Dual mode control of an integrated on-board charger powered BLDC drive

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ABSTRACT

The high adoption of electric vehicles in transportation has created a demand for compact, efficient, and cost-effective charging solutions for them. Conventional onboard chargers are often bulky, which adds to the overall cost of the drive system, whereas off-board charging infrastructure remains limited. In order to address these issues, this work illustrates the design and modelling of an active power factor corrected integrated onboard charger which gets reconfigured from the electric vehicle drive train components. The proposed circuit setup is designed to work in dual mode, i.e., in the role of a DC-DC converter while charging the vehicle battery and as a three-phase inverter while driving the vehicle. The front-end power factor correction circuit, in addition to the reconfigured DC-DC converter, charges the 24 V, 20 Ah lead acid battery under constant current constant voltage (CC-CV) mode, achieving a power factor close to unity. Modelling and control of the proposed 200 W reconfigurable converter-fed 24 V, 180 W brushless direct current (BLDC) drive is validated using MATLAB/ Simulink Software. Simulation results demonstrate a power factor of 0.996 in grid-connected operation with a total harmonic distortion (THD) of 4.96%. The proposed architecture achieves a compact structure with only 8 switches enabling charging, propulsion and regenerative braking operation. The proposed converter thus contributes to a cost-effective electric vehicle and provides the scope of future extension to vehicle to home (V2H), vehicle to load (V2L), and vehicle to vehicle (V2V) applications as well.

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1. INTRODUCTION

Electrification of transportation is crucial for mitigating greenhouse gas emissions, reducing fossil fuel dependency, and enhancing air quality, particularly in urban areas. Considering the large contribution of the transportation sector to air pollution and climate change, transitioning to electric vehicles (EVs) provides a clean option that aligns with the global decarbonization objectives. Moreover, EVs are cheaper to run and maintain, more energy-efficient, and may be powered with renewable energy, thus an integral part in developing cleaner, smarter, and more resilient mobility systems. Widespread research is carried out on the EV drive train to improve its performance and overall efficiency. An EV drive train typically has an energy storage system like rechargeable batteries, a battery charger unit, electric motors, and a power electronic converter to drive the motors [1].

Battery chargers can be classified into two types, onboard chargers and off-board chargers, depending on where the power conversion is done [2], [3]. Onboard chargers are built into the vehicle and transform alternating current (AC) power from the grid to direct current (DC) power to charge the battery. These provide convenience to charge anywhere there is an appropriate outlet or charging station. These are normally employed for slower Level 2 or Level 1 charging. Off-board chargers, by contrast, are outside the vehicle and conduct the AC to DC conversion externally and feed DC power directly to the battery. These are deployed in DC fast charging stations, enabling much faster charging, and are appropriate for commercial or long-distance use.

Onboard chargers have several advantages over off-board chargers. They provide charging convenience with no additional infrastructure. Thus, vehicles with onboard chargers can be recharged wherever a single-phase utility is available. Also, onboard chargers offer an effective and practical solution for vehicle-to-vehicle (V2V) and vehicle-to-home (V2H) applications [4], [5]. Research studies are going on to make these chargers more space-saving so that they are compatible with different regions and different models.

This paper provides an extensive evaluation of the proposed integrated onboard charger-fed brushless direct current (BLDC) drive. Although various studies have addressed integrated on-board chargers [6]–[8] and BLDC drive separately, limited research has addressed the integration of dual-mode integrated onboard chargers incorporating active power factor correction and regenerative braking in a BLDC drive system. Significant contributions of this paper are summarized as follows: i) Development of an integrated on-board charger architecture that reduces component count and hardware redundancy; ii) Implementation of dual mode operation enabling seamless transition between propulsion and charging modes; iii) Achievement of input power factor correction during grid charging to comply with power quality standards; finally, iv) Simulation-based validation of dual mode operation, including regenerative braking capability, demonstrating effective energy recovery under practical operating conditions.

The paper proceeds as follows: i) Section 1 introduces foundational concepts and motivation for the study; ii) Section 2 gives an outline about the conventional onboard charger fed EV drive; iii) Section 3 describes the design, modeling and control of the proposed bidirectional integrated onboard charger fed BLDC drive; iv) Theoretical studies are validated by doing simulation studies in section 4; v) Results are discussed in section 5; and vi) Section 6 concludes the work and provides its future scope.

2. CONVENTIONAL ONBOARD CHARGER FED EV DRIVE

A conventional battery charger performs energy conversion in two sequential stages of AC to DC and DC to DC conversion. In the first stage, a single-phase AC source undergoes rectification using a diode bridge rectifier, and in the next stage, the required DC voltage is obtained by installing a suitable DC-DC converter. On the other hand, propulsion and regenerative braking modes are obtained by controlling the power flow between the source and the motor through an inverter. Altogether, large numbers of power electronic converters are required in an EV drive [9], [10]. To reduce the number of power electronic converters, a compact integrated converter is proposed as the onboard charger for EV applications.

3. PROPOSED INTEGRATED BIDIRECTIONAL ON-BOARD CHARGER FOR EV APPLICATION

Traditional electric drive trains employ two distinct circuits for propulsion and charging mode. However, the use of two separate circuits contributes to a more complex and costly drivetrain. Since the battery is charged when the vehicle is idle, the motor driving circuit can also be utilized in charging mode, thereby reducing the overall cost to 30% [11]. Systems where the EV drivetrain components, typically employed for propulsion, are also utilized for battery charging are called integrated on-board chargers [12]. Figure 1 illustrates the block-level representation of the proposed integrated on-board charger [8].

3.1. Bidirectional integrated onboard charger circuitry configuration

The proposed integrated onboard charger incorporates a boost active power factor correction (APFC) converter at the input stage, two relays, relay 1 and relay 2 [13] for the reconfiguration, a three-phase inverter-fed BLDC drive, and a 24 V, 20 Ah battery set as depicted in Figure 2. The functioning of the converter involves two modes, charging mode and propulsion mode. In charging mode, relay 1 is closed, and relay 2 is open [14]. In propulsion mode, relay 1 remains open, and relay 2 will be closed. The EV motor draws power from the battery through the three-phase inverter. Dual-mode operation of the circuit is described in the following subsections.

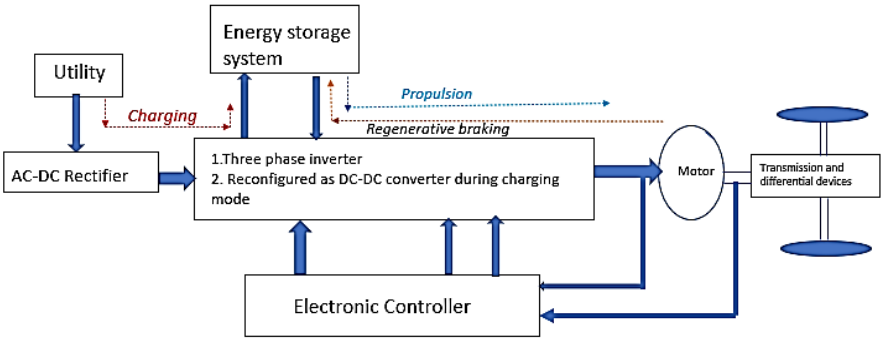


Figure 1. Block-level representation of the proposed integrated on-board charger for EV

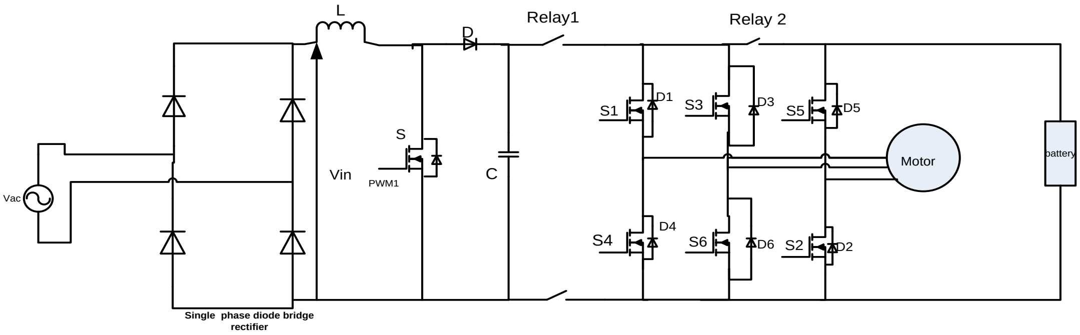


Figure 2. Circuit setup for proposed bidirectional integrated onboard charger fed BLDC drive

3.1.1. Charging mode

In this mode, relay 1 is activated while relay 2 remains in the OFF state. The single-phase diode bridge rectifier along with a boost APFC converter with inductor L and switch S corrects the input AC waveform to a pure sine wave. The MOSFET switches of the three-phase inverter, which is reconfigured as a DC-DC converter is controlled to obtain CC-CV charging. The process of reconfiguring the proposed circuit as a DC-DC converter is described as an equivalent circuit in Figure 3. Here, switch S2 is operated in pulse width modulation (PWM) mode, and S1 remains ON. In mode I, S1 and S2 are in conducting state. From the equivalent circuit as shown in Figure 3(a).

$$V_{dc} = V_{L1}$$
$$V_{L1} = (L_s + L_s)\frac{di_L}{dt} = 2L_s\frac{\Delta I}{DT}$$
$$\therefore \Delta I = \frac{V_{dc}\,DT}{2L_s} \tag{1}$$

Where V_{dc} indicates the output voltage of the rectifier, V_{L1} represents the voltage across the motor inductance in mode I, i_L represents inductor current, L_s indicates the motor winding inductance, D stands for duty ratio, and 'T' denotes the switching period.

In mode II, switch S2 is turned off, and the inductor reverses their polarity, so the diode D5 becomes forward-biased and starts conducting. The inductor will start discharging through the battery. Still, the supply is linked to the battery, and the battery voltage will be the sum of the inductor and supply voltage. Therefore, the circuit steps up the input voltage. From the equivalent circuit shown in Figure 3(b),

$$V_o = V_{batt}$$
$$V_{dc} = V_{L2} + V_{batt} \ where \ V_{L2} = 2Ls\frac{di_L}{dt}$$
$$V_{dc} = 2Ls\frac{-\Delta I}{t_{off}} + V_{batt} \tag{2}$$

Here, V_{L2} is the voltage across the inductor during mode II and t_{off} is the switch turn off time. Sub (1) in (2):

$$V_{dc} = -2L_s \frac{(\frac{V_{dc}}{2Ls}DT)}{T-DT} + V_0$$
$$\frac{(V_{dc}D)}{1-D} + V_{dc} = V_{batt}$$
$$V_{batt} = \frac{V_{dc}}{1-D} \quad (3)$$

where V_{dc} is the rectified output voltage, V_{batt} is the voltage across the battery, and D is the duty ratio. Hence, from (3) it is clear that as a result of mode I and mode II charging methods, the step-up operation occurs during charging mode. The control algorithm for switch S2 is designed to obtain the CC-CV mode.

In CC-CV mode of charging [15], till 80% state of charge (SoC), the battery undergoes constant current charging, and above that, it is charged with constant voltage. For both modes, the actual battery current and voltage are compared with their respective reference values and controlled using PI controllers to get the desired results. The reference current can be set from 0.1C to 0.3C for standard rate, where C is battery capacity in Ah. The reference voltage can be set to a nominal voltage of 25.2 V. The switching strategy with APFC for switch S and CC-CV mode for switch S2 is as shown in Figure 4. APFC enhances grid interaction by lowering reactive power consumption, resulting in near unity power factor (UPF). It also minimizes losses, improves voltage stability, and results in efficient grid operation.

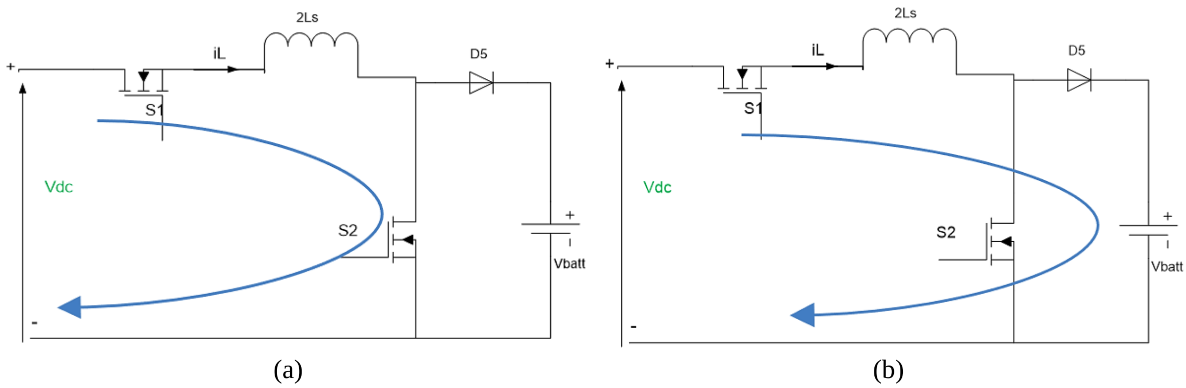


Figure 3. Equivalent electrical model for charging operation: (a) mode I and (b) mode II

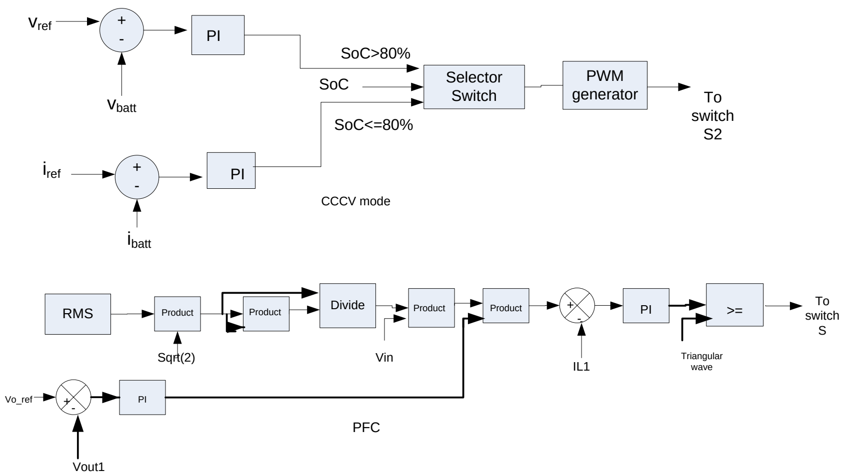


Figure 4. Switching strategy with PFC and CC-CV control for the switch S and the inverter switch S2 in charging mode

3.1.2. Propulsion mode

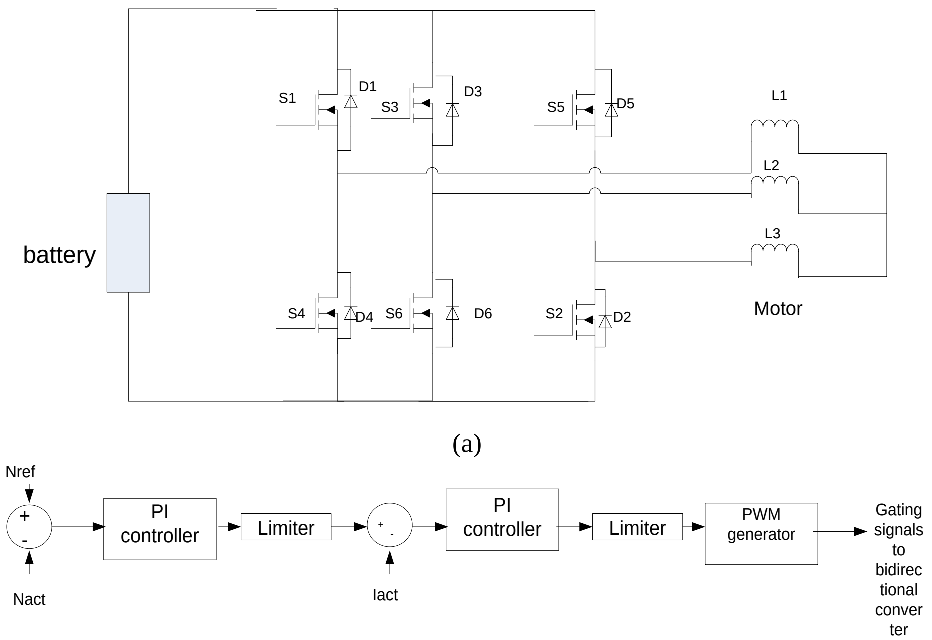
In this mode, relay 1 is in the open state while relay 2 is closed, and the equivalent circuit can be seen in Figure 5(a). A battery powers the BLDC motor through a six-switch three-phase inverter. The inverter switches through six commutation states in one electrical cycle, which is known as six-step or trapezoidal commutation. During propulsion mode, depending on the motor's rotor position sensors, two inverter switches are turned ON to energize the stator windings from the battery in a proper sequence for continuous rotor rotation. Speed control is implemented by incorporating outer speed control combined with inner loop current control as shown in Figure 5(b) [16].

When the brake is applied, relay 1 stays open and relay 2 is engaged, and its equivalent circuit is depicted in Figure 5(a). The switching pulses to the three-phase inverter are given in such a way that the energy is transferred from the traction motor to the battery, which eventually recharges the battery. In this mode, all the high-side switches in the inverter remain in the OFF state, and the lower switches operate in PWM mode. Figure 6 demonstrates the equivalent circuit of the inverter when S4 is in the PWM state. When S4 is in ON state, a closed path is formed along with the motor windings as illustrated in Figure 6(a). When S4 is turned OFF, the energy accumulated in the windings of the motor is fed back to the supply, and thus the energy regeneration happens as it is shown in Figure 6(b). This harvested energy can be stored in battery for energy reuse.

The proposed integrated onboard charger has only 8 power switches, significantly reducing the switch count of the existing topologies, which typically require 10-22 switches [17]–[21]. Table 1 compares the proposed topology with the various battery charger topologies reported in the literature. The reduction of switches simplifies the circuit, reducing the switching and conduction losses and reduced gate driver circuitry which in turn increases the overall converter efficiency [22].

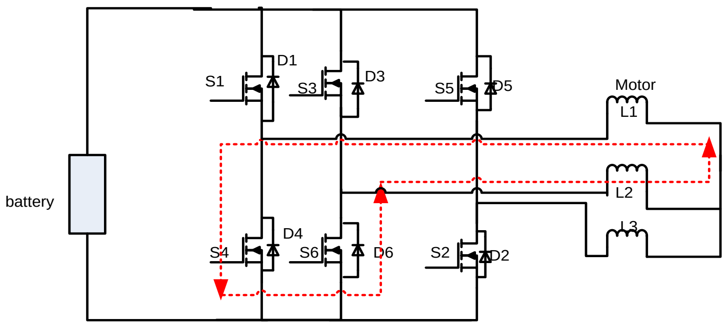
Table 1. Comparative study based on switch count in various onboard chargers in the literature, with the proposed onboard charger

Sl no	Literature	Total number of switches
1	[19]	22
2	[21]	21
3	[18]	18
4	[17]	10
5	[20]	10
6	Proposed integrated on-board charger	8

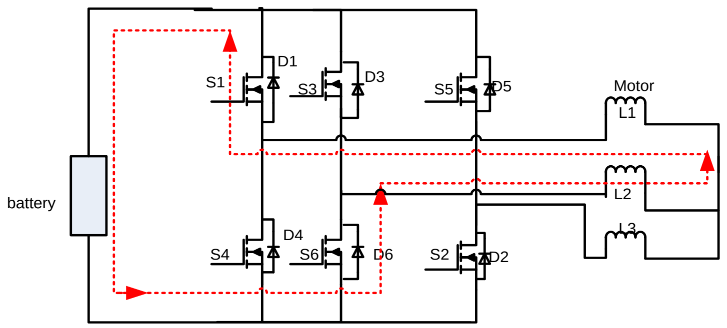


(b)

Figure 5. Propulsion mode operation of the bidirectional integrated onboard charger: (a) equivalent schematic of the proposed bidirectional on-board charger during motoring and regenerative braking phases and (b) closed loop control implemented in propulsion mode



(a)



(b)

Figure 6. Current flow in the drive during regenerative braking mode when the lower switch is operated in PWM mode and all the upper switches are turned OFF: (a) S4 in ON state and (b) S4 in OFF state

4. SIMULATION STUDIES OF THE BLDC DRIVE POWERED BY THE PROPOSED INTEGRATED ONBOARD CHARGER

Simulation studies of the proposed converter-fed BLDC drive are done in MATLAB/Simulink software [23]–[25]. Simulation parameters are listed in Table 2. Figure 7 depicts the simulation model of an integrated on-board charger-fed BLDC motor. Expanded view of the developed integrated onboard charger and its dual mode control logic is given in Figure 8. In charging mode, S1 and S2 switches are controlled to get the CC-CV mode of charging. During propulsion mode, the operation of the inverter switches follows the hall sensor pattern.

The motor drive is powered by the 24 V, 20 Ah lead-acid battery set and the desired motor speed is achieved by inner current controlled and outer speed controlled closed loop algorithm. When brake is applied, the switching sequence is programmed so that reverse power flow from motor to battery is activated and energy regeneration happens. Front-end active power factor correction is added to the circuit using a boost converter. Figure 9 illustrates the expanded view of the converter, along with its control logic, which achieves an input power factor of 0.996.

Table 2. Simulation parameters of the proposed converter fed BLDC drive

Sl no	Parameters	Value
1	Switching frequency (APFC front end converter)	65 kHz
2	DC link voltage	400 V
3	k_p,k_i(voltage loop PI controller (APFC front end converter))	0.25, 35
4	k_p,k_i (current loop PI controller (APFC front end converter))	2000, 0.25
5	Battery voltage and ampere hour	24 V, 20 Ah
6	Switching frequency (CC-CV controller)	10 kHz
7	k_p,k_i(CC-CV controller)	0.001, 0.01
8	k_p,k_i (CC-CV controller)	0.01, 0.01
9	k_p,k_i (outer voltage loop in speed controller)	100, 0.5
10	k_p,k_i (inner current loop in speed controller)	100, 0.5
11	Switching frequency (speed controller)	25 kHz
12	BLDC motor ratings	3 phase, 24 V, 2 kW

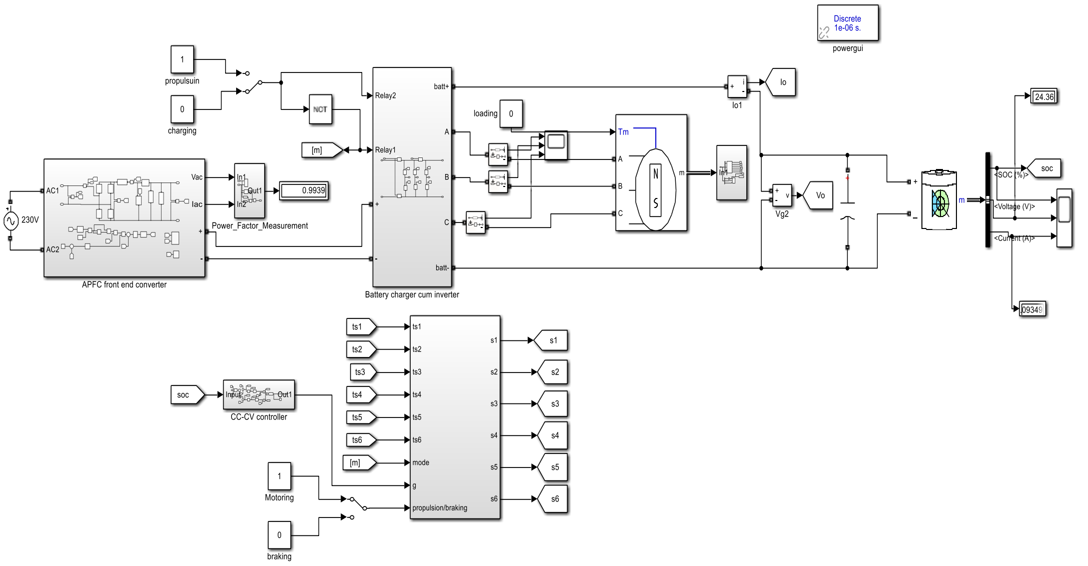


Figure 7. Simulation setup illustrating the proposed bidirectional integrated onboard charger-fed BLDC drive

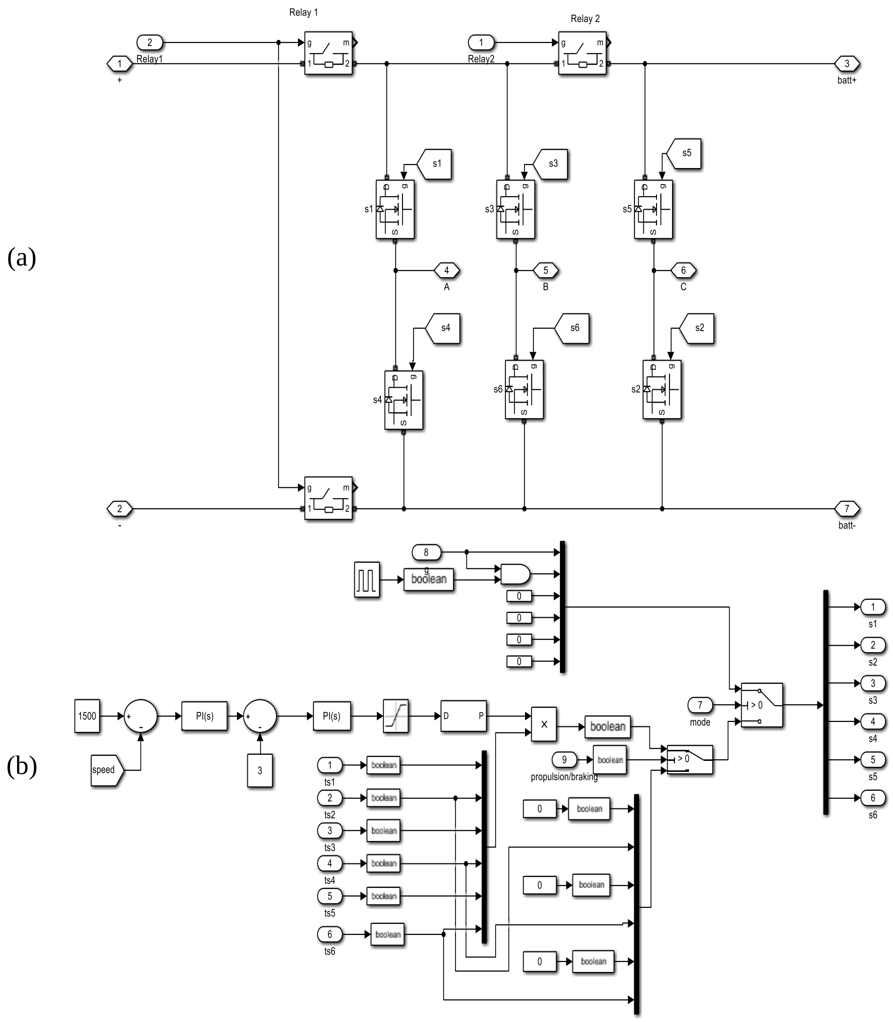


Figure 8. Expanded view of reconfigurable integrated on-board charger: (a) circuit diagram and (b) control algorithm for dual mode operation

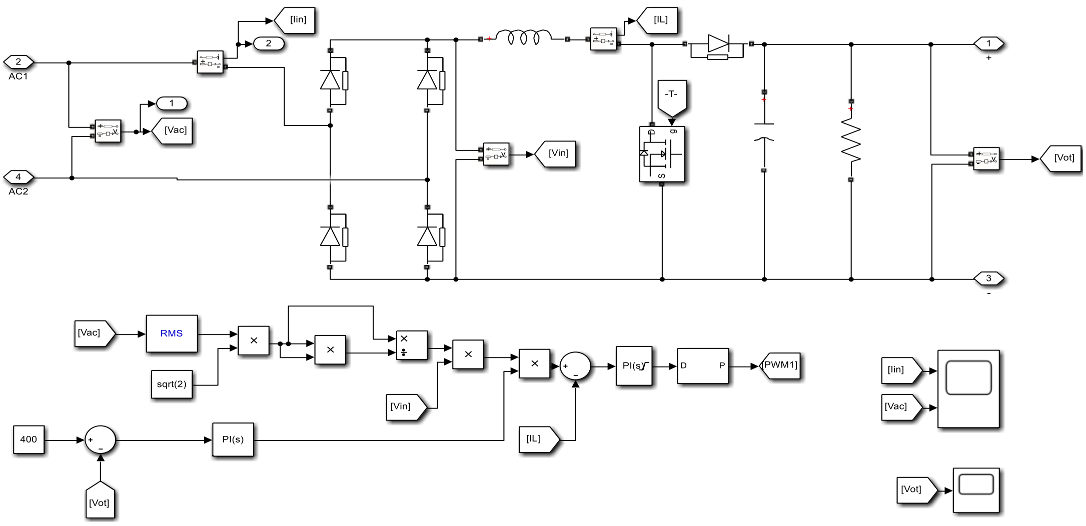
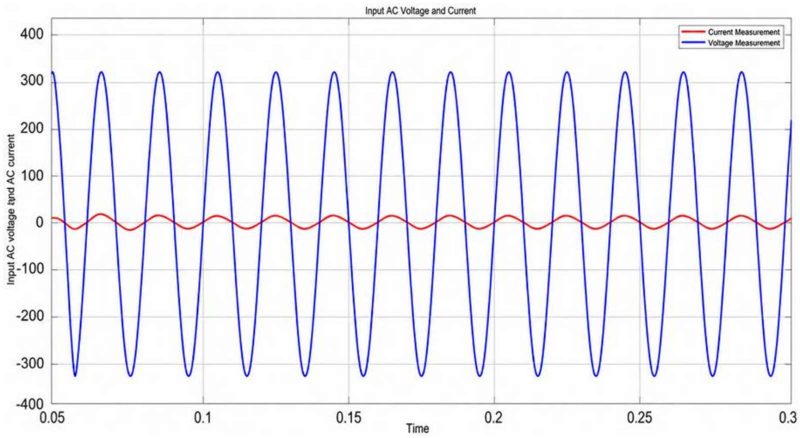


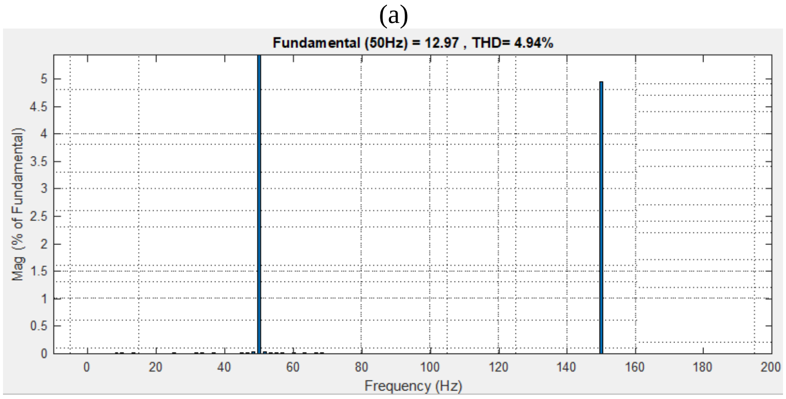
Figure 9. Expanded view of the APFC front-end converter along with its control logic

5. RESULTS AND DISCUSSION

Initially, a 230 V, 50 Hz single-phase supply is converted to 400 V DC using an APFC front-end converter. The control pulse fed to the converter MOSFET switch will aid in correcting the input current waveform in phase with the input voltage, as shown in Figure 10(a). The input voltage and current with an RMS value of 230 V and 10.6 A, respectively, have an input PF of 0.996. Total harmonic distortion (THD) of the input current is found to be 4.94%, as shown in Figure 10(b), which is under the permissible limit.



(a)



(b)

Figure 10. Input performance analysis of the proposed system: (a) input current and voltage waveforms and (b) THD of the input current of the developed converter-fed BLDC drive during its charging mode

Figure 11 indicates the battery SoC, voltage, and current waveforms during charging mode. The battery SoC is found to be increasing with voltage, slightly increasing till 80%, and remains constant at 24.37 V, and the battery current is controlled to within the safe limit [26]. The proposed charger combines the DC-DC and DC-AC stages into a compact architecture, enabling charging and propulsion modes. In charging mode, the system achieves near UPF with CC-CV mode, while in propulsion mode, it ensures proper speed control and regenerative braking operation.

In propulsion mode, during motoring operation, the desired speed of 1500 rpm is obtained by a closed-loop PI controller-based speed control, which is merged with the commutation sequence of the BLDC drive. When the brake is applied, the commutation sequence of the drive is changed to facilitate reverse energy flow from the motor towards the battery. Figure 12 indicates the motor gaining the reference speed of 1500 rpm at 0.07 seconds. The brake is applied from 0.22 to 0.43 seconds, the speed effectively getting reduced from 1500 to 300 rpm. During this duration, battery SoC is increasing, which is a clear indication of energy regeneration.

The bidirectional property of the proposed integrated converter enables its application in various V2X operating modes. In V2L/V2H operations, the front-end diode rectifier can be replaced with a three-phase PWM rectifier with APFC to ensure near UPF. For V2V operation, commonly adopted topologies such as bidirectional DC-DC converters, interleaved bidirectional converters, and dual active bridge converter [27], [28] can be incorporated. With suitable modifications, the proposed converter can be extended to support these V2X functionalities.

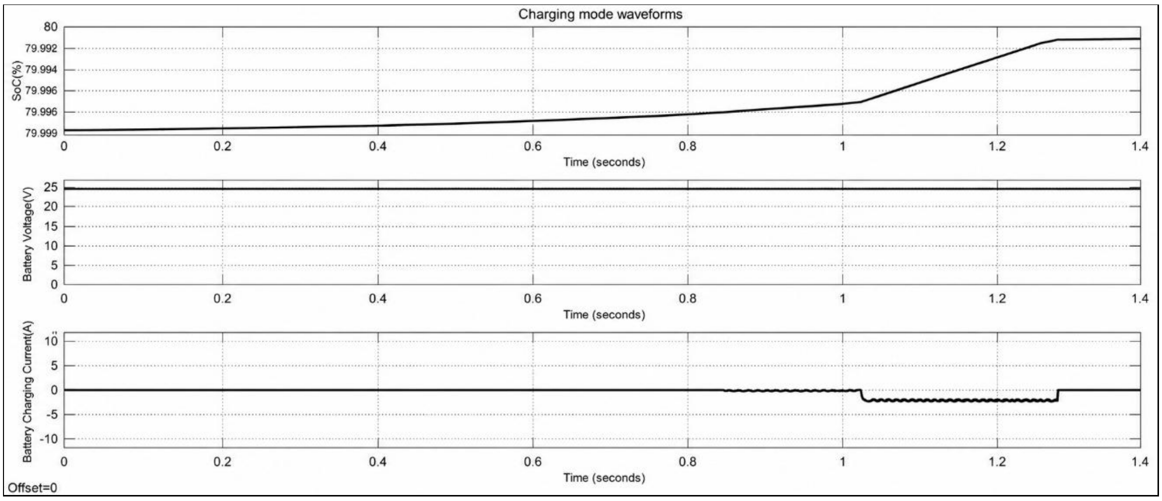


Figure 11. Battery SoC, voltage, and current waveforms during charging mode

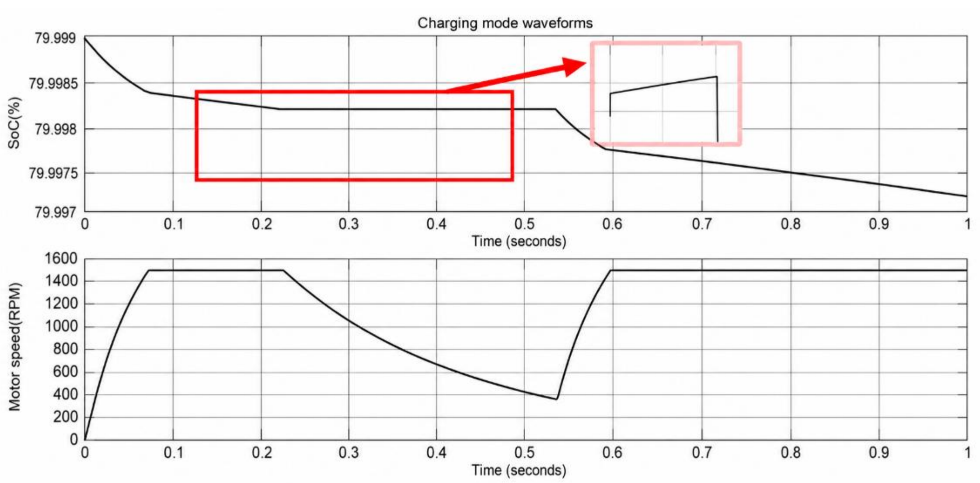


Figure 12. Motor drive speed and the corresponding battery SoC during transition from motoring to regenerative braking in the dual mode operation of the converter

6. CONCLUSION

This work developed and validated a novel dual-mode control technique for a bidirectional integrated onboard charger-fed BLDC drive, particularly for EV applications. This charger is capable of operating both as a charger and as an inverter, depending on the system requirements. By reusing the drive train components in the charger unit, the switch count is limited to 8, and the overall cost can be reduced to 30%. The control system ensures a near unity power factor (PF = 0.996) with THD of 4.96% during grid-connected charging, promoting better quality and enabling precise speed control during inverter-driven propulsion. Simulation findings verify the effectiveness of the proposed approach in achieving bidirectional power flow, mode transition, and system-level target achievements. Detailed power loss analysis and thermal behavior will be addressed in future hardware-based studies. Advanced features may be added to the proposed approach to achieve V2V and V2L modes of charging.

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AUTHOR CONTRIBUTIONS STATEMENT

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Varghese Jegathesan				✓		✓		✓		✓	✓	✓	✓	

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 authors confirm that the data supporting the findings of this study are available within the article. The data that support the findings of this study are available from the corresponding author, [CAS], upon reasonable request.

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