proposed integrated topology is introduced and operation modes are explained in detail.
- The proposed converter is compared with other possible basic single-stage charger topologies.
- In addition, detailed analyses on size reduction, loss, and reliability are presented in this section.
- The overall control scheme developed for controlling each essential operation mode is explained in detail.

3. OVERVIEW OF HYBRID ELECTRICAL VEHICLE

A hybrid electric vehicle (HEV) uses both an internal combustion (IC) engine and an electric motor in the powertrain, and also uses a bank of batteries to recapture and store energy from braking. This combination of an electric motor and an IC engine is more efficient from a system viewpoint than a conventional powertrain. There are many different configurations of hybrid electric systems, including series, parallel, and power-split platforms. All PHEVs in this study have a parallel hybrid configuration with a pre- transmission motor location and a continuously variable transmission (CVT). This configuration is shown in Figure 2. The addition of HEV technology to a vehicle design improves efficiency primarily by four ways. First, the addition of the electric system allows the IC engine to operate in a more efficient range a greater amount of time. Typically, IC engines are more efficient at a higher load near wide open throttle. In a conventional vehicle, power requirements at cruising and idling are so low that the engine is forced to run at a lower than optimum loading. However, with a hybrid configuration, the IC engine can run at the most efficient load most of the time, using the excess power to charge the batteries. If the batteries are charged, the electric motor can provide the small amount of power required to propel the vehicle while the engine remains off.

Second, having the power of an electric motor at hand, it makes it possible to downsize the engine. Electric motors have higher torque at low rpm range while I.C engines typically have high torque at high rpm range. This makes using an electric motor combined with an engine during acceleration, a time when the highest torque is needed, more efficient that using a larger equivalent torque I.C engine. Also, having a smaller engine reduces the engine braking load, leaving more energy available to be recovered by regenerative braking. Thirdly, having an electric motor allows the I.C

engine to completely shutoff instead of idling. The electric motor can simultaneously start the car moving and start the engine. Not having the engine idling while sitting at a traffic light significantly increases fuel economy in city driving.

Figure 2. PHEV Parallel Pre-Transmission Configuration with CVT

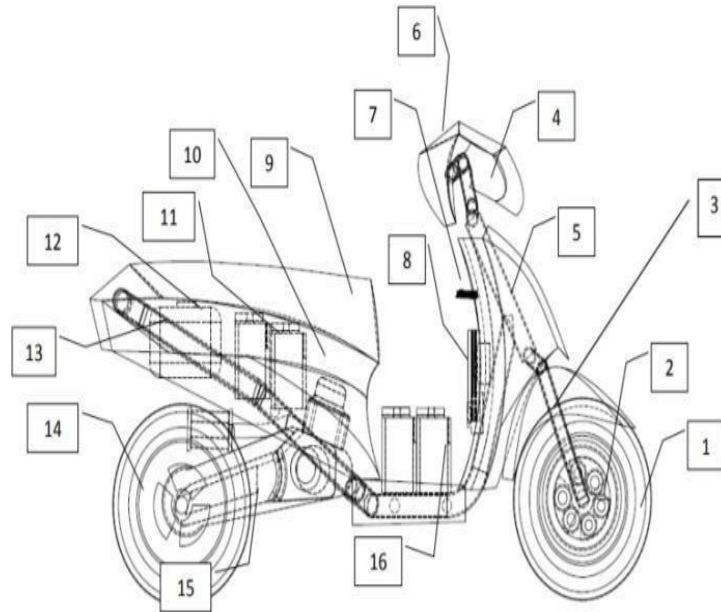


Fig 3. Wire Frame Model Side View

Battery Pack: - The battery pack is the main electrical energy storage device. It is typically made up of a number of modules, connected in series with an open circuit voltage in the range of 100 to 300 volts, with the best designs at the higher end of this range. Each module is made of a number of cells. Battery packs can be come in many different chemistries, but the most common are Nickel Metal Hydride (NiMH), Lead Acid (Pb Acid), and Lithium Ion (Li Ion).

These are the chemistries considered in this study. Each chemical battery type has its own power, energy, and voltage characteristics. The battery pack’s energy capacity is given in amp-hours and its state of charge (SOC) is defined as:

$$SOC = \frac{(C_{max} - C_{used})}{C_{max}}$$

Where C_{max} is the nominal rated C/3 capacity of the pack in A- h and C_{used} is the capacity of the

pack in A-h that has been used since the pack was fully charged. $C/3$ is the capacity rating where the entire charge of the pack is discharged in 3 hours. The safe operating SOC range varies with different battery chemistries but is forced to stay over the constant range of 0.2 to 1 for this study. For most battery chemistries, the battery pack starts to be damaged at a SOC less than 0.2.

Electric Motor: - The electric motor, often referred to as simply the motor, converts electrical energy from the battery pack to mechanical power into the CVT. The electric motor can also be used in reverse as a generator, converting mechanical energy from braking into electrical energy to be used to charge the battery pack. There are two main types of electric motors used in HEVs. The first is permanent magnet motors, using a permanent magnet to create the magnetic field needed to produce power. The second is an induction motor, which uses current to create the magnetic field. This study investigates only permanent magnet motors, the more common of the two in HEV applications.

Power Electronics: - Since the battery pack is basically a constant voltage device, a motor controller is needed to vary the current so that the motor produces the necessary torque. The power electronics are typically designed to the specific characteristics of the electric motor and are typically comprised of a microprocessor, power switching semiconductors, and a thermal management system.

4. PROPOSED TOPOLOGY AND OPERATION MODES

The proposed integrated interface, shown in Fig.4, is essentially non-isolated. However, it can be isolated from the grid using an LF transformer placed either on board or off board, if needed.

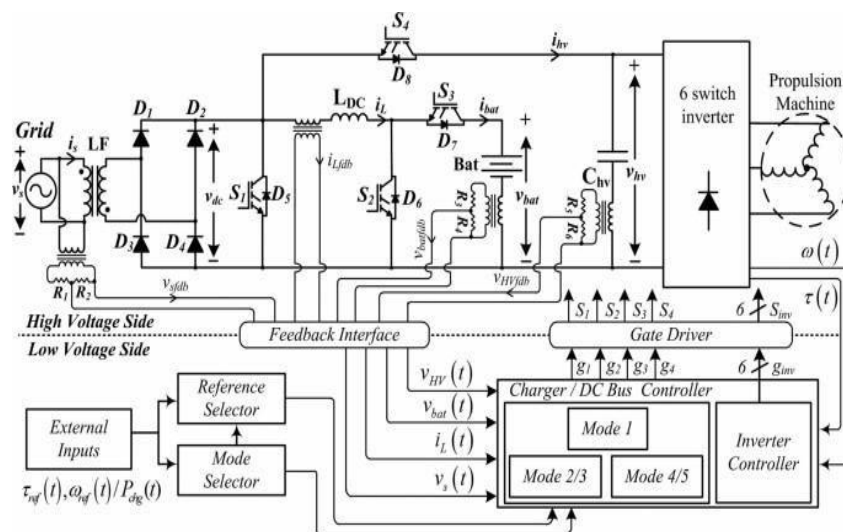


Fig. 4. Proposed integrated topology

TABLE I- OPERATION MODES AND SWITCHING SEQUENCE OF THE PROPOSED CONVERTER

Operation Mode	Energy Flow	Mode #	S ₁	S ₂	S ₃	S ₄	D ₅	D ₆	D ₇	D ₈
Propulsion	$V_{bat} \rightarrow V_{dc}$	BOOST	1	PWM	OFF	ON	OFF	.	.	PWM'
	$V_{bat} \rightarrow V_{dc}$	BUCK	2	OFF	OFF	PWM	OFF	.	PWM'	ON
Regenerative Braking	$V_{dc} \rightarrow V_{bat}$	BOOST	3	OFF	PWM	OFF	ON	.	.	PWM'
	$V_{dc} \rightarrow V_{bat}$	BUCK	4	OFF	OFF	OFF	PWM	PWM'	ON	.
Charging	$V_{grid} \rightarrow V_{bat}$	BOOST	5	OFF	PWM	OFF	OFF	.	.	PWM'

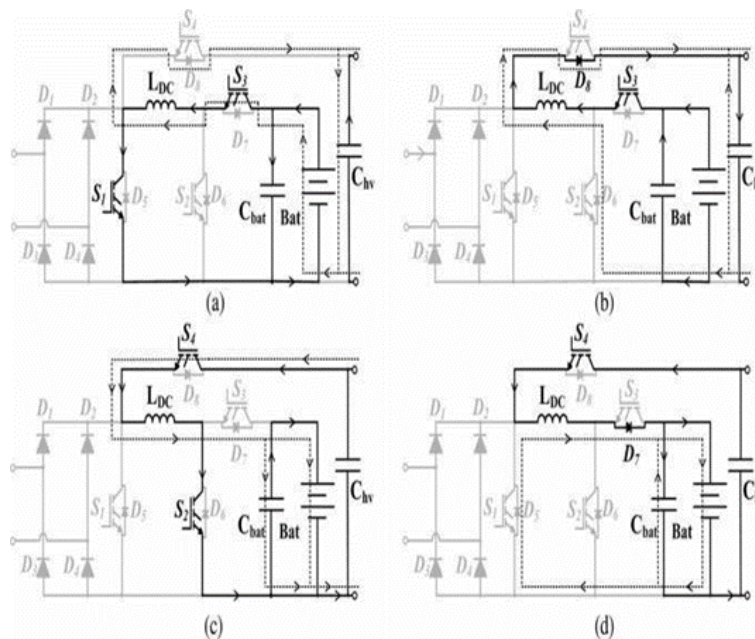


Fig. 5 Operation modes of the converter: (a) boost operation during propulsion, (b) buck operation during propulsion, (c) boost operation during regenerative braking, (d) buck operation during regenerative braking

Basically, the circuit consists of four active switches with body diodes, one inductor and one diode bridge. In charging mode, it operates as a power factor correction (PFC) boost rectifier. Considering that the battery voltage varies between

300 and 400V, the charger can operate universally from single-phase 120/220/240 VAC.

Moreover, the propulsion machine controller can be used to control the charging stage. With the feedback acquired by the voltage sensor placed on the grid side of the passive rectifier, charger controller can also be integrated with the motor controller. The proposed integrated topology has basically three modes of operation namely charging, propulsion, and regenerative braking. During propulsion and regenerative braking operations, both stepping-up and stepping-down capabilities are possible, allowing more flexible control, capability of efficiently capturing regenerative braking energy, as well as flexibility of choosing wide ranges for battery nominal voltage. The states of the switches in each mode are summarized in Table I, where PWM' represents the complementary signal of PWM.

A. Mode 1: Boost Mode during Propulsion

In this mode, integrated converter will boost the battery voltage to the dc bus voltage. The conduction paths according to the state of the boost switch $S1$ are shown in Fig. 5(a). In this operation, $S1$ is used as the main boost switch and $S3$ is turned ON. When $S1$ is turned ON, the inductor stores energy and meanwhile capacitor supplies energy to motor through an inverter. When $S1$ is turned OFF, inductor transfers the stored energy to motor by generating a voltage high enough to force $D8$ to conduct and charges the high voltage bus capacitor Chv .

B. Mode 2: Buck Mode during Propulsion

In buck mode [see Fig. 5(b)], only $S3$ is pulse width modulated and the other switches are always in OFF state. When $S3$ is turned ON, the input voltage source supplies energy to the inductor and to the load whereas, when $S3$ is turned OFF, $D6$ is forward biased and energy is transferred to the load. During propulsion, the energy flow is from battery to inverter in both buck and boost modes.

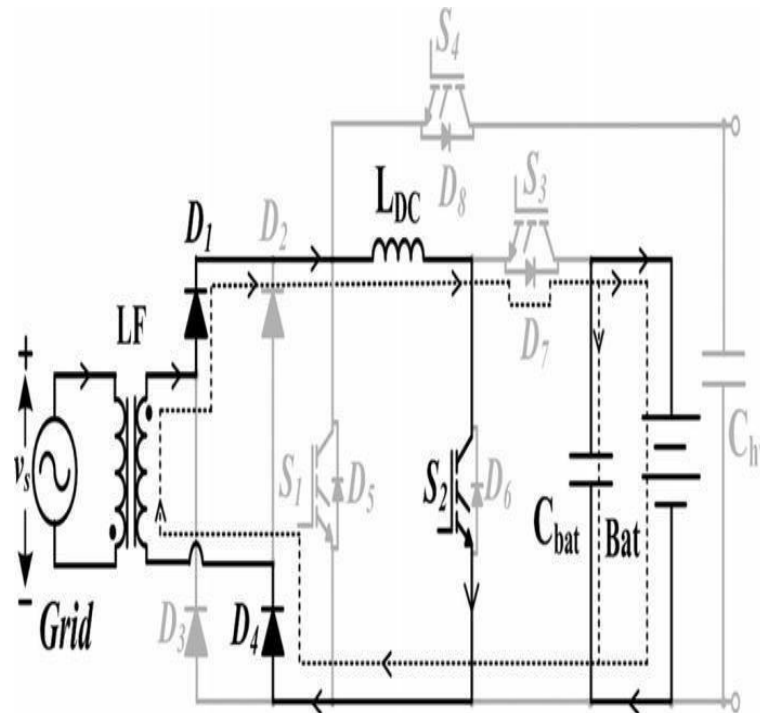


Fig. 6. Current flow during charging

C. Mode 3: Boost Mode during Regenerative Braking Boosting capability during regenerative braking operation provides additional advantage, through capability of capturing the power during low speeds. In fact, in urban traffic, where vehicles are driven in low speeds, the generated voltage across the terminals of the propulsion machine is lower and if the interface converter does not have boosting capability during regenerative braking, this energy will be lost. With boosting capability in reverse direction (from machine to battery), this energy can be recovered. The buck and boost operating modes during regenerative braking are similar to the ones during propulsion but in reverse direction. The conduction intervals are shown in Fig. 5(c). In this mode, S_4 is always ON, and S_2 is pulse width modulated and the rest of switches are in OFF state.

D. Mode 4: Buck Mode during Regenerative Braking

The buck operation is an essential mode as the highest braking energy emerges at high speeds inducing high voltage across the propulsion machine terminals. The operation of the circuit in this mode is shown in Fig. 5(d). The high voltage at the output of the inverter is stepped down by switching S_4 . In the conduction period of S_4 , inductor stores energy with a terminal voltage of $V_i - V_o$ and energy is transferred from high voltage dc bus to battery through D_7 . During freewheeling

operation, inductor transfers its energy to battery, where capacitor discharges over the battery as well.

E. Mode 5: Charging Operation

The integrated on-board charger operates as an ac/dc boost rectifier with PFC capability. The operation of the circuit in charging mode is shown in Fig. 6. When S_2 is ON, the inductor is short circuited and stores a certain amount of energy based on applied input voltage. Meanwhile, the capacitor connected in parallel to battery supplies energy to the load. Only diodes D_1 and D_4 are conducting in this mode. Diodes D_2 and D_3 will conduct depending on the grid voltage polarity. During the time when S_2 is turned OFF, D_7 is forced to conduct and the inductor current decreases under the influence of $V_{grid} - V_{bat}$. At the same time, the capacitor in parallel with battery is charged as well.

5. SIMULATION AND RESULT DISCUSSION

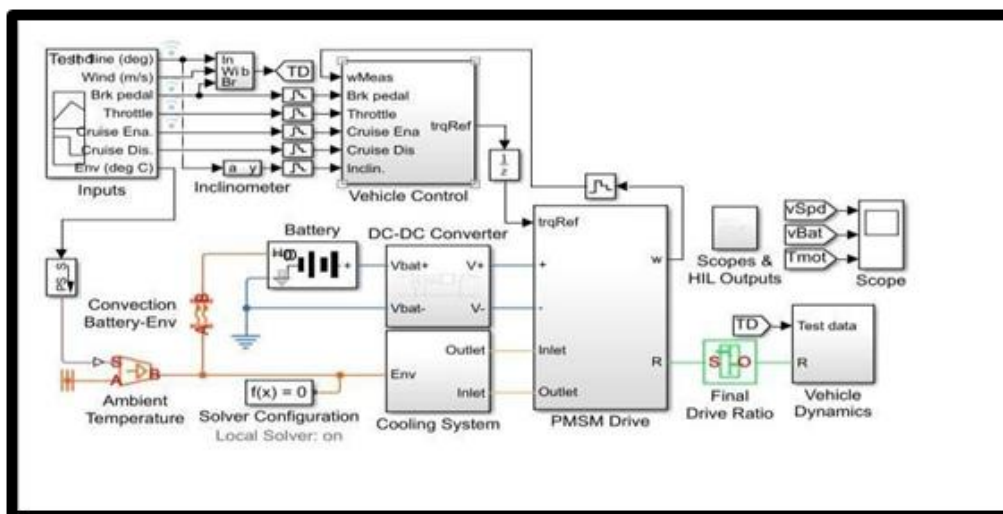


Fig.7 Electrical Vehicle Charging System

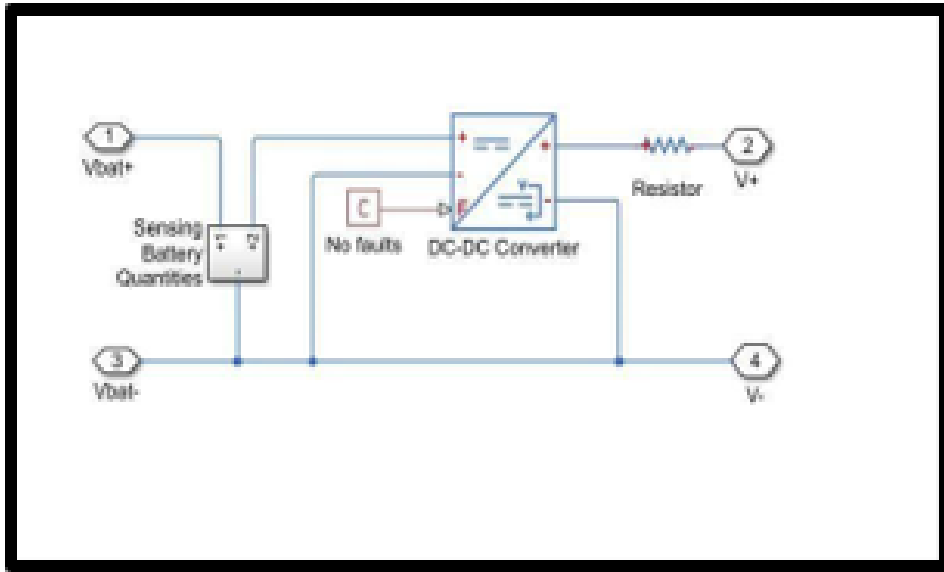


Fig 8- DC-DC Converter for Proposed System

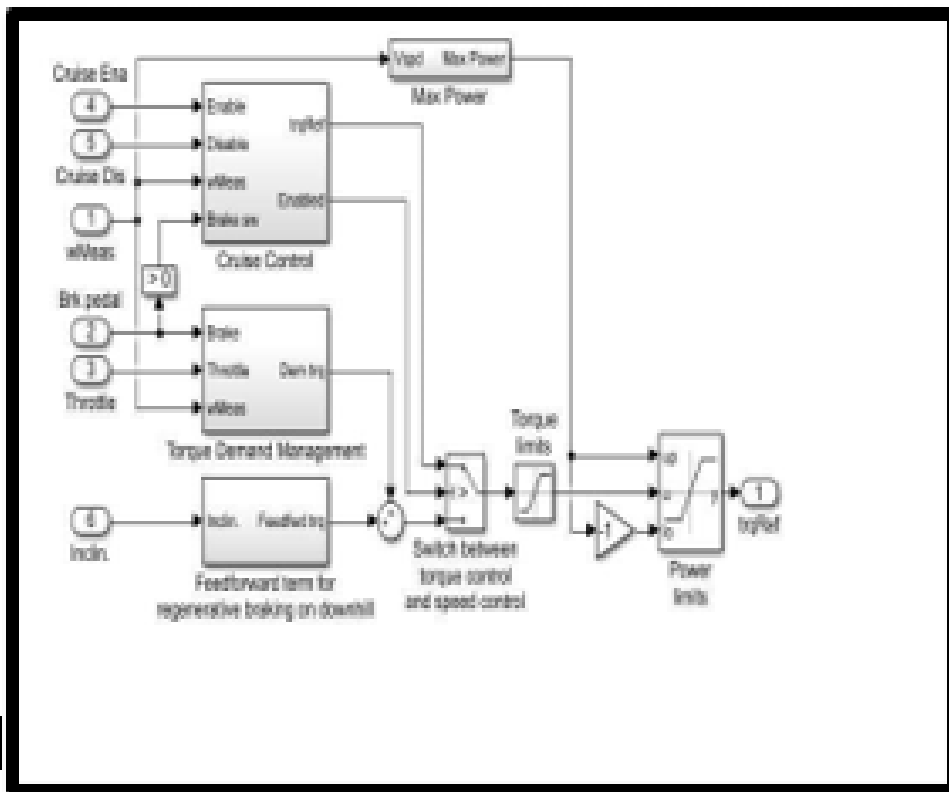


Fig.9- Vehicle Control Subsystem

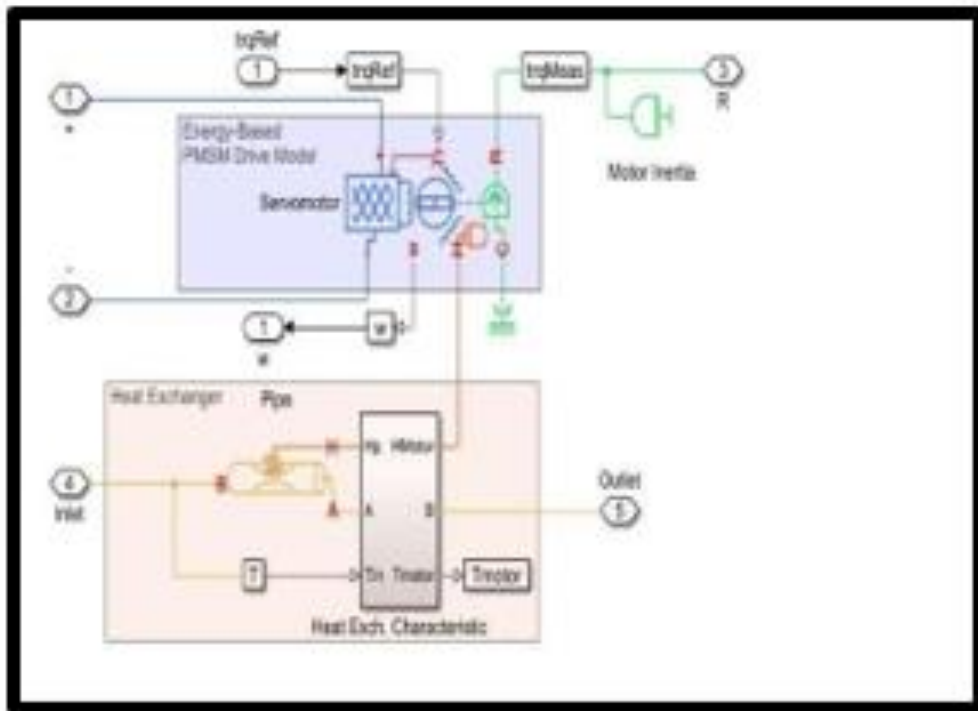


Fig.10-PMSM Drive Subsystem

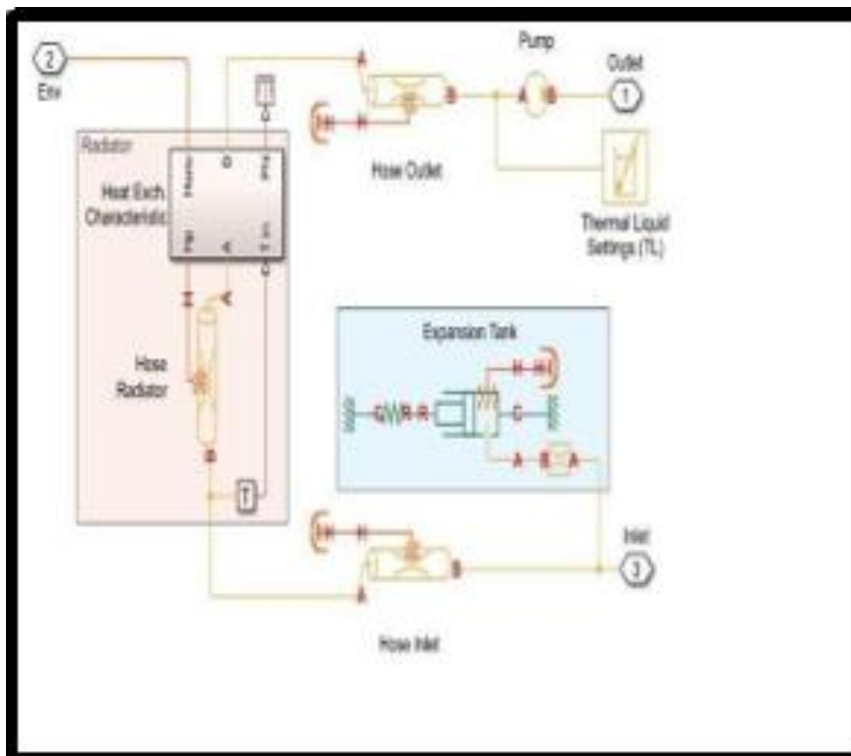


Fig.11- Colling Subsystem

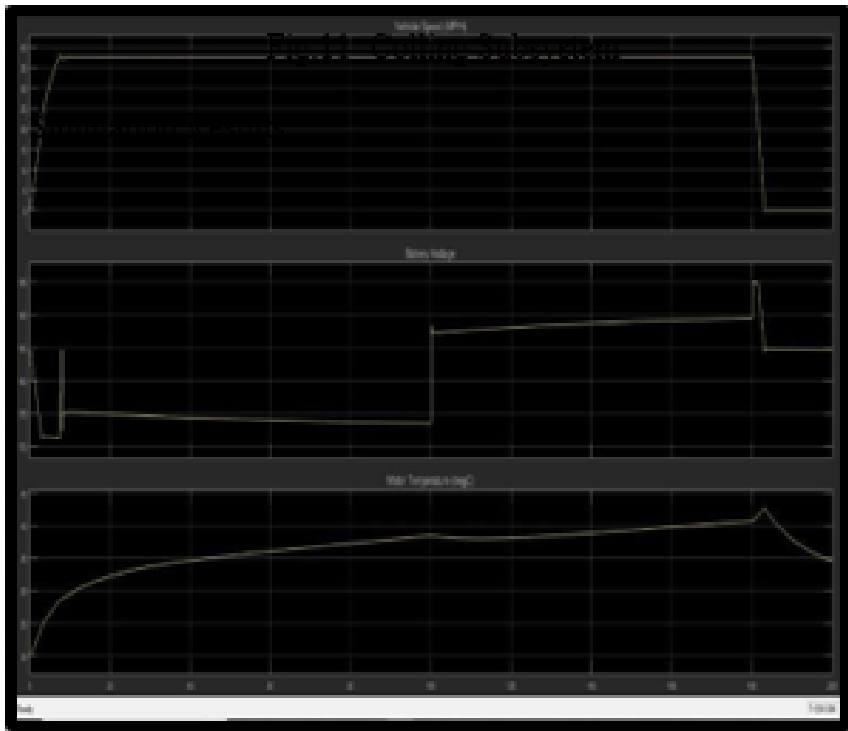


Fig.12 Electrical Vehicle output system

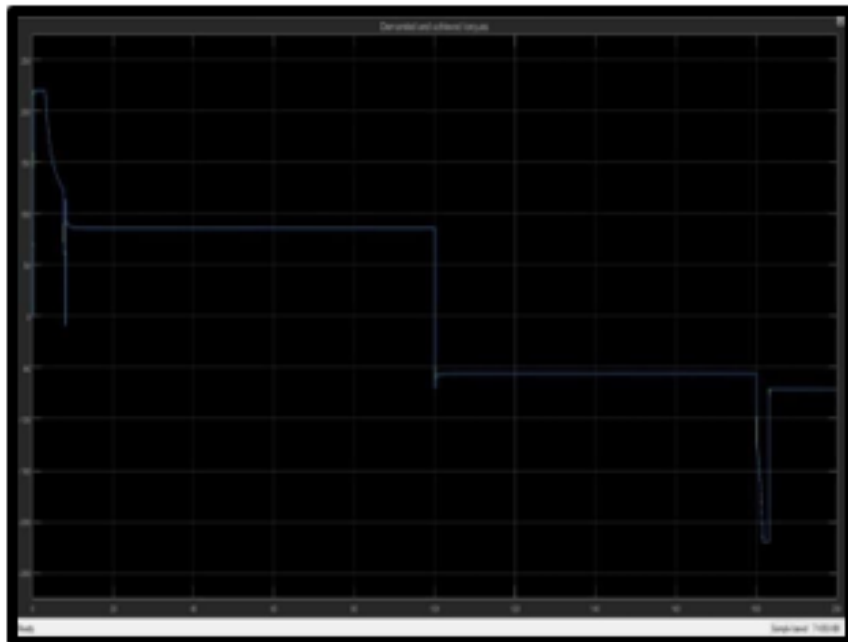


Fig.13 Torque Variation after controlling

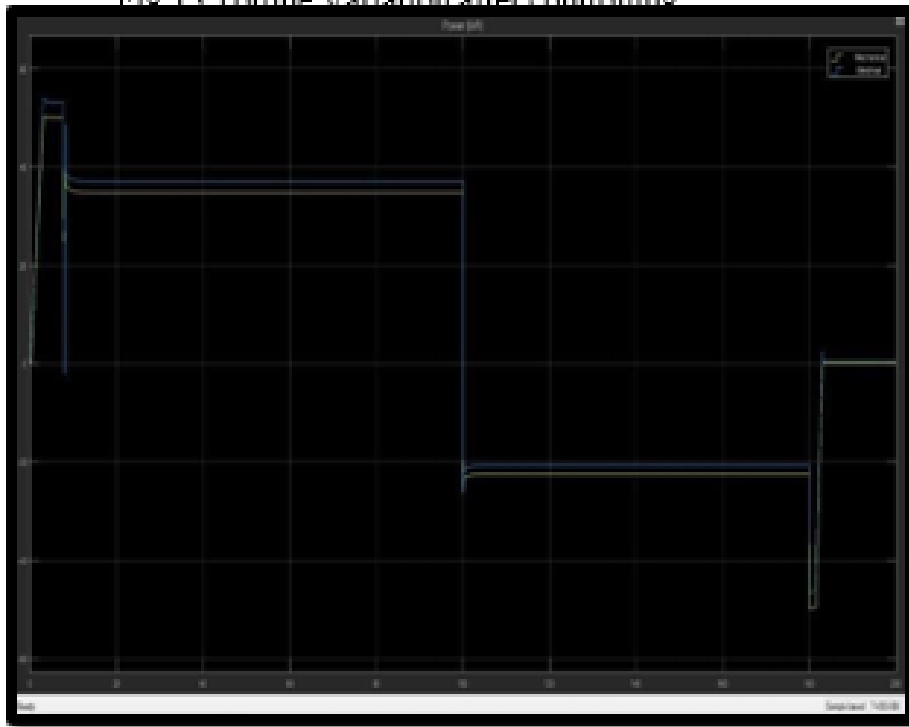


Fig.14- Mechanical and Electrical Power Variation

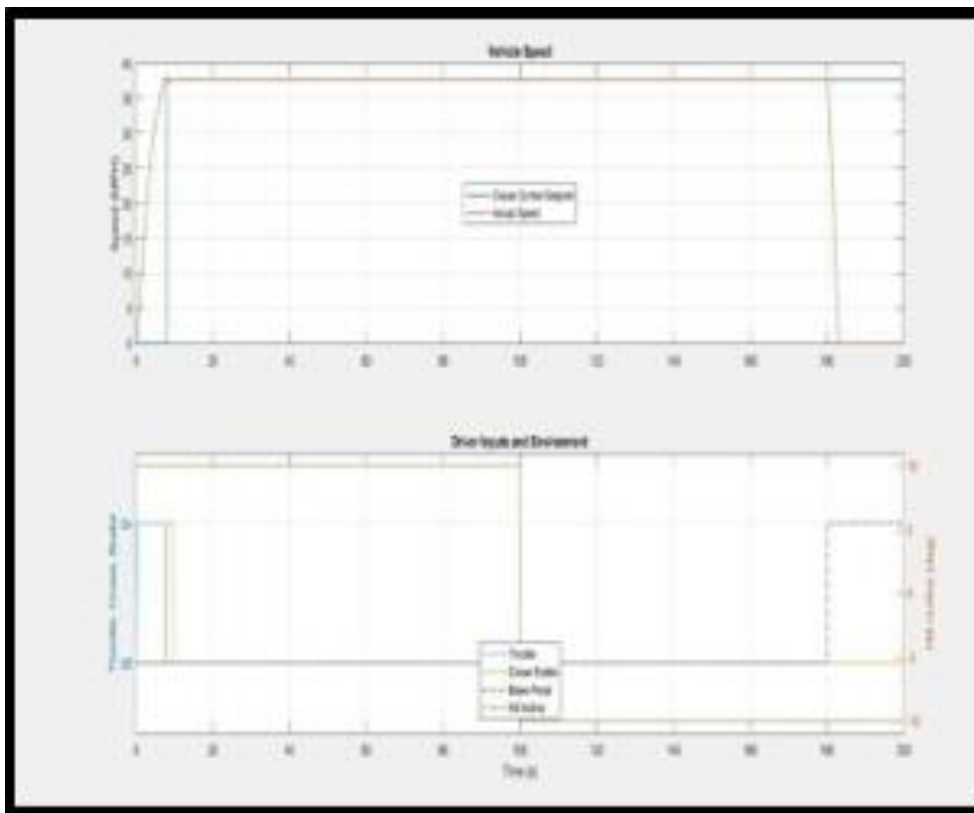


Fig.15- Vehicle Parameters

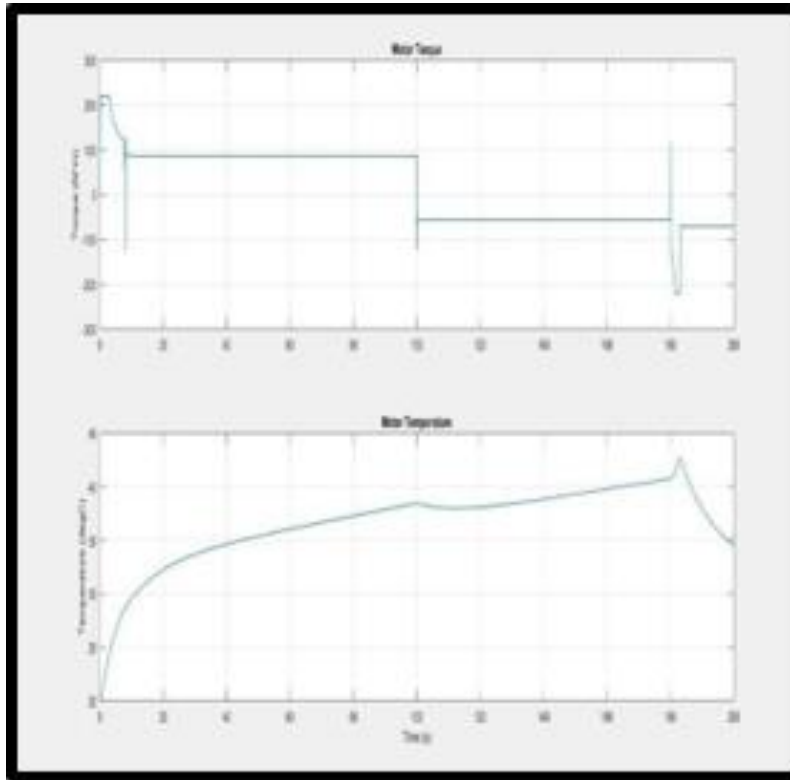


Fig.16- Motor parameters

Simulation of Proposed system

Simulation tests are carried out for charging, propulsion boost, and regenerative braking buck modes at various power levels. The screenshot of the current and voltage waveforms during charging with 1.8 kW power is shown in Fig. 5.19. The input (grid) and output voltages are measured through the voltage sensor, which outputs 6 mV per each Volts. The input voltage is 150VAC and the output voltage is kept constant at 250VDC. The input (grid) current is also measured through the current sensor.

When the switch is turned ON, the inductor current (battery side) increases with a constant slope. The dc bus current is continuous and smooth because of the output filters. Small voltage spikes are observed on the dc-link voltage. These happen in the instances of switching due to the reverse recovery losses, which slightly reduces the efficiency as previously discussed in the additional loss analysis. This can be overcome through active soft-switching techniques such as zero-voltage-zero-current switching and using faster switches to reduce the switching losses, particularly the reverse recovery losses.

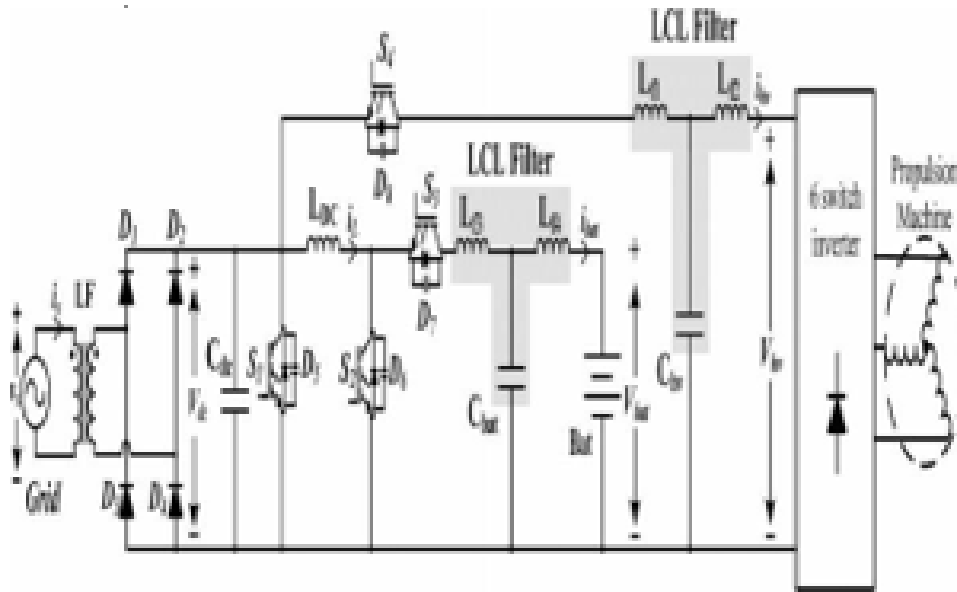


Fig.17. Schematic of the converter with deployed *LCL* filters.

Case-I PFC boost rectifier Operating mode

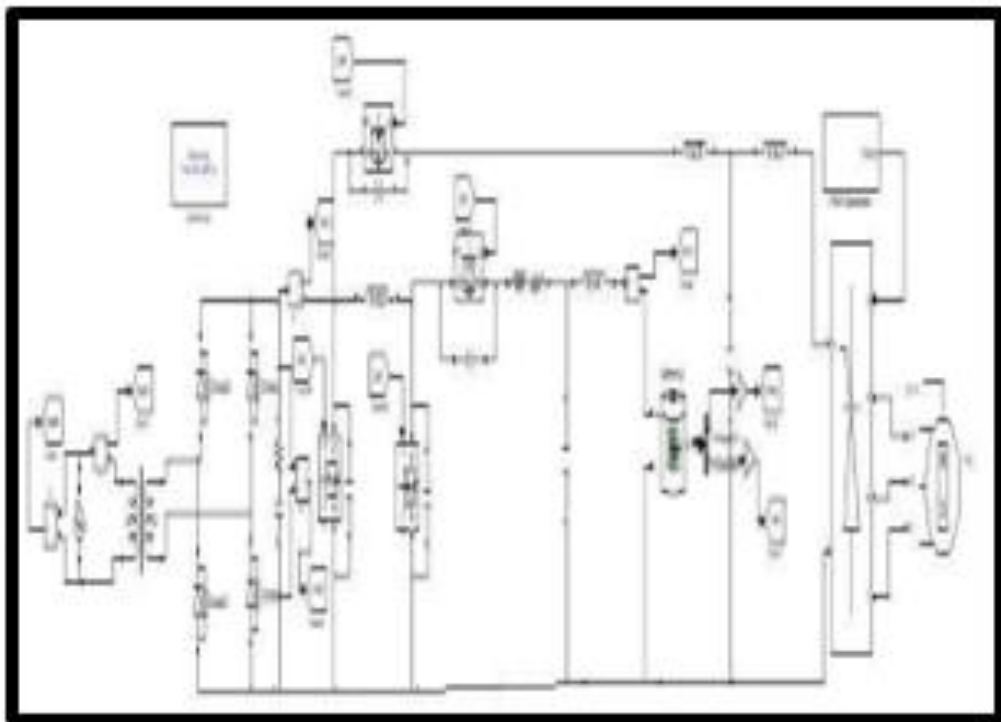


Fig 18- Main Proposed system

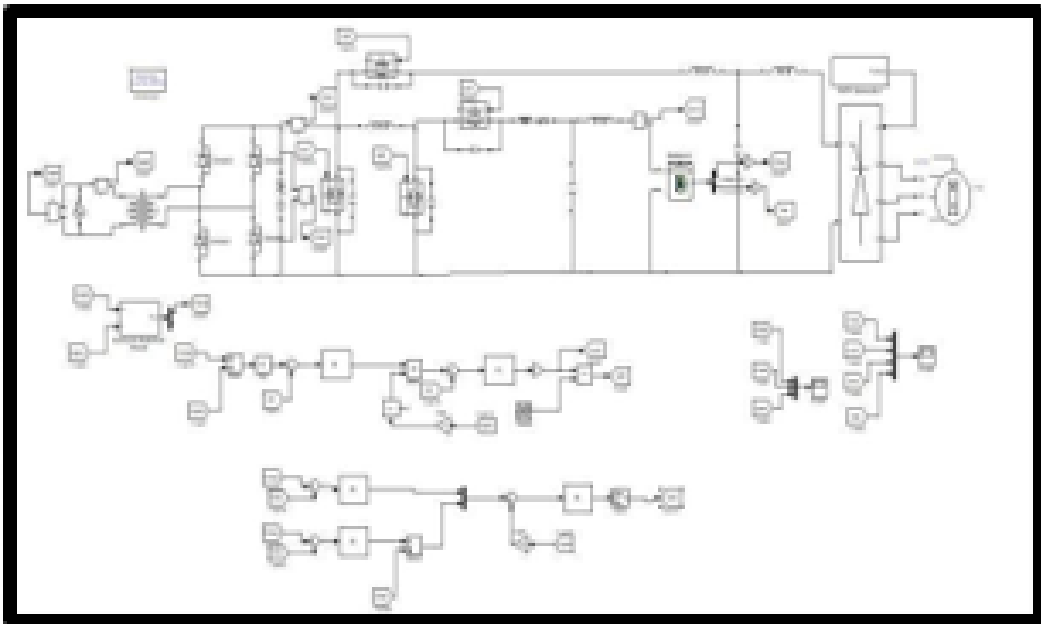


Fig.19 Whole Test model using Matlab

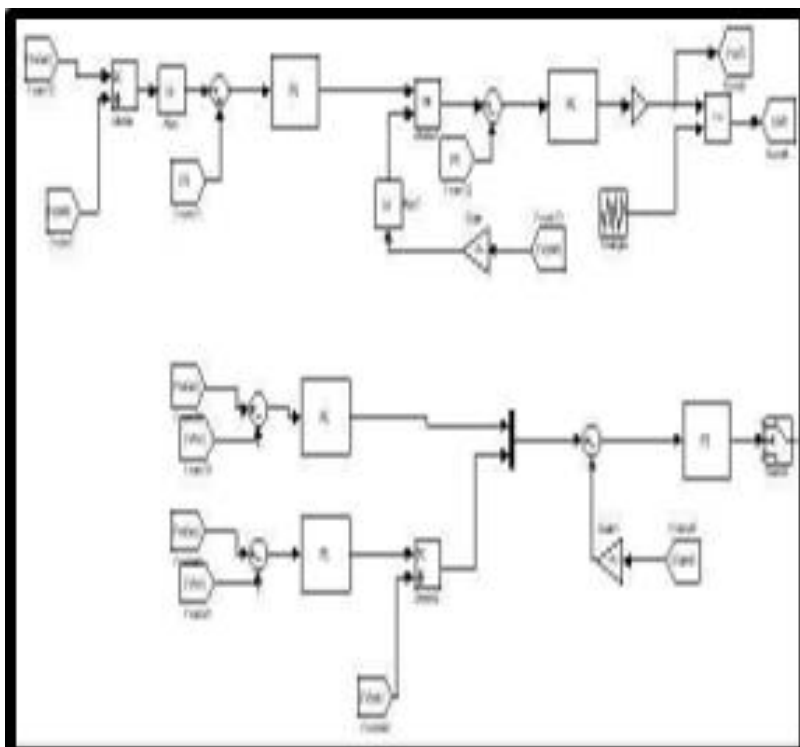


Fig.20- Controlling subsystem

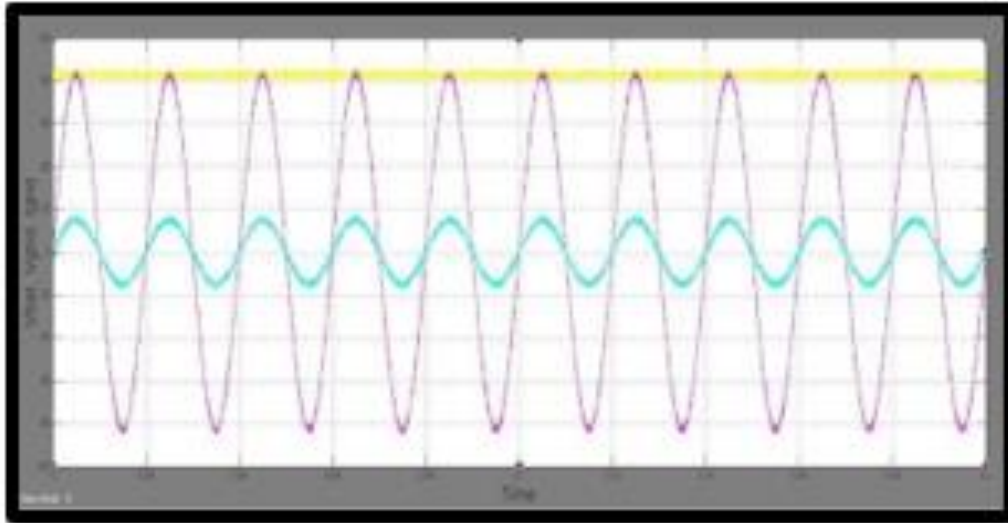


Fig.21- Battery voltage-Vbat, Vgrid and I grid (Grid Voltage and current)

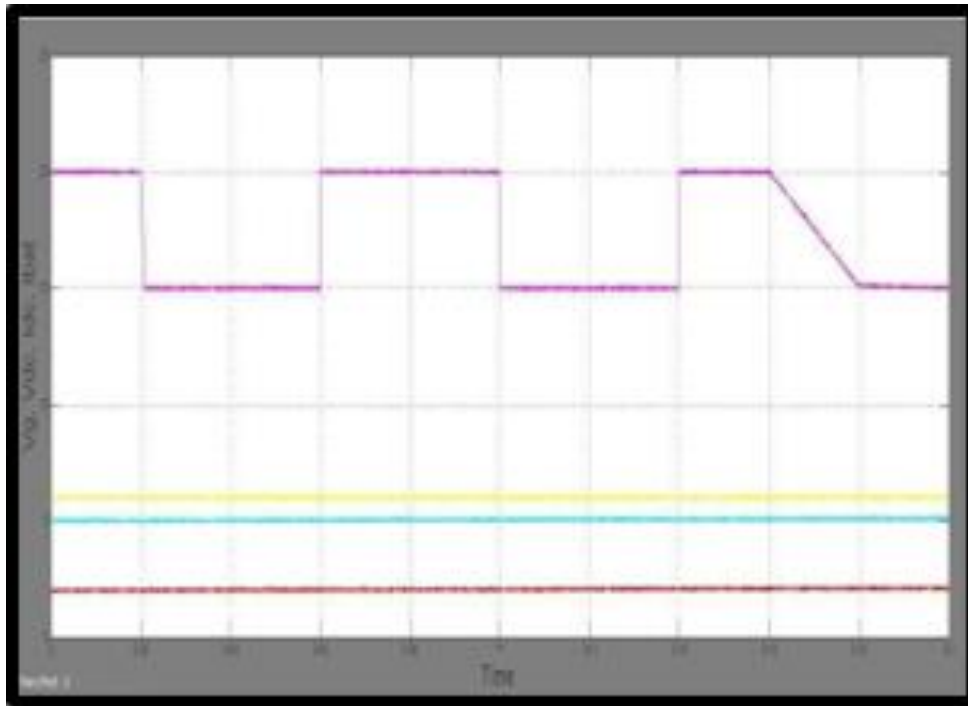


Fig.22- gate signal, battery side current, dc bus voltage and dc bus current

Case- II semi active dual PFC boost rectifier operating mode

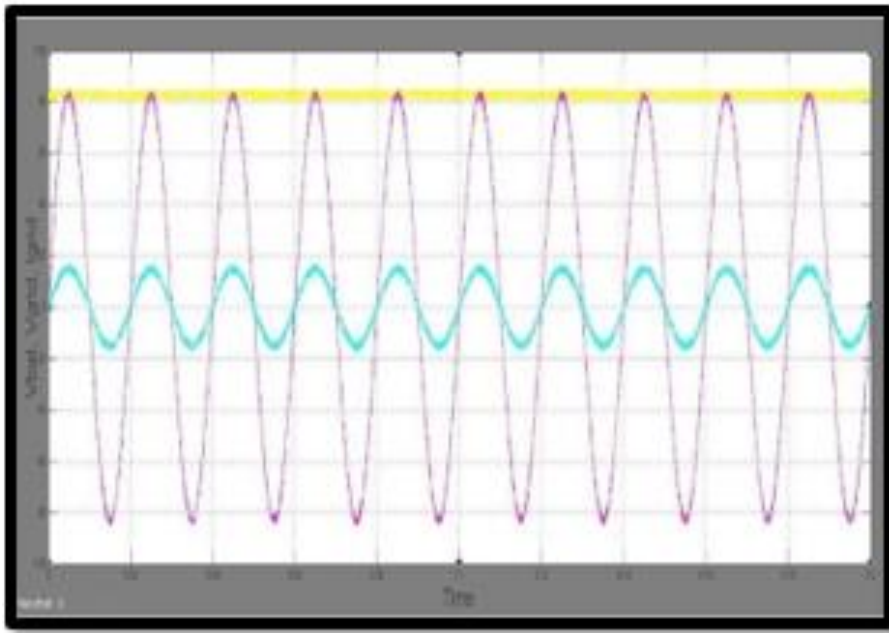
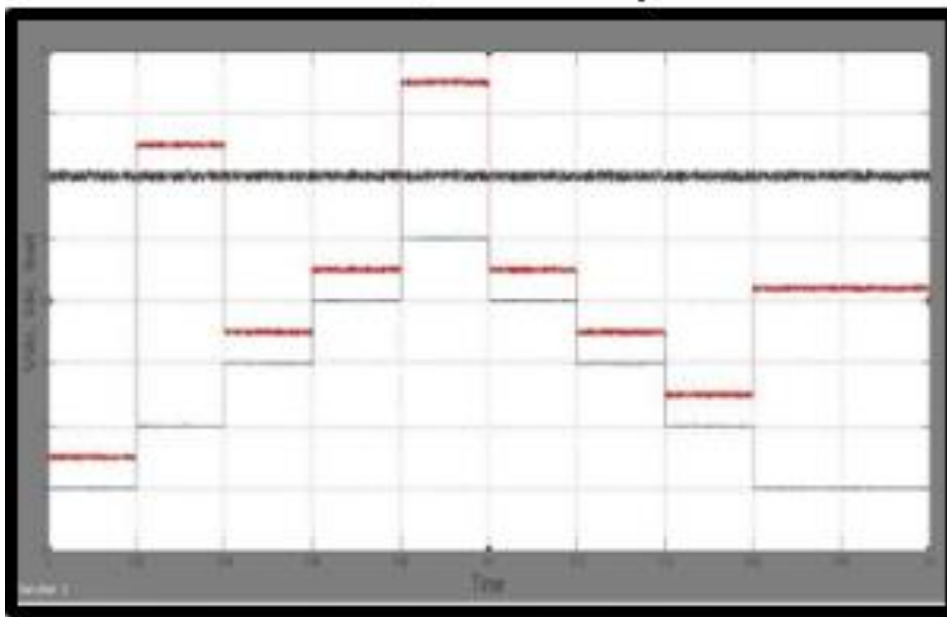


Fig.25- Battery voltage-Vbat, Vgrid and I grid (Grid Voltage and current) for case study-2



**Fig.26- battery side current, dc bus voltage and dc bus
Current**

Case-III inverting buck/boost PFC rectifier operating mode

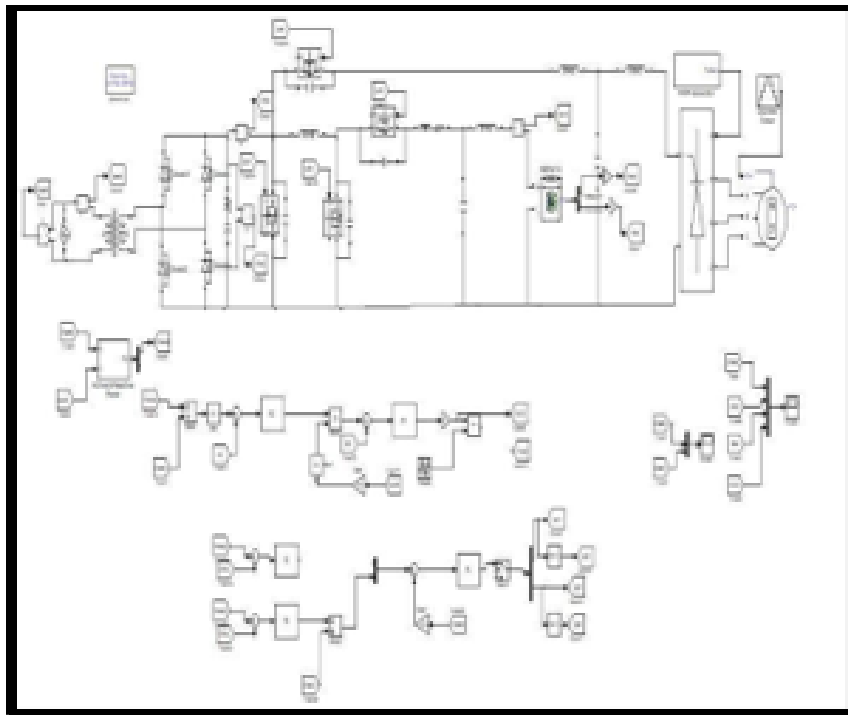


Fig.27- Matlab model of inverting buck/boost PFC rectifier operating mode

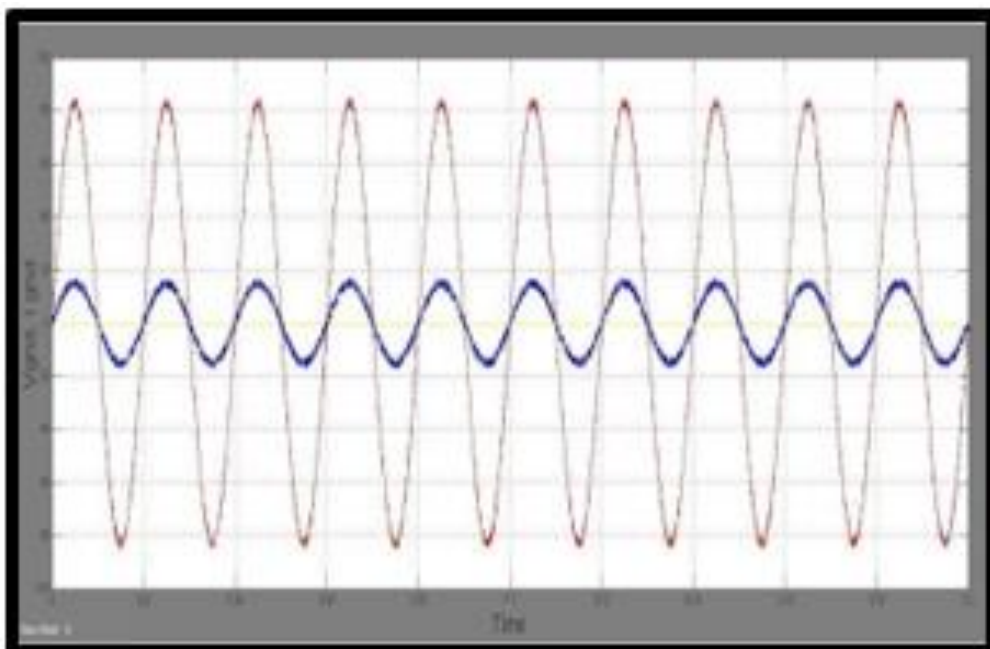


Fig.28- Grid voltage and current

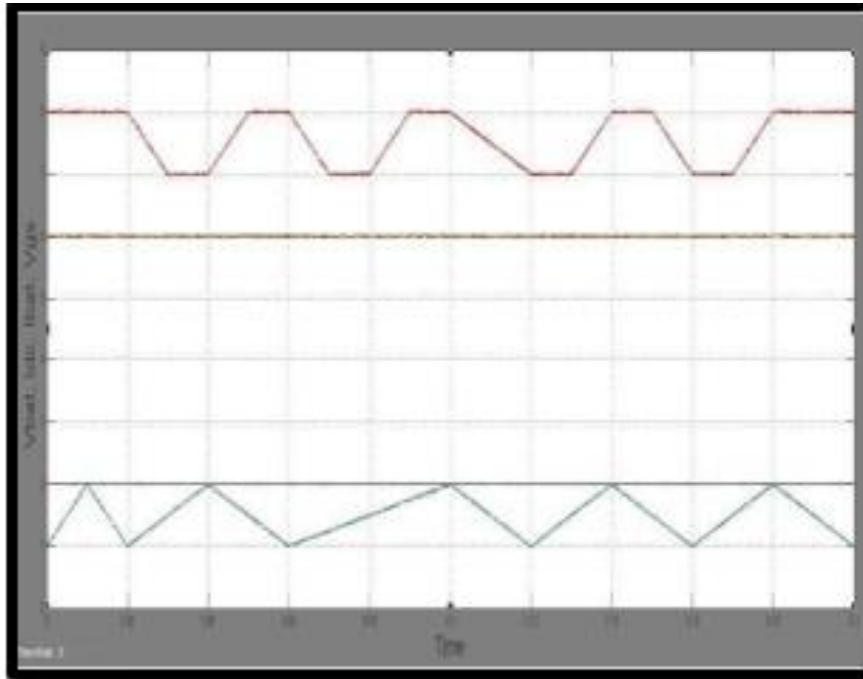


Fig.29- Battery voltage and Current (Vbat, Ibat), dc bus current (Idc), gate signals

Case-IV positive buck/boost PFC rectifier operating mode

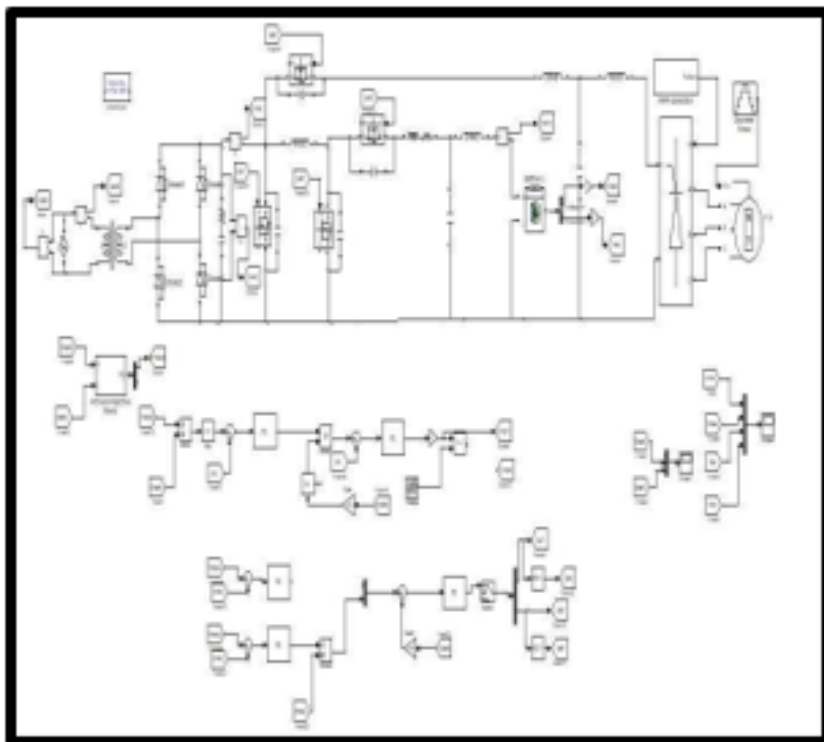


Fig.30 Matlab model of positive buck/boost PFC rectifier operating mode

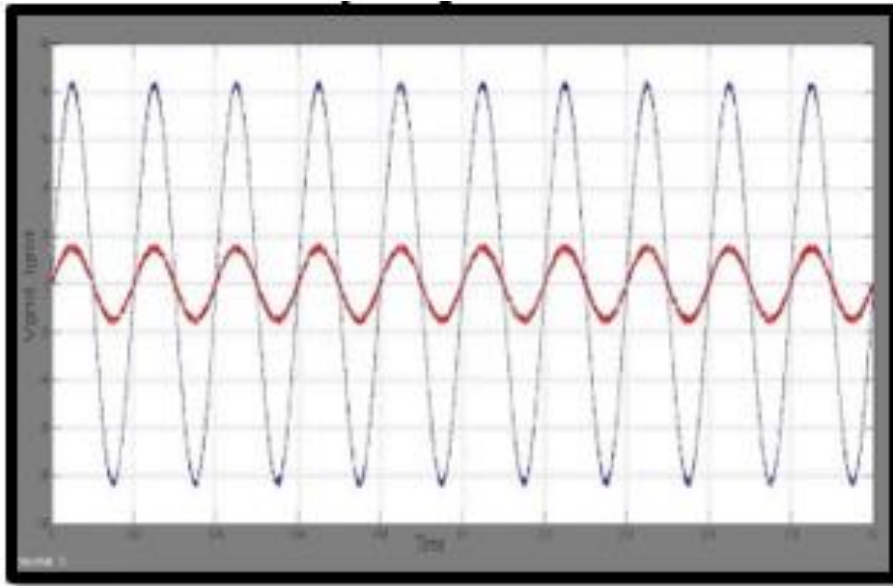


Fig.31- Grid voltage and Current

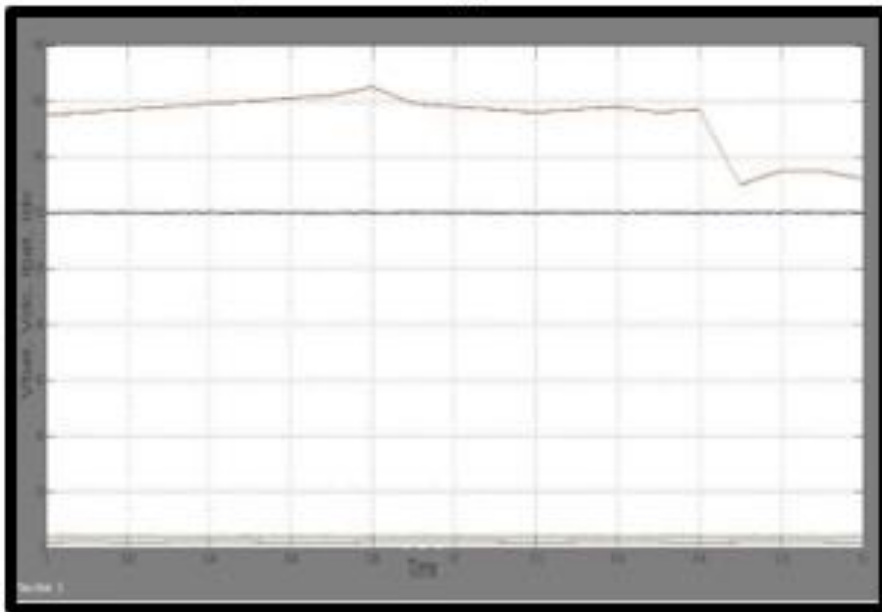


Fig.32- Vbat, Ibat and Vdc, Idc

6. CONCLUSION

This paper highlighted the importance of electric vehicles (EVs) and their practical implementation. The EV system was modeled and simulated using MATLAB Simulink. The proposed charging method, which prioritizes charging based on vehicle needs, was tested successfully through both simulations and experiments. This approach allowed EVs to receive different amounts of energy based on their priority.

Further research can focus on reducing the overall charging time and examining how constant switching might impact battery life. The proposed EV charger design eliminates the need for a large inductor core, which is typically used in conventional systems with two separate power converters for power factor correction (PFC). Instead, the system uses just four switches and a diode bridge to handle all driving modes. Simulation results confirmed that the proposed integrated design works effectively and achieves all required functions. The MATLAB simulation successfully demonstrated the performance of the EV charging system and proved that the control strategy works well.

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