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Modeling and Analysis of Conductive and Inductive Charging Development for EV Systems with MATLAB Implementation of Battery Controlled Split-Pi Converter

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Abstract: Zero emission mobility is one of the most important applications in the electric vehicle market being in a continuous growth where new charging technologies are getting popular with new developments. Developing fast charging topologies and strong infrastructure can be the solution to limit the autonomy of vehicles which is growing faster and need to be in consideration. This research article shows and discuss the recent topologies and the methodologies of EV charging module, and finally comes in a new charging system for the better solution covered with Split-Pi power electronic converter based on conductive and inductive (wireless) charging applications. These fundamentals are related to the electric vehicles. The problems resulting from global warming and with direct involvement of the most severe issues such like burning and consumption of fossil fuels needs modification and improvement, and EVs are the ultimate solution there. The detailed design and analyses of the new topologies has been performed with controlled front-end stage AC-DC converter, control of Split-Pi DC-DC Converter, and battery based on simulation using MATLAB/Simulink. The entire simulation analysis and design parameters, associated with the proposed converter and battery controller has been highlighted, and discussed regarding ideas on the advancement of conductive and inductive charging scheme for battery electric vehicles.

Index Terms: Split-Pi Converter, Battery Charger, Battery Charge Controller, Conductive Charging, Inductive or Wireless Charging, Front-End Stage AC-DC Converter.

I. INTRODUCTION

The world is facing global warming and climate change continuously, and these are the most dangerous threat to this universe now-a-days. This is now a very common issue throughout the world. The entire universe is facing and experiencing a lot of weather crises such as floods, droughts, heat waves, extreme rainfall because of the high rise of sea-level and melting of ice shields. The weather is becoming dangerous day by day and causes global warming with frequent climate change. If these problems are not addressed as soon as possible, then severe consequences must come in the upcoming decades. Heat is the main element for extreme heat in the weather as electricity is produced from burning of fossil fuels and heat, and carbon dioxide produces greenhouse gases which cause severe climate change while mixing in the atmosphere.

Global climate change is really a matter of concern and these negative consequences like flood, droughts, rainfall, heat waves, sea levels rising and melting ice shields are harming the ecosystems, and animals are also greatly affected by it. These problems should be eradicated as soon as possible by reducing the burning of fossil fuels or heat trapping greenhouse gases that are accelerating the weather and global warming crisis. Powering vehicle and transportation is one of the alternative ways to overcome the climate change and to save the world. [1, 2]. The world is now pursuing electric-powered transportation systems that can help us reduce petroleum consumption. The battery electric vehicle will be connected to the grid and its charging is done on-board through the grid or off-board. Electric vehicles are a very important option in a world where carbon emissions and pollution are gradually increasing.

This research article will discuss conductive and inductive battery charging architecture of EV systems which can reduce the use of fossil fuels in the future and can build sustainable transportation therefore saving the environment. To build up an EV charging infrastructure is critical so that delivers fast and constant charging performance.

Developing a fast and an efficient EV charging infrastructure is necessary, and here other policies such as competing industry standards, available technologies, grid impacts, and some other technical issues should be taken into consideration [3, 4]. Power electronics converter topologies are applicable for EV charging infrastructure and suitable for fast battery chargers. This research work specifically focuses on the conductive battery charger with AC-DC Split-Pi converter and wireless battery charger design, and why DC-DC Split-Pi converter-based battery charging system is the most efficient and suitable in these applications, has been presented with explanation in this article.

Generally, two types of EV charging systems are applicable and they are known as conductive and inductive/wireless charging approaches. Conductive chargers have non-isolated and hard-wired connection between the power supply and power electronic interfaces to transfer the charging across the battery, and basically consist of an AC-DC rectifier followed by a DC-DC converter. On the other hand, inductive charging is different from conductive charging which does not use a wired connection between the supply and the power electronic interfaces for charging purposes.

Inductive or wireless charging techniques use primary (transmitter) and secondary (receiver) coils for transferring power using the principle of magnetic induction [5, 6, 7]. The scope of optimizing advanced wide-bandgap materials such as silicon carbide and gallium nitride devices in EV chargers has also been discussed in the last section of this article.

II. DIFFERENT POWER ELECTRONIC CONVERTERS FOR BATTERY CHARGING APPLICATIONS

The charging of EV batteries is a complex process, and several factors can affect the system's performance. Several studies have evaluated various battery charging technologies to improve charging efficiency and increase the charging speed. The PWM technique is the most widely used method for charging batteries despite its drawbacks. Different topologies and control improvements with variation were proposed in recent literatures. Fast charging betterment with analyses were discussed, and to improve the performance under a wide operating range and various modulation schemes have been proposed earlier. Several key and traditional battery charging approaches with associated optimization methods have been presented in the recent research developments.

The previous works define that the three-level boost converter can increase efficiency and reduce the size of the magnetic components. However, the three-level boost converter has many limitations such as high electromagnetic interference (EMI) in terms of common mode noise and this noise has a negative impact on the battery system. The three-level boost converters cannot be paralleled easily, and it is another drawback. Another potential three-level topology for battery EV chargers is a flying capacitor converter which has been shown in a research work.

This three-level topology has a smaller inductor connection compared to a boost converter and also the power rating of the converter can be easily increased by paralleling and interleaving multiple phase legs. However, the short circuit protection design is challenging due to the presence of the flying capacitor. Moreover, the switching commutation loop of the flying capacitor converter involving the uppermost and lowermost devices is larger than that of three-level boost converter which may cause undesired voltage overshoot during switching. Another concern is the DAB Converter which produces high frequency charging ripple resulting from the reactive power that is a restriction of converter operation and switching losses are present there.

The controllability of CLLC converter is another challenge, as the voltage gain curve against frequency tends to be steady in a specific frequency range. T-type Vienna rectifier preserves all the advantages of three-level converters, but this converter also has some common issues as example: three-level converters need a DC-link capacitor for voltage balancing. Another major limitation for Vienna rectifier is the unidirectional power flow and limited reactive power control, and the range of achievable reactive power is narrow due to the restricted modulation vector [10, 11]. The above problems can be solved through designing the proposed Split-Pi Bidirectional converter-based battery charger for charging EVs through conductive and inductive methodologies.

The Split-Pi Converter provides constant rectification in both voltages step up and down. Its control is simple, utilizes less electronic components, easy protection against reverse current resulting from the battery, provides size reduction, and efficiency improvement over the parameter implementations by minimizing overall power loss in the energy conversion and charging process. Topologies built on Split-Pi Bidirectional DC-DC converter must be useful which can provide solutions to all major issues of charging technologies and to observe the battery response [12, 13]. This newly proposed converter will have an easy design, control, and implementation process.

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TABLE I
COMPARISON OF BIDIRECTIONAL AC-DC CONVERTER TOPOLOGIES FOR BATTERY CHARGING METHODOLOGIES

No.	Converter	Switches/Diode	Bidirectional	Control Complexity
1.	PWM Converter	6/0	Yes	Low
2.	NPC Converter	12/6	Yes	Moderate
3.	DAB Converter	8/0	Yes	Moderate
4.	CLLC Converter	8/0	Yes	Moderate
5.	Split-Pi Converter	4/0	Yes	Very Low

The Split-Pi converter technology has shown great potential as a possible alternative to PWM technology. Some of the benefits of the Split-Pi converter over PWM converters include fewer switching losses, low EMI, and reduced cost due to lower component count.

The Split-Pi converter can also operate at variable input and output voltages, making it more flexible than traditional PWM-based conversion [15, 16, 17]. This research aims to investigate the Split-Pi converter technology's suitability for the proposed battery charging and explore design control strategies for optimized charging performance.

III. FRONT-END STAGE CONVERTER (AC-DC RECTIFIER)

A. Topologies

Rectifiers convert AC supply voltage to a DC output voltage at a fixed and specified rate. They are not only used in various industrial applications (Such as electronic ballasts, household electric appliances and motor drives), but also, they are used in in battery charging, power conversion, high voltage direct current (HVDC) applications etc. Although rectifiers provide a DC output, they have some disadvantages such as AC-side harmonics, output ripple, and mean voltage which are reduced by output filter capacitors. Due to the wide range of applications, rectifiers have different configurations and classifications.

Rectifiers are mainly classified into two types: Full Wave Rectifier and Half Wave Rectifier. AC-DC converters can be further classified according to line or naturally commutated rectifiers and forced commutated rectifiers, and each of these two can be classified into either regenerative or non-regenerative.

DC fast chargers convert AC power to DC within the charging station through the rectifier and deliver DC power to the battery through DC-DC converter. Hence, Center Tapped Rectifier has been implemented in this research work and simulation.

This rectifier is generally known as a full wave rectifier. A center tapped full wave rectifier is a type of rectifier that uses a center tapped transformer and two diodes to convert the complete AC signal into DC signal [14]. This rectifier is used to convert high input AC voltage to low DC voltage. These rectifiers are used to provide power to motors, LEDs, etc. The Center tapped rectifier model with simulation values in MATLAB/Simulink is shown in Fig. 1.

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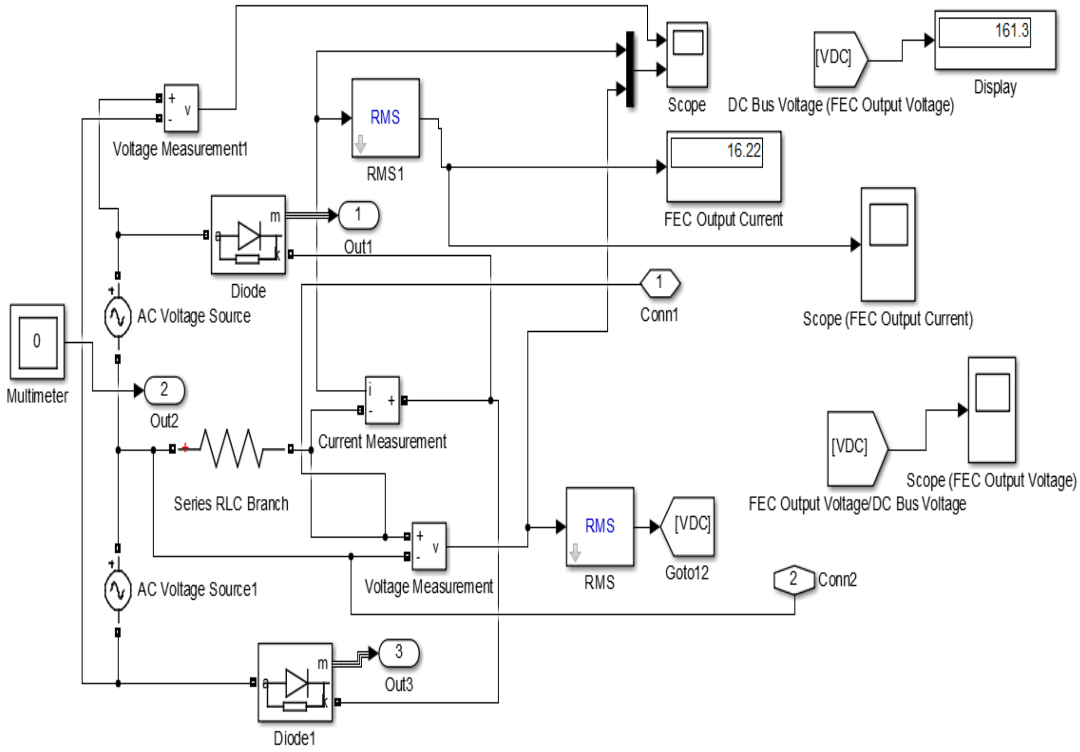

Fig. 1. Rectifier (Center-Tapped) Simulation in MATLAB/Simulink

B. The Rectifier Closed Loop Controller System/Front End Converter Controller System

Center-Tapped Rectifier/Front-End AC-DC Converter controller system is shown in the Simulink model in Fig. 2. An abc-dq control loop is implemented for unity power factor. The proposed control model provides regulated output DC voltage with unity power factor and superior input power quality. The rectifier input voltage is three phase 220 V and 50 Hz. The rectifier output voltage we have got is 161.3 VDC and the rectifier output current is 16.22 Amps DC shown in simulation in Fig. 1. The simulation of AC-DC front end rectifier is done in MATLAB Simulink based on the voltage control strategy. Voltage controller is implemented in synchronous rotating dq frame to control active and reactive power separately by controlling currents in d and q axes respectively [18].

C. Rectifier dq-Equations

Following the Park Transformation, we get

$$\mathrm{V}_{dq} = \mathrm{V}^{c} e^{-j\theta} \quad (1)$$

Here, V^{c} is a space vector ($\mathrm{V}^{c} = \mathrm{V}_{\alpha} + j v\beta$). We find that,

$$u_{dq} e^{j\theta} = \mathrm{R} i_{dq} e^{j\theta} + \mathrm{L}\,(e^{j\theta}\,(jwi_{dq} + \frac{di}{dt} dq)) + e^{j\theta}\, u_{sdq} \quad (2)$$

$$u_{dq} = \mathrm{R} i_{dq} + \mathrm{L}\frac{di}{dt} dq + jLWi_{dq} + u_{sdq} \quad (3)$$

With separation of real and imaginary part, we get

$$u_d = Ri_d + L\frac{diq}{dt} - wLi_q + u_{sd} \quad (4)$$

$$u_q = Ri_q + L\frac{diq}{dt} - wLi_d + u_{sq} \quad (5)$$

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There will be two principal parts for the control model of the rectifier (AC-DC front-end stage converter): They are controller and modulation signal which are shown in Fig. 2.

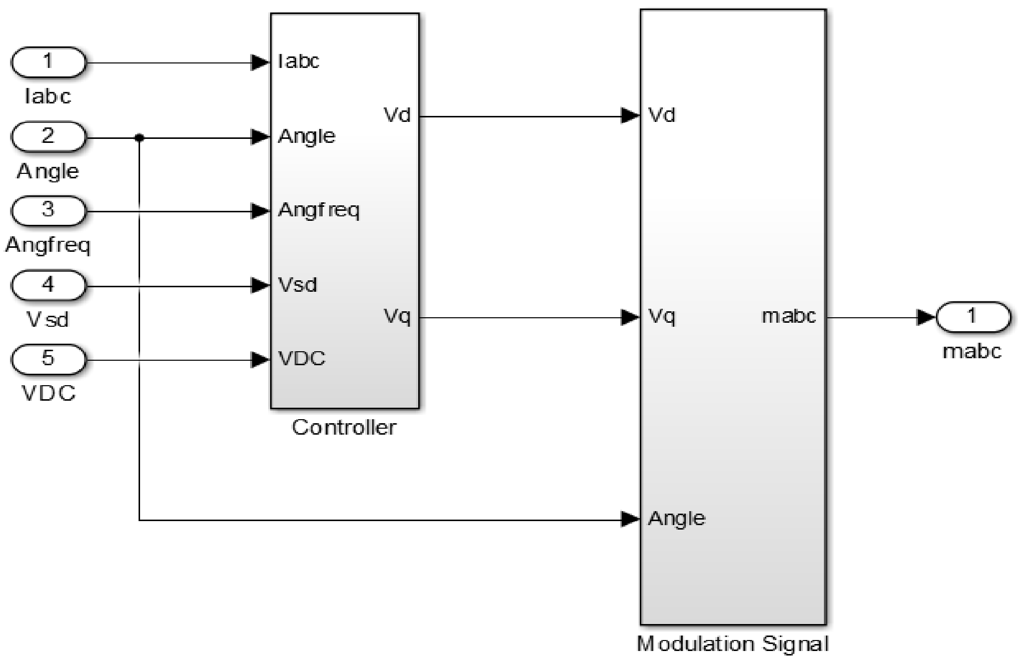

Fig. 2. Control Model of Front-End AC-DC Rectifier

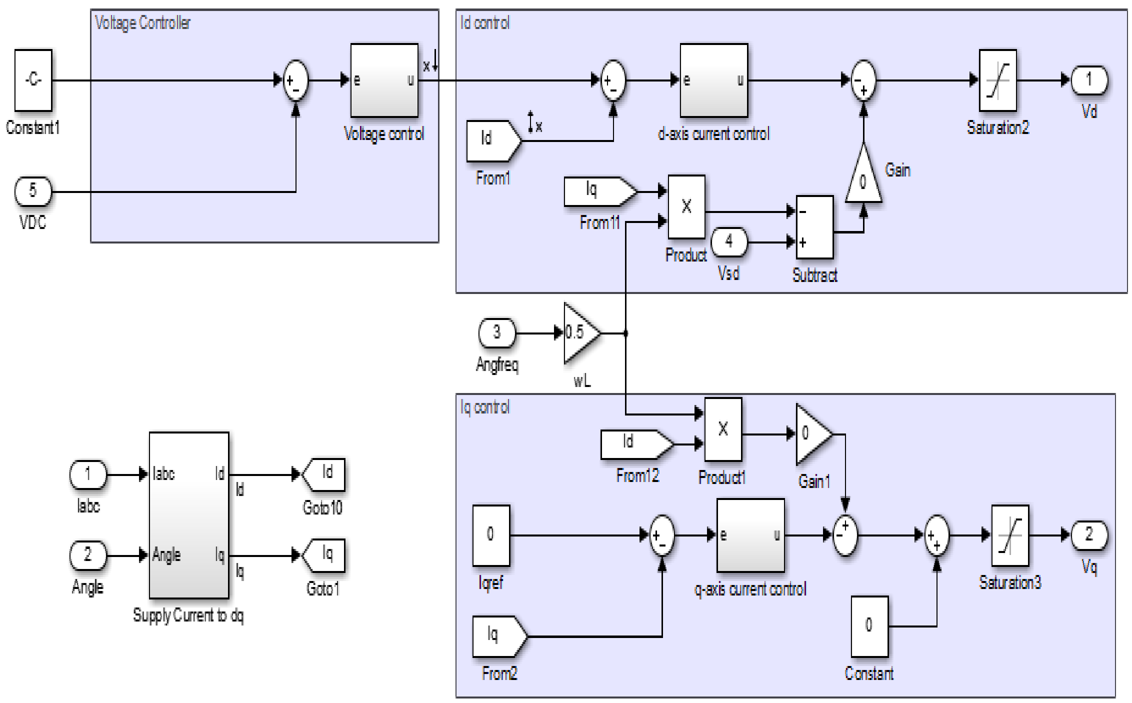

Fig. 3. Inside the Controller Block in FEC Controller Circuit

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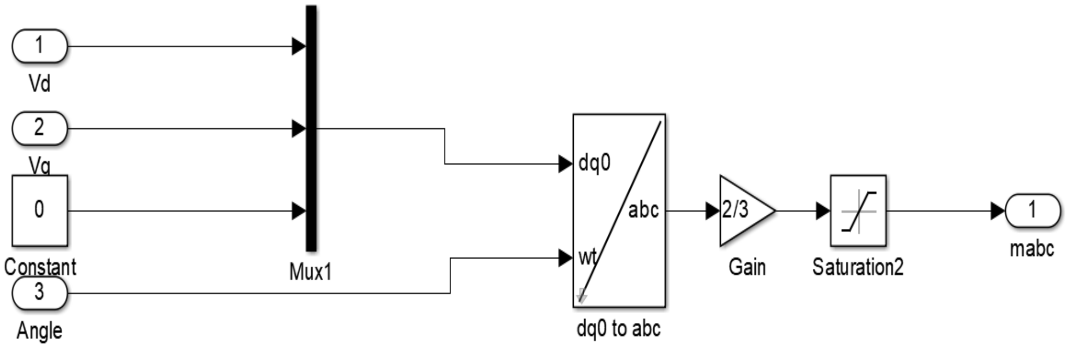

Fig. 4. Inside the Modulation Signal Block in FEC Controller Circuit

D. Overall Rectifier/Front End Converter Simulation

The simulation of closed-loop AC-DC rectifier with controller shown above has been presented in MATLAB/Simulink. The FEC output voltage or rectifier output DC voltage is 161.3V DC shown in Fig. 5. The FEC output current or rectifier output DC current is 16.22 Amps displayed in Fig. 6. The FEC Output DC voltage is fed to the Split-Pi DC-DC Converter system to get the constant voltage DC output which can be lower or higher voltage according to the battery charging voltage.

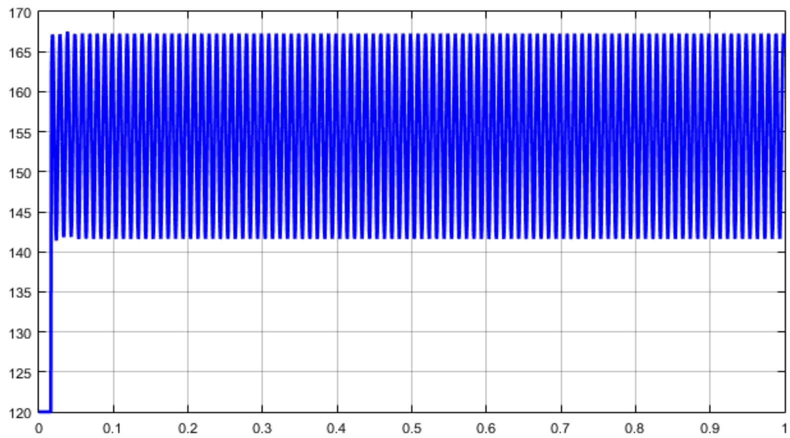

Fig. 5. Front End Converter (AC-DC Rectifier) Output DC Voltage

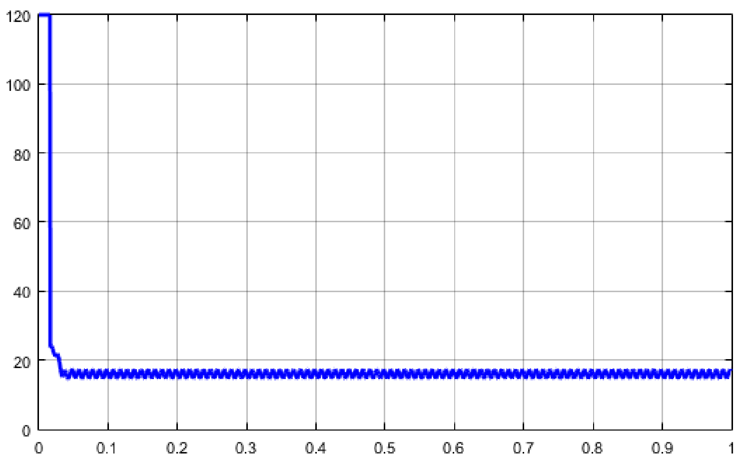

Fig. 6. Front-End Rectifier Output DC Current

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IV. CONTROLLER SUBSYSTEM OF SPLIT-PI CONVERTER

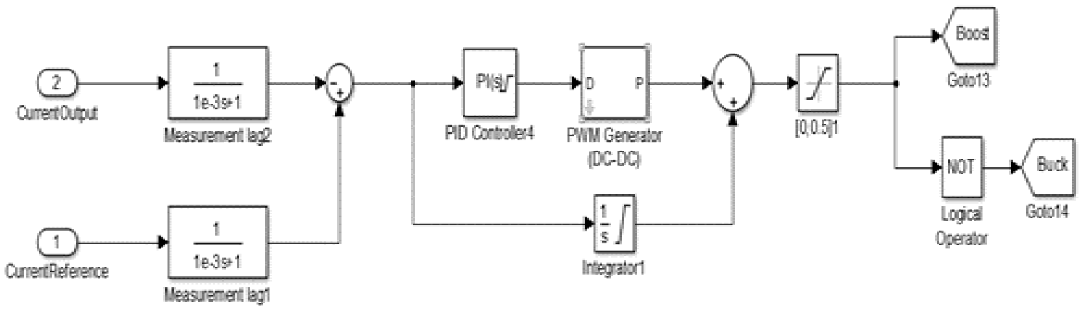

Fig. 7. Converter Controller Block in Simulink

The bidirectional Split-Pi converter works as both forward and reverse modes in case of electric vehicles, and for regenerative braking while charging the battery. A PWM control-based technique has been used here (shown in Fig. 7) to control the charging of the battery using a Split-Pi converter. PI Controller is used to control the output DC voltage. PI Controller generates a control signal (Vcs) and reduce the current error Ie(k) which is generated from the reference DC link current Ib(k) and a sensed DC link current Ic(k) at a kth instant of time as,

$$Ie(k) = Ib(k) - Ic(k) \quad (6)$$

The output of the PI controller Vout(k) can be written as,

$$Vo(k) = Vo(k-1) + Kp\,\{Ie(k) - Ie(k-1)\} + KI\,Ie(k) \quad (7)$$

Here, Kp and KI are the proportional and integral gains of the PI controller. This technique is applicable to the buck mode as well as boost mode and to get the control signals for the bidirectional Split-Pi converter.

V. SPLIT-PI CONVERTER CONNECTED WITH BATTERY PACK FOR EV SYSTEMS

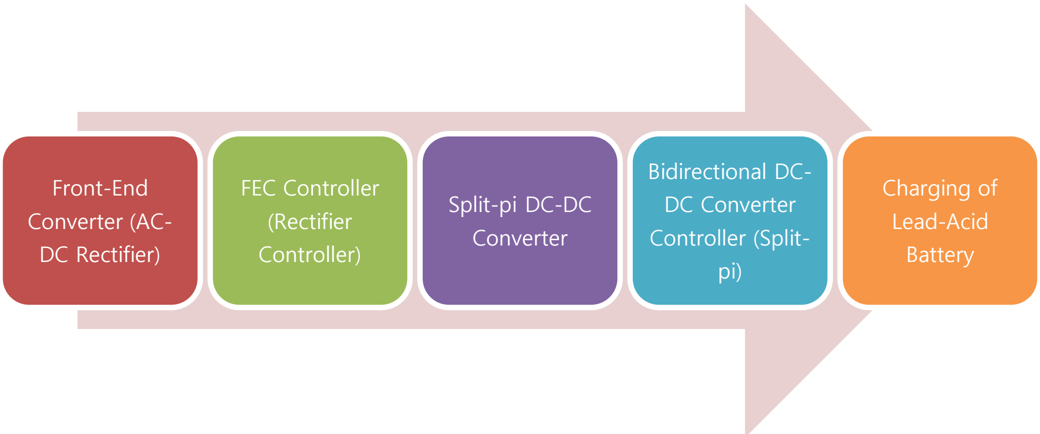

Fig. 9. Block Diagram of the Conductive Charging Scheme

In EV applications, a converter with bidirectional power flow capability is very much needed to link the battery with DC bus and transfer energy between them with flexible control in all their operating modes. The Split-Pi converter is expected to exchange energy between the batteries and the drive motor. In the forward mode, the converter feeds the DC bus and in the reverse mode, the drive motor works in regenerative mode charging the battery pack through the Split-Pi converter again. Both step up and step-down operation are the characteristics of this DC-DC converter and it works as bidirectional mode. This converter is suitable for EVs as the batteries can be operated at well understood voltage also [8, 19]. So, Split-Pi topology operates also in reverse mode for charging the battery during regenerative braking because of bidirectional capabilities. Hence, the need for an additional power electronic converter for charging the battery at a time can be easily solved.

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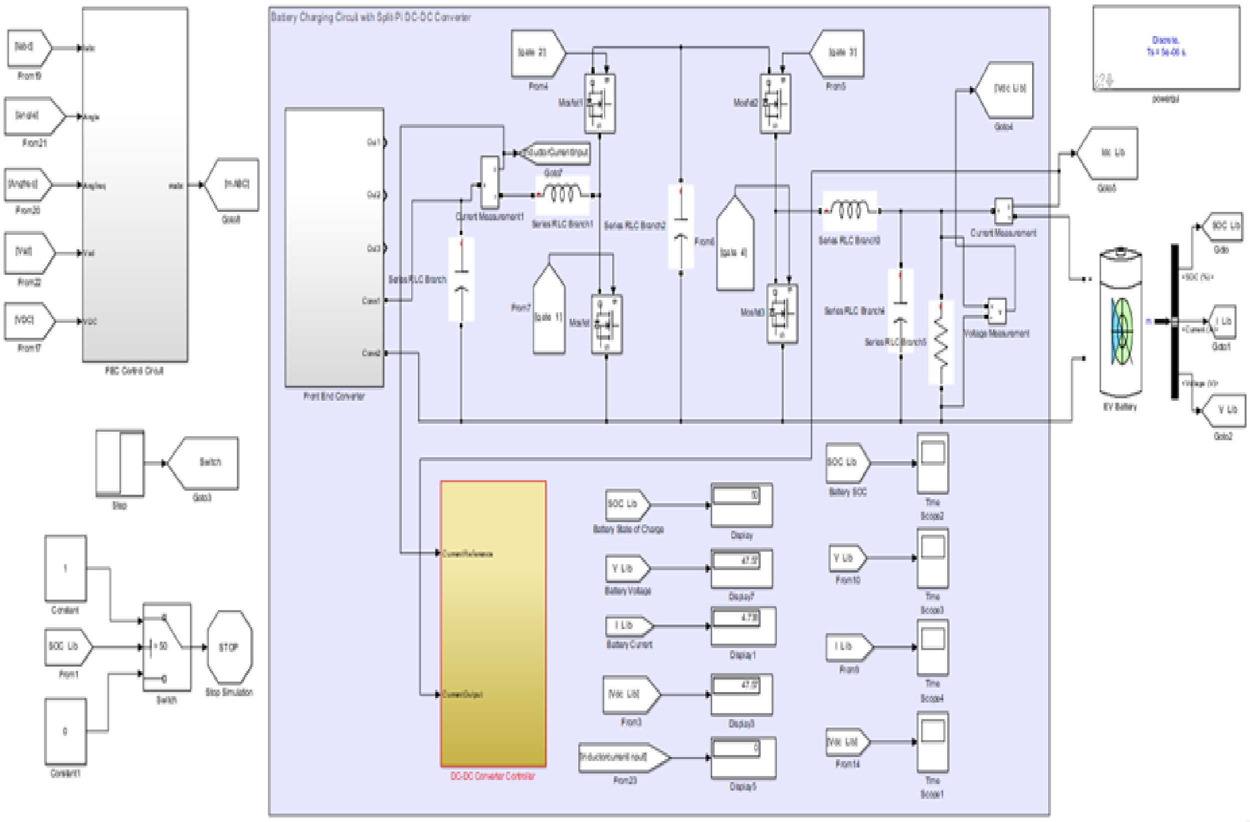

Fig. 8. Modeling of Simulation on Conductive and Fast Battery Charging in MATLAB/Simulink

TABLE II
SIMULATION PARAMETERS OF SPLIT-PI DC-DC CONVERTER FOR CONDUCTIVE BATTERY CHARGER

No.	Parameters	Value
1.	Input Voltage (Rectifier Output Voltage) Vin	161V
2.	Output Voltage (Vout)	48V
3.	Inductors L1, L2	100mH
4.	Capacitor C1, C2	100µF
5.	Switching Frequency	10KHz
6.	Capacitor C	500µF

Lead acid battery has been selected in the simulation for analyzing the charging outputs. Battery Nominal voltage is 48V, rated capacity is 150Ah, and state of charge (SOC) is 50% identified for lead acid battery.

Finally, the battery response time and the simulation time has been put 1 Second to check the battery charging outcomes.

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VI. SIMULATION DEVELOPMENT FOR CONDUCTIVE BATTERY CHARGING

The entire simulation process consists of Split-Pi DC-DC Converter, Battery, Front End stage converter/Center tapped rectifier, Rectifier controller, DC-DC Converter controller, etc. (shown in Fig. 8) with all simulation values including parameters. For the full simulation, lead acid battery has been chosen consisting of nominal voltage (48V) and rated capacity of 150 Ah. The simulation is designed and controlled for 1 second run time, and the outputs have been found out through observation of battery response time.

VII. SIMULATION RESULTS WITH SPLIT-PI CONVERTER BASED BATTERY CHARGER

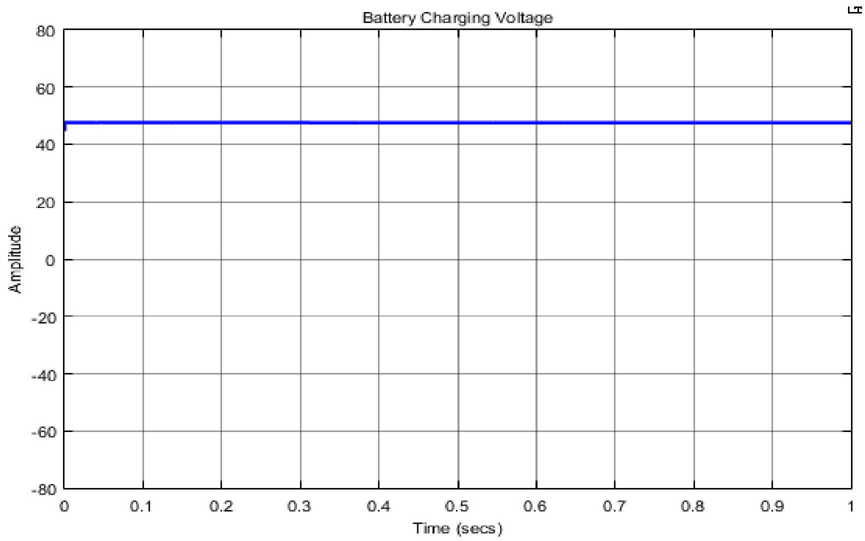

Fig. 10. Battery Charging Voltage in Conductive Mode (48V)

Battery charging voltage is 47.57V that has been simulated with lead acid battery shown in Fig. 10. Converter output voltage is constant and same as battery charging voltage. Closed-loop simulation output obtained is 47.57V (displayed in Fig. 8).

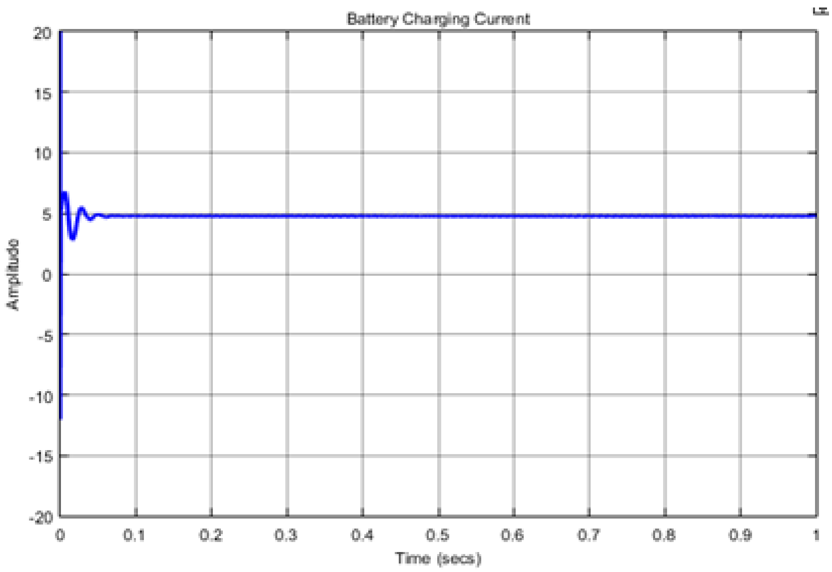

Fig. 11. Battery Charging Current in Conductive Mode

Battery charging current is 4.738 Amps shown in Fig. 11. The charging current/output current depends on the output load resistance of the converter. If output load resistance is high, then the charging current will be low. The lower the output load resistance, the higher the battery charging current.

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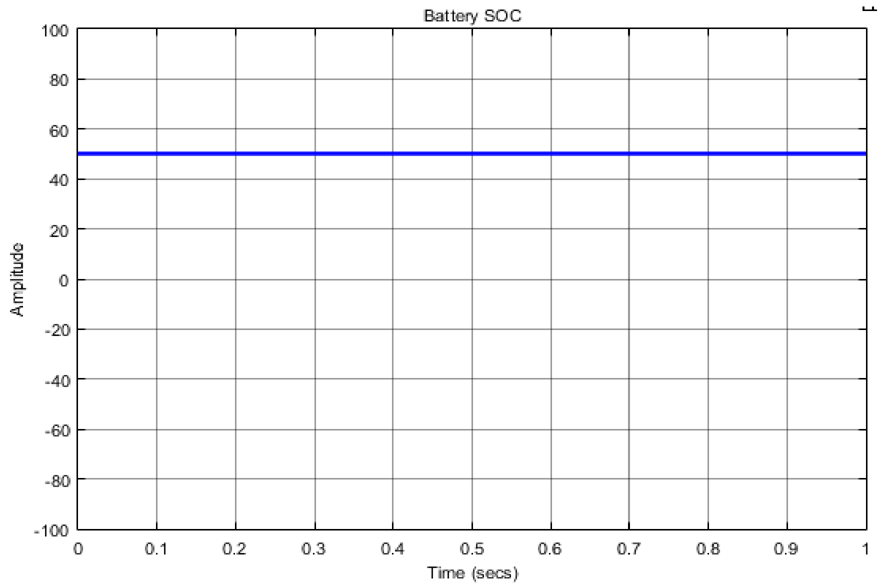

Fig. 12. Battery State of Charge (SOC)

Battery SOC is 50% as shown in Fig. 12. From the simulation displayed in Fig. 10, Fig. 11 and Fig. 12, it can be understood that the system compactness can be achieved, and the conductive battery charging will be enabled with no disturbance through the proper implementation of Split-Pi Converter based battery charger.

VIII. INDUCTIVE EV CHARGING TOPOLOGY WITH BATTERY CONTROLLED SPLIT-PI CONVERTER

The detailed simulation on inductive/wireless EV charging with Split-Pi Converter has been shown in Fig. 14. The inverter will convert DC supply through DC source into AC Supply. Here, two coils have been simulated such as charging station side in primary coil and the secondary coil includes an electric vehicle which consists of rectifier, Split-Pi DC-DC Converter and battery. Rectifier inside an electric vehicle converts AC Supply from inverter into the DC Supply and then this DC Supply is fed to Split-Pi DC-DC Converter to maintain the lower or higher DC output voltage in the battery side according to reference voltage and DC battery voltage. Through the primary and secondary coil, energy is transferred wirelessly as explained in Fig. 14 (simulation and parameter values included). Lead acid battery has been chosen for analyzing the charging performance where the battery nominal voltage is 10V, rated capacity is 2Ah, and initial state of charge is 50%. With the assistance of battery controller, battery is controlled as it gives wireless charging voltage and current with estimated state of charge. Simulation subsystem of Battery charge controller has been demonstrated in Fig. 15.

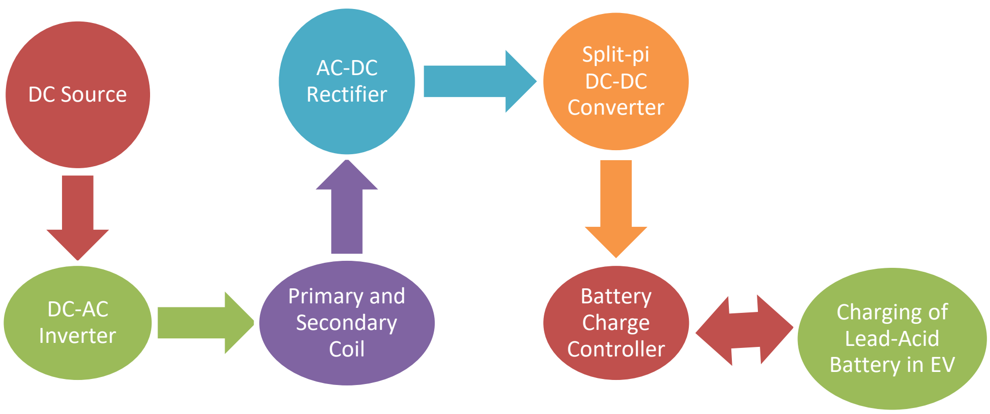

Fig. 13. Block Diagram of the Proposed Wireless Charging Scheme

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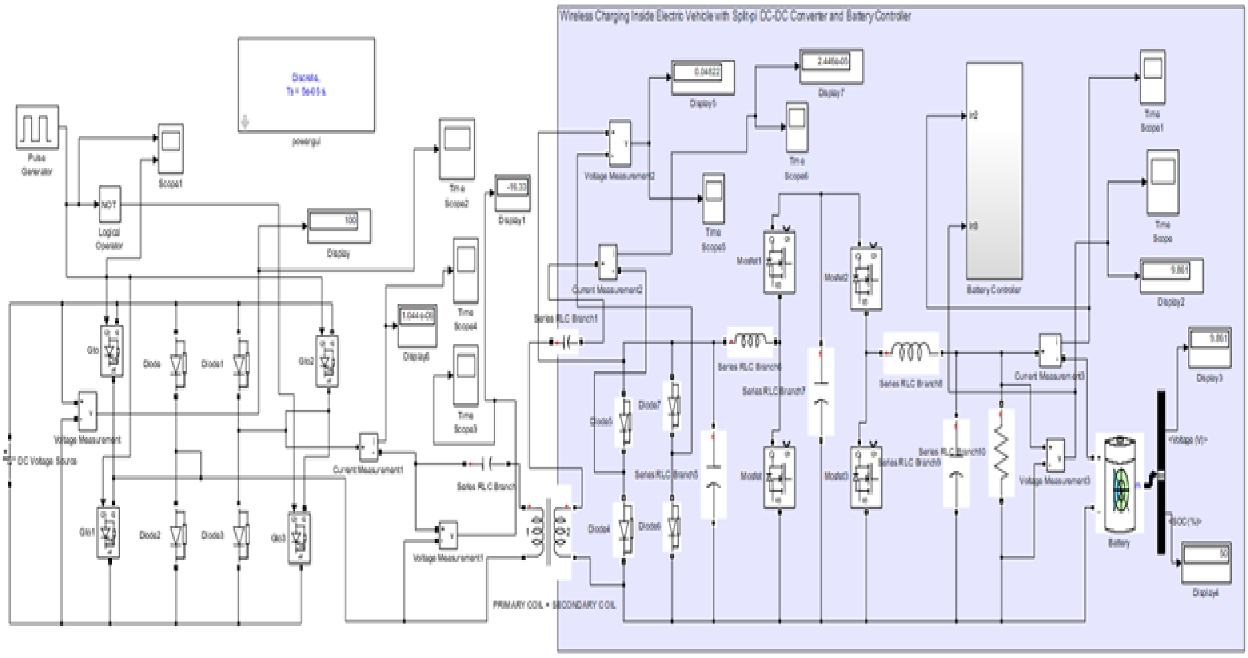

Fig. 14. Simulation Model with Split-Pi DC-DC Converter for Wireless (Inductive) EV Charging Scheme

Here, simulation parameters of Split-Pi converter for inductive chargers are given as: Inductors L1, L2: 100mH, Capacitor C1, C2: 100µF, Capacitor C: 500µF, PWM Switching Frequency: 10KHz. Moreover, the battery nominal voltage is 10V, rated capacity is 2Ah, and state of charge is 50%.

Lead Acid Battery is further selected in simulation here to check the battery charging performance. Battery response time is kept at 1 second as the charging performance has been obtained up to 1 second in MATLAB/Simulink implementation.

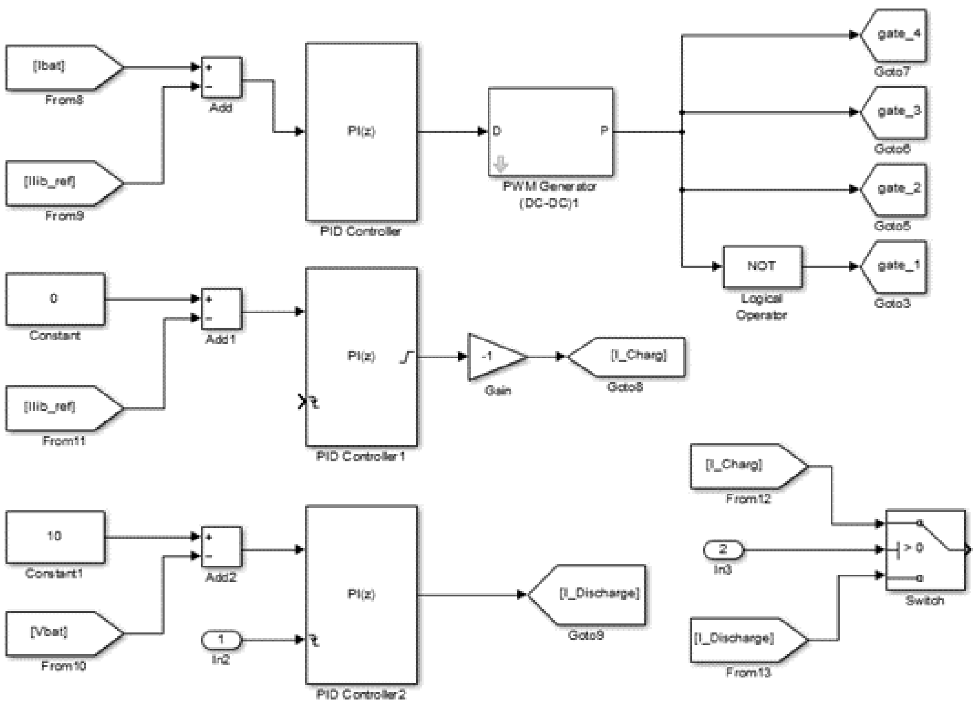

Fig. 15. Simulation Model of Battery Controller for Inductive Charging Implementation

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The battery controller (shown in Fig. 15) is needed to charge a battery pack safely. This controller protects the battery from overcharging and prevents reduction in the battery life of the EV charging system.

IX. SIMULATION RESULTS ON WIRELESS EV CHARGING DEVELOPMENT

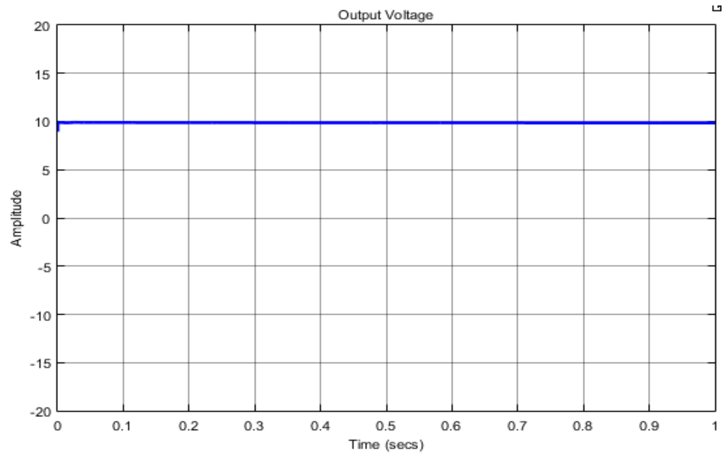

Fig. 16. Battery Voltage in Wireless Charging Simulation

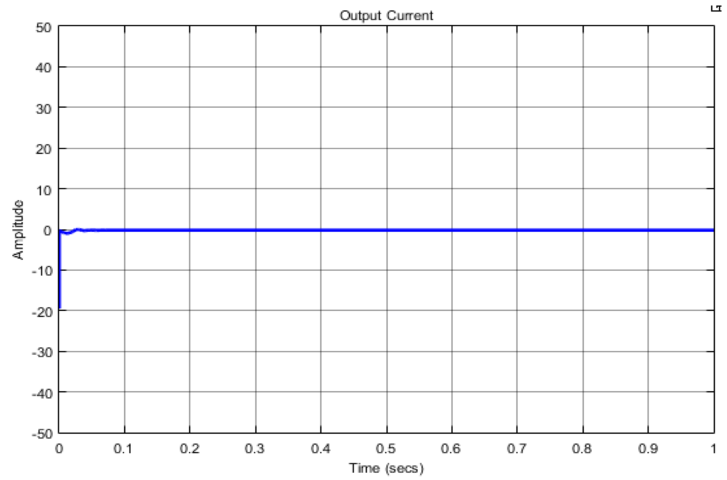

Fig. 17. Battery Current in Wireless Charging Simulation

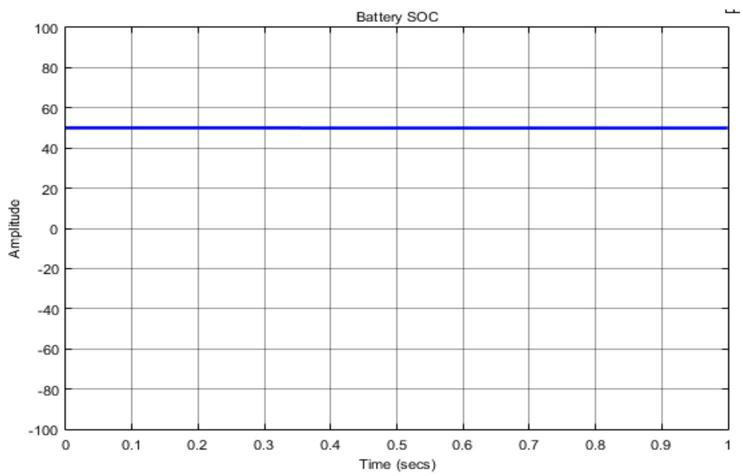

Fig. 18. Battery SOC

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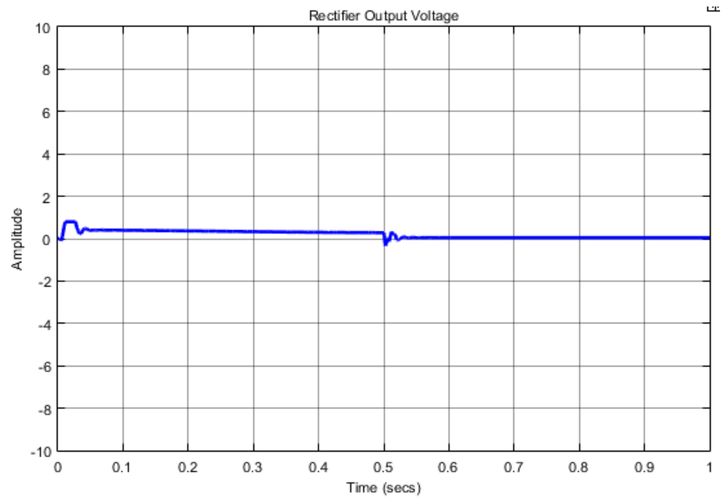

Fig. 19. AC-DC Rectifier (Inside Wireless EV Charging Block) Output DC Voltage

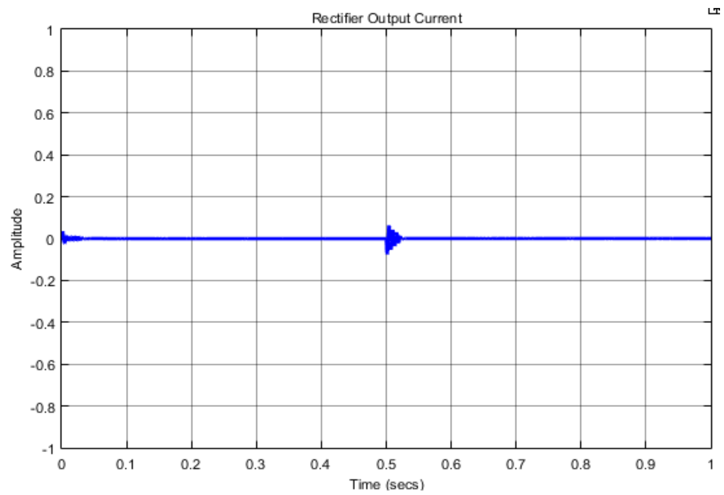

Fig. 20. AC-DC Rectifier (Inside Wireless EV Charging Block) DC Output Current

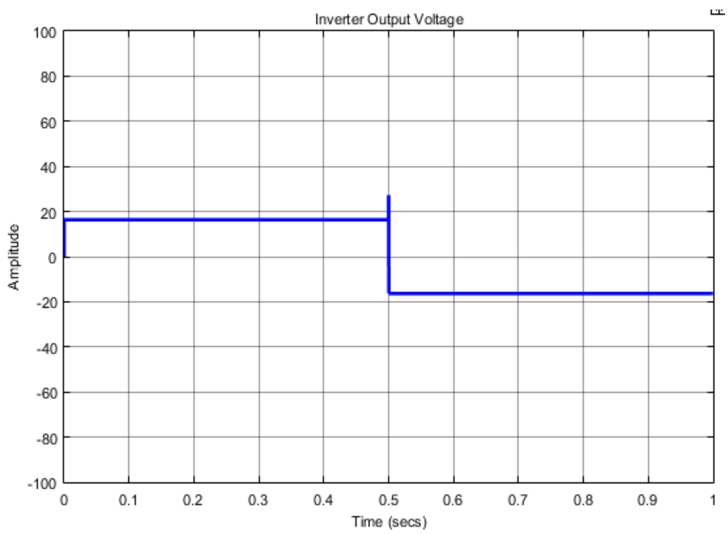

Fig. 21. Inverter Output AC Voltage

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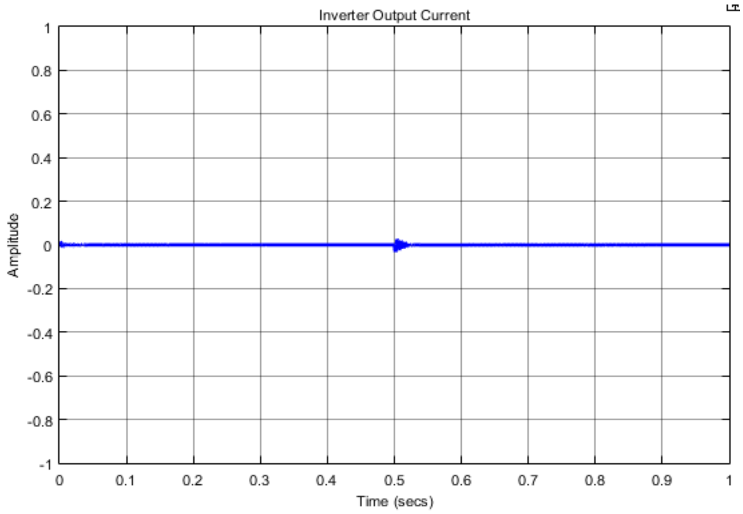

Fig. 22. Inverter Output Current

From the simulation results (Fig. 16 to Fig. 22), we find that the battery charging voltage is 10V (approximately), Battery Charging current/Output current is almost 0A, Battery SOC is 50%, Rectifier output voltage is 0.04822V, Rectifier output current is 0.00002A, Inverter output AC voltage is -16.33V, and Inverter output AC current is 0.000001A all of which has been carried out in inductive charging analysis on Simulink (shown in the simulation model in Fig. 14). Analyzing all the simulation outputs, it can be well observed that Split-Pi converter topology is working properly through its parameter's configuration in the development of wireless (inductive) EV charging operation.

The most useful and efficient battery technology for electric vehicles has been lithium-ion batteries until now. Among all kinds of functional batteries, nickel-based batteries such as nickel–cadmium (Ni–Cd), nickel–metal hydride (Ni–MH), and nickel–iron (Ni–Fe) have gained a lot of popularities. Besides all these, lead-acid batteries are also very beneficial. For simulation perspectives, lead-acid batteries are implemented here for better charging performances. Moreover, Split-Pi bidirectional converter is capable of providing dynamic outputs with a battery controller system by which the charging performances are well efficient.

X. WIDE-BANDGAP DEVICES

In this section, the importance of utilizing wide-bandgap semiconductor devices in case of converter switches used in EV chargers has been discussed. Almost all electric vehicle chargers vary from one to another in case of power density, size, and weight specifications. So topological configurations and control strategies become more difficult, and they are not able to meet performance targets alone. Electric vehicle manufacturers are now finding the usage of wide-bandgap materials such as SiC or GaN based switching devices for better charging applications. The wide-bandgap-based chargers are the reliability of switching devices for higher acceptance and easiest implementation [23]. In the near future, the SiC devices might be used in everywhere for high-power charging applications, and the GaN devices will be the best solution for low power charging applications.

A. SiC Devices

SiC based devices regulate very fast and are workable up to three times over Si-based devices. A SiC based EV charger would always have higher power density and efficiency which is far better than the Si devices. The filter size and HF transformer size can be significantly reduced in case of SiC device and SiC based device can operate at higher frequencies for their operational ability. These materials have fast reverse recovery applications, and operate very faster and smoothly compared to ultrafast Si devices [20, 21]. Such devices are also applicable for drivetrain propulsion machine inverters. In fact, they are the most useful and valuable components at present.

B. GaN Devices

GaN and SiC devices have similar power ratings, but the manufacturing cost of GaN is lower than SiC. The GaN devices provide many advantages such as a higher critical electric field, high power mobility and high-power density. The electron mobility in a GaN device is twice compared to SiC device. For this reason, GaN device is faster than SiC devices.

The main advantage of using wide bandgap materials for EV applications is to help the machines in cooling requirements and adjustment, and GaN devices are useful for low power applications in there. In addition to these, they are more active as one fourth time of SiC devices [22, 23]. But, GaN technology is less mature compared to SiC technology in some of the EV applications such as motor inverters, battery chargers, and PFC circuits etc. Besides that, GaN devices have some limitations in comparison with SiC devices as examples: they sometimes have lower power rating, lower thermal conductivity, and lower operating voltage etc.

XI. CONCLUSION

This article has discussed and analyzed the development of battery charging technologies based on different control strategies focusing and designing of Split-Pi converter-controlled DC conductive charging and inductive charging system for EVs. The simulation involves with modeling of the battery-controlled Split-Pi converter comparing its performance alongside other bidirectional converter-based charging systems and analyses over unidirectional converters as well. Battery charging is an essential factor for EV performance and fast charging is vital to meet the growing demand for electric cars now a days. Electric vehicles are becoming more popular as they offer a cost-effective and efficient means of transportation while reducing environmental pollution at the same time. The pulse width modulation techniques consisting of other converters managements are widely used to charge batteries; however, these methods suffer from several drawbacks such as high switching losses and electromagnetic interference etc. These drawbacks have led to the exploration of alternative technologies, mostly as selection of the Split-Pi DC-DC converter and controller processes shown in this research work. It's bidirectional power flow capability, power quality control, scalability makes it a promising choice for the EV charging infrastructure.

Furthermore, the design of efficient wide bandgap-based chargers needs proper knowledge of the physical operation of semiconductor power devices and learning of their thermal and electrothermal behavior. Continued emphasis on charging systems will deeply accelerate the process for battery EV chargers to take advantages and gains of advanced wide bandgap semiconductor materials such as SiC and GaN devices. Those wide-bandgap devices market is growing very high these days which could be essential for converter-based battery chargers and also for cost reduction in electric vehicle systems in the upcoming decades. However, the findings presented in this paper has been presented for the widespread adoption of the Split-Pi converter for future EV charging applications, and all the results have shown this converter technology's suitability for charging requirements and better performance. All the output results provide accuracy into the Split-Pi converter's charging feasibility as well as using of controllers on converter specifications.

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