Vol. 39, No. 2, August 2025, pp. 783~796
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v39.i2.pp783-796

A simulation-based investigation into the bidirectional charge and discharge dynamics in lead-acid batteries

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Article Info

Article history:

Received Aug 24, 2024
Revised Mar 24, 2025
Accepted Jul 2, 2025

Keywords:

Battery
Bidirectional DC-DC converter
Electric vehicles
Push-pull converter
State of charge

ABSTRACT

This paper presents a comprehensive simulation-based investigation into the bidirectional charge and discharge dynamics of lead-acid batteries within electric vehicles (EVs) and energy storage systems (ESS). Utilizing a bidirectional DC-DC converter (BDC) integrated with a lead-acid battery, the study explores the performance of these batteries through various charging and discharging scenarios. The simulation model, implemented using MATLAB, assesses the impact of charging strategies on battery behavior, focusing on key metrics such as state of charge (SOC), energy performance, and charging rates. The results reveal that lead-acid batteries, when paired with appropriate charging infrastructure and strategies, demonstrate enhanced performance and reliability in both EV and ESS applications. The study highlights the significant role of BDC topology in facilitating efficient energy transfer and optimizing battery usage. The findings underscore the potential for improved performance and widespread adoption of bidirectional converters in sustainable energy solution.

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1. INTRODUCTION

The increasing demand for electric vehicles (EVs) is driven by concerns over fossil fuel dependency, environmental pollution, and energy security. Traditional internal combustion engine vehicles contribute significantly to carbon emissions, necessitating a transition to cleaner transportation alternatives. EVs offer a viable solution with reduced emissions and improved energy efficiency. However, their widespread adoption is hindered by battery performance limitations and the efficiency of charging infrastructure. EVs are considered highly efficient in engine performance since they generate no tailpipe emissions and do not cause pollution from fuel evaporation or refining processes [1], [2]. Integrating EVs with power grids through vehicle-to-grid (V2G) technology enables bidirectional energy flow, optimizing grid stability and energy utilization. Energy storage systems (ESS) serve a vital function in this ecosystem, acting as buffers to balance energy demand and supply. The effectiveness of ESS in supporting EV infrastructure depends on the efficiency of bidirectional DC-DC converters (BDC), which regulate power transfer between EVs and ESS while ensuring minimal energy loss.

EVs are becoming increasingly popular for lowering carbon emissions and enhancing energy efficiency. Recent studies have extensively reviewed V2G system impacts and optimizations, highlighting the role of renewable energy sources and the potential benefits of ESS in EV charging solutions [3]–[5].

Researchers have also explored battery optimization strategies, highlighting the role of bidirectional converters in enhancing energy efficiency. However, existing solutions exhibit limitations, such as efficiency losses in bidirectional energy transfer and battery degradation over time. The success of EVs largely relies on the efficiency of charging infrastructure, especially DC chargers. Additionally, the type of EV battery plays a crucial role in charging behavior, directly influencing overall EV performance. As the stress of grid will affect the charging station of the EVs to charge the battery, the ESS is a backup for charging the battery. The BDC was chosen due to its robust design [6]–[11] which ensures efficient energy transfer, high reliability, and the ability to handle fluctuating power levels during both charging and discharging cycles. Therefore, evaluating the charging and discharging performance of EV and ESS batteries on DC chargers, along with the presence of a BDC, is essential for identifying optimal charging strategies and infrastructure. This research introduces novel BDC topology with galvanic isolation [12] has been proposed to investigate battery EV and ESS charging and discharging performance. The most commonly used major batteries in power applications include lead-acid [13], [14].

However, there are notable issues with ESS batteries that must be addressed. These issues include limited battery lifespan, degradation over time, and performance variability under different environmental conditions [15]–[17]. Additionally, ESS battery's high initial cost and maintenance requirements can pose significant barriers to widespread adoption. These challenges highlight the need for optimized charging and discharging strategies to improve the reliability and efficiency of ESS in supporting EV infrastructure. This study aims to tackle these issues by evaluating the performance of ESS batteries alongside EV charging systems, focusing on the effectiveness of BDC topology with galvanic isolation.

A lead-acid battery is constructed with lead-based electrodes and grids [18]. The lead oxide in the battery is crucial in enabling the charging and discharging process through electrochemical reactions. This process involves using An electrolyte, along with both positive and negative electrodes, to facilitate the battery electrochemical reactions [19]. An open-loop control strategy is described for the converter operation in charging and discharging modes. Then, the battery-powered EV is linked to this BDC to ESS. The functionality of the system was confirmed using MATLAB. This article provides a preliminary simulation analysis of the charging and discharging performance of batteries utilized in EVs and ESS. This study analyzes the charging process, including energy transfer and charging rate, offering valuable insights for future research on charging performance [20]. Through simulation implementation, the study demonstrates enhanced energy transfer efficiency.

The novelty of this study lies in its demonstration of a BDC topology specifically designed to enable bidirectional energy flow for both charging and discharging of EV's and ESS. This study provides a comprehensive evaluation of how this BDC topology facilitates seamless energy transfer between EVs and ESS, revealing that lead-acid batteries, when integrated with such a converter, can achieve enhanced performance and reliability. By exploring various charging strategies and their impact on battery behavior through simulation, the research highlights the critical role of BDCs in optimizing battery usage and performance. The study provides an experimental simulation of the proposed topology effectiveness. The findings offer new insights into the potential for improved performance and broader adoption of bidirectional converters in sustainable energy solutions, paving the way for future advancements in battery management and energy transfer technologies. By addressing key limitations in bidirectional converters, this research provides a scalable and efficient solution for integrating EV's with ESS, contributing to the advancement of sustainable energy management.

The study addresses the identified gaps by evaluating the performance of lead-acid batteries in bidirectional charge-discharge scenarios. A novel BDC topology with galvanic isolation is proposed to facilitate efficient energy transfer between EVs and ESS. Through MATLAB-based simulations, the study assesses charging and discharging efficiency, state of charge (SOC), and energy transfer effectiveness. The key contributions of this study on development of a simulation framework to analyze lead-acid battery dynamics in EV and ESS applications andm to validate BDC push-pull converter topology for bidirectional energy transfer effectiveness.

2. METHOD

2.1. Overall framework system architecture

A simulation study was conducted using MATLAB to assess the charging and discharging performance of lead-acid batteries for EVs and ESS. Initially, the grid infrastructure was modeled, incorporating the grid source, transformers, and distribution network. Next, the DC charger was modelled, considering parameters such as charging rate, as well as voltage and current constraints, were considered. The onboard EV charger was then integrated, consisting of a rectifier, a DC-DC converter, and a control system. The flow of the charging and discharging through BDC was evaluated using the charging rate, voltage compatibility, and current limitations. BDC is essential for allowing energy to flow in both directions within the context of EV and ESS battery management, facilitating both charging and discharging processes. It considers the battery's capacity, voltage, and charge/discharge features. This setup ensures efficient energy transfer and works well with battery needs.

Simulation scenarios were considered using critical factors such as charging duration, energy efficiency, and SOC. The study focused on evaluating the performance of EV and ESS batteries for bidirectional energy transfer. The study systematically examined the functionality of the BDC converter, emphasizing its role in ensuring seamless energy transfer between EV and ESS batteries. It ensured the converter worked within the voltage and current limits set by the grid and battery specifications. The study shows the BDC’s performance and the needed infrastructure for EV and ESS.

Figure 1 presents the overall simulation flow of the system architecture. The system framework outlines the flow of energy from the electrical grid to the EV battery through a series of interconnected components. The process begins with a 415 V AC grid connection that supplies power to a 4 kW DC charger. This charger converts the AC power to DC, which is then directed to the EV’s onboard charger with a capacity of 480 W, allowing it to charge the EV battery. The EV battery, with a nominal voltage of 48V and a capacity of 50 Ah, stores the energy necessary for vehicle operation. Additionally, an ESS battery, with the same specifications as the EV battery, is integrated into the system to store energy for both the EV and as a backup for the grid. The energy flow between the EV battery and the ESS is managed by a 2.4 kW BDC, which enables efficient energy transfer during charging and discharging modes. It is an electronic device that can convert DC power from one voltage to another and vice versa [21]. Overall, the system ensures efficient and safe energy conversion and storage, minimizing losses and optimizing the charging process for the EV.

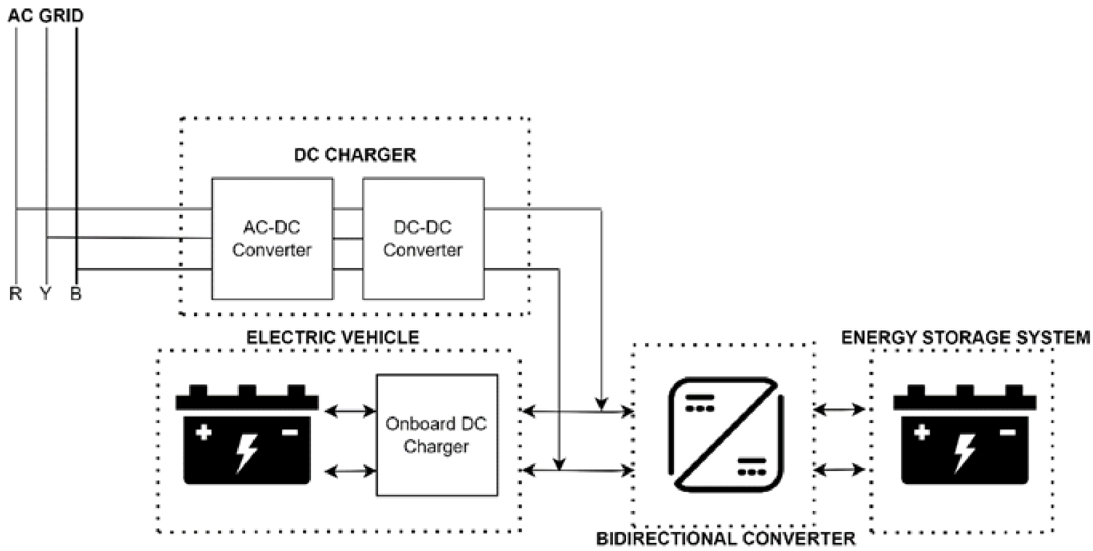


Figure 1. MATLAB simulation of the system

The operational flow of the system, as depicted in Figure 2, involves a sophisticated bidirectional charging control logic designed to continuously monitor and manage the voltage levels of both the EV battery and the ESS battery. The process begins with the control system measuring the voltage of both batteries. Based on these measurements, the system determines the appropriate charging action. If the EV battery voltage exceeds 48 V while the ESS battery voltage is below 48 V, the system initiates the charging of the ESS battery using the energy from the EV battery. Conversely, if the EV battery voltage falls below 48 V and the ESS battery voltage exceeds 48 V, the system triggers the charging of the EV battery using the ESS battery. This entire bidirectional charging process is facilitated by the BDC, which enables efficient energy transfer between the EV and ESS batteries according to their respective voltage levels.

2.3. Simulation setup

Figure 3 illustrates the schematic diagram of the BDC, specifically the push-pull converter. This configuration is particularly effective for efficient energy transfer between two DC sources, making it ideal for applications such as EV’s and ESS. The BDC push-pull converter operates using a pair of switches that alternately connect the primary winding of a transformer to the input voltage. This alternating action produces a pulsating AC voltage in the transformer's primary winding, which is then rectified and filtered to generate a stable DC output. This method offers advantages, including higher power handling capacity and straightforward control mechanisms.

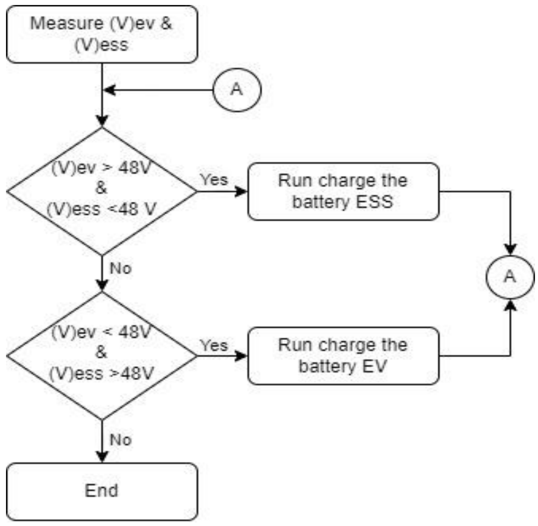


Figure 2. The operation flow of the system

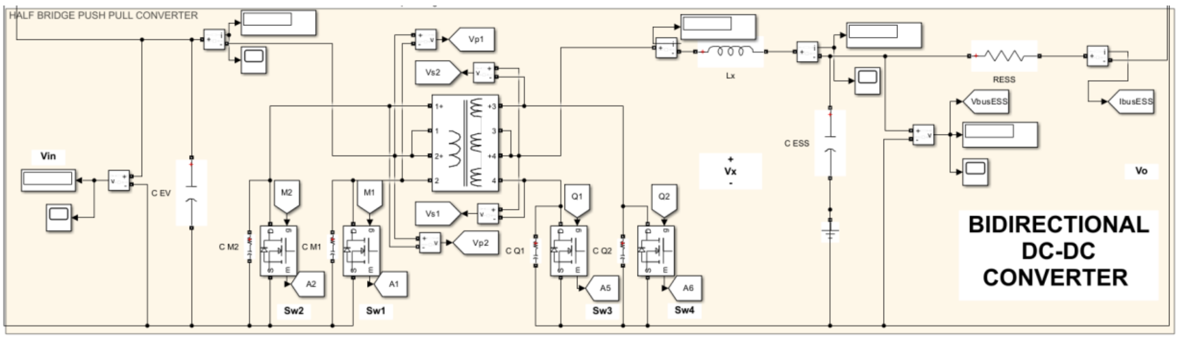


Figure 3. BDC push pull schematic

2.3.1. Converter specifications

The push-pull bidirectional converter is critical in modern power electronic systems, facilitating efficient energy transfer between disparate voltage domains [22]. Table 1 shows the BDC specification and the converter operates within a primary side voltage domain of 48 V and a secondary side voltage of 50 V, providing the necessary voltage differential for bidirectional power flow. Maximum Continuous Current (Idc) with a maximum continuous current handling capability of 10 A, the converter ensures robust operation under varying load conditions, accommodating dynamic power demands. The converter exhibits a nominal power rating of 2.4 kW, signifying its capacity to efficiently transfer power bidirectionally while maintaining stable operation and performance. Operating at a switching frequency of 10 kHz, the converter employs high frequency switching to minimize switching losses and enhance overall energy conversion efficiency. Characterized by a duty cycle of 50%, the converter achieves symmetrical operation, effectively distributing power between the primary and secondary sides during both charging and discharging cycles. It is equipped with an inductor (L_x) of 33 uH, and the converter leverages inductive energy storage and release mechanisms to ensure smooth energy transfer and voltage regulation. A capacitor (C_{EV}), (C_{ESS}) rated at 1000 uF facilitates the filtering of ripple currents and stabilization of the output voltage, thereby ensuring a consistent and reliable power supply to the load.

A push-pull bidirectional converter epitomizes a sophisticated electronic power solution that is adept at addressing the demands of bidirectional power transfer applications [23], [24]. It's robust design and high-efficiency operation and voltage regulation capabilities underscore its significance in contemporary energy management systems. Recent studies highlight the importance of optimizing power electronics to enhance the efficiency and reliability of energy storage systems, with bidirectional converters playing a crucial role in this advancement [25]. Additionally, advancements in control strategies for bidirectional converters have shown significant improvements in dynamic performance and energy efficiency [26]. The integration of such converters in electric vehicle charging infrastructure can also lead to substantial reductions in energy losses and operational costs [27]. Furthermore, the development of high-power bidirectional converters with advanced thermal management systems has been pivotal in improving the overall performance and lifespan of energy storage solutions [28].

Table 1. BDC specifications

Parameters	BDC
Primary side	48 V
Secondary side	50 V
Max, Idc	50 A
Nominal power	2.4 kW
F_{sw}	10 kHz
Duty cycle	50%
Lx	33 uH
C_{EV}, C_{ESS}	1000 uF

2.3.2. System parameter

The power range differences among the DC charger, DC onboard charger, and BDC stem from their distinct charging requirements and objectives. DC chargers are designed to deliver high power rapidly, facilitating fast charging at dedicated stations. In contrast, DC onboard chargers provide slower, more convenient charging within the EV, making them ideal for daily use. The BDC enables bidirectional energy flow between EV and ESS batteries for both charging and discharging. Table 2 summarizes the design parameters of the DC charger, onboard EV charger, and BDC. The DC charger has a rated power of 4 kW, whereas the onboard EV charger and BDC operate at 2.4 kW. Both the onboard EV charger and BDC share a DC voltage of 48V. While the DC charger has a higher current rating of 10 A, the onboard EV charger also has a 10 A rating. Additionally, all three systems operate at a switching frequency of 10 kHz, which enhances system integration and compatibility in the simulation. These parameters provide essential insights into the performance characteristics and capabilities of each charging system.

Table 2. System parameters simulation setup

Parameters	DC Charger	Onboard EV charger	BDC design
Prated	4 kW	480 W	2.4kW
Vdc	400 V	48V	48V
Max, Idc	20 A	10A	50A
F_{sw}	10 kHz	10kHz	10kHz

The simulation design emphasizes maintaining a constant voltage for both the onboard EV charger and BDC, ensuring a stable 48 V across the battery terminals throughout the charging and discharging process. This approach provides a controlled and consistent charging environment. The power rating of the chargers is determined based on the load design. A dedicated controller is integrated into the simulation to regulate the charging and discharging process. It manages two distinct charging and discharging scenarios, adjusting the parameters of the EV and ESS batteries accordingly. This controller plays a vital role in maintaining system stability, regulating charging and discharging modes, and ensuring the desired operational behavior.

Table 3 presents the critical parameters characterizing the behaviour of lead-acid batteries in EV charge and ESS discharge modes based on the parameter that leads ESS charging the EV. The nominal DC voltage for the EV charge mode state is 43 V, while for ESS discharge mode, it is 50 V. Peak voltages recorded during operation are 50.05 V for EV charge mode and 58.19 V for ESS discharge mode. To prevent over-discharge and safeguard battery integrity, cut-off voltages of 32.25 V and 37.5 V are implemented for EV charge and ESS discharge modes, respectively.

Furthermore, both batteries exhibit a rated capacity of 50 A and a nominal discharge current of 21.74 A, underscoring their comparable energy storage and power output capabilities. These parameters are set to their rated values, ensuring standardized performance across lead-acid battery units. The parameter for

EV charging mode to ESS shown EV will be charge and ESS discharge, detailing the same parameters but in the context of EV discharge and ESS charge modes. This delineation is crucial for maintaining consistency in charging and discharging operations, as operational parameters align with those specified. Such uniformity facilitates controlled energy management within EV and ESS systems, optimizing their performance and longevity.

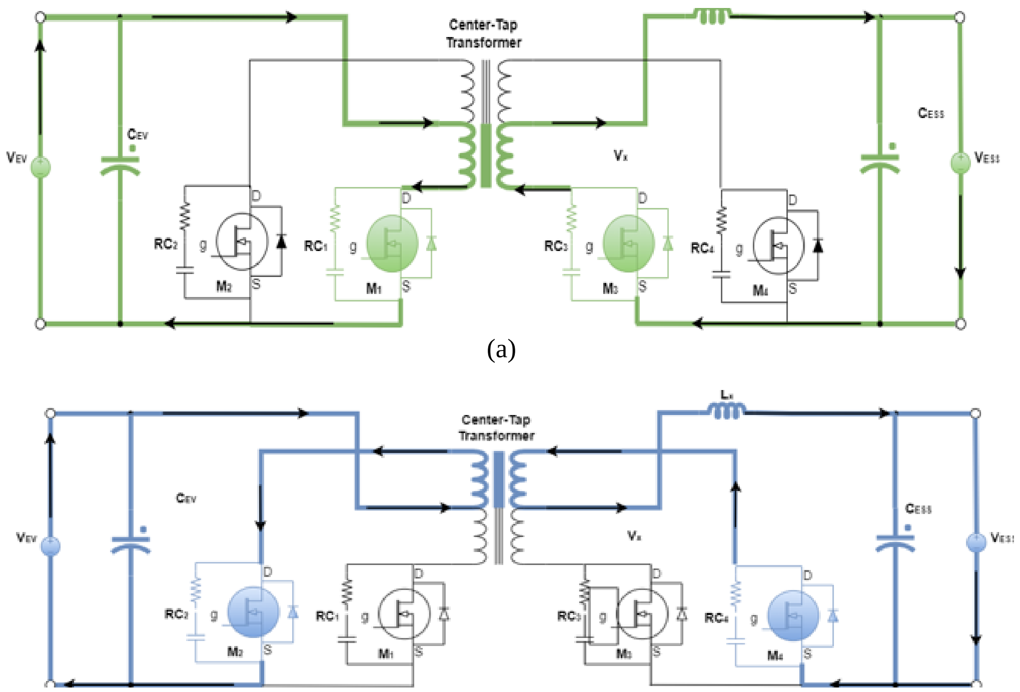
Table 3. Lead acid size for EV and ESS and characteristic simulation parameters on charge & discharge mode

	Parameter for ESS charging mode to EV		Parameter for EV charging mode to ESS	
	EV (Charge)	ESS (Discharge)	EV (Discharge)	ESS (Charge)
Nominal DC voltage	43 V	50 V	50 V	43 V
Peak voltage	50.05 V	58.19 V	58.19 V	50.05 V
Cut-off voltage	32.25 V	37.5 V	37.5 V	32.25 V
Rated capacity, Ah	50 Ah	50 Ah	50 Ah	50 Ah
Nominal discharge current	21.74 A	21.74 A	21.74 A	21.74 A

2.3.3. Control strategy and theoretical formula

The complete switching cycle of this converter is composed of two primary steps. The direction operation mode of mode 1 and mode 2 is shows in Figure 4. For Figure 4(a) is the mode 1 involves the activation of switches M1(Sw1) and M3(Sw3), while M2(Sw2) and M4(Sw4) remain off. During this phase, current flows through the primary winding of the transformer, inducing a voltage across the secondary winding. This enables energy transfer from the ESS to the EV or vice versa, depending on the direction of power flow. This step represents the first half of the switching period.

In step 2 show in Figure 4(b), the switching roles reverse, with Sw2 and Sw4 turning on while Sw1 and Sw3 turn off. The current flows through the opposite winding of the transformer, completing the energy transfer in the opposite polarity. This creates the second half of the switching cycle. Together, these two steps form a complete cycle (T), enabling bidirectional power flow between the EV and ESS, facilitating both charging and discharging operations. The alternating switching method, combined with the center-tapped transformer, ensures efficient energy transfer with galvanic isolation between the two sides. This method is crucial for maintaining stable and bidirectional energy flow in the system.



(a)

(b)

Figure 4. Operation mode (a) mode 1 (SOC) and (b) mode 2

The equation given based on the mode which is for mode 1 Sw1 and Sw3 is turned on transferring energy to secondary winding. Mode 2 which is Sw2 and Sw4 is turn on the reversing power flow occurs. This mode represents the operation of the switching of the BDC. The center tap transformer is given in (1) for mode 1 and (2) for mode 2.

$$V_x = V_{s1} = \frac{Ns}{Np}\ (V_{in}) \tag{1}$$

$$V_x = V_{s2} = \frac{Ns}{Np}\ (V_{in}) \tag{2}$$

Where N is the number of turn and the voltage of inductor, V_{Lx} is given in (3) for mode 1 and (4) for mode 2.

$$V_{Lx} = V_{s1} - V_O = [\frac{Ns}{Np}\ (V_{in})] - V_O \tag{3}$$

$$V_{Lx} = V_{s2} - V_O = [\frac{Ns}{Np}\ (V_{in})] - V_O \tag{4}$$

The current for inductor is given in (5) for mode 1 and (6) for mode 2.

$$\frac{di}{dT} = \frac{Vs1 - Vo}{L} \tag{5}$$

$$\frac{di}{dT} = \frac{Vs2 - Vo}{L} \tag{6}$$

3. RESULTS AND DISCUSSION

While earlier studies have analyzed bidirectional energy flow in lead-acid batteries, they have not explicitly addressed the impact of BDC on charging efficiency and energy transfer. The simulation results indicate that lead-acid batteries maintain stable voltage and current profiles across both EV and ESS applications. The bidirectional DC-DC converter facilitated efficient energy transfer, with minimal energy loss. Lead Acid batteries experience charging and discharging cycles that flow through the BDC, the bidirectional flow is performed by adjusting the parameter on the battery voltage of EV and ESS on charging and discharging mode as shown in Table 3. Table 4 presents the simulation results. The results highlight the behaviour of the batteries in terms of voltage, current, power, the initial state of discharge (SOD) - initial (SOC), and the status of battery electric vehicles (BEVs) during the experiment. The lead-acid batteries undergo charging and discharging cycles, as detailed in Table 3. To evaluate the BDC performance under different bidirectional power flow conditions, multiple simulation trial scenarios were designed. The MATLAB simulation ran for 60 seconds per trial, recording performance metrics, which are battery voltage and current behavior during charge and discharge cycles. The trials involved in this study are structured to observe the battery behavior during different operational modes, with four trials conducted in total. Trials 1 and 4 focus on charging, while Trials 2 and 3 focus on discharging. For the data processing the collected voltage, current and power data was analyzed using MATLAB to determine BDC efficiency.

Lead-acid batteries undergo charging cycles. Notably, the initial voltage of the EV battery in trial 1 is 43 V, with a negative current of 2.90 A, resulting in a power output of 124.70 W. Similarly, in trial 3, the EV battery exhibits discharge behavior, with an initial voltage of 50 V and a current of 3.81 A, yielding a power output of 190.50 W. These observations suggest lead-acid batteries' efficient charging and discharging capabilities in EV applications, as they maintain stable voltage and power outputs during these processes. The consistent power output during charging indicates minimal energy loss and effective energy storage.

Conversely, in the ESS trials, the lead-acid batteries discharge energy to power external systems. Trial 2 demonstrates the discharge of the ESS battery, with an initial voltage of 50 V and a positive current of 6.02 A, resulting in a power output of 301.00 W. Additionally, trial 4 illustrates charging behavior, where the ESS battery exhibits an initial voltage of 43 V and a negative current of 1.43 A, generating a power output of 61.49 W. These findings underscore the versatility of lead-acid batteries in supplying power to external systems during ESS discharge operations and accepting energy during charging cycles, as they adapt to different operational requirements while maintaining performance. Overall, the experimental results affirm the suitability of lead-acid batteries for both EV and ESS applications, highlighting their capability to efficiently undergo charging and discharging cycles while maintaining stable voltage and current profiles. These insights contribute valuable information to the ongoing research and development of battery technologies for sustainable energy storage solutions.

Table 4. Simulation result

Types of battery	Battery	Time (secs)	Initial voltage (V)	Current (A)	Power (W)	SOD-SOC	BEVs status
Lead acid	Trial 1. EV	0-60	43	(-)2.90	124.70	70% - 70.10%	Charge
	Trial 2. ESS	0-60	50	6.02	301.00	90% -89.81%	Discharge
Lead acid	Trial 3. EV	0-60	50	3.81	190.50	90% -89.87%	Discharge
	Trial 4. ESS	0-60	43	(-)1.43	61.49	70% - 70.05%	Charge

Figures 5 and 6 illustrate the SOC trends for both the EV and ESS. Figures 5(a)-(d) illustrate the EV battery's performance in charging mode. Monitoring these SOC trends is critical for ensuring optimal performance and longevity. Figures 6(a)–(d) present the performance of the ESS battery in discharging mode. The SOC trends help optimize energy distribution. Monitoring these SOC trends is critical for ensuring optimal performance and longevity of both systems. For EVs, tracking SOC helps prevent overcharging or deep discharging, which can degrade battery life. For ESS, maintaining an appropriate SOC balance is essential to ensure that the system is ready to provide backup power or absorb excess energy when needed, thereby enhancing overall energy efficiency and reliability. In Figure 5(a), the SOC is shown to increase during the charging phases, indicating that the battery is storing energy. This increase in SOC reflects the battery's capacity to accept and store electrical energy efficiently, which is crucial for extending the operational range of EVs and enhancing the performance of ESS. On the other hand, Figure 6(a) illustrates the decrease in SOC during discharging phases, where the stored energy is utilized to power external systems or the EV itself. The decrease in SOC during discharging indicates the effective delivery of energy from the battery to the load, demonstrating the battery's ability to provide reliable power when needed. These SOC trends are critical indicators of the battery's health and performance, providing insights into its efficiency and capacity in real-world applications.

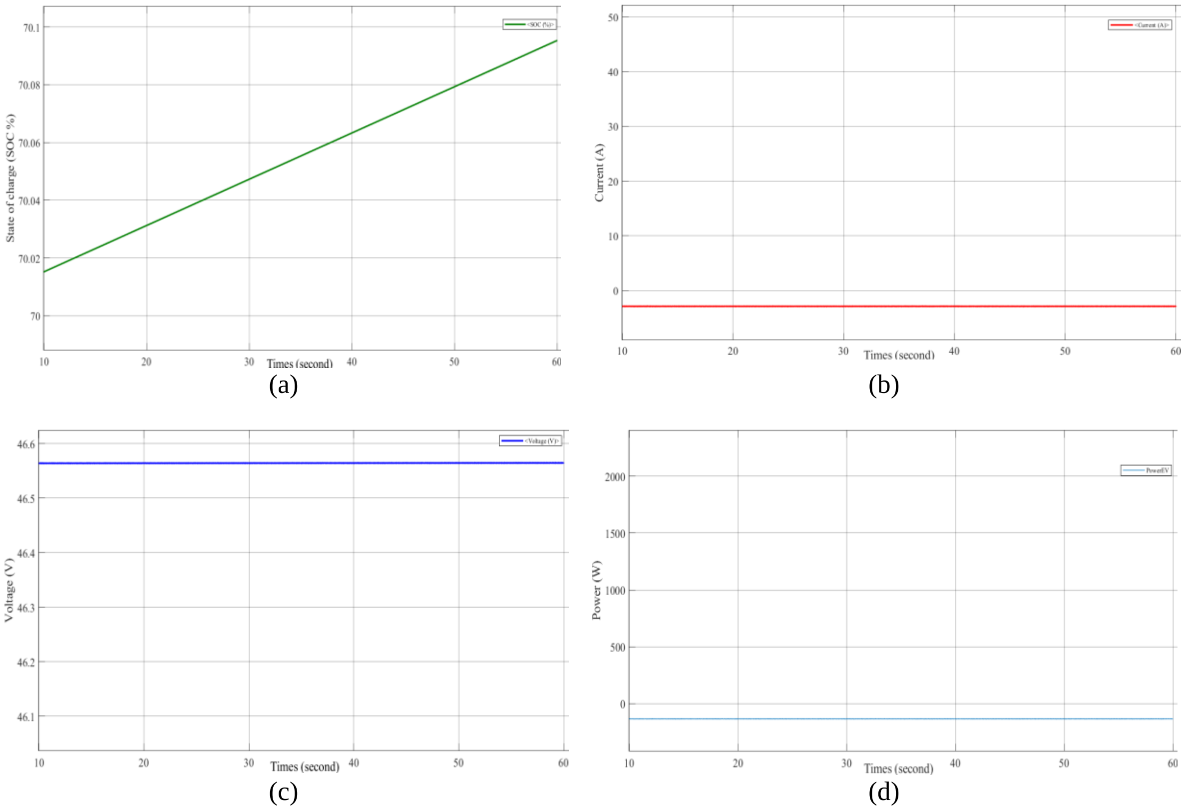


Figure 5. Result of (a) SOC, (b) battery current (A), (c) battery voltage (V), and (d) power (W) for EV battery while in charging mode

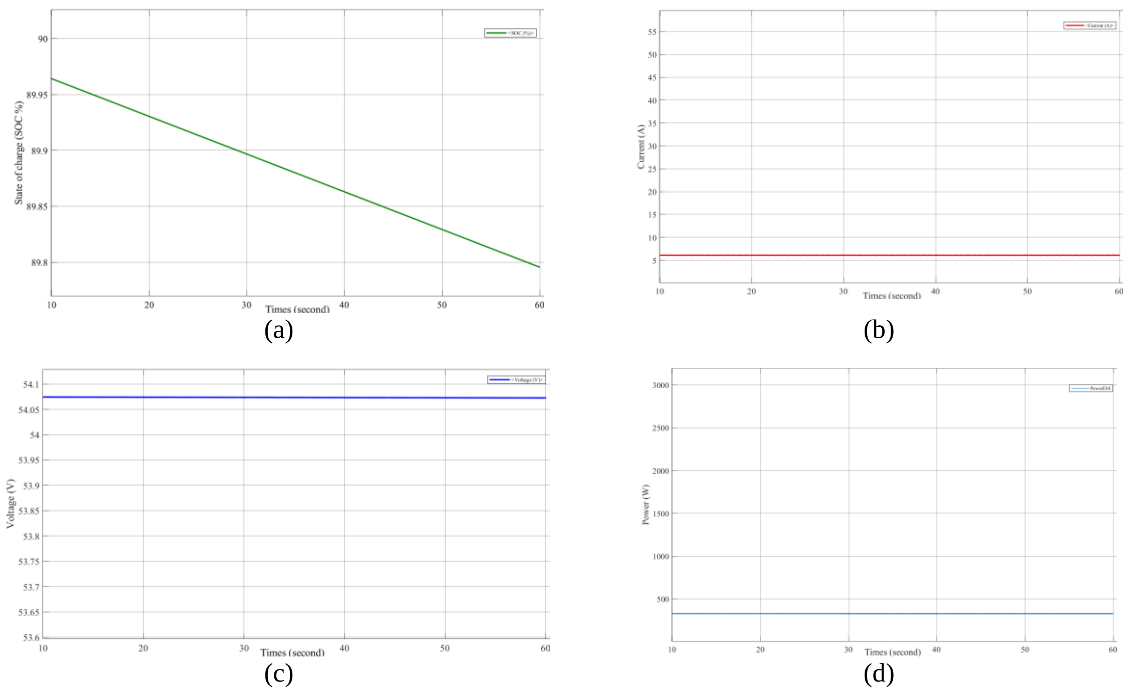


Figure 6. Result of (a) SOC, (b) battery current (A), (c) battery voltage (V), and (d) power (W) for ESS battery while in discharging mode.

Figures 7 and 8 present a detailed analysis of the battery performance in the simulation during discharging and charging modes, respectively, for the EV and the ESS. These parent figures illustrate how the BDC regulates the energy transfer between EV and ESS by displaying trends in four key parameters which is SOC, battery current, battery voltage, and power output. Figures 7(a)–(d) further illustrate the EV battery's behavior during discharge mode. The results highlight stable voltage regulation and energy efficiency and Figures 8(a)–(d) present the charging performance of the ESS battery, reflecting stable energy absorption.

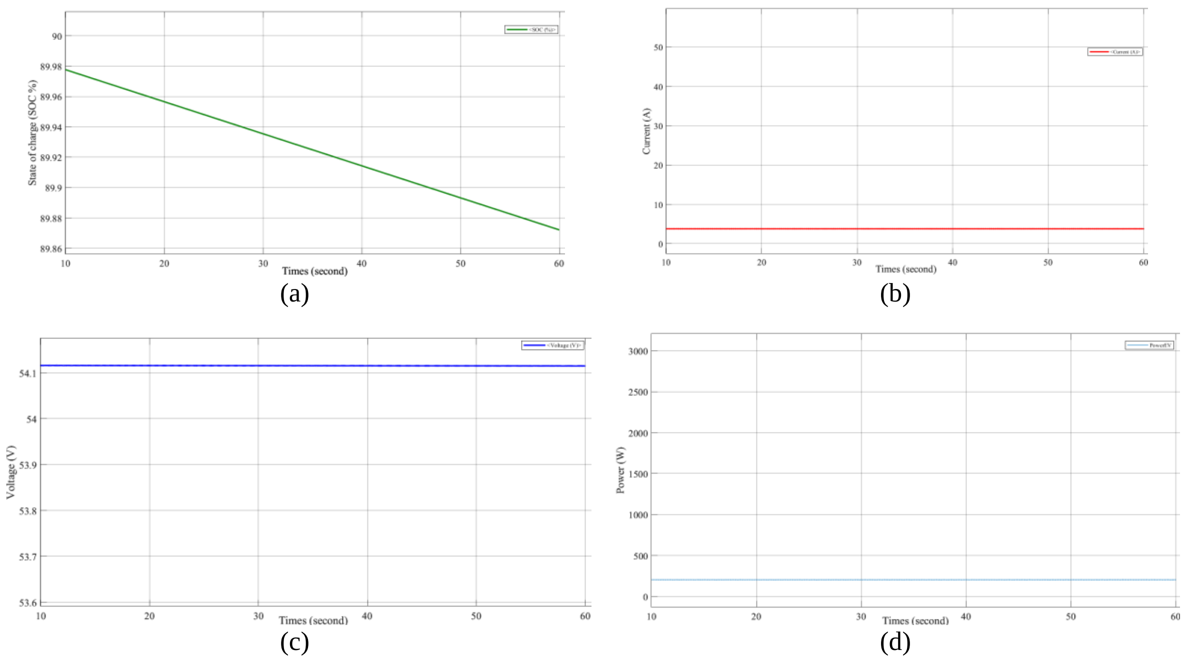
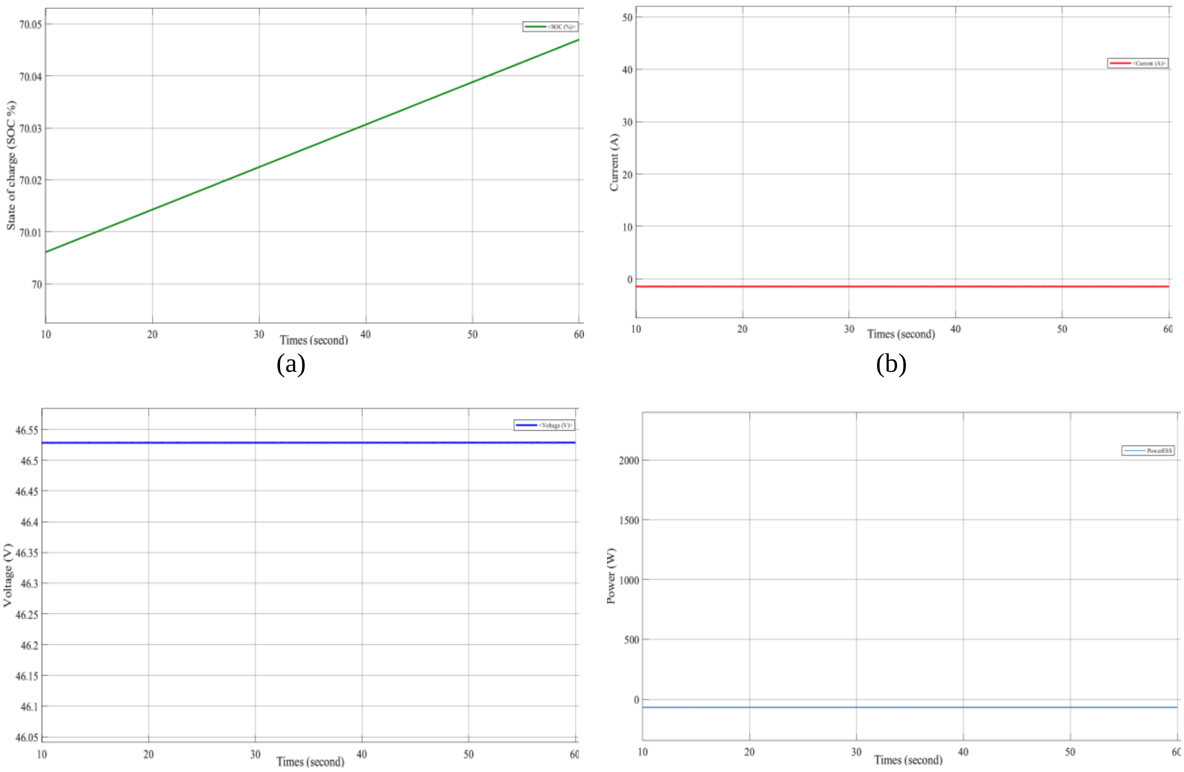


Figure 7. Result of (a) SOC, (b) battery current (A), (c) battery voltage (V), and (d) power (W) for EV battery while in discharging mode

Similarly, Figures 7(a) and 8(a) reflect the SOC trends observed in Figures 5(a) and 6(a). In Figure 6(a), the SOC decreases during the discharging phases, mirroring the behavior in Figure 5(a) and further demonstrating the battery's ability to effectively deliver energy to external systems or the EV. Conversely, Figure 7(a) shows an increase in SOC during charging phases, similar to the trend in Figure 5(a), indicating the battery's efficient energy storage capabilities. These figures collectively underscore the robust performance of lead-acid batteries in both charging and discharging scenarios, reinforcing their suitability for EV and ESS applications.



(a) (b) (c) (d)

Figure 8. Result of (a) SOC, (b) battery current (A), (c) battery voltage (V), and (d) power (W) for ESS battery while in charging mode

Table 5. shows that in the EV-to-ESS mode, the primary side of the converter maintains a stable voltage of 50 V, coupled with a primary current of 40 A, indicating a consistent power input from the EV. On the secondary side, the converter effectively steps down the voltage to 48 V, while concurrently delivering a secondary current of 3 A. This demonstrates the converter’s capability to efficiently charge the ESS, enabling the storage of surplus energy generated by the EV. Notably, the status indicates that the EV is actively charging the ESS, exemplifying the utilization of excess energy for future use.

Conversely, in the ESS-to-EV mode, the primary voltage remains consistent at 50 V, albeit with a negative primary current of (-)50 A, signifying reverse current flow from the ESS. Similarly, on the secondary side, the converter maintains a voltage output of 48 V, accompanied by a negative secondary current of (-)6 A. This reverse power flow indicates the converter’s ability to effectively channel energy from the ESS to the EV for propulsion. The status indicates that the ESS is charging the EV, illustrating the utilization of stored energy to power the vehicle.

Unlike prior research, which reported significant efficiency losses in bidirectional energy transfer, our study demonstrates that an optimized BDC topology with galvanic isolation enhances overall system efficiency. The results demonstrate the converter's stable voltage regulation and efficient power transfer in both operational modes. The consistent voltage and current levels indicate minimal losses and high efficiency in energy conversion, which is crucial for optimizing overall system performance. The implementation of a BDC using push pull converter represents a novel approach in this research. The primary findings indicate that the BDC significantly enhances the efficiency and stability of energy transfer between EVs and ESS.

The BDC design ensures higher power handling capacity and superior voltage regulation, leading to minimized energy losses during bidirectional operations. This advancement provides substantial benefits to the industry by improving the reliability and performance of EV charging infrastructure, thereby promoting the broader adoption of EVs. Furthermore, this research contributes to the industry by offering a scalable and efficient solution for integrating ESS with EVs, optimizing energy utilization, and reducing the overall cost of energy storage and management systems.

The bidirectional capability of the converter facilitates seamless power exchange between EVs and ESSs, supporting diverse operational scenarios. Furthermore, maintaining voltage compatibility between the converter and EV and ESS systems ensures efficient energy transfer without compromising system integrity. The implications of the study hightlights the importance of bidirectional converters in sustainable energy solutions particularly for integrating EV's and ESS. The findings suggest that optimizing BDC topology could lead to improved battery longevity and energy efficiency.

Table 5. Simulation data for the BDC

Types of converter	Direction	Primary voltage (V_1)	Primary current (A_1)	Secondary voltage (V_2)	Secondary current (A_2)	Power (kW)	BEVs status
Push-pull converter	EV-to-ESS	50	40	48	3	2.0	EV charge the ESS
	ESS-to-EV	50	(-)50	48	(-)6	2.5	ESS charge the EV

4. CONCLUSION

In conclusion, simulation results demonstrate the effectiveness of lead-acid batteries in maintaining stable voltage and current profiles during both charging and discharging operations for electric vehicles (EVs) and energy storage systems (ESS). During EV trials, the battery charged at 43 V, -2.90 A, and 124.70 W, while discharging at 50 V, 3.81 A, and 190.50 W. Conversely, during ESS trials, the battery discharged at 50 V, 6.02 A, and 301.00 W, and charged at 43 V, -1.43 A, and 61.49 W. The stable performance of lead-acid batteries was observed across these scenarios. Additionally, the bidirectional DC-DC (BDC) converter effectively facilitated efficient energy transfer with consistent voltage regulation of 50 V in both directions, supporting seamless bidirectional energy flow between EVs and ESS. The result confirms the stable efficient energy transfer, supporting the feasibility of lead-acid batteries in EV's and ESS integration.

The analysis confirms that lead-acid batteries when paired with an effective BDC converter, can deliver dynamic performance across operational modes. The BDC topology is essential for enhancing battery system performance and reliability by enabling smooth energy transfer. Future research should focus on hardware validation to confirm simulation results and optimization of BDC topology for high-power applications of the proposed topology and investigate alternative battery chemistries to compare their performance also on thermal management strategies to mitigate battery degradation. This research advances sustainable energy solutions by establishing a foundation for integrating bidirectional converters into battery management systems. The findings confirm that bidirectional converters significantly enhance lead-acid battery performance in EV and ESS applications, supporting their feasibility for sustainable energy solutions.

ACKNOWLEDGMENTS

The authors sincerely appreciate the individuals and organizations that contributed to this research project. First, they extend their gratitude to Petronas Research Sdn. Bhd. for their support. They also acknowledge the CHAdeMO Association for its ongoing technical assistance. Lastly, the authors express their appreciation to the College of Engineering, Universiti Teknologi MARA, for providing excellent research facilities, administrative support, and technical assistance

FUNDING INFORMATION

This research was supported by PETRONAS Research Sdn. Bhd. under the project titled "AC & DC Intelligent Charging Station" with the project number UTVSB/CS/P.20221025007. The authors acknowledge the financial support provided for the development, implementation, and execution of this study. The funding agency played no role in the study design, data collection, analysis, interpretation of results, or manuscript preparation.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [Muhammad Nabil Bin Hidayat].

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