Advancing Sustainable Mobility with Hybrid Energy Storage Systems for smart charging Applications Using Zeta-SEPIC Converters

M Kowsalya[1] ,Dr. J Anitha[2], Dr. Dhanraj G[3], Lakshmi Priya G[4], Dr. Silamboli J [5]

1. Department of Electronics & Communication Engineering, Karunya Institute of Technology and Sciences, Coimbatore-641114, India ,kowsalyam@karunya.edu.in
2. Department of Electronics & Communication Engineering, Karunya Institute of Technology and Sciences, Coimbatore-641114, Indiaanithaj@karunya.edu
3. Department of Mechanical Engineering, CSI College of Engineering, Ketti ,dhanrajguru77@gmail.com
4. Department of Electrical and Electronics Engineering, CSI College of Engineering, Ketti lakshmivinod2210@gmail.com
5. Department of Electronics and Communication ,CSI College of Engineering, Ketti
silamboliece@gmail.com

Abstract

This study introduces a Zeta converter-based bidirectional energy transfer system intended for bidirectional smart flow applications. The system enables effective energy exchange between the grid and a hybrid power storage system, which is made up of a super capacitor (SC) and a lithium battery. The Zeta converter incorporates a sophisticated energy management feature that offers both the step-up and steps down capabilities. The state-space averaging method is used to analyze stability in both modes. To guarantee steady voltage and current outputs, a control strategy is created depending on the energy storage systems charge state. Steady Current (CC) and Fixed Voltage (CV) modes are used to charge the lithium battery. Bode plot analysis is used to design voltage and current controllers in the frequency domain. Through in-depth simulations and practical investigations, the suggested Zeta converter design is verified, proving the system's electrical feasibility and the efficacy of the control approach. The findings demonstrate the Zeta converters enormous potential for effective energy exchange and control in EV to grid systems, offering a dependable way to incorporate electric cars into smart grid infrastructures.

Keywords: Zeta Converter, Lithium-ion battery, Super capacitor.

1. Introduction

Over the past decade, the global shift toward green energy has accelerated, largely due to stricter carbon tax policies and the 2016 Paris Agreement, which aims to limit global temperature rise to below 2°C. According to the International Renewable Energy Agency (IRENA), renewable energy production—especially solar power—has increased significantly, with Asia leading this growth. IRENA projects that by 2050, renewable will supply over two-thirds of global energy needs.

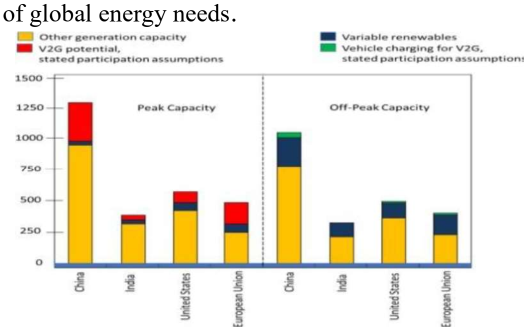


Fig 1: EV-to-network potential and renewable capacity vs. total generation needs in the Sustainable Development Scenario.

A key part of this transition is the rise of electric vehicles (EVs), supported by government incentives and better charging infrastructure. EVs are far more efficient than internal combustion engine (ICE) vehicles and emit about 40% less greenhouse gases. However, the expected growth in EV numbers—over 130 million by 2030—poses new challenges for existing power grids, which are not yet fully equipped to handle the added and fluctuating demand.

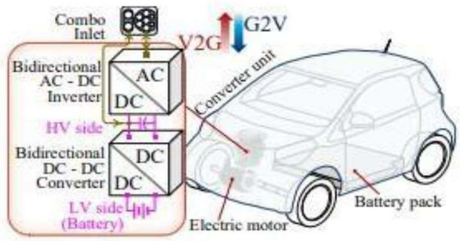


Fig 2: Layout of electric vehicle

To meet these challenges, upgrades to grid infrastructure are essential. Vehicle-to-Grid (V2G) technology allows EVs to act as mobile energy storage, supplying excess power back to the grid during off-peak hours. Hybrid Energy Storage Systems (HESS), which combines lithium-ion batteries with super capacitors, help meet peak demand more effectively. While both unidirectional and bidirectional V2G models are being tested, bidirectional systems offer better support for grid services like voltage and frequency regulation. Only a 15–25% increase in capacity is needed to meet peak demand, as 90% of power plants already run continuously. In key regions such as Asia, North America, and Europe, peak EV-driven electricity demand may soon exceed 600 GW. With a total battery capacity of 16,000 GWh, and assuming 60% usage and 20% energy loss during DC to AC conversion, about 7,680 GWh would still be available—enough to exceed peak demand by 1,500 GWh in emergency situations.

2. Proposed System

The bidirectional Zeta converter plays a pivotal role in enabling seamless power transfer between EVs and the grid. Unlike traditional unidirectional converters, the bidirectional Zeta converter allows energy to flow in both directions, facilitating not only the charging of EVs but also their ability to contribute excess energy back to the grid. This bidirectional capability enhances the versatility and utility of EVs as dynamic grid assets, promoting a more integrated and sustainable energy ecosystem.

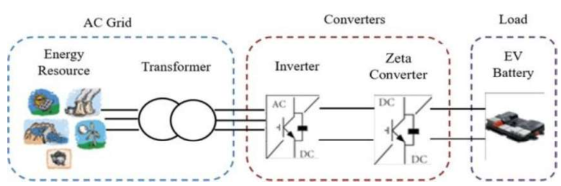


Fig 3:Layout of electric vehicle

The proposed switching bidirectional zeta converter with a Hybrid Energy Storage System (HESS) comprises five main components: a lithium-ion battery, a switching bidirectional buck-boost circuit, a super capacitor (SC), a full-bridge inverter, and the grid. Three addition switches (D1, D2, and D3), a super capacitor, and an inductor are all included in the circuit. A single gate signal can control these three extra switches since the gate signals of switches Sp and Sos are complementary to and identical to the gate signal of switch Sot. Because of its special converter design, the system can transmit power in both directions and function in both buck and boost modes. System Configuration The configuration of the Vehicle-to-Grid (V2G) system is illustrated in Figure 2. The system comprises three sections: the AC grid, converters, and loads. The AC grid supplies the initial alternating current (AC) voltage. The converters include an AC/DC converter and a DC/DC converter. The AC/DC converter transforms AC power into direct current (DC) power. The bidirectional DC/DC converter links the battery to the DC bus. In this context, charging the battery is referred to as a positive process, while discharging is considered negative.A Zeta converter is a type of DC-to-DC converter employed to deliver a regulated DC power output from an unregulated DC power source. Similar to other traditional converters, Zeta converters can step up or step down the input DC voltage depending on the duty cycle. Like other DC-to-DC converters, a Zeta converter achieves a stabilized output by transferring energy between capacitors and inductors. The quantity of energy transferred is controlled by a switch, with its operation governed by adjusting the duty cycle.

3. Fundamental Working Principle of a Zeta Converter

The Zeta converter operates using a MOSFET switch, two inductors (L1 and L2), two capacitors (C1 and C2), a diode (D), and a load resistor (R). It functions in continuous conduction mode (CCM), cycling between ON and OFF states during switching.

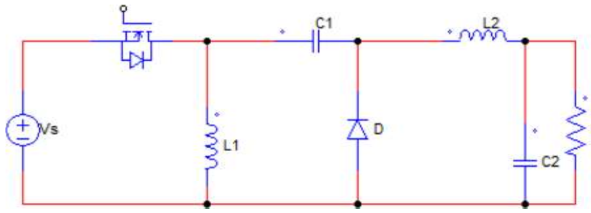


Fig 4–Basic equivalent circuit of zeta converter

Working of a Zeta Converter:

Mode1: The switch, diode, and inductor drain current from the source voltage (Vs) when it is in the ON state. The electricity that passes through the inductor tends to increase linearly, saving energy in the ON condition mode of operation. The input or source voltage will be almost identical to the inductor voltage across [3]. Capacitor C1 starts to charge to output voltage simultaneously. The two inductors (L1 and L2) will store energy from the source when the MOSFET is in the ON condition, and C1 and L2 will also supply output currents [2].

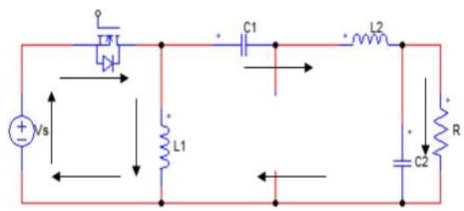


Fig5:Mode1 Of Zeta Converter

Mode 2: When the switch is in the OFF state, the diode is now forward biased, the capacitor is parallel to the L2 inductor, and the output voltage across the inductor is available since C1 gets drained and C2 is charged to the output voltage. The load resistor will receive any energy that is kept in the inductor (L). Thus, conditions are being discharged by this type of operations.

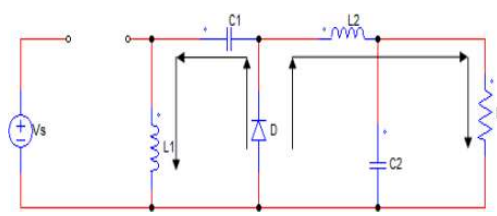


Fig 6-mode 2 of Zeta converter

Vehicle to grid mode

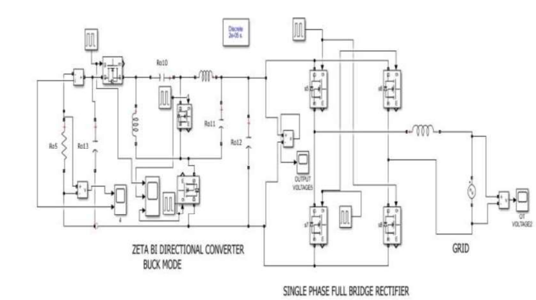
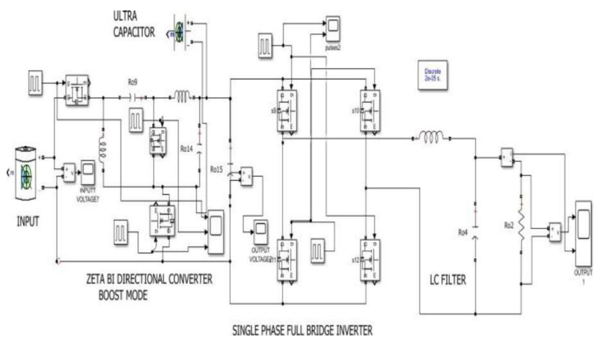


Fig 7 Vehicle to grid mode circuit diagram

Grid to vehicle mode:

From the MATLAB simulation the output for operating modes, both grid to automobile and automobile toward grid modes are acquired. The battery voltage is 48v. By applying the gate pulse in sequence



themode1andmode2operationcan be performed and the required output can be obtained.

Fig 8 Grid to Vehicle mode circuit diagram

4. Results &Discussion:

The battery voltage is applied to the inverter connected in the automobile into a grid mode conversion. The inverter in this mode has semiconductor switches and by applying the gate pulse to this switch the output AC voltage can be obtained. The output AC voltage is connected

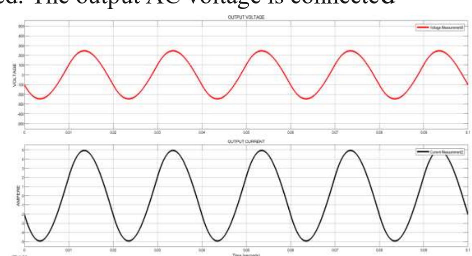
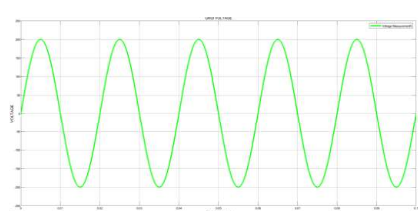


Fig 10-Output voltage from the vehicle to grid

to the Grid. The battery voltage is applied to the inverter connected in the automobile into a grid mode conversion. The inverter in this mode has semiconductor switches and by applying the gate pulse to this switch the output AC voltage can be obtained. The output AC voltage is connected to the Grid, the Fig.10 represents



the grid voltage

. **Fig11- Grid voltage**

The grid voltage is AC and this voltage is feedback to the rectifier in the Grid to vehicle conversion mode. The rectifier contains semiconductor switches which is controlled by gate pulse and produces DC Output. The Fig 11 shows the Grid voltage = 200V

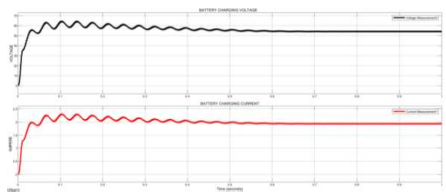


Fig12-Battery charging voltage and battery charging current

5. Conclusion

This paper presents the hybrid energy storage forV2G system with the help of Zeta converter. This converter as improved efficiency and reduced loss for the energy conversion. The future depends on the rise of electrical vehicles and technologies. The storage system is supplied with two modes from grid to automobile and automobile to network. This creates an efficient storage system for future.

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