IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.021 ⁘ Peer-reviewed & Refereed journal ⁘ Vol. 12, Issue 4, April 2024

DOI: 10.17148/IJIREEICE.2024.12402

Design and Control of Split-Pi DC-DC Converter for Vehicle to Grid and Grid to Vehicle Applications with Development of Energy Management System in MATLAB/Simulink

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Abstract: Electric vehicles (EVs) are very useful for reducing carbon emission and energy-efficient transportation. Green energy and minimization of emissions are the needs which are regularly thriving automakers to produce electric transportations. Electric vehicles market is highly increasing day by day and its share will be growing even more higher in the upcoming future. To build up EV battery chargers need AC-DC converters and DC-DC converters. EV chargers can optimize vehicle-to-grid (V2G) and grid-to-vehicle (G2V) operations through properly using bidirectional DC-DC converters. The Split-Pi converter is a recently invented DC-DC converter that can support V2G and G2V operation with its bidirectional functionalities. This paper presents a detailed analysis and control of Split-Pi converter for V2G and G2V operation, and development of energy management system. The energy management combination of Lithium-Ion batteries and supercapacitors in EVs can minimize cost, maximizing its range, efficiency and reliability. The EV charging system employing Split-Pi converter analyzed for V2G and G2V applications has been designed in the MATLAB/Simulink platform. Although many topologies and ideas are modified regarding those applications, there are still some processes to identify the new methodologies. Split-Pi converter-based battery and energy management system must be taken into consideration to prevent battery problems such as battery aging, power losses, and slow charging. Both battery lifetime and efficiency can be improved by this way.

Index Terms: Split-Pi DC-DC Converter, Battery Charger, Electric Vehicle, Vehicle to Grid (V2G), Grid to Vehicle (G2V), Energy Management.

I. INTRODUCTION

Electric vehicles (EVs) are getting popularity day by day because of their advantages of zero carbon emissions, protection from pollution, and free of dependency from fossil fuels which is greatly responsible for climate change and environmental damage. Battery continuously supplies the necessary power to run the motor in electric vehicles and so the battery needs frequent charging in all the times. The battery chargers need to be fast, efficient, smooth and reliable which is commonly made of simultaneous connection and operation of AC-DC and DC-DC converters [1]. EV batteries are getting charged from the AC power coming from the grid which is regulated into DC power smoothly through bidirectional DC-DC converters. This is known as grid to vehicle (G2V) operation. However, in modern power systems, EVs can also generate power to the grid as a distributed energy resource whenever necessary. With vehicle to grid (V2G) operation, EV batteries can supply power to the grid during peak load and local load conditions which is beneficial for powering the grid. Bidirectional DC-DC converters play a very important role in V2G applications for EVs [2][3]. Among many kinds of bidirectional DC-DC converters, Split-Pi converter has been chosen for EV charger here because of its advantages of low cost, less components, higher power ratings, and higher efficiency. For all of those advantages, the Split-Pi converter is the best solution used in power electronics for electric transportation and battery charging applications.

This converter is a combination of boost and buck converter with a capacitor used between them, and this can be highly useful in electric vehicles. The Split-Pi converter has three modes – buck, boost and buck-boost mode. MATLAB/Simulink software has been used to model and analyze the V2G and G2V operation of battery charger system highlighting of the Split-Pi converter in this article. Vehicle to grid concept can be allowed while charging at night when the load demand is low and sending power back to the grid is needed when demand is high.

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An electric vehicle pack has a large amount of energy stored in its battery. The energy from electric vehicle can be transferred to the grid where there is peak demand of loads or when electric vehicle is kept in parking for charging in the lean period of loads [4][5][6]. Besides, the energy management system of an electric vehicle is very important to maintain good battery life, safety, and reliability. Energy management in EV demonstrates the feasibility of the operating system. The battery as an electrochemical device falls down losing the designed capacity and so it needs replacement or further management [12][13]. In order to solve this, a hybrid energy storage system consisting of battery and ultracapacitors has been studied in recent years. A smart and sufficient energy management system is required to control the battery lifetime and performance for further energy transformations. Hence, a new improvement on energy management strategies has also been shown in this article.

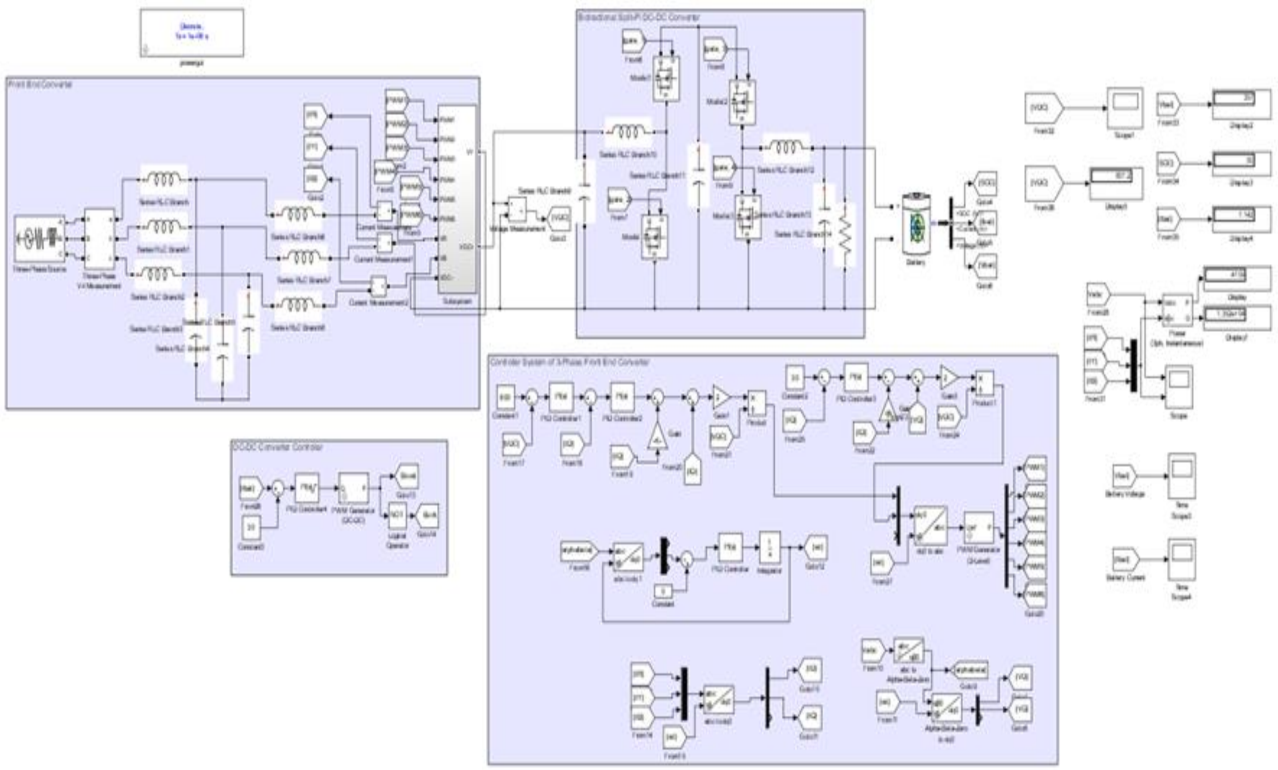

Fig. 1. MATLAB/SIMULINK model for energy transfer from vehicle to grid and grid to vehicle

II. MATLAB BASED MODELING

A. *Design of the System Parameters*

The MATLAB/Simulink model of the proposed topology for vehicle to grid and grid to vehicle power transfer applications is shown in Fig.1. At the input, we have Front End Converter also known as Active Rectifier which converts the AC Grid voltage to DC and maintains the constant voltage across the DC bus. IGBT has been used in the inverter bridge. Then we have a bidirectional Split-Pi Converter used to control the battery current during charging and discharging operation.

Grid voltage: 415V RMS at 50 Hz
Filter Inductance: 5mH
Capacitance: 30 mF
Bus Capacitance: 5600 mF
Battery Nominal Voltage: 360V (Lead Acid Battery)
Switching Frequency of Converters: 10 KHz
Total Rated Power: 2.55KW
DC Reference Voltage across the Bus: 800V

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Let us assume that the input source voltage V_s is given as,

$$V_s = V_{sm} Sinwt \quad (1)$$

Here, *Vsm* is the maximum value of the source voltage. The value of *Vsm* is 586V, Grid voltage V_s = 415V RMS and ω = 2*πf*.

The input current will be,

$$Is = \frac{V_s}{R_e} = Ism\ Sinwt \quad (2)$$

Here R_e is the emulated resistance and V_s is 415V RMS. The normalized input voltage *Ms* can be given as,

$$Ms = \frac{V_{sm}}{V_{dc}} = Mg\ Sinwt \quad (3)$$

Here the value of V_{sm} is 586V and the value of V_{dc} is 800V. The calculated value of *Ms* from eq. (3) is 0.7325. The value of emulated resistance R_e will be,

$$R_e = \frac{V_{sm}^2}{2Po} \quad (4)$$

Here, V_{sm} is 586V and *Po* = 2.55KW. Hence, the calculation of R_e is 67.33Ω.

Power factor cosθ = cos $[\tan^{-1}(\frac{X_L}{R_e})]$ (5)

The calculated value of the power factor from eq. (5) is 1.

Split-Pi Converter Parameters: Inductors (L1, L2): 100mH, Capacitor (C1, C2): 100µF, Capacitor C: 500µF.

The design of the various components of proposed configuration for energy transfer from vehicle to grid and grid to vehicle consists of a three-phase front-end converter, Split-Pi Bidirectional DC-DC converter, controllers, and a battery pack for EV system. The detailed design of the control scheme is given in the following section.

B. Control Algorithm

The controller for different blocks of the proposed system is given in this section. Controller for both DC-DC converter and front-end converter plays an important role in the operation of these applications, and both controllers are explained below.

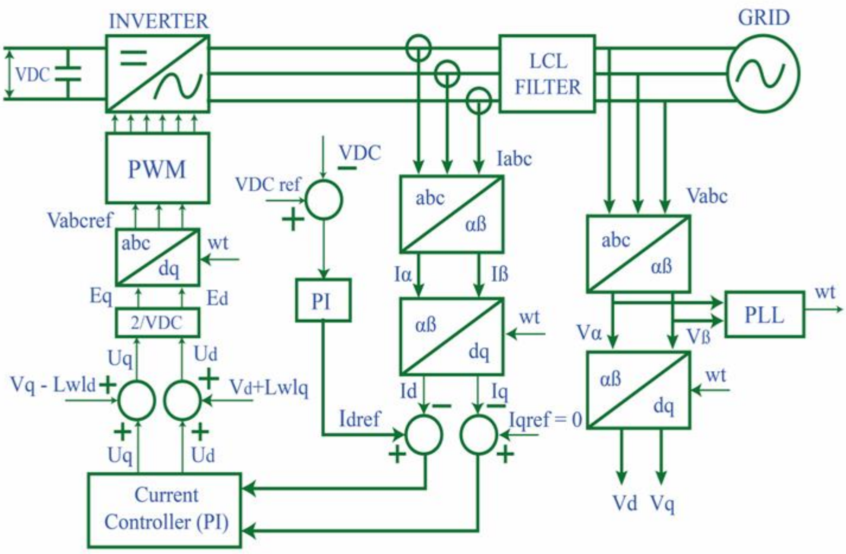

Fig. 2. Control Block Diagram of Three Phase Front-End Converter

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Fig.2 shows the controller block diagram of three-phase front end converter. This controller is used to regulate 800VDC across the bus.

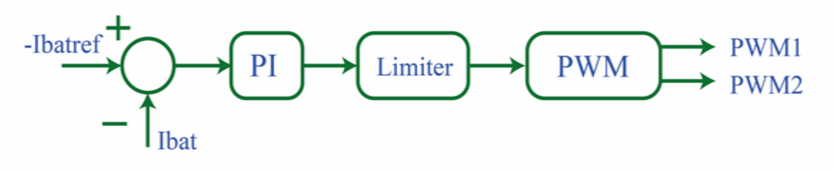

Fig. 3. Control Block Diagram of Bidirectional Split-Pi Converter

Fig.3 shows the controller block diagram of bidirectional Split-Pi converter. This controller is used to control the battery charging and discharging current.

III. RESULT AND DISCUSSION

Simulation is carried out in MATLAB version of 7.8 the sim power system toolbox using ode (23tb/stiff/TR-BDF-2) solver in discrete mode at 1e-6 step size.

A. Output Results on Vehicle to Grid Operation:

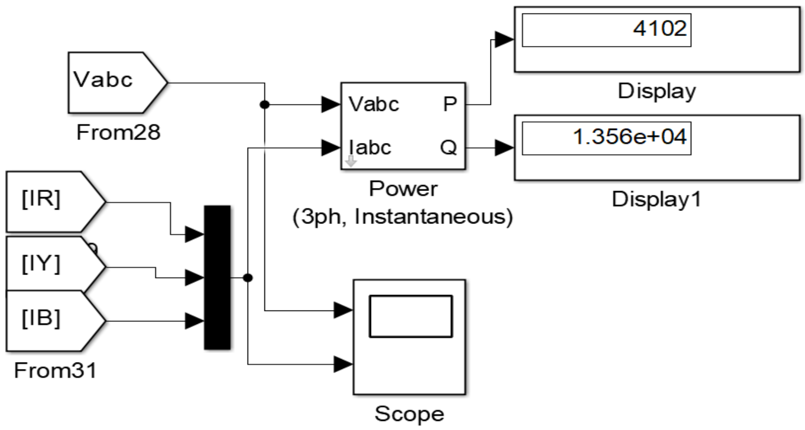

Fig.4. Simulation Output on Vehicle to Grid Mode (V2G)

From Fig.4, we can see that the values of active power P and reactive power Q is positive, which means that power flow is from battery to the grid. So, the system is working on vehicle to grid mode.

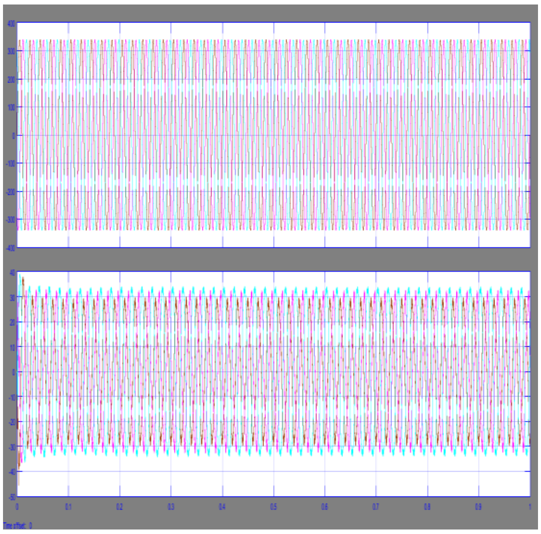

Fig. 5. Voltage and Current Waveform on Vehicle to Grid Operation

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From Fig.5, we can observe that both voltage and current are on the same line and phase which means that power is transferred from vehicle to the grid.

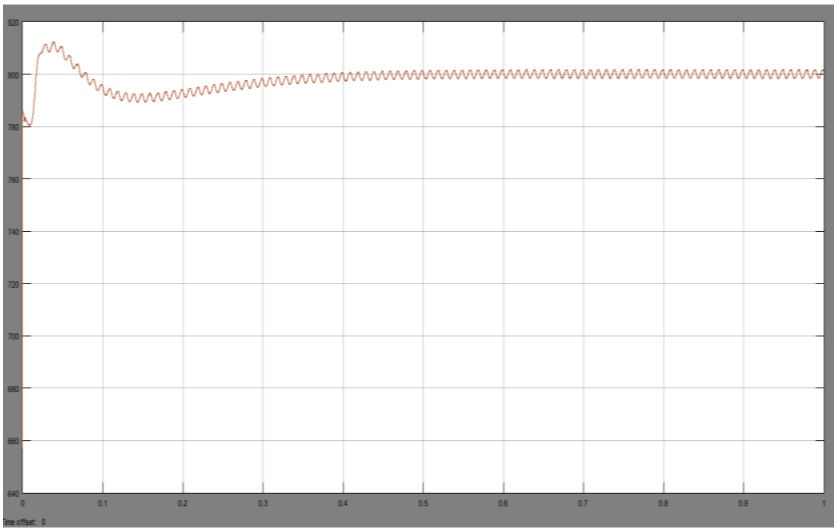

Fig. 6. DC Bus Voltage Output (800V Approximately) on V2G Mode

DC Bus voltage is 800V during vehicle to grid operation shown in Fig.6.

B. Output Results on Grid to Vehicle Operation:

Assuming the current reference will be negative (-30A) for front-end converter controller, the system will be made workable for the grid to vehicle operation.

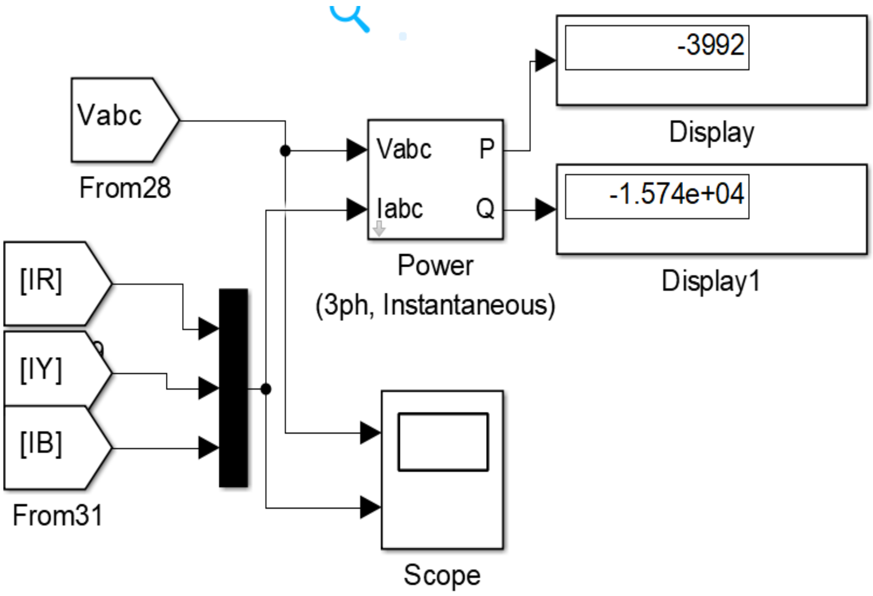

Fig. 7. Simulation Output on Grid to Vehicle Mode (G2V)

From Fig.7, we can observe that the values of active power P and reactive power Q is negative which means that power flow is transferred from the grid to the battery. So, the system is working on the grid to vehicle mode and power is taken from the grid to charge the battery.

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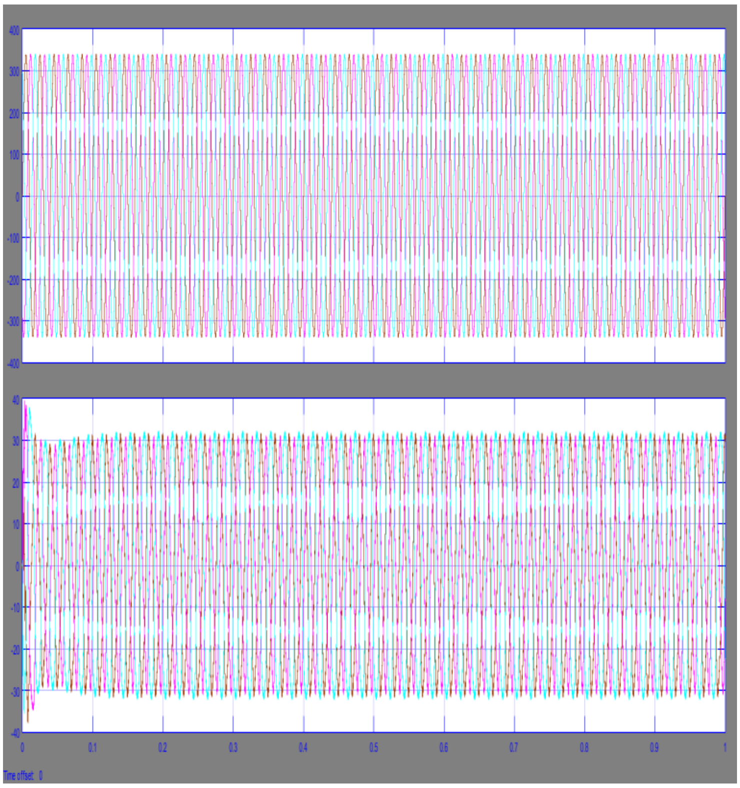

Fig. 8. VGRID and IGRID Output on G2V Operation

From Fig.8, we find that both the voltage and current waveform is on the same line and phase which means that power is taken from the grid.

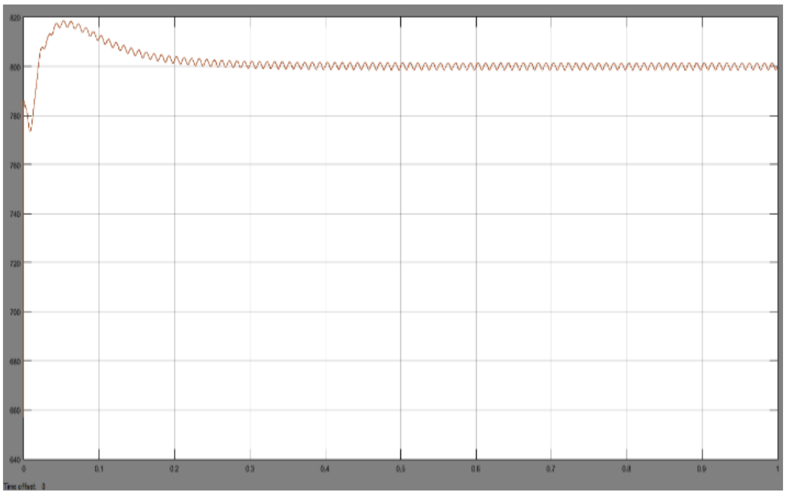

Fig. 9. Bus Voltage (800V Approximately) During Grid to Vehicle Operation

DC Bus voltage is same as 800V during grid to vehicle operation shown in Fig.9.

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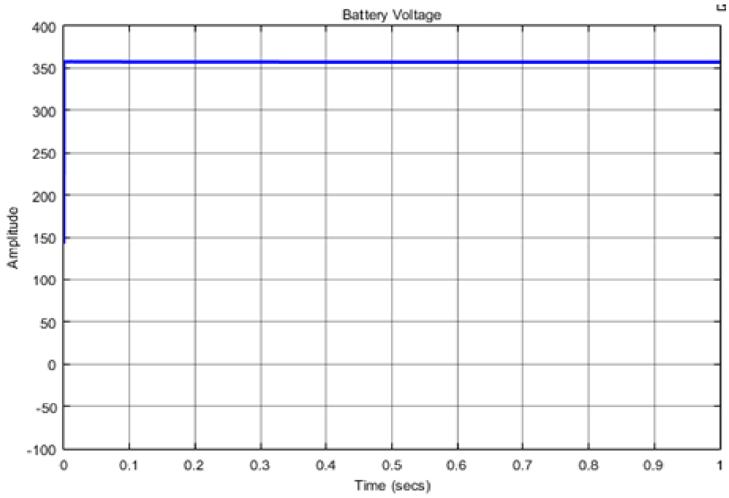

Fig. 10. Battery Charging Voltage (360V Approximately) during V2G and G2V Operation

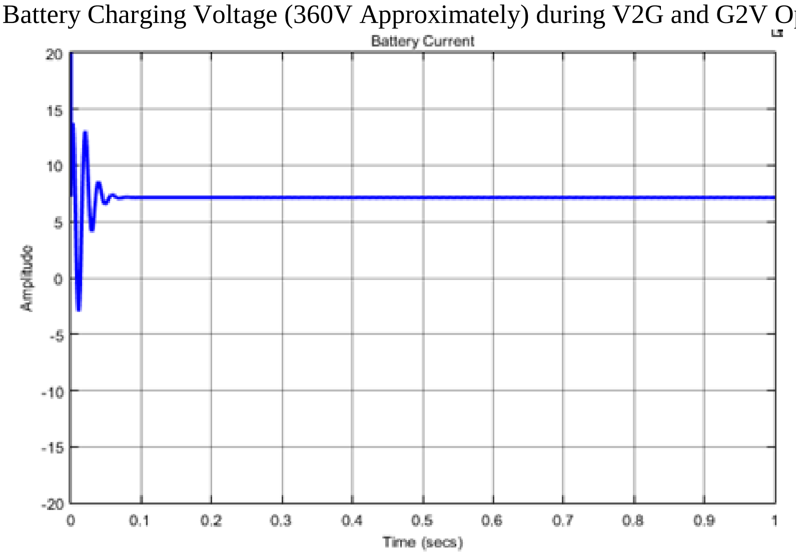

Fig. 11. Battery Charging Current during V2G and G2V Operation

Battery charging voltage is 357V and battery charging current is 7.142A found from simulation respectively, and shown in Fig.10 and Fig.11 with respect to initial state of charge and rated capacity. Lead acid battery has been chosen for the simulation and observed through analyzing with 1 second battery response time.

IV. ENERGY MANAGEMENT SYSTEM

Fig. 12 shows the simulation model of energy management system used in EV to manage the energy flow between Li-ion battery, supercapacitor, and the traction system. The battery output goes to the power inverter, and the supercapacitors inject energy to Li-ion battery and further on inverter through the DC-DC Split-Pi converter while decreasing the battery voltage. By this way, the battery maintains its constant voltage at maximum times and helps the EV for better acceleration [7]. During regenerative braking, the supercapacitors recover the energy to avoid overvoltage at the battery terminals, and EV maintains better speed and range.

The energy management system always maintains the stored supercapacitor energy according to battery SOC. Only a small amount of energy stored in the supercapacitor is needed if the battery maintains its full charge [8][9]. In this way, all the energy recovered from regenerative braking will be stored in the supercapacitor.

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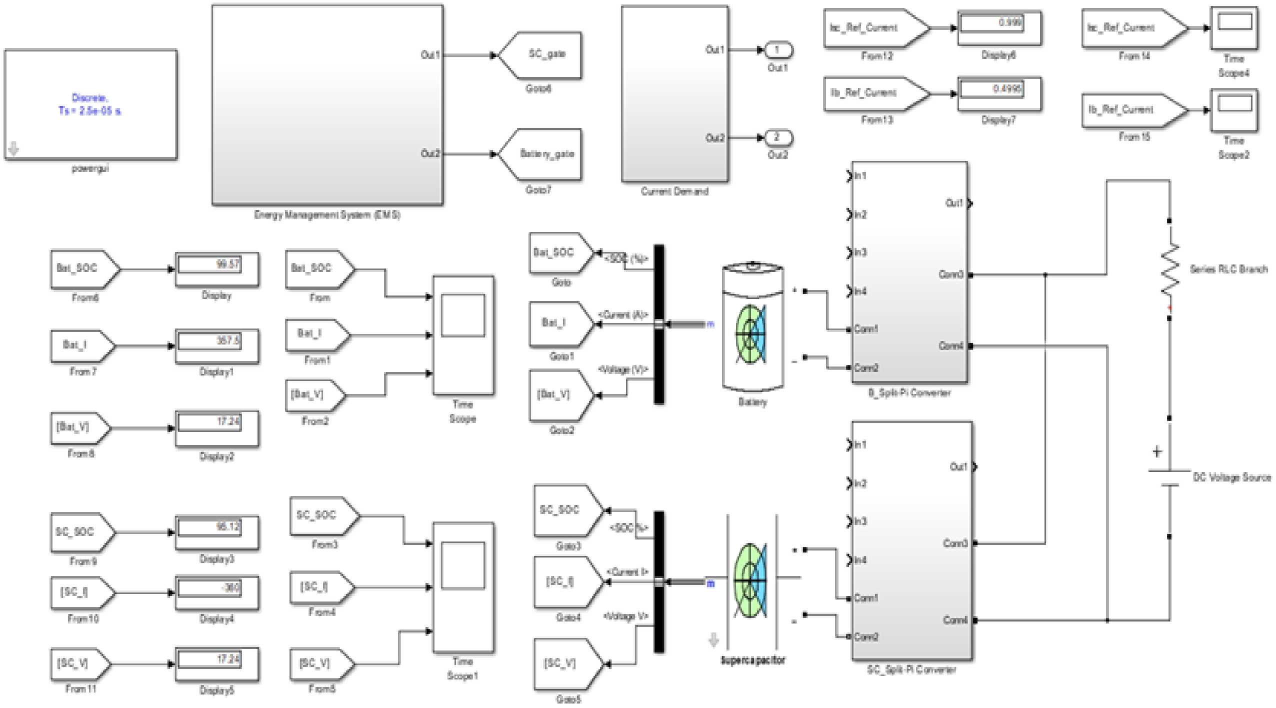

Fig. 12. MATLAB Model of Energy Management System with Combination of Battery and Supercapacitor

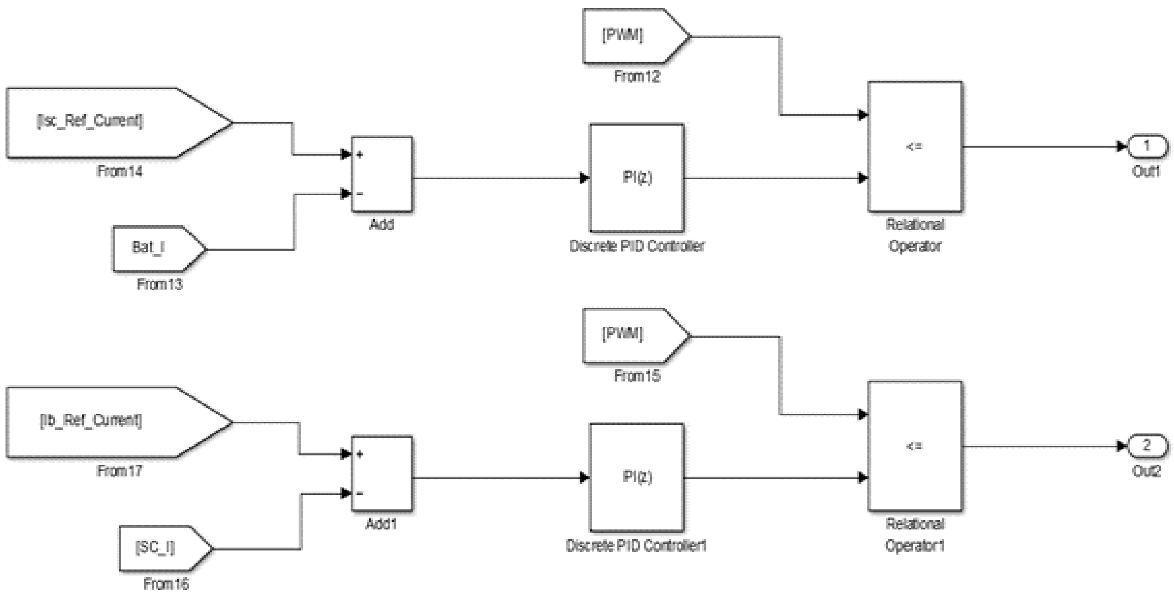

Fig. 13. Energy Management System Block with PWM and PI Control in MATLAB/Simulink

Fig.13 shows a typical energy management topology performed with PI Controller. The control system outputs are pulse width modulation (PWM) signals, which commutate the four switches in the Split-Pi DC-DC converter. Sometimes, the battery SOC is not enough, the supercapacitor should store a minimum level of energy higher than its normal conditions [10][11].

The combination of Li-ion battery with Supercapacitor helps an electric vehicle operate with higher range, good acceleration, and full regenerative braking capability.

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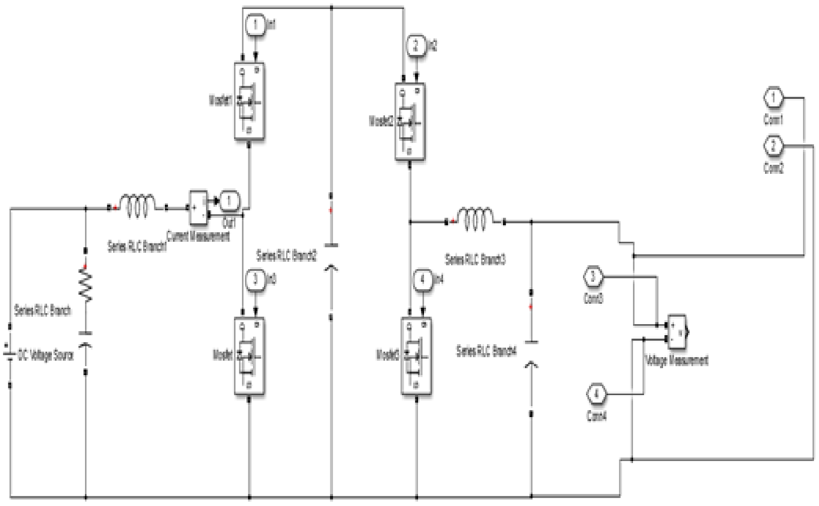

Fig. 14. Bidirectional Split-Pi Converter Circuit Used for Both Battery and Supercapacitor

Selection of parameters for Battery-Converter and Supercapacitor-Converter are given as: Inductors (L1, L2): 1000mH, Capacitor (C1, C2): 200µF, Capacitor C: 500µF. Fig.14 shows the bidirectional Split-Pi converter used for battery management including battery and supercapacitor.

V. SIMULATION RESULTS

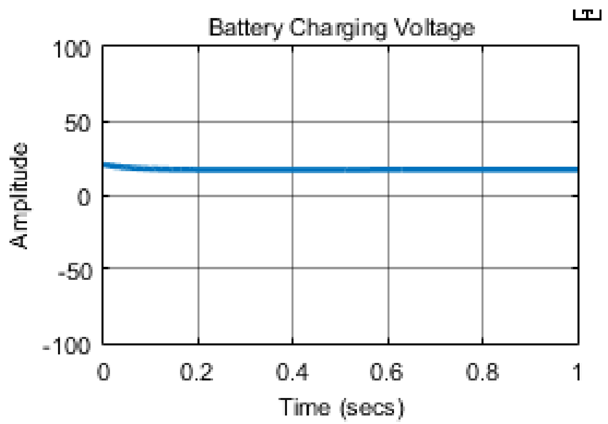

Fig. 15. Battery Charging Voltage (17.24V)

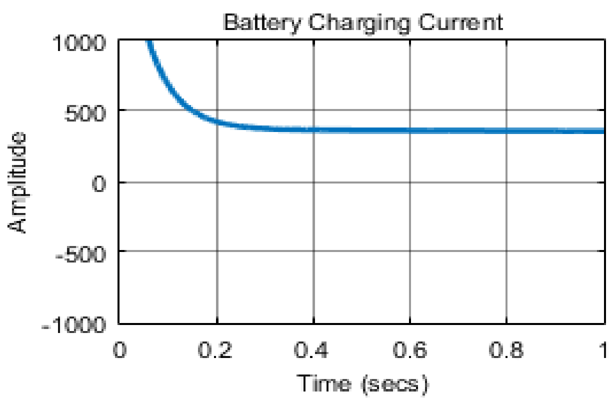

Fig. 16. Battery Charging Current (357.5A)

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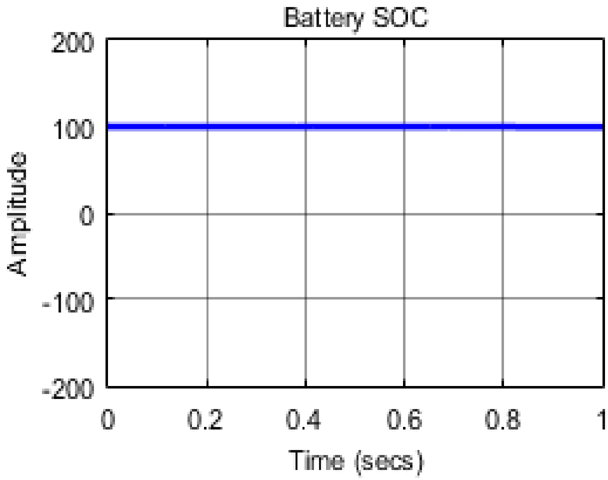

Fig. 17. Battery SOC (99.57%)

From the simulation results in the case of Li-ion battery (Fig.15, Fig.16, and Fig. 17), we can see that Split-Pi controlled battery keeps the battery charging voltage and charging current with initial state of charge according to particular battery parameters under energy management process.

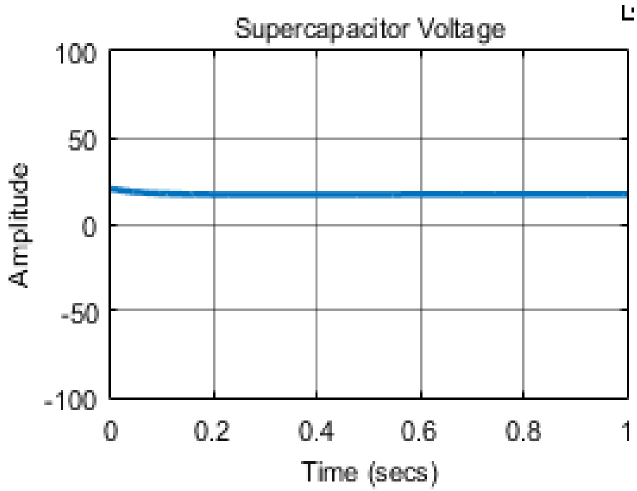

Fig. 18. Supercapacitor Voltage (17.24V)

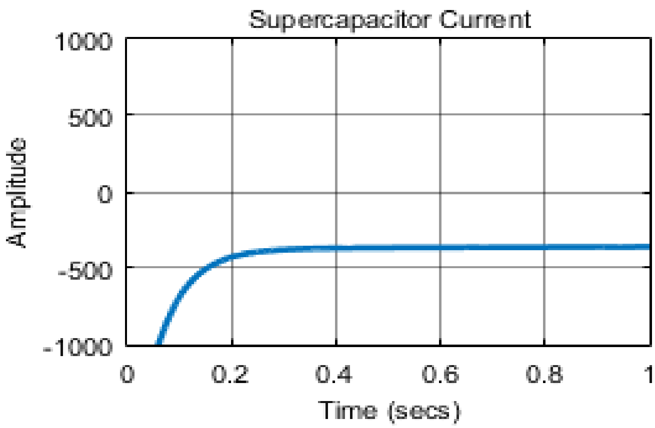

Fig. 19. Supercapacitor Current (-360A)

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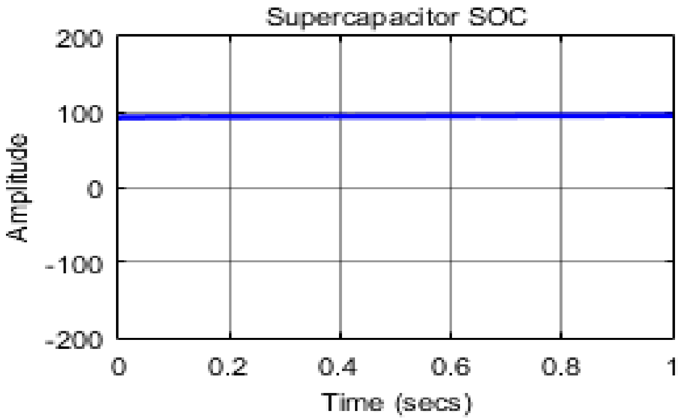

Fig. 20. Supercapacitor SOC (95.12%)

From the simulation results in case of supercapacitor (Fig.18, Fig.19, and Fig. 20), we notice that Split-Pi converter modulated supercapacitor formulation indicates a decent range of voltage and current, up to state of charge 95.12%, improving of charging control.

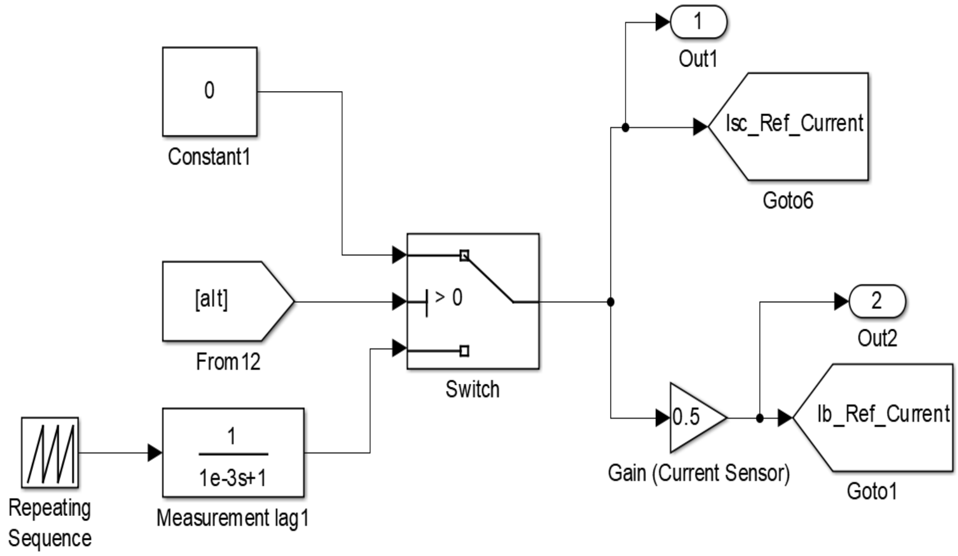

Fig. 21. Current Demand and Alternator

The current demand and the hybrid current based on the reference current is applied by the current sensor to the DC-DC Split-Pi converter shown in Fig.12 and Fig.21.

The alternator is the origin which works as a sensor to divide the whole current (Gain 100%). Hence, the battery is supplying 50 percent (0.5) of the required current which means the battery will supply to the load during zero to two seconds and it will start charging. Then the switch will be closed, and the battery and supercapacitor current reference will be almost zero shown in Fig.12.

The current demand is therefore zero and the DC bus voltage starts charging the battery using the bidirectional DC-DC Split-Pi converter.

Being charged by ±360A current (approximately), here both the battery and supercapacitor is connected to the load. And the battery is being charged by the load. Fig.22 and Fig.23 indicates the battery reference current and supercapacitor reference current analyzing energy management system implementation. Battery reference current achieved through current demand is 0.4995A and Supercapacitor reference current is 0.999A shown in MATLAB Simulation (Fig.12).

IJIREEICE
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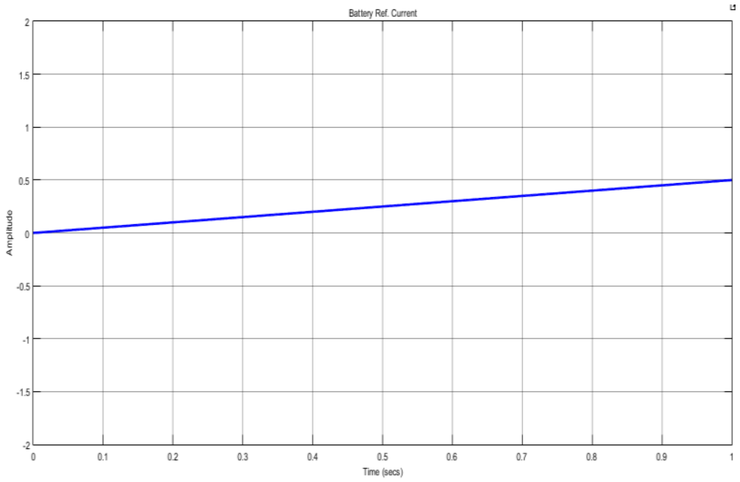

Fig. 22. Battery Reference Current

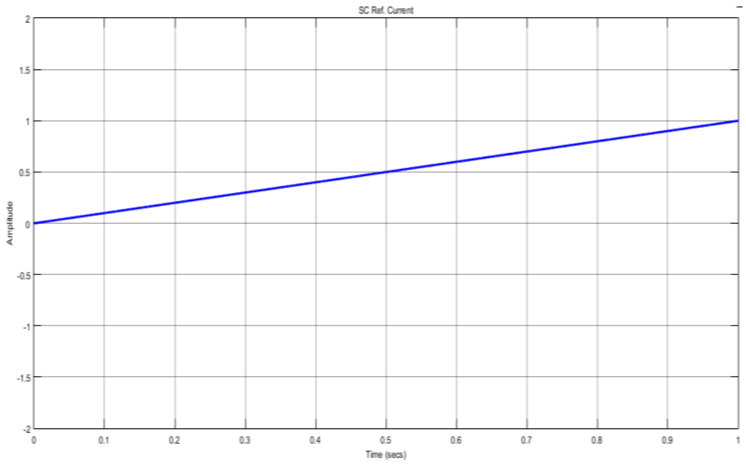

Fig. 23. Supercapacitor Reference Current

Figure 24 shows the overall block diagram of the energy management system with combination of battery and supercapacitor which can be used for betterment of EV management.

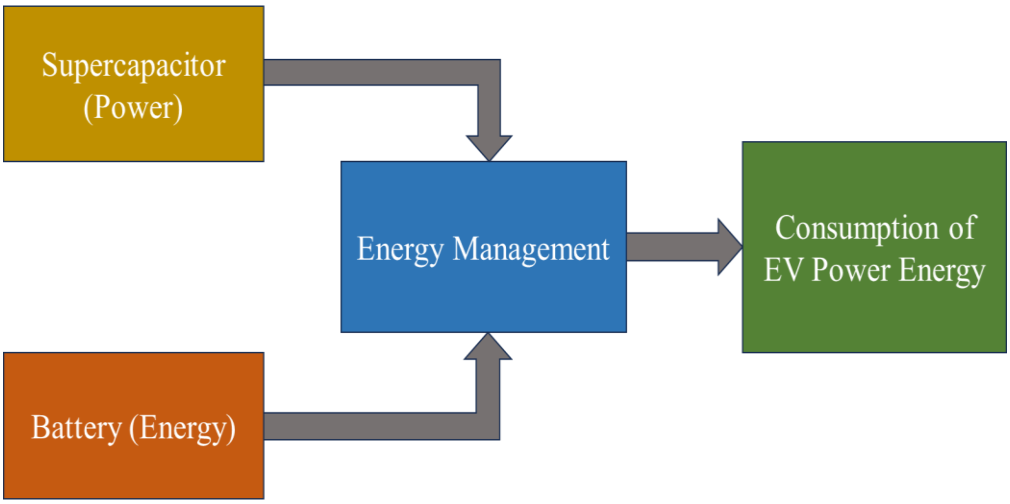

Fig. 24. Block Diagram of the Proposed Energy Management Scheme

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VI. CONCLUSION

Split-Pi converter is always essential for EV charging applications because of its bidirectional power flow, lower components and less switching losses. In addition to these, this converter provides power quality control, scalability, advanced control options stabilizing smooth and reliable energy transfer between the electric vehicle and the power grid.

The performance and benefits of the Split-Pi converter system have been investigated through simulation studies with necessity of storage battery management for vehicle to grid and grid to vehicle operation including battery electric vehicles in this paper. The simulation results and discussion for a combination of a battery with supercapacitor in order to maintain a proper energy management system is shown briefly.

When this battery works with the help of supercapacitor to run the motor combining a battery management module, then the electric vehicles behave very nicely and safely. Split-Pi converters structure, component selection, and control strategy has been presented in detail, providing an insight into the technical aspects of its operation, showcasing the converter's ability to facilitate V2G and G2V applications properly, and implying an efficient and stored energy management system possibilities.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor Professor **Dr. Wensheng Song** for his enormous support, patience, motivation, and immense knowledge during this research work. His guidance helped me a lot all the times, and also in continuing and writing of this research article.

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IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.021 ⁙ Peer-reviewed & Refereed journal ⁙ Vol. 12, Issue 4, April 2024

DOI: 10.17148/IJIREEICE.2024.12402

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