

Innovative Reconfigurable Power Converters Enabling Electric Vehicles to Integrate Two Batteries

Kampelli. kiriti¹, Arpula Krishnaiah², Maisakshi . Pavan Kumar³

¹Electrical and Electronics Engineering & KLR College of Engineering and Technology

²Electrical and Electronics Engineering & KLR College of Engineering and Technology

³Electrical and Electronics Engineering & KLR College of Engineering and Technology

Abstract - As the demand for sustainable transportation solutions continues to grow, the demand for battery electric vehicles (BEVs) has soared. Worries about reliability of the system and the limited driving range of EVs, however, are still stopping the EV revolution. Dual-battery systems have garnered much interest as a possible answer to these issues, especially with electric two-wheelers. In this work, two novel reconfigurable converter topologies are proposed which are able to support operation of two batteries. Depending on the requirement, these Converters can be configured in different ways: The batteries can be set in series or parallel, or even one battery can be used alone for charging or propulsion.

The converter output can be directly connected to the charging unit or the traction drive system. In order to keep circulation currents to a minimum while using parallel batteries, it is crucial to keep the terminal voltages almost similar. Hence, in order to keep the battery potentials balanced, the suggested topologies have a built-in voltage equalization mechanism. Two batteries can be charged simultaneously as tested by embedding the converter in a non-isolated inverter charger design. System transfer functions are built by using state-space averaging methods and small-signal analysis, the K-factor approach is used to generate controller settings. Extensive calculations (in MATLAB) and experimental prototype results have been used to validate the suggested converter designs regarding their practicality and performance.

Key Words: Dual battery, electric vehicle, EV charger, transportation electrification, battery reconfiguration.

1.INTRODUCTION

The worldwide quest for more environmentally friendly modes of transportation has been sped up in recent years in response to mounting pollution and other environmental crises. Transportation also contributed approximately 20% of global CO₂ emissions in 2022 and approximately 29% of CO₂ emissions in the US [1]. Hence, EVs or the electric cars are taking over the car industry rapidly replacing the traditional ICE vehicles. This transition can be achieved successfully, as evidenced by the rise in the proportion of EVs in the market from 3% in 2010 to more than 86% in 2022 in Norway [2].

Apart from reduced GHG emissions, EVs offer a number of other benefits including improved energy efficiency, reduced noise levels, reduced running costs, reduced maintenance costs and easier driving comfort [2]. However, high initial cost, limited range, lengthy charging time and reliability issues remain hurdles for the EV industry.

There have been a number of suggestions put up to alleviate concerns about battery life, such as faster charging infrastructure, battery swap methods, and more sophisticated battery technology. However, much progress will not be possible until battery technology and rapid charging is well researched over a long period. Although it is an attractive alternative, the size and weight of batteries, makes battery switching a difficult choice in larger vehicles such as passenger car and commercial truck. Problems with battery ownership, a lack of a reliable infrastructure for exchanging batteries, and the lack of standardized methods all work against broad adoption [3].

To remove some of these barriers to EV adoption, the dual energy storage architecture is one viable solution. Several researchers have studied multiple energy storage device integration in electric cars. Many studies rely on batteries as primary energy storage devices with ultracapacitors (UCs) as secondary. UCs have high power density, and can efficiently satisfy both peak and transient power requirements, enhancing vehicle range, extending primary battery life and minimizing battery stress. However, they can't be a replacement for the battery in case of failure or full discharge which is due to their comparatively low energy density. The other researchers have investigated the different electrochemical properties of dual batteries. These setups have the potential to substantially extend the driving range of a vehicle with just one charging cycle. Previous studies [16] indicate that there are several energy storage possibilities to meet power and energy requirements in EV applications. Some researchers [20] were able to achieve dual battery by using open end winding type motors with twin inverter topologies running in parallel.

In all-wheel-drive systems, however, distinct sets of wheels are powered by separate battery packs, hence these methods mostly ignored this fact. The possibility of reconfigurable batteries with the ability to dynamically

change between series and parallel modes of operation under traction situations have been underexplored. Much less study has been carried out on the best ways to charge these dual-storage configurations. Recently, in the electric two-wheeler industry, several EVs have been introduced, some of which have more than one battery pack [23]. However, for maximum system efficiency and flexibility, such systems are not always designed for reconfigurable battery operation and for concurrent dual battery charging.

2. Proposed Topologies

The schematic of the proposed converter and an Inverter-Charger System (ICS) is shown in Fig. 1(a) serving as a rectifier during battery charging and an inverter during starting the vehicle. The detailed circuit implementation of the ICS used in Figure 1(b) was used to verify the feasibility of the proposed converter topologies. The proposed design in the figure 1 is a non-isolated one. But the concept of dual-battery operation presented in this study could also be extended and experimented with an isolated ICS set-up. The proposed converters especially designed for the dual energy storage are presented in Figures 2(a) and 2(b) with their circuit details. The topology shown in Figure 2(a) is known as the Contactor-Based Converter (CBC), as the roles of the contactors are very predominant. Similarly, the setup shown in Fig. 2(b) which primarily consists of bidirectional switches is called as Bidirectional Switch-Based Converter (BSC).

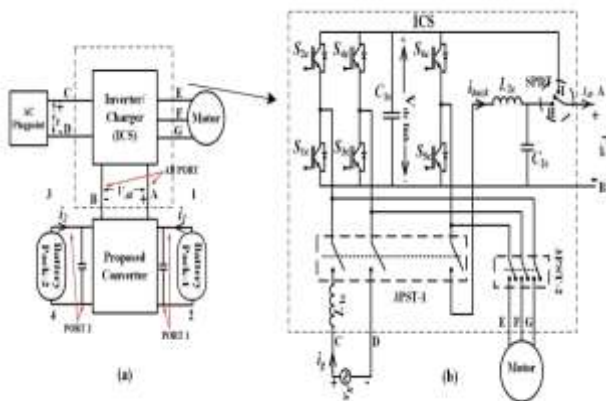


Fig.1

Fig. 1. (a) Block diagram showing proposed converter connected to an Integrated Charger Power converter System (which is capable of connecting either to a grid or traction motor), (b) Circuit diagram of the Integrated Charger Power Co the various modes of operation of the contactor-based converter (CBC) are shown in figure 3. It is now operated in the following modes: (a) Battery Pack-1 (BP-1) alone, (b) Battery Pack-2 (BP-2) alone, (c) connection of both battery packs in series, (d) connection of both battery packs in parallel and (e) voltage balancing operation inverter System (ICS) .

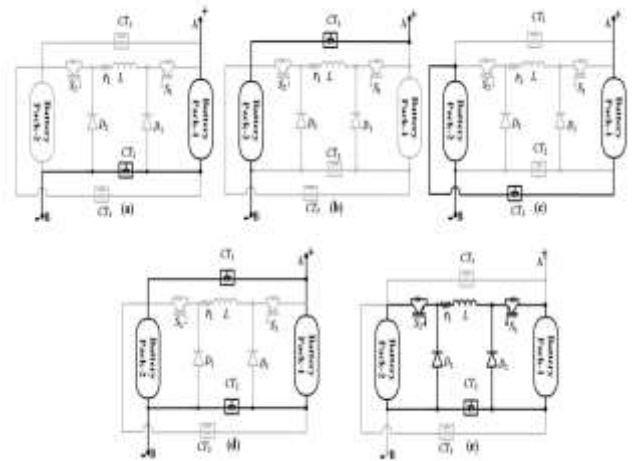


Fig.2.

The various modes of operation of the contactor-based converter (CBC) are shown in figure 2. It is now operated in the following modes: (a) Battery Pack-1 (BP-1) alone, (b) Battery Pack-2 (BP-2) alone, (c) connection of both battery packs in series, (d) connection of both battery packs in parallel and (e) voltage balancing operation.

To avoid the buck converter step, the SPDT switch is set to state I when the battery voltage goes over around 1.15 times the peak AC input voltage. On the flip side, buck converter operation is enabled by shifting the SPDT switch to position H as long as the battery voltage stays below this threshold. This configuration enables charging at a wide range of battery voltages, providing flexibility in charging. Since the Inverter-Charger System (ICS), can operate in both directions, it creates opportunities for new functions such as Vehicle-to-Vehicle (V2V), Vehicle-to-Load (V2L) and Vehicle-to-Grid (V2G). In grid connected operation the Totem-Pole switching control is used for active power regulation. The ICS can supply active and reactive power by using the same inverter techniques and unipolar sinusoidal PWM control technique for unconnected loads.

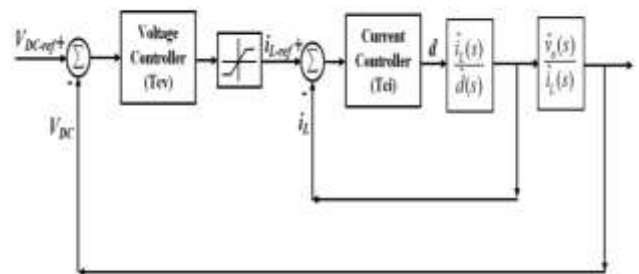


Fig.3. Block diagram showing dual loop control for a power converter

The converter in voltage balancing operation is in buck converter mode to maintain the voltage level of the battery packs and to control energy transfer. The converter stage (front-end) is shown in Figure 3, as a dual-loop control system that is based on the Totem-Pole converter design. Inner control loop is a current control loop and the outer control loop is a voltage control loop.

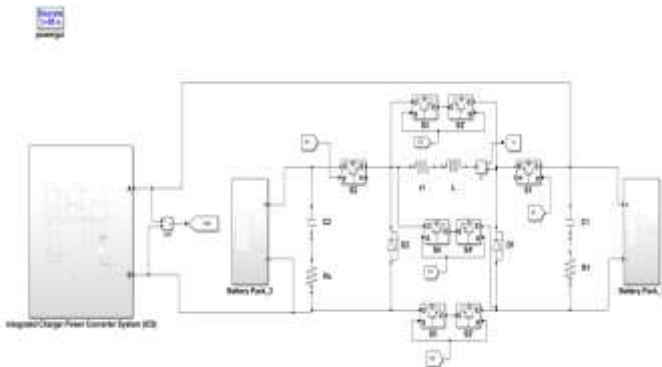


Fig.4. MATLAB/SIMULINK circuit of the system

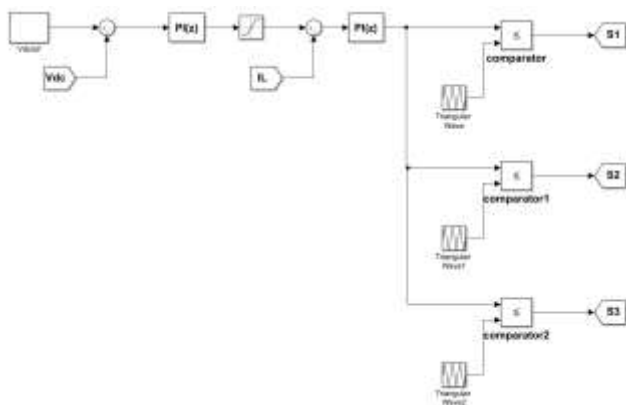
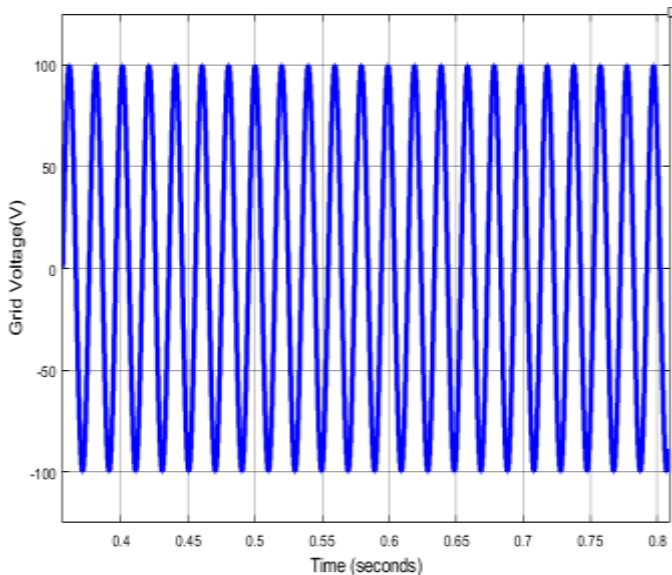
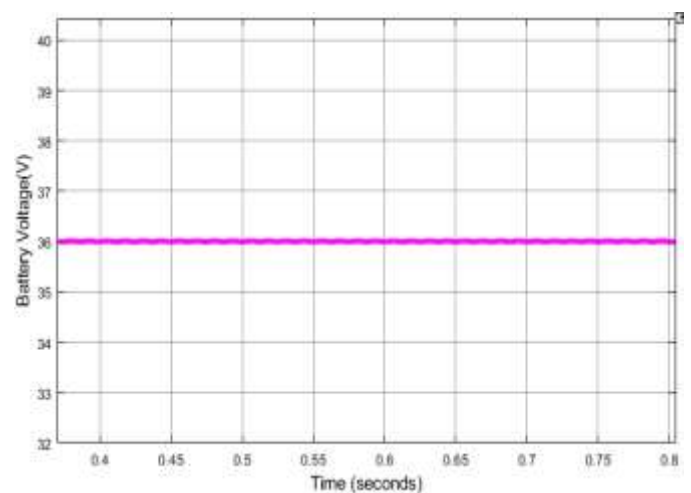
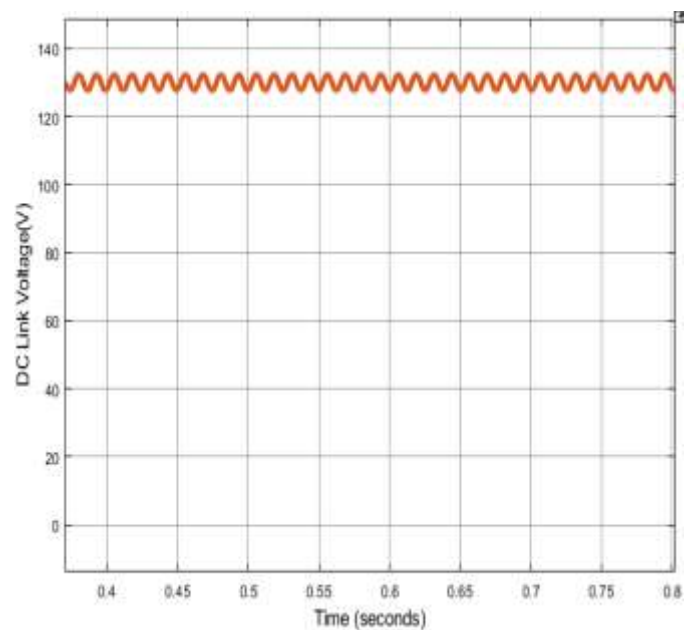
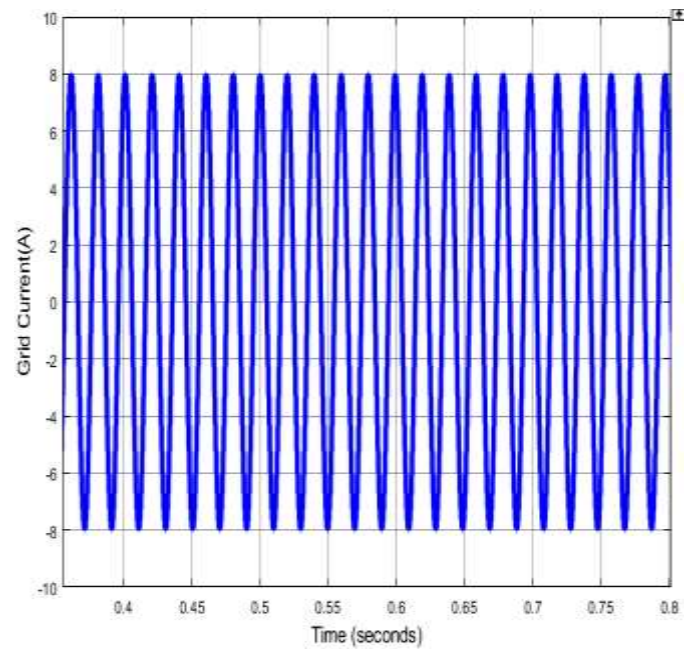
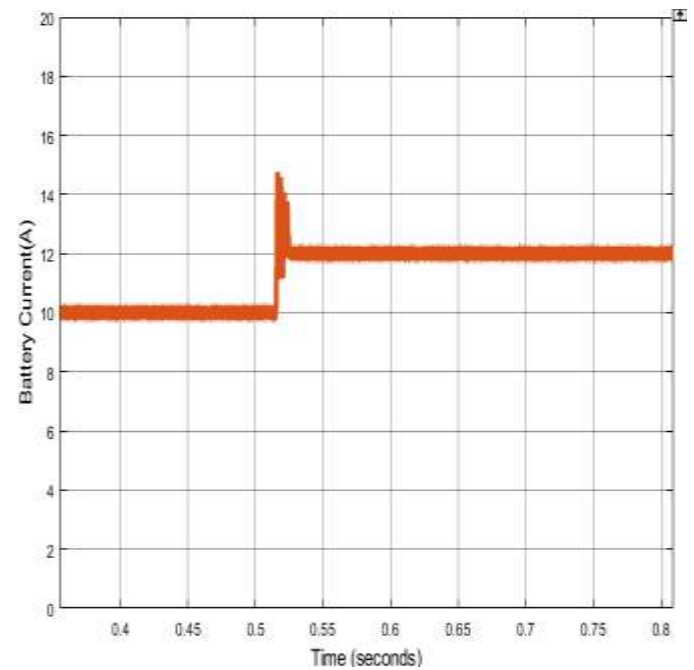
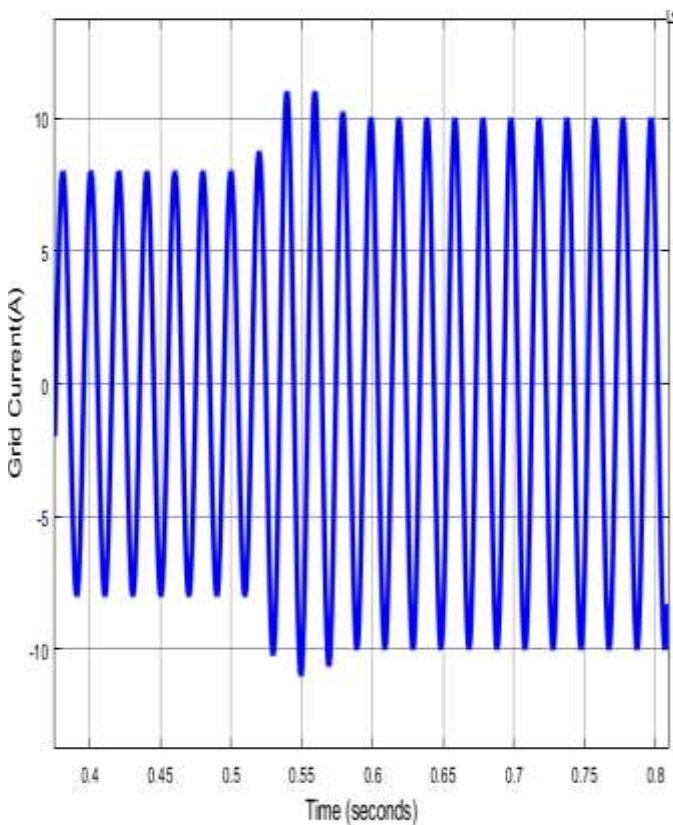
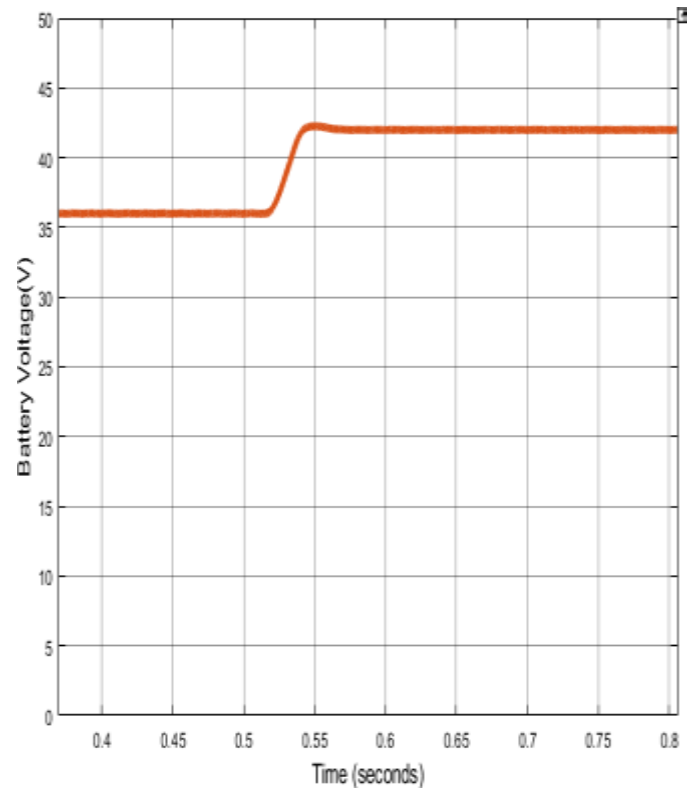
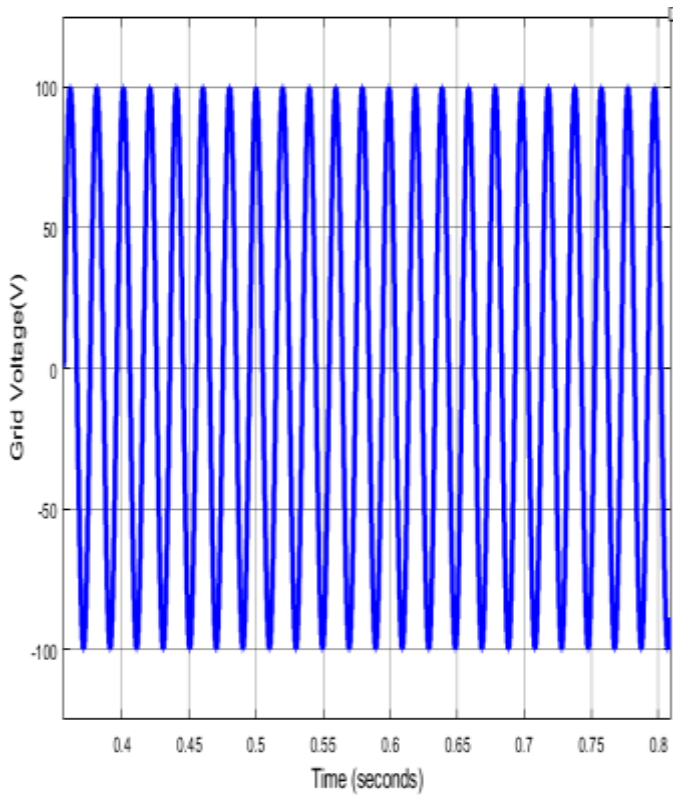


Fig.5. Control system with PI controller





The simulation results are given as follows: (a) Waveforms of grid voltage, grid current, DC-link voltage and battery terminal voltage; (b) When one battery is charged; (c) When two batteries are charged in parallel; (d) When two batteries are charged in series; (e) Response to the reference voltage variation and current controllers; and (f) Response to the reference current variation.

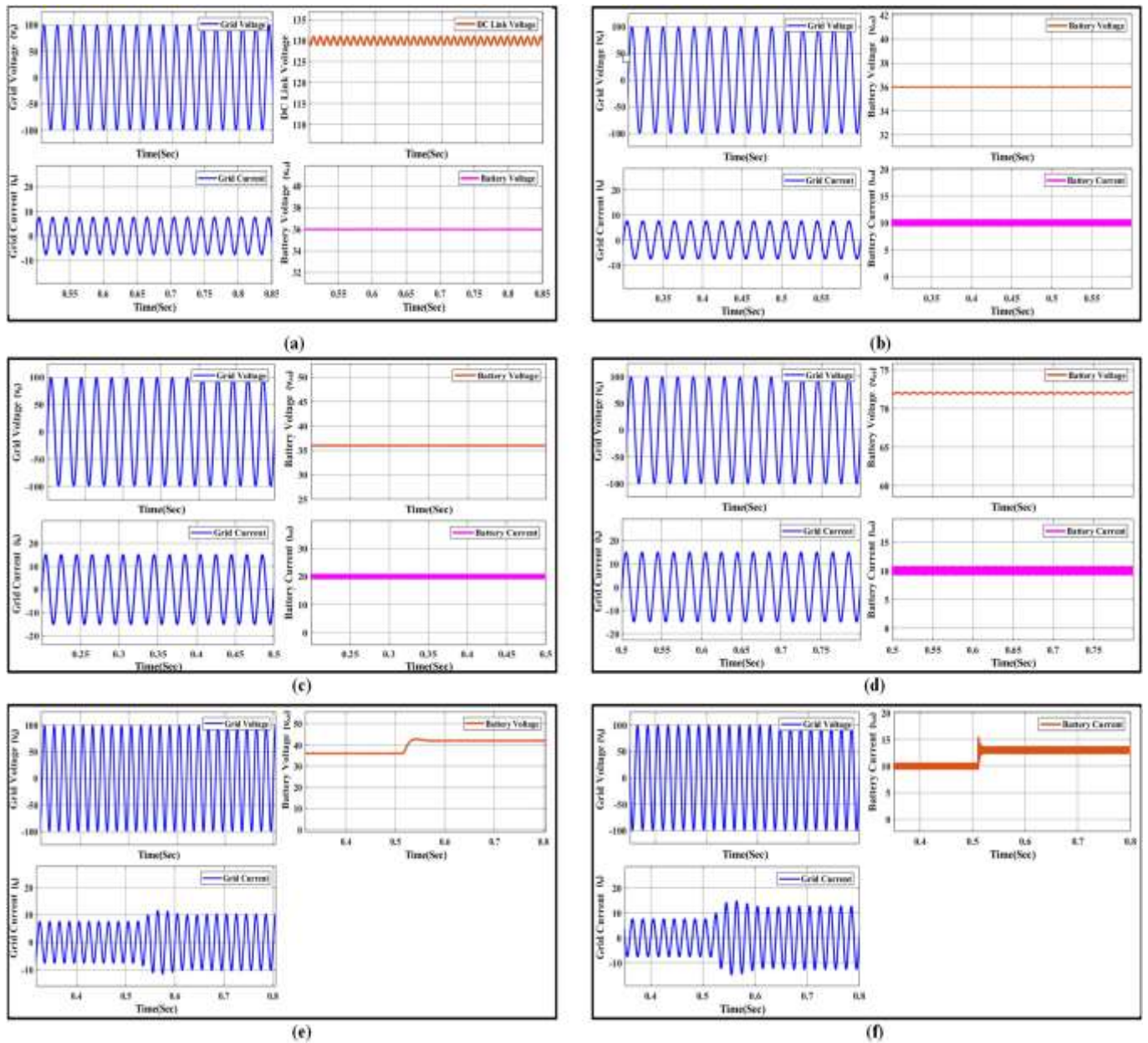


Fig. 6. Simulation results (a) Showing grid voltage, grid current, dc link voltage and battery terminal voltage (b) Single battery charging alone, (c) Dual battery charging in parallel, (d) Dual battery charging in Series, (e) voltage controller reference change, and (f) current controller reference change.

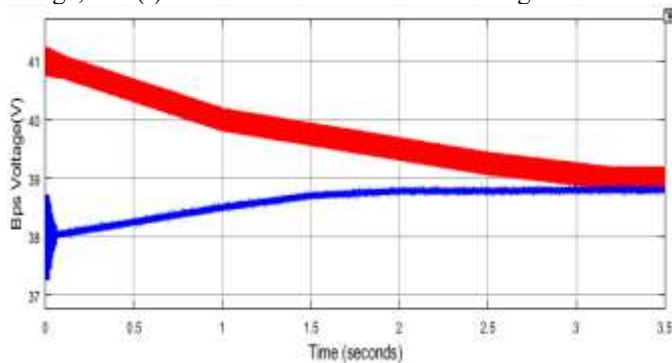


Fig. 6. Simulation Result for Voltage Balancing Facility with BP's of different SoC.

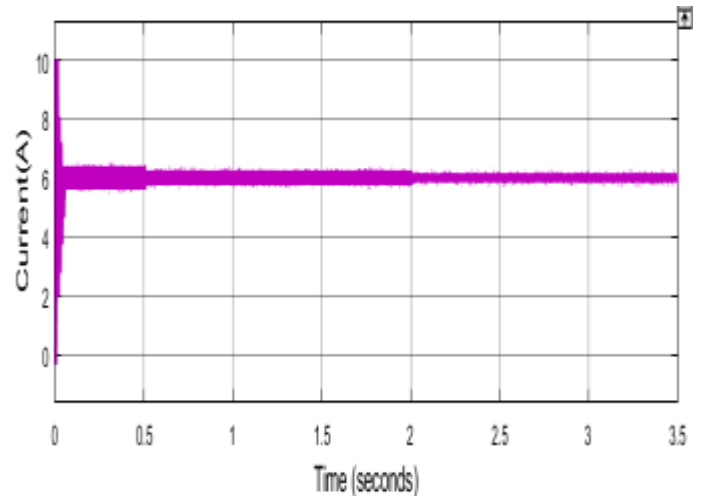


Fig. 7. Simulation Result for current Balancing Facility with BP's of different SoC.

3. CONCLUSIONS

For use in electric vehicles that use two batteries, this research introduced and examined in detail two novel reconfigurable power converter topologies: the Contactor-Based Converter (CBC) and the Bidirectional Switch-Based Converter (BSC). The suggested dual-battery design's charging capabilities were tested by including a non-isolated Inverter-Charger System (ICS) into the system architecture. Comprehensive MATLAB simulations and experimental hardware implementation were used to test the reconfiguration features of the converters that were suggested. These functions include single battery operation, battery series, battery parallel in charging and traction conditions.

The obtained results indicate that the proposed converter topologies enhance the utilization of the batteries and offer greater flexibility in operations due to the battery load sharing among the battery packs. The capacity to choose link either battery pack to the output terminals is a major strength of the suggested system that improves system dependability, fault tolerance, and battery design adaptability. Besides, the suggested converters before the parallel operation provide a voltage-balancing function, which can balance the battery voltages at the battery pack terminals.

This allows the batteries to last longer and operate more reliably by minimizing the amount of current flowing between the packs of batteries, which in turn reduces the stress on the batteries. Both simulation studies and hardware validation have been performed and the suggested converter designs are effective, resilient and can be adapted to a wide range of operating conditions. One of the biggest challenges that lie in the path of EVs is their limited range, lack of dependability, and operating flexibility.

The proposed dual-battery integration technique is feasible and effective in the solution. Further benefits of the reconfigurable topology are improved functional safety, enhanced system resilience, extended battery life and uninterrupted operation in case of partial battery failure. Despite the slightly higher hardware cost initially introduced by the proposed architecture, it provides a cost-effective and attractive solution for future applications of electric vehicles because of its high reliability, low maintenance, better battery performance and continuity.

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Kampelli. kiriti, Received B.Tech and from JNTU Hyderabad, pursuing M.Tech in Electrical Power Systems. in KLR College of Engineering and Technology.



Arpula. Krishnaiah received the B.Tech and M.Tech from JNTU Hyderabad, working as Assistant professor and Head of the Electrical and Electronics engineering department in KLR Engineering College, he has Teaching in 17 years of experience in various institutions, published in 11 international publications.



Maisakshi. Pavan Kumar received the B.Tech and M.Tech from JNTU Hyderabad, He is currently working as an Assistant Professor in the Department of Electrical and Electronics Engineering at KLR College of Engineering and Technology, where he has been serving for the past five years. He has published in 11 international publications.