



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 13, Issue 4, April 2024

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.423

9940 572 462

6381 907 438

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Off-Board Electric Vehicle Battery Charger Using PV Array

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ABSTRACT: Over the past decade, the automobile industry has seen a significant surge in the development of electric vehicles (EVs), largely driven by the advancement of electric vehicle technology. A crucial aspect of this advancement lies in the battery charging system used in EVs. However, charging these batteries from the traditional grid can strain the power supply. To address this issue, a novel solution is proposed in this study: a photovoltaic (PV) array-based off-board EV battery charging system. This system aims to charge EV batteries consistently, regardless of solar irradiation levels. To achieve this, a backup battery bank is incorporated alongside the PV array. The setup utilizes a sepic converter and a three-phase bidirectional DC-DC converter. During periods of peak sunshine, both the EV battery and the backup battery are charged simultaneously. Conversely, during non-sunshine hours, the backup battery steps in to support the charging of the EV battery. To validate the effectiveness of the proposed system, simulations were conducted using Simulink in MATLAB software. Additionally, an experimental prototype was constructed and tested in a laboratory setting. The results of these tests are detailed in this study, demonstrating the feasibility and functionality of the PV array-based off-board EV battery charging system.

KEYWORDS: Electric vehicles (EVs), Battery charging systems, Traditional grid, Photovoltaic (PV) array, Off-board, Backup battery bank, Sepic converter, Three-phase bidirectional DC-DC converter, Peak sunshine hours, Non-sunshine hours, Simulations, Simulink, MATLAB software.

I. INTRODUCTION

The rise in greenhouse gas emissions from traditional internal combustion engines has sparked environmental concerns, leading to the surge in pollution-free electric vehicles (EVs). However, charging EV batteries from the grid strains electricity demand and increases bills for EV owners. This necessitates the use of renewable energy sources (RESs) like solar power to charge EVs, promoting 'green transportation'. Lithium-ion batteries are favored for their efficiency and fast-charging capability. Power converters with voltage control are essential for precise battery charging. Multiport converters (MPCs) are preferred for their ability to connect various power sources to EV loads, but they add weight and complexity. Off-board chargers, where the EV battery remains in the vehicle while solar panels and backup batteries are stationed elsewhere, offer a solution. Among converter topologies, the sepic converter is favored for its versatility. However, during low solar conditions, a bidirectional converter is needed to utilize backup batteries efficiently. Non-isolated bidirectional converters like the bidirectional interleaved DC-DC converter offer advantages such as improved efficiency and reduced size. This system charges EV batteries from solar power using a combination of converters and backup batteries, ensuring uninterrupted charging even during non-sunshine hours.

1.1 MOTIVATION

An off-board charger for electric vehicle (EV) batteries is designed to alleviate the strain on the grid caused by charging. This system utilizes solar PV arrays to charge the EV battery when it's parked, and then the battery powers the EV when it's in use. To enable this dual-mode functionality, a three-phase bidirectional DC-DC converter is employed. When the EV is stationary, the PV array provides power to charge the battery, and when it's on the move, the battery supplies power to the vehicle's DC load. This off-board EV charger relies on renewable energy sources (RESs) and is environmentally

friendly. However, since solar power can be inconsistent, power converters are necessary to ensure uninterrupted charging of the EV battery.

1.2 OBJECTIVES

Off-board electric vehicle (EV) charging with a photovoltaic (PV) array taps into renewable energy, lessening reliance on fossil fuels and aiding in the fight against climate change. This approach can lead to cost savings, as solar energy is often more economical than grid electricity over time. Depending on factors like PV array size and sunlight availability, it's even possible to completely eliminate charging expenses. Furthermore, off-board PV charging promotes energy independence for EV owners. They become less dependent on external energy sources like the grid, which may experience disruptions or fluctuations.

1.3 CONTRIBUTION

An off-board charger powered by a PV array can replenish an electric vehicle's battery using solar energy. This setup employs a bidirectional DC-DC converter to charge the battery while the vehicle is parked and then uses the battery to power the vehicle's DC load while it's in motion. This system operates in two modes, allowing the battery to receive power from the PV array when the vehicle is stationary and enabling it to supply power to the DC load when the vehicle is moving.

II. LITERATURE SURVEY

[1] Santhosh, T.K., Govindaraju, Dual input dual output power converter with one-step-ahead control for hybrid electric vehicle applications" is a paper by T.K. Santhosh and C. Govindaraju published in IET Electrical Systems in Transportation in January 2017. The paper is about developing a predictive current controller for multi-port DC/DC converters. It also proposes a simplified structure of dual input dual output (DIDO) with single-stage power conversion for hybrid electric vehicle accessory applications. The topology is synthesized using pulsating source cells.

The paper is related to the development of dual input dual output with specific focus to the onboard automotive loads. It also discusses the rapid conversion of automotive accessory loads to the electrical domain, which demands a power converter to interface between the on-board source and storage units with the accessories.

Transportation electrification is gaining momentum due to recent interest in energy efficiency and environment pollution. Though the clean carbon footprint of electric vehicle (EV) is debated seriously, its acceptance rate is increasing. Automotive sector electrified not only the power-train but also the accessories that have transformed from mechanical to the electrical domain. Meanwhile, EV in its course of evolution has included several sources and storage units into its architecture. With the increase of electrical loads in an EV, the demands have to be quenched by the on-board power sources and storage units. Several power converter architectures proposed for supplying multiple loads in the literature could be broadly classified into two types: isolated and non-isolated. Isolated converters are preferred if the voltage difference between the source and load voltage is comparatively large. Isolated converters show a common trend of shared secondary winding with individual primary windings for multiple sources. Although isolated converters are beneficial in output voltage control and isolation, the peripheral circuitry and multi-source operation are highly difficult. Non-isolated converters are preferred for rugged, compact structure with simple control. Non-isolated multiple input converters (MICs) were initially paralleled basic converters with time-multiplexed operation. The concept of pulsating source cells (PSCs) was introduced and two families of MICs were generated and analysed in. Behjati and Davoudi extended the concept of Photo basic non-isolated converters and proposed rules to synthesise them. On the synthesis of MIC, the study of is one of the earliest works done on the generation of DC/DC converters, and extended this by proposing rules to recognise basic topologies that are suitable for extension to multiple input versions. A three port converter synthesis and its analysis are handled in. Though these articles elaborate on multiple inputs and loads, the work done on the simultaneous utilisation of sources has received much less attention. This work investigates the feasibility of a non-isolated dual input dual output (DIDO) power converter suitable for automotive auxiliary applications.

The power converter also has several constraints on source utilisation, constant current operation and fault diagnosis. Out of the control techniques, predictive control method is a suitable technique to ensure constant current operation irrespective of the load condition. This work utilises a modified predictive control that applies the predictive control

action considering duty cycle and load current constraints. This constant current operation could reduce the sudden variations in source current thereby improving its life cycle. This research work proposes a DIDO converter suitable for hybrid electric vehicle (HEV). The synthesis of DIDO with a generic switch model, switch realisation, mathematical modelling, design and control implementation are presented in this work. The originality of the work lies in the utilisation of one-step-ahead control to the synthesised DIDO power converter with mode selection logic.

[2] Shukla, A., Verma, K., Kumar, R.: 'Voltage-dependent modelling of fast charging electric vehicle load considering battery characteristics' Electric vehicle (EV) integration into the power grids is increasing rapidly. To analyse the effect of charging of EVs on the distribution system, most of the literature considered EV load as constant power load (CPL) which do not represent the exact behaviour of these uncertain loads. An accurate EV load modelling is developed by determining the relationship between power consumption by EV, grid voltage and state of charges of fast charging EV load. The derived relationship is validated by simulating a realistic fast charging system to obtain a battery charging behaviour characteristics and is curve fitted on standard exponential load model. Further the impact of stochastic 24-h load profile of fast charging EVs considering the exponential load model is investigated on IEEE 123 bus distribution system and is compared with the constant impedance-constant current-constant power (ZIP) load model and CPL model. The stochastic 24-h load is developed using queuing analysis-based method. The results show that the exponential load model is the better representation of fast charging EV load and 10.19% of the reduction in annual energy demand and 11.19% of the reduction in annual energy loss is observed for exponential load model compared to the existing CPL model.

[3]. Wirasingha, S.G., "Pihef: Plug-In Hybrid Electric Factor" is a conference paper by Sanjaka G. Wirasingha and Ali Emadi, published in 2009 in the IEEE Transactions on Vehicular Technology. The paper presents a new classification for plug-in hybrid electric vehicles (PHEVs) called "Pihef", which is the average ratio of the energy provided by the grid to the sum of the energy provided by the grid and fuel. PHEVs use batteries to power an electric motor, as well as another fuel, such as gasoline or diesel, to power an internal combustion engine or other propulsion source. PHEVs can charge their batteries through charging equipment and regenerative braking. The paper discusses the growing consumer expectations, legislations pushing for higher fuel economy and lower emissions, higher fuel prices, and the realization that petroleum is a finite resource.

III. PROPOSED STRUTURE OF OFF-BOARD SYSTEM

The proposed PV-EV battery charger comprises several components: a PV array, a sepic converter, a half-bridge bidirectional DC-DC converter (BIDC), an EV battery, a backup battery bank, and a controller (refer to Fig. 1). The controller plays a key role by generating gate pulses for the sepic converter to maintain a constant output voltage at the DC link. It also controls the operation of the BIDC, switching it between boost mode to charge the backup battery from the PV array and buck mode to charge the EV battery from the backup battery. Additionally, the controller manages the auxiliary switches Sa, Sb, and Sc. During periods of high solar irradiation, all auxiliary switches are activated to connect the DC link with the PV array via the sepic converter, the backup battery via the BIDC, and the EV battery. However, when solar irradiation decreases, switch Sa is turned off to isolate the PV array and sepic converter from the DC link. Similarly, when solar power is insufficient to charge the backup battery, switch Sc is turned off to disconnect the BIDC and backup battery from the DC link. The system operates in three modes: Mode 1, where both the EV battery and backup battery are charged simultaneously from the PV array; Mode 2, where the backup battery charges the EV battery during low solar conditions; and Mode 3, where only the EV battery is charged from the PV array.

3.1:DESIGN OF THE CONVERTERS USED IN THE PROPOSED CHARGER

In the proposed charging system, the sepic converter plays a crucial role in maintaining a constant output voltage, regardless of the fluctuations in the PV array voltage. It achieves this by adjusting its duty ratio using a PI controller. The sepic converter is composed of one IGBT switch, one diode, two inductors, and two capacitors. One of its key advantages is its ability to function in both boost and buck modes, determined by the duty ratio. Unlike other converters like buck-boost and cuk converters, the sepic converter ensures that the output voltage maintains the same polarity as the input voltage. The voltage gain of the sepic converter is provided by a specific equation.

$$\frac{V_{dc}}{V_{PV}} = \frac{D}{1 - D}$$

In the equation provided, Vdc represents the DC link voltage, VPV denotes the voltage of the PV array, and D stands for the duty ratio of the sepic converter. The selection of inductors and capacitors for the sepic converter is determined based on certain criteria outlined in equations (2) to (4). These criteria involve factors such as the minimum voltage of the PV array (VPVmin), the ripple in input current (ΔiPV), the switching frequency (fsw), and the DC link current (Idc).

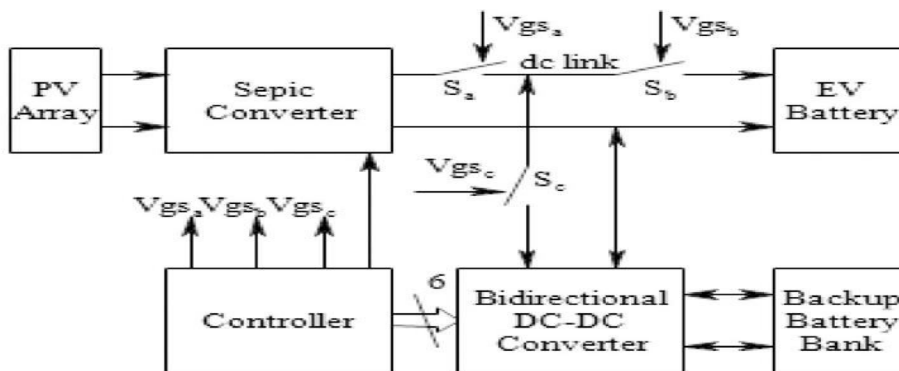


Fig3.1:Block diagram of the EV battery charger

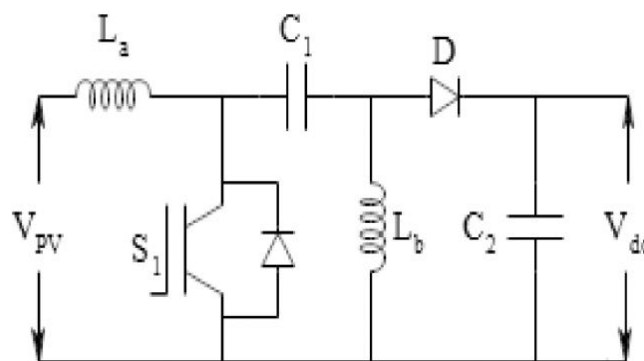


Fig3. 2 : Schematic diagram of sepic converter

The "current" mentioned refers to the flow of electricity, while "ΔVC1" represents the fluctuation in voltage across capacitor C1, known as voltage ripple. Similarly, "ΔVdc" refers to the fluctuation in the output voltage. Lastly, "Dmax" stands for the maximum duty ratio, which is calculated as follows:

$$D_{max} = \frac{V_{dc} + V_D}{V_{PVmin} + V_{dc} + V_D}$$

where V_D is the diode voltage drop. The schematic diagram of the bidirectional interleaved DC-DC converter (BIDC) used in the proposed charging system is depicted in Fig. 3. In this setup, the backup battery bank is situated on the high voltage side, while the DC link resides on the low voltage side of the converter. The converter operates in boost mode when charging in the forward direction and switches to buck mode when discharging in the reverse direction. During boost mode, active switches SL_1 , SL_2 , and SL_3 are engaged, while in buck mode, switches SU_1 , SU_2 , and SU_3 take over. Each switch is accompanied by an antiparallel diode and a parallel snubber capacitor to manage energy flow efficiently. In boost mode, inductors L_1 , L_2 , and L_3 serve as boost inductors, while in buck mode, they function as a low-pass filter. Capacitors C_L and C_H act as smoothing energy buffer elements for the converter. Interleaved inductor currents help minimize current ripples. The converter's modes of operation are analyzed by considering the operation of a single leg converter. The voltage conversion ratio of the BIDC in boost and buck modes are provided.

$$\frac{V_{BackupBatt}}{V_{dc}} = \frac{1}{1 - D_{Boost}}$$

$$\frac{V_{dc}}{V_{BackupBatt}} = D_{Buck}$$

The equation provided involves variables such as $V_{BackupBatt}$, which represents the voltage of the backup battery, and duty ratios D_{Boost} and D_{Buck} for the boost and buck modes of the BIDC, respectively. It's noted that the inductors' values are chosen to be lower than critical inductance values in both modes to ensure the converter operates in discontinuous conduction mode, thereby enhancing efficiency.

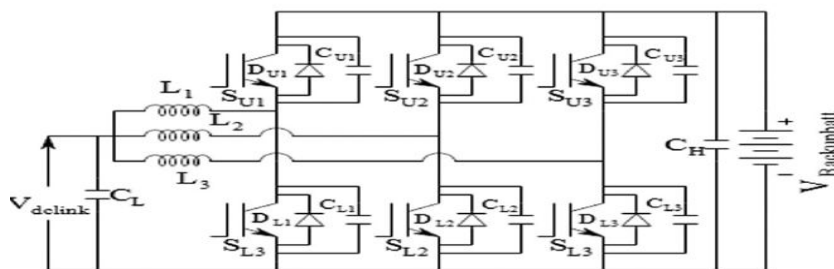


Fig3.3:Schematic diagram of half-bridge BIDC

3.2:SYSTEM CONTROL

The controller of the proposed charger is responsible for generating gate pulses for the switches in the sepic converter, BIDC, and the three auxiliary switches. This controller follows an algorithm outlined in Fig. 4. It monitors the voltage and current of the PV array and calculates its power output. If the power generated by the PV array exceeds the rated power of the EV battery (PR), the controller activates all auxiliary switches to charge both the EV battery and the backup battery simultaneously from the PV array. When the PV array power is lower than the rated power of the EV battery but higher than the minimum required power (PM), the controller turns off switch S_c to disconnect the backup battery and activates switches S_a and S_b to charge the EV battery alone from the PV array. If the PV array power falls below the minimum required power (PM), switch S_a is turned off to isolate the PV array and the sepic converter, while switches S_b and S_c are turned on to allow the backup battery to charge the EV battery. Additionally, a PI voltage controller is employed in the charging system to generate gate pulses for the MOSFET in the sepic converter, ensuring a constant voltage at the DC link regardless of variations in the PV array voltage. Regarding the BIDC, it consists of three legs with two switches in each. The controller generates six gate pulses to the BIDC based on the PV array power. If the PV array power exceeds PR, gate pulses are provided to operate the BIDC in boost mode, stepping up the DC link voltage to charge the backup battery bank. In this mode, the gate pulses are phase-shifted accordingly to control the switches in each leg. Conversely, if the PV array power is less than PM, the BIDC is operated in buck mode to produce a step-down voltage at the DC link sufficient to charge the EV battery using the backup battery. Again, the gate pulses are phase-shifted appropriately to control the switches in each leg.

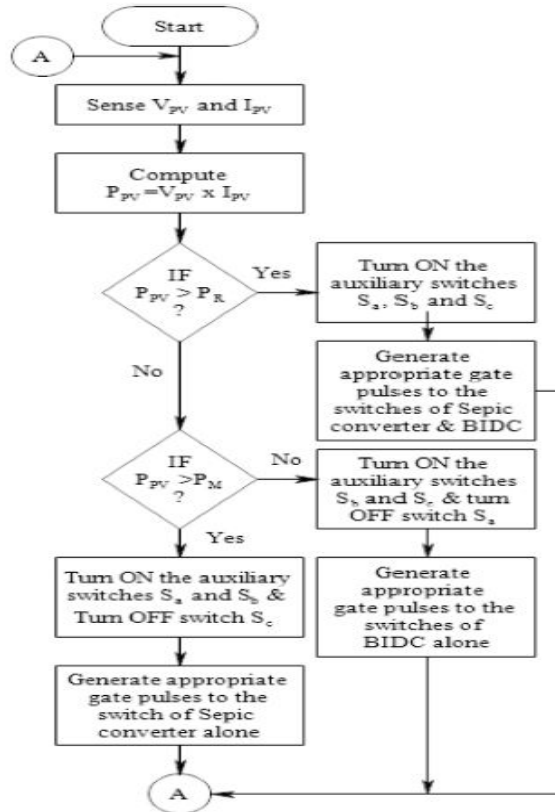


Fig:3.4 Flowchart of gate pulses generation for the auxiliary switches

3.4 BATTERY

Electricity is exceptionally versatile due to its highly organized nature, enabling efficient conversion into various other energy forms. It boasts near-perfect efficiency in transforming into mechanical energy or heat, unlike heat energy, which struggles to convert back to electricity with similar efficiency due to its atomic disorder. Consequently, typical fossil thermal power plants exhibit less than 50% efficiency in converting heat to electricity.

However, a notable drawback of electricity lies in its challenge for large-scale storage. Presently, the majority of generated electric energy is used immediately upon generation. This isn't an issue for conventional power plants, which can adjust fuel consumption based on demand. Yet, intermittent sources like wind and solar power struggle to meet energy demands consistently throughout the year. To address this, various energy storage technologies are being explored for standalone wind or solar power systems. These include electrochemical batteries, flywheels, compressed air systems, and superconducting coils. Each holds promise for enhancing energy storage and reliability in renewable energy systems.

IV. SIMULATION RESULTS AND DISCUSSION

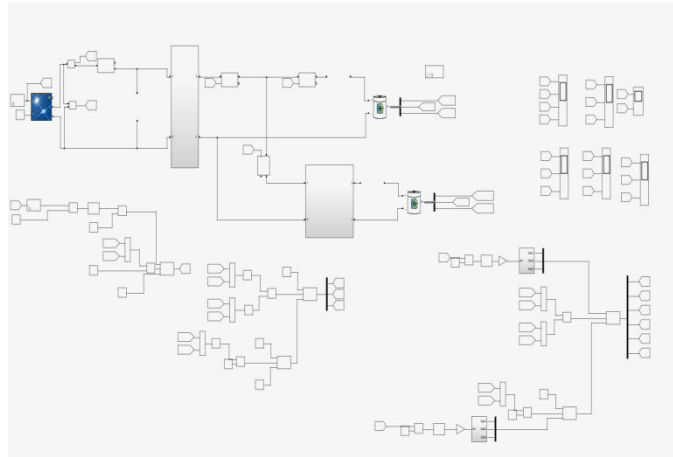


Fig4.1:Simulation studies and results

The simulation studies of the proposed system are conducted using Simulink, a feature of MATLAB software. The PV array is represented in the simulation using its classical equation. Models of the Sepic and BIBC converters are built using power MOSFETs, inductors, and capacitors from the SimPowerSystems Blockset available in the Simulink library. Additionally, the controller is designed using various components such as PWM generator, pulse generator, logic gates, comparator, multiplier, and PI controller, all of which are accessible in the Simulink library. These components are integrated into the simulation to simulate the behavior of the entire system accurately.

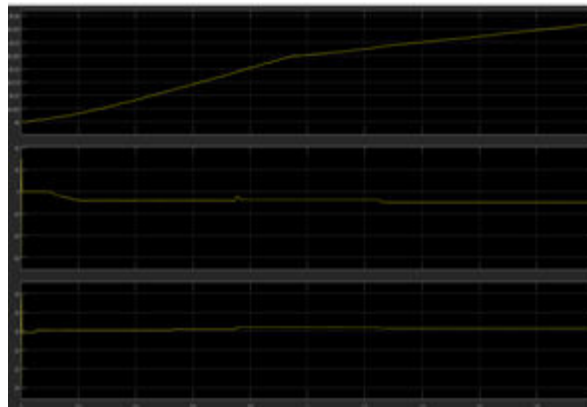


Fig 4.2:output of the pv array

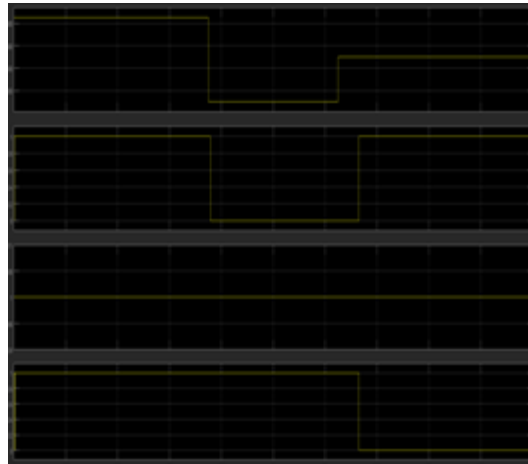


Fig 4.3:output of the EV battery

V. LIMITATIONS

One significant drawback of off-board electric vehicle chargers using a photovoltaic (PV) array is their reliance solely on sunlight for charging the EV battery. To overcome this limitation, some chargers integrate a PV array with a sepic converter, bidirectional DC-DC converter, and backup battery bank. The sepic converter is versatile, operating in both boost and buck modes even during periods of low solar irradiation or non-sunshine hours.

During times of low solar irradiation, the PV array may not generate sufficient power to charge the EV battery effectively. To address this issue, the PV array can be disconnected from the DC link by turning off switch Sa and instead connecting the EV battery to the backup battery through the bidirectional DC-DC converter (BIDC).

Furthermore, these off-board chargers are engineered for high charging rates and boast minimal limitations on weight and size, ensuring efficient and flexible charging solutions for electric vehicles.

VI. CONCLUSION

This paper introduces an off-board electric vehicle (EV) battery charging system powered by a photovoltaic (PV) array. It explores the system's capability to consistently charge the EV battery regardless of irradiation conditions. The system is meticulously designed and simulated using the Simulink environment within MATLAB software. Laboratory testing is conducted to assess the performance of the proposed charging system across its three distinct modes of operation. The results of these simulations underscore the effectiveness and reliability of the proposed charger.

VII. ACKNOWLEDGMENTS

If required, acknowledge the entities that contributed to the research's development.

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