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Article

An innovative control of the charging and discharging for the battery management operation using a bidirectional converter

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ABSTRACT

This research article explores the control strategies for managing the battery charging and discharging operations using a bidirectional converter. Bidirectional converters offer flexibility and allow batteries to receive and deliver power. Battery systems are an important part of electrical vehicles (EVs), and they can be charged by renewable energy integration and the public grid. The battery bank manages the DC (Direct Current) link and fulfills the load requirement for charging. The main aim of this article, the proportional integral derivative (PID) controller, is to design and control the duty cycle of the bidirectional converter to ensure efficient and safe battery operation. In this regard, the current of battery banks is regulated during the charging and discharging phases. To ensure optimum charging and discharging control, further work can be implemented using artificial intelligence (AI) based technology in the battery management system (BMS) operation.

1. Introduction

A battery is a chemical device that converts chemical energy into electrical energy. The battery consists of one (or more) electrochemical cells which contain positive (Anode) and negative (Cathode) terminals. The battery is used in the EVs, which means a chemical reaction occurs inside the cell due to electrons flowing from the cathode to the anode terminal. The movement of the electrons creates an electric current that can be used to power devices and charging stations for EVs [1]. There are two types of batteries: primary and secondary. Primary batteries are called disposable batteries that cannot be recharged. It is used once and depleted. Secondary batteries are called rechargeable batteries, which can be recharged several times using an electric current through a power system [2]. Batteries are important devices for various applications, such as cars, laptops, smartphones, cameras, and toys. Power can be generated by many sources for battery-changing framework management. It can be supplied from renewable energy sources. In this regard, plentiful energy is found in nature, which produces power for the rural and regional communities. It improves the quality of life and living standard of humans [3]. Among the many natural sources are solar, wind, hydro, fuel cells, etc. The traditional electric grid cannot be extended to far places due to rising transmission losses and per-unit generation costs. Small-scale power generation units can be a viable solution for various locations. The growing concerns about environmental impact and the depletion of conventional energy sources like fossil fuels have led nations to transition towards renewable energy sources. The availability of these sources is a main factor in determining their adoption [4, 5]. Solar energy is a promising renewable energy but a challenging option for power generation. Its intermittent nature due to fluctuations in solar radiation (SR) and environmental temperature can significantly impact the load. Factors like weather conditions, tree shading, cloud cover, dust, and mismatching of photovoltaic (PV) modules can contribute to these variations [6,7]. To ensure a reliable power supply under all SR conditions, a complementary energy source is necessary. This combination results in a hybrid framework.

Although wind turbine renewable energy is another renewable source its highly intermittent nature makes it unsuitable as a backup supply. Supercapacitors are primarily used for short-duration energy storage in location-specific hydro-power generation. Batteries are recommended as a secondary supply to provide a dependable power source for extended periods [8, 9]. Figure 1 shows the proposed block diagram of battery management operation with a bidirectional converter and controller. BMS is an essential managerial component for ensuring optimal performance, safety, and lifespan of battery banks.

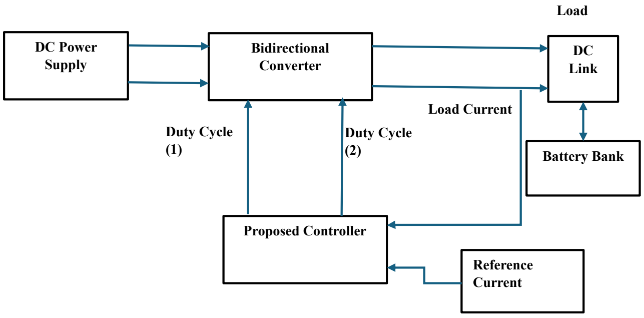

Figure 1. Proposed block diagram of battery management operation

A critical aspect of a BMS is controlling the charging and discharging processes of the battery banks. This control becomes more complex with the bidirectional power converters. Bidirectional converters enable two-way power flow between the battery and the connected source such as the grid, charger, etc [10-13]. This offers advantages in various applications.

- Bidirectional converters allow EVs to not only charge their batteries but also feed excess power back to the smart grid.
- Renewable energy sources like solar PV and wind, being intermittent bidirectional converters, enable storing excess energy in batteries during peak production and discharging it back to the smart grid during peak demand.

This article explains the design and performance analysis of integrating a battery bank with a bidirectional converter and PID controller. The rest of the work is structured as follows: Section 2 represents a brief description of bidirectional power converters. Section 3 describes the PID controller. Simulation of the proposed model is described in section 4. Section 5 presents the simulation results and their analysis, and the conclusions are presented in Section 6.

2. Brief description of bidirectional power converters

A bidirectional DC-DC power converter is a power electronic circuit that allows for the flow of energy in both directions between two DC sources which means charging and discharging of the battery based on the load [14]. Unlike conventional unidirectional converters, such as buck or boost, which can only step the voltage down or up respectively. This versatile device can control both functionalities of these conventional converters. It is a decisive component in defendant applications, especially involving energy storage and management. The bidirectional power converter's working principle combines electronic switches and diodes controlled by a dedicated circuit. These switches are turned on and off rapidly to manipulate the flow of current and regulate the voltage at the output. The converter can be dependent on the following primary modes to obtain its desired operation [15, 16].

2.1 Boost mode

When the input voltage of the converter needs to be increased to a desired level at the output which type of the converter operates in boost mode. This is obtained by controlling the switching sequence such that energy stored in an inductor is released to boost the output voltage.

2.2 Buck Mode

When a lower voltage is required at the output voltage compared to the input voltage, which type of converter switches to buck mode. In this case, the switches and diodes work together to divert excess energy that is effectively stepping down the output voltage. The important elements are used in the bidirectional DC-DC power converter which are briefly described in the following manner.

Switches – MOSFETs act as electronically controlled conductors. The direction and timing of the current flow are determined using turning it on and off strategically.

Diodes – It is unidirectional devices that allow current flow only in one direction. They play an important role in controlling the flow of current during different switching states.

Inductors – Inductors store energy in the form of a magnetic field when current flows through them. It stored energy is then released later in the cycle to influence the output voltage.

Capacitors – It is acting as temporary energy reservoirs that capacitors help smooth out the pulsating nature of the output voltage from the switching process.

Control circuit – It is the brain of the operation. It monitors the input and output voltages and currents and employs control algorithms to calculate the switching pattern for the transistors based on the desired mode such as boost and buck power converter. Bidirectional converters are used in various aspects.

Energy efficiency – It enables efficient two-way power flow, making them ideal for applications like regenerative braking in electric vehicles where energy captured during braking can be fed back to the battery.

Energy storage integration – It facilitates the seamless integration of energy storage devices such as batteries and supercapacitors into power systems, enabling efficient charging and discharging.

Flexible power management – It provides greater control over power flow between different voltage levels, which makes it valuable in applications like DC microgrids and distributed power generation.

3. Description of PID controller

A PID controller is a valuable tool for regulating the charging and discharging of a battery system using a bidirectional converter. The basic operation of a PID controller is a feedback control system that uses three components Proportional (P), Integral (I), and Derivative (D) terms. It measures the various (errors) between a desired output (i.e. reference voltage) and the actual output voltage of the battery during charging and discharging. Based on the error, the PID controller calculates an adjustment value that is fed into the control circuit of the bidirectional power converter. The control circuit is used to modify the duty cycle of the DC-DC power converter, which influences the output voltage and current to minimize the error. This controller helps maintain the battery voltage at the desired setpoint during charging and discharging, which ensures optimal battery performance and lifespan. The proportional term allows for fast adjustments based on the current error and minimizing voltage oscillations [17-19]. The integral term eliminates any remaining error over time, ensuring the battery voltage converges to the desired output value. The derivative term helps anticipate future errors and proactively adjusts the control signal, leading to smoother transitions during charging and discharging cycles—the general methodology for using a PID controller in a bidirectional power converter for BMS.

Define reference voltages: Set separate reference voltages for charging and discharging based on battery specifications and desired operating conditions.

Measure battery voltage: Continuously monitor the actual voltage of the battery using a voltage sensor.

Calculate error: Subtract the actual battery voltage from the corresponding reference voltage (charging or discharging) to determine the error.

PID control algorithm: To apply the PID control algorithm to the error signal. This involves calculating the proportional, integral, and derivative terms based on pre-determined control gains. The sum of these terms becomes the control output.

Adjust duty cycle: The control output from the PID controller is used to adjust the duty cycle of the switches in the bidirectional converter. By increasing or decreasing the duty cycle, the converter regulates the output voltage and current to minimize the error and drive the battery voltage toward the reference.

4. Simulation structure of the proposed model

Figure 2 shows the simulation model of the proposed framework management using a novel controller. In this research article, the proposed framework consists of the battery bank, bidirectional converter, and PID controller. Tuning the PID gains (proportional, integral, and derivative) is crucial for optimal performance. These gains can be adjusted based on the specific battery characteristics, converter design, and desired control behavior. Separate PID controllers might be employed for charging and discharging modes to account for potential differences in battery behavior during these processes. Safety features like current limiting and over-voltage protection should be integrated into the control system to ensure safe battery operation.

While PID control offers a robust solution, more advanced control algorithms like fuzzy logic control or state-space control might be explored for even finer control over the battery charging and discharging process. The specific implementation details will vary depending on the chosen bidirectional converter topology and the control circuit design. The main motive of the research is to find the maximum power for EVs and vice versa. The simulation time set in the complete model is 2 seconds, and the discrete sampling time is 1 microsecond. Table 1 and Table 2 show the specifications of the battery bank and bidirectional converter with their values.

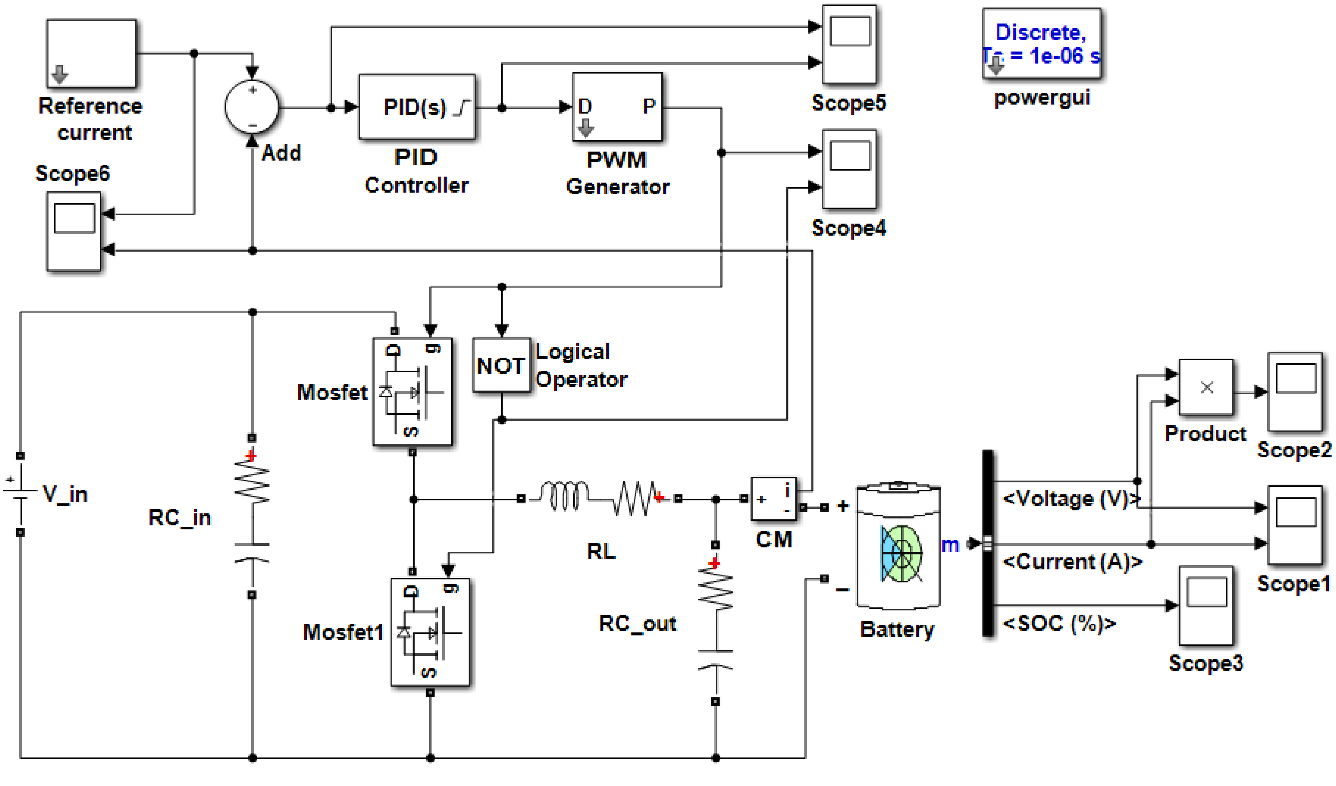

Figure 2. Simulation model of proposed framework management using novel controller

Table 1. Specifications for the battery bank with their values

Sr. No.	Parameters	Value
1	Nominal Voltage of Lead-Acid Battery	415V
2	Rated capacity	150Ah
3	Initial SoC	50%
4	Battery response time	1s
5	Maximum capacity of battery	156.3Ah
6	Cutoff voltage	311.3V
7	Fully charged voltage of battery	451.9V
8	Nominal discharged current	30A
9	Initial resistance	0.03Ω

Table 2. Specifications for the Bidirectional Converter with their values

Sr. No.	Parameter of Bidirectional Converter	Value
1	V_{in}	850V
2	RC_{in} (Resistance & Capacitance)	10mΩ & 1000μF
3	MOSFET Switch used	2
4	NOT Gate (Logical Operator) used	1
5	RL (Resistance & Inductance)	10mΩ & 13mH
6	RC_{out} (Resistance & Capacitance)	10mΩ & 20F
7	Switching frequency of the PWM generator	5kHz
8	Sample-time of the PWM generator	1μs

5. Simulation results and their analysis

Simulation results are carried out using the proposed framework with the controller. It provides better output response performance. Figure 3 shows the responses of the reference current and load current for the proposed controller, Figure 4 shows the responses of the control signal and error value of the framework, and Figure 5 illustrates the duty cycle of boost and buck for the bidirectional converter. Battery current and voltage characteristics are presented in Figure 6. Figure 7 shows the power response of the battery framework, and Figure 8 shows the power response (zoomed) of the battery framework. Figure 9 shows the charging and discharging characteristics of SoC (%) for the battery and Figure 10 shows the charging and discharging characteristics (zoomed) of SoC (%) for the battery framework.

PID controller is usually used in control frameworks to control a process variable to a desired setpoint. In the context of electrical frameworks, the process variable might be a current, voltage and power. The reference current is the desired or target current value that the controller aims to achieve. It is essentially the setpoint for the system. The load current is the actual current flowing through the load or the controlled element. It is the measured output of the system.

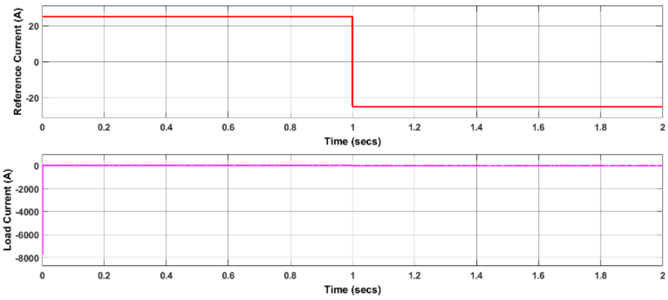

Figure 3. Responses of reference current and load current for proposed controller

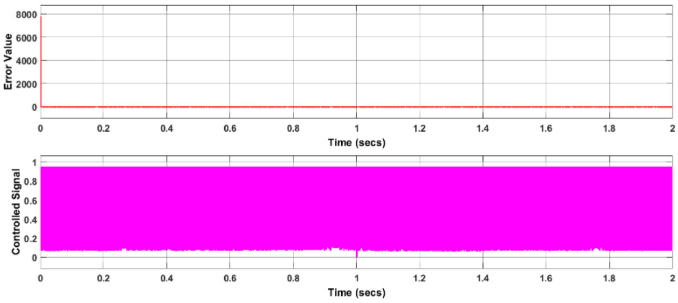

Figure 4. Responses of Control Signal and Error Value of the Framework

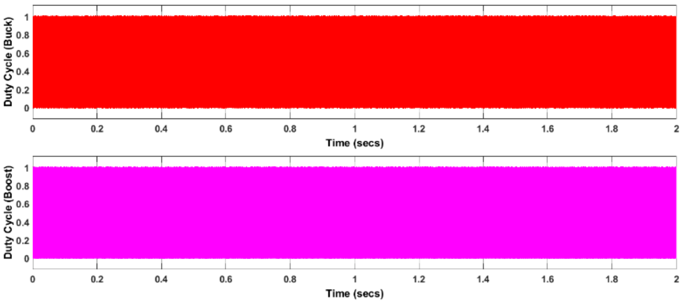

Figure 5. Responses of Duty Cycle of Boost and Buck for Bidirectional Converter

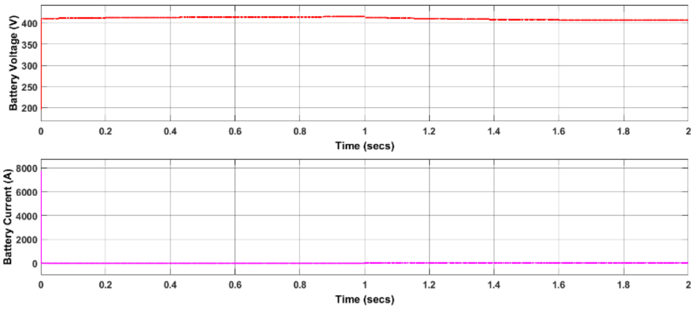

Figure 6. Output responses of voltage and current of battery bank

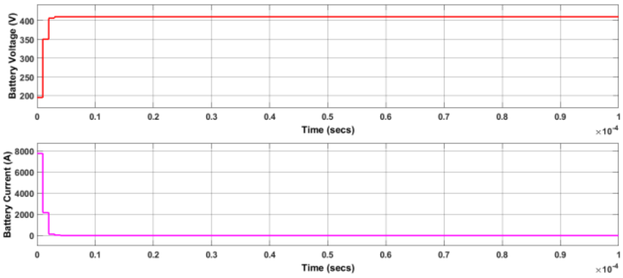

Figure 7. Output responses (zoomed) of voltage and current of battery bank

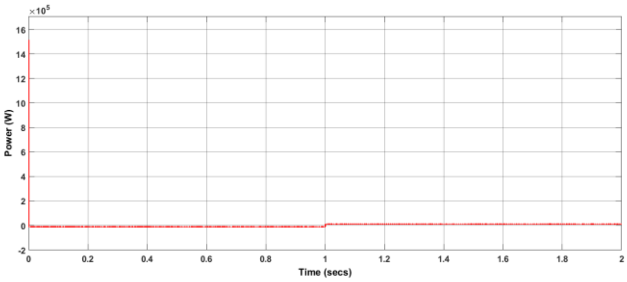

Figure 8. Output responses of power of battery framework

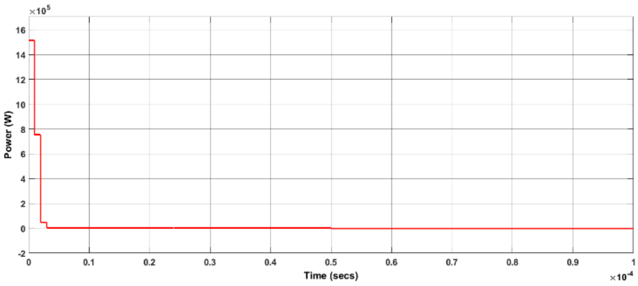

Figure 9. Output responses (zoomed) of power of battery framework

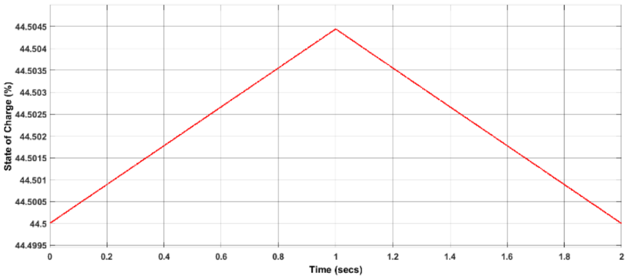

Figure 10. Charging and discharging characteristics of SoC (%) of battery framework

Figure 10 depicts a graphical representation of how a battery's SoC changes during charging and discharging cycles. The charging curve is a line that starts at a low SoC (44.5%) and rises steadily as the battery is charged, reaching a maximum (%) at the end of the charging cycle. The discharging curve is a line that starts at maximum SoC and decreases as the battery is used, reaching a lower SoC (%) at the end of the discharge cycle.Analysis of the results is discussed with the following performance such as reference current is set the values (25A and -25A). Accordingly, calculate the value from the load is 25.3A at time 0.354s. Similarly, the output performance of the battery in terms of voltage, current, and power values are 415.3V, 26.16A, and 10830W, respectively, at time 1s. These results can clearly be seen in Figure 7 and Figure 8. The charging and discharging characteristics of the battery are defined using the SoC (%) which is shown in Figure 10.

6. Conclusion

Effective control strategies are essential for utilizing bidirectional converters in battery management operations. These control systems regulate the battery's charging and discharging currents and voltages, ensuring efficient power transfer, safety, and extended battery life. The specific control techniques employed depend on the application and converter topology. In this research article, simulation results are carried out based on the output performance of power, current, and voltage of the proposed model. The battery is outputting 415.3V and 26.16A at time 1 second, resulting in a power output of 10830W. Further research and development in control algorithms will continue to enhance the efficiency and functionality of bidirectional converters for BMS. The renewable energy framework is important in integrating renewable energy sources like solar and wind into the grid by enabling efficient power flow and energy storage management.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The datasets analyzed during the current study are available and can be given upon reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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